SAND96-1290C
CONF-960543--1

Spectroscopic Diagnosis of Foam Z-Pinch Plasmas on SATURN

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ABSTRACT

Solid and annular silicon aerogel and agar foams were shot on the accelerator SATURN to study plasma initiation, acceleration, and stagnation. SATURN delivers 7 MA with a 50 nsec rise time to these foam loads. We fielded several spectroscopic diagnostics to measure plasma parameters throughout the z-pinch discharge. A spatially resolved single frame time-gated EUV spectrometer measured the extent of plasma ablation off the surface of the foam. A time integrated crystal spectrometer showed that characteristic K shell radiation of silicon in the aerogel and of S and Na impurities in the agar were all attenuated when the foam loads were coated with a conductive layer of gold. The time-resolved pinhole camera showed that in general the quality of the pinch implosions was poor but improved with increasing efforts to improve current continuity such as prepulse and conductive coatings.

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

I. Introduction

Foam z-pinch loads could offer many advantages to the gas puffs and small-wire-number wire arrays generally shot in the past on TW scale drivers. Until recently the radiated power of a z-pinch never exceeded the electrical power of the generator.[1] The recent power gain was accomplished by improving azimuthal symmetry by using a large number of wires with wire to wire spacing much less than one mm.[2] A further improvement in azimuthal symmetry is possible by using an low density annular or cylindrical foam. In general it is difficult to produce foams with low enough density (< 3 mgm/cc) and mass (< 1 mgm) to couple efficiently to the SATURN generator, but improvements in foam technology and larger generators in the future can make foam z-pinch loads more attractive. Also foam z-pinch loads that are coated or surrounded by optically thick high z material are possible configurations for driving fusion capsules. With this in mind we have shot a variety of foam loads on SATURN with the purpose of studying current initiation, plasma acceleration, and pinch stagnation.

II. Experimental Arrangement

In these experiments the z-pinch load was an annular or cylindrical foam composed of either agar or aerogel. The composition of agar is $C_7H_{13}NO_5$ with trace impurities of S and Na. The composition of the aerogel is SiO_2. The loads all were 1 cm long and had an outer diameter of 1 cm. Annular loads had an inner diameter of 0.9 cm. The shot matrix including type of load and initiation techniques is shown in Table 1. The primary goal was to study to effects of initiation techniques including flash boards, conductive coatings, and prepulse on the initiation and subsequent evolution of the pinch plasma. To carry out this study a number of diagnostics were used. A four channel x-ray diode array measured soft x-ray emission in a number of spectral bands. A bolometer measured total radiated yield . A time-integrated radially resolved crystal spectrometer measured emissions above 1 keV. A time-resolved and radially resolved EUV spectrometer was used to measure surface emission from the foam loads. Time-resolved pinhole cameras were used to measure the quality of the stagnated pinch .

III. Results from X-ray Diodes and Bolometers

On shots without prepulse the x-ray diodes showed multiple spikes and often no signal at all at the predicted implosion time. This is illustrated in figure 1 which shows the x-ray diode trace for an cylindrical aerogel load shot with no effort made to assist the initiation. The trace shows two spikes occurring at 40 and 60 nsec into the current pulse. The predicted implosion time for this 3.9 mgm/cm load is 80 nsec and there is no emission of x-rays at this time. This load did not implode properly because of poor initiation.

The foam shot with the largest radiated power was obtained by using all of prepulse, conductive coating, and flash boards. This well-initiated shot 2258 is compared with the uninitiated shot 2249 in figure 2. The well-initiated shot radiated over 6 times as much power in the keV band as the uninitiated shot. A more complete discussion of the results of the SATURN foam initiation runare given in reference 3. [3]

IV. Spectroscopic Results

The data from the time-integrated crystal spectrometer showed that K line radiation of materials Si, S, and Na were greatly attenuated on shots with high Z conductive coatings. Figure 3 compares the KAP crystal spectra for gold-coated and uncoated aerogel loads. The gold coated load performed much better giving 200 kJ total yield and over 6 kJ in the keV band as measured by the bolometer and beryllium-filtered x-ray diode respectively. The uncoated foam gave only 50 kJ total and 2 kJ in the keV band. Even with higher total yield the gold-coated loads showed lower yields in silicon K radiation by a factor of 7. This is thought to be due to the opacity of the gold absorbing the silicon K line radiation.

A plot the optical depth of gold as calculated by U. Wisconsin UTA opacity code EOSOPA is shown in figure 4. [4] A temperature of 200 eV and a rho*r of 0.0015 gm/sq cm are estimates of the gold conditions at the time of silicon K emission. There may be gradients in the temperature and density of the gold which would alter this opacity plot. The optical depth is predicted to be 1 at the energy of the silicon he-alpha and lyman-alpha lines. This may be enough to explain the observed attenuation of the silicon K lines.

We recorded sulfur and sodium K shell line emission on shots with agar loads. These are due to sulfur and sodium as trace impurities at percentages by mass of approximately 1 and 0.5 respectively. [5] Figure 5 shows the crystal spectrum with these lines recorded on an agar shot with no conductive coating. An analysis by the program RATION [6] shows that the sulfur emits from regions of approximately 1 keV temperature, while the sodium average temperature is 400 eV. Similar results are obtained from the U. Wisconsin line ratio code.[7] This is not surprising since the population of the 2p level of helium-like sodium experiences a maximum at only 100 eV where the excited K shell levels of sulfur are essentially unpopulated.

The lines of sulfur and sodium are also attenuated when agar is shot with a high Z conductive coating. This is shown in figure 6 for shots 2252 and 2255. The only difference in the loads for these two shots was that shot 2255 had 2000 Å of palladium/gold as a coating over the agar. The sulfur K lines are completely eliminated by the coating. This is consistent with the gold opacity curve of figure 4 which shows increased opacity at the sulfur K shell lines.

The EUV spectral region also reveals differences between coated and uncoated loads. In figure 7 one sees lines of Li-like oxygen atop weak continuum from an uncoated agar load. For a coated aerogel load the oxygen lines are nearly overwhelmed by increased continuum. A time-gated radial profile of the EUV emission for the gold-coated aerogel load is shown in figure 8. The profile is nearly gaussian about the original 10 mm diameter of the load, indicating an optically thick emitter in this spectral band. The emissions extend out to large diameter and backlight colder current return metal. This indicated the plasma has ablated off of the original load and expanded to larger diameter at the time of the gating pulse. On this shot the time gate was 30 nsec into the current rise, well before any inward motion of the pinch load.

IV. Summary

Foams that were shot with prepulse and conductive coatings performed better as indicated by reduced nonthermal spikes in the x-ray diodes and increased radiated power. Many poorly initiated foams did not even radiate at the predicted implosion time. Time integrated crystal spectra showed that high Z coating on the foam absorbed the K-shell line radiation of silicon and sulfur. This is consistent with calculations of the opacity of the conductive coating. EUV emissions were stronger with high-Z coatings on the foam and extended to diameters greater than the initial foam diameter.

References

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3. Derzon, M. S. , these (Monterrey) proceedings, 1996

4. Wang, P., MacFarlane, J. J., and Orzechowdki, T. J., these (Monterrey) proceedings, 1996

5. McNamara, F., private Sandia memorandum

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7. MacFarlane, J. J., these (Monterrey) proceedings, 1996

Figure Captions

1. Two x-ray diode spikes indicative of flashing occur 40 and 60 nsec into the current trace for a cylindrical aerogel load without initiation assistance. At the predicted implosion time of 80 nsec there is no signal because of poor initiation.

2. Comparison of keV signals for a well-initiated load (flash boards, prepulse, and conductive coating) and an uninitiated load.

3. Conductive coating of gold on aerogel traps silicon K radiation.

4. Gold opacity, calculated by U. Wisconsin UTA opacity code EOSOPA, may be strong enough to absorb silicon K radiation.

5. Agar has trace impurities of sulfur and sodium which emit K shell line radiation.

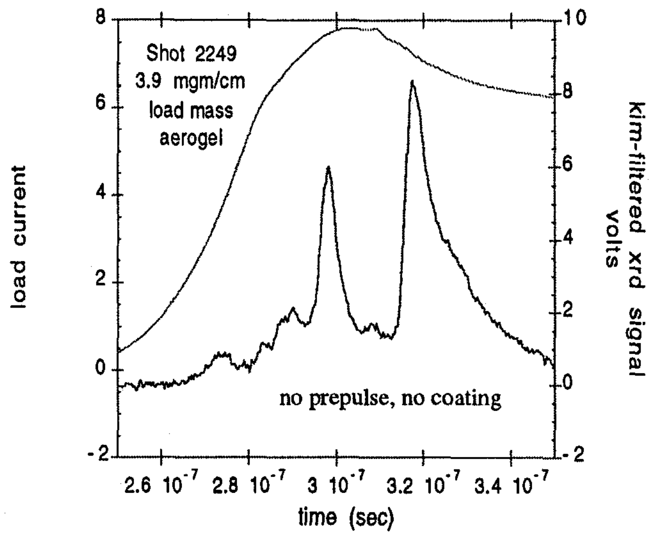
6. Sulfur K shell radiation is absorbed by the palladium /gold coating.

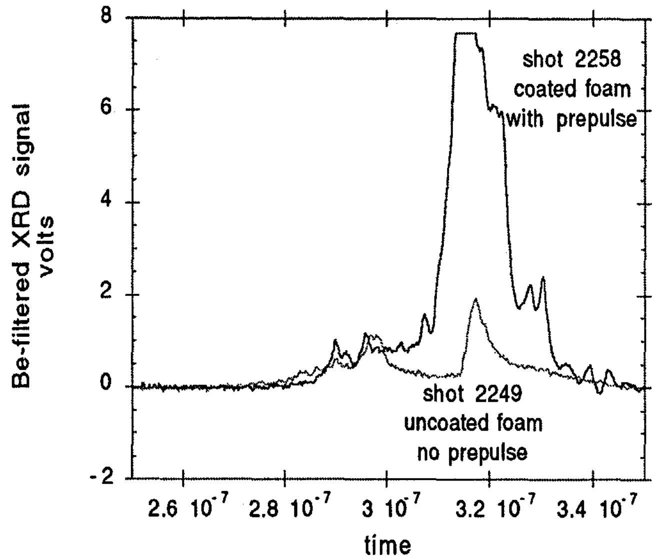
7. Gold-coated aerogel emits much more continuum than uncoated agar in the EUV region.

8. The radial profile of EUV emissions for a gold-coated aerogel target is nearly gaussian, indicating an optically thick shell.

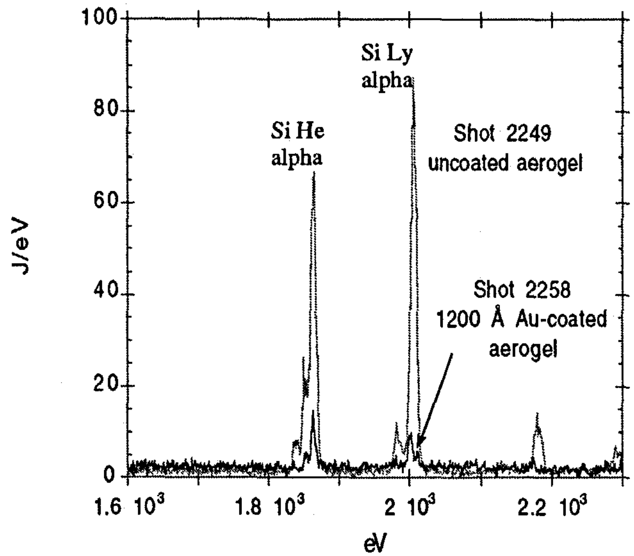
Table 1. Shot Matrix for Foam Initiation Run on SATURN

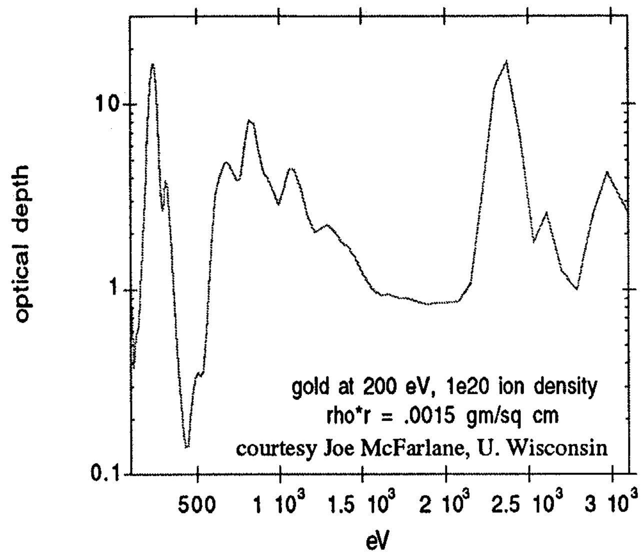
shot #	foam den mgm/cc	foam type	annular/ cylindrical	linear mass mgm/cm with coat	flash bds	prepulse	coating
2249	5	aerogel	cyl	3.9	no	no	no
2250	5	aerogel	cyl	3.9	yes	no	no
2251	10.8	agar	annul	1.6	yes	no	Au/Pd, 100 Å
2252	10.8	agar	annul	1.6	y	no	none
2254	10	agar	cyl	7.8	y	no	Au/Pd 1200 Å
2255	10	agar	annul	2.5	y	no	Au/Pd 2000 Å
2256	7	aerogel	cyl	6.5	y	yes	Au 2000 Å
2257	7	aerogel	cyl	5.5	y	yes	none
2258	3	aerogel	cyl	3	y	yes	Au 1200 Å

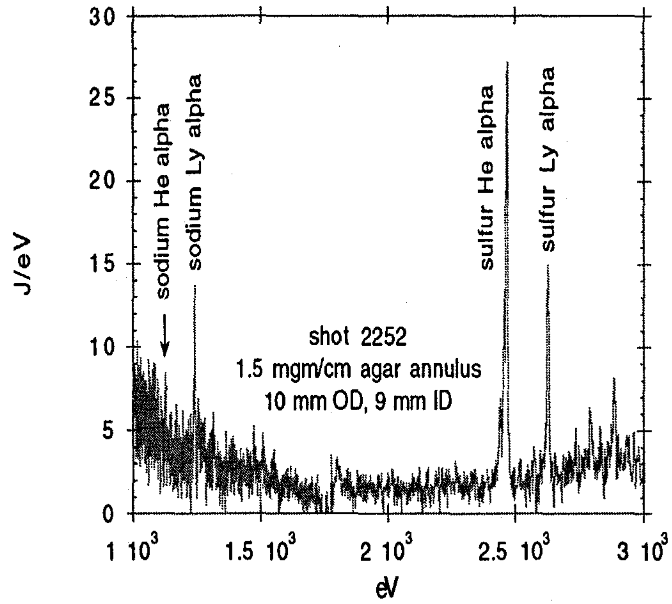

Shot 2249
3.9 mgm/cm
load mass
aerogel
no prepulse, no coating
load current
kim-filtered xrd signal
volts
time (sec)
2.6 10-7
2.8 10-7
3 10-7
3.2 10-7
3.4 10-7

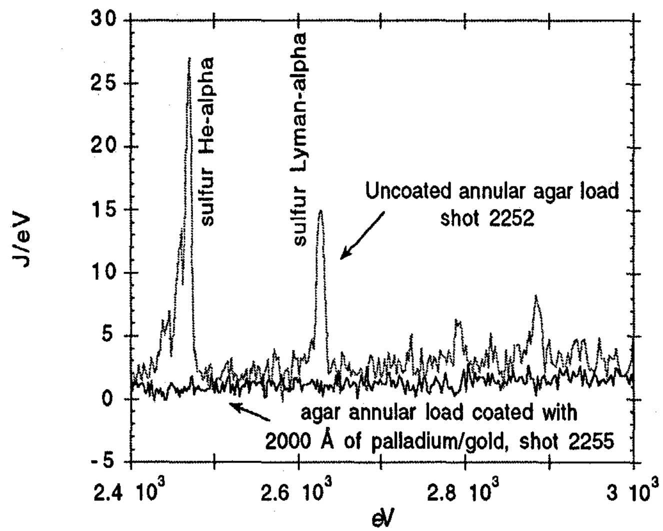


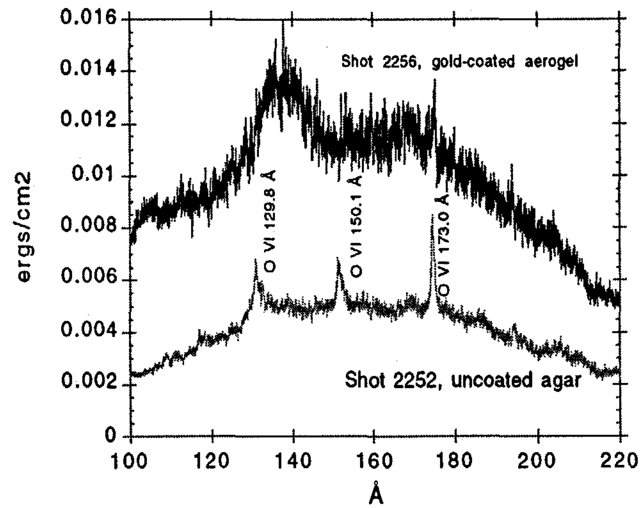
Be-filtered XRD signal
volts
8
6
4
2
0
-2
shot 2258
coated foam
with prepulse
shot 2249
uncoated foam
no prepulse
2.6 10-7
2.8 10-7
3 10-7
3.2 10-7
3.4 10-7
time

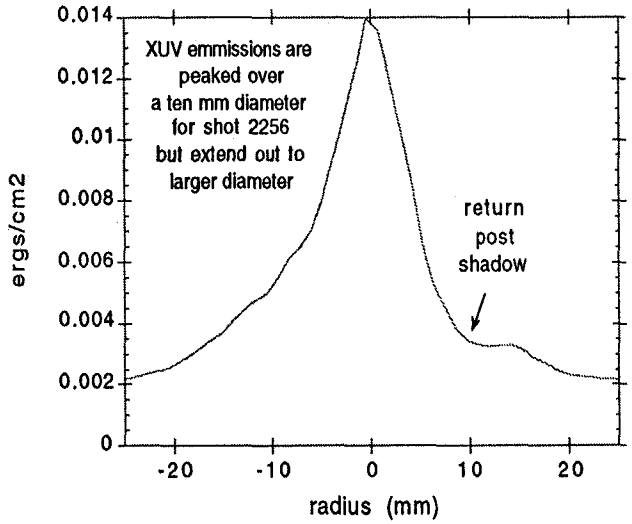

J/eV
100
80
60
40
20
0
1.6 10³
1.8 10³
2 10³
2.2 10³
eV
Si He
alpha
Si Ly
alpha
Shot 2249
uncoated aerogel
Shot 2258
1200 Å Au-coated
aerogel


gold at 200 eV, 1e20 ion density
rho*r = .0015 gm/sq cm
courtesy Joe McFarlane, U. Wisconsin
optical depth
10
1
0.1
500
1 10^3
1.5 10^3
2 10^3
2.5 10^3
3 10^3
eV


J/eV
30
25
20
15
10
5
0
1 10^3
1.5 10^3
2 10^3
2.5 10^3
3 10^3
eV
sodium He alpha
sodium Ly alpha
sulfur He alpha
sulfur Ly alpha
shot 2252
1.5 mgm/cm agar annulus
10 mm OD, 9 mm ID


J/eV
30
25
20
15
10
5
0
-5
2.4 10^3
2.6 10^3
2.8 10^3
3 10^3
eV
sulfur He-alpha
sulfur Lyman-alpha
Uncoated annular agar load
shot 2252
agar annular load coated with
2000 Å of palladium/gold, shot 2255


Shot 2256, gold-coated aerogel
Shot 2252, uncoated agar
O VI 129.8 Å
O VI 150.1 Å
O VI 173.0 Å
ergs/cm2
Å
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
100
120
140
160
180
200
220


XUV emmissions are
peaked over
a ten mm diameter
for shot 2256
but extend out to
larger diameter
return
post
shadow
ergs/cm2
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-20
-10
0
10
20
radius (mm)