Study of magnetic diffusion in the LaPD

Master Thesis
presented by

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Erasmus Mundus Master on Nuclear Fusion Science and Engineering Physics

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July 2008

Koen Kemel
Abstract

In this work a study was made of the early stages of the expansion of a laser produced plasma (LPP) at the Large Plasma Device (LaPD). In the experiment a high density plasma is created by firing a 5 ns laser pulse at a carbon rod. The expansion takes place inside an ambient background plasma while a uniform magnetic field (0.05-0.2 T) is applied.

We used both optical and magnetic diagnostics. A CCD camera was used to take filtered (CII and CIII filter) pictures of the expansion from two angles. A $8 \times 8$ cm $xy$-plane at 2 cm in the $z$ direction away from the initial explosion was scanned with a magnetic probe to obtain time derivatives of the magnetic field in 3 directions.

Pictures taken along the device axis show a ring like structure of CIII emission and a smaller CII structure. The magnetic data shows a magnetic cavity structure.

Two mechanisms contribute to the diamagnetic cavity. The first is that unmagnetised carbon ions move out and create a radial electric field towards the held back magnetised electrons. This field causes an azimuthal electron Hall current that in its turn generates a magnetic field that counteracts the initially applied field. The second mechanism is an electron pressure gradient.

We find that the azimuthal diamagnetic current that also heats electrons enough to allow them to excite ions as they pass, hence the ring like radiation patterns. In other regions electrons are not heated, cool down adiabatically until they are too cold for excitation. The difference between pictures of different ionisation stages can be explained by a cloud structure with highly charged ions in the outer regions of the expansion and CII ions close to the creation point.

As the ions move out, two space charges are created: the negative electrons in the cavity and the expanding positive ion cloud. In a search as to how these charges are neutralised different mechanisms have been compared. We can divide these mechanisms in two categories: neutralisation of both charges through interaction with the background plasma or a way for the electrons to follow the ions in their expansion. Interactions with the background plasma are responsible for the creation of the studied waves, but are in these early stages not sufficiently present to neutralise the space charges.

We found that the dominating process should be a diffusion process. The resistivity needed for such a process is far higher than can be reached just taking into account collisions. A higher resistivity can be created by instabilities.

Comparing the magnetic field penetration time of 100 ns with that into a plasma cloud at rest, we find that the penetration time is several orders of
magnitude faster than would be obtained with the classical transverse resistivity.

The number of electron gyrations per effective collision time is a key parameter for both the resistivity and the magnetic field diffusion time into plasma. The needed resistivity would correspond to a value of $\omega_{ge}\tau_c$ of the magnitude order unity, but with a large uncertainty. A value 2 for this parameter has also been encountered in experiments by Hurtig (2004-2005 [1, 2, 3]) and Lundin (2008 [4]). In one of the experiments by Hurtig [3] the resistivity was traced back to the modified two-stream instability. As we have a strong current across a magnetic field, one of the instabilities that can arise in our case is also this modified two-stream instability.
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Chapter 1
Introduction

Diffusion of a plasma into a magnetic field (or the other way round, depending on the chosen rest frame) can be the result of collisions of electrons, or interaction of electrons with fluctuations or turbulence. While initially bound to the magnetic flux surfaces (“frozen-in”), through collisions, electrons can through such mechanisms gain a resulting momentum perpendicular to the magnetic surface, allowing them to move deeper into the field.

This transport has been approximated by Spitzer (“classical diffusion” ’56 [5]) and Bohm (instability-induced fluctuations ’49 [6]). In several very different experiments [1]-[4],[7],[8] a diffusion rate has been found which is higher than both previously mentioned approximations. The common feature is that these are pulsed, with time scales smaller than, or of the order of the

![Figure 1.1](image_url): Magnetic field lines in the VASIMR nozzle: if only subjected to the Lorentz force, the exhaust electrons stick to the field lines and cannot escape the spacecraft.
ion gyro time scale. The objective of this research was to study magnetic field diffusion and particle transport phenomena using the LArge Plasma Device (LaPD).

With understanding of the conditions for this anomalous transport one could start thinking of applications concerning electron detachment from magnetic field lines. This topic is currently one of the problems faced in in-space plasma propulsion (an example is the VASIMR project shown in Fig. 1.1): whereas ions are heavy enough to cross the magnetic field lines and escape in the magnetic nozzle, electrons stick to the field lines. This will lead to a negatively charging of the thruster.

A detachment process is the opposite of what is desired in fusion research: for the latter it is the goal to limit particle transport through the magnetic barrier and as such improve confinement.

The experiment described here is an expansion of a high density plasma in a magnetised plasma background, reminiscent of the pellet ablation cloud during pellet injection as used in tokamak fuelling. Although the parameters of the background in LAPD differ strongly from fusion conditions, we get an idea of the occurring processes. The interaction of the background plasma and the Alfvén waves generated in this event [9, 10, 11, 12, 13, 14], is one of the main research topics at the LAPD facility but falls outside the view of this thesis.

The magnetic field evolution over time was measured using 3 directional $dB/dt$-probes and the plasma cloud expansion was linked to optical observation of carbon radiation (CCD camera + CII and CIII filter).
Chapter 2

Theoretical background

2.1 Charged particles in a magnetic field

Charged particles in a uniform magnetic field are subject to charge and mass dependent interactions perpendicular to the orientation of this field.

2.1.1 Magnetic force on a charged particle

\[ m_d \vec{v} = q \vec{v} \times \vec{B} \]

We can now split the equation in two components:

- Parallel to B we get \( m_d \vec{v}_\parallel = 0 \), this is a linear motion with constant velocity

- Perpendicular to B we find \( m_d \vec{v}_\perp = q \vec{v}_\perp \times \vec{B} \), this is a rotation with Larmor frequency \( \omega_L = \frac{qB}{m} \) and larmor radius \( r_L = \frac{mv}{qB} \) (Fig 2.1).

\[ \text{Figure 2.1: Movement of charged particles in a magnetic field.} \]
2.1 Charged particles in a magnetic field

Figure 2.2: Drift movement of a charged particle in a magnetic field due to an external charge independent perpendicular force.

2.1.2 Drift movements in a B field

\[ md_t \vec{v} = q \vec{v} \times \vec{B} + \vec{F}(x) \]

We can again split the equation up:

- Parallel to B: \( md_t \vec{v}_\parallel = \vec{F}_\parallel \), this is Newton’s inertia law.
- Perpendicular to B: \( md_t \vec{v}_\perp = q \vec{v}_\perp \times \vec{B} + \vec{F}_\perp \).

Decomposing the velocity according to time dependance gives \( \vec{v}_\perp(x, t) = \vec{v}_L(x, t) + \vec{v}_D(x) \), we can again split up the equation into two parts.

\[ md_t \vec{v}_L = q \vec{v}_L \times \vec{B} \] which is the Larmor rotation we found in the previous section and \( \vec{v}_D = \frac{\vec{F} \times \vec{B}}{qB^2} \), which is a centre guide drift motion perpendicular to both the magnetic field and the other applied force [15] (Fig 2.2).

2.1.3 ’Unmagnetised’ ions

When studying length scales much smaller than the Larmor radius, which is larger for particles with a low charge to mass ratio, we can consider the effect of magnetic interaction neglectable over these distances. As such for any geometry we can find a certain B field range where we will obtain a plasma of magnetised electrons and unmagnetised ions.

In this experiment we will find for a magnetic field of 0.15 T an electron Larmor radius of the order 100 \( \mu \)m while the CIII and CII ions gyrate with a radius 5-10 cm, depending on the charge. As the longest dimension of the observed structures in the direction perpendicular to the magnetic field is about 5 cm, we can make this magnetised electron - unmagnetised ion simplification.

2.1.4 Magnetic diffusion

Magnetic diffusion is a key process in the discussion throughout this thesis. There is a close connection between the processes of electric Hall and Pedersen conductivity across a magnetic field, particle diffusion, and the diffusion of a magnetic field into a plasma. They are all determined by the transverse resistivity \( \eta_\perp \) which is defined by the rate of momentum exchange, between electrons and ions, in the direction of a cross-B current density. I will therefore introduce this phenomenon from three points of view: a drift motion due to a finite transverse resistivity, a drift motion due to electron collisions in and magnetic field diffusion equation. The laser-produced ions in the described
experiments can be considered unmagnetised and do not feel the magnetic field, as such the diffusion process we are looking at is an interaction between the magnetic field and an electron cloud.

One difference between diffusion of a magnetic field into a plasma and the diffusion, or motion, of the plasma into the field is a choice of the inertial rest frame. In the two more qualitative descriptions, the second option is chosen because particle movements are intuitively easier to imagine.

In a first approach we look the electron drift in response to a force across $B$ (Fig. 2.3).

Applying an external force $\vec{F}_1$ results in a primary electron drift $\vec{v}_{D,1} = \vec{F}_1 \times \vec{B}/eB^2$, which can also be seen as a current $\vec{J}$ in the direction opposite to this drift.

A finite resistivity $\eta$ gives a force $\vec{F}_\eta$, proportional to $\eta$, on the electrons in the direction opposite to the current. This force results in a secondary drift $\vec{v}_{D,2} = \vec{F}_\eta \times \vec{B}/eB^2$, in the direction of the initial force $\vec{F}_1$.

The net effect is that an electron transport across $B$ in the direction of the force.

A second way to look at the electron drift across $B$ is through collisions of electrons. In Fig. 2.4, a macroscopic force, acts on the electrons in the direction downwards. Electrons are bound to magnetic field lines and can only move into the field through collisions giving a momentum perpendicular to the
2.1 Charged particles in a magnetic field

magnetic field surface. These collisions are the same ones that cause a resistive behaviour against the diamagnetic current.

This is probably a good time to introduce a dimensionless parameter $\omega \tau$, where $\omega$ is the electron larmor frequency and $\tau$ the time between two collisions (or more generally, the time constant for electron momentum loss). A higher number of collisions per gyration of an electron corresponds to faster diffusion. This parameter can be linked to the transverse resistivity through [15]:

$$\eta_\perp = \frac{m}{ne^2} v_{ei} = \frac{B}{en_e \omega_{ge} \tau_e}$$  \hspace{1cm} (2.1)

The third point of view is that the magnetic field moves through the plasma. Let us here start from the generalised Ohm’s Law for electrons:

$$\frac{me}{e} d_t \vec{J} + en_e \eta \vec{J} + \vec{J} \times \vec{B} = en_e \left( \vec{E} + \vec{v}_i \times \vec{B} \right) + \vec{\nabla} p$$  \hspace{1cm} (2.2)

To demonstrate the principle, we here consider the magnetic penetration into a plasma cloud at rest, where $v_i$ and therefore also $v_i \times B$ are zero. The inertial (first) term can be neglected on timescales $\gg$ electron gyro times where it is much smaller than the Hall term. (This is true for our lpp, where the magnetic diffusion time scale is 100 ns, and the electron gyro time is $1/\omega_{ge} \approx 0.2$ ns). We also consider only the components across the magnetic field, and therefore replace $\eta$ with $\eta_\perp$. We then can simplify (2.2) to

$$\eta_\perp \vec{J} + \vec{J} \times \vec{B} = \vec{E} + \vec{\nabla} p$$  \hspace{1cm} (2.3)

Taking the rotor of this equation and applying Maxwell’s laws (using also $\nabla \times (\nabla \times \vec{B}) = \nabla (\nabla \cdot \vec{B}) - \nabla^2 \vec{B} = -\nabla^2 \vec{B}$) one obtains a diffusion type equation

$$\frac{\eta_\perp}{\mu_0} \nabla^2 \vec{B} = d_t \vec{B}.$$  \hspace{1cm} (2.4)

Approximating the differentials by typical length and time scales $l_B$ and $t_B$, this gives the familiar formula for the diffusion of an external magnetic field, into a stationary plasma, due to a finite resistivity [15]:

$$t_B = \frac{\mu_0 (l_B)^2}{\eta_\perp}.$$  \hspace{1cm} (2.5)

This is the time constant for “complete diffusion” of a magnetic field into a previously unmagnetized plasma cloud, i.e. $\Delta B = B$. In case of a partial diffusion where $\Delta B / B < 1$ one instead obtains

$$t_B = \frac{B}{\Delta B} \frac{\mu_0 (l_B)^2}{\eta_\perp}.$$  \hspace{1cm} (2.6)
2.2 A laser generated plasma

2.2.1 Plasma cloud generation in vacuum without background field.

A pulsed laser evaporation process (Fig 2.5) can be described as follows [15, 16]:

Intensely heating of the target surface layers releases the electrons from their bonds, thus creating a negatively charged cloud just above the surface and a strong electric field perpendicular to the surface which then rips the ions from their lattice positions.

This way we get a hot plasma expanding in the direction normal to the surface (widening due to density gradients). The initial high density of the created plasma will lead to a plasma frequency above the laser frequency and thus a reflection of the laser light. As the plasma cloud expands, the density lowers again and we get absorption of the beam in the plasma as well as more interaction of the target surface with a now attenuated beam (note: the laser intensity itself is not constant over time). The continued ablation of the target, laser heating of the vapor and several ionisation processes (photo-ionisation, impact ionisation, thermionic emission by the hot target surface) result again in plasma creation. The properties of the generated plasma are determined by laser parameters and the optical and thermophysical properties of the target material.

During the laser interaction the plasma expansion can be considered isothermal: electrons and ions receive the same amount of energy.

![Figure 2.5: The 4 phases occurring during the plasma creation: an unaffected bulk (I), surface ablation (II), a dense plasma near the surface absorbing laser light (III) and an expanding, less dense plasma, transparent for the laser (IV) [15]](image-url)
2.2 A laser generated plasma

2.2.2 Expansion into a magnetic field.

When a plasma expands into a magnetic field several forces come into play and drifts arise that can give rise to instabilities. Here we consider three MHD phenomena which can be relevant to the experimental observations.

The first phenomenon is related to the global translation of the plasma cloud. It was argued in [17] that Hall drift will create charge asymmetry in the direction perpendicular to field and expansion. As the electric field caused by this polarisation is curved due to a velocity gradient in the plasma, a focussing of the expanding plasma was observed (Fig 2.6). Because the main topic of this work is the expansion rather than the collective motion of a plasma we will neglect this effect in the analysis. This approach can be seen as treating the expansion of the plasma in the moving lpp plasmas rest frame, there the polarization field $\vec{E}_p = -\vec{v} \times \vec{B}$ inside the cloud vanishes.

The second and third phenomenon are related to the expansion, they both result in the creation of a diamagnetic cavity (Fig 2.7).

The interaction of a steep pressure gradient and the magnetic background field will result in an electron current (ions are unmagnetised) such that $\vec{J} \times \vec{B}$ balances $-\nabla p_e$. This current in its turn will generate a B field in the opposite direction of the present one, creating a diamagnetic cavity [16].

The third mechanism is due to the fact that the ions are not hindered by the B field while electrons remain trapped on the magnetic surfaces, we get a charge separation. The radial electric field created by these charges will cause an electron Hall drift that will add to the diamagnetic currents.

2.2.3 Expansion into a magnetic plasma.

The background and laser produced plasma can interact through currents and plasma waves.

\[ \nabla \vec{V} = \frac{\vec{E} \times \vec{B}}{B^2} \]

**Figure 2.6**: Focussing of the expanding plasma because of polarisation [17, 18]
Laser produced plasma (lpp) electrons can escape along the magnetic field as their charge position will be filled by background electrons.

This mechanism as well as the other processes (cavity formation, density variations, ambipolar electric field) can radiate waves and drive current systems throughout the ambient background plasma. As argued in section 5.1 below, we assume that this does not significantly influence the cloud processes during the early times we study here.
Chapter 3

Experimental setup

In the Large Plasma Device (Fig 3.1) at UCLA a pulsed DC discharge is used to create an ambient plasma background in which experiments can be performed. The experiment discussed here describes the expansion of a laser impact created plasma inside this background plasma. The three subsections of this chapter treat the user facility in its most general setup (briefly), the experiment specific additions and the used diagnostics.

Figure 3.1: A picture from the LaPD with several mounted magnetic probes
3. Experimental setup

3.1 LaPD

3.1.1 Discharge chamber

The experiment takes place in a long, cylindrical vacuum vessel (Fig 3.2).

The 21 m steel chamber has 450 access ports, 65 of which have vacuum interlocks that probes and probe drives can be attached to while the machine is running.

Throughout this text the standard LaPD machine coordinate system will be used:

- $z$: axial towards the plasma source,
- $y$: upwards,
- $x$: towards the probe ports (left when facing the plasma source).

The (0,0,0) coordinate is given to the intersection point between the chamber axis and the target rod axis.

3.1.2 B-field

An array of copper coils generates a uniform (to 1%) axial B field in the direction towards the plasma source.

3.1.3 Background plasma

Electrons are released by thermionic emission from a BaO coated Ni cathode (temperature $\sim$1200 K) and directed towards the anode grid (Mo) by an applied potential ($\sim$70 V) difference. This current ($\sim$4.5 kA) is kept constant for 10-20 ms. The beam is used to ionise a noble gas of choice to create a background plasma. The plasma density is determined by the fill pressure.

The discharge is repeated with a frequency of about 1 Hz. The discharge is highly reproducible.
3.2 Experiment specific

3.1.4 Plasma parameters

In table 3.1 some typical parameters for the LaPD operation are given. In the right column we find values more specific for this experiment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>general [REF]</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma length</td>
<td>17 m</td>
<td></td>
</tr>
<tr>
<td>Plasma diameter</td>
<td>0.5 m</td>
<td></td>
</tr>
<tr>
<td>B field</td>
<td>0.04-0.25 T</td>
<td>0.05-0.2 T</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>0.5-8.0 eV</td>
<td>∼ 5 eV</td>
</tr>
<tr>
<td>Ion temperature</td>
<td>0.5-1.5 eV</td>
<td>∼ 1 eV</td>
</tr>
<tr>
<td>Plasma density</td>
<td>$10^{17} - 4 \cdot 10^{18}$ m$^{-3}$</td>
<td>$2 - 3 \cdot 10^{18}$ m$^{-3}$</td>
</tr>
<tr>
<td>Ion species</td>
<td>He, Ne, Ar</td>
<td>He</td>
</tr>
<tr>
<td>Plasma repetition rate</td>
<td>1 Hz</td>
<td></td>
</tr>
<tr>
<td>Discharge duration</td>
<td>5-15 ms</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Typical discharge parameters

3.2 Experiment specific

3.2.1 Laser

In table 3.2 we find the parameters of the laser as used in this experiment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>IR</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>10 ns</td>
</tr>
<tr>
<td>Power density</td>
<td>$10^{15}$ W/m$^2$</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>1.5 J</td>
</tr>
<tr>
<td>Focus spot size</td>
<td>D&lt;0.5 mm</td>
</tr>
</tbody>
</table>

Table 3.2: Laser parameters

3.2.2 Target

Because the target, a 0.02 m diameter graphite rod hanging from a port in the upper side of the machine, is eroded by the laser (impact at approximately (-0.01, 0, 0) machine coordinates), the target is rotated by a computer-controlled stepping motor every five shots and after a complete rotation lowered 1 mm by another motor.
3. Experimental setup

3.3 Diagnostics

During the experimental session different diagnostics were used in order to be able to coordinate magnetic, photographic and spectroscopic data.

3.3.1 Magnetic measurements

For measuring the $\mathbf{B}$-field we used a probe consisting of 3 pick up loops in orthogonal directions (each of them made of coils with opposite orientation to reduce electrostatic pickup). Magnetic data was obtained by scanning a 8 by 8 cm ($17 \times 17$ points) $xy$-plane centered around (-2, 0, -2). The resulting time traces, each an average over 8 shots, are proportional to $dB/dt$ (Faraday principle) by a constant known from calibration. They were integrated to find the 3 components of the $\mathbf{B}$-field in space and time.

3.3.2 Optical measurements

Photographs were made of the emitted light from 2 angles, see Fig. 3.3: from the side (negative $x$-axis) and from the end of the machine (negative $z$-axis). To obtain sufficient detail, additional optical systems were used: in the first case a telelens and in the second a Schmidt-Cassegrain telescope.

A CCD camera (opening time 3 ns) was used to take 10 pictures in separate discharges for each time step (so there are no two pictures of exactly the same discharge). Averaging of these pictures gives an idea of the temporal evolution of the emitted light. This way shot-to-shot variations were neglected in favour of the study of the larger structures.

To distinguish between the emission from CII and CIII, two filters were

![Figure 3.3: A schematic indicating the location of the laser, the target and the expanding plasma, the magnetic probe and the measured plane and the viewports for the camera](image)
used. For CII we used a 3 nm width filter around a central wavelength 426.7 nm \( (= \lambda_{\text{CII}}) \). CIII light was selected by a filter with central wavelength 460 nm and width 10 nm \( (= \lambda_{\text{CIII}}) \).
Chapter 4

Results

In this chapter we have a look at the obtained data from the different measurements with an interest for four questions:

1) What do we have?
2) What cannot be deduced from this experimental data?
3) What can be deduced?
4) What kind of additional measurements would maximise the usefulness of this data?

The subsections in the analysis of both datasets below coincide with these four questions.

4.1 Camera observations

4.1.1 “Pictures”

Fig 4.1 shows the time evolution of the light that has passed through the CIII filter in the frontal view. We see a central bulk which dies out rather quickly. A ring structure arises when the cavity gets formed. During the collapse we find a more chaotic structure. Fig 4.2 compares the two angles for CIII emission and the frontal view for CII at a time where the magnetic cavity is growing. Note that all images are averages over 10 experiments.

4.1.2 In the shadow

The problem with looking at emitted plasma light is that there are two conditions to be met for radiation: the presence of ions at the selected ionisation stage CII or CIII and the presence of electrons with energy high enough to excite these ions.

When the picture is dark it can mean that either of these conditions is not met.
4.1 Camera observations

Figure 4.1: Time evolution of the radiation seen through the CIII filter with the camera looking along the machine axis. The times are chosen, based on Fig 4.6 below, to correspond to: a) soon after laser impact (t=60 ns), b) growth of the magnetic cavity (200 ns), c) maximal cavity (300 ns) d) collapsing cavity (400 ns). B=0.15 T.

Therefore, the motion of the light structure in the picture can indicate real ion movement but it can also indicate a region of hot electrons moving in a volume where ions are present, simply highlighting them while passing.

4.1.3 Possible conclusions

a) thermal radiation

The spot coinciding with the target edge (x ~ −1 cm) is the thermal radiation of the carbon rod after being heated by the laser. It therefore appears using both the CII and CIII filters. NB: As this light intensity presumably is independent of the magnetic field strength, this light spot can be used to obtain a common intensity calibration between different photographs. It should also be possible to obtain an absolute calibration of all these photographs “in retrospect” based on the intensity of this light spot compared to a calibrated source.
**b) about correlation between movement and brightness**

As we assume that the ion movement is relatively unaffected by the magnetic field (which we will conclude below in section 4.2.3.b, based on the magnetic data), the fact that pictures scale with field strength (Fig 4.3) indicates that we are mainly looking at regions with hot electron.

It is likely that the light trace just indicates the regions where electrons are heated by currents maintaining the magnetic cavity.

In order to derive ion velocity estimations, we therefore choose to look at early stage pictures where there is no significant spatial difference in electron temperature and the electrons are still hot enough to excite the light wherever there are ions. The velocity magnitude order $1 \sim 2 \cdot 10^3$ m/s deduced from the pictures is consistent with previous experiments [9, 18]. This way we can estimate the initial average directed ion energy to be of the order 0.5 keV.

Another indication for the correlation between brightness and electron temperature is the fading out central bulk structure (Fig 4.4). Without additional electron heating the electron temperature in this region drops and the light goes out.

Assuming equal energy partition between ions and electrons during the laser phase we get an average electron energy $T_0$ of 0.5-1 keV. The cloud
4.1 Camera observations

Expansion speed at this stage is of the order $10^5$ m/s, at the end of the 10 ns pulse we have a semispherical volume $V_0$ with radius $\sim 10^{-3}$ m. Adiabatic expansion ($\gamma = 1.5$) of the electrons to a volume $V = 5 \cdot 10^{-5}$ m$^3$ (at 300 ns) would give an electron temperature of the order 5 eV, this is of the same order as temperature of the background electrons. However, this adiabatic cooling rate is likely to be reduced by the magnetic field, the complexity of the estimation increases when we take a realistic electronic velocity distribution and effects like joule heating into account.

c) different ionic states

The significant difference in the light pattern of carbon ionic states could be explained by a structure proposed in Fig 4.5:

1. The thermal radiation is present in both CII and CIII pictures.
2. Fig 4.2 a: the CII picture can be completed by adding the thermal radiation to the intersection of the CII and hot electron regions.

3. Fig 4.1 c: the CIII picture can be completed by adding the thermal radiation to the ring like intersection of the hot electron region with the CIII ion region.

4. Fig 4.3 b: there is too little energy in the cavity to heat the electrons much, the CIII ring is barely visible

5. Fig 4.1 b and Fig 4.4: we have a ring of hot electrons but the far end lies in the CIV structure and we get an incomplete ring.

This structuring of the ion cloud into different regions containing CII, CIII, and CIV is due to a longer interaction between the outer layers of the plasma and the laser during the initial expansion, with a higher ionisation level in this region as a result.

The heating mechanism for the electron ring will be discussed in the magnetic data section.

We can neglect ionisation after the initial laser phase as timescales are smaller than the CIII ionisation times.

### 4.1.4 Useful complementary data

As the current photographic data only consists of the first two ionised states of carbon it would be interesting to obtain similar data bout the third ionic state in order to verify the structure we proposed in the previous section.
4.2 Magnetic data

4.2.1 Probe measurements

The raw magnetic data is a time series of 3 components of the B-field time derivative, spatially distributed over a 8cm$\times$8cm $xy$-plane 2 cm away in the negative $z$-direction from the expansion centre. To enable further data analysis, noise is removed using a high frequency filter.

When we integrate these measurements we can see a magnetic cavity appear and collapse again. Fig 4.6 shows the $z$-component of the magnetic field and its time derivative in 2 points along the $x$-axis. In Fig 4.7 we see again the $z$-component of the magnetic field at different phases of the expansion.

4.2.2 Out of reach

The main flaw in the obtained data is that we are not looking at the actual centre of the cavity, but at a small but significant axial distance.

If we look at pictures from the side view (Fig 4.2) we can see that our data plane is already very close to the edge of the cavity.

Figure 4.6: The time evolution of the $z$-component of the magnetic field and its time derivative in two points on the $x$-axis (blue: 0.02 m, green: 0.03 m, $B=0.15$ T) previously seen in [9]
4. Results

Figure 4.7: The time evolution of the cavity in the magnetic field (100 ns (a), 200 ns (b), 300 ns (c) and 400 ns (d) after laser impact, B=0.15 T)

4.2.3 Maxwell’s equations and plasma parameters

a) currents

Starting from Ampere’s equation we can straightforwardly derive the axial current densities in the measuring plane.

Measurements show the appearance of a coaxial current structure (Fig 4.8). A central, z-oriented current of the order $2 \cdot 10^5$ A/m² indicates electrons moving out along the B-field lines in axial direction. In the outer shell, a lower current density flows away from the ion cloud: electrons from the background plasma moving towards the positive charges.

To calculate azimuthal current densities we would in principle need derivatives of the B-field in z, which cannot be obtained from a measurement in a plane orthogonal to this direction.

However, from the observed structure in the photographs (Fig 4.2), we can assume variation in the z-direction to be limited so that z-derivatives can be neglected in magnitude order calculations.
b) magnetic energy

Can the expansion of the carbon ion cloud be influenced significantly by the magnetic pressure? A comparison between the peak magnetic energy in the cavity and the ion kinetic energy shows that this is not likely: integration over the cavity volume gives an estimate of the energy stored and released during its growth and decay. To estimate the magnetic energy stored in the bubble, we need an idea about the volume of the cavity and the strength of the diamagnetic field.

From the pictures we can estimate the volume $V$ of the magnitude order of $2 \cdot 10^{-5}$ and an average 30% cavity (measurements in [9] give a 40% cavity in the centre) then we find a magnetic energy $E_B \sim 6 \cdot 10^{-2}$ J.

This is a factor 25 below the laser pulse energy 1.5 J. If a significant part of the laser energy is converted to directed ion energy, we conclude that the ion velocity should be essentially unchanged during the expansion.

c) electric field

As we can calculate the magnetic flux through an area in the measuring plane, one can obtain through Faraday’s law the line integral of the electric field along the edge of this area. If we find a line along which the electric field could be approximately constant, we could obtain this value. A likely candidate for

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**Figure 4.8:** The profile of the $z$-component of the current density at the magnetic cavity maximum, $t=300$ ns ($B=0.15$ T)
Figure 4.9: A $J_x$ and $J_y$ vector plot in the xy-plane shows the electron currents creating the magnetic cavity, t=200 ns (a) and 300 ns (b), currents are (auto)scaled to fit the grid. ($B = 0.15$ T)

this estimate is a contour along the cavity edge. As the rate of change of the magnetic flux varies between $-4$ and $4 \cdot 10^2$ T/m$^2$s, the azimuthal electric field has the range $-7$ to $7$ kV/m (0 at the time of max cavity).

If the contribution from the electron pressure is negligible, the cavity is created by currents caused by an electron Hall drift due to a radial electric field. In the applied axial $B_0$ field, we can calculate the magnitude order of this electric field:

$$J_\phi = en_e \frac{E_r}{B_0},$$

giving an upper limit to the radial field of magnitude order 3 kV/m.

d) plasma parameters

In table 4.1 we see the relevant parameters for the laser produced plasma.

4.2.4 Useful complementary data

It would be interesting to have magnetic data from the cavity without a background plasma. This way we would eliminate the possibility of current and wave interactions with this background, allowing to estimate the importance of current system charge neutralisation mechanism (see next chapter) more accurately.
4.3 Bright currents

The ring shaped pattern observed in the pictures agrees in space and in time with the current structure as derived from the magnetic data (taking into account that we do not measure at the $z$-coordinate of the centre of the cavity). This indicates Joule heating. The CIII light pattern at later times indicates that this then also happened in the central cloud. As the magnetic cavity collapses $J_{\phi}E_{\phi} > 0$ and the magnetically stored energy can be transferred to the particles through whatever is the resistive mechanism. If all the magnetic energy released would be transferred to electrons, this electron heating comes to up to 80 eV/electron, enough energy to further excite the CII and CIII lines (studied timescales < ionisation time). This could explain the apparent inward motion of the glowing ring during the collapse phase (Fig 4.1c).

As the electrons have already during the expansion phase (200 ns, Fig 4.1b) become too cool to excite the CIII line significantly in the cloud centre, in the collapse phase (400 ns, Fig 4.1d) both the CIII density and the electron density have very likely decreased further in the centre. In spite of this, there is an increased light emission. This strongly indicates energisation of the electrons in this region. The cavity collapse results in a high energy electron population without an obvious structure and a rather chaotic image is visible.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron density</td>
<td>$8 \cdot 10^{19} \text{m}^{-3}$</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>5 eV</td>
</tr>
<tr>
<td>Electron gyro radius</td>
<td>$4 \cdot 10^{-6} \text{m}$</td>
</tr>
<tr>
<td>Ion density</td>
<td>$4 \cdot 10^{19} \text{m}^{-3}$</td>
</tr>
<tr>
<td>Average ion energy</td>
<td>0.5 keV</td>
</tr>
<tr>
<td>CII gyro radius</td>
<td>$8 \cdot 10^{-2} \text{m}$</td>
</tr>
<tr>
<td>CII gyro radius</td>
<td>$4 \cdot 10^{-2} \text{m}$</td>
</tr>
<tr>
<td>Cavity volume</td>
<td>$5 \cdot 10^{-5} \text{m}^3$</td>
</tr>
</tbody>
</table>

Table 4.1: Estimated parameters at maximal cavity ($t \sim 300 \text{ ns}$), $B=0.15 \text{ T}$.
Chapter 5

Electron cloud expansion

In this chapter we have a look at the expected relative importance of five competing mechanisms to neutralise the occurring space charges during the expansion of a laser produced plasma in a magnetic field. The driving mechanism is that ions move out across the B field lines while electrons do not. This gives rise to an inwards directed $E_r$-field. Out of the five alternatives below the one that neutralises the growing space charge at the lowest $E_r$-field becomes dominant. We try to determine the dominant process in the used setup by comparing this analysis with experimental data. A small introduction of the competing mechanisms:

1) While the surplus of electrons at the centre move out in field aligned currents, the radially expanding ions are neutralised by electrons attracted from the background plasma.

2) Radial expansion by pushing out the magnetic field by creation of a 100% cavity

3) Limited expansion: ion expansion is stopped by the electric field caused by charge separation.

4) Spitzer diffusion: electron currents normal to the expansion velocity generate electron transport in the radial direction through plasma resistivity.

5) Anomalous diffusion: similar to 4 but resistivity is enhanced by the presence of plasma instabilities.

5.1 Background plasma currents (mechanism 1)

The electron charge build up next to the target is reduced by electrons streaming out along the magnetic field lines in the axial direction. The positive charge of outgoing ions is neutralised by a return current of electrons from the background plasma. This way we get a coaxial structure [14] with a central positive
5.1 Background plasma currents (mechanism 1)

The ionic space charge is neutralised by electrons, either from the ambient plasma (mechanism 1), or through some mechanism that enable the plasma cloud’s 'own' electrons to cross the \( B \)-field (mechanism 2-5); adapted from [9].

This current system is probably operating in the phases of the cloud expansion, later than the times studied here. It is currently one of the main reasons for experiments like this one at the LaPD facility. The currents are generate shear Alfvén waves, whistler and lower hybrid waves [9, 10].

While the current system (Fig 5.1) is clearly present (and an important process for the LaPD experiments), it need not be the most dominant neutralisation mechanism: pictures of the plasma in the early stages of the expansion with or without background plasma show a similar behaviour (Fig 5.2).

An estimate for the importance of this process can be made by integrating the axial currents flowing towards the bubble over the whole process. This way we find an estimate for the number electrons that escaped the cavity in this direction (multiplication by 2 as we assume symmetric behaviour at the other cavity end).

A crude estimate gives \( 7 \cdot 10^{13} \), about 2% of the electrons in the cavity.

We can conclude that the space charges are not neutralised through interaction with the background plasma but through a mechanism that allows the lpp electrons to follow the ion expansion.

Figure 5.1: Lpp electrons expand axially while ions can escape in all directions. The ionic space charge is neutralised by electrons, either from the ambient plasma (mechanism 1), or through some mechanism that enable the plasma cloud’s 'own' electrons to cross the \( B \)-field (mechanism 2-5); adapted from [9].
5. Electron cloud expansion

5.2 Pushing out the magnetic field (mechanism 2)

Currents perpendicular to the magnetic background field arise due to electron drifts caused by forces normal to the same $B$-field. These currents will generate a magnetic pressure gradient which counteracts the applied force. If the diamagnetism is strong, we can get a magnetic cavity with $B=0$. With no $B$-field the electrons are unmagnetised and move freely (Fig 5.3). The forces that start these currents are the electron density gradient and the inwards radial electric field generated by the expanding unmagnetised ion cloud (charge separation).

The generated magnetic cavity would be proportional to the total generated electron current: the integral of the electron density and drift velocity in the cavity. If we have a full cavity this integral will be limited to a thin current layer along the edge as the azimuthal drift $E_r \times B_z$ inside will be zero where $B_z$ is zero.
5.3 Limited expansion (mechanism 3)

Ions move out while the electrons remain behind, trapped by the magnetic field. This charge separation creates an electric field that will strongly slow down the ions until the expansion is stopped.

The feasibility of this mechanism can be estimated by comparing the energies associated with the charge separation and the ion kinetic energy.

As the ions move out they create an electric field, through this electric field they supply the energy needed to create the magnetic cavity. We calculated the energy stored in the magnetic cavity in section 4.2 and obtained a value of $6 \cdot 10^{-2}$ J, this energy is a magnitude order smaller than the ion energy (order 1 J). Ion motion is as such only marginally affected by whatever happens to the electrons and will certainly not stop.

5.4 Spitzer diffusion (mechanism 4)

As explained in the second chapter (2.1.4), electrons are bound to magnetic field lines and can only diffuse into the field through collisions giving a momentum perpendicular to their magnetic field surface. From magnetic diffusion speed it is possible to see if collisions are sufficient to explain the occurring effects.

For a fully ionised plasma we can approximate the resistivity by the Spitzer resistivity due to electron-ion (coulomb) collisions:

$$\eta_\perp = 10.4 \cdot 10^{-5} \frac{Z \ln \Lambda}{T_e(eV)^{\frac{3}{2}}} \Omega m$$

In chapter 2 we found an expression 2.6 that related magnetic diffusion and resistivity:

$$\Delta t_B = \frac{B_0 \left(t_B\right)^2}{\Delta B \eta} \mu_0 \approx 5 \mu s.$$ 

Filling in the right half using magnitude order estimates gives a process that is far slower than the one observed.

5.5 Anomalous diffusion (mechanism 5)

Instead of only a collisional resistivity as in section 5.4, we could also have a far higher resistivity generated by plasma instabilities. As we have a strong
azimuthal diamagnetic current perpendicular to B, a modified two-stream instability (cf 2.3.2) comes to mind as a possible candidate for this. It would however be interesting to find other indications for this specific instability. An enhanced transverse resistivity will increase magnetic diffusion speed.

Taking again an average 30% cavity and the length scale from outer edge to the centre $l_B = 0.015$ m (from the optical observations in Fig 4.1), we get an estimate of the resistivity:

$$\eta_\perp = \frac{B}{\Delta B} \frac{(l_B)^2}{\mu_0 t_B} \approx \frac{1}{0.4} \frac{4 \pi \cdot 10^{-7} (0.015)^2}{10^{-7}} \approx 7 \cdot 10^{-3} \Omega m.$$  

We can now approximate:

$$\omega_{ge} \tau_c = \frac{B}{\eta_\perp e n_e} \approx \frac{0.15}{9 \cdot 10^{-3} 1.6 \cdot 10^{-19} \cdot 10^{19}} \approx 1.7.$$  

This is not a very exact estimate but it is clearly below the value of Bohm diffusion $\omega_{ge} \tau_c \approx 16$ and right in the range of the experiments in [1, 2, 3, 4] where a value of $\omega_{ge} \tau_c \approx 2$ was found.

In one of these experiments the instability was identified to be the modified two-stream instability [3].

The modified two-stream instability can occur when we have a current perpendicular to a magnetic field which only magnetises electrons.

Since in this setup we have a strong diamagnetic electron current perpendicular to a magnetic field it is possible for such an instability to arise and to enhance the resistivity to the found value.
Chapter 6

Summary and discussion

Using only a subset of the obtained data, we arrived at mainly two conclusions.

The first result is a proposed ion expansion structure (Fig 4.5) and its relation to the camera observations and current measurements: the ion cloud has consists of regions with ions at a different ionisation step, explainable by the laser creation. Hot electrons mark their presence in these regions by the electronic excitation we observe with the CCD camera. Since, during the cavity phase we studied here, the electrons are heated by the diamagnetic current surrounding the cavity, we observe the ring like intersections of hot electrons and carbon ion regions.

A second conclusion relates to the dominant charge neutralisation mechanism. From the magnetic data we concluded that this neutralisation does not take place through interaction with the background plasma and from the ion kinetic energy to cavity magnetic energy ratio we found that ion movement is only marginally affected by the created magnetic cavity. As such we can conclude that the lpp electrons find a way to follow the carbon ions. After eliminating several other mechanisms we propose an instability enhanced magnetic diffusion: the diamagnetic current across the magnetic field gives rise to an instability. The effect of this instability can be interpreted as a strong resistivity (two magnitude orders higher than the Spitzer resistivity), enabeling the electrons to diffuse into the magnetic field to neutralise the carbon ions. A possible instability would be the modified two-stream instability.

As a continuation of this work it would be interesting to verify the results found in chapter 5 with the unused magnetic data sets. Also repeating this experiment with a CIV filter, as explained in chapter 4, would be desirable to confirm the proposed expansion structure as described above. Furthermore, experiments with zero background plasma density would definitely prove that the charge neutralization from the ambient plasma can be ruled out.
Bibliography


Acknowledgements

Thanks to

Professor Brenning, for patience, advice, insights, support,

Professor Gekelman, for advice and the opportunity to work at the LAPD facility

Andrew, for always being around to answer dumb questions, to help me out and to have lunch, for pushing buttons which I was not allowed to touch.

And all the other people who made my stay in LA more easy (specially Zoltan and Marvin for tech support) and a bit less lonely (Meg & the grad students).

Professor van Oost, for talking a bit too inspiringingly about fusion and this program during his lectures, swaying me to leave for France earlier this year.

Darya, for grammatical, illustrative and moral support.

This work was supported by the Erasmus Mundus program. The experiment was performed on the Large Plasma Device which is part of the Basic Plasma Science Facility. The BaPSF is funded by a cooperative agreement between the US National Science Foundation and Department of Energy.
Declaration in lieu of oath

Herewith I declare in lieu of oath that I have prepared this thesis exclusively with the help of my scientific teachers and the means quoted by him.

City, the

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Koen Kemel