MEASUREMENT OF MTF TARGET PLASMA TEMPERATURE USING FILTERED PHOTODIODES

J.M. Taccetti, F.J. Wysocki, G. Idzorek, H. Oona, R.C. Kirkpatrick, I.R. Lindemuth, P.T. Sheehey
Los Alamos National Laboratory, Los Alamos, New Mexico

Abstract

Magnetized Target Fusion (MTF) is an approach to fusion where a preheated and magnetized plasma is adiabatically compressed to fusion conditions. Successful MTF requires a suitable initial target plasma with a magnetic field of al least 5 T in a closed-field-line topology, a density of roughly 10^{18} cm^{-3}, a temperature of at least 50 eV but preferably closer to 300 eV, and must be free of impurities which would raise radiation losses. The goal of these experiments is to demonstrate plasma conditions meeting the requirements for an MTF initial target plasma. The plasma is produced by driving a z-directed current of 1-2 MA through either a static gas-fill or a 38 μm diameter polyethylene fiber. The data obtained from an array of filtered photodiodes is used to estimate the plasma temperature. The filter material and thickness for each diode is chosen such that the lowest absorption edge for each is at a successively higher energy, covering the range from a few eV to 5 keV. The analysis assumes a fully stripped optically thin plasma which radiates as either a blackbody, a bremsstrahlung emitter, or a group of emission lines (gaussian-like).

I. MAGNETIZED TARGET FUSION

Magnetized target fusion (MTF) is an alternative approach to fusion which combines elements from both magnetic and inertial confinement fusion (ICF). As in ICF, the plasma is compressed to fusion temperatures, but it is done adiabatically (velocities are in the cm/μs range). This is made possible by suppressing thermal conduction of the electrons to the confining walls via an embedded magnetic field of at least 5 T with closed-field-line topology. The initial plasma should have a density of roughly 10^{18} cm^{-3} and a temperature around 300 eV. Impurities must be avoided, as they would increase radiation losses and reduce the lifetime of the plasma.

The target plasma under study in our experiments is a diffuse z-pinch which is allowed to expand and fill a plasma containment region of 2 cm height and 2 cm radius. The magnetic field used to insulate the plasma in this case is that of the z-directed current itself. The two types of diffuse z-pinch examined were a solid fiber and a static gas-fill. The fiber(s) used were either one or more 38 μm diameter polyethylene (CH_2 chain) fibers, and the static gas-fill was a low-pressure (~1 Torr) H_2 fill. The viability of the resulting plasma for use as an MTF target was studied. The compression of the plasma to fusion conditions is not considered in this study.

Previous simulations have shown [1] a wall-confined plasma of similar dimensions lasting long enough for adiabatic compression to take place (although the plasma in this case was initiated with a cryogenic deuterium fiber and did not include the power-flow channels of the plasma formation region, introduced below).

The results and analysis of signals obtained using an array of seven filtered silicon photodiodes is presented. These give an idea of the plasma temperature by assuming a certain spectrum for the emission and fitting this to the obtained signals. The spectra examined are blackbody, bremsstrahlung, and 'gaussian-like', where the latter simulates a group of emission lines.

II. DESCRIPTION OF THE EXPERIMENT

The experiments were driven by the Colt capacitor bank at LANL, a two-stage Marx module of 24 6-μF capacitors with a maximum charge voltage of 60 kV Marxed to 120 kV, and a system inductance of 60-65 nH. Colt is capable of dumping a maximum of 0.25 MJ, in 2.5 μs current rise-time discharges, with currents in the 1-2 MA range.

As stated above, two different types of diffuse z-pinch plasmas studied included fiber and gas-fill shots. The behavior of each of these is detailed and compared. While each behaves differently during the pinch phase, their late-time behavior is qualitatively very similar.

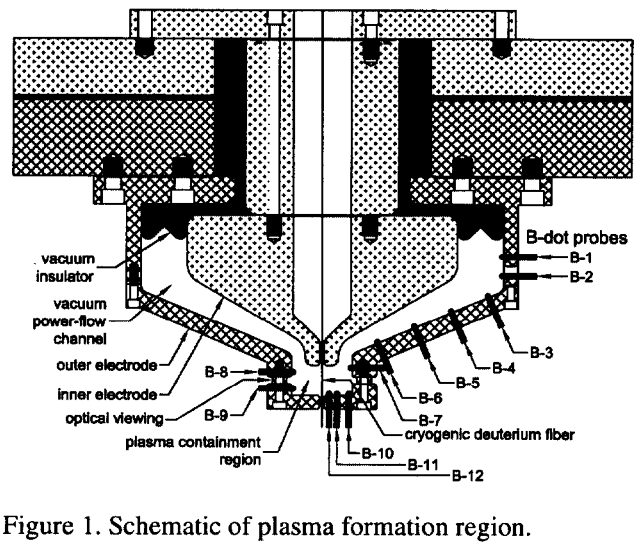

Figure 1. Schematic of plasma formation region.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1999	**N/A**	**-**

4. TITLE AND SUBTITLE	
Measurement Of Mtf Target Plasma Temperature Using Filtered Photodiodes	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Los Alamos National Laboratory, Los Alamos, New Mexico**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

Magnetized Target Fusion (MTF) is an approach to fusion where a preheated and magnetized plasma is adiabatically compressed to fusion conditions. Successful MTF requires a suitable initial target plasma with a magnetic field of al least 5 T in a closed-field-line topology, a density of roughly lOI* cme3, a temperature of at least 50 eV but preferably closer to 300 eV, and must be free of impurities which would raise radiation losses. The goal of these experiments is to demonstrate plasma conditions meeting the requirements for an MTF initial target plasma. The plasma is produced by driving a zdirected current of l-2 MA through either a static gas-fill or a 38 l.trn diameter polyethylene fiber. The data obtained from an array of filtered photodiodes is used to estimate the plasma temperature. The filter material and thickness for each diode is chosen such that the lowest absorption edge for each is at a successively higher energy, covering the range from a few eV to 5 keV. The analysis assumes a fully stripped optically thin plasma which radiates as either a blackbody, a bremsstrahlung emitter, or a group of emission lines (gaussian-like).

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

A schematic of the plasma formation region (electrodes and insulators) with the cylindrical containment region at the bottom is shown in Fig. 1 (the fiber shown is not present during gas-fill shots). A vacuum exists between the two electrodes and in the containment region during the fiber shots. Voltage is applied and a breakdown occurs along the fiber in the containment region, which in turn becomes a plasma and expands to fills the volume. During gas-fill shots, a low pressure gas-fill exists between the electrodes. Initial breakdown occurs at the top end of the power-flow channel (near the insulator) and is forced down this channel, finally increasing the pressure in the containment region and forming a vertical diffuse pinch.

The polyethylene fibers were selected as a replacement for the desired solid deuterium (or hydrogen) fiber. Four distinct phases in time can be distinguished in all fiber shots. In the first phase, an axisymmetric 'sausage' instability develops, and 2-8 very energetic (visible in high energy channels) short-lived pulses are measured. This then evolves into an asymmetric 'kink'-like instability. This is followed by an axisymmetric re-pinching of the plasma column (1-2 longer-lived pulses), including a measurable increase in inductance. The final phase is characterized by uniform visible light emission and quiescent B-dot signals.

In contrast to the fiber plasmas, the gas-fill shows no high-energy short-lived x-ray pulses. Instead, it exhibits a single wide x-ray pulse, often 'stepped'. Similar to the fiber shots, though, it does end with a uniform visible light emission.

III. FILTERED SILICON PHOTODIODES

Among other diagnostics [2], a set of filtered silicon photodiodes was fielded to obtain a measure of the emitted radiation. The seven photodiodes are assembled together in a compact array of about 1 cm in diameter and located 53 cm from the symmetry axis of the plasma region. There is no other obstacle between the diodes and the plasma but the filters; a fast-closing valve protects the filters from the shock wave caused by the shot.

The photodiodes themselves are extremely sensitive (~2 A/W in the visible and hard x-ray region) and have a response which includes the 1 eV to 10 keV range (the actual response varies with wavelength, and must be taken into account in the analysis). The signals obtained with these photodiodes are therefore an integral over the entire range of wavelengths. Use of particular filters allows one to select a specific band of wavelengths out of the spectrum. Combinations of these filtered signals can therefore be used to bracket the emission wavelengths.

The mass per unit surface and material of the six filters used (one of the channels was left open) are: 66×10^3 $\mu g/cm^2$ polystyrene (visible only – in our range of interest), 1.028×10^3 $\mu g/cm^2$ aluminum (high energy), 322 $\mu g/cm^2$ Parylene-n, 323 $\mu g/cm^2$ Kimfol, 452 $\mu g/cm^2$ nickel, and 1.143×10^3 $\mu g/cm^2$ titanium. (Note that thickness variation as well as material selection can be used to screen out different ranges.) The Parylene-n filter actually lasted for only one shot, and was not replaced because the material becomes more opaque and brittle with repeated exposure to UV radiation.

V. RESULTS AND ANALYSIS

The signal for each diode can be written in analytic form as

$$S^{1\ldots n}_{diode} = \int_{plasma} \int_{diode\ area} \int_{E=1eV}^{10keV} R_{diode}(E) T_{filter}(E) \times \times P_{spectrum}(E,\vec{x}) dE d\Omega(A_{diode},\vec{x}) dV(\vec{x}) \qquad (1)$$

where S_{diode} is the signal of the n^{th} diode (indicated by superscript). As shown in Eq. 1, these signals are composed of the plasma spectral shape $P_{spectrum}(E,\boldsymbol{x})$, a function of both the energy E and position vector $\boldsymbol{x}$, the filter transmission coefficient $T_{filter}(E)$, and the photodiode response $R_{diode}(E)$, integrated over the energy range, diode surface area, and plasma volume.

The plasma is assumed to be optically thin and uniform inside the containment region. (The plasma is viewed with access ports at the axial midplane of the containment region.) The radiation over the area of the diode array is also assumed uniform. The absorption due to H_2 present in the chamber between the plasma containment region and the diodes is taken in to account for static gas-fill shots.

Of all the factors in Eq. 1, the only unknown one is the spectral shape $P_{spectrum}(E,x)$. The analysis proceeds then by selecting a spectral shape for the plasma, integrating with all the appropriate factors to obtain a simulated diode signal, and comparing this to the actual signal. The difference between the two is minimized using a downhill simplex method algorithm (the principal subroutine of this algorithm is amoeba [3]). At each point in time, a maximum of seven data points are available, with this number being even less in some cases where there were no signals in the higher energy filters.

The selection of spectral shapes is therefore driven by the fact that one can only have as many unknown parameters as data points. For this reason only two or three parameter functions were used. These were blackbody, bremsstrahlung, and gaussian-like spectra. The first two are two-parameter functions, with an amplitude and a characteristic T_e, while the latter is a three-parameter one. The gaussian spectral shape, used to approximate a group of emission lines due to impurities in the plasma, consists of a gaussian curve, the three parameters representing the magnitude, the energy of the peak, and the width of the gaussian at half-height.

The characteristic temperature (in eV) obtained for one

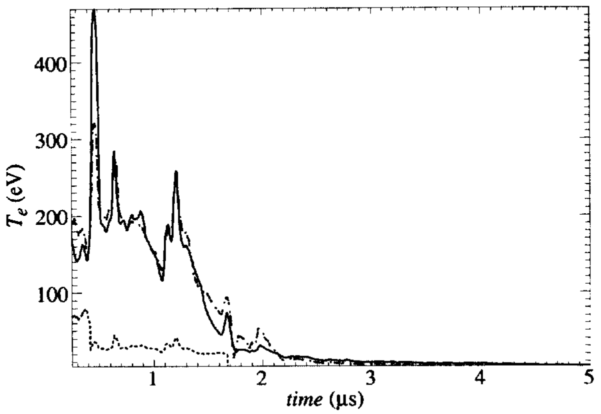

Figure 2. Electron temperature for the different spectra, for the fiber shot (solid = gaussian, dot-dash = bremsstrahlung, dotted = blackbody).

of the analyzed polyethylene fiber shots, for all three spectral shapes, is shown in Fig. 2. The temperature of the gaussian spectrum is defined as the sum of the center temperature and the width of the gaussian. The blackbody spectrum is included merely for completeness; the plasma is not expected to emit as a blackbody. The relative goodness of the fits (χ) were 714, 1300, 1400 for the gaussian, bremsstrahlung, and blackbody, respectively. The fact that the gaussian fits the data significantly better is an indication that there are many impurities present. The temperature does reach an average of 150-200 eV, but drops off too rapidly to be useful for MTF.

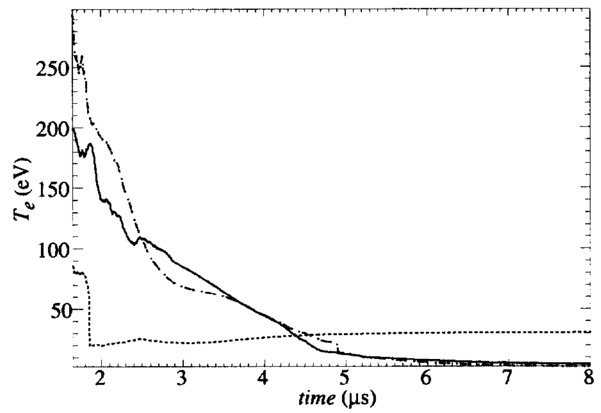

Figure 3. Electron temperature for the different spectra, for the gas-fill shot (solid = gaussian, dot-dash = bremsstrahlung, dotted = blackbody).

Similar data is shown for a gas-fill shot in Fig. 3. The χ in this case were 40, 636, 2100 for the gaussian, bremsstrahlung, and blackbody, respectively. Again, the gaussian spectrum fits much better than the other two. The temperature again reaches an acceptable value but does not remain there for long enough (note that in the gas-fill case the emission starts at around 1.6 μs due to the time it takes for the gas to travel down the power-flow channel).

The evolution of the gaussian spectrum, the best fitting spectrum, for the fiber case is shown in Fig. 4. The curves

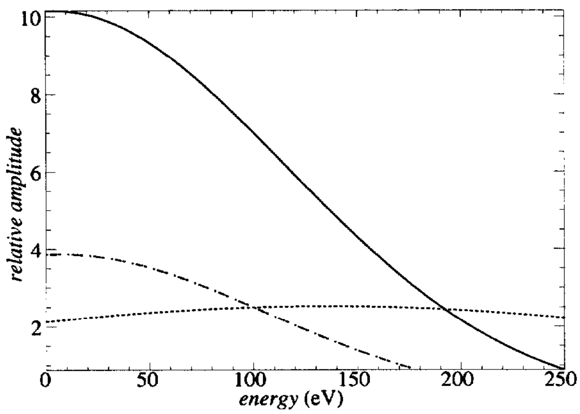

Figure 4. Spectral evolution of the gaussian spectrum for the fiber case (dotted = 0.45 μs, dash-dot = 1.1 μs, solid = 1.3 μs).

show the spectrum at three times: 0.45 μs (dotted), 1.1 μs (dash-dot), and 1.3 μs (solid). The spectrum at early time is peaked at an energy away from zero, indicating that the plasma emits more as a group of emission lines than as a bremsstrahlulng emitter (which would peak at zero).

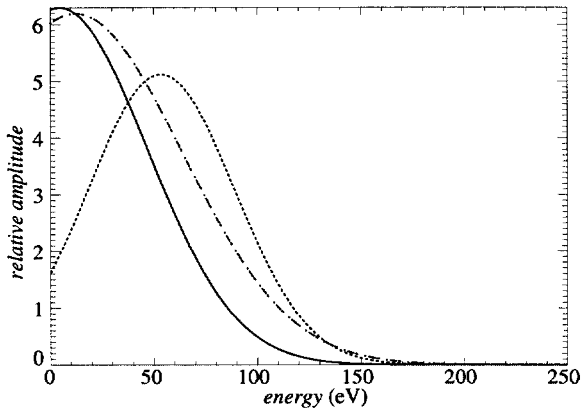

Figure 5. Spectral evolution of the gaussian spectrum for the gas-fill case (dotted = 2.4 μs, dash-dot = 3.0 μs, solid = 3.5 μs).

A similar plot for the gas-fill case is shown in Fig. 5. The curves show the gaussian spectrum at 2.4 μs (dotted), 3.0 μs (dash-dot), and 3.5 μs (solid). Again, the spectrum is peaked at a temperature greater than zero at early time, indicating the presence of impurities.

The total emitted energy for both the fiber (solid) and gas-fill (dotted) cases is shown in Fig. 6. These are both obtained from their gaussian-spectrum fits. Calculations assuming a 150 eV plasma indicate that the total emitted energy found for the gas-fill, ~600 kJ, corresponds to about 30 % of the total energy in the plasma [4].

IV. CONCLUSIONS

It seems that a large part of the power input is lost to radiation. More conclusive diagnostics are necessary, though, to accurately determine what these impurities are.

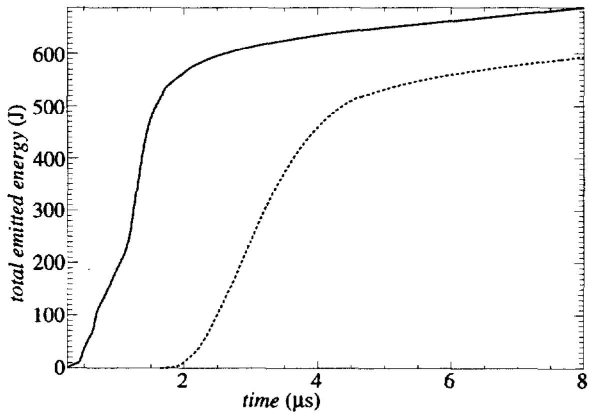

Figure 6. Total emitted energy (solid = fiber, dotted = gas-fill; both fit by gaussian spectrum).

A second set of filtered photodiodes is ready to be fielded simultaneously with the first. This will provide us with additional data points and perhaps allow for more complex spectral shapes (for example: a gaussian and a bremsstrahlung combination). A gold transmission grating spectrograph is also planned to give a more detailed picture of the spectrum of the plasma.

V. REFERENCES

[1] P. Sheehey *et al.*, "Two-dimensional direct simulation of deuterium-fiber-initiated Z pinches with detailed comparison to experiment," *Phys. Fluids B.*, 4(11), pp. 3698-3706, Nov. 1992.

[2] F. J. Wysocki *et al.*, "Progress with developing a target for magnetized target fusion," in *Digest of Technical Papers for the 11th Int. IEEE Pulsed Power Conf.*, Baltimore, USA, 1997, p. 1393.

[3] W.H. Press *et al.*, *Numerical Recipes in Fortran, Second Edition.* New York, NY: Cambridge University Press, 1992.

[4] F. J. Wysocki *et al.*, "Analysis of data from z-pinch MTF target plasma experiments," presented at 12th Int. Pulsed Power Conf., Monterey, USA, 1999.