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ORIGINAL PAPER

Fusion reaction scaling in a mega-amp dense plasma focus

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Abstract. The dense plasma focus (DPF) is one of the most efficient sources of fusion reactions for a given energy input. For smaller DPFs, fusion output scales as I^4 or faster, where I is peak current. However, energy output in high-current machines saturates at 10^{12} reactions with deuterium as fill gas. To attempt to overcome this saturation, experiments at the focus fusion-1 (FF-1) facility have tested the use of smaller-radius electrodes (2.8 cm radius anode) and higher fill-gas densities > 30 T.

Key words: dense plasma focus (DPF) • fusion reaction scaling • neutron yield saturation

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Introduction

There are sound theoretical reasons for predicting that fusion yield in DPFs could further scale at least as rapidly as the I^4 scaling observed in many such devices [2]. For a given fill gas, density (n) in the small plasmoids where fusion reactions take place scales with the fill-gas pressure. Since optimized run-down velocity is approximately constant, fill-gas pressure scales with I^2 for a given electrode radius. Fusion-reaction rates scale as n^2 and thus as I^4. The same theory indicates that reducing the electrode radius, thus increasing the optimal fill pressure for a given current, should also improve yield.

Based on this theory, the authors constructed the FF-1 DPF in 2009 which has relatively small electrodes – 5 cm radius cathode and 2.8 cm radius anode, currently each 14 cm long. With a 113 μF capacitor bank charged up to 35 kV (70 kJ stored energy), we have achieved above 1.1 MA with a quarter-cycle time of 2.2 μs. The device has a peak design capacitor potential of 45 kV which we expect to reach soon. The experimental setup is shown in Fig. 1.

In our initial experiments in 2010, with current up to 0.7 MA, FF-1's performance was very close to theoretical predictions, as has been previously reported (Ref. [2], Fig. 2). Scaling of fusion yield with current was considerably faster than I^4 – almost I^7 – and the total neutron yield of 10^{11} was nearly ten times higher than that reported from any other DPF at a current of 0.7 MA. However, this scaling did not continue as current was increased to 1 MA. In fact, the best yield plateaued at 10^{11} neutrons per shot. In experiments over the past year, we have tried to determine what caused this plateau and how

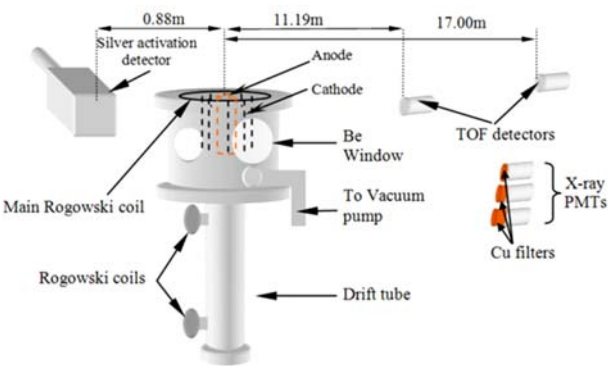

Fig. 1. Experimental setup of focus fusion-1 (FF-1).

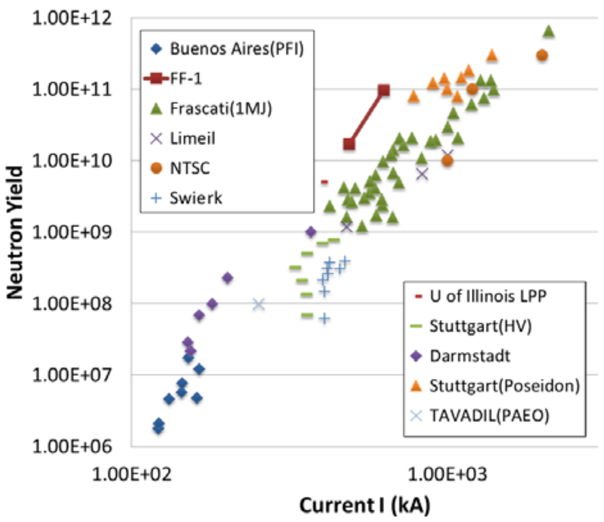

Fig. 2. Improvement in yield/current scaling.

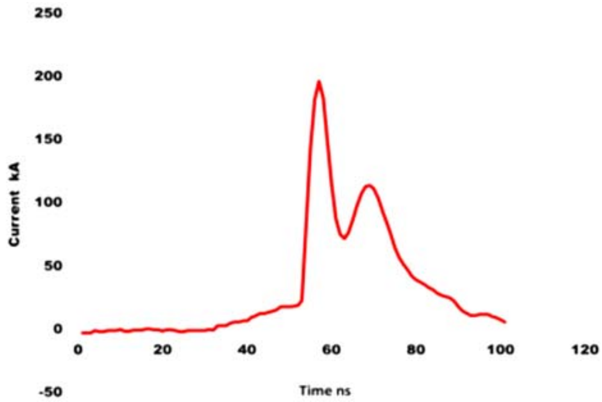

Fig. 3. A typical double-pulse ion beam; shot 05121104.

to extend the rapid scaling of fusion yield. We wanted to determine if the problem was with declining efficiency of energy transfer into the plasmoid, lack of increase in the energy of ions trapped in the plasmoid, decrease in density of the plasmoid, or some other cause, such as the fusion reactions not coming from the plasmoid at all, but rather from an unconfined beam.

Experimental results

We found that at currents up to 1 MA, the efficiency of energy transfer into the plasmoid, and from the plasmoid to the ion and electron beams, remained relatively high. We measured the ion beam with a Rogowski coil located 31 cm from the end of the anode and determined the average energy of the ions in the beam by the time-of-flight, comparing the ion beam arrival time with the emission time of the X-ray pulse produced by the electron beam arriving at the anode itself. A typical pulse with a double peak is shown in Fig. 3. The ion beam characteristics are summarized in Table 1. The best shots show good agreement with predictions in the total current and charge carried by the ion beams, but are about a factor of two off in average ion energy and total delivered energy. For comparison, about 30 kJ had been delivered to the electrode by the time of the pinch, so nearly 7% of total available energy is converted to beam energy, counting both ion and electron beams. (It should be noted that beam current could be larger than the value measured by the Rogowski coil if the beam is partially neutralized by electron currents inside the coil radius). Since in these same shots, neutron yield was a factor of 15 below theoretical predictions, we concluded that energy transfer to the plasmoid was unlikely to be the primary contributor to lower-than--expected fusion yield.

We also concluded that average ion energy T_i in the plasmoids was high and, for the best shots, scaled rapidly with I. We measured T_i by measuring the distribution of emitted neutron energies with time-of-flight detectors located at 11 and 17 m, 90° from the axis of FF-1. We determined an average ion energy for each shot using the formula $E_i = 2E(W^2 - \tau^2)/t^2$, where E_i is mean ion energy; E is neutron energy derived from the fusion reaction; t is the time required for a neutron of energy E to travel to the detector; W is the full width at half maximum (FWHM) of the pulse at the detector, and τ is the duration of the neutron pulse at the origin of the pulse. This formula is an accurate fit (within 5%) to numerical values calculated by Bogdanov and Volosov [1] over a range in E_i from 2–100 keV assuming Maxwellian plasma. For a non-Maxwellian distribution, the average energy is higher for the same W. While there was considerable scatter in the results when T_i was plotted against I, the upper envelop of T_i (the highest T_i for a

Table 1. Ion beam characteristics

	Range	Mean	Prediction
Peak current I (kA)	110–290	190	280
FWHM (ns)	6–12	7.5	8
Charge (mC)	1.1–2.2	1.6	2.2
Ion energy (keV)	200–251	320	900
Peak power (GW)	42–93	57	250
Energy (kJ)	0.32–1.1	0.49	2.0
Neutron yield (10^{10})	2.1–4.6	3.7	65

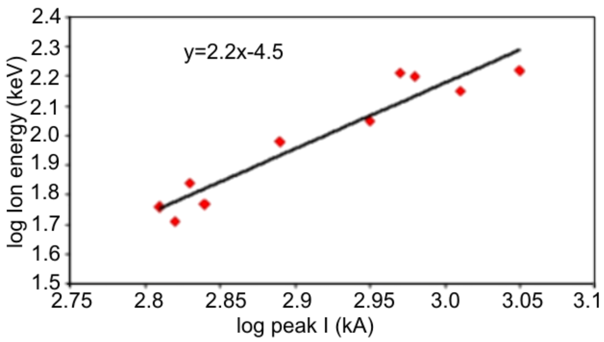

Fig. 4. Ion energy scales as I^2 (upper envelope).

given I) scaled approximately as I^2, faster than theoretically predicted linear scaling with I (see Fig. 4).

To determine if the neutrons actually came from the ions confined in the plasmoid or from an unconfined beam, we measured the anisotropy of the neutron production. In contrast to many other DPF devices, we found that there was no observable anisotropy between the axial and perpendicular directions. We measured neutrons with up to five bubble detectors in the plane perpendicular to the axis and at various azimuths, and with bubble detectors at 12°, 4° and 0° from the axis. We found no statistically significant anisotropy and could put a two-sigma upper limit of 1.25 on the anisotropy (ratio of axial to perpendicular neutron production) at 12°. Since we knew from the ion beam time-of-flight measurements that the ions were accelerated to the range of 0.25–0.5 MeV, we could calculate that neutrons produced by the interaction of an unfenced axial beam with the plasmoid should have an anisotropy of 2.6. From this, we calculate that 80% of the neutrons must be produced by ions that are confined in the plasmoid and are not moving primarily along the axis.

With other possibilities eliminated, we concluded that lower-than-predicted density in the plasmoid must be the main problem. Observation of the plasmoid in UV and visible light with a 0.2 ns-exposure ICCD camera confirmed this conclusion (Fig. 5). The plasmoids observed had radii of about 500 μm and lengths of 1500 μm, while the theoretically predicted plasmoids are considerably smaller – with radii of 40 μm. Density of the plasmoid is predicted to increase from 2.4×10^{21}/cc to

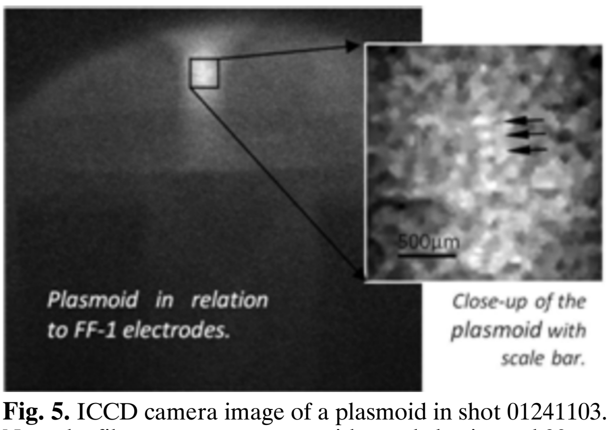

Fig. 5. ICCD camera image of a plasmoid in shot 01241103. Note the filamentary structure, with nearly horizontal 30-μm radius filaments (arrows) wrapped in a 180-μm coil. Exposure 200 ps in visible and near-UV. This is the highest-resolution image of a DPF plasmoid yet obtained [3].

5×10^{21}/cc with I increasing from 0.7 to 1 MA, but observations indicated that plasmoid density was decreasing from 10^{20}/cc to around 10^{19}/cc instead. Linear compression was 10 times less than predicted.

As reported earlier [2], we suspected that this lack of expected compression was linked with an early ion and electron beam, which were observed occurring *prior* to the pinch. This beam was first observed as a small upward spike in current right before the large drop in current at the time of the pinch. We observed this phenomenon in greater detail by comparing the timing of the ion and electron beam, as measured by the ion beam Rogowski coil and two photomultiplier tubes (PMT) observing radiation from the electron beam. This was combined with the timing of the heating of the plasmoid, as observed by an X-ray PMT collimated to view only the radiation from the plasmoid (Fig. 6). The early beam, occurring before the pinch compressed the plasma enough for heating and fusion to occur, drained energy from the magnetic field and thus reduced the pinch force available for compression.

In May, 2011, we observed the probable cause for this early beam. The inner edge of the cathode in FF-1, surrounding the insulator, has 100 tungsten pins which act as a field enhancer to assist in initial breakdown. We found that the pins had become uneven in height due to machine vibration, and only two pins which were higher than the others were initially carrying the current. This created an asymmetric sheath with one part leading the rest and creating the early beam during a premature pinch. We adjusted the pins to be even within 25 μm and fired again, finding that indeed the early beam had disappeared, confirming our hypothesis as to its origin.

Based on the resolution of this problem, we began a new series of shots at 0.9 MA $< I <$ 1.2 MA. We achieved pinches and fusion yields in these shots while using a very wide range of deuterium fill pressures, from 4 up to 75 T, which we believe is a record for any DPF. Yields of more than 5×10^{10} neutrons were achieved in a fill-gas pressure range of 18–40 T. This shows that DPFs can indeed function with fill-gas pressures over 30 T. We have not yet had time to perform more than a preliminary exploration of this wide range of conditions to see if yields much higher than 10^{11} can be obtained.

We observed a range of pinch-voltage spike heights (voltage obtained at the time of the pinch minus the smooth trend of voltage) from 1.5–30 kV. For spike voltage $V <$ 10 kV, there was a surprisingly tight correlation of neutron yield Y with V, with $Y \sim V^{2.74}$ and a standard deviation in Y around this curve of only 22% (Fig. 7). For $V >$ 10 kV, this correlation appears less steep with V, and there is more scatter, but this conclusion is tentative as our examination of this part of the correlation range is just beginning.

Conclusions

In firing FF-1 over a peak current range of 0.7–1.1 MA, we found that energy transfer into the plasmoid and thence into the beams was within a factor of two of theoretical predictions. In the best shots, average ion energy scaled rapidly as I^2 and reached above 100 keV. Low anisotropy indicated that the fusion reactions were

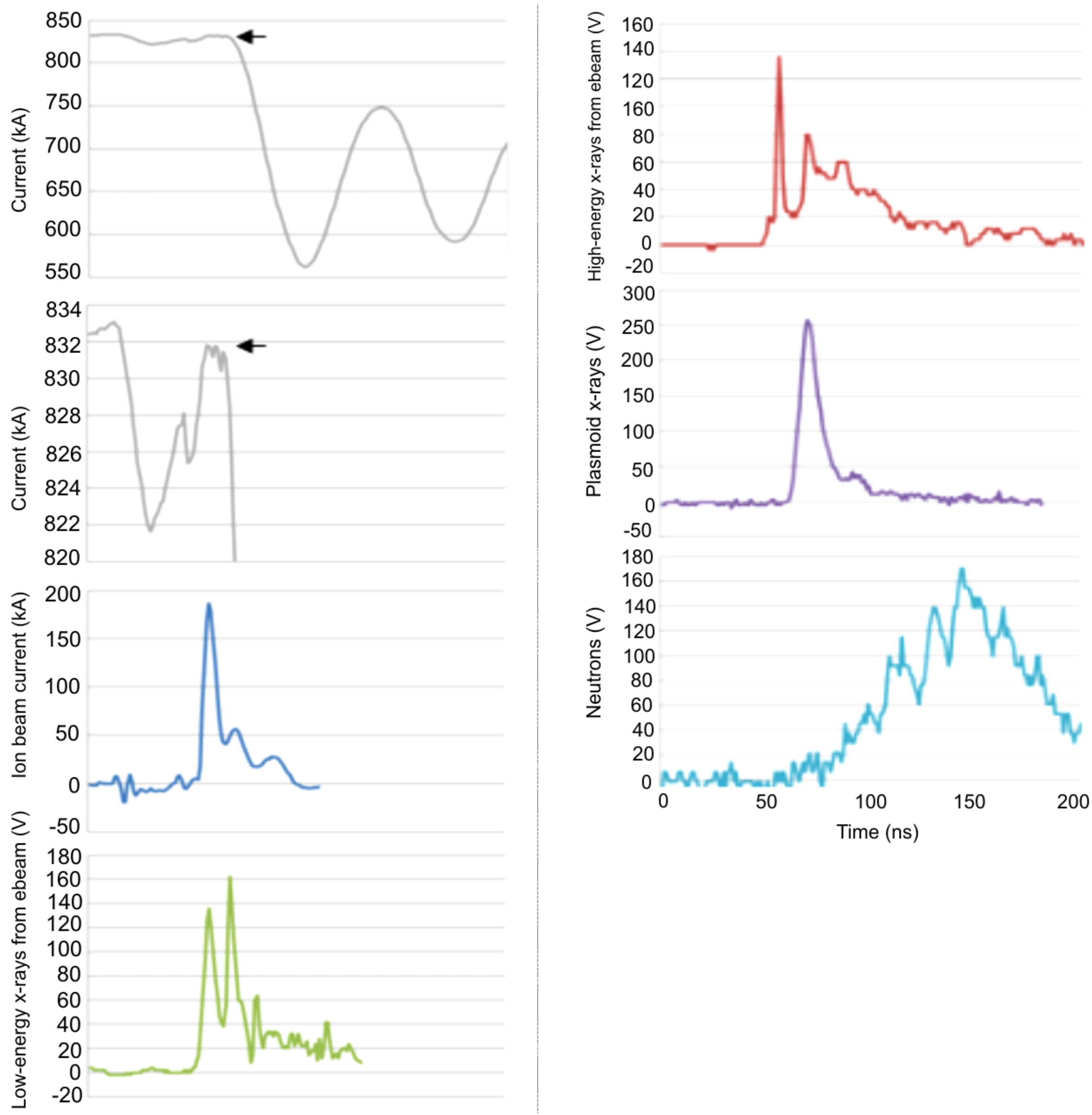

Fig. 6. The early beam (arrows in current overview and in close-up), first peak in beams, shot 05121108.

predominantly produced by ions trapped in the plasmoid. The probable cause of the plateau of neutron yield Y at 10^{11} neutrons was lower plasmoid density than predicted, due to an early beam that interfered with plasmoid compression. In turn, this early beam was caused by uneven

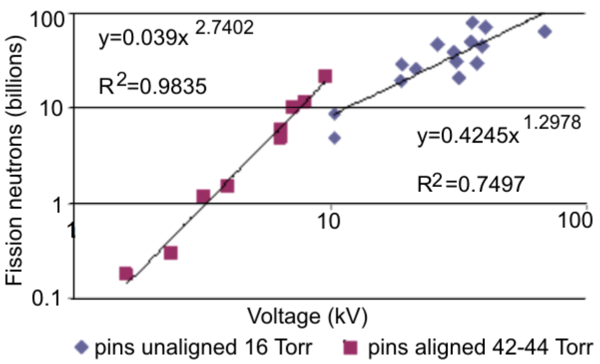

Fig. 7. Fusion yield vs. pinch height. Note reduced scatter at high pressure (squares).

tungsten pins at the base of the cathode plate, where the current sheath first forms. Correcting this unevenness eliminated the early beam. Subsequent firing showed a broad range of pressure up to 40 T where $Y > 5 \times 10^{10}$ neutrons was obtained. For smaller pinches with a pinch-voltage spike $V < 10$ kV, there was a tight correlation of neutron yield Y with voltage spike. We expect to be able to move well above the 10^{11} neutron yield level with thorough exploration of this wide pressure range.

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