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High technology research, development and consulting in plasma physics, X-ray sources, and Focus Fusion

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Measurements of Ion Energy/Temperature

Summary *– Analysis of shots we did in March gives more convincing evidence of high ion energies, certainly more than 40 keV (440 million degrees) and probably above 65 keV in the best shot (715 million degrees). These are very encouraging results, as they are as good as or better than those obtained in Texas at peak currents that were nearly twice as high. This note is more technical that our others have been, but this is necessary to make clear how we arrive at our conclusions.*

A well-established technique allows us to calculate the average energy of ions in the plasmoid by measuring the energies of the neutrons emitted in the fusion reactions. The neutrons have the energy of the fusion reaction, 2.45 MeV in the case of deuterium, in addition to the energy of the ions that collided to produce their action. Since the orientation of the velocities of the ions is random, they produce a spread in the energy and velocity of the neutrons. This in turn produces a spread in the arrival times at the two time-of-flight detectors.

If we make the simplifying assumption that the temperature or average energy of the ions is a constant during the pulse (we'll get back to this assumption later), then there are simple formulae for calculating both the length of the neutron pulse at the plasmoid and the average ion energy:

1) $t = ((F_1/t_1)^2-(F_2/t_2)^2)/(1/t_1^2-1/t_2^2))^{0.5}$
2) $T_i = (F_2^2- t^2)2E/t_2^2$

where t is the duration of the pulse at the plasmoid, F_1 and F_2 are the width of the pulses at half their maximum height at the Near and Far Time-of-Flight (NTF and FTF) detectors respectively, t_1 and t_2 are the amount of time for the neutrons to reach the NTF and FTF respectively, T_i is average ion energy, and E is the neutron energy.

These formulae predict that the ratio of the width (full width at half maximum, or FWHM) of the neutron pulses at the NTF and FTF detectors should be somewhere between 1 and 1.53 of the ratio of the distances of the two detectors from the source.

We examined 10 shots in detail which had both high FTF and NTF signals and no overlap between the earlier X-ray signals and the neutron signal. They are described in Table 1. Six of the shots had width ratio R within the predicted limits, including one whose R was very slightly above 1.53, but within measurement errors. Three shots had R>1.53, and one had R<1.0. Four shots exhibited unexpected behavior that needs an explanation.

Table 1

Shot	FWHM NTF ns	FWHM FTF ns	R
32404	40	84	2.10
32505	59	49	0.83
32507	56	84	1.50
33003	61	85	1.39
33004	38	44	1.15
33005	41	64	1.56
33006	61	92	1.52
33007	72	82	1.14
33009	45	101	2.24
33010	32	87	2.72

It is difficult to produce a distribution of neutron velocities that converges rather than diverging, or diverges considerably faster at some points than at others. By abandoning the assumption of constant temperature, and assuming the plasmoid is heating up during its existence, you can get some of the faster neutrons produced later catching up with slower ones produced earlier. But some of the hot neutrons produced later will have lower energies, because the ions are traveling in the opposite direction from the random ones that the neutrons are emitted in. Those neutrons will both be slow and late and spread out more. Only in the case where there is a non-random distribution of velocities will a pulse tend to converge as it travels, rather than spread out.

A possible confounding effect would be a small number of scattered neutrons which might spread out the NTF and FTF pulses unequally. This is unlikely, since scattered neutrons generally have a very broad direction of energy, but it is still possible. To eliminate such scattered neutrons from the calculation, we could only consider the neutrons that have more energy than 2.45 MeV, the fusion reaction energy, and therefore arrive on the early side of the observed pulse. To do this, we could measure the half-width half maximum, or the time from first half-maximum to the peak, instead of the full-width half maximum.

However, the difficulty with this approach is that the exact peak of the pulse is somewhat random, depending on how the neutrons observed are bunched together. We can avoid this difficulty by calculating a synthetic peak (or “syn FW” for synthetic, full width) based on the measured shape of the pulse. We do this by taking the center point of the quarter-maximum values, the center point of the half-maximum value, and then linearly projecting from these two center points to the presumed peak. Since this method assumes a triangular shape to the pulse, while the pulses are in fact more rounded, we need to apply a correction factor so that the mean of the synthetic peaks lies at the same instant as the mean of the actual peaks.

As seen in Table 2, this method produces somewhat different results, but there are still several shots with R ratios outside the theoretical range.

Table 2

Shot	syn FW NTF	syn FW FTF	R
32404	37.4	61.4	1.64
32505	16.4	22.4	1.37
32507	53.4	89.4	1.67
33003	50.4	66.4	1.32
33004	87.4	21.4	0.24
33005	66.4	5.4	0.08
33006	62.4	117.4	1.88
33007	69.4	95.4	1.37
33009	70.4	110.4	1.57
33010	9.4	32.4	3.45

While formulae 1 and 2 can only be used for shots with R between 1 and 1.53, we can look at the shots with R>1.53 and get a minimum estimate of it, by assuming that the pulse duration t at the plasmoid is no more than the pulse duration at the NTF. Since the shorter the original pulse is assumed to be, the more it must have spread out due to the energy range, this method gives a minimum estimate of T_i (minT).

If we look in Table 3 at the four methods of estimating it, we see that in the case of three shots, 032507, 033006 and 033009, there is reasonably good agreement between two separate methods of estimation. In all three cases, T_i exceeds 40 keV, and in the best shot it exceeds 65 keV. This is strong additional evidence that FF-1 is achieving ion energies comparable to those in the Texas A&M experiments in 2001, but at currents of only 700 kA, as compared with the 1.2 MA used in Texas. This is encouraging, and we will no doubt have much stronger evidence of high ion energies as we get more shots at higher currents. For comparison, ion energies of around 100 keV will be enough to ignite pB11 fuel, given adequate density.

Table 3 Ion energies in keV

Shot	minT	minT syn	T	syn T
32404	44	19		
32505				3
32507		42	57	
33003			50	27
33004			7	
33005	19			
33006			68	
33007			22	62
33009	67	59		
33010	53	7		