Current Filamentation in neutral electron-positron plasma jets


Document Version:
Other version

Queen's University Belfast - Research Portal:
Link to publication record in Queen's University Belfast Research Portal

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.
Current filamentation in neutral electron-positron plasma jets

For the completion of MSci programme in Physics

CORMAC HYLAND

Supervisor

DR. GIANLUCA SARRI

Queen’s University, Belfast

1
Abstract

One of several proposed explanations for synchrotron emission from neutral astrophysical particle jets is current filamentation instability (CFI). Experiments were conducted to study the phenomenon of CFI in neutral electron-positron pair plasma jets. Pair plasma jets were found to filament in such a way that would produce the synchrotron emission observed from astrophysical jets. This is consistent with the predictions of most analytical models, and strongly suggests that CFI is indeed the mechanism that causes the radiation emission observed from Earth. It was also found that due to the symmetry between the two charges of particle, the electron-positron jet could filament and retain a smooth particle distribution, an effect not observed in electron-proton jets. The jet studied in this experiment was found to have a magnetic energy equipartition of $\varepsilon_B \sim 1$, indicating that its magnetic behaviour is very similar to that of some of the shocks within the astrophysical jets being emulated, thus validating the potential use of laboratory-accelerated plasma jets to study astrophysical particle jets.
C. Reexamined simulation results

IV. Conclusion
   A. Results
   B. Future work

References

Acknowledgments

A. Unfiltered 2D background subtractions
I. INTRODUCTION

The aim of this project is to analyse data from a laser based particle acceleration experiment to study current filamentation in astrophysical electron-positron pair plasma jets. These are typically observed to emanate from the centres of super-massive black holes such as those found at the centre of galaxy Messier-87 (or M87). This was done by creating a neutral electron positron jet, using fluorescent screens to image and analyse the laser-accelerated jet profile directly, and using proton radiography to measure the magnetic fields inside the jet. The magnetic energy partition of the jet was then used to compare the dynamics of the jet produced in the laboratory with those observed in astrophysical objects.

A. Astrophysical Jets

1. Observations

Most of the particle jets that have been observed fall into one of two categories based on their composition - pair plasma (i.e. electron-positron) or normal plasma (i.e. electron-proton) jets[1]. The plasma that is being studied here, is a neutral pair plasma. This experiment has only been possible due to recent work done in creating neutral matter-antimatter jets[2]. One example of this kind of jet has been observed from the super-massive galaxy M87, an image of which is shown in Figure 1. Several methods are used to determine the jet’s composition, one of which is to analyse the spectrum of the jet to measure its optical thickness. For example M87’s jet is optically thin and therefore likely consists of light particles i.e. positrons and electrons,[3].

2. Possible origins

The most likely energy source for these jets is the accretion disc around the black hole. As the matter collapses into the black hole, it loses gravitational potential energy, much of which is converted into the jet’s kinetic energy, mass-energy and x-ray emission (however the details of this process are still subject to debate).

The mass accretion rate of M87’s black hole is[1]
\[ \dot{M} = \frac{dM}{dt} \approx 0.1 M_\odot yr^{-1} \]

where \( M \) is the total mass of the black hole and \( M_\odot \) is the mass of the sun. Not all of this energy is emitted in the particle jet. The total luminosity \( L \) (equivalent to power output) of the jet is given by\[1\]
\[ L_{\text{acc}} = \eta \dot{M} c^2 \]

where \( \eta \) is the energy efficiency parameter, and \( c \) is the speed of light in a vacuum. For thermonuclear burning of H into He mass is converted into heat with an efficiency of \( \eta \approx 0.007 \). In the case of a dormant black hole this figure can be as high as 0.1. While M87’s accretion rate is small for a black hole, this still amounts to a colossal power output of the order of \( 5 \times 10^{37} \) W.

3. Magnetic field energy

The very high energies in these jets often lead to very powerful shocks forming - these are visible in Figure 2 as the jet is clearly split into fragments instead of being uniform, and are also visible (although more difficult to see) in M87, Figure 1. These shocks tend to be dominated by collision-less shocks caused by scattering in magnetic fields\[^6\]. The importance of magnetic fields in the dynamics of these types of jets can be described by the equipartition parameter \( \varepsilon_B \):

\[ \varepsilon_B = \frac{U_B}{U_{\text{jet}}} = \frac{B^2 / 2 \mu_0}{n_e m_e \gamma c^2} \]

where \( U_B \) is the magnetic energy density and \( U_{\text{jet}} \) is the kinetic energy density of the jet. \( B \) is the local magnetic field strength, \( n_e \) is the number density of charged particles in the jet and \( \gamma \) is the Lorentz factor for the particles in the jet.

This is the ratio between the kinetic energy of the jet and the energy contained in the magnetic fields inside the jet. The gamma-ray emission from M87’s jet infers that this parameter is typically in the range \( 10^{-5} < \varepsilon_B \leq 10^{-1} \), however this parameter can reach as high as \( \sim 1 \) in the brightest shocks\[^7\].

4. Open questions

Astrophysical jets are known to have relativistic kinetic energies [1]. The spectrum of these jets is very consistent with synchrotron radiation (plotted in Figure 3). Hence synchrotron radiation is believed to be the mechanism that allows the jets to be visible from
Figure 3. IR and UV spectrum of M87's jet[8]. IR data from Stocke et al. [9], Smith et al. [10], and Killeen et al. [11]. UV data from Perola and Tarenghi [12].

However, many other questions remain - the mechanism by which these jets are created is still debated. So far, all jets that have been observed are inferred to be neutral. This is mostly due to the lack of any space-charge effect that would be observed in a charged jet. The emission spectrum of the jets raised another question. If these beams were neutral overall, how could synchrotron radiation be emitted? Synchrotron emission requires strong magnetic fields, which in the absence of a ferromagnet requires very strong currents, but if the beam has no overall charge how can currents be present? One of the proposed explanations for this is a phenomenon known as Current Filamentation Instability (also known as CFI).
B. Current Filamentation Instability

1. Qualitative description

Current filamentation in a neutral particle jet is an instability arising from non-uniformities in the distribution of the charged particles in the jet (some regions may have a higher concentration of electrons, others will have a higher concentration of positrons or protons). These non-uniformities are caused by the jet interacting with a relatively static background gas (which in the case of astrophysical jets is the interstellar medium). The protons in the background gas are fixed in space compared to the electrons (due to the huge difference between the masses of the two particles), so the jet sees mostly a distribution of positive charge. This is similar to the electrostatic screening effect seen in plasmas. The particles in the jet react in opposite ways to the protons in the background gas, causing variations in the jet’s particle density profile. Since the jet contains high velocity charged particles, variations in the particle density results in regions of current flow being generated inside the jet. Small currents generate weak magnetic fields and these magnetic fields create a positive feedback loop which amplifies the variation of the jet charge density. This rapidly leads to the jet splitting into 'filaments', or regions containing either only electrons or only positrons. The result of an effect similar to this can be seen in Figure 4.

Consider the neutral jet (which in this case is an electron-positron pair plasma jet) propagating upwards in Figure 5 A). This illustrates the scenario where more electrons are flowing on the left side of the jet and more positrons are flowing on the right - the particle flux is indicated by the weight of the arrows (blue arrows representing the electron flux and red arrows representing the positron flux). Since there are not equal numbers of each charged particle flowing at a specific point, the jet is locally non-neutral and this creates variations in the current flow inside the jet, illustrated in Figure 5 B) (grey lines). This current flow then creates magnetic fields, illustrated by the black circulating lines in Figure 5 B). The magnetic fields at the transition between the two regions will be all in the same direction (in this case out of the plane of the page). This means that the particles in both regions will experience magnetic force in the same direction, and will be forced towards the region with more positrons and the electrons will be forced towards the region with more
Figure 4. CCD image of filamenting beam (N.B. this image is of a purely electronic beam; however the result for a neutral jet will be broadly similar)[13]. a) shows the beam after propagating though 2cm of no background plasma (so no filamenting), b) through f) show increasing strength of filamenting of the beam as the background pressure increases electrons as illustrated in Figure 5 C). This example uses an electron-positron jet but the effect will have a similar result with an electron-proton jet (only lacking symmetry due to the huge difference in mass between electrons and protons, which results in the electrons filamenting much faster than the protons).

2. Quantitative description

Consider a jet uniform along z propagating in the y-direction with velocity $\vec{v}$, and varying charge density along the x-direction $\rho(x)$ (as illustrated in Figure 6B). This creates a variation in the current density along the x-axis $\vec{J}(x) = \rho(x)\vec{v}$ (assuming all particles have approximately the same velocity). This creates a magnetic field $\vec{B}$ described by

$$\vec{\nabla} \times \vec{B} = \mu_0 \rho(x) \vec{v}$$

where $\mu_0$ is the permeability of free space. Since the current is only in the y-direction, the only components of the curl of B are

$$\vec{\nabla} \times \vec{B} = (\frac{\partial B_z}{\partial z} - \frac{\partial B_y}{\partial x})\hat{y} = \mu_0 \rho(x) v_y \hat{y}$$
Figure 5. Diagrams illustrating current filamentation instability. A) shows the charge distribution inside the jet. B) shows the currents and magnetic fields resulting from this charge distribution and C) shows the particle trajectories caused by these magnetic fields.

where \( \hat{y} \) is a unit vector in the y-direction. Since the jet in this case is uniform in the z-direction, \( \partial B_x / \partial z = 0 \) therefore

\[
- \frac{\partial B_z}{\partial x} = \mu_0 \rho(x) v_y
\]

The force on a positively charged particle (in this case, a positron) is given by

\[
F_B = q \vec{v} \times \vec{B} = e \mu_0 v^2 \hat{x} \int \rho dx
\]

in the positive x-direction. For most charge distributions that increase along the positive x-axis the magnetic force on a positively charged particle is exclusively rightward i.e. towards the positron jet.

Note that the individual particles will still experience Coulomb force (the space-charge effect) - this will tend to counteract the magnetic force and cause the filaments to diverge.
Figure 6. Diagrams showing current variation in the jet. A) shows the jet’s charged particle distribution. B) shows the numbers of each type of particle and C) shows the resultant current from this particle distribution.

The electric force is described by

\[ \nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \]

\[ |F_E| = q|E| = \frac{e \int \rho dx}{\varepsilon_0} \]

The ratio between these two forces is approximately given by

\[ \frac{|F_B|}{|F_E|} = \frac{e \mu_0 v^2 \int \rho dx}{e \int \rho dx / \varepsilon_0} = v^2 \mu_0 \varepsilon_0 = \frac{v^2}{c^2} = 1 - \frac{1}{\gamma^2} \]

where \( \gamma \) is the relativistic Lorentz factor for the particles in the jet. Clearly for the magnetic force to be significant (which is required for filamentation to occur) the electrons and positrons must have a relativistic velocity. This is consistent with the behaviour of the astrophysical jets and also means that an accelerator capable of relativistic particle energies must be used to study filamentation.
3. Growth rates

Like any form of instability, filamentation will grow at some initially linear rate before becoming non-linear and eventually saturating. This can be seen in the simulation shown in Figure 9 - notice that the initial behaviour (i.e. within the first 5mm of propagation) is the same for both jet divergences. In this case the B-field is being used as a measurement of the degree of filamentation (the more the jet has filamented, the stronger the currents in the jet are and hence the stronger the magnetic fields). Saturation is to be expected once the jet becomes completely fragmented and consists of pure electron and positron filaments.

Several competing theories exist to describe this behaviour. Some models describe the filamentation as being independent of the density of the background plasma; however the model used here describes the maximum growth rate $\Gamma_{\text{max}}$:

$$\Gamma_{\text{max}} \approx \frac{\omega_{pe}}{\sqrt{\gamma}} \sqrt{(1 - 2\sqrt{2} \frac{\gamma_{\perp}}{\gamma}) \propto \sqrt{n_p}}$$

where $\gamma$ and $\gamma_{\perp}$ are the total relativistic jet momentum and momentum perpendicular to the jet propagation respectively, $\omega_{pe}$ is the background plasma density, and $n_p$ is the number density of the background plasma$[14]$. This typically results in filamentation forming over a distance within an order of magnitude of the skin depth of the background gas, with the skin depth being proportional to $1/\sqrt{n_p}$.

II. EXPERIMENT

A. Particle In Cell (PIC) Simulations

1. Initial conditions

PIC simulations of the experiment outlined here were conducted by a team of researchers in Instituto Superior Técnico (IST) in Portugal. The set-up conditions for the simulation are illustrated in Figure 7.

Figure 7 A) illustrates the spatial profile of the simulation starting conditions, axes in units of the background plasma skin depth $(c/\omega_p = 5.3\mu m)$. The jet at this point is a disc of particles $2\sigma_{\perp} = 600\mu m$ ($56.4c/\omega_p$) wide and $2\sigma_{||} = 9\mu m$ ($1.69c/\omega_p$) thick (or 30fs propagation time). The simulation uses a box 2800 cells ($560c/\omega_p$) wide, 2800 cells tall and
Figure 7. Plots showing initial conditions for the PIC simulation. A) shows the spatial profile of the starting jet, graph axes are in units of $c/\omega_p \approx 5.3\mu m$. B) shows the momentum profile of the jet both parallel (bottom graph) and perpendicular (right graph) to the jet propagation.

200 cells ($16c/\omega_p$) deep. The jet profile is given by

$$n_b = n_{b0} \exp\left(-\frac{r^2}{\sigma^2}\right) \exp\left(-\frac{z^2}{\sigma^2_{\parallel}}\right)$$

where $n_b$ is the bunch density (i.e. the density of the jet), $n_{b0}$ is the central bunch density ($\sim 0.31\%$ background plasma density). The jet is 52% electrons and the rest are positrons. While a real jet would include a very large gamma-ray background this will not affect the simulation (and shouldn’t affect the filamenting) so has been omitted.

Figure 7 B) plots the initial momentum profile of the jet. The lower graph (momentum on the horizontal axis) shows the (Maxwellian) distribution of the momentum parallel to the jet propagation. This is effectively the jet’s relativistic energy spectrum, peaking at a relativistic gamma factor of $\gamma = 15$. The graph on the right (momentum on the vertical axis) shows the momentum spread perpendicular to the jet propagation - this is a Gaussian distribution with FWHM of $0.74m_ec$. These give the jet a peak energy of 7.65MeV and a divergence of 50mrad. These parameters are the same as those in the experiment and were picked so that the simulation results would be close to what can be expected in the experiment.
Figure 8. 2D simulation results of the positron (red, upper graph) and electron (blue, lower graph) particle distributions inside the jet. Axes in units of the background plasma skin depth.

2. Simulation results

Initially the system was simulated in 2D - snapshots of the electron and positrons in the jet were taken after 4.9mm of propagation (161ps) and are shown in Figure 8 (in these images the jet is propagating from left to right). As before the axes are in units of the background plasma skin depth (note that the scale of the horizontal axis is roughly 40 times smaller than the vertical axis), the red image (upper) shows the positrons in the jet and the blue (lower) shows the electrons (also note that the heat maps are actually plotting current - while this is equivalent plotting to the number of particles it results in the electron distribution being negative). It is clear that the jet is not homogeneous - the filaments (the dark lines) are clearly defined by this point and are roughly symmetric between the positrons and electrons (this is to be expected - the particles are identical bar opposite charges, unlike an electron-proton jet).

Figure 9 shows results for the maximum B-field at various points through the jet’s 2D simulation. In this case the B-field is being used as a measurement of the degree of filamentation (the more the jet has filamented, the stronger the currents in the jet are and hence the stronger the magnetic fields). Two graphs are plotted - one with a jet divergence of 50mrad and one at 33mrad. It is clear that the filamentation is starting to form almost instantly and also saturates quickly (~5mm for the 50mrad jet and ~7mm for the 30mrad jet). Saturation is to be expected as the jet filaments become purely electronic or purely positronic. It was also demonstrated that reducing the jet divergence increased the magnetic fields - this is to
Figure 9. Peak magnetic field variation in 2D PIC simulations for two different jet divergences.

Figure 10. Cross sections of jet profile. A) shows the spatial profile, B) shows the magnetic field structure.

be expected since a tighter jet will have a higher particle flux per unit volume, therefore higher currents and higher magnetic fields.

The jet propagation was subsequently simulated in 3D for 64mm (213ps). A cross section of the jet profile was also measured after 33mm of propagation, this is shown in Figure 10 (with the jet propagating along the $X_1$ axis). Figure 10 A) shows the distribution of the particles in the jet - it is clear that the jet has split into filaments by this stage. The red regions of the jet contain only positrons and the blue regions contain only electrons. This is can be seen more clearly by looking at the 2D projection onto the back surface of the simulation box i.e. the 2D red and blue pattern on the right of the image. Figure 10 B)
Figure 11. Schematic of experimental setup (not to scale). Viewed from top, neutral jet propagating from left to right, proton radiography beam propagating from top to bottom.

shows the magnetic fields inside the jet at this point. While the two graphs look similar, it is interesting to observe that the magnetic field structure has a slight circular symmetry not present in the particle distribution. Also the complex magnetic field structure appears to extend beyond the size of the jet; however the 0.032T surface contours that are plotted here are contained within the jet.

B. Setup

The experiment described here was conducted in December 2014 using the Astra-Gemini laser system in STFC’s Central Laser Facility in Rutherford Appleton Laboratory, Oxford. A schematic diagram of the experiment is shown in Figure 11.
1. **Electron acceleration**

The first stage of the experiment is to use one of Gemini’s 500TW laser beams (labelled ‘South beam’, red triangle) to accelerate an electron beam (blue) towards the lead target (the grey triangle). This is done by firing a laser pulse into a gas jet, accelerating electrons to energies of about 7.65MeV using a method known as laser wake-field acceleration (LWFA)[15].

2. **Quantum Electrodynamic (QED) cascade**

The electron beam is then incident on a lead target, or ‘converter’ (shown in grey). A QED cascade occurs inside the converter which creates the positrons to be used for the experiment. This method does not produce a completely neutral jet (only ~45% positrons)[2]; however this is sufficient for the purposes of the experiment. The electron-positron jet then passes through a second gas cell - the gas in this cell is the analog for the intergalactic medium that the astrophysical jets propagate through and is necessary for filamentation to occur. The pressure in this cell can be varied, which should affect the growth rate of the filamentation.

3. **Proton radiography**

The second of Gemini’s laser beams is then incident on a gold foil, creating a proton beam using a particle acceleration method known as Target Normal Sheath Acceleration (TNSA)[15]. This proton beam then passes though the gas and terminates in a stack of radiochromic film (known as RCF, shown in the RCF stack in Figure 11). The radiochromic film is initially green and turns blue upon irradiation (an example of which can be seen in Figure 12 - the ’84B’, however, is not part of the signal), effectively imaging the spatial profile of the proton beam perpendicular to it’s propagation direction. When the proton beam passes through a magnetic field the protons will be deflected, much in the same way as a magnetic spectrometer works. This deflection will change the shape of the beam, this effect is illustrated in the difference between the two RCF’s in Figure 12. The clearly defined top, left and bottom edges of the irradiated area of the film are caused by the window of the mount holding the films in place. The less clear edge (down the centre of the image) is caused by the wall of the cell containing the background gas - the radiography was set to
Figure 12. Scans of two RCFs (approximately 3cm wide, so 1:1 scale when printed on A4 paper). Note that the proton beam has a magnification effect so the neutral jet itself is ~10 times smaller than shown in the RCFs here. Also these have been processed to increase the visibility of the deflection observed in number 89B. Neutral jet propagating from right to left.

measure the jet filamentation as soon as it began to form. As the jet here is propagating from right to left, this occur at the right side edge of the gas cell. The image labelled 84B is of a single Gaussian beam profile, the beam imaged in 89B is split in two by a magnetic field, this is visible as a light area in the centre. The image can be used to measure the magnetic fields in the jet. However, no analytical solution to this problem exists so this is done using a particle tracer - effectively estimating a magnetic field structure, simulating what would be visible on the RCFs and attempting to match this result with the real RCFs.

4. Phosphor screen

A phosphor LANEX™ scintillator screen has also been placed across the jet path (labelled 'LANEX phosphor screen (i)') - this fluoresces upon irradiation, and when combined with a CCD camera allows the cross section of the jet to be imaged directly. However, the scintillator screen responds equally to the electrons, positrons and gamma rays in the jet (the gamma rays dominate by a factor of ~10). This not only makes distinguishing between electron and positron filaments impossible, the gamma rays will make detecting any variation in the jet’s particle density profile caused by the filamentation difficult to detect. Fortunately, background subtraction (i.e. subtracting one shot from another) can be used to cancel the gamma ray background signal (as these gamma rays are only formed when the jet is created, the gamma rays are unaffected by and do not affect magnetic fields and so will be the same whether or not filamentation is occurring) and distinguishing between the two sets of filaments is not important. Note that the jet was realigned near the end of the experiment -
this has created two different sets of images of the jet profile, but should not affect the final result.

5. Magnetic spectrometer

A magnetic spectrometer is also installed where the jet terminates - this consists of plastic and lead shielding, a magnetic field and two scintillator screens ('LANEX phosphor screens (ii)'). The magnetic field causes the particle paths to bend according to their charge and energy and thus allows the quantities and energy spectra of the two species of particle to be measured.

C. Method

1. Vary converter thickness

The target is shaped as a wedge to allow its thickness (and therefore the jet composition) to be varied between shots. It was found in previous experiments that approximately 25mm of lead (or 5 radiation lengths\(^1\)) was required to generate an approximately neutral electron-positron jet, whereas 5mm produced a jet containing only \(\sim 10\%\) positrons[2]. This allows study of the effect of jet neutrality on the degree of filamentation; however it was expected that this would only be visible for a roughly neutral jet, so only the results for a neutral jet were analysed in detail.

2. Vary gas pressure

The pressure of the gas in the interaction cell (labelled, Figure 12) is variable. The growth rate of current filamentation \(\Gamma \propto \sqrt{n_p}\) where \(n_p\) is the density of the background gas. Varying the gas pressure allowed study of this relationship, and also allowed the filamentation to be ‘switched off’ to provide a reference to obtain the gamma ray background and isolate the filamentation from the LANEX scintillator photographs.

\(^1\) 1 radiation length is the distance over which a high energy electron loses \((1 - e^{-1})\) of its energy.
III. RESULTS

A. Neutral jet spatial profiles

Figures 13 and 14 show images of the first phosphor scintillator screen - this is effectively a direct image of the jet's spatial profile normal to its propagation. The jets in these images was formed with 25mm of lead converter in place so the jet was approximately neutral, the background pressure increases between shots going from left to right. Filamentation should be absent in the left image, visible in the centre and very strong in the rightmost image. No variation between the images is visible with the naked eye so clearly more rigorous analysis is needed.

1. Jet profile analysis (Fourier transforms)

The first stage of the frequency analysis of the jet profile was to reduce the 2D image to a 1D 'line-out' - while frequency analysis could have been done with a 2D Fourier transform, using a 1D transform is much more intuitive.
The PIC simulations suggest that the filamentation will produce a modulation with the order of 10-20 filaments across the diameter of the jet, so if filamentation were taking place this would be visible in the Fourier analysis of the line-outs as a peak at the 10-20 'bins' mark. A fast Fourier transform (FFT) algorithm is being used here, so the frequency is measured in units of 'bins' where a frequency of 1 bin has one complete oscillation over the extent of the signal - a 15 bin frequency would produce a sinusoid that oscillates 15 times over the width of the signal. The data used for this analysis is an average of a 20 pixel wide horizontal bar across the centre of the image to reduce the effect of random noise; however any oscillations below 50 bins should still be visible.

Figures 15 and 16 show Fourier transforms of the two sets of LANEX images. The large peaks below the 5 bin mark create the overall jet profile so will not show filamentation at the frequency indicated by the simulations. It is clear from Figure 15 that varying the background gas pressure (which should affect the rate of filamentation) has no significant effect on the frequency spectrum of the jet profile. This is in complete contradiction to
the simulations and analytical estimates\(^2\) which suggested that a peak within the plotted frequency range should be clearly visible - even outside the 10-20 bin frequency range the same pattern is visible.

2. *Jet profile analysis (background subtraction)*

The next method used to try to find evidence of filamentation was to use background subtraction to remove the gamma ray profile from the image of the jet. This was done by subtracting the profile of a jet after propagating through a low pressure background gas from the profile of a jet after propagating through a high pressure background gas. The resulting image should show only the modulation in the electron-positron jet. This produces Figures 17 and 18 where clearly no such high frequency modulation is visible. Note that a Gaussian blur was applied to these images to remove the very high frequency, high amplitude noise that skewed the colour bar and made the image difficult to see - however any frequencies below 80 bins are still resolvable. The unfiltered images are in Appendix A.

The same analysis was done for the 1D line-outs - this produced Figures 19 and 20. This shows even more clearly that modulation in the expected frequency is completely absent - only some low frequency variation (more likely due to the jets not quite being aligned the same way with each shot) and very high frequency random noise. Even if the low frequency variation could be filamentation, there is no significant difference between the behaviour of the jet at low and high background gas pressures (unfortunately no measurements were taken with a neutral jet propagating through 0 gas pressure). Also, while it is a possibility that the jet is actually able to saturate at the low gas pressure, the probability of all 8 jets forming exactly the same pattern of filaments is vanishingly small.

It is clear that directly imaging the jet profile shows no evidence of any filamentation occurring inside the jet. Other methods will be required to study any filamentation that may be present.

\(^2\) Using the parameters given in Section II A 1 the filamentation is estimated to form after \(~5\text{mm}\) of propagation.
Figure 17. Surface plot of LANEX shot number 113035 (50mbar background pressure) subtracted from shot number 113037 (800mbar background pressure) with a weak Gaussian blur applied to remove noise.

Figure 18. Surface plot of LANEX shot number 112888 (50mbar background pressure) subtracted from shot number 112877 (500mbar background pressure) with a weak Gaussian blur applied to remove noise.

B. Radiography

Another possible way of measuring the filamentation in the jet is to measure the magnetic fields frozen into the background gas after the jet has passed through it\(^3\). This can be done using proton radiography. The RCF responds linearly to irradiation by its optical depth \(\tau\) increasing, however the brightness value read by a scanner is a logarithmic function of the optical density. The incident proton flux \(n_p\) is therefore given by:

\(^3\) Since the neutral jet has already passed through the gas, it cannot be affected by the proton beam.
Figure 19. Residuals from 1-D measurements of jet spatial profile using shot number 112650 (Background gas pressure 50mbar) as reference.

Figure 20. Residuals from 1-D measurements of jet spatial profile using shot number 113035 (Background gas pressure 50mbar) as reference.

\[ n_p \propto \tau \propto -\log \left( \frac{P}{65535} \right) \]

where \( P \) is the total brightness value measured by a scanner with a 16-bit (i.e. 65535 colours) colour depth and \( n_p \) is given in arbitrary units.

The RCFs showing the structure of the proton beam after passing through the magnetic fields in the plasma are shown in Figures 21 through 24. Each of these graphs shows the scan of the RCF (left, green) and a 1D plot of a slice of the beam profile (right). The data plotted was taken from the red bar drawn on the RCF - this was next to where the jet entered the plasma, due to the jet’s divergence this is where the magnetic fields were expected to be easiest to measure. The blue line plots the direct measurement of the beam profile, the red line plots a Gaussian fit representing the unaltered distribution of a TNSA-accelerated (Target Normal Sheath Acceleration) beam and the yellow line is the residual from the Gaussian fitting.
Figures 21 and 22 show the results from a neutral jet propagating through a low-density background plasma. The proton beam profile here is relatively smooth - not quite a Gaussian distribution but is still clearly a single beam. This is to be expected as a low density background plasma will not facilitate a fast growth of filamentation, so no strong magnetic fields are present. This shows that there is little to no filamentation present in these jets.

![Figure 21](image1.png)

**Figure 21.** (right) Scan of RCF number 60. (left) Plot of number of protons incident on the RCF along the region highlighted by the red bar, a Gaussian fit and the residual from this fit.

![Figure 22](image2.png)

**Figure 22.** (right) Scan of RCF number 75. (left) Plot of number of protons incident on the RCF along the region highlighted by the red bar, a Gaussian fit and the residual from this fit.

Figures 23 and 24 show the same analysis for the neutral jet propagating through a higher density background plasma. Although the two graphs are showing slightly different signals, two distinct peaks are clearly visible. Since the TNSA does not produce uneven beam profiles like this, this must be caused by a magnetic field interfering with the paths of the protons in the beam, and since the jet is neutral, the jet must be filamenting. However, since no analytical description of this behaviour exists, numerical analysis in the form of
Figure 23. (right) Scan of RCF number 61. (left) Plot of number of protons incident on the RCF along the region highlighted by the red bar, a Gaussian fit and the residual from this fit.

Figure 24. (right) Scan of RCF number 89. (left) Plot of number of protons incident on the RCF along the region highlighted by the red bar, a Gaussian fit and the residual from this fit.

particle tracing software is required to measure the strength and structure of the magnetic fields inside the jet.

1. Particle tracing

Using the particle tracer required an estimate of the magnetic field structure to work from. The first estimate of the jet structure was of a column of positrons shrouded by a cylinder of protons, effectively 2 filaments, shown in Figure 25, top left. This is not inconsistent with the simulation results in section II A 2 suggesting that dozens of filaments should be visible - the proton radiography is measuring the magnetic fields immediately after the jet starts to filament, whereas the jet in the simulations has propagated for a
Figure 25. Jet and magnetic field structure used for particle tracing. Current density (arb. units) shown at top left, radial magnetic field (T) shown at top right, bottom graphs show distributions of x- and y-components of the magnetic field. Distance scale in arbitrary units.

longer distance (and potentially formed more filaments). RCF number 89B (shown in Figure 24) was examined and the single-filament magnetic field structure was found to be quite accurate. This measurement suggests a peak magnetic field strength of 6T, notably this is approximately an order of magnitude higher than indicated by the PIC simulations. Work is currently ongoing to resolve this discrepancy, one possible explanation is that the magnetic fields frozen in to the gas might not be the same strength as those created by the jet.

The jet here has a modal Lorentz factor of 15 and a number density of \( \sim 10^{15} \). This gives an equipartition parameter of \( \varepsilon_B = 1 \) i.e. most of the jet’s energy is contained in the magnetic field. This is potentially very significant as this shows that the dynamics of the
jet produced in this experiment are consistent with those in the brightest shocks in real astrophysical jets, where the equipartition has been measured to have been as high as $\sim 1[7]$.

C. Reexamined simulation results

Interesting as this result is, it still contradicts the results from imaging the jet profile showing no filamentation. In an attempt to resolve this, the results of the PIC simulations that indicated that the filamentation should be visible were re-examined. A 1D measurement of the particle distribution in the filamented jet profile was plotted and is shown in Figure 26. The red line (upper) shows the current due to the positrons and the blue line (lower) shows the current due to the electrons. This simulation refers to an earlier point in the jet’s propagation than measured in the experiment, hence the modulation is of a lower frequency than expected in the jet profile images. The modulation in the two graphs is clearly visible (8 filaments of each particle), and clearly the positron filaments will occur in the same place as the vacancies between the electron filaments, and vice versa. What is more interesting, however, is how closely the two graphs match - even small dips inside the positron filaments (such as that at $x = 33c/\omega_p$) are mirrored in the electron distribution, and vice versa. The total distribution of charged particles was then plotted (since this resembles more closely what the scintillator screen will see) in Figure 27. This shows absence of the modulation that was expected from the graphs shown in Figures 10 A) and B). Re-analysing the results shows that rather than producing variation in the jet profile, the filaments in the electron-positron jet form in such a way that still allows the particle distribution to remain smooth - this is very significant as this behaviour is not observed in electron-proton jets. This also explains the apparently contradicting measurements of the jet profile and magnetic fields inside the jet.

IV. CONCLUSION

A. Results

The proton radiography shows conclusively that magnetic fields are present inside the jet. Since we know from the magnetic spectrometer results that the jet is neutral overall, the only way that magnetic fields can be produced is for the jet to be filamenting and producing
regions of net current. The direct images of the jet’s spatial profile also show that this variation is not visible in the overall jet profile. While these results were initially seen to be contradictory, the PIC simulations showed that this was not necessarily the case.

The most interesting result from this experiment is how the filaments were able to still have a smooth particle distribution. This behaviour is not observed in electron-proton jets - the electrons in these asymmetric jets will filament significantly faster than the protons due to the protons being approximately 2000 times more massive than electrons. However, this experiment represents a perfectly symmetric system - equal amounts of matter and antimatter, so the negative and positive parts of the jet are able to filament equally and the positron filaments are able to exactly fill the voids between the electron filaments and vice versa.

The most significant result, however, comes from the proton radiography. The magnetic
fields inside the jet were measured to have a strength of $\sim 1T$. This would give an equipartition parameter of roughly 1. Studies of jets such as M87 have placed the same figure for these jets within the range of $10^{-5} \sim 10^{-1}$, however in very bright shocks this can be as high as 1. This shows that the filamenting jet produced in the lab is behaving in a very similar way to shocks within the jets observed by astrophysicists. This is very strong evidence that filamentation is occurring within the jets, this also validates the potential use of laboratory setups to study astrophysical objects.

B. Future work

There are, however, improvements that can be made to this experiment. One of its main limitations is the range of the jet - because the jet had a divergence of $\sim 50\text{mrad}$, it very quickly diffused beyond the point of being able to study the magnetic field structure. Figure 28 shows the variation of the maximum magnetic field according to the 2D PIC simulations. The magnetic fields between 0 and $\sim 10\text{mm}$ of propagation illustrate the linear phase of the filamentation growth and 16mm onwards shows the non-linear (saturation) phase of the filamentation. The experiment here was only able to study the jet for about $200\mu\text{m}$ of propagation; however if the jet were more collimated (which would also bring it closer to the behaviour of real astrophysical jets) it could be studied for long enough that this would be possible.

Figure 9 shows a similar plot of a pair of 2D simulations. The scale is slightly different due to the reduced dimensionality $^4$, but the behaviour is similar. The 2 lines on this graph

---

$^4$ The 2D simulation were primarily used to check that the simulation was producing sensible results before
show that a tighter beam has the potential to saturate at a higher magnetic field, this could also be tested using a more collimated neutral jet.

Fortunately, this has been shown to be achievable. PIC simulations have shown that using a converging electron jet (i.e. $\theta = -20\text{mrad}$) to generate the neutral jet, can create a jet that is highly collimated. A revision to the experiment here that hopes to achieve this, is currently at the design phase. The main alteration to this experiment required to create a collimated jet is a set of quadrupole particle lenses that bring the electron beam divergence from $+5\text{mrad}$ to $-20\text{mrad}$. An artist’s impression of the proposed experiment is shown in Figure 29.

---


committing to the weeks of server time required to simulate the experiment in 3D.


**ACKNOWLEDGMENTS**

Thanks to J. Vieira, K. Schoeffler, N. Shukla, L.O. Silva of Instituto Superior Técnico, Lisbon, for conducting the PIC simulations used here. Also thanks to Richard Warwick for conducting the particle tracer analysis used in section III B1.
Appendix A: Unfiltered 2D background subtractions

Figure 30. Unfiltered 2D plot of (background subtracted) jet spatial profile 112877 (500mbar background gas pressure). This should show the modulation in the jet profile caused by filamentation at 500mbar background gas pressure.

Figure 31. Unfiltered 2D plot of (background subtracted) jet spatial profile 113037 (800mbar background gas pressure). This should show the modulation in the jet profile caused by filamentation at 800mbar background gas pressure.