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INVERSE FOR THE PEGASUS Z-PINCH

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SUBMITTED TO Third International Conference on Dense Z-Pinches
19-23 April 1993
Imperial College, London

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SOURCE TO DETECTOR SPECTRUM TRANSFORMATION AND ITS INVERSE FOR THE PEGASUS Z-PINCH

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ABSTRACT

We have developed a ray-tracing code which enables us to calculate the spectrum from a 2-D source simulation and compare directly with experimental data. This code also allows us to study the various spectral components which can potentially be used to determine the source from measured data.

INTRODUCTION

Pegasus, the Los Alamos pulsed power Z-pinch facility, generates x-rays by imploding a thin cylindrical foil. Peterson has modeled the implosion dynamics with a 2-D, 3-temperature radiation magnetohydrodynamic (RMHD) code. These Eulerian calculations show good agreement with various experimental measurements, as reported in a separate paper at this conference.¹ Recently we have developed a ray-tracing code which calculates side-on spectra from 2-D Eulerian configurations at specified times using temperature and density dependent, multi-group opacities. Calculated spectra agree reasonably well with measured spectrometer data (Pegasus I, shot 41 is emphasized in this paper). We also are developing schemes, coupling the ray-tracing code with a parameter optimization technique, to determine the temperature and density distribution which gives the best fit to measured spectral data.

PEGASUS EXPERIMENT

The Pegasus foils are 2.0 cm in length and 5.0 cm in radius and are centered in a 56 cm radius vacuum chamber. The x-ray diagnostics are at the end of 1 to 3 meter long line-of-sight (LOS) pipes mounted normal to the vacuum chamber. The x-ray diagnostics considered here consist of a transmission grating spectrometer (TGS), x-ray diodes (XRD), a pinhole camera and a framing camera. This particular TGS is relatively new and is still being developed. Its early time signal is questionable and will not be included. The TGS measures the time dependent spectrum between photon energies of about 70 eV and 2.5 keV. The data are resolved into 49 bins of increasing width for increasing photon energies. A typical late time spectrum from the TGS, along with the error envelope, is shown in Fig. 1. The large error envelope at low photon energies is due to uncertainties in calibration; however, we believe the bottom values to be more accurate. The large error envelope around 400 eV is inherent since the spectrum does not monotonically decrease with increasing photon energy. Consequently, higher order corrections to the spectrum for the second peak have the effect of subtracting two large numbers to get a small number, hence

a large error envelope. The second peak around 800 eV is sometimes questioned, but we believe it to be real, based on the calculations below.

The XRDs produce time dependent currents from the Z-pinch spectrum. The detector responses of different XRD channels are shown in Fig. 2. We mention that we plan to measure the second peak of the spectrum around 800 eV, with an XRD channel having a single lobed response past 400 eV photon energy, since its existence is not firmly established.

The pinhole camera makes time-integrated x-ray images for four different responses. One such image as displayed in Fig. 3 shows two bright spots. Even though they are not on axis, the intensity contours are somewhat symmetric about the line passing through these two spots, implying an approximate symmetry about a tilted axis. (Calculations, of course, are about an axis at $r=0$.)

The framing camera, which is under development, gives multiple 2-D x-ray images at several different times. The different images at one time are for different photon energy responses. The framing camera will be calibrated and should allow us to do the axially symmetric 2-D fit discussed below.

Fig. 1. TGS data at 19.15 μ sec.

Fig. 2. Response functions for three different XRD detector channels.

SIMULATION OF THE Z-PINCH

The actual imploded foil was 7500 Å Al backed with 1000 Å parylene. The 2-D simulation, in which all material was taken to be Al, is discussed in detail by Peterson¹. The simulation assumes the pinch to have a reflection symmetry about $z = 0.0$ cm. The simulations have high density hot spots on axis and density decreasing with radius. Densities are approximately 10^{-1} , 10^{-3} , 10^{-5} and 10^{-6} g/cc at radii of 0.0, 0.4, 2.0 and 2.2 cm, respectively, at 19.25 μ sec. The three temperatures decrease with radius, see Fig. 4, out to a radius where the density is low, and then increase. This temperature increase in the very low

Fig. 3. Film density contours from time-integrated pinhole camera.

Fig. 4. Electron (Te) and radiation (Tr) temperatures versus radius for two values of z in the 2-D Eulerian calculation at $19.25 \mu\text{sec}$.

density region is believed to be a code artifact. The three temperatures are close together (except in this low density region). This is important since our method of computing the spectrum assumes local thermal equilibrium (LTE).

SPECTRA CALCULATIONS

Spectra are calculated along the rays traced through the 2-D Eulerian calculational grid as illustrated in Fig. 5. One ray passes through the center of each rectangular calculational zone in a plane perpendicular to the line-of-sight (LOS). Since the sizes of the x-ray source and the detector are much smaller than the distance between them, we can consider all rays connecting them to be parallel. Let $I_\nu(x, t)$ be the specific intensity of the x-rays along the direction toward the detector, at a source point x and time t . The ray-tracing code simply integrates the equation

$$\frac{d}{dx} I_\nu(x, t) + (\kappa_\nu + \sigma_\nu) I_\nu(x, t) = \kappa_\nu B_\nu(T(x, t))$$

over x , where x is the traced distance, $B_\nu(T)$ is the specific intensity for black-body radiation at temperature T , κ is the absorption coefficient, σ the scattering coefficient, and ν the photon frequency. We note that κ and σ depend on x through their dependence on density and temperature. This approach can provide us a realistic spectrum if LTE is approximately satisfied. Our model includes out-scattering but no in-scattering. This is acceptable since the absorption opacity is always much larger than the scattering opacity in the applications considered. The spectrum from a given ray is in units of brightness. The brightness spectra along all rays, multiplied by the cross sectional area of the associated zone, can be summed to get a total output spectrum (spectral

power). Also partial spectra can be calculated by starting photons only in zones within a specified radial interval while including all attenuation.

Column densities along rays (Fig. 6) and $h\nu$ dependent opacities (Fig. 7) are helpful in understanding the features in a spectrum. In Fig. 6 the sum is only over half the traced distance, and r is the distance between the ray and the center line, see Fig. 5.

Fig. 5. Schematic of ray-tracing through 2-D grid.

Fig. 6. Column densities at 19.25 μ sec tracing along rays from a point x to the outside, where $x=0$ is defined in Fig. 5.

Fig. 7. Al opacities for five temperature and density pairs as indicated.

Fig. 8. Calculated total spectrum at 19.25 μ sec which is the sum of partial spectra from three radial intervals.

Insight can be gained by studying how a total output spectrum is composed of partial spectra and how the spectrum brightness shape changes over (r,z) , see Figs. 8 and 9. The peak at 800 eV comes from the pinch center, the lowest photon energies come from farther out and the spectrum in the intermediate range come from the outside. These features are consistent with the column densities and $h\nu$ dependent opacities. The 60 eV Planckian from the pinch center contributes mainly to the spectrum below the K-edge of Al where the opacity is low, forming the peak at 800 eV. After this peak the spectrum decreases like a 60 eV Planckian and then drops off suddenly at the K-edge. The center of the pinch emits approximately as a Planckian since it is optically thick to all photon energies, see Figs. 6 and 7. Likewise, the outer radii of the pinch dominate the spectrum in the 200 to 400 eV range where the opacity is high, and nothing from the center can get out.

The brightness spectra vary over (r,z) , with the spectra varying little along the axis but varying greatly off axis, see Fig. 9. The high energy peak is only found at small values of r . With increasing r , and decreasing density, the low energy part of the spectrum decreases while the spectrum in the 200 to 400 eV range does not change. This is consistent with the column densities and opacities.

The question of calculational sensitivity to various approximations is addressed in Fig. 10. Curve 1 is a spectrum from a fine zoned Eulerian calcula-

Fig. 9. Calculated spectral brightness of rays at 19.25 μ sec. All rays are at $z = 0.25$ cm but lie at different distances r from the center line.

Fig. 10. Comparison of spectra calculated with various approximations at 19.25 μ sec.

tion, $\Delta r=0.0125$ cm and $\Delta z=0.025$ cm, with only densities above 10^{-5} g/cc contributing to the spectrum. The high temperatures past a radius of 1.9 cm are not included in this spectrum calculation, curve 3 being the only curve shown which includes these high temperatures at large radii. Curve 2 only includes densities above 10^{-4} g/cc. Curves 1 and 2 are almost alike, and we believe these two to be the best calculations. Curve 3 includes the high temperatures at large radii and all densities, 10^{-8} g/cc being the lowest. In all spectra except curve 4, pure Al opacities are used. Curve 4 opacities assume the Al and parylene backing to be uniformly mixed. Pure Al spectrum calculations assume the parylene to be on axis of the pinch and not contributing to the spectrum. Curve 5 is for a coarse zoned Eulerian calculation, $\Delta r=0.05$ cm and $\Delta z=0.05$ cm, with temperature and density cut-offs as in curve 1. For curve 6, the coarse zoned Eulerian calculation is subzoned into finer zones in the radial direction, with interpolation done on temperature, before calculating a spectrum. Subzoning the fine zoned calculation makes little change in curve 1. Even though there is some variation among the curves at high photon energies, they all have mostly the same features.

COMPARISON WITH EXPERIMENTAL RESULTS

We find the calculated and TGS spectra to agree as well as one could hope at this early stage of the project. Peak time and late time comparisons are shown in Figs. 11 and 12, respectively. The comparisons are on an absolute

Fig. 11. Calculated spectra and TGS data compared at two times

Fig. 12. Calculated spectra at two times compared with TGS error envelope from Fig. 1.

scale. Both have the large peak at low photon energies, a dip at 300 eV and a second peak at 800 eV. The calculated low photon energy peak is much higher at late times than the lower curve of the TGS error envelope, which we currently

believe to be closer to the actual spectrum. The optimization fitting scheme below addresses this difference.

Spectra from calculations and the TGS are folded with the XRD responses in Fig. 2 to calculate currents which are directly comparable to the measured XRD currents, see Fig. 13. Calculation and XRDs are on an absolute scale. The relative magnitudes of the TGS currents are correct, but the TGS is normalized to the XRD (channel 2) at peak time ($19.0 \mu\text{sec}$). The major features of these three sets of currents agree well, but differences exist in detail. These differences are being addressed.

OPTIMIZED FITTING SCHEME

Figures 11-13 show some differences between calculation and experiment. We can alter the temperature and/or density distribution at a given time of an Eulerian calculation, with the use of a parameter optimization scheme², to make the calculated spectrum better fit the data. The optimization scheme does least square fitting for an arbitrary non-linear system. The variables to be determined by the fit are temperature and/or density multipliers at specified radii. Multipliers are defined between specified radii by interpolation. These multipliers are applied to an Eulerian grid as a function of radius, independent of z , and a spectrum is calculated for this new temperature and density distribution. Also different importance weights can be assigned to the different parts of the spectrum when finding the sum of squares. Calculated spectra at $19.25 \mu\text{sec}$, with and without optimization, are compared with data at $19.15 \mu\text{sec}$ in Fig. 14. We use $19.25 \mu\text{sec}$ since it is close in time and better approximates the data, see Fig. 12. Also the coarse zoned Eulerian grid was used with sub-

Fig. 13. Comparison of XRD currents. Fig. 14. Spectrum from optimized Channel 2 curve has dots. fit compared with data at $19.15 \mu\text{sec}$.

zoning in the optimization process to keep computation time reasonable. The importance weights were set low between 280 and 500 eV. The optimized spec-

trum fits the data better, especially the two peaks. The temperature multipliers here are 1.4, 0.7, 0.3, 1.6, 0.4 and 0.4 at radii of 0.0, 0.1, 0.2, 1.0, 1.7 and 6.5 cm, respectively. The density multipliers were fixed at 1.0 inside 0.2 cm and optimized to 0.04 outside 1.0 cm, interpolation in between. Since this fit is underconstrained, the fit is not unique and details of the fit cannot be believed, but higher temperatures on axis and lower temperatures at small radii is probably correct.

We are also developing a fitting scheme, based on the framing camera described above, which will completely constrain the fit. The fit does not require an existing 2-D calculation. At a given time, the framing camera records several images, each having a response of the type in Fig. 2. The pinhole camera shows in Fig. 3 that an assumption of symmetry about a slanted axis is probably acceptable. The data from the several images, at a given spacial point (r,z) , can be used to fit a spectrum along a ray through that point. See Fig. 5. For a constant z and starting at the outermost r , the fitting scheme determines the temperature and density distribution that produces a spectrum which best matches the framing camera data at the given point, after being folded with the response functions. Next we move to a slightly smaller radius and solve for a temperature and density in this next ring, keeping fixed the temperatures and densities already determined at the outer radii. This process is repeated for small steps in r to the center of the pinch. All sweeps at given z are independent of the others, except one can make a check on the total mass and compare the total spectrum to the TGS data.

ACKNOWLEDGEMENTS

We acknowledge George Idzorek and Hal Kruse for the XRDs and pinhole camera, respectively; John Benage and Dave Scudder for the framing camera; Richard Bowers, Jack Brownell, and Art Greene for theoretical discussions; and Joe Mack, who years ago introduced one of the authors to non-linear parameter optimization.

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