Experimental Investigation of
Magnetically Confined Plasma Loops

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1. Introduction

Solar prominences in the photosphere can store large amounts of magnetic energy until releasing them in an eruptive coronal mass ejection. They are commonly described as magnetic flux ropes and can be stable on timescales ranging from minutes to days despite steep density gradients. While solar prominences have been the subject of numerous satellite missions (e.g. SOHO, TRACE\(^1\)), in recent years also several laboratory experiments emerged which are devoted to simulation of magnetic flux ropes with similar topology [BH98, OMY+11, SKM+10]. In the latter, the focus is on the investigation of the transition to the explosive instability phase. By contrast, basic observations concerning the flux rope's geometric structure – both in solar prominences and the laboratory simulations – are still poorly understood.

X-ray images taken during the Yuhkoh satellite mission showed coronal loops with a surprisingly uniform cross section along the arch-shaped structures (see e.g. [Kli00]). Since the plasma is strongly magnetized, this contradicts the expectation of an axial magnetic field that diverges towards the apex with increasing height, because the strongly magnetized plasma should follow the topology of the photospheric magnetic field. Klimchuk and Klimchuk et al. investigated by means of numerical simulation whether a localized twist of a flux tube could cause the uniform thickness [KH00, KAN00]. The authors conclude, that the observed coronal loops do not show a sufficiently strong twist to explain the uniformity. Furthermore, a limit is set to the increase of the twist due to the onset of kink instability. A different approach was proposed by Bellan [Bel03]: Starting from an axial magnetic field configuration that shows “flaring” towards the apex of the coronal loop, he conceived on a phenomenological basis a mechanism which transports plasma from the footpoints towards the center of the plasma arch. In addition, frozen poloidal flux is transported along the flux tube causing it to pinch and also to twist. Subsequent laboratory investigations in a solar coronal loop simulation experiment showed no inconsistencies with this picture (e.g. [YYB05]).

Giving up the paradigm of flared magnetic field topology, Titov and Démoulin proposed an analytical model to describe the evolution of solar prominences where an axial mag-

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Magnetic field is prescribed by a sub-photospheric line current \cite{TD99}; subsequent numerical simulations performed by Török and Kliem on the basis of this model topology reproduced the evolution of a certain class of solar prominences remarkably well \cite{TK03}. However, the presumed magnetic field topology in total was more complicated requiring further components and neither the question of uniform flux rope thickness nor the analysis of expansion velocities was in the authors’ focus.

Another common property of the flux tubes generated in the laboratory simulation experiments of Bellan and coworkers and the FlareLab device under investigation in the frame of this work is the development of a constant expansion velocity \cite{Han01, TKM+12}. It is observed over a wide range of experimental parameters, including the flared magnetic field configuration investigated by Bellan et al. and the (partially realized) line current mode proposed by Titov and Démoulin. This indicates that the characteristic of constant expansion velocity is correlated to fundamental properties of the discharges under investigation. In the solar context, observations of the expansion velocity of coronal loops in the photosphere (in solar-radial direction ascending from the surface) are scarce and usually focused on the explosive phase of developing coronal mass ejections. Gary and Moore provided velocity measurements of a helical solar magnetic flux tube recorded by the TRACE satellite \cite{GM04}. They found saturation of the expansion velocity at approximately constant value after a short acceleration time interval. Furthermore, their estimates show good agreement between the measured coronal loop expansion velocity and estimates of the local Alfvén velocity.

In this work, the expansion of magnetic flux tubes in the FlareLab coronal loop simulation experiment is investigated. Driving mechanisms of the plasma evolution will be introduced in chapter 2. First, the concept of Bellan’s MHD transport mechanism will be discussed briefly. This is followed by the introduction of drift-like expansion mechanism, which possibly gives a reason for the observed constant expansion velocities.

The plasma discharge is investigated via magnetic probes and elementary optical emission spectroscopy for density and temperature determination; further diagnostics include current and voltage probes and laser interferometry. The working principles of the employed diagnostics are given in chapter 3. Subsequently in chapter 4 details on the experimental setup will be given.

Results of plasma density determination and an estimate of the electron temperature will be given in section 5.2 followed by an extensive analysis of the different components of the measured plasma magnetic field in section 5.3. Expansion velocities obtained from the various diagnostics are discussed in section 6.1 and compared to Alfvén velocity profiles constructed from the different data provided previously. The results are furthermore compared to previous results obtained at a modified version of the experimental setup for
considerably different discharge conditions. On the basis of the obtained results, in section 6.2 the relevance of Bellan’s transport scheme on the plasma evolution in the experiment and the drift-like mechanism possibly causing the constant expansion velocity are discussed. A conclusion of the presented results and an outlook on further investigations will be given in chapter 7.
2. Driving Mechanisms of Flux Tube Expansion

A solar coronal loop can be described as plasma-filled magnetic flux tube. In the solar context, sub-photospheric convective flows can produce a loop-shaped magnetic field above the surface. Bellan followed the assumption that the magnetic field strength decreases towards the apex of the loop as the distance to the source currents increases [Bel03], which is also a common assumption in the solar context. From this condition and further assumptions he developed an analytical magnetohydrodynamic (MHD) model of an axial transport mechanism leading to plasma flows from the loop’s foot points towards its apex. Limitations due to the simplifications necessary for analytic treatment may be partly overcome in numerical simulations. Such simulations may help bridge the gap between coronal loops both in the laboratory simulation and the solar context. From the results of MHD simulations, initially performed by L. Arnold and J. Dreher and the work now continued by T. Tacke and J. Dreher, a mechanism was deduced leading to a drift-like expansion motion of the simulated flux tube. In the following section, Bellan’s transport model and its predictions on the dynamic evolution of magnetic flux tubes generated in coronal loop simulation experiments will be summarized. Subsequently, the basis of the MHD simulations will be outlined and the fundamental idea of the drift expansion presented.

2.1. MHD pumping

For analytical treatment, the arch-shaped geometry of a coronal loop comprising a magnetic flux tube is straightened to a cylindrical shape. As is shown in figure 2.1, the resulting magnetic field topology retains the larger field line spread towards the center and compressed field lines towards the ends representing the loop’s foot points. In this straight configuration, the centrally bulged topology is reminiscent of a magnetic mirror trap. Assuming ideal MHD, the axial current $I$ will flow along the bulged magnetic field lines. The current-generated azimuthal magnetic field component will twist the axial magnetic field lines depending on the strength of the respective field components. The resulting helical current path becomes susceptible to plasma instabilities – namely kink and sausage modes – as the twist increases and overcomes the stabilizing effect of the axial magnetic
2. Driving Mechanisms of Flux Tube Expansion

field. Therefore, the axial magnetic field \( B_z \) is presumed strong enough to stabilize against instabilities and the geometric dimensions and magnetic field components must hence obey the Kruskal-Shafranov stability criterion [KTG73].

\[
q(a) = \frac{2\pi a B_z(a)}{LB_\theta(a)} > 1, \quad (2.1)
\]

where \( L \) is the length of the (linear) plasma.

Under the influence of the axial current, the plasma column will pinch until the radial pressure balance is achieved:

\[
(J \times B)_r = \nabla r P \quad (2.2)
\]

Assuming a uniform current density across the flux tube diameter \( a \), the pressure gradient is integrable. Note that \( a = a(z) \) was prescribed implicitly together with the bulged shape of the axial magnetic field. The pressure balance is not satisfied in axial direction along the field lines. The resulting difference is the force

\[
F_z = (J \times B)_z - \nabla z P = \mu_0 I^2 \frac{1}{2\pi^2 a^3} \left(1 - \frac{r^2}{a^2}\right) \frac{\partial a}{\partial z}, \quad (2.3)
\]

where the axial pressure gradient was obtained from the integrated radial pressure balance [Bel03]. This force is strongest on the axis, its sign is given by the slope of \( a \). Therefore, it points towards the center field line bulge from both end points. As a consequence, plasma is ingested from both ends and transported axially towards the apex, where both flows converge and stagnate.

Alongside with the plasma, azimuthal magnetic flux is accumulated in the apex, enhancing the pinch effect there. Ultimately, this leads to a plasma column with axially uniform cross section where no further plasma transport can occur.

Bellan already noted that pinching the axial magnetic field will increase the stored magnetic energy therein considerably. In order to compensate for this, he proposed that the flux tube contracts not only radially but also axially. While this is not possible in the simplified straight configuration, a looped flux tube would have the option to shrink e.g. reduce its major radius like a deflating tire. However, constraints or influence of a curved geometry with additional radial gradients in the magnetic field are not discussed.

Bellan's group conducted extensive investigations of the pumping mechanism in a solar coronal loop simulation laboratory experiment including Doppler flow velocity measurements and detection of enhanced plasma density. In section 6.2.1, these data will be critically reviewed and discussed in the context of measurements at the FlareLab experiment.
2.2. Arch Expansion in Numerical Simulations

From the beginning, the experimental work in the frame of the FlareLab project has been accompanied by complementary MHD simulations performed initially by L. Arnold and J. Dreher and continued now by T. Tacke and J. Dreher. Originally, the numerical simulations focused on the investigation of a plasma structure that is initially arch-shaped and expands under the magnetic forces described in terms of the MHD equations. Implicitly, such a formulation assumes an Ohm’s law of the shape

\[ E + \frac{1}{ne} j \times B = \eta j \]  

(2.4)

The resistivity \( \eta \) has been included here as fixed isotropic quantity and initially served exclusively to enhance numerical stability (along with further terms e.g. for numerical divergence cleaning, see reference [Arn08, ADG+08] for details). Despite the additional terms in the set of MHD equations, the physical interpretation was focused on an ideal MHD plasma.

Initial and boundary conditions are chosen in accordance with the experimental setup (cf. section 4.1): The plasma is prescribed as initially resting, semi-circular current and density distribution along the circular vacuum field of an external linear current. However, the surrounding simulation volume is not empty but filled with a dilute plasma. Values
for plasma parameters such as local densities, temperatures, and vacuum magnetic field strengths have been adapted from the experiment. The initial conditions do not describe a force-free configuration, which is, however, in accordance with the experiment. An extension of the experimental setup by an additional magnetic field component to achieve the initial force equilibrium as proposed by Titov and Demoulin [TD99, Ste11] is in progress. It is already successfully implemented in the simulation but presently discarded for the sake of comparability.

At the electrode plane boundary, the velocity is given a non-zero z-component. Plasma is ingested along the whole face of the simulation volume. The amplitude of the velocity is defined as half-wave of a sinus function, thus peaking in the center of the boundary. Furthermore, the electric field surrounding the electrodes is chosen so that

$$\mu_0 \partial_t j_z = \partial_t [\nabla \times B]_z = -\nabla \times (\nabla \times E)$$

(2.5)

yields a continuous rise of the current along the plasma arch as in the experiment. From the induction equation it is evident that this is equivalent to continuously injecting magnetic flux into the plasma.

The resistivity, originally introduced to enhance convergence, is set to values according to Spitzer’s formula for fully ionized plasma with temperatures taken from the measurements. It is not calculated dynamically or even consistently, instead it is set uniform in the whole volume.

2.2.1. Drift-like Expansion

The simulation has been iteratively extended to mimic the characteristic evolution observed in the experiment.

Upon analyzing the current density distribution in the simulation volume it becomes evident, that additional current paths besides the main plasma arch must exist. In figure 2.2 current density distributions from a simulation (performed by T. Tacke [Tac12]) with external current drive are presented. The top row shows the absolute current density in the $y = 0$ plane, spanned by the line connecting both electrode centers and the z-direction towards which the arch expands (cf. section 4.1). Since the entire simulation volume has a fixed finite resistivity, current flow is possible at any location. Specifically, current sheaths form outside the arch as mirror-currents to the expanding flux tube. Furthermore, considerable current flow is observed below the arch connecting the electrodes, as can be seen from the x-component of the current density in the bottom row of figure 2.2. This implies importance of the residual electric field between the electrodes and the existence of residual plasma below the arch able to carry current.

From the evolution in repeated numerical experiments, a simplified scheme driving the $z$-expansion of the plasma arch was derived by J. Dreher: Following the vacuum electric
2.2. Arch Expansion in Numerical Simulations

and magnetic fields, the plasma arch ignites as rather broad channel. Consequently, the arch collimates to a more compact flux tube as sketched in figure 2.3, but residual plasma surrounds the arch and more or less homogeneously fills the volume below it. Underneath the arch, the electric field retains its vacuum shape. Along the arch however, the current density is enhanced and the electric field reduces to the resistive field along the highly conductive plasma. Furthermore, the plasma current produces an azimuthal magnetic field which is, due to the semi-circular shape of the current channel, approximately constant inside the loop. Naturally, this magnetic field changes sign while crossing the current channel outwards and, again due to the curvature, shows a reduced amplitude above the arch.

In figure 2.3 components of the electric field (black) and magnetic field (red) are sketched in a Cartesian coordinate system, where the x-z-plane corresponds to a cut through the

Figure 2.2.: Total current density evolution during one simulation for two time steps (top row) and x-component of the current density connecting both electrodes (bottom row). The simulation data are scaled to dimensionless quantities. (Data provided by T. Tacke [Tac12].)
2. Driving Mechanisms of Flux Tube Expansion

Figure 2.3.: Stepwise change in the topology of electric (black) and magnetic (red) fields during ignition phase (top), collimation phase (center) and expansion phase (bottom).

arch in the electrode plane.
Essentially, the remaining vacuum electric field component \( E_x \) and the current-generated azimuthal magnetic field \( B_y \) cause an \( \mathbf{E} \times \mathbf{B} \)-drift. Along the \( z \)-axis through the apex, the fields have approximately the profiles sketched in figure 2.4. The electric field (top) decays like a dipole field in the regions below and above the plasma arch and transits continuously to the considerably reduced resistive field along the arch. The magnetic field is largely uniform below the arch and reduces steeply in the current-carrying arch region. Outside, it has changed sign and reduced amplitude, the total amplitude change being a rough measure for the total current through the arch according to Ampère’s law.\(^1\) From Ohm’s law (2.4), the drift motions can be calculated by multiplying with \( \mathbf{B} \times \) from the left:

\[
0 = \mathbf{B} \times (\mathbf{E} - \eta \mathbf{j}) + \mathbf{B} \times \mathbf{v} \times \mathbf{B}
\]

Below the arch, considerable total current may flow. However, as the area spanned between apex and electrode plane is considerably larger than the collimated arch cross section, the current density is assumed negligible in the volume below the arch. Written component-

\(^1\)For a curved geometry, additional field components enter the curl of \( \mathbf{B} \) which are omitted in the presented discussion.
2.2. Arch Expansion in Numerical Simulations

By Ex00

"above" plasma arch

"below" plasma arch

vacuum field regions

resistive field region

collimated plasma region

nearly uniform "inside" arch

Figure 2.4.: Qualitative sketch of x-component of the electric field (top) and z-component of the magnetic field (bottom) along the z-axis crossing the arch’s apex.

wise, the above equation then simplifies to \( E \equiv E_x e_x, B_z \) neglected:

\[
0 = -v_x (B_x^2 + B_y^2) + B_x (v_x B_x + v_y B_y) \quad (2.7)
\]

\[
0 = -v_y (B_x^2 + B_y^2) + B_y (v_x B_x + v_y B_y) \quad (2.8)
\]

\[
0 = E_x B_y - v_z (B_x^2 + B_y^2) \quad (2.9)
\]

Here, \((2.8)\) and \((2.9)\) are identical. The vacuum magnetic field \(B_x\) causes velocities in \(x\) and \(y\)-direction. The \(z\)-component \((2.9)\) yields a drift in expansion direction.

Following the field profiles of figure 2.4, three regions have to be considered: Below the arch, the residual electric field in \(x\)-direction will cause a \(z\)-component of the drift velocity in the magnetic field of the arch current. Inside the current channel, the electric field along the arch is considerably decreased due to the concentrated plasma current. Similarly, the current-generated magnetic field decreases inside the current distribution according to Ampère’s law, resulting in a drift velocity component, which decreases continuously towards the center of the current distribution where it disappears together with the magnetic field. Outwards from there on, the magnetic field increases again, albeit with reversed sign, and consequently the drift velocity now pushes inwards. The resulting drift of the entire plasma arch as a whole should nevertheless point outwards, because the amplitudes of both the electric and magnetic fields causing the drift movement \((E_x\) and \(B_y)\) are lower outside the arch (the electric field due to the higher distance from the electrodes, the magnetic
2. Driving Mechanisms of Flux Tube Expansion

field because of the curvature of the arch enhancing the field strength within the loop). At the same time, the total magnetic field in the denominator of equation (2.9) changes less due to the $B_x$ dependence on the external magnetic guiding field, which decays only as $1/r$. However, any resulting compressional effect will not be distinguishable from the collimation due to the pinch effect.

As a consequence of this phenomenological expansion mechanism, the plasma arc should undergo three phases which, however, will probably show smooth transitions between each other: Ignition and collimation, in which the arch should largely be at rest, and a drift-like expansion movement with almost constant velocity in $z$-direction subsequently. In section 6.2 the presented expansion and evolution schemes will be discussed in context of measurements at the FlareLab device.
3. Experimental Methods

Various different diagnostic techniques are employed to obtain the different plasma parameters: Via Stark broadening of the Balmer $\alpha$ and $\beta$ lines, electron densities are determined, and from the assumption of local thermodynamic equilibrium an estimate for the electron temperature in the plasma arch is obtained. Profiles of the line-integrated plasma density are obtained by means of CO$_2$ laser interferometry and, via a numerical Abel inversion scheme, estimates of the local plasma density across the arch’s diameter is obtained. The toroidal and poloidal component of the plasma magnetic field are measured with an array of induction probes.

For the interpretation of the collected data, the theoretical background of the diagnostic methods will be laid out in the following sections. A brief overview over the theoretic concepts in describing the broadening of spectral lines in plasmas due to electric fields will be given in section 3.1.2 with the focus on the experimental applicability for diagnostic purpose. Subsequently, arguments for the assumption of local thermodynamic equilibrium are discussed and the method of electron temperature determination from spectral line intensity ratios under these conditions is introduced. In section 3.2 the working principle of magnetic induction probes is explained. Finally, in section 3.3 complimentary diagnostic methods are briefly introduced.

3.1. Emission Spectroscopy

Spectroscopic investigation of the plasma emission is wide-spread tool for non-invasive diagnostic of plasma density and temperature. For precise determination of these parameters in most experimental operating regimes elaborate collisional radiative models and the comparison of a wide range of spectral line intensities are required.

A method of obtaining the plasma density independently of such models relies on investigating the profile width of suited spectral lines broadened by the electric micro fields of ions and electrons in the plasma, namely the Balmer $\alpha$ and $\beta$ lines of atomic hydrogen. Obtaining plasma densities from these profile shapes takes advantage of quantum-mechanical theories developed in the past 80 years. Basics of the energy shift of atomic energy levels caused by the Stark effect and how this leads to broadening of optical transitions in the atom due to the electric field distribution in the plasma will be given in the following sec-
3. Experimental Methods

...tions with the focus on diagnostic application. Subsequently, the employed method of line profile deconvolution into contributions by different physical effects will be discussed and the determination of plasma densities using conversion calibration factors from computer calculations will be explained. Finally, it will be discussed whether the plasma under investigation can be considered in a state of local thermodynamic equilibrium. An elementary method for the determination of the electron temperature under this circumstance is presented.

3.1.1. Stark-Effect

Energy levels of atoms and ions exposed to an external electric field $E$ are shifted depending on the field strength. The interaction of field and electric dipole moment $p_{el}$ of the target ion can be accounted for as additional potential in the system’s Hamiltonian [Dem96]:

$$\Delta H = p_{el} \cdot E$$  \hspace{1cm} (3.1)

In the case of ions with a permanent electric dipole moment, the interaction with the field causes the energy levels to shift linearly with the field strength. Ions without permanent dipole moment still experience energy level shifts due to the induced polarization dipole moment; the resulting shift depends on the square of the field strength. In frequency units, the shift of the $k$-th Stark component can be expressed as

$$\Delta \omega(E) = C^{(k)}_{m} E^{m} = C^{(k)}_{m'} R^{-m'}$$  \hspace{1cm} (3.2)

where $m=1,2$ refers to the linear and quadratic Stark effect, respectively, and the right expression illustrates the different radial dependencies of the frequency shifts according to the sources of the electric field (e.g. $m' = 2$ for the linear Stark effect caused by the field of neighboring perturbers which carry a charge).

The degeneracy of energy levels in the angular momentum of hydrogen and hydrogen-like ions causes the wavefunctions of the associated states to mix such that the ion as a whole has a permanent electric dipole moment. In a classical picture, the electron follows Keplerian trajectories in the central potential of the nucleus. As the law of equal areas states, the movement is accelerated towards the periapsis, yielding an asymmetric charge distribution in the temporal average.

The associated spectral line of an optical transition of an ion in an electric field splits into multiple components as both upper and lower state display splitting (and possibly shifts) according to the Stark-effect.

\footnote{Here, the movement of the system’s center of mass has been ignored which is equivalent to neglecting the fine structure splitting in Sommerfeld’s picture of the H-atom.}
3.1.2. Broadening of Spectral Lines in Plasmas

For diagnostic purposes, the correlation between full half-width (in wavelength dimensions) $\Delta \lambda_{1/2}$ and the local electron density $n_e$ for line profiles of hydrogen-like ions is given by [HLL+65]:

$$\Delta \lambda_{1/2} = 2.50 \times 10^{-9} \alpha_{1/2} n_e^{2/3}$$

(3.3)

with the theoretical (half) half-width $\alpha_{1/2}$. Essentially, this density scaling reflects the linear Stark shifts in a nearest neighbor approximation of the electric field strength. Obtaining appropriate values for $\alpha_{1/2}$ for different spectral lines has been the aim of many numerical and analytical studies. The problem is commonly approached by breaking down the plasma-generated electric field at the position of an emitter into the contributions of the plasma constituents – e.g. electrons and ions, as charged perturbers will naturally show stronger interaction – separately. As a consequence of the mass ratio of ions and electrons, the time scales of their interactions with the emitter differ considerably: The electrons passing an emitter on a hyperbolic trajectory generate a highly fluctuating electric field which can be described as short collision process, whereas the ion’s inertia leads to a field distribution that can be considered static on the timescale of the emission. This leads to two opposing approximations which will be outlined in the following paragraphs.

Impact Approximation

The interaction of perturbers and emitter is interpreted as binary collision process. Consider the duration of such a collision to be short as compared to the mean time $\tau_c = \rho/\bar{v}$ between collisions. Here $\bar{v}$ denotes the mean relative velocity (i.e. the thermal velocity) across the length $\rho$, the distance of closest approach of the colliding pair. This distance can therefore be interpreted as an impact parameter for the collision. Under this condition, the autocorrelation function $\phi(s)$ can be calculated, which depends on the probability of a collision event. Hence, it links the line shape to atomic collision cross sections and the perturber velocity distribution function. Following Fujimoto, the following expression is obtained [Fuj04]:

$$\phi(s) = \exp \left[ -N \left\langle v (\sigma_r - i\sigma_i) s \right\rangle \right]$$

(3.4)

Here $N$ denotes the number of particles, $\langle \ldots \rangle$ the average over the velocity distribution and $\sigma_r$ and $\sigma_i$ the real and imaginary part of the impact broadening cross section, respectively. These cross sections comprise all inelastic collisions linking upper and lower level of the investigated transition with other perturbing states of the atom as well as the cross section for elastic collisions [Bar58]. However, energy transfer onto the perturbers during the
3. Experimental Methods

collision process (back-reaction) is neglected. The Fourier-transform of $\phi(s)$ of equation (3.4) can be calculated directly, it gives the Lorentzian line profile $I(\omega)$ [Kun09]:

$$I(\omega) = \frac{\gamma}{2\pi} \frac{1}{(\omega - \omega_0 - \Delta)^2 + (\gamma/2)^2}$$ (3.5)

With the half-width $\gamma = N \langle v\sigma_r \rangle$ and the central frequency $\omega_0$ shifted by $\Delta = N \langle v\sigma_i \rangle$. The width can be interpreted as collision-induced reduction of the state’s lifetime causing an increased uncertainty of the corresponding energy state. The shift originates when the perturber nearing the emitter changes the oscillator frequency at the moment of emission. As all these perturbations of a statistical ensemble have the same sign, they cause a shift in the resulting average as well.

The line width is dominated by collisions causing large phase shifts e.g. with small impact parameters. These strong collisions are defined as causing a phase shift larger than 1 rad. As integrating the radius-dependent frequency shift (3.2) over the duration of a collision for a particle moving with $\bar{v}$ yields the caused phase shift, the impact parameter for a phase shift of 1 rad can be obtained [TLJ99], it is called Weisskopf radius $\rho_0$. From quantum-mechanical calculations of hydrogen line broadening, the Weisskopf radius (for perturbing electrons with $T_e = 1$ eV) can be expressed as [KG68] (via [TOAD00]):

$$\rho_0 = \frac{\hbar(n^2 - n'^2)}{m_e v_e} \approx 1.5 \times 10^{-9} \text{ m}$$ (3.6)

Here, $n = 4$ and $n' = 2$ refer to the principle quantum number of the upper and lower state of the spectral transition of H$\beta$, respectively. The resulting half width due to particle collisions can be expressed in terms of the mean time between strong collisions $\gamma = 1/\tau_e$ (where $\rho \equiv \rho_0$) which leads to the following approximation of the cross section in terms of the Weisskopf radius [Coo66]:

$$\gamma \propto \rho_0^2 n \bar{v}$$ (3.7)

with the particle density $n$. The cross section of the Stark broadening in the impact approximation is given by the circular surface spanned by the Weisskopf radius.

The impact approximation is valid in the frequency interval $\Delta \omega$ around the unperturbed frequency $\omega_0$ [TLJ99]:

$$\Delta \omega = |\omega_0 - \omega| < \frac{1}{\tau_e} = \frac{\bar{v}}{\rho_0}$$ (3.8)

If the validity interval is larger than the profile width $\gamma$ the entire profile shape is impact dominated. A condition for this can be deduced comparing (3.7) and (3.8):

$$\frac{\Delta \omega}{\gamma} \approx \frac{\bar{v}}{\rho_0 n \bar{v}} = \frac{1}{\rho_0^2 n} > 1$$ (3.9)
Impact processes therefore dominate when the number of particles in the Weisskopf sphere around the emitter is very small.

**Quasi-static Perturbation**

Consider now the opposite extreme of large mean time between collisions,

\[
\Delta \omega > 1/\tau_c \propto \bar{v}/\rho_0. \tag{3.10}
\]

The maximal shift is reached when the distance \( \rho_0 \) is shortest. As condition (3.10) implies a phase shift of 1 rad, this closest distance amounts to the Weisskopf radius.

Since the interaction time of perturber and emitter is large compared to the duration of a transition, the electric field generated by the plasma ions can be considered constant for the duration of an emission process. First considerations to calculate this microfield go back to Holtsmark [Hol19]. He assumed the ions to be statistically independent (from each other as well as the perturber) and randomly distributed and thus obtained an expression for the field distribution function in terms of the reduced field strength \( \beta = F/F_0 \), which is the electric field strength \( F \) at the position of the emitter normalized to the field strength \( F_0 \) of a neighboring perturber.

In Holtsmark’s considerations, ions and electrons are regarded independent. Hooper extended the calculations to account for correlations in terms of Debye-shielding of the ionic microfield [Ho06]. This was achieved by introducing a scaling parameter \( \alpha = \rho_m/\rho_D \), the ratio of mean interparticle distance \( \rho_m \) and Debye-radius \( \rho_D \), which leads to a flattening of the distribution for small values of the reduced field. However, as the strongest contribution arises from the nearest neighbor, the distribution’s wing and asymptotic behavior remain unaltered. In the case of linear Stark effect, the field distribution given by Holtsmark (resp. Hooper’s modifications thereof) directly gives the shape of the spectral intensity distribution of the respective Stark component.

**Computer Simulation of Plasma Electric Fields**

For interpretation of measured half-widths in terms of electron densities in the frame of this work, theoretical half-widths by Gigosos and Cardeñoso will be employed [GC96]. While the authors’ focus lies on including ionic microfields into their calculation to properly include the contribution to the profile width, they do not aim to produce properly shaped profiles. Cardeñoso and Gigosos simulated a “plasma” environment with different numbers of particles in a spherical volume around an emitter to generate a time sequence of the electric field seen by an emitter. This electric field is then entered into Schrödinger’s equation to solve for the time-dependent quantum-mechanical autocorrelation function. In the time average (being equivalent to an ensemble average in this scheme, as the plasma
3. Experimental Methods

Figure 3.1.: Electron density as a function of half-width for the plasma simulation approach \([GC96]\) and fit via equation (3.3).

particles are presumed to be statistically independent and moving randomly) the line profile is obtained from the Fourier-transform of the autocorrelation function. The results of the calculations are tabulated in terms of the full width of the profiles. In figure 3.1 the electron density dependence on the profile half width is plotted for the hydrogen Balmer \(\alpha\) and \(\beta\) lines at plasma temperatures of 15000 K. The curves follow relation (3.3), as indicated by fits to the simulation points. Doppler broadening due to thermal motion is not taken into account in the calculation. However, this can be included by a simple convolution. Specifically in the low density case, the simulated line widths show considerable influence of the ion dynamics and, according to the authors, agree better to experimentally obtained results than (analytic) calculations by Griem and Vidal, Cooper and Smith \([KG68, VCS73]\). The authors state that calculated widths are overestimated by up to 3\%, a value obtained from comparison of different simulation runs with higher plasma densities inside the simulation sphere.

Gigosos and Cardeñoso do not provide complete line profiles. In order to obtain an error estimate, measured line profiles are compared with tabulated profiles provided by Stehlé and Hutcheon \([SH99]\). Their model microfield method (MMM) is based on a scheme originally devised by Frisch and Brissaud: Here, the interaction of perturber and emitter is
3.1. Emission Spectroscopy

described in terms of stochastic changes of the surrounding microfield’s amplitude [FB71, BF71]. This amplitude is constant for the time between abrupt changes, the distribution function of these “jumps” itself is a function of the field amplitude. For the distribution functions of the microfields, they chose Hooper’s modifications to the Holtsmark fields, as introduced in section 3.1.2.

While a wide range of plasma parameters is already covered, the authors furthermore provide an interpolation routine to generate profiles for arbitrary intermediate plasma parameters.

3.1.3. Deconvolution of Measured Spectra

In the previous sections, line shapes resulting from different regimes in the interaction of charged particles have been discussed. A line profile would even comprise contributions of impact and quasistatic broadening for different perturber species. However, for plasma diagnostic purposes, e.g. determination of the plasma density from the profile width, knowledge of the detailed line profile is not required. In fact, it is quite customary to assume a Lorentzian profile shape for the Stark broadening: According to the derived validity criterion (3.9), the number of particles in a Weisskopf-sphere should be small considering the radius of $1.5 \times 10^{-6} \text{m}$ calculated before and the plasma density of $1 \times 10^{22} \text{m}^{-3}$ expected in the experiment. The line shape will therefore be dominated by impact processes with modification to the profile in the center due to ionic contributions.

In this work, for the Stark-broadened contribution to the total line width a Lorentzian distribution with width $\omega_S$ is presumed, even for the hydrogen Balmer-β line, which has a considerably different shape in the line center. To investigate the error arising from this fitting method neglecting parts of the underlying physics, a sample of profiles will be compared with complete line profiles by Stehlé and Hutcheon [SH99].

Advantages of this procedure are the reduced computational cost and the possibility to separate broadening by different contributions: The total width $\omega_T$ of a line profile comprises the apparatus width $\omega_A$ and the desired Stark-broadening width $\omega_S$. Depending on the plasma conditions, further processes such as Doppler broadening with width $\omega_D$ can contribute as well. The apparatus profile (cf. section 4.3) as well as potential Doppler broadening contribution emerge as Gaussian line shapes. The profile resulting from the convolution of Gaussian contributions and the assumed Lorentzian shape for the Stark broadening will be a Voigt profile function.

For the total Gaussian contribution $\omega_G$ holds [Kum09]:

$$\omega_G = \sqrt{\omega_A^2 + \omega_D^2} \quad (3.11)$$

Further reason for the physically inappropriate fit function originates from the fact that the small dimensions of the plasma under investigation here lead to observation through layers
with different plasma conditions. Apparently, emission from regions of lower electron density will show considerably less broadening, they may even be as narrow as the apparatus profile. To account properly for this, the total fit function applied to all measured profiles presented in this work has the shape:

$$F = \text{Gaussian}(\omega_A) + \text{Voigt}(\omega_L, \sqrt{\omega_D^2 + \omega_A^2})$$  \hspace{1cm} (3.12)

The contributions from different plasma layers will be discussed together with an estimate of the error of the determined plasma densities in section 5.2.2 in the frame of an exemplary line shape analysis. Since the narrow emission covers the line center, the chosen fit function can be interpreted as fitting to the profile wings, where a Lorentzian shape should prevail. Modeling a more physical line shape (e.g. multiple layers of intensity contribution to the total detected profile with individual local densities, or, in the case of $H\beta$, a double-peak fit function properly representing the line structure) would require considerably more fitting parameters. Such an approach would therefore probably lead to a more ambiguous result.

### 3.1.4. Temperature Determination

In fully ionized plasmas, Coulomb collisions determine the plasma resistivity which is for this case given by Spitzer’s formula. Since charges carrying the current also add to the resistive drag reducing it, the resistivity is only weakly dependent on the plasma density (via the Coulomb-logarithm) and thus essentially determined by the plasma temperature, $\eta \propto T^{-3/2}$ (cf. [Che84]). At the same time, the resistivity determines whether magnetic fields are advected with the plasma or can diffuse across it. For the purpose of the presented experiment, a strong coupling of plasma and magnetic field is desirable and the plasma temperature therefore a crucial quantity.

Since no elaborate collisional-radiative model was available to solve for the temporally-resolved plasma emission, a more crude approach is chosen for a temperature estimate. Taking the high electron density of the order of $1 \times 10^{22} \text{m}^{-3}$ into account, the electronic collision frequency is very high ($\nu \geq 1 \times 10^{13} \text{s}^{-1}$ assuming a $T_e$ of 1 eV). At the same time, the current-carrying drift velocity $j = e n v_D$ is small. As a consequence, the velocity distribution function of the electrons can be assumed Maxwellian with a small shift along the plasma arch. The level populations may therefore be in local thermodynamic equilibrium (LTE) and hence given by the Boltzmann distribution and the degree of ionization by the Saha-Eggert equation. For hydrogen and hydrogenic ions, Griem derived a validity criterion for assuming LTE [Gri64]. Demanding that the population dynamics be dominated by collisions, e.g. the collisional depopulation rate of a level be greater by a factor 10 (arbitrarily chosen) than the
corresponding radiative rate he obtained:

\[ p > 28 \cdot \left( \frac{T_e}{z^2} \right)^{17} \left( \frac{n_e}{z^7} \right)^{-2} \]  \hspace{1cm} (3.13)

with the electron density \( n_e \) in \( \text{m}^{-3} \) and electron temperature \( T_e \) in electron volts. \( z \) denotes the ionic charge of the next ionization step (e.g. for singly ionized argon \( z = 2 \)). The relation yields for \( n_e \sim 1 \times 10^{22} \text{m}^{-3} \) and \( T_e \sim 1.5 \text{eV} \) that all states with \( p \geq 2 \) can be considered in LTE, that is all states beyond the ground state.

Fujimoto and McWhirter reined this criterion investigating a collisional-radiative model \[FM90\]. They give analytic fit functions for their numerically obtained results.

\[ p \geq \left( \frac{T_e}{z^2} \right)^{-0.43} + 279 \left( \frac{n_e}{z^7} \right)^{-0.15} \]  \hspace{1cm} (3.14)

For the same values as above, this considerably raises the threshold of levels to be expected in LTE to \( p \geq 6 \).

Condition (3.14) is more strict than Griem’s derivation. In fact, the authors motivate their work with experimental examples where non-LTE emission was observed although condition (3.13) was fulfilled (e.g. the positive column of an argon glow discharge). Therefore, Griem’s threshold is a necessary condition, but not a sufficient one. Unfortunately, most ionic emission levels observed in this work will be in the range of \( p = 3 \sim 6 \) and not from hydrogen-like ions. All results regarding temperatures should therefore be considered with great care.

Under the assumption of LTE the electron temperature can be determined comparing the relative intensities of different emission lines: The measured intensity \( I_{pq} \) of a transition from level \( p \) to level \( q \) can be written as

\[ I = \frac{A_{pq}Lhc}{\lambda_{pq}} Q(\lambda_{pq})n_p \]  \hspace{1cm} (3.15)

with the Einstein coefficient \( A_{pq} \), the length of the observational volume \( L \), wavelength \( \lambda_{pq} \) of the transition, quantum efficiency \( Q \) of the detector and the population density \( n_p \) of the upper excited level. The population density can be expressed in terms of the ground state density of the according ionization stage via the Boltzmann distribution and (for only singly ionized plasmas) the Saha-Eggert equation can be used to express the ratio of ionic to atomic ground state. The ratio of the measured intensities of an ion line (subscript \( i \)) and a neutral line (subscript \( a \)) is then:

\[ \frac{I_i}{I_a} = \frac{1}{2n_e} \frac{A_i \lambda_i g_i Q_i}{A_a \lambda_1 g_1 Q_2} \left( \frac{2\pi m_e}{h^2} \right)^{3/2} \cdot T^{-3/2} \exp{(E_a - E_i - E_{ion})/T} \]  \hspace{1cm} (3.16)
3. Experimental Methods

where the \( pq \) notation for the transitions has been dropped, \( g_i \) and \( g_a \) denote the statistical weights of the excited states from which the emission originates, \( E_a \) and \( E_i \) the excitation energy from the corresponding ionic ground state and \( E_{\text{ion}} \) the ionization potential. Note that the temperature \( T \) is in electron volts. For given parameters and intensities, the equation is then solved numerically for the temperature. The required parameters were taken from the database of the National Institute of Standards and Technology (NIST) [RKR12].

3.2. Magnetic Probes

To determine magnetic fields in pulsed power discharges, it is common practice to employ induction-based probes, e.g. \( \dot{B} \)-probes. The change of magnetic flux \( \Phi \) across the area of a conducting loop induces a voltage drop which is recorded with an oscilloscope:

\[
U_{\text{ind}} = -\frac{d\Phi}{dt} = -\frac{d}{dt} \int \mathbf{B} \cdot d\mathbf{A} \approx \dot{\mathbf{B}} \cdot \mathbf{A} \quad (3.17)
\]

Since the area \( A \) of the probe is fixed, the time-integral of the signal is then proportional to the average magnetic field strength perpendicular to the loop area. While the proportionality factor ideally should be the area of the loop, it is easier and more precise to determine a calibration factor experimentally for miniaturized probes. To this end, a magnetic field source of known strength is required. Commonly employed for this purpose are Helmholtz coils (as e.g. in [Rah07]), since the magnetic field on their axis can be expressed analytically. Here, a singly-wound \( \Theta \)-pinch coil has been used. The field (for a coil of negligible thickness with homogeneous current density) on the axis can be calculated solving Biot-Savart’s law:

\[
\mathbf{B}(r, z) = \frac{\mu_0 I}{2L} \left[ \frac{1}{\sqrt{(r-R)^2 + (z-L/2)^2}} - \frac{1}{\sqrt{(r-R)^2 + (z+L/2)^2}} \right] R e_r + \ldots \quad (3.18)
\]

\[
+ \frac{\mu_0 I}{2L} \left[ \frac{z-L/2}{\sqrt{(r-R)^2 + (z-L/2)^2}} - \frac{z+L/2}{\sqrt{(r-R)^2 + (z+L/2)^2}} \right] \frac{R}{r-R} e_z
\]

where \( e_r \) and \( e_z \) are the radial and axial unit vectors, \( I \) the total coil current, \( L \) the length of the coil (positioned such that \( z = \pm L/2 \) gives the coil ends) and \( R \) is the coil radius. The radial dependency arises from the finite length of the coil. For calibration measurements, the probe can be placed at either the center of the coil \( (r = z = 0) \) or on axis at the top surface \( (r = 0, z = L/2) \) in order to detect the axial magnetic field. Here, equation 3.18
simplifies to:

\[
B_z(0,0) = \frac{\mu_0 I}{2} \sqrt{\frac{1}{R^2 + L^2/4}}, \quad \text{and} \\
B_z(0, L/2) = \frac{\mu_0 I}{2} \sqrt{\frac{1}{R^2 + L^2}} 
\]

The calibration factor \(c\) for the probe can then be determined for each probe by measuring the coil current according to:

\[
c = \int U_{\text{probe}}(t) \, dt / B_{z,\text{coil}}(t) 
\]

Comparison with equation 3.17 confirms that \(c\) is essentially the probe area. As is obvious from their working principle, magnetic probes of this type are only sensitive to changes of the magnetic field. Furthermore, their size and number of windings are limited by the required time resolution as both increase the inductivity. The construction of the employed probes will be discussed in section 4.4 together with the calibration procedure.

3.3. Complementary Diagnostics

Ionization gauge

As the neutral gas supply of the discharge is injected shortly prior to the discharge (cf. section 4.1), the distribution is spatially strongly non-uniform and transient on a millisecond timescale. Most commercial pressure gauges, however, are not built for detecting rapidly changing gas pressures. Therefore, a home-made ionization gauge was constructed to determine the neutral gas density in the frame of a diploma thesis [Tac11].

The employed ionization gauge consists of two collector electrodes and a heated emission filament, following the design of Schulz and Phelps [SP57]. Applying a voltage of the order of 100V across the collectors and keeping the emission filament on a potential between both collectors, the thermionic electrons will be drawn towards the positive collector. If the voltage difference is large enough, they will undergo several ionization processes before reaching the electrode, the thereby produced ions being drawn towards the negatively biased collector. For a simple geometry with a parallel-plate configuration of the collectors and the filament in the volume between them, the currents to both collectors can be correlated to the pressure via a proportionality constant. This constant can be obtained in a calibration measurement with stationary environment pressure via comparison with a commercial pressure gauge. With the calibration factor, measurements of the time sequence of both collector currents can be converted into time sequences of the neutral gas pressure at the position of the probe tip. Details of the method, including the calibration procedure and error estimates of the results, can be found in reference [Tac11].
Electrostatic Triple Probe

Electrostatic probes are a common diagnostic for steady state plasma experiments. A single conducting probe tip is introduced into the plasma and the current to the tip is detected for a range of potential differences between probe and plasma. From this current-voltage relation, plasma density and temperature and even the electron energy distribution function can be obtained (e.g. [LL94]).

In the case of transient pulsed discharges, the timing often does not allow for measuring the entire current-voltage relation. Instead, multiple probe tips are introduced into the plasma, assuming the same plasma conditions at all probe tips. An electrostatic triple probe consists of three probe tips: two probe tips are biased versus a third floating tip. Monitoring the bias voltages and measuring the currents to these probe tips, an estimate for electron density and temperature can be obtained assuming a Maxwellian energy distribution of the plasma electrons.

Details on the evaluation of triple probe data can be found in [CS65], the construction is thoroughly described in [Mac09]. Considerable magnetic field strengths at the probe tips can be expected during the discharge operation. An analysis of the significant influence of the magnetic field on the obtained results for our experiment can be found in [MKS+11].

CO$_2$ laser interferometer

For independent determination of the electron density, a CO$_2$ laser interferometer operated at a wavelength of 9.3 µm in a classical Michelson-like layout is employed. Plasma interferometry takes advantage of the change in phase velocity caused by the free charges in the plasma. The index of refraction $n$ for an electromagnetic wave with frequency $\omega_{em}$ traveling through plasma is:

$$n = \sqrt{1 - \frac{\omega_p^2}{\omega_{em}^2}} \approx 1 - \frac{\omega_p^2}{2\omega_{em}^2}$$

(3.22)

with the electron plasma frequency $\omega_p$. Note that in the derivation of relation 3.22, it was assumed that the wave frequency is much larger than the electron gyro frequency. Taking the maximum local magnetic field to be of the order of 1 T the ratio of these frequencies is about $10^{-3}$. As the wave frequency is furthermore much larger than the electron plasma frequency (ratio of about $3 \times 10^{-2}$), the square root can be expanded into a Taylor series and a linear dependence of the phase velocity on the electron density is obtained.

The change in phase of the scene beam crossing a plasma column of thickness $L$ versus the reference beam is then (assuming $n_{air} = 1$ for the reference arm):

$$\Delta \phi = re\lambda_{em} \int_L n_e dl$$

(3.23)
3.3. Complementary Diagnostics

Figure 3.2.: Illustration of the radial profile reconstruction following Gottardi: In a stepwise process discs are stacked. After increasing the stack size, the projected profile is calculated and compared to the input profile obtained from a measurement. Size and position of the next disc are chosen from this comparison.

where $\lambda_{em}$ is the laser wavelength, $r_e$ the classical electron radius and $n_e$ the local electron density [PSS05, HWF65].

The phase shift can be measured with high temporal resolution. Therefore, when the plasma arch crosses the scene beam in the experiment a radial profile of the line-integrated electron density is recorded (cf. section 4.5). In order to obtain local electron densities, a numerical inversion procedure has been applied, which will be discussed in the following section.

Gottardi Inversion Technique

An algorithm proposed by Gottardi is employed to invert the line-integration [Got79]. The working principle is visualised in figure 3.2. Circular discs of predefined thickness are stacked in a step-wise process. Starting from the wings of the projected profile, at first a disc of equal diameter as the profile is chosen. For this disc the contribution to the projected profile is calculated. Subsequently, this contribution is subtracted from the original projected profile, yielding an intermediate profile (indicated as blue dashed line in the figure). Due to the contributions from the first disc, the profile will be reduced in the wings and be more narrow than the original profile. At this point the next disc is added to
the stack, with a reduced diameter determined from the width of the intermediate profile. These steps are repeated until the original profile is reproduced completely. In the course of the procedure, an asymmetric projected profile will lead to relative shifts of the positions of the centers of discs in the stack, as shown in the center of figure 3.2. Finally, the contributions of the individual discs are added, the sum yielding the local profile at a position parallel to the “projection screen” of the measured (projected) profile.

Certain conditions have to be satisfied for proper application of this algorithm: The stacked circular discs are contour lines of the inverted profile. In a rigorous treatment the algorithm is therefore not applicable if non-circular contour lines are expected. The procedure is sensitive to the decay of the wings of the projected profile. Uncertainties and offsets there lead to considerable errors in the inverted profile, because the projection length through the discs becomes very short there. This short length has to be compensated by “thicker” discs (or equivalently by stacking multiple discs). Finally, the routine as employed in the frame of this work does not account for hollow profiles. In principle it is possible to modify the algorithm accordingly, however, Gottardi already showed that under this condition the solution is not unique anymore.

For application to interferometric data and camera luminosity measurements, specifically the condition of circular contour lines is probably violated. Furthermore, a hollow profile of the luminosity is observed at various axial positions along the arch.
4. Experimental Setup

The experimental setup comprises multiple components: In sections 4.1 and 4.2 different designs for the modular plasma source will be presented. General properties, e.g. concerning the timing and the electrical properties of the discharge will be laid out. However, more in-depth description concerning design choices in view of the theoretical model proposed by Titov and Démoulin can be found in [Ste11]. Subsequently, the design of the diagnostic devices with focus on the spectroscopic system and the employed magnetic probes is presented.

4.1. Line Current Source

The discharge chamber is a cylinder of 66 cm length with a diameter of 68 cm (resulting in a volume of roughly 250 l). A two-stepped pumping system (comprising a rotary vane pump and a turbomolecular pump) yields a base pressure below $1 \times 10^{-4}$ Pa. On the front face of the cylindrical vessel the electrode system flange can be mounted. Diagnostic access is possible via several lateral flanges as well as a flange at the opposing face of the chamber. Furthermore, a linear translation stage inside the chamber allows for movement in a range of 30 cm in z-direction of employed probes in between discharge operation.

The line current source (LCS) is chronologically the second electrode design, it is shown schematically in figure 4.1(a). It comprises two thin slotted disk electrodes of 2 cm diameter mounted symmetrically in a ceramic plate (23 cm diameter, 1.7 cm thickness) with a distance of 8 cm of their respective centers. Via centered drillings, these disks serve simultaneously as gas injection orifices and electrodes. The electrodes are connected to a capacitor bank with a total energy of 1 kJ. Each electrode is connected to a 120 mF capacitor, the capacitors are symmetrically charged to up to $\pm 3$ kV versus ground. The total voltage difference of up to 6 kV is applied simultaneously to both electrodes by means of a special semiconductor switch (ABB Switzerland). The discharge current is a damped sinus with a (gas type dependent) maximum amplitude of approximately 35 kA in hydrogen discharges reached after a rise time of 13 µs.
4. Experimental Setup

Behind the ceramic mounting plate of the electrodes and thus outside the vacuum chamber, a linear conductor is attached. The linear conductor is orthogonal to a line connecting both electrode disk centers and parallel to the mounting plate. It is connected to a capacitor bank designed as pulse forming network (PFN). For a duration of approximately 10µs, this bank provides a constant current of up to 20kA at a charging voltage of 25kV. This current generates a circularly symmetric magnetic field of up to 90mT (at 4cm distance) that scales linearly with the charging voltage, indicated in red in the figure. The field lines connect both electrodes on a curved path albeit with no gradient in the field strength along their length. Note that the feeds to the line current contribute to the total field reducing it along the center line between the electrodes by roughly 20% as compared to an infinitely long conductor. Furthermore, inductive losses in the electrodes reduce the magnetic field on their surface by about 40%.

Externally, the charging voltages of PFN and main discharge capacitor bank can be modified to study the influence of different ratios of axial to azimuthal magnetic field on the plasma formation and evolution. Furthermore, a gas mixing chamber allows for custom gas combinations that can then be injected via the fast gas valve. By means of a flow controller and gas-type-insensitive pressure gauge, the mixing ratios can be controlled. Furthermore, the pressure in this mixing vessel determines the amount of gas injected, which can have considerable influence on the plasma parameters. As the neutral gas cloud expands roughly with the mass-dependent sound speed, ignition delays have to be adapted when changing mixtures. As has been determined by means of a fast ionization gauge, the delays range from about 1ms for hydrogen to 6ms for argon, these two gases marking the lightest and heaviest under investigation.

In the course of an experiment, the first step is to inject gas via a fast gas valve. Within 1ms to 6ms (depending on the operating gas) the gas clouds emerging from the electrode orifices overlap. Next, the capacitor bank connected to the linear conductor is triggered. After a delay of 6.5µs allowing for the line current to reach its plateau value, the main discharge is triggered. Across the overlap of the gas clouds emanating from the electrodes, an arch-shaped current channel forms and begins to expand. Note that the electronics of the semiconductor switch introduce another delay of 1.3µs, the plasma ignition as monitored with ccd cameras begins at 7.8µs. In figure 4.1(b), the timing of the capacitor discharges is shown in terms of the current signals. The average “life time” of the arch-shaped flux tube is indicated as gray rectangle. The time scales in data presented here will always refer to the trigger of the PFN as zero point.
4.1. Line Current Source

(a) Side view of the line current source electrode system (from [Ste11]).

(b) Current measured with Rogowski coils to illustrate the timing.

Figure 4.1.: Schematic of the line current source side-on (a) and timing of the various discharge components in terms of line current and main discharge current (b). The coordinates used for description throughout this work are sketched in the left figure: The x-axis connects the centers of both electrodes, its origin is centered between the electrodes; the z-axis is perpendicular to the ceramic mount plate.
4. Experimental Setup

4.2. Permanent Magnet Source

In previous electrode system design, large semicircular electrodes were employed (diameter 22 cm) with eccentric drillings for the gas injection, again at a distance of their centers of 8 cm. Figure 4.2 shows a sketch of the electrode system, it follows closely the design of the coronal loop simulation experiment proposed by Bellan and Hansen [BH98, Han01]. A thorough description of the realization of this design at the FlareLab experiment is given in [Ste11].

Figure 4.2.: Sketch of the permanent magnet source electrode design with bulged magnetic field topology. The discharge forms along the overlap of gas clouds. To avoid short-cutting across the gap between electrodes in later stages of the discharge a plastic spacer is placed in between (form [Ste11]).

Instead of a line current, a permanent horseshoe magnet mounted outside the discharge chamber provides the magnetic field connecting the electrodes. The magnetic field has a strength of about 100 mT on the electrode surfaces which decays rapidly to about 10 mT at 4 cm distance from the electrodes where the plasma usually forms. As a consequence of the almost dipolar field topology inside the vacuum chamber, there are considerable gradients in magnetic field strength along the field lines connecting both electrodes. Specifically in front of the electrodes, the surfaces of constant magnetic flux form a funnel-like shape as is required by the magnetohydrodynamic pumping model introduced in section 2.1.

Further components of the setup as introduced in the previous section remain unaltered, with the exception of the PFN which is not employed in this configuration. The discharge timing is therefore given with respect to the main discharge trigger as zero point.
4.3. Spectroscopic System

The central element of the employed spectroscopic system is a Spex 1704 Czerny-Turner-type spectrograph. It has a focal length of 1 m and an f-number of f/9. With the employed grating (1200 grooves/mm, blazed at 500 nm), and a linear dispersion of 8 Å/mm. The characteristics of the system are summarized in Table 4.3. The theoretical resolving power is given by:

$$\frac{\Delta \lambda}{\lambda} = (mN)^{-1} \leq 8 \cdot 10^{-6} \tag{4.1}$$

with the number of illuminated grating grooves $N$ and the order $m$ of diffraction. All measurements are performed in first order.

<table>
<thead>
<tr>
<th>Spex Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>focal length</td>
<td>1 m</td>
</tr>
<tr>
<td>f-number</td>
<td>f/9</td>
</tr>
<tr>
<td>grating: grooves</td>
<td>1200 gr/mm</td>
</tr>
<tr>
<td>grating: blaze</td>
<td>500 nm</td>
</tr>
<tr>
<td>res. power, $m = 1$</td>
<td>$8 \times 10^{-6}$</td>
</tr>
<tr>
<td>linear dispersion</td>
<td>8 Å/mm</td>
</tr>
<tr>
<td>apparatus width $\omega_A$ (for 100 µm slit)</td>
<td>0.66 Å</td>
</tr>
</tbody>
</table>

Figure 4.3.: Characteristic properties of the spectroscopic system.

A Roper Scientific PiMax 2 gated intensified CCD camera is employed as detector. The CCD chip of the camera has a resolution of 1340 x 1300 pixels with a pixel size of approximately $20 \times 20$ µm$^2$, the spectral sensitivity is plotted in Figure 4.4(a) in terms of the quantum efficiency. Together with the linear dispersion, this yields a dispersion per pixel of 0.16 Å. This is an approximate value, as in the derivation the grating inclination was neglected. Figure 4.4(b) shows the wavelength-dependent dispersion experimentally obtained with an argon spectral lamp. Across the spectrum, the dispersion varies by about 5% due to the changing inclination angle of the grating. This influence is indicated by a sinusoidal fit to the dispersion (red line). The data points marked in red were not considered in the fit as the light source’s lines were comparatively weak in this region which might have led to wrong identification and thus to the considerable deviation.

To determine line widths from measured profiles, the instrumental broadening must be accounted for. This apparatus profile, determined with a spectrally narrow He-Ne-laser
4. Experimental Setup

Figure 4.4: (a) Spectral sensitivity of the employed ccd detector in terms of the quantum efficiency, reproduced from the documentation; (b) experimentally derived dispersion curve as function of wavelength (and hence, grating angle)

beam which was widened to ensure proper illumination of the grating, is displayed in figure 4.5 as a function of width of the entrance slit. As expected, the instrumental profile width increases linearly with increased slit width (black line). The colored plots show the individual profiles, the narrowest taken with a slit width of 30\textmu m. Most measurements were performed with a 100\textmu m slit. The corresponding apparatus profile is plotted in orange, crosses indicate the individual ccd pixels the curve comprises. A solid blue line shows a Gaussian fit to this profile, with a full width of 0.66\textmu m.

Two different measurement setups were used, as is displayed in figure 4.6. For end-on measurements, a lens with a long focal length (89 cm) is placed outside the vacuum chamber looking through the window at the cylinder face opposite of the electrode system. This allowed for looking directly onto the anode thus increasing the possible exposure time interval. For side-on measurements, a 10 cm focal length off-axis paraboloid mirror was employed, because an equivalent short-focus lens and mirror combination would have demanded too much space. Due do the considerable weight and thereby caused requirements for a sturdy mount of the mirror, the closest measurement position was limited to about 3 cm in front of the electrodes.

Two lenses with a focal length ratio of 2:1 serve the purpose of compressing the beam diameter. A small iris aperture is placed in the common focal point of both lenses to suppress stray emission from nearby plasma volumes. An approximately 2.5 cm diameter beam is coupled into the spectrograph via a 25 cm focal length lens. Note that the f-number matching employing these stock lenses is not perfect: under perfect alignment conditions 8% of the grating grooves would not be illuminated. However, as plasma densities are fairly
Figure 4.5.: Instrumental profile as a function of the entrance slit for the He-Ne-laser line at 632 nm

high, the loss in resolving power is not a crucial problem in the line profile measurements. Furthermore, the effective grating area is reduced due to its inclination, including the 4.9° angle of incidence imposed by the Czerny-Turner configuration, the required 23° are easily reached in practice, which is also apparent from the experimentally obtained dispersion. On the other hand, the chosen focal length ratios lead to a compression of the image by a factor of 10 (for the side-on setup), enhancing the detected intensity considerably. This is more crucial due to the constraints of the exposure time imposed by the transient nature of the discharge.
4. Experimental Setup

4.4. Magnetic Probes

Magnetic $\vec{B}$-probes were constructed to measure two components of the magnetic field simultaneously. To this end, first a small probe with a diameter of 5 mm and two windings was built. Around these two coil windings, a single elliptical loop of about $5 \times 7$ mm was wound perpendicularly. The loops were positioned such that their winding planes intersect in the respective loop centers; this position was fixated by two-component epoxy. Despite not explicitly being recommended for such use, the epoxy had only negligible effect on the vacuum conditions after an extended drying time. The loops were soldered to thin coaxial cables (diameter $0.9$ mm, length about $12$ cm) that terminate in SMA connectors. To increase the stability against bending and for better mounting, a $1$ mm diameter steel stake was glued at the tip to the probes and along its length to the coaxial cables using the same epoxy. For enhanced shielding, the conductors were wrapped in a copper mesh starting from close to the inductive loops to beyond the

Figure 4.6.: Light paths for the spectroscopic system. Only the first lens is changed for the different observation directions.
4.4. Magnetic Probes

Figure 4.7.: (a) Schematic of the detected field components in the discharge geometry for the chosen probe position and orientation; (b) drawing of the probe construction.

SMA connectors thus covering them as well. As the probes would otherwise be directly exposed to plasma, they had to be shielded via a glass test tube of 1 cm diameter. Figure 4.7(b) illustrates the resulting probe design.

The probes were calibrated using the known magnetic field of a singly-wound Θ-pinch coil as described in section 3.2. To this end, a probe pair was placed at either the coil center or at the face of the coil on its axis. The magnetic field can then be calculated from equation (3.20) for a given current. The coil current was provided by the PFN capacitor bank, taking advantage of the fast current rise (around 20 kA within 2 µs) to assure the constructed probes react fast enough. Figure 4.8(a) shows an example calibration measurement: The
4. Experimental Setup

(a) Exemplary calibration curve

(b) Table of calibration data

<table>
<thead>
<tr>
<th>Probe Component</th>
<th>Calibration Factor [mT/\mu V s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe 1: Poloidal</td>
<td>55.7 ± 1.5</td>
</tr>
<tr>
<td>Probe 1: Toroidal</td>
<td>150.3 ± 1.5</td>
</tr>
<tr>
<td>Probe 2: Poloidal</td>
<td>75.6 ± 3</td>
</tr>
<tr>
<td>Probe 2: Toroidal</td>
<td>134.0 ± 3</td>
</tr>
</tbody>
</table>

Figure 4.8.: (a) Exemplary calibration measurement showing the pinch coil current and measurement with a probe pair with one probe oriented to detect the generated field and another oriented parallel to the field and (b) table with the calibration factors for all probes.

A single error bar indicates the deviations in the calibration factor obtained from repeatedly positioning the probe in the pinch coil. The error in the measurements will therefore be at least of the order of 10 \% to 15 \%. Unfortunately, the error of the Rogowski coil cur-
rent measurements should be of similar magnitude so that the subsequent error is rather in the range of 20% to 25%.
The signal shape of the “minimum” probe (with area parallel to the magnetic field) deviates considerably from the expected plateau-shape. This is caused by strong perturbations from the spark gap switch of the PFN which could not be successfully filtered. As this is a minimum probe signal, the signal-to-noise ratio was very small and both could not be separated. Furthermore, the induction voltage raw signal of this perturbation exceeded the dynamic range of the oscilloscope as the sensitivity had to be increased for the minimum signal detection. This further complicates the removal of the spark gap noise.

The calibration factors determined for the \(2 \times 2\) probes are displayed in table 4.8(b). As the probes were constructed in a similar manner, the calibration factors of corresponding probe orientations differ only little.

Both probe pairs were mounted on the displacement stage inside the vacuum chamber. An existing lead-through flange served for guiding the measurement data to an outside oscilloscope. The oscilloscope has a battery pack allowing for ground-free measurements to avoid ground loops. To this end, an opto-electronic coupler was used to keep the timing synchronized to the grounded discharge electronics, which introduces a signal jitter of approximately 200 ns.

The probes were placed in the apex region of the plasma at a distance of 1 cm. They were oriented to detect the (poloidal) magnetic field generated by the plasma current on crossing the probe and the (toroidal) component parallel to the external line current field as illustrated in figure 4.7(a).

4.5. Supplementary Diagnostics

Ccd Cameras

The overall discharge evolution and propagation properties can be monitored with ccd cameras. To this end, two cameras are employed: A multi-frame camera (comprising internally four individual camera modules) that allows for taking up to eight images in the duration of one discharge through the same lens. This allows for studying dynamics within one plasma discharge, albeit at the cost of reduced dynamic range. Secondly, a single-frame camera with increased dynamic range. Furthermore, the multi-frame camera allows for inserting spectral bandpass filters in the parallel light path behind the lens for each individual camera module. A detailed description of operating principle as well as a comparison of specifications and image quality of both cameras can be found in [Ste11].

Unfortunately, the detected luminosity is generally an unknown function of electron density and temperature. It has been shown in previous works, that the position of the bright arc
4. Experimental Setup

Figure 4.9.: Sketch of the interferometer beam path taking advantage of the linear displacement stage.

determined from camera images and the current-generated magnetic field measured with \( \dot{B} \)-probes coincide well [Ste11]. The luminosity may therefore serve as very rough measure of the current density, which is also a common interpretation in comparable experiments (e.g. [OMY+11]).

**CO\(_2\) Laser Interferometer**

Comparative electron density measurements were performed with a CO\(_2\) laser interferometer [KMS+10b]. By placing two mirrors on the linear displacement stage, the accessible measurement volume could be greatly extended. Figure 4.9 shows the beam path through the discharge vessel. So far this method has been applied exclusively to the apex region, as continuous expansion of the plasma arch is required to interpret the phase shifts properly (cf. section 5.2.1).

Further measurements of electron temperatures and densities were obtained with an electrostatic triple probe, introduced into the chamber through the flange on the opposing side of the discharge vessel. For neutral gas distribution measurements, an ionization gauge was introduced at this position. Apparently, many diagnostics are mutually exclusive due to their space requirements. E.g. magnetic probe data and plasma density measurements could not be obtained during the same plasma discharge, as both require considerable space on the linear displacement stage. However, the overall discharge reproducibility, as will be shown from ccd images, is good enough to justify serial use of diagnostics.
Current and Voltage Probes

The total discharge current as well as the line current are monitored by means of Rogowski coils. Basically, they consist of a coil of multiple windings that is bent around a conductor. Thus, if the current through the conductor changes, the magnetic flux through the coil loops changes and a voltage is induced. Refinements to the coil design include guiding the conductor of the coil back through the windings to avoid induction effects across the area enclosed by the windings or anisotropic distribution of the coil windings to detect shifts in the investigated current distribution. Details on the design employed in the experiment can be found in the references [Ste11]. Furthermore, the voltage drop across the discharge is monitored via a commercial high voltage probe (Tektronix P6015A).
5. Measurements

Measurements at the line current plasma source will be presented in this chapter. As an introduction to the overall discharge shape and evolution, ccd images of the plasma arch will be presented in section 5.1. Subsequently in section 5.2 plasma density measurements will be discussed. To this end, Abel-inverted profiles of line-integrated plasma densities obtained via laser interferometry will be compared with peak local plasma densities from Stark broadening measurements. Temporal profiles and deduced spatial profiles of the magnetic field will be presented component-wise in section 5.3.

5.1. Ccd Images

Two sets of discharge images from the line current source are shown in figure 5.1. The images were taken by means of a single frame Roper Scientific PiMax II intensified ccd camera in a series of subsequent shots. No filters were employed, the exposure time varies between 10 ns to 3 ns. Within one row the brightness scaling is identical and linear for all images. For better contrast at early times, the images have been inverted. The delays with respect to the trigger of the PFN capacitor bank are given in the figure. The top row shows a discharge sequence without magnetic guiding field. The arch forms along the overlap of the gas clouds emanating from both electrode orifices. Initially, the current channel is rather diffuse and clearly follows a curved trajectory (cf. image at 9 µs). As the current rises, the arch collimates and then begins to expand upwards. This expansion continues for several microseconds and the movement is even maintained when the arch’s foot points visually detach from the electrodes at 15 µs to 16 µs.

A blue line has been overlaid the image sequence connecting roughly the apex positions at all times. After the initial collimation when the arch is largely at rest, the apex moves upwards linearly from 10 µs and onwards. In the time between 11 µs and 17 µs, the arch crosses a distance of roughly 5.6 cm. This absolute length is obtained from the known distance of the electrodes of 8 cm as indicated in the last image of the series. Note that the upward expansion may be underestimated by as much as 10% due to the uncompensated observational angle of the camera. From this image series, a mean expansion velocity of approximately 0.9 cm/µs is obtained.
Figure 5.1.: Ccd camera images of a series of argon discharges at 3kV charging voltage of the discharge capacitor bank. The top row shows discharges without toroidal magnetic guiding field, the center row corresponding images for a strong toroidal field (given in terms of the pfn charging voltage). The bottom row is a selection of the images with guiding field.
5.1. Ccd Images

The center row shows a similar image series for the case of strong magnetic guiding field. The field strength is thereby given in terms of the capacitor bank charging voltage, the given value corresponds to a magnetic field of 85 mT in a distance of 4 cm from the electrodes. This distance coincides well with the location where the plasma arch forms in the first image of the center row.

The expansion seems largely uninfluenced by the toroidal field: The arch forms and collimates on a similar timescale as in the case without guiding field. As in the top series, the emission intensity increases starting from the electrodes and crawling up to the apex. The expansion velocity is also constant and has roughly the same value. However, the expansion movement seems to begin earlier in the evolution. Further analysis of the expansion velocities will be given in chapter 6.1.

It is impossible to adjust the contrast range of the ccd images in a way to show the arch evolution at all times without saturating, since the discharge brightness increases considerably over time. As a complement, figure 5.2(a) shows the luminosity evolution of different select positions along the arch. Considering a line connecting both electrodes in the ccd images and a second line crossing the first at an angle of 30° in the point located centrally between the electrodes. Where this second line slices through the arch, the brightness is read out. A 90° angle therefore points along the z-axis through the apex of the arch while the 0° angle points at the upper electrode (cf. bottom row of figure 5.1). The corresponding luminosity values are therefore read out at the center of the apex, and , as the arch expands with time, these angles point to different absolute lengths along it.

Figure 5.2.: Luminosity of the plasma arch at different positions along the arch (a) and position where luminosity profiles have been extracted (b).

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1Details concerning the conversion to magnetic field strengths can be found in [Ste11].
5. Measurements

From the ccd images it can already be seen that the intensity at the electrodes is greatly enhanced as compared to the rest of the plasma structure, it therefore had to be plotted on a separate scale. There, the luminosity rises continuously and begins to decay when the collimation to a thin thread-like structure at the electrodes starts to kink around 15 µs. Along the rest of the arch, the luminosity rises approximately linearly as well, though noticeably quicker at the 30° position. There, when the “cloud” in front of the electrode has risen enough, the intensity nearly doubles. Between 60° and the apex the luminosity does not vary much, it shows the same linear increase at both positions.

The images in the bottom row of figure 5.1 show a magnified view on five images discussed before. Representing the ignition phase at 9 µs, the first image shows an almost semicircular plasma arch which follows exactly the magnetic field lines of the external line current connecting both electrodes. As compared to the field-free case, the arch seems considerably less smeared-out radially and seems to have a rather homogeneous width along the arch. The same semicircular overlay has been copied onto the subsequent images to emphasize how little change the plasma shape undergoes: While there is clearly a slight increase of the radius of curvature, the center of curvature gets transported equally along with the arch structure. In the whole time sequence, the arch expands radially just enough to cross the indicated semi circle.

Red rectangles are overlaid in the region below the arch. They roughly represent the connection distance of the curved “upper” part of the arch with the electrodes. Here, the plasma becomes strongly collimated and, over the course of several microseconds, develops a pronounced kink instability that points laterally outwards. From these sketches can be seen that the upwards expansion is nearly linear in time and at the same time the lateral expansion is almost negligible to the point of onset of instability in the electrode proximity. The length of the plasma structure therefore changes at a rate only slightly higher than the constant expansion velocity.

5.1.1. Neutral Gas Distribution at Plasma Ignition

As was mentioned in section 4.1 for each plasma discharge neutral gas is injected through orifices in the electrodes. To optimize the discharge timing and investigate the importance of neutral gas distribution on the plasma ignition, the distribution has been measured by Thomas Tacke in the frame of a diploma thesis [Tac11]. There, details on construction, calibration and operation of the probe can be found.

A selection of his results from measurements in the arch plane using a home-made ionization gauge are presented in figure 5.3. In order to obtain the contour, the time dependent probe currents are measured during a gas injection with the fast gas valve. No plasma is ignited during these measurements. Subsequently, the probe is moved to another measurement
5.1. Ccd Images

Figure 5.3.: Hydrogen neutral gas pressure distribution in front of the electrodes (positions indicated with crosses) measured by means of a home-made calibrated ionization gauge, data from Tae11. The figure on the right shows a properly scaled ccd image taken right after plasma ignition as overlay over the measured gas distribution.

position. The contour is then constructed reading out the pressure at every measurement position for one selected time.

The presented data shows a hydrogen gas puff at 1.2 ms after triggering the gas valve. Two clouds emanating from the electrode orifices (indicated by crosses) overlap at approximately 4 cm distance from the electrode plane. Below this overlap, the gas pressure is greatly reduced. Due to the high gas densities right in front of the electrodes cooling effects impeded measurements there, which shows as grayed-out areas in the plot. Furthermore, the spatial resolution is limited by the probe head size of about 1 cm³, the individual measurement positions are indicated with black dots.

On the right hand side of figure 5.3 a ccd image of the discharge at ignition has been superimposed the gas distribution measurements. The image is scaled properly so that the location of the electrode centers of image and data scale match. For the plasma discharge image, the delay between gas injection and plasma ignition was set to 1 ms. The plasma ignition follows the overlapping gas clouds and clearly prefers the region of higher pressure. Furthermore, the gas density distribution reaches out until 20 cm from the electrodes.
5. Measurements

5.1.2. Luminosity Profiles

From the ccd images, profiles of the line-integrated luminosity across the arch were extracted. The positions were chosen in accordance with the Stark-broadening measurement points (cf. section 5.2.2), they are illustrated as overlay across the corresponding discharge image in figure 5.2(b). To smooth the data in preparation for Abel inversion, a polynomial of sufficiently high order (in the range of four to six) is fitted to the camera luminosity profile. The luminosity always show residual intensity at the ends of the extracted cuts, this is removed by setting the offset of the polynomial fit to zero. Furthermore, the profiles are interpolated linearly from zero to the first (or last) data point, so that the whole to-be-inverted function starts and ends at zero intensity. This is necessary since the starting and ending intensity of the extracted profiles in general do not match. Finally, the inversion routine described in section 3.3 is applied to obtain local luminosities.

Results of this procedure are presented in figure 5.4 obtained from the images at 15 µs and 16 µs with PFN in figure 5.1. Positive radial coordinates point towards the outside of the arch, the origin of the axis was defined at the peak local luminosity. For the four different positions, the original extracted profiles are shown in red, the polynomial fit (with removed offset and linear interpolations at select starting and ending points) in black and the Abel-inverted profiles in blue. The center of the radial position was defined as the position of peak intensity; the positive radial direction points outwards from the arch.

Generally, the shape of the inverted profiles comprises two components: A localized, almost parabolic profile around the (defined) center and an asymmetrically decreased decay – in some cases almost plateau-like – towards the outside of the arch. This decay towards the outside probably does not follow the circular symmetry required for the inversion algorithm. Furthermore, artifacts from the disk-stacking inversion routine are clearly visible as step-like structures, especially where one flank of the original profile rises steeply and where the projected profile has a local minimum.

The procedure of removing the offset of the polynomial is arguable, keeping it would reduce the center amplitude thus flattening the profiles. However, specifically towards the inside the arch’s limit is difficult to define yet the profile has to be cut off somewhere. From the top row of figure 5.4(b) it can be seen that sometimes removal is not necessary and the inverted profile still retains the described partially parabolic shape.
5.1. Ccd Images

Figure 5.4.: Luminosity profiles from argon discharge images at 15 µs and 16 µs for 3 kV main discharge voltage.
5. Measurements

5.1.3. Ccd Images: Filters

For the overall expansion characteristics, the reproducibility of the plasma discharge is adequate to employ a single-frame camera. However, in order to investigate local dynamics, time sequences within a single plasma discharge are required. Furthermore, due to the gas injection procedure that does not provide a uniform background and may show local deviations of unknown impact between shots, specifically images taken through spectral filters should be compared only for the same plasma discharge and therefore a multi-frame camera is employed.

In the previous section, the evolution of the plasma structure has been discussed extensively for the case of a pure argon discharge. For spectroscopic purposes, a considerable amount of hydrogen had to be admixed to the argon gas. The large mass difference may lead to de-mixing of both species in the gas injection process, which in turn may have consequences for line-broadening measurements. Employing spectral filters in the multi-frame ccd camera,

![Filter Images](image)

Figure 5.5.: Argon and hydrogen discharge simultaneously seen through bandpass interference filters (blue: unfiltered image, magenta: Hα filter, green: 410 nm filter, black: 705 nm filter) showing the whole arch (left) and a magnified view on the upper electrode (right).

this de-mixing can be investigated qualitatively. To this end, bandpass filters with a half-width of 10 nm have been employed with the central wavelengths 410 nm, 656 nm and 705 nm. While the spectrum shows no lines besides the Hα line within the filter range, multiple lines are detected employing the other filters. However, spectra showed exclusively argon neutral lines around 705 nm and vastly dominating lines of singly-ionized argon around 410 nm. The emission is therefore integrated over several spectral lines which, however, should share similar excitation channels.

Figure 5.5 shows the discharge through these filters, the individual spectral components are colored (cf. figure caption). Comparing the unfiltered image and the “argon ion filter”
image, a close resemblance even of details of the structure becomes apparent, though the contrast is reduced due to the filter. This also reflects on an increased exposure time of 200 ns for the filtered image as compared to 3 ns for the unfiltered one. The images as seen through the H\textalpha filter (200 ns exposure time) and the argon neutral filter (3 \(\mu\)s exposure time) show considerably different behavior. In the hydrogen image, the position of the arch from the unfiltered image is indicated with a thin line. Looking closely, the hydrogen emission in the apex seems to begin further outwards, forming a halo around the argon arch. The positions of peak luminosity of hydrogen and argon apparently do not coincide anymore in the apex, whether this is due to the initially mentioned gas de-mixing or caused by strongly differing excitation mechanisms is not known.

The argon neutral filtered image shows only glow around the electrodes. As will be shown in the following sections, the plasma densities are of the same order as the neutral gas density, therefore little emission was to be expected from the plasma arch. Furthermore, the overall luminosity is limited due to the very small Einstein coefficient of the specific lines.

For the upper electrode, the filter images have been superimposed the unfiltered emission. The result is shown in figure 5.5(b). There is only little difference in the emission patterns around the electrode. The hydrogen emission seems to propagate faster along the arch and laterally more strongly confined, but there is no specific region where the gas types de-mix entirely.

## 5.2. Optical Measurements

### 5.2.1. Interferometry: Line-integrated Plasma Density

The interferometric setup has been introduced in section 4.5. The scene beam crosses the apex perpendicularly to the expansion plane of the plasma arch. For the experimental conditions under investigation (magnetic field strength, plasma density and laser wavelength) the line-integrated plasma density is directly proportional to the detected phase shift. However, the high densities cause phase shifts of several times \(2\pi\). When the signal passes to another interferometer fringe, signal discontinuities arise, which have to be deconvolved manually. As the plasma crosses the beam, the phase shift first rises up to the peak line-integrated density and then diminishes – but not necessarily symmetrically. In order to obtain the correct temporal phase shift evolution, a singly-peaked profile is assumed which shows zero phase shift before the arch approaches and returns to this value “long after” the arch’s passage. Under these assumptions, it is in most cases possible to identify a turning point, e.g. the point where the phase shift reaches its maximum. A more detailed description of the determination of the phase shift can be found in [KMS10a]. There also the procedure of establishing the absolute phase shift from an in-situ calibration is
5. Measurements

By parallel displacement of the scene beam along the z-direction, different measurement positions can be reached, corresponding to different plasma currents and arch expansion positions. In figure 5.6, line-integrated electron densities measured by S. Ridder in the frame of a diploma thesis are presented [Rid11]. The measurements were performed in argon with 3kV charging voltage and a magnetic guiding field strength of about 80mT (at 4cm from the electrodes, corresponding to a charging voltage of the pfn of 23kV). Due to the size of the employed mirrors and the requirement of sturdy mounting, the closest measurement distance accessible was 55mm from the electrodes.

The determined peak densities move linearly away from the electrodes with high precision at a value of 1.0cm/µs, reproducing the value estimated from the ccd images in figure 5.1. Also the absolute positions agree quite well with the apex positions in that series: Considering the expansion begins after a short ignition/collimation phase, the real expansion starts only around 9µs and from then on linearly with fixed velocity. Therefore, about 2µs
are required to reach the first interferometer measurement position, which shows the peak
density at 11 \( \mu \)s.
Together with the expansion of the arch and the rise of the total discharge current, the
measured peak electron density increases by a factor of 8. Note that the ridged structure
when following the maximum density diagonally in the contour plot is an artifact of the
plotting routine. Furthermore, the diameter of the dense channel remains constant up
to 16\( \mu \)s when the arch detaches from the electrodes and also starts to widen in the ccd
images. At later times, the profiles develop a considerable asymmetry. Since the scene
beam is initially located “outside” the arch, this implies a steeper density gradient at the
outer boundary of the arch and a smeared-out density distribution towards the inside. A
profile asymmetry is also present in the luminosity profiles, albeit in inverse direction: The
profiles in figure 5.4 show a “pedestal” at the outboard side above the arch. However, the
region below the arch seems to be filled with luminous plasma right from the ignition (as
can be seen in the ccd images) and remains there for the whole duration. This feature is
hidden in the selected luminosity profiles as the wings towards the inside do not decay to
zero intensity in all cases. At early times, the residual plasma luminosity below the arch
as seen in the camera images is more pronounced than the density gradient asymmetry in
the interferometric profiles.

**Radial Density Distribution**

From the individual time-dependent density measurements it is possible to obtain the local
density. To this end, the time axis is converted to a spatial coordinate by multiplication
with the expansion velocity as obtained from the measurements, taking advantage of the
constant expansion movement. By defining the peak of the line-integrated density as cen-
ter of the density distribution, the origin of the spatial axis is then shifted to this center
yielding a radial profile. Since the plasma arch moves across the scene beam of the in-
terferometer, the density values before the maximum originate from the beam entering the
plasma, whereas the values after the maximum are detected “inside” (or below) the arch.
It is therefore convenient to adjust the sign of the radial profile axis such that it coincides
with the \( z \)-axis of the electrode coordinate system.
An example of a line-integrated density profile taken from figure 5.6 converted to radial
coordinates is presented in figure 5.7. There also the result of the Abel inversion procedure
described in section 3.3 is shown. Note that the plots show only the range of \(-3\) cm to \(3\) cm
of radial positions, while the entire interferometer signal was used during the numerical
inversion procedure.

At measurement positions close to the electrodes, the profiles are very symmetric, resulting
Figure 5.7.: Comparison of line-integrated and local electron density profiles for various measurement positions at 3kV discharge voltages.

in equally symmetric inverted profiles. Positions further away from the electrodes (equivalent to later times during the discharge) show a pronounced asymmetry towards the inside of the plasma arch. Furthermore, the inverted profiles sit on a broad “socket” originating from the first disc added to the stack during the inversion process. This indicates that the wings of the projected profile are not resolved well enough in the measurements.

In section 3.3 it was pointed out that the inversion routine assumes circular contour lines of the inverted profile. For the symmetric profiles this condition seems well satisfied. However, the developing asymmetry is probably partly due to deviations from this circular shape and the influence of this effect increases with distance from the defined profile center. The obtained local values of the electron density should therefore be considered with great care.

Results of further inversion calculations for measurements at 3kV main discharge voltage are presented in figure 5.8. The representation as contour plot is helpful to get an overview over the profile characteristics: The data show the trend of increased central density up to a measurement position of 10cm, which corresponds to a time of this maximum of about 15µs after trigger, whereas the line-integrated density increases beyond this measurement position (cf. figure 5.6). At the same time the inverted profile begins to widen with a velocity of roughly 0.2cm/µs.

Subsequently, a pronounced asymmetry towards the inside of the arc develops for the measurement positions from 10cm to 14cm, which is accompanied by a reduction of the peak density. At least up to a measurement position of 12cm (for which the time of peak
line-integrated density coincides approximately with the detachment of the arch at the electrodes) there is no reason for a reduction of the peak density. This is therefore a strong indication that the asymmetric contribution to the measured density profiles do not satisfy the condition of circular symmetry (or of circular contour lines). An explanation may be density building up in the region below the arch due to current flow that is electrotechnically parallel to the arch.

Figure 5.8.: Radial density profiles obtained from inversion at different measurement positions for 3kV.
5. Measurements

5.2.2. Stark Broadening: Local Electron Densities

Line profiles of the hydrogen Balmer $\alpha$ and $\beta$ lines have been recorded in argon plasmas with considerable hydrogen admixture (in terms of partial pressures in the gas mixing chamber: 2 bar argon and 1 bar hydrogen for all measurements presented here). In this section, the determination of the Stark-contribution to the broadened line profiles will be discussed and an error estimate for the derived densities will be given. Subsequently, densities obtained at different positions (and hence times during the discharge evolution) will be presented.

H$\beta$ Line Profile

An exemplary line profile for the Balmer $\beta$ line is presented in figure 5.9. The measurement was performed with 3 kV charging voltage of the main discharge capacitor bank and a charging voltage of 20 kV of the PFN, the measurement position was at 3 cm distance from the anode in z-direction. The figure shows the measured line profile in black together with the fit function comprising the sum of a Gaussian and Voigt function that has been introduced in section 3.1.3. For fitting, the region surrounding the argon ion lines displayed in gray has not been taken into account. The Voigt contribution to the line profile is plotted individually in blue, it shows a nice agreement in the profile wings, specifically towards the lower wavelengths where no further spectral lines disturb the spectrum. Unbroadened emission from less dense plasma regions surrounding the current channel is shown in green.

Figure 5.9.: Measured and fitted line profile showing the fit function components for an exemplary measurement at 3 kV main discharge voltage 11 $\mu$s after trigger.
The Voigt profile itself also comprises a Gaussian component, convoluted with the Stark-broadened profile. This Gaussian is attributed to the apparatus profile and therefore ignored. An additional Gaussian component may arise from line-broadening due to the Doppler effect. Since the ion temperature should not be higher than the electron temperature of about 1.5 eV (cf. section 3.2.3), the corresponding profile full width amounts to 3/4 of the apparatus profile. Due to the errors introduced employing an inherently flawed fitting function, the possibility of deconvolving this contribution is not further explored. Using the density-half width relation plotted in figure 3.1, the Lorentzian component's half-width can be converted into an electron density. For the presented case, a density of $6 \times 10^{21} \text{m}^{-3}$ is obtained for an estimated plasma temperature of 15 000 K.

However, the Balmer $\beta$ line should have a considerably different shape towards the line center since it lacks the unshifted Stark component there. In order to estimate the error arising from the chosen fitting procedure, the measured profile will be compared to MMM profiles by Stehlé and Hutcheon [SH99]. For the measurement presented in figure 5.9 four profiles with densities around the determined value have been plotted, for an estimated plasma temperature of 15 000 K. The area of the normalized profiles has been rescaled to match the measurement, they are displayed in figure 5.10(a) together with the original data. Apparently, profiles in a density range of roughly 15% around the determined value still fit acceptably well and this will be taken as approximate accuracy of the method for densities in this range. The error will become considerably larger with lower densities as separation of the different emission components becomes more difficult and thus the relative error of the determined half widths increases.

Finally, the assumption of superimposed emission from different plasma layers can be verified: In figure 5.10(b) the difference between the scaled Stehlé profile for the previously determined density and the measurement data is plotted in blue. The residual intensity profile has a nearly Gaussian shape, albeit with a width considerably increased as compared to the apparatus width. This is plausible, as there might be slightly broadened emission from regions closer to the current channel. A more detailed modeling of the line profiles, however, does not seem very promising since it would greatly increase the number of assumptions (and hence, fitting parameters) which would not necessarily increase the accuracy of the density determination.

In the already presented examples, two argon ion lines are detected on the wing of the profile. Furthermore, the H$\beta$ wings partially overlap with neighboring argon lines. Adhering strictly to the theory, the H$\beta$ line has to be isolated, e.g. have a distance of the order of the line width to the next spectral line, since the possible transitions between the excited states of emitter and argon perturber are not considered in the models. The impact of this intermixing on the line profiles is unknown but generally ignored in diagnostic applications (e.g. in [BH08]).
5. Measurements

Figure 5.10.: (a) Comparison with line profiles according to [SH99]; (b) Difference between measurement and such a line profile.
5.2 Optical Measurements

**Hα: Electrode Orifice**

For measurements inside the electrode orifice, the Hα line has been used. This line does comprise a shifted central component and should therefore not show a central dip in the profile. With exception of the profile wings, the enveloping profile of the sum of shifted Lorentzian Stark components is not necessarily itself of Lorentzian shape. However, C. Stelhélé proved that for the hydrogen Lyman and Balmer series, the overall Stark-broadened shape is indeed a pure Lorentzian [Ste96]. Hence the Voigt fitting procedure chosen for data evaluation should be accurate. An exemplary measurement looking into the electrode orifice is presented in figure 5.11 for a main discharge voltage of 3 kV. Here, the top image shows the CCD detector intensity with a clear dip towards the line center due to self absorption of the Hα line. Different detector rows correspond to different positions along the image of the entry slit and therefore to different positions inside the electrode orifice. The size of the orifice on the detector is indicated approximately by the yellow rectangle, given the imaging ratio of the employed lenses it corresponds well to the approximately 5 mm diameter of the drilling. The signal is partly blocked by a cover plate screening a part of the entry slit. This screening, however, is imperfect as can be seen from the signal continuing in the bottom rows.

One row of the CCD image is shown separately in figures 5.11(b) and 5.11(c) together with the fitting as was employed for the Hα line and with profiles tabulated by Stelhélé and Hutcheon. The full half-width obtained from the fit yields a density as high as $8 \times 10^{23} \text{m}^{-3}$. Comparison with the theoretical profiles, however, yields considerably lower densities around $5 \times 10^{23} \text{m}^{-3}$. While self absorption would cause overestimation of the profile width, the effect seems yet very localized in the line center and well-compensated by the chosen fit function. Furthermore, the tabulated line shape matches the measured one very well, whereas strong influence due to absorption should appear as considerable relative deformation of the profiles under comparison.

From the profile presentation in figure 5.11(b) it can be seen that the central wavelengths of (narrow) absorption signal and broadened Balmer line do not match. As was explained in section 3.1.2, the central wavelength exhibits a red-shift due to electron impact processes. The fit function yields a shift of the central wavelength of both components of 1.3 Å, however, a blue-shift of the central wavelength of the broadened line is detected. A theoretical model of Balmer line shifts by Oks suggests that ion impact processes may become of importance at moderate and high densities and can lead to “center of gravity” shift towards lower wavelengths [Oks99]. For a laser-induced underwater plasma with densities of $1 \times 10^{24} \text{m}^{-3}$ to $4 \times 10^{24} \text{m}^{-3}$ at temperatures of 16 000 K this was experimentally verified [FOV03]. Comparison with the authors’ results indicates, that a shift of 1.3 Å would be consistent with the lower densities obtained from the Stelhélé-fit procedure.
5. Measurements

(a) Self absorption of Hα inside the electrode orifice

(b) Line profile with fit

(c) Comparison with profiles according to Stehle, Hutch

Figure 5.11.: Self absorption of the Hα line in the electrode orifice (size approximately given by the yellow rectangle in the figure). Figures (b) and (c) show one line profile with Voigt fit and tabulated profiles by Stehle and Hutcheon.
Doppler shifts due to relative movement of emitter and absorber (in this case, along the z-axis and hence out of the electrodes in expansion direction) can cause a blue shift of the spectral line. However, a shift of $1.3\,\text{Å}$ would require a relative velocity of $6\,\text{cm/µs}$, which is twice the expansion velocity of the plasma arch for hydrogen discharges and six times the expansion velocity when operated with an argon-hydrogen mix. Furthermore, in the ccd images there is no indication for a plasma movement at such high velocities.

Another aspect not represented in the tabulated profiles is additional broadening due to enhanced plasma temperature in the confined space of the electrode orifice. However, in order to obtain considerable effect very high emitter temperatures would have to be achieved (larger than $10\,\text{eV}$). This is unlikely, as plasma temperatures determined along the arch are of the order of $1\,\text{eV}$. However, due to the confinement in the tight electrode orifice the power density is considerably increased and the hypothesis cannot be discarded. Finally, the resulting convoluted profile would have enhanced width and therefore the Lorentzian component would have to be even narrower. In conclusion, the density error resulting from the evaluation of Hα spectra is of the order of $40\%$, despite a physically accurate fitting function.

### Local Electron Densities

Measurements were performed in an argon-hydrogen mixture (one part hydrogen in two parts argon) with $20\,\text{kV}$ to $21\,\text{kV}$ charging voltage of the PFN and $2\,\text{kV}$ and $3\,\text{kV}$ main discharge charging voltage. Figure 5.12 shows the different measurement positions together

![Illustration of the positions along the arch where spectroscopic measurements were performed. The colored points represent positions 3 cm in front of the anode (yellow), 4 cm in front of the anode and 0.5 cm below it (green), 5.5 cm in front of the anode and 1 cm below it (red), and the apex at 6 cm and 7.7 cm distance (magenta). The observation volume for measurements inside the electrode orifice is indicated in red.](image)
with a plasma arch at different times. As can be seen from the underlying ccd image, the density should rise after approximately 11 µs when the plasma arch enters the observation volume. Inside the cloud in front of the electrodes, considerable density should prevail up to at least 15 µs. Here images for 3 kV and pure argon discharges have been used for comparison so time scales may vary slightly, specifically when changing the main discharge voltage.

The results of density measurements at these positions are presented in figure 5.13. There, the black squares show the electron density inside the electrode orifice as obtained from the broadening of $H\alpha$, whereas the remaining colored symbols show exclusively results from $H\beta$ broadening. The one-sided error bars indicate the exposure time of the ccd detector. Two colored areas at the bottom of the plots indicate the densities corresponding to line widths as large as the apparatus profile: For the $H\beta$ line this limit lies around $2.5 \times 10^{20} \text{m}^{-3}$ (dark gray area), for the $H\alpha$ line at $2 \times 10^{21} \text{m}^{-3}$. Measurement results within these regions should be considered with great care, as the error is greatly increased with low densities and only those determined densities larger by a factor 3-5 than these thresholds are reliable.

Interpreting the results as peak densities along the arch, they indicate that there is only little gradient in the plasma density along the arch from 3 cm distance and outwards. However, towards the electrodes a density increase of one order of magnitude is detected. The measurements in the apex were not successful. While $H\beta$ is faintly visible there, the emission is not broadened. The apex density obtained from the interferometry is of the same order of magnitude as the locally determined densities presented in this section. Therefore, it seems more likely that the cause of this problem is the de-mixing of argon and hydrogen. This has been discussed in section 5.1.3 and, specifically for the apex region of the discharge, this problem is visible in ccd images of the discharge taken through interference filters.

Peak densities obtained from the Abel inversion of interferometric data showed indeed higher densities in the apex for 3 kV main discharge voltage. Though of course the errors from the original phase shift determinations were enhanced by the inversion routine, there are further sources of this deviation to consider: The different working gas (pure argon in case of the interferometer measurements) may lead to higher densities in the current channel, specifically if the plasma temperature is low. Also, considering the exposure times of the spectroscopic measurements with the transit time of the plasma arch through the observational volume, the thus obtained densities are averaged over a considerable section of the arch’s diameter.
5.2. Optical Measurements

Figure 5.13.: Electron densities at different times and measurement positions for 2kV and 3kV main discharge voltage.
5. Measurements

5.2.3. Emission Spectroscopy: Electron Temperature Estimate

(a) Electron temperature, for 2kV at 14µs (b) Electron temperature, for 3kV at 13µs

Figure 5.14.: Electron temperatures determined from line pair intensity ratios assuming LTE. Color indicates the same Ar I level (cf. legends), the wavelengths of the Ar II lines is presented as label to each data point.

In section 3.1.4 criteria for reaching the state of local thermodynamic equilibrium were established. From the estimations presented it is plausible to consider the discharge under LTE, however it could not be finally verified. In the LTE case, the electron temperature can be determined from the intensities of emission line pairs if the electron density is known. To solve for the electron temperature from equation 3.16 coefficients from the database of the National Institute for Science and Technology [RKR12] were used. Temperatures determined at the measurement position at 5.5cm from the anode using the electron densities determined from Stark broadening (cf. figure 5.13) for 2kV and 3kV main discharge voltage are given in figure 5.14. The resulting temperatures lie in the range of 1.5eV for both main discharge voltages, though the spreading of the data points is considerably reduced at 3kV. There is an indication that the temperature is slightly elevated for the higher charging voltage. Note that due to the different charging voltages, the observation times differ slightly. The measurements were performed at 13µs for 3kV main discharge voltage and 15µs for 2kV. However, it should not be overlooked that the data evaluation involves comparing line ratios of measurements from different discharge shots: The neutral lines, which were used to extend the energy difference between compared lines are isolated in the spectrum and neutral argon lines in the range of 4000Å could not be used due to considerable Stark broadening leading to strong overlap with nearby ion lines. Therefore, each data point in figure 5.14 comprises spectra from three individual discharges (two for line intensities and a third for the electron density).
As was pointed out in section 3.1.4, it is furthermore questionable whether the assumption of LTE is justified for the transitions under consideration here. Indeed the main quantum number $p$ of most ionic states is in the range of 4 to 6, whereas for the experimental parameters LTE is only verified for states with $p \geq 6$. Furthermore, all relations presented there were derived for hydrogen and hydrogen-like ions. Their applicability to argon is certainly limited and is probably amplifying the large spread of 30\% of the electron temperatures in figure 5.14(a) for 2kV. However, it is interesting to note that the determination of temperatures seems more accurate at 3kV, despite the only modestly enhanced density of around 20\% which leads to identical estimates for the validity of the LTE assumption.

Similar electron temperatures have been reported by measuring the current density distribution and the plasma electric field and solving for the electron temperature from Spitzer’s relation for the plasma conductivity, whereas Measurements with an electrostatic triple probe showed temperatures in the range of 3eV to 6eV [Mac12]. However, each of these methods assumes implicitly a Maxwellian energy distribution while specifically the probe diagnostics are sensitive to even small overpopulations in the high-energetic tail of the distribution. The determined electron temperatures are therefore plausible, but more elaborate methods are required in order to achieve higher accuracy and reliability of the results.
5. Measurements

5.3. Magnetic Probe Measurements

As explained in section 4.4, four magnetic probes were introduced in the apex of the plasma arch. In the following section these probes will be named after the respective magnetic field component for which they are oriented to detect, e.g. the poloidal current-generated magnetic field and the toroidal (initially exclusively line-current-generated) magnetic field. The double probe assembly (comprising a toroidal and poloidal probe) closer to the electrodes will simply be named probe one, probe two therefore referring to the second probe at 1 cm further away from the electrodes along the z-axis. Due to limitations in the displacement stage range and the probe mount, the closest measurement position accessible by probe one was at a distance of 5.5 cm from the electrodes.

The measurements presented in the following sections were performed in an argon-hydrogen mixture (one part hydrogen in two parts argon) with a total valve pre-pressure of 3 bar, which was kept constant with frequent refills of the gas mixing chamber. The main discharge voltage was varied between 2 kV and 3 kV, the line current field in terms of the PFN charging voltage was around 20 kV to 21 kV. Slight variations were necessary due to maintenance of the spark gap, however never within one sequence of position variation measurements.

First, the poloidal field component will be discussed in section 5.3.1. The data acquisition and analysis process will be outlined. In the next step, poloidal magnetic fields from both consecutive probes will be presented and compared for a set of probe positions. Analogously, the toroidal probe data will be discussed in section 5.3.2. Finally, spatial profiles of the “total” magnetic field comprising these two components will be presented.

5.3.1. Poloidal Field Component

Multiple steps are necessary to obtain the magnetic field from a probe measurement. Firstly, the induced voltage during a plasma discharge is recorded. As was shown in section 4.4, the induction probes are also sensitive to stray signals. In case of the poloidal field probes, the main source of intermixing signals from other magnetic field components is the toroidal line current field that can be picked up to some extent. To compensate for this, after every discharge a PFN-only “noise” signal is recorded for the respective probe position. An example of such a measurement is shown in figure 5.15. The raw probe voltages for plasma operation (which of course includes the PFN) and PFN-only operation are shown as black and blue curves, respectively.

In the plasma discharge signal evolution, the ignition of the PFN spark gap switch (at 0 µs) shows up as a high frequency perturbation. Instead of applying an averaging or Fourier filtering method, the signals are integrated obtaining the red and dotted blue curves. The difference of these two signals is then interpreted as magnetic field for the respective probe
5.3. Magnetic Probe Measurements

Figure 5.15.: Exemplary measurement of the poloidal magnetic field with probe one at 6.5 cm distance from the electrodes to illustrate the data analysis procedure. The probe signal with plasma (blue) and the perturbations of a PFN discharge (black) are integrated (red and dotted blue). For comparison, the total discharge current is plotted as overlay (dotted olive).

position. Small offsets caused by the oscilloscope digitizer are integrated to a linear function in these magnetic field signals. This tilted baseline is manually corrected for by subtracting a linear function for each measurement. As the probe signal should be zero and constant before the PFN ignition, this data correction is performed removing any slope in the region before 0 µs. The resulting curve is multiplied with the calibration factors given in table 4.8(b) for the respective probe to obtain the magnetic field in Tesla.

The plasma signal shown in figure 5.15 is taken for a very long duration as compared to the life time of the arch structure. From the ccd images in the previous section (cf. figure 5.1), the detachment of the plasma arch starts around 17 µs to 18 µs. Externally, the current from the discharge capacitor bank continues to oscillate since no crowbar is employed. This behavior can be seen in the (green) discharge current signal in figure 5.15.

At later times (with respect to the arch detachment), the magnetic field detected by the probe follows the current signal in phase and amplitude. The reason for this is unclear: Discharge current continues to flow somewhere between the electrodes at these later times.
However, the signal amplitude seems a factor two too large to result from such a current as no propagating plasma structure forms anymore and thus the distance to the probe remains high. Perturbations due to current flow onto the probe can be excluded as they would show a 90° phase shift to the current signal due to the signal integration. Furthermore, all measurements were performed ground-free and the probe therefore should not have drawn any net current.

Within the arch lifetime of roughly 10µs duration, the signal deviates considerably from the current pulse: As soon as the plasma current begins to rise, the poloidal magnetic field develops. At first, a small local minimum forms, followed by a steep increase and a maximum magnetic field at times close to the arch detachment as seen from the camera images. The signal shape can be illustrated by a straight conductor carrying an axial current being pulled across a magnetic probe sensitive to the current-generated field. Outside the current-carrying region, the magnetic field shows a $1/r$ decay. The detailed shape of the magnetic field inside the conductor is determined by the current density distribution. However, assuming this distribution peaks on-axis, the extrema of the magnetic field lie on the edge (or, in general, slightly inside from the edge) of the current density distribution. As the field lines change direction with the conductor crossing the probe, the resulting signal is therefore a waveform with slowly decaying wings, a zero crossing at the center of the current distribution and two extrema marking the edges of said distribution. This already gives the general shape of the magnetic field detected during the arch crossing. The pronounced asymmetry between maximum and minimum originates from the curved shape of the arch, which leads to a field distribution similar to crossing from the outside towards the inside of a current loop and, possibly, the current rise. In reference Ste11, similar magnetic probe measurements were performed in a hydrogen discharge albeit with a different electrode design. While the detailed dynamics and timescales differ considerably, the general signal shape is similar. In that work, extensive analysis and comparison with the numerically integrated magnetic field of arbitrarily skewed arch-shaped current distributions verified the interpretation of this simple picture.

Signal Reproducibility and Probe Comparison

In the context of the ccd images presented before, the high reproducibility of the discharge has been discussed briefly. For the magnetic probe measurements, various examples of signal reproducibility are given in figure 5.16 for a main discharge voltage of 2kV. Three repeated measurements of the poloidal magnetic field with the same probe at a fixed position are shown in figure 5.16(a). Within the plasma arch lifetime as indicated by the gray rectangle, the discharge operates very reproducibly. Only when the electrode detachment starts, the signals begin to spread noticeably. Since the arch expansion in
terms of a well-defined flux tube ends at the latest around 20\,\mu s, only the selected signal interval is shown.

In figures 5.16(b) and 5.16(c), examples of measurements with both poloidal probes are given for probe distances of 1\,cm and 3\,cm. To this end, the probes were moved between two discharges so that in the next shot probe 1 took the position of probe 2 in the previous discharge. Signals thus obtained should not deviate strongly. The relative variation of both probes is of the order of 10\% of the signal amplitude, which is well within the error from the calibration procedure. The signals presented show no systematic deviation, e.g. probe 1 does not show consistently higher or lower amplitudes. As up to 10 measurements have been performed between the two shots presented for each position, small effects, like reduced neutral gas pressure due to depletion, may have accumulated. This might be enough to explain the signal deviation as compared to the repeated operation of the same probe at the same position.

However, the drifting-apart of both probe signals becomes enhanced by increasing the distance between both probes as presented in figure 5.16. Before, the amplitudes showed variation, but the timing (e.g. time when first minimum, zero crossing and the maximum are assumed) remained unaltered. For the increased distance now also the signal slopes and zero crossings differ slightly within the regular arch lifespan. As was already seen from the ccd images, the dynamics at later times during the discharge when coming close to the detachment is less reproducible. Since the increased probe distance requires observation at later times during the arch’s evolution, the deviation might be attributed to shot-to-shot variations. Furthermore, if probe 1 perturbs the plasma, higher probe distance may provide more time for the signals to diverge further due to this perturbation.
5. Measurements

Figure 5.16.: Reproducibility of the poloidal magnetic probe measurements: signal of repeated probe measurements (a) and poloidal field as detected by both probes when moved to the same position for 1 cm probe distance (b) and 3 cm probe distance (c) (all for 2kV main discharge voltage).
Magnetic Field Measurements

Taking advantage of the linear translation stage inside the vacuum chamber, the poloidal magnetic field along the z-axis was measured in 0.5 cm steps for 2 kV and in 1 cm steps for 3 kV main discharge voltage. Results of the evaluation method described in the previous section are presented in figures 5.17 and 5.18. The discharge currents are plotted as blue overlay (note that the main discharge current always rises sinusoidally around 7.7 µs). The shape of the field component is very similar at all positions and matches the description in the previous section. An analysis of the flux tube velocities obtained from individual probe signals in a sequence of shots and subsequent probes in individual discharges will be presented in section 6.1.

From the contour plot it is obvious that the magnetic field amplitude does not scale like the externally measured main discharge current. Furthermore, comparing the maximum amplitude in figures 5.17(a) and 5.18(a) for 2 kV and 3 kV main discharge voltage it only changes by about 20%. While the charging voltage implies a 50% increase of current, looking at the current rise in fact only a 30% higher current is detected when the highest field amplitudes are reached. The reason for this discrepancy is the accelerated dynamics for higher charging voltage. Due to the accelerated evolution, the maximum field amplitude is reached earlier and hence at (relatively) reduced main discharge current.

Comparing the results of probe 1 and probe 2 for the different main discharge voltages, the measured amplitudes seem to agree largely, as was discussed previously on the basis of an exemplary measurement. However, the signal shape of probe 2 deviates more strongly from that of probe 1 for higher charging voltage. The slow decrease after the maximum amplitude that is characteristic to all other measurements is missing from figure 5.18(b). Instead, the plot shows high field amplitudes caused by integrating high frequency perturbations in the raw signal that left the sensitivity range of the oscilloscope.

While an accelerated evolution for higher main discharge voltages is also observed in ccd images and the interferometer signals, the current channel usually becomes better confined for higher voltages. This could be seen in detail in the Abel-inverted luminosity and density profiles that yielded considerably smoother results for the 3 kV case.
Figure 5.17.: Contour plots of the poloidal magnetic field in a series of discharges with 2kV main discharge voltage. The probes were positioned at 1cm distance, the nearest distance to the electrodes for probe 1 was 5.5cm and for probe 2 6.5cm. The measurements were performed during the same discharges.
Figure 5.18.: Contour plots of the poloidal magnetic field in a series of discharges with 3kV main discharge voltage. Further conditions identical to figure 5.17.
Figure 5.19.: All poloidal probe signals for 2kV to 3kV main discharge voltage. Same line style indicates that the measurement was performed during the same discharge shot.
5.3. Magnetic Probe Measurements

(a) Total magnetic field change vs. probe position, 2kV
(b) Total magnetic field change vs. probe position, 3kV
(c) Total magnetic field change vs. time of maximum amplitude, 2kV
(d) Total magnetic field change vs. time of maximum amplitude, 3kV

Figure 5.20.: Difference of detected magnetic field minimum and maximum value by probe position (top row) and by time of occurrence of the maximum (bottom row) for different main discharge voltages.

From figures 5.19(a) and 5.19(b) the values of the maximum and minimum amplitudes of the magnetic field have been read out together with the time when the respective value is assumed. As was mentioned in chapter 3.2, the difference of magnetic field between minimum to maximum value is roughly proportional to the axial plasma current with corrections due to the curved geometry:

\[ B_{pol} \bigg|_{\text{max}}^{\text{min}} \propto I_{\text{incl.}} \]  \hspace{1cm} (5.1)

This is a simplified form of Ampère’s law. The current \( I_{\text{incl.}} \) is included between the crossing times of maximum and minimum over the probe. Since the expansion velocity is constant within the margin of error (as was obtained from ccd images in the previous section), this
crossing time interval can be directly converted into an absolute length yielding a rough estimate of the diameter of the current distribution. In figures 5.20(a) and 5.20(b), this change in magnetic field has been plotted for different probe positions. Apparently, the probes yield very similar field amplitudes within the 25% error margin from the calibration procedure. On a second scale, the times when the maximum magnetic field value is reached is shown. Only the first few measurement points can be interpreted as part of the evolution of the arch structure since the detachment of the arch occurs the latest around 18 µs. For these measurement positions, the included current decreases by about 1/4, while at the same time the external discharge current is still rising. The magnetic probe data imply therefore, that the main discharge current does not flow entirely through the plasma arch. In fact, the plasma current seems to decrease over a time of several microseconds. From this time interval and only considering the further rise of the external discharge current, it can be estimated that at least 15% of the total current does not flow through the plasma arch. This value has to be understood as lower limit, however, for a proper analysis all components of the magnetic field are required with more tightly spaced probes in order to evaluate all terms in Ampère’s law.

A very rough estimate of the current through the plasma arch can be obtained from Bennett’s relation [Bel06]:

$$2Nk(T_e + T_i) = \frac{\mu_0 I^2}{4\pi}$$  (5.2)

Where \(N\) is the number of electrons per unit length on the axis. This value is obtained from the local electron density under the assumption of a circular cross section of the arch with a diameter of 2 cm. Using the electron temperature of 1.5 eV from the LTE estimate and a density of \(1 \times 10^{22} \text{ m}^{-3}\) a plasma current of approximately 4 kA is obtained, for which a radial equilibrium would be reached. This is an order-of-magnitude estimate. However, in order to produce poloidal magnetic field amplitudes of only 120 mT to 150 mT, currents of up to 10 kA suffice. And the estimated arch currents from all performed estimates are considerably lower than the total discharge current at the same time, in most cases by a factor between 2-5.

For evaluation of the discharge current thus far only the temporal magnetic field evolution at a single probe position has been considered, corresponding to a horizontal cut in the contour plots 5.17 and 5.18. From the sequence of measurements, the magnetic field for different positions can be plotted for the same time, equivalent to vertical slices through the contour plots. For probe 1 this is presented in figure 5.21 for main discharge voltages of 2 kV and 3 kV. The signal shapes are very similar for both main discharge voltages. Following the blue line at 14 µs for 3 kV, the shape is furthermore very similar to the temporal profiles: Inside the arch – now displayed on the left end of the plot – a local
5.3. Magnetic Probe Measurements

![Graphs showing poloidal magnetic field from different discharges and probe positions at the same time.](image)

Figure 5.21.: Poloidal magnetic field from different discharges and probe positions at the same time.
maximum develops which subsequently evolves into a uniform magnetic field strength plateau across several measurement positions. Towards the outside, the amplitude decreases, crosses zero and reaches a local minimum with strongly reduced amplitude. Before the plasma arch crosses the first measurement position, e.g. between 8\(\mu s\) to 10\(\mu s\) (due to the lower expansion rate 11\(\mu s\) for 2kV), all probes see a plausibly small negative field amplitude.

Considering again the argument from before that local changes in magnetic field imply current flow, in conclusion current must flow across a range of several measurement positions. For instance at 17\(\mu s\) in figure 5.21(a) and at 15\(\mu s\) in figure 5.21(b) the magnetic field changes across the whole range of measurements implying a finite \(x\)-component of the current density for nearly the whole volume below the arch. Despite the localized density and luminosity measurements, the magnetic probe results therefore indicate a broad current distribution.

Furthermore, the continuous rise of magnetic field strength towards the first measurement positions implies that the current through the arch saturates at an early stage and that already close to the electrodes additional current channels parallel to the arch (in an electro-technical sense) must develop. The spatial distribution of the magnetic field at different times therefore confirms the results obtained from the temporally resolved measurements at different positions.

FloatBarrier Returning to the complete time-dependent data set as presented in figure 5.19, the amplitude behavior can be further analyzed. The time difference between minimum and maximum increases with distance from the electrodes and, therefore, with time. The entire signal shape gives the impression of a current channel that is loosely confined by magnetic forces of an axial current but starts to broaden again due to diffusion. From the temporal and spatial behavior as displayed in figure 5.20 an order of magnitude estimate of the magnetic diffusivity \(\eta_{mag}\) can be obtained. To this end, the diffusion equation for the magnetic field is analyzed in a discrete formulation:

\[
\frac{\Delta B}{\Delta t} = \eta_{mag} \frac{\Delta B}{\Delta x^2}
\] (5.3)

For the sake of comparability, the maximum signal should appear while the arch is still attached to the electrodes. Therefore, the estimate is restricted to the first few measurement points. For 3kV, the magnetic field change as measured with probe 1 over the first three measurement positions (from 5.5cm to 7.5cm, hence \(\Delta x = 2cm\)) coincides with an increase of the time difference between occurrence of maximum and minimum by around 1\(\mu s\). These values yield a magnetic diffusivity of around 400\(m^2/s\).

Unfortunately, the change of the magnetic field amplitude due to diffusion across the probe distance of 1cm is too small as compared to the signal variations. Therefore, from the extensive measurements presented so far, no further estimate of diffusivity within one discharge can be obtained.
From control measurements with inter probe distance increased to 3 cm such an estimate is possible. For four select probe positions the poloidal field component is shown in figure 5.22. Comparing again how the time between the extrema changes across the probe distance of 3 cm, diffusivities of the order of 360 \( \text{m}^2\text{s}^{-1} \) to 900 \( \text{m}^2\text{s}^{-1} \) are obtained. The large spread originates from the difficulty to determine the maximum in the signal of probe 2. Since they largely occur after the detachment of the arch, it is not surprising that larger diffusivity is obtained.

The magnetic diffusivity can also be determined via the electric resistivity \( \eta_{el} \). For fully ionized plasmas, this is given via Spitzer’s formula [Che84]. For an electron density of \( 1 \times 10^{22} \text{m}^{-3} \) and an electron temperature of about 1.5 eV one obtains for the electrical resistivity \( 5 \times 10^{-4} \Omega\text{m} \) and for the diffusivity:

\[
\eta_{mag} = \frac{\eta_{el}}{\mu_0} \approx 800 \text{m}^2/\text{s} \tag{5.4}
\]
5. Measurements

The values for the electron temperature and density used were taken from the optical measurements as presented in section 5.2 and were therefore obtained independently. Despite the numerous assumptions and simplifications applied, the two estimates show the same order of magnitude.

The result is also relevant in so far, as the magnetic diffusivity directly enters into the magnetic Reynolds number. Using the values presented so far, the magnetic Reynolds number should be of the order of one. Therefore, neither of the common MHD simplifications (neglecting either advection or diffusion processes) is adequate for the interpretation of the experiment under the specific conditions of these measurements.

5.3.2. Toroidal Field Component

In principle, the analysis of the toroidal magnetic field component comprises the same steps as the poloidal field component. However, the external PFN field is a regular component of the measured local toroidal field. Therefore, it it is generally not removed (by subtraction) as was the case for the poloidal component. The toroidal component probes are located at the same position as the poloidal magnetic probes: At two apex positions with 1cm distance from each other.

![Figure 5.23.: Probe raw signals illustrating the data evaluation (at 3kV and a probe position of 5.5cm).](image)

In analogy to figure 5.15 figure 5.23 shows an example of the toroidal probe raw and integrated signals. For comparison, a plasma discharge measurement and a shot only with the PFN magnetic field are plotted. As is expected, the plasma signal only begins to deviate, when the plasma discharge ignites around 7.7µs as indicated by the gray box.
Figure 5.24.: Reproducibility of measurements for a main discharge voltage of 3 kV at a probe position at 5.5 cm distance from the electrodes.

In figure 5.24, multiple measurements at the same position during subsequent discharges are plotted for comparison. To demonstrate more clearly the reproducibility of the plasma-induced signal component, the PFN pulse was removed numerically in these measurements. They show a decent reproducibility, despite the considerably smaller signal amplitudes. However, the probe signal also shows small indications of a current-generated component: Similar to the poloidal field component, the toroidal field has a very small negative amplitude followed by a strongly asymmetric maximum. This feature would not be easily visible without removing the PFN pulse component, though it becomes more pronounced at later times and further positions.

For both toroidal probes, signals taken at the same position are plotted in figure 5.25(a). Here, the PFN pulse is not removed, as can be clearly seen from the signal of probe 1. However, the signal shape gives rise to many questions. First of all, the amplitude of the PFN magnetic field should be reduced with larger distance, as seen for probe 1. Probe 2 on the other hand shows considerably less amplitude for the signal at the same position. To further complicate matters, the PFN pulse is not reproduced properly neither in shape nor in absolute amplitude for neither probe. At the charging voltage of 21 kV of the PFN, the magnetic field at 6.5 cm probe position (corresponding to 8.2 cm distance from the line conductor outside the discharge chamber and a line current of roughly 15 kA) amounts to at least 30 mT, which is twice as much as probe 1 detects.

Despite the successful calibration measurements in the Θ-pin coil, the signal shape detected in the chamber also considerably deviates from the PFN current pulse, as is illustrated in figure 5.25(b). From the signal of probe 1 as well as the calibration measurements it is safe to assume that the deviations are not caused by too high inductance of the probe.
5. Measurements

Figure 5.25.: Comparison of toroidal signals of probes one and two at various positions for 2kV main discharge voltage.

circuit. The temporal resolution of the probe suffices to resolve the rise time of the current through the PFN. However, during the current plateau the raw signal continuously shows perturbations which, after integration, lead to a deformation of the shape of the pulse. Apparently, the probe raw signals are very small. This is naturally the case during the current plateau, but also the field reversal is hardly distinguishable from the zero axis. Unfortunately, the high frequency perturbations during the PFN ignition did not allow for further increasing the oscilloscope resolution, as cutting them would have lead to integration errors at the beginning of the pulse. Since for the calibration magnetic field strengths of magnitude (approximately 35 mT) were used, the probe sensitivity should suffice to properly resolve the PFN pulse inside the discharge vessel.

Multiple reasons may cause the deviation: Cross-coupling of the toroidal probes 1 and 2 might reduce the toroidal signal. Upon larger distance between both probes this effect should be reduced, which could not be observed in measurements. The interaction of the toroidal and poloidal signal components of one probe assembly might be responsible for the signal form of probe 2, which shows structures reminiscent of the poloidal field component. However, those might as well be caused by a twisted plasma or not perfectly aligned probe, which partly captures “real” poloidal magnetic flux. Another cause of signal deviations is the additional copper mesh shielding, which was not used during the calibration measurements and might allow for eddy currents blocking part of the probe signal. On the other hand, due to the probe orientation this would mainly influence the poloidal signal.

Finally, continuous discharge operation – specifically with employing argon gas – is known to degrade the electrodes. Apparently at some point during the discharge, hot electrode spots form that lead to localized melting points. This also happens along the electrode
slits, possibly during the collimation and kink phase before detachment. From ccd images it can be seen that the thin plasma thread meanders outwards along the slit. Melting and setting of the copper can lead to partial closure of the slit, enhancing eddy currents in the electrode and effectively reducing the magnetic field. While this issue should be investigated to adapt the experimental maintenance schedules accordingly, unfortunately no data to quantify this effect is available yet.

However, the discussed reasons for signal deformation would equally apply to both probes and cannot explain the different behavior of probe 2 as compared to probe 1. From the calibration factors in table 4.8(b) it can be seen that the area of probe 2 should be larger by about 10% and the probe therefore be rather more sensitive than probe 1. Since the detected PFN pulse is very reminiscent of the pulse shape detected during calibration in the minimum-signal probe orientation (cf. figure 4.8(a)) it seems most likely, that the probe area was not chosen sufficiently large.

Magnetic Field Measurements

Despite the problems encountered when analyzing individual probe signals, the results of measurement sequences will be presented briefly. Figure 5.26 shows the toroidal magnetic field measured in the same discharges as the poloidal component presented in figure 5.17 with 2kV main discharge voltage.

The signals of both probes show similar features: First of all, they become very chaotic as soon as the arch detaches. The large negative amplitudes are an integration artifact caused by fluctuating signals leaving the detection range of the oscilloscope. This was also observed for the poloidal component, but due to lower signal amplitudes the effect is considerably more pronounced here. For all probe positions, this chaotic oscillation of the signals begins around 18µs. Since this is definitely after the electrode detachment, no coherent signals are expected to continue. However, as can be seen from figure 5.25(b), this is also the time when the PFN plateau decays. The influence of the removal of the external field on the dynamics of the arch at this stage is unknown, it might even contribute to the detachment at the electrodes.

Furthermore, the PFN field is clearly visible in the signal of probe 1. Apparently, the probe also develops considerable difference from the rectangular signal shape with increasing distance from the electrodes, although there is yet no plasma current. The toroidal guide field is completely absent from the signals of probe 2.

Both probes only show considerable signal during a short period of 5µs and only in the electrode proximity. Comparison with the poloidal component measurement (e.g. from figure 5.19(a)) indicates that the toroidal signal maximum appears when the poloidal signal crosses zero. This implies that the interpretation of the zero crossing as flux tube center
position was correct, since the toroidal signal should be largest inside the plasma. In [Ste11] was argued, that the toroidal magnetic field component should essentially consist of magnetic flux which is “frozen” into the plasma at ignition and advected along it. However, the previously determined magnetic diffusivity suggests that the plasma has a considerable resistivity. It would therefore be very desirable to get a verification of the previously estimated magnetic diffusivity also from this field component. Analyzing the amplitude evolution of the peak toroidal signal over time and at different probe positions, the magnetic diffusivity can be estimated similarly to the procedure applied to the poloidal field component. Here, considerably lower values around $250\,\text{m}^2\text{s}^{-1}$ are obtained. Investigating instead how the increase of the signal width during the crossing of the plasma arch for different probe positions, a value of $800\,\text{m}^2\text{s}^{-1}$ is obtained (to this end, the PFN pulses were removed from the signals, cf. 5.24). The order of magnitude is therefore consistent with the values obtained from the poloidal component. The detected toroidal magnetic field is therefore likely caused by a twisted plasma structure and not by frozen-in magnetic flux.

Finally, the toroidal signal seems to propagate outwards since it appears later at positions further from the electrodes. Following a tangent to the contours, the velocity can be estimated to be approximately $1\,\text{cm/\mu s}$ which is close to the expansion velocity.

In conclusion, although doubtful in some aspects, the toroidal probe measurements generally support the results obtained from the poloidal magnetic field component. There exists a signal component traveling with the arch expansion velocity. Its shape is furthermore similar to that of comparable measurements performed at the permanent magnet source (cf. ref. [Ste11] and section 6.1.2), sharing the aspect of increased initial toroidal field. However, the smallness of the signal amplitudes lead to considerable detection problems outside the current channel center.
Figure 5.26.: Contour plots of the toroidal magnetic field in a series of discharges with 2kV main discharge voltage. The presented signals include the PFN pulse.
6. Results

The transient character of the discharge is double-edged concerning the impact on diagnostics: For the spectroscopic measurements presented in 5.2.2 the rapid movement effectively reduces possible exposure times. On the other hand, the assumption of a defined density distribution crossing the interferometer scene beam is helpful for the interpretation of the phase shift signal and the deconvolution of the signal jumps when moving to the next fringe. Furthermore, reproducing the expansion velocity of the plasma arch as detected by other means is one of the first tests for any diagnostics.

Expansion velocities have been determined for a wide range of parameters using different diagnostics at the FlareLab experiment. While exact values differ for specific conditions, certain expansion characteristics are retained during the plasma evolution, i.e. uniform current channel diameter along the plasma arch. In a first step to give a physical explanation for similar observations at the Caltech Solar Corona Loop Simulation Experiment, Bellan proposed the MHD pumping mechanism that has been introduced in section 2.1. On the other hand, to understand certain properties of the expansion velocities observed in the FlareLab experiment, J. Dreher et al. proposed the simplified drift-like expansion scheme outlined in section 2.2.1.

At the beginning of this chapter, a summary of previous measurements of the expansion velocities at the FlareLab discharge will be given. Subsequently in section 6.1 velocities obtained from the magnetic probe measurements of the previous section will be discussed on this basis. Finally, from the spatial density and magnetic field profiles a first estimate for Alfvén velocities will be given in section 6.1.1 and compared with previous measurements at a different plasma source in section 6.1.2.

In the next step, published experimental evidence in confirmation of the MHD pumping model will be compared to results obtained at the FlareLab device in section 6.2.1 in order to investigate its impact on the discharge dynamics. On the basis of the ample experimental findings, the possibility of drift-like expansion of the arch-shaped flux tubes will be discussed in section 6.2.2.
6.1. Flux Tube Velocities

Determination of the average velocity of the plasma arch is possible with every diagnostic by noting the timing of a characteristic feature of the respective diagnostic signal at different measurement positions. For the interferometer data, the peak line-integrated plasma density is such an easily traceable feature. From the data presented in section 5.2.1 and further measurements at different main discharge voltages, apex expansion velocities in the range of 1 cm/µs to 1.3 cm/µs were determined.

Ccd images allow for determination of velocities in various directions. However, the signal interpretation is more ambiguous: As can be seen from the sequence of images presented in figure 5.1 and some of the luminosity profiles in figure 5.2, it can be difficult to define a proper edge of the apparent current channel. This is specifically a problem for the regions below the arch. Furthermore, there is no proper length scale present in the images. It is therefore customary to “calibrate” them using the electrode distance of 8 cm, which is perpendicular to the apex expansion and hence errors due to the inclination angle of the camera are introduced.

Nevertheless, ccd images provide the quickest way of establishing expansion velocities. In table 6.1(a), apex expansion velocities (that is, in z-direction) and lateral expansion velocities are given for pure argon discharges with 2 kV and 3 kV main discharge voltage and 20 kV to 21 kV charging voltage of the PFN. Already in the discussion of the ccd images in the previous chapter was noted that the plasma arch shows only little lateral expansion dynamics. The determined apex velocities are close to those determined by interferometry, 10% to 20% error seem an adequate margin for this method. Apex expansion velocities have been determined for various pure gases with a slightly modified version of the plasma source. A reprint of the data from [Ste11] is given in figure 6.1(b). Apparently, flux tube velocities decrease with increasing mass. At low masses, considerable differences between the expansion velocities are noted, whereas heavier elements such as argon and neon show the same expansion velocity within the error margin of about 0.8 cm/µs for 3 kV main discharge voltage. The characteristic of constant expansion velocity is kept for each of the listed gases. No physical explanation has yet been found for this mass scaling, nor is known which other gas-specific parameters might determine the value of the constant expansion velocity.

Expansion Velocity from Magnetic Probes

In section 5.3.1 the zero crossing of the poloidal magnetic field signal was interpreted as giving approximately the center of the current distribution crossing the position of the probe. Therefore, the velocity of the flux tube expansion can be obtained either from a
### 6.1. Flux Tube Velocities

<table>
<thead>
<tr>
<th>Diagnostic/conditions</th>
<th>Determined velocity</th>
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</thead>
<tbody>
<tr>
<td><strong>Interferometer:</strong></td>
<td></td>
</tr>
<tr>
<td>2 kV</td>
<td>1 cm/µs</td>
</tr>
<tr>
<td>3 kV</td>
<td>1.3 cm/µs</td>
</tr>
<tr>
<td><strong>ccd camera:</strong></td>
<td></td>
</tr>
<tr>
<td>2 kV, z-component</td>
<td>0.9 cm/µs</td>
</tr>
<tr>
<td>3 kV, z-component</td>
<td>1.1 cm/µs</td>
</tr>
<tr>
<td>2 kV, x-component</td>
<td>0.2 cm/µs</td>
</tr>
<tr>
<td>3 kV, x-component</td>
<td>0.2 cm/µs</td>
</tr>
</tbody>
</table>

(a) Expansion velocities from ccd images and interferometry

(b) Gas type dependence of expansion velocity (from [[Ste11], 3 kV])

![Graph showing velocity vs. mass number of ions]

Figure 6.1.: Flux tube expansion velocities obtained from ccd imaging and interferometry in argon for different main discharge voltages and about 20 kV charging voltage of the PFN and gas type dependence of the velocity determined from ccd images.
series of measurements with one probe or in situ by comparing both subsequent probes in a known distance.

In figure 6.2 the time of poloidal signal zero crossing is plotted for different probe positions. From the slope of the linear fit the average expansion velocity can be obtained. The method yields 1.1 cm/µs for 2 kV and 1.4 cm/µs for 3 kV main discharge voltage. Furthermore, instantaneous velocities can be obtained from comparing these zero crossing times for the two subsequent probes in a distance of 1 cm. The spread of these local velocities is increased, but they nevertheless confirm the results obtained from the sequence of discharges.

![Diagram](image.png)

(a) Times of zero crossing, 2kV

Figure 6.2.: Flux tube velocity from times of zero crossing of the poloidal magnetic field for different main discharge voltages.

Unfortunately, the obtained values for the velocities are too high: As the discharge is dominated by the argon gas, velocities should be close to those of pure argon discharges. Furthermore, sample measurements with the ccd camera showed identical expansion velocities for the gas mix as for those listed in table 6.1(a). In figure 6.1(b) velocities for different gas types were presented showing no difference between argon and neon. Taking the mean atomic mass of the argon-hydrogen mix of 27 u, the expansion velocity should be around the value of 0.8 cm/µs determined for pure argon and pure neon at 3 kV main discharge voltage. While there may certainly be further parameters influencing the velocity (e.g. the plasma temperature), these should agree largely with the respective values in the pure argon discharge case.

Indeed it seems more likely that the initial assumption of the zero crossing giving the position of the flux tube is flawed: Considering the fact that large amount of discharge current is not flowing through the arch-shaped structure itself but rather through the volume below it, this will lead to an additional poloidal field offset. This offset in turn leads to a shift of
the zero crossing position away from the electrodes. This effect causes an overestimate of the expansion velocity, though it would not necessarily scale linearly in time.

To compensate for this, a different feature of the poloidal signal is investigated. For each measurement, the half-height between the initial minimum and the maximum after the zero crossing is determined and the corresponding time is read out. Compared to the zero crossing method, this approach does not rely so much on the small negative initial signal which can be easily perturbed by additional currents and their respective magnetic fields. While the choice of read-out point is arbitrary, our choice is easily and objectively extracted from all measurements.

Times when this half-amplitude is reached during a discharge are plotted for all measurement positions and different main discharge voltages in figure 6.3. At a first glance, the linear expansion characteristic is retained. However, the obtained expansion velocities of this feature are considerably reduced to about 0.9 cm/µs for 2 kV and 1.1 cm/µs for 3 kV. Also for this feature, instantaneous velocities can be determined via the probe distance. The values confirm the averaged results well. However, the signal spread increases, especially at later times when the arch has detached from the electrodes.

Velocities obtained from the movement of the half-amplitude point match well the expansion velocities determined from pure argon discharges and also fit to sample measurements with the ccd camera for the argon-hydrogen mix. They also confirm the mass-dependence of the expansion velocity as reported previously and are therefore taken as the correct values for the expansion velocity.
6. Results

6.1.1. Spatial Alfvén Velocity Profiles

In a mechanical system, the sound velocity determines how fast the information about changes in the system can be transported. Similarly, in magnetized plasmas the Alfvén velocity determines the speed at which changes of the magnetic topology (e.g., due to changing current flows) can propagate. From the dispersion relation of ionic plasma sound waves, the following simplified expression can be obtained [BS03]:

\[
v_A = \sqrt{\frac{B^2}{\mu_0 \rho}}
\]  

(6.1)

For the plasma mass density \(\rho\), a specific atomic mass of 40\,u is assumed since the density values were obtained in pure argon; this choice is somewhat arbitrary, because the weighted average specific mass for the hydrogen-argon-mix would amount to 27\,u. For the order-of-magnitude estimate presented here, the error introduced is acceptable since the Alfvén velocity scales only with the square root of the mass.

In section 5.2.1 radial profiles of the plasma density were constructed for interferometric data. Similarly, profiles of the “total” magnetic field can be calculated using the data presented in section 5.3. To this end, the absolute value of the field vector is calculated using the two measured components (and hence assuming the missing component is small in the apex). Because the expansion velocity is constant, the time axis of the measurements can be converted into a spatial axis by multiplication with the corresponding velocity from table 6.1(a). On this new spatial axis, the zero-crossing of each poloidal magnetic probe signal is read out and interpreted as current center position of the arc. Shifting each spatial axis of each measurement by the respective value converts the scale into a radial axis. Note that the orientation of the spatial axis has been adapted so that positive radial positions are outside the arc, identically to the case for the local plasma density profiles. From the local electron density and the thus obtained total magnetic field profiles an estimate for the Alfvén velocity can be obtained: Density and magnetic field measurements have been overlaid as per measurement position. Results of the Alfvén velocity estimate are presented in figure 6.4 for various measurement positions and a main discharge voltage of 3\,kV. A radial profile presentation is chosen again, the peak plasma density is assumed in the center (cf. figure 5.8 for the original densities contours). The different measurement positions correspond to different times when the plasma arc crosses the probe (and scene beam) positions. Apparently, the Alfvén velocity in the current channel is very low – much lower, in fact, than the expansion velocity of the arch. Mainly, the high plasma density of \(1 \times 10^{22}\,\text{m}^{-3}\) and above leads to a localized reduction of \(v_A\) inside the current channel. To obtain an Alfvén velocity of the order of the expansion velocity at such a plasma density, about 250\,mT of magnetic field strength are required. This is twice as much as even for the poloidal magnetic field has been measured. And since this field strength would be required
inside the plasma channel, it would have to be provided mainly by the toroidal guiding field component, for which only 50 mT have been measured.

Outside the arch, if plasma is present, the density is below the detection limit of the interferometer. Moreover, the absence of the toroidal PFN pulse in the corresponding probe signals (cf. section 5.3.2) further reduces the determined Alfvén velocities, which are considerably underestimated in this region. Below the arch, depending on the measurement position detectable residual density prevails. Here, also the current-generated magnetic field is predominant and therefore considerable Alfvén velocities – even of the order of the expansion velocity – are reached. Little variation is found between the results for 2 kV and 3 kV main discharge voltage. Since density and magnetic field values obtained are of the same order of magnitude this is not a surprising result.

As possible consequence of low Alfvén velocities inside the plasma arch, the magnetic field twist induced by the rising external current cannot propagate along the structure up to the apex fast enough. Current that is injected at the electrode boundaries will not reach the apex, but rather bifurcate at some position along the “legs” of the plasma arch. As a closed circuit is required, the current has to ow through the volume below the arch or outside towards the grounded discharge vessel.

In the previous chapter, the indications of current flow components beside the visible arch structure has been discussed on the basis of the magnetic probe measurements. The hy-
6. Results

Hypothesis seems plausible that the apex current increases only slightly – if at all – after the onset of arch expansion. However, the current from the capacitor bank as detected externally continues to rise. At the same time, there is no clear evidence of the location of this current flow. Preliminary measurements with a large Rogowski coil introduced into the plasma to directly measure the axial current through the arch confirm this result. They yield arch currents as low as 5 kA to 6 kA for main discharge voltages of 3 kV in argon [Mac12] and at times currents of up to 15 kA to 20 kA are measured externally at the capacitor bank. Further measurements at various distances in front of the electrodes indicate, that the axial current increase is transported along the arch’s “legs” at a similar rate as the plasma luminosity shown in figure 5.2(a). This confirms the initial statement that the luminosity can be interpreted as roughly proportional to the local current density. While the ccd images presented in figure 5.1 would allow for diffuse currents, those would be parallel and thus tend to attract each other. During the course of a discharge further visible current paths should therefore emerge. Nevertheless, there is pronounced residual luminosity below the arch which might indicate volume currents. Furthermore, already early during the discharge evolution around 11 µs arcade-shaped structures develop pointing from the clouds in front of the electrodes towards the grounded steel circumference of the electrode system flange, which indicates current flow towards the chamber wall. Investigation of the ceramic mounting plate of the electrodes as well as the surrounding stainless steel flange indicate plasma contact during operation and the surface roughness implies sputtering impacts. However, it could not yet be observed whether this occurs during the arch expansion phase of the discharge or during subsequent oscillations of the discharge capacitor bank.

In conclusion, the rough estimate of Alfvén velocities presented here does fit into the emerging picture of the discharge evolution. Despite the considerable rise of the current leaving the external capacitor bank, the plasma current inside the arch does not increase very much since the propagation of the current-induced twist of the magnetic field may not travel as fast along the arch as the arch expands. In consequence, further current paths form, leading ultimately to considerable volume current below the arch. This current, while implicitly visible in the magnetic probe data, has unfortunately not been clearly verified by means of ccd imaging, possibly due to insufficient contrast versus the more pronounced sections of the plasma arch. However, similar observations were made in experimental setups with comparable experimental conditions (e.g. [BKS+10], where no current back-flow is observed in ccd images of a pulsed plasma jet).

6.1.2. Comparison with Permanent Magnet Source

For a different plasma source design where the toroidal magnetic field is provided by strong permanent magnets (cf. section 4.2), plasma density and magnetic field measurements have
Figure 6.5.: Experimental data obtained for hydrogen discharges in the permanent magnet source. The plasma densities were obtained by means of an electrostatic triple probe, the magnetic field was measured via a magnetic induction coil.

been performed in previous works by F. Mackel and H. Stein. A sequence of ccd images of the discharge is shown in figure 6.5(a). The discharge evolves within a time interval of 6µs. A line connecting the apex positions indicates that the characteristic of constant expansion velocity is maintained for this plasma source design. The apex expands along the z-axis with a velocity of about 2.0cm/µs, which is faster than the argon discharges discussed previously by about a factor two. The evolution of the arch structure ends with the development of instabilities close to the electrodes around 7.5µs after trigger. Subsequently, a short-circuit across the small gap between both electrodes develops followed by the detachment of the arch at the electrodes. Then the arch begins to fade. Note that the timing of the data presented in figure 6.5 is given with respect to the trigger of the discharge. Since no PFN is applied, the delay till discharge ignition is reduced to about 1.5µs.

Plasma density measurements in the apex region performed by F. Mackel [Mac09] by means
of an electrostatic triple probe are presented in figure 6.5(b). The probe currents are measured in a time sequence in which the passage of the plasma arch shows as temporary increase in plasma density to values approaching \(1 \times 10^{21} \text{ m}^{-3}\). While the currents to the probe tips have been continuously detected, discontinuities arise from the data evaluation with increased distance from the density maximum as the probe currents decrease and the signal-to-noise ratio increases. These discontinuities have been masked in the plot for better overview. Furthermore, more closely spaced measurements are available, but have been omitted in the presentation.

<table>
<thead>
<tr>
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<tr>
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</tr>
<tr>
<td>Collisional Ionization, H (5eV)</td>
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<td>Collisional Ionization, H (1.5eV)</td>
<td>(1 \times 10^{-11} \text{ m}^3/\text{s})</td>
</tr>
<tr>
<td>Collisional Ionization, H(_2) (1.5eV)</td>
<td>(1 \times 10^{-11} \text{ m}^3/\text{s})</td>
</tr>
<tr>
<td>Collisional Ionization, H(_2) (5eV)</td>
<td>(5 \times 10^{-10} \text{ m}^3/\text{s})</td>
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Figure 6.6.: Collisional dissociation rate coefficients for hydrogen molecules from the ground state and collisional ionization rate coefficients from the ground state of atomic hydrogen (from [JLEJPJ87])

The probe data show a plasma structure of constant diameter (arbitrarily defined as the half-width of the signal peak) and density. The obtained plasma densities seem lower by at least an order of magnitude than the neutral gas densities. However, comparison with interferometric plasma density measurements showed that the triple probe tends to underestimate the plasma densities due to short interaction times and thus inductive limitations in the probe circuit [MKS+11]. Even taking this measurement effect into account, the plasma density in argon is considerably higher. This is possibly due to the metastable states of neutral argon effectively reducing the ionization potential.

In the case of hydrogen, additional energy is required to dissociate the molecules. Using the rate coefficients in table 6.1.2 (taken from [JLEJPJ87]) it can be estimated whether the dissociation suffices during the short plasma duration: For an electron density of \(1 \times 10^{21} \text{ m}^{-3}\) and a neutral gas background of \(1 \times 10^{22} \text{ m}^{-3}\), the dissociation rate is in the range of \(1 \times 10^{20} \text{ m}^{-3} \text{m}^{-1} \text{s}^{-1}\) to \(5 \times 10^{22} \text{ m}^{-3} \text{m}^{-1} \text{s}^{-1}\) for a temperature range of 1.5 eV to 5 eV. Molecular hydrogen may therefore still be present, especially considering that peak electron densities have been used in the estimate. As the rate coefficients for collisional ionization from ground state of hydrogen atom and molecule are identical for these low temperatures, the
density increase is probably carried by molecular ionization as the atomic density only grows with the previously estimated rate.

Magnetic field measurements performed by H. Stein are shown in figure 6.5(c) (from [Ste11]). A single magnetic induction probe was employed for measurements, the magnetic field was measured in the plasma apex. In a sequence of discharges, the probe was moved to different positions along the z-axis. Furthermore, all results presented in the figure are averaged over a set of five subsequent measurements at the same probe position. The probe data are reminiscent of the measurements of the poloidal magnetic field in argon discharges presented in section 5.3.1. They show a very similar structure including the zero-crossing of the field strength attributed to the passage of the toroidal current distribution and the amplitude asymmetry of field strengths determined inside and outside the plasma arch. For the first measurement positions, which are within the radius of plasma ignition, the negative signal component vanishes. The absolute amplitudes detected are up to 20% increased as compared to the previously presented measurements in argon. Furthermore, the total amplitude (as difference of the positive inside signal and negative outside component) of the magnetic field remains constant until electrode instabilities arise around 7.5 µs. This indicates a reduced magnetic diffusivity and hence implies an enhanced plasma conductivity and temperature as compared to argon discharges. Nevertheless, an estimate following the previous approach for the argon case yields a similar diffusivity of about 500 m²s⁻¹.

During the discharge expansion, the amplitude asymmetry of the signal is reduced drastically: The amplitude ratio decreases from 1:10 at the first measurement positions to 1:1.3 at the furthest present measurement position. From the ccd images can be seen that, at the same time, the radius of curvature of the plasma arch increases in the apex region, leading to an almost straight plasma front moving across the probe position in the apex. This encourages to estimate the plasma current through the magnetic field structure using Ampère's law for a straight conductor. Using the averaged amplitude of 60 mT and a plasma diameter of 3.2 cm (from the time between maximum and minimum and the expansion velocity of 2 cm/µs), a plasma current of 5 kA is obtained. This is of similar magnitude as for the argon discharges discussed previously and corresponds to one third of the externally measured discharge current at 7.5 µs.

Complementing the measurements of the poloidal magnetic field component, measurements of the toroidal field component have been performed by H. Stein under the same discharge conditions. Following the steps of the preceding section, radial profiles of the “total” magnetic field (comprising again only the toroidal and poloidal components) and the plasma density were constructed. With these, profiles of the Alfvén velocity similar to those of the previous section can be constructed, four selected profiles are presented in figure 6.7.

Compared to the argon discharges, the Alfvén velocities are greatly enhanced: The differences in the detected plasma density and the greatly reduced specific mass of hydrogen
6. Results

Figure 6.7.: Radial profile of the Alfvén velocity (solid lines) in hydrogen discharges at 3kV main discharge voltage in the permanent magnet source at different distances from the electrodes. For comparison, the total magnetic field is plotted with dashed lines.

already lead to increased Alfvén velocities by a factor of 20. Furthermore, even inside the plasma arch the toroidal magnetic field component is more pronounced in the permanent magnet source – despite the fact that the toroidal magnetic field provided externally is considerably lower in this electrode design. Towards the inside of the arch (e.g. negative radial positions), the Alfvén velocities diverge as problems with the density determination increase (cf. figure 6.5(b)).

For the case of the hydrogen plasma discharge, the resulting Alfvén velocities are of the same order of magnitude as the overall plasma expansion velocity. Previously it was argued that low Alfvén velocities would not allow the capacitor bank current to reach the apex of the arch. In the case of the hydrogen discharge, this argument is not plausible. Nevertheless, similar behavior concerning constant arch current is observed and furthermore the magnetic diffusivities are of the same order of magnitude. Instead of an Alfvénic constraint on the plasma current, the comparison indicates similar conductivities in the arch structure. External measurements showed that the electrode potentials are almost constant for the duration of the plasma arch, with a voltage between both electrodes of about 1kV independent of the operating gas type. This implies similar plasma arch currents for both hydrogen and argon plasma discharges, though no values can be estimated as the voltage drops across both electrode sheaths are unknown.
6.2. Model Comparison

6.2.1. Relevance of MHD Pumping

In the ccd images discharges operated in both the line current source and the permanent magnet source (cf. figures 5.1 and 6.5(a)) the flux tubes show constant diameter over large sections of the arch. As was stated in section 2.1, in the case of the permanent magnet source this may be a consequence of plasma transport driven by the axial current distribution in the initially flared magnetic field configuration.

Experimental verification of the relevance of MHD pumping was claimed by Tripathi, Yun and Bellan [TBY07], You, Yun and Bellan [YYB05] and Yon and Bellan [YB10] investigating the Solar Coronal Loop Simulation Experiment at the California Institute for Technology (Caltech). The FlareLab permanent magnet source design was constructed in close resemblance to the Caltech experiment. This includes the electrode geometry and size, the gas injection procedure, shape of the toroidal magnetic field and the energy capacity of the discharge capacitor bank, as introduced in section 4.2. However, due to lower inductance of the discharge circuit, the current rise time is considerably shorter at the Caltech experiment and thus the maximum discharge current reaches up to 72 kA after 9.5 µs (cf. [Han01]). Furthermore, at the Caltech experiment horseshoe-shaped electromagnet provides the toroidal magnetic field with bulged topology while permanent magnets are employed at the FlareLab device. The electromagnets provide an about four times higher magnetic field strength (measured on the electrode surface) as the setup employing permanent magnets. Ccd images of discharges in both experiments show strong resemblance, which becomes more evident in videos of the discharges (compiled from ccd image sequences) available in the supplemental material of references [TBY07] and [KMS10a]. Both discharges share properties like the constant arch diameter and the constant expansion rate in z-direction, though the absolute values of the velocities are larger at the Caltech experiment – possibly due to the faster current rise. In neither experiment a retrograde contraction movement of the arch is observed in order to compensate for the increased magnetic energy due to pinching of the flux tube (cf. section 2.1).

Spectroscopic Doppler blue-shift measurements of Ar\(^+\) ions performed at the Solar Coronal Loop Simulation Experiment showed ion velocities of around 4 cm/µs [TBY07], which is slightly higher than the arch expansion velocity. The authors attribute this velocity component exclusively to plasma flows along the arch caused by MHD pumping, although the same signal appears in lines of sight parallel and perpendicular to the arch. Moreover, they do not discuss the absence of a signal component showing the arch expansion velocity, despite the similar magnitude. The Doppler shift measurements are therefore not conclusive. Unfortunately, due to the limited spectral resolution no spectral shift measurements could be performed at the FlareLab discharge.
From the electrostatic probe measurements presented in figure 6.5(b) it can be seen that the plasma density of hydrogen discharges remains constant and also the density profile width does not vary by much. Since its volume increases along with the arch’s expansion, additional plasma has to be generated in order to maintain the density distribution. The obvious conclusion of ionizing and ingesting further neutral gas from the preceding gas injection was denied by the Caltech group: They performed spectroscopic plasma density measurements in a similarly operated pulsed jet experiment, claiming that the results can be directly transferred to the Solar Coronal Loop Simulation Experiment. Plasma densities of the order of \(1 \times 10^{22} \text{m}^{-3}\) are reported and compared to measurements of the neutral gas density (without plasma ignition) of \(1 \times 10^{17} \text{m}^{-3}\) \(^{[YYB05]}\). The enormous density increase of five orders of magnitude is attributed to the MHD pumping mechanism ingesting plasma from the electrode orifices and transporting it along the arch. At room temperature, the claimed neutral gas densities are equivalent to a pressure of \(4 \times 10^{-4} \text{Pa}\) in front of the electrodes. For hydrogen and argon the minimum breakdown voltage is reached for a pressure-distance product of \(1 \text{Pa m}\) and \(0.5 \text{Pa m}\), respectively. This would lead to unreasonably high electrode distances of the order of kilometers in order to achieve plasma ignition.

Similar measurements of the neutral gas background were performed at the FlareLab device and were presented in figure 5.3 by means of a home-made calibrated ionization gauge. The measurements show two overlapping gas clouds in front of the electrodes with a pressure (at room temperature) of approximately \(200 \text{Pa}\) – equivalent to a neutral gas density of about \(5 \times 10^{22} \text{m}^{-3}\). This is the gas density at the position of plasma ignition, the distribution spreads further outwards and even at 15cm to 20cm distance from the electrodes there should be enough gas available to compensate for the plasma arch volume increase. Specifically, no density increase over the neutral gas density is observed.

Similar results were obtained for the line current source: From the line-integrated plasma density in \(^{[3.3]}\) can be seen, that the peak densities even increase over time. Due to the different magnetic field topology provided by the line current, MHD pumping cannot be effective in this plasma source. Nevertheless, similar discharge behavior (concerning e.g. the constant expansion rate) is observed. It is also not clear at which times the proposed mechanism should be effective: As a prerequisite, the magnetic field along the plasma length should be larger than the azimuthal field generated by the plasma current so that the Kruskal-Shafranov-criterion (cf. equation \(^{[2.1]}\)) is sacrificed. Investigating the toroidal field strengths and the axial currents for both the Caltech experiment and the FlareLab device it becomes evident that this criterion is violated already 1\(\mu\)s after ignition. In this estimate, the enhanced current rise at the Caltech device compensates the higher toroidal magnetic field strength. All measurements presented in confirmation of the transport
mechanism were taken at later times, when the current-generated poloidal magnetic field dominates the toroidal field component. In conclusion, no evidence for the influence of MHD pumping on the evolution of plasma discharges in the FlareLab device was observed [TKM+12].

6.2.2. Drift-like Expansion

In section 2.2.1, a drift-like expansion scheme was proposed. Essentially, the magnetic field of the axial plasma current causes an $\mathbf{E} \times \mathbf{B}$-drift of the apex outwards in $z$-direction. The results from section 6.1 show that the experimentally obtained expansion velocities become constant almost instantly, i.e. no time interval of acceleration to these final velocities can be observed.

Magnetic probe measurements presented in section 5.3.1 showed that the arc current does not follow the rise of the external capacitor discharge current. Instead, the current through the arch seems to saturate already early during the discharge evolution. From the probe measurements, rough estimates of the arc current of the range of 5 kA to 10 kA were obtained for a large variation of experimental conditions, including different electrode system designs, main discharge voltages and working gases. A direct measurement of the arc current by introducing a large Rogowski coil into the discharge vessel and detect the axial current during the arch’s crossing was recently performed by Felix Mackel [Mac12]. It provided more precise values of the axial current in the plasma apex of around 5 kA to 6 kA for an argon discharge at 3 kV charging voltage. The capacitor discharge current reaches these conditions around 9 µs after the trigger pulse, shortly before the arch expansion initiates between 9 µs to 10 µs as determined from the ccd images in figure 5.1. Furthermore, preliminary Rogowski coil measurements of the arc current at various distances in front of the electrodes indicate that the externally measured discharge current propagates only little along the arch. The “excess” current not passing through the arch apparently has to choose different paths, which unfortunately have not been located yet. Nevertheless, the magnetic probe measurements show additional current flow below the arch in the case of argon discharges. Also, the luminosity propagates along the arch similarly to the detected current.

High voltage probe measurements performed externally at the electrodes furthermore showed that during the arch evolution, the voltage drop across the electrodes remains quite constant at about 1 kV. Under these conditions, the model assumptions of the electric field distribution seem plausible: As the externally applied potential difference shows little temporal variation during the arch’s lifetime so should the electric field outside the current channel. From the comparison of order of magnitude estimates of Alfvén velocities in hydrogen and argon (cf. sections 6.1.1 and 6.1.2) it seems possible that the plasma current is limited by the conductivity, which would lead to an electric field distribution
inside the current channel similar to the model assumption. In order to achieve an expansion velocity of 1 cm/µs for the poloidal magnetic fields of the order of 100 mT, an electric field strength of roughly 1 kV/m is required. The electric field inside the current channel can be estimated from the arch current of 5 kA distributed homogeneously across a cross section of 3 cm diameter and the Spitzer resistivity of $5 \times 10^{-4}$ Ω m, which was obtained from the temperature estimates in section 5.2.3. This yields an electric field strength of 3.5 kV/m. The orders of magnitude agree for required and estimated electric field. Maximum magnetic and electric field are assumed at different locations and thus could cause the observed expansion velocities. Because the poloidal magnetic field changes sign crossing the current channel a retaining drift component develops (cf. section 2.2.1) and the required electric field should be larger than the estimated value.

The drift-like expansion scheme shows promising agreement with several independent measurements. Specifically, the lack of any accelerated expansion movement points to such a drift mechanism: If the expansion was due to an accelerating force, development of a constant velocity would require precise force balance – developing quickly and for a wide range of varied parameters.

The gas type dependence of the expansion velocity (cf. figure 6.1(b)) in a force-driven expansion scheme furthermore would contain a mass-dependency. However, already the measurements presented in section 6.1.2 for the permanent magnet source show that the plasma mass is reduced by a factor 400 (the factor comprising of reduced plasma density and lower atomic mass of the species) as compared to the argon plasmas investigated in the line current source setup. Nevertheless, the expansion velocity differs only moderately by a factor of 2, suggesting that the plasma mass has a very limited influence on the overall expansion.

So far only values in the apex have been taken into account. Along the z-axis through the apex, the different electric and magnetic field strengths should lead to zones of different flow velocity: The orientation change of the poloidal current-generated field should cause an additional pinch effect on the current channel. Furthermore, “excess” current (the capacitor discharge current fraction that does not flow through the plasma arch) below the arch may lead to additional drift movement in the electric field between the electrodes. For different positions along the arch so far only ccd imaging and spectroscopic data are available, as the interpretation of many probe data is substantially easier for the continuous arch crossing movement in the apex. In table 6.1(a) expansion velocities for argon discharges from the ccd images were given. The data showed z-expansion happening at a rate higher by a factor of 5 than the “radial” expansion movement of the arch. This contradicts the simple drift movement, as electric field and magnetic field generated by the arch current should lead to an outwards drift at every position along the arch and has not been resolved so far. For the line current source this effect is reduced, because the electric field between the electrodes
should have a dipolar topology, i.e. it should be more parallel to the electrode plane than to the legs of the plasma arch. Assuming that the current through the arch’s legs is higher as compared to the apex region, the increased magnetic field might also reduce the drift velocity.

Finally, the influence of the toroidal magnetic guiding field on the drift movement is yet unclear due to the complicated three-dimensional configuration. As was shown in 2.2.1, x- and y-components of the velocity should develop. The value of these components should differ considerably; specifically the y-component inside the arch should be greater due to the magnetic field scaling from equation (2.9). Instead of a rotation of the plasma arch it should therefore flow apart. This would not be visible in the ccd images, as in this simplified picture the derived velocity would be along the line of sight. Images taken from a different perspective in top view onto the electrodes indeed show a flux tube with greater width. However, due to the integration of the luminosity along the line of sight it is not clear whether the detected intensity originates from regions close to the apex of the arch or rather from the volume below it. As furthermore no distinctive current channel is visible anymore (despite the evidence from the lateral observations), these frontal images are not conclusive and further investigation is required.
7. Conclusion and Outlook

Arch-shaped magnetic flux tubes generated in a pulsed-power plasma experiment were investigated with a variety of diagnostics concerning their expansion properties. Specifically, the expansion velocity was of interest, which is observed as constant for a wide range of experimental parameters.

An MHD transport mechanism is investigated as possible cause of a uniform arch cross section: Axial transport of poloidal magnetic flux along the plasma may cause a pinch force leading to a uniform diameter along the arch. Despite numerous experimental findings at a very similar experimental setup, no indication for the relevance of this process could be found. Instead, magnetic probe data showed that the plasma current in the apex region is constant – in contrast to the current rise of the external discharge capacitor bank. The observation of constant plasma current is consistent with ccd images showing little change in luminosity in the arch regions more distant from the electrodes.

A constant expansion velocity was observed for considerably different experimental conditions. This included different plasma source designs with fundamentally different toroidal magnetic field topology and variation of the working gas, which lead to plasma densities lower by an order of magnitude. Inside the current channel of the arch, Alfvén velocities were estimated. To this end, plasma density profiles obtained from interferometry were inverted to obtain local densities, which were in turn verified by means of Stark broadening of hydrogen Balmer lines. Furthermore, measurements of multiple components of the magnetic field of the plasma arch were performed. The obtained Alfvén velocities varied greatly between the different investigated conditions. Initially, it seemed possible that the low Alfvén speed constrains the current rise in the plasma arch as the injected poloidal magnetic flux cannot propagate fast enough along the arch. However, comparison with results at lower plasma density and with reduced atomic mass of the plasma particles made this argument less plausible. These data showed an order-of-magnitude agreement of expansion and Alfvén velocity, which is also observed in the solar context. Furthermore, they indicated that the arch current is limited by the low conductivity. An estimate for the conductivity was obtained from Spitzer’s formula for fully ionized plasma using electron temperatures obtained from elementary optical emission spectroscopy. The obtained value confirmed the observation of magnetic field diffusion.
obtained with the magnetic induction probes. Interpretation in terms of the drift-like expansion mechanism so far was not conclusive. From the presented data of ccd imaging, magnetic field probes, and to lesser extent, interferometry, the underlying assumption of residual plasma (and considerable plasma currents through it) below the actual arch structure is very plausible. Rough estimates of the electric field strength along the arch and results of the magnetic field measurements showed, that the detected expansion velocities could be caused by these fields. The result of constant arch current despite the rise of the external discharge current as well as the approximately constant voltage drop across the electrodes together could lead to a constant expansion velocity. Furthermore, a drift-like movement of this type would explain why no extended acceleration phase of the plasma movement is observed.

Measurements until now are only extensively available in the apex of the plasma arch. Ccd images showed little dynamics along the rest of the arch till it detaches at the electrodes. Specifically, the lack of radial expansion of the arch (like an inflating tire) possibly contradicts the drift mechanism, as it should produce a radial component at every position along the arch. Furthermore, the opposed orientations of the poloidal magnetic field inside and outside the arch should lead to a small compression effect, which is not observed in any measurement. Finally, the influence of the toroidal magnetic field on the drift movement as well as the different electric field configurations in the presented electrode configurations are yet to be investigated.

The presented results clearly show that the argon discharges under investigation cannot be described in terms of ideal MHD. The magnetic Reynolds number of the order of unity suggests considerable influence of resistive effects on the plasma, which are observed for instance in terms of the diffusion of the magnetic field. For the initially introduced scope of the experiment this is bad news, as such discharge conditions are far from reproducing the conditions under which solar coronal loops develop and evolve.

From the measurements presented in this work it is apparent that considerable amount of external capacitor discharge current does not flow through the main plasma arch. It is important to investigate these current paths, e.g. by means of local Rogowski coil or magnetic probe measurements and to reduce currents that are electrotechnically parallel to the arch. Increasing the arch current should also increase Ohmic heating, hence increase the conductivity and shift the plasma conditions further from the resistivity-driven dynamics currently observed.

In the current state of the experimental works, diagnostics are mainly employed in the apex of the discharge, with the exception of the presented Stark broadening results. It was shown that the apex plasma current is considerably reduced as compared to the externally measured discharge current. Hence the next step should be to extend the diagnostics
to further plasma regions. Unfortunately, many employed methods implicitly require the constant expansion of the apex for interpretation of the measurement results. The magnetic probes need to be extended to detect all three spatial components simultaneously in order to be effectively applicable outside the apex region.

For further investigation of the drift-like expansion, information regarding the electric field distribution would be useful. This is a difficult quantity to come by, specifically in the lower density regions below the arch structure. Inside the arch, preliminary measurements of the potential difference between two floating probe tips at close distance inside the main current channel showed promising results for the electric field along the arch. However, due to the greatly reduced plasma density outside the current channel and the close proximity to it as a source of signal perturbations, it does not seem an adequate tool for investigation of the regions surrounding the current channel.

For further analysis of the plasma dynamics a precise knowledge of the plasma temperature is required. So far, estimates originating from methods requiring very crude assumptions indicate results of the same magnitude (around 1 eV to 2 eV) for argon discharges, measured by means of electric probes in the apex and obtained from emission spectroscopy assuming LTE in the electrode proximity. Thomson scattering would provide a tool to obtain the electron temperature without making assumptions concerning the state of the plasma. Considering the high electron densities, a single-shot Thomson scattering diagnostic seems possible.

In comparison with the MHD simulations, these data could lead to finally solving the question of expansion of the arch-shaped magnetic flux tubes in the experiment.
## A. Plasma Parameters

### Assumed Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arch length</td>
<td>20 cm</td>
</tr>
<tr>
<td>Arch minor radius</td>
<td>1 cm</td>
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### Measured Parameters: Line Current Source

Argon, 3kV main discharge, 20kVPFN

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge current (externally measured, after 5µs)</td>
<td>20kA</td>
</tr>
<tr>
<td>Plasma current (through arch)</td>
<td>5kA to 6kA</td>
</tr>
<tr>
<td>Magnetic guiding field (at 4cm)</td>
<td>70mT</td>
</tr>
<tr>
<td>Poloidal magnetic field strength (max.)</td>
<td>175mT</td>
</tr>
<tr>
<td>Poloidal magnetic field strength (min.)</td>
<td>−20mT</td>
</tr>
<tr>
<td>Electron density in apex (interferometer, Gottardi-inversion)</td>
<td>$1 \times 10^{22} \text{m}^{-3}$ to $9 \times 10^{22} \text{m}^{-3}$</td>
</tr>
<tr>
<td>Electron density at 3cm from electrodes (Stark broadening)</td>
<td>$3 \times 10^{22} \text{m}^{-3}$</td>
</tr>
<tr>
<td>Electron temperature (spectroscopy, LTE, 3cm from electrodes)</td>
<td>1.5eV</td>
</tr>
<tr>
<td>Probe measurements (apex)</td>
<td>1 eV</td>
</tr>
<tr>
<td>Expansion velocity (z-component)</td>
<td>1.1 cm/µs</td>
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<tr>
<td>Expansion velocity (&quot;radial&quot; component)</td>
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</tr>
</tbody>
</table>

### Derived Quantities

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Electron Larmor radius</td>
<td>25 µm</td>
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<tr>
<td>Ion Larmor radius</td>
<td>6 mm</td>
</tr>
<tr>
<td>Debye length</td>
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</tr>
<tr>
<td>Electron plasma frequency</td>
<td>$2.5 \times 10^{12} \text{1/s}$</td>
</tr>
<tr>
<td>Electron cyclotron frequency (pol. field)</td>
<td>$1.8 \times 10^{10} \text{1/s}$</td>
</tr>
<tr>
<td>Spitzer resistivity</td>
<td>$5 \times 10^{-4} \Omega m$</td>
</tr>
<tr>
<td>Electron collision time</td>
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</tr>
<tr>
<td>Alfvén velocity</td>
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</tr>
<tr>
<td>Ion sound velocity (Bohm velocity)</td>
<td>0.3 cm/µs</td>
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<tr>
<td>Magnetic Reynolds number</td>
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</tr>
<tr>
<td>Lundquist number</td>
<td>0.1</td>
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</tbody>
</table>
### A. Plasma Parameters

**Measured Parameters: Permanent Magnet Source**

**Hydrogen-Helium Mix, 3kV main discharge**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge current (externally measured, after 5µs)</td>
<td>20kA</td>
</tr>
<tr>
<td>Plasma current (through arch, $\mathbf{B}$-probe estimate)</td>
<td>10kA</td>
</tr>
<tr>
<td>Magnetic guiding field (at 4cm)</td>
<td>15mT</td>
</tr>
<tr>
<td>Poloidal magnetic field strength (max.)</td>
<td>150mT</td>
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<tr>
<td>Poloidal magnetic field strength (min.)</td>
<td>$-50$mT</td>
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<tr>
<td>Electron density in apex (triple probe)</td>
<td>$5 \times 10^{20}$ m$^{-3}$</td>
</tr>
<tr>
<td>Electron temperature (triple probe)</td>
<td>5 eV</td>
</tr>
<tr>
<td>Expansion velocity (z-component)</td>
<td>2.5 cm/µs</td>
</tr>
</tbody>
</table>

**Derived Quantities**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Electron Larmor radius</td>
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<tr>
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<td>Electron plasma frequency</td>
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<td>Electron collision time</td>
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<tr>
<td>Lundquist number</td>
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</table>
Bibliography

Three-dimensional magnetohydrodynamical simulation of expanding magnetic
flux ropes.

[Arn08] L. Arnold.
Dynamik magnetischer Flussröhrren.

Simplified quantum-mechanical theory of pressure broadening.

[Bel03] P. M. Bellan.
Why current-carrying magnetic flux tubes gobble up plasma and become thin
as a result.

[Bel06] P. M. Bellan.
Fundamentals of Plasma Physics.

Theory of stark broadening—I exact line profile with model microfield.
1783, December 1971.

Laboratory simulations of solar prominence eruptions.

[BH08] K. Behringer and T. Höschen.
Spectroscopic diagnostics of pulsed arc plasmas for particle generation.
[BKS+10] P. M. Bellan, D. Kumar, E. V. Stenson, S. K. P. Tripathi, G. S. Yun, and A.
L. Moser.
Laboratory simulations of astrophysical jets and solar coronal loops: new re-
sults.
2010.

The physics of plasmas.
Cambridge Univ Pr, 2003.

[Che84] F. F. Chen.
Introduction to plasma physics and controlled fusion: plasma physics, vol-
ume 1.

Plasma spectroscopy.

Instantaneous direct display system of plasma parameters by means of triple
probe.

Experimentalphysik 3, Atome, Moleküle und Festkörper.
Springer-Verlag Berlin, 1996.

[FB71] U. Frisch and A. Brissaud.
Theory of stark broadening—I soluble scalar model as a test.
1766, December 1971.

Validity criteria for local thermodynamic equilibrium in plasma spectroscopy.

Comparison of the stark widths and shifts of the h-alpha line measured in a
flash tube plasma with theoretical results.
*Plasma Spectroscopy.*  

[GC96] M. A. Gigosos and V. Cardeñoso.  
New plasma diagnosis tables of hydrogen stark broadening including ion dynamics.  

Eruption of a multiple-turn helical magnetic flux tube in a large flare: evidence for external and internal reconnection that fits the breakout model of solar magnetic eruptions.  

Evaluation of electron density profiles in plasmas from integrated measurements.  

Plasma spectroscopy.  

[Han01] J. F. Hansen.  
*Laboratory Simulations of Solar Prominences.*  

*Plasma Diagnostic Techniques.*  

Über die Verbreiterung von Spektrallinien.  

Electric microfield distributions in plasmas.
Bibliography


Plasma diagnostics with microwaves.

*Elementary processes in hydrogen-helium plasmas*.

Twisted coronal magnetic loops.

Improved stark profile calculations for the hydrogen lines $h\alpha$, $h\beta$, $h\gamma$, and $h\delta$.

Cross-sectional properties of coronal loops.

Electron density measurement in a pulsed-power plasma by FIR laser beam
deflection and/or interferometry.

Electron density measurements in rapidly moving pulsed-power plasmas by
means of a CO2 laser interferometer.

Principles of plasma physics.

*Introduction to Plasma Spectroscopy*.

Principles of plasma discharges and materials processing.
1994.

[Mac09] F. Mackel.  
Zeitaufgelöste Messungen der Elektronendichte und Elektronentemperatur in gepulsten Plasmen mittels elektrostatischer Dreifachsonden.  
Diplomarbeit, Ruhr-Universität Bochum, Bochum, March 2009.

Internal communication, 2012.

Electrostatic probe measurements in a pulsed-power plasma and comparison with interferometry.  

Advance in diagnostics for high-temperature plasmas based on the analytical result for the ion dynamical broadening of hydrogen spectral lines.  

Experimental verification of the kruskal-shafranov stability limit in line-tied partial-toroidal plasmas.  

A simple far-infrared laser interferometer for measuring electron densities in reactive low-temperature plasmas.  

[Rah07] K. Rahbarnia.  
Charakterisierung der elektromagnetischen Turbulenz im Torsatron TJ-K.  

Ortsaufgelöste Messung der Elektronendichte mittels Laser-Interferometrie in einem gepulsten Plasma.  
Diplomarbeit, Ruhr-Universität Bochum, Bochum, 2011.

Extensive tabulations of stark broadened hydrogen line profiles.

FlareLab: early results.

Ionization gauges for measuring pressures up to the millimeter range.

Paschen lines of hydrogen and he+ ion.

_Experimental Studies of Magnetic Flux Tubes_.

Messung und Modellierung schneller Änderungen der Neutralgasdichte an einem gepulsten Plasma-Experiment.
Diplomarbeit, Ruhr-Universität Bochum, Bochum, 2011.

Internal communication, 2012.

Observation of kinetic plasma jets in a coronal-loop simulation experiment.

Basic topology of twisted magnetic configurations in solar flares.

The evolution of twisting coronal magnetic flux tubes.
On the relevance of magnetohydrodynamic pumping in solar coronal loop simulation experiments.

*Spectrophysics, Principles and Applications.*

Review of the advanced generalized theory for stark broadening of hydrogen lines in plasmas with tables.

Hydrogen stark-broadening tables.

Plasma tubes becoming collimated as a result of magnetohydrodynamic pumping.

Dynamic and stagnating plasma flow leading to magnetic-flux-tube collimation.
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Lebenslauf

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