17

Increasing plasmoid ion density in a MA plasma focus device

E. J. Lerner, D. Shannon, F. Van Roessel, I. Karamitsos and A. Blake
Lawrenceville Plasma Physics, Inc., 128 Lincoln Boulevard, Middlesex, NJ 08846, USA

The FF-1 plasma focus facility has previously demonstrated confinement in a plasmoid of ion energies >150 keV [1]. However, the ion density of the plasmoids, at ~3x10^{19} /cm^3, has been well below the best values of >10^{21}/cm^3 reported with other PF devices [2]. We have previously associated this lower density with the appearance of an early beam in FF-1, emitted 30-50 ns before the pinch (time of minimum dI/dt)[3]. We here show that the early beam, which can have peak power in excess of 300 GW, is associated with an inner current sheath, which in turn appears due to impurities introduced by oxidation of the copper anode. We are now attempting to entirely eliminate oxidation with a 25-micron silver plating of the anode. If, as anticipated, this leads to the production of single sheath, current through the pinch will approximately double with a concomitant increase in density and fusion yield of an order of magnitude or more.

1. Introduction

To achieve net energy production from a fusion device, plasma above critical density and mean ion energy must be confined for more than a critical duration. In experiments performed with the "Focus Fusion-1" (FF-1) plasma focus (PF) device at Lawrenceville Plasma Physics' laboratory, we confined plasma with ion energies >150keV for durations of 30-50ns[1]. With adequate plasma density,~10^{24}/cm^3, we calculate that these conditions would be sufficient for production of net energy from a pB11 fuel[3]. However, the actual densities observed in FF-1's plasmoids until now fall well short of this goal and are instead ~3x10^{19} /cm^3. This is also a much lower density than has been observed in other PF devices, which have been reported in the range of 10^{21}/cm^3 [2].

The hot plasma in our device is confined in plasmoids whose cores are about 200-300μ in radius and about 1.5 mm in length. This is considerably larger than the smaller plasmoids that have been observed in some PF devices, which are around 50 μm in radius and 400 μm in length [4]. Thus the compression of the plasmoids by the pinch forces generated by their own currents does not proceed as far in FF-1 as in some other PF devices, creating plasmoids with ~100 times more volume and >100 times less density.

In previous work [3] we showed that the lower density is associated with the consistent appearance of an early beam (EB), a simultaneous emission from the plasmoid of an ion beam and electron beam at 30-50 ns before the pinch time (the time of minimum dI/dt, where I is the total current flowing through the electrodes.) We hypothesized that the EB deprived the subsequently-formed plasmoid of magnetic energy, so that the pinch forces could not compress the plasma to high density. We further hypothesized that azimuthal asymmetries in the pinch caused some parts of the sheath to move ahead of other parts, leading to the production of the EB when the leading edge of the sheath reached the axis.

The questions that remain, and which we examine here, are: how exactly do asymmetries lead to the production of the EB, what causes the asymmetries in the first place and how can those causes be mitigated or eliminated?

2. Experimental observations

2.1 Experimental device

The FF-1 device is energized by a 113 μF, 12-capacitor bank. The copper cathode, consisting copper rods in a base plate, has a radius of 5 cm, and the copper anode has a radius of 2.8 cm, while in the present configuration both have a length of 14 cm, with a 2.8-cm-long ceramic insulator between them. The capacitor bank in these experiments was charged to either 35kv or 40 kV, with a rise time of 2 μs and peak current of 1.0- 1.2 MA. Fill pressure was 16-20 torr of deuterium at 35kV and 24-30 torr D at 40 kV.

2.2 Timing and energy observations

We were able to determine the relative timing of the main events in these shots using a number of instruments. In all shots, the timing of the EB and the pinch were measured from the main Rogowski coil (MRC) output that measured dI/dt. The EB was evident as a sharp minimum in dI/dt, followed by a period of positive dI/dt, while the pinch was the much deeper minimum in dI/dt which followed 30-50 ns later, as shown in Fig.1. The x-rays generated by the collision with the anode of the e-beams produced first by the EB and then by the plasmoid were detected in all cases by a PMT-scintillator (the VPMT) at 1.34 m from the device axis, which had a field of view that included the anode, but not the plasmoid.

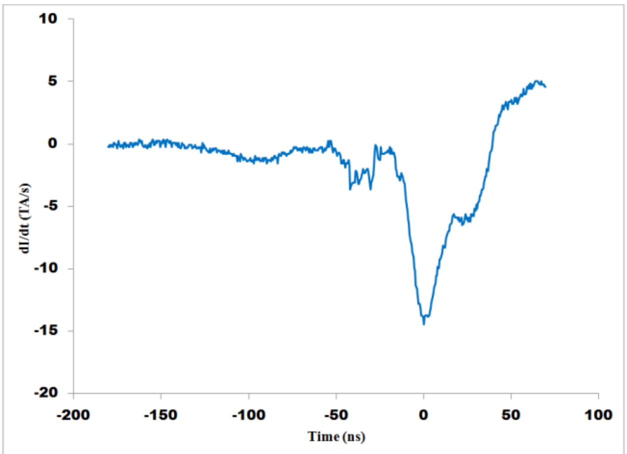


Figure 1. Main Rogowski coil (MRC) signal for shot 02281304 in tera-amps/s. Note EB as sharp fall in dI/dt at -45 ns and rise to positive values from -25 to -15 ns, followed by much deeper pinch.

In some shots, the ion beam was also detected by the upper Rogowski coil (URC) located on axis 31 cm from the end of the anode and, in a few shots also by the lower Rogowski coil (LRC) located on axis 1.15 m from the end of the anode. The URC and LRC are 2.5 cm in radius and the ion beam is only occasionally sufficiently aligned with the axis to go through them. In these shots the current and mean ion energy to the beams could also be measured based on the RC signals and time-of-flight calculations.

The integrated URC signal for ion current for one such shot, 02281304, is shown in Fig.2. Time of flight calculations using LRC, URC and PMT data are consistent with a mean ion energy of 3 Mev. From these data it is seen that the large EB, on left, originated 43 ns before the pinch time while the smaller beam at right originated just 9 ns before the pinch, referring to the peak current time in both cases.

The EB in this shot had a peak power of 380 GW, the highest observed so far with FF-1, and a FWHM of 3ns. Since the energy generated by the electron beam, accelerated by the same potential, must be equal to that of the ion beam, both EBs together carried away ~2.3 kJ, about 5% of the total bank energy released up to that time.

From two other PMT-scintillators located at 11m and 17 m from the axis of the device we can measure neutron TOF and determine the origin time of the neutron pulse. This is typically very close to the time of minimum current I, which is 30-50 ns after the pinch. The FWHM of the neutron pulse, projected back to the origin, is also in the range of 30-50 ns.

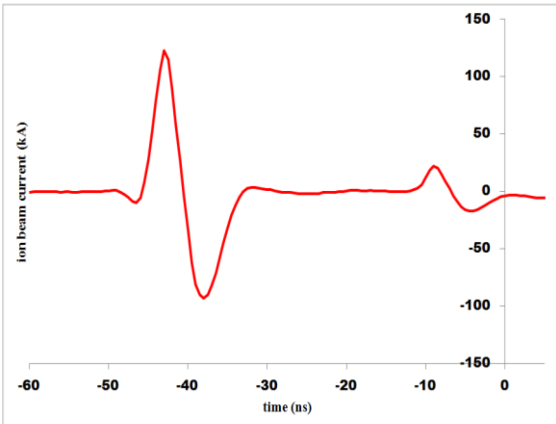


Figure 2. Upper Rogowski coil integrated signal for shot 02281304. Note EB on left and smaller plasmoid beam on right. The time relative to the pinch time is corrected for the 20 ns TOF to the coil.

Thus we find that the EB precedes the pinch and a second beam by 30-50 ns, while the neutron pulse begins shortly after the pinch time and peaks an additional 30-50 ns later.

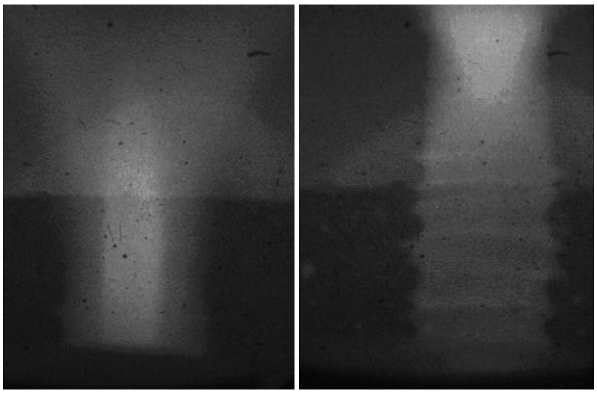
2.3 ICCD images

To understand what was happening at each of the critical times in the development of the plasmoid, we took ICCD images of the region near the end of the anode and grouped them according to the difference between the time of the image (indicated by a signal from the camera) and the pinch time. Each image had an exposure time of 0.2 ns.

For images taken at the time of the EB, we see in several images that an inner sheath has converged on the axis, forming an elongated dense blob, or jet, as in Figure 3A. These blobs have typical radii of about 1.5 mm and length of about 1 cm. After formation, they move away from the anode along the axis, at approximately 10cm/μs.

After the jet has moved out of the way, the outer sheath develops an m=0 instability, as in Figure 3B. As this develops, a second beam is emitted. At the time of the pinch, the instability is rapidly developing and , shortly after the pinch time, (again defined as minimum dI/dt) there is a sharp contraction of the column and the plasmoid forms (Figure 4) The plasmoid core is a factor of 5 shorter than the preceding blob and a factor of 7 smaller in radius.

The plasmoid then starts to move away from the anode along the axis, but much more rapidly than the jet, moving about 100 cm/μs. During this period, the neutron generation begins. Thus far we have not tracked the plasmoid to the time of maximum neutron production.



A B

Figure 3(A). ICCD image, shot 03131302, 66 ns before pinch, simultaneous with EB peak. The image shows the central 1 cm diameter region around the axis of the anode, looking at an angle into the cylindrical hole in the anode. The jet or blob, formed by the inner sheath is seen. Up is away from the anode and the black boundary is the edge of the anode. Black dots are ICCD flaws. (B)Shot 03131305, 6 ns before pinch. The jet (top) has now moved out of the way of the outer sheath, which is undergoing an m=0 instability.

In a few earlier images taken with a wider field of view, the jet and the plasmoid are both visible in one image, as in Figure 5, which clearly shows that the jet and the plasmoid are attached to two separate current sheaths.

These images make clear that the EB is a symptom of the existence of an inner current sheath and that it therefore affects the plasmoid not only by the prior release of energy in the beams, but also by shunting a significant portion of the current into a sheath that does not flow through the plasmoid.

2.4 Anode observations

After each disassembly of the electrodes, we observed that that erosion marks near the end of the anode, presumably made by the current sheath filaments, were irregularly spaced, evidence of the azimuthal asymmetries into sheath. We also observed that the anode was covered with irregular patterns of oxidation, with oxide layer thickness estimated by color as up to at least 0.2 μm.

We concluded that the proximate cause of the current sheath asymmetries was the uneven effect of the oxide layers on the motion of the filaments, which then became unevenly spaced.

Since the mass density of the oxide is 30-120 micrograms/cm^2, the vaporized copper becomes a substantial fraction of the plasma mass, so any variations in this layer can be expected to have a substantial impact on filament motions and sheath dynamics.

3. Comparison with earlier work

Other researchers have observed the phenomena of the PF producing very closely-spaced current sheaths. Using a smaller, 0.3 MA, PF, Nikulin et al [5] observed such sheaths and the production of a moving jet of plasma emerging from the inner sheath. They also associated such additional sheaths with asymmetric distribution of current filaments in the initial sheath.

They pointed out that impurities in the sheath can encourage the formation of a second sheath in several ways. First, heavy impurities can by their radiation cool the sheath, decreasing its conductivity and making it less magnetized. This allows axially-flowing current to more easily form a second sheath. Second, the decreased conductivity increases the skin depth of the sheath, also encouraging instabilities that lead to asymmetries. Finally, the asymmetries in the sheath can more easily allow large quantities of plasma to pass through the sheath and become available for the formation of a second sheath.

This explanation is consistent with our observations. We further elaborate it here in a number of ways. First we point out that, with copper electrodes, an inevitable source of impurities is the copper oxide layer that is always present on the copper and that must be cut through and partially vaporized by the filaments.

Second, we put forward a possible explanation of why the inner or first sheath does not itself form a pinch. In our theory [3], the pinch forms through a kink inability that tightly twists the central current filament into the plasmoid. For the inner sheath, the attractions of the filaments to those of the outer sheath immobilize the inner ones azimuthally and prevent the kinking instability from forming. However, for the outer sheath, no other sheath is present, so the kinking can take place.

Some evidence for this hypothesis is provided by 2D MHD simulation carried out recently by Baronova et al [6] showing the production of a jet morphologically similar to those we have observed and with similar velocity. A 2-D simulation by necccesity suppresses azimuthal motion and arrives at a jet, not a plasmoid, in the same way we hypothesize the azimuthally-immobilized inner sheath produces the observed jets.

Third, we point out that this initial compression also produces the EB that we have observed.

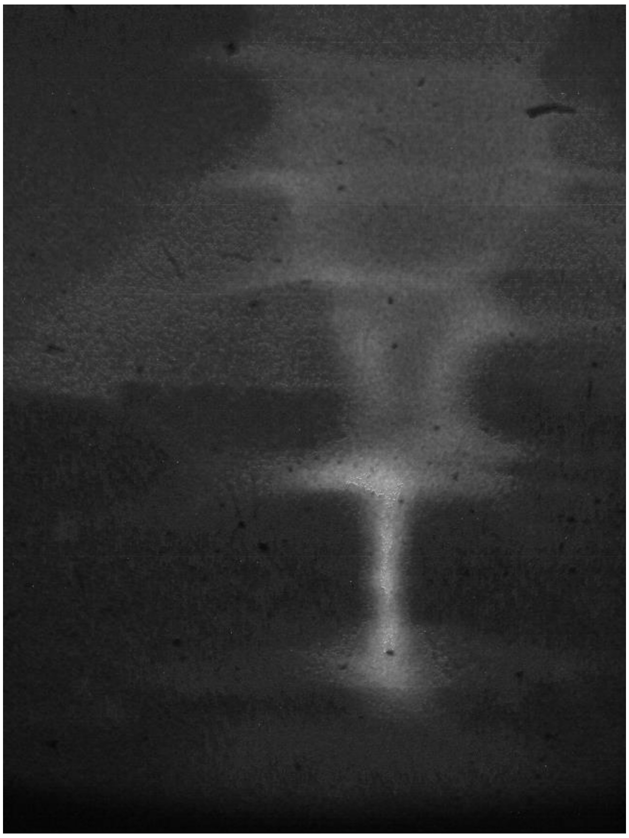


Figure 4. ICCD image, shot 03131306, 8 ns after pinch. The image again shows the central 1 cm diameter region around the axis of the anode. The plasmoid, bottom narrow object, has formed, still attached to current sheath.

4. Causes of the oxide layers and possible mitigations

We have identified several contributions to the uneven oxide layers and have eliminated them in turn. First, we noted that a circle of tungsten pins that were attached to the cathode plate, next to the insulator, and used to initiate the current filaments, could become uneven in height, thus unevenly concentrating the initial current and the resulting oxide layers. We first evened the pins, and then replaced them with a solid tungsten plate, with a set of machined teeth.

We additionally noted various sources of arcing that contributed heavy uneven impurities to the sheath, depositing them unevenly on the anode. We eliminated the contact resistances that led to this arcing by coating all conductor contact surfaces with silver and joining them with indium wire, checking that all contact resistance was <2 micro ohms.

To eliminate oxygen entering the chamber, we reduced the leakage to 300 microtorrs/min. We also chemically coated the anode with a 1 μm layer of silver.

However, we found that transient leaks during shots, created by the overpressure from the shot itself, could allow in enough oxygen to continue formation of the oxide layer, which enabled the continued existence of the sheath asymmetries and EB phenomenon, even though its amplitude has become less.

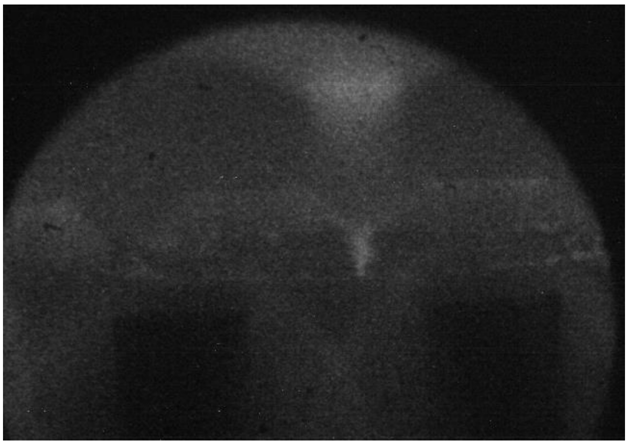


Figure 5. ICCD image, shot 01031215, at time of pinch. Here, the image is 5 cm wide, rather than 1 cm as in the previous images. The pinch column, central narrow bright object, has formed, attached to lower current sheath, while the remains of the jet (upper flattened bright object) is spreading out attached to the upper current sheath.

In order to prevent diffusion of the copper through the silver layer, we have plated on a 25-μm-thick layer of silver. Together with prevention of transient leaks, we expect this to eliminate the copper oxide layer. If this as well eliminates the inner sheath, we expect a sharp increase in plasmoid density and fusion yield. For example, if the inner sheath now shunts half the current, the fusion yield without this sheath could be expected, by scaling theory, to increase by I^4 or 16-fold.

5. References

[1] E.J. Lerner, S. K. Murali, D. Shannon, A. M. Blake, F. Van Roessel, Phys. Plasmas **19** (2012) 032704

[2] J. S. Brzosko, J.R. Brzosko, B.V. Robouch, L. Ingrosso, Phys. Plasmas **2** (1995) 1259

[3] E. J. Lerner, S. K. Murali, A. Haboub, J. Fusion Energy, **30** (2011) 367

[4] W. H. Bostick, V. Nardi, W. Prior, Ann. NY Acad. Sci., **251** (1975) 2

[5] V.Ya. Nikulin, S.N. Polukhin, A.A. Tokomirov, Plasma Phys. Reports, **31** (2005) 591

[6] E.O Baronova et al, Plasma Phys. Reports, **38** (2012) 751