ZAPP: An Inexpensive Versatile X-Ray Source

D. D. Dietrich, R. J. Fortner, D. F. Price and R. E. Stewart*
Lawrence Livermore National Laboratory
Livermore, California 94550

Summary

The Z-pinch atomic physics project (ZAPP) in E-Division at the Lawrence Livermore Laboratory has been established to study the physics of high temperature high density plasmas. Using a linear hollow gas puff or a cylindrical wire array we can obtain electron temperatures in the keV region and densities of $10^{20} - 10^{22}$/cm$^3$ for virtually any element or mixtures of elements. At the center of this project is a 100 kV, 55 kJ capacitor bank which discharges through low inductance switches and transmission lines into the load developing peak currents in the $2.5 \times 10^6$ amp range. One of our goals is to have all major diagnostics temporally and spatially resolved. Included in this list are pinhole photography, grazing incidence and bent crystal spectroscopy, laser interferometry and holography, and pulsed laser scattering. We have also implemented an array of PIN diodes, XRD detectors and Rogowski coils. With a clean, repeatable, well diagnosed plasma we can address a wealth of questions concerning both plasma and atomic physics. The main experimental emphasis centers on the investigation of plasma properties such as line broadening and shifting of spectral lines and in general testing the ability of existing codes to predict observed spectra of both lines and continuum radiation. Other plasma properties to be studied are the formation of hot spots and the production of stabilized plasmas. Atomic physics experiments include the study of radiative and relativistic effects in highly stripped heavy ions, radiation transport phenomena, collisional excitation rates and level populations to test inversion schemes.

Introduction

Progress in obtaining a clear understanding of high density processes can be made only when accurate and unambiguous experimental data exist under conditions that are well characterized and can be controlled by the experimenter. Difficulties in obtaining such data are that the plasmas are often highly transient in nature with substantial spatial gradients. It is the requirement of an accurate characterization of the plasma, including time and space dependencies, that has hampered experimental progress in this area. For such a program to be successful it is necessary to push the limits of current technology in developing improved instrumentation in order to characterize such a plasma.

Plasma Production

ZAPP represents a substantial upgrade on a device built by Shiloh at U.C. Irvine. Its operation is based on the injection of a hollow cylinder of gas into a vacuum system. The electrical energy is provided by a 10.8 nF, 100 kV capacitor bank capable of storing 55 kJ Joules and delivering 1 TWatt to the load at a maximum current of $2.5 \times 10^6$ amperes. The hollow cylinder of gas provides a current path between the anode and the cathode, through which the capacitor bank is discharged. A cylindrical plasma is formed and implodes via a conventional Z-pinch. The plasma velocity and radius can be predicted as a function of time with a simple calculation based on the snowplow model. The hottest ($\gtrsim$ keV) and densest ($10^{18} - 10^{22}$/cm$^3$) plasmas exist at pinch time and persist for tens of nanoseconds.

Diagnostics

Of equal importance to the building of the plasma machine is the development of a set of diagnostic that can be used to determine important physical quantities accurately (i.e. line widths) and to characterize the plasma (i.e. Ne, Te, etc.). The diagnostics planned for ZAPP are designed to provide several simultaneous, independent measurements of density and temperature both as a function of time and space. The diagnostics include state of the art developments in time resolved high resolution spectroscopy, as well as the use of a high power pulse ruby laser to probe the plasma. Initial time resolved diagnostics indicate whether or not a pinch has taken place. As shown in Fig. 1, the dI/dt in the current and I traces are correlated with the x-ray burst in the PIN diode. Pinhole photographs

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*a Scope traces indicate when pinch occurs.

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Fig. 2 Pinhole photographs using ≥ 3 keV x-rays.

(Fig. 2) and grazing incidence spectra (Fig. 3) provide spatial and wavelength information on film. Other data currently on film include normal incidence spectra, x-ray crystal spectra and pulsed laser holography. The next generation of diagnostics will update the x-ray crystal spectrometer to yield nanosecond time resolution. This is accomplished by fitting each device with a microchannel plate with a segmented anode. Each segment is then sequentially turned on for the desired time interval. After converting the resulting electrons to visible light with a phosphor the image is proximity focused using a fibre optics plate to a conventional high speed film, Fig. 4 shows the framing camera attachment for the GIS. Calculations\(^3\) indicate that we will be able to photon count with these devices, hence the detection efficiency will be limited only by the quantum efficiency of the front surface of the microchannel plate. We are also investigating the use of reticon and CCD devices to eliminate the need for film entirely.

Fig. 3 Argon spectra showing lines from Argon IX to XIII.

Fig. 4 The framing camera fits on the Rowland circle and can either take snap shots (1-100 ns) for temporal resolution or be left on with position defining slits for spatial resolution.

**Experiments**

In a typical experiment, several techniques will be used to characterize the plasma. Once that is done, several areas relating to high temperature and density plasmas can be studied. One area directly relates to our ability to calculate the final observed densities and temperatures given well defined initial conditions; also to identify mechanisms important in the formation of hot spots or the maintaining of stability. Most of our experiments will relate directly to the spectra observed. By examination of the line spectrum we can determine cross sections (or rate coefficients) for collisional excitation, etc. In systems where these collisional rates are known, relative population can be studied and schemes to produce population inversions can be tested.
At very low energies the continuum radiation from ZAPP is characteristic of a blackbody radiator. While in the soft-x-ray region it is more characteristic of optically thin bremsstrahlung radiation. In the intermediate region the spectral shape is dominated by radiation opacity. Measurements in this region coupled with observations on optically thick resonance lines will enable us to test our ability to calculate radiation transport in hot dense matter. Detailed investigation of the line structure will reveal other broadening mechanisms, especially on optically thin lines. The line shape is normally a Voight profile, where the half width is dominated by the Gaussian shaped Doppler effects. However the wings will be determined by Lorentzian line shapes such as those produced by collisional broadening mechanisms. Theories\textsuperscript{4-6} attempting to calculate the shifting of lines due to the screening of free electrons differ by orders of magnitude and even in sign in some cases. With ZAPP we hope to resolve these controversies and in some cases do precision measurements to test quantum electrodynamic effects.

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