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# NEW DIAGNOSTIC DEVELOPMENTS FOR INTENSE ION BEAM MEASUREMENTS ON PBFA II

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Abstract. A new diagnostic package has been developed for the Sandia National Laboratories' PBFA-II accelerator. The package—which emphasizes off-axis Rutherford-scattering measurements—includes the following: off- and on-axis multi-frame dE/dx ion pinhole cameras, an off-axis energy-resolved ion movie camera, an on-axis time-resolved ion movie camera, an off- or on-axis time-resolved Rutherford magnetic spectrograph which has a one-dimensional imaging capability, time-integrated and time-resolved K$\alpha$ X-ray pinhole cameras, a plasma visible spectroscopy diagnostic, an elliptical crystal spectrograph, and a high bandwidth transient data recording system based on fiber-optic and streak camera technology. Additionally, several other new diagnostic systems are currently under development. These consist of an ultra-fast X-ray framing camera based on sealed MCP imaging tubes, a time-resolved K$\alpha$ X-ray pinhole camera that has a film/scintillator image plane coupled to a 14 $\times$ 18 element array of 100-$\mu$m-diameter fiber optics, a large-radius Rutherford beam diagnostic, a proposed flash radiography system, and a Doppler neutron time-of-flight diagnostic.

## INTRODUCTION

Intense ion beams are being investigated as a driver technology for inertial confinement fusion (ICF) experiments on the Particle Beam Fusion Accelerator II (PBFA-II) at Sandia National Laboratories.[1]

Presently, multi-TW ion beams are being produced at peak voltages of more than 8 MV in an ~ 20-ns FWHM pulse. A major difficulty in the PBFA-II experimental program is the development of a diagnostic package that can adequately measure the parameters of such intense ion beams. In part, this difficulty is due to the fact that the intense beams generated must be nearly 100% space-charge and current-neutralized in order to propagate, which precludes many electrical measurements. Another difficulty is that the diagnostic package must be capable of operating in an 8-10 MeV endpoint bremsstrahlung environment of $10^9$-$10^{11}$ Rad/s.

In an effort to overcome these difficulties, a series of integrated diagnostic packages have been developed and fielded to measure the parameters of proton and lithium beams generated on PBFA II; the latest is shown in Fig. 1. The ion beam is generated with the applied-B field diode shown schematically in Fig. 1.[1] This diode has a radius of 15.5 cm and generates an intense ion beam that is directed radially inward from a cylindrical anode surface. The upper portion of the diagnostic package is embedded in a 1000-kg tungsten shield and divides the 360° beam into four sectors, each of which nominally extends 90° azimuthally and ±17° vertically. Each sector is observed with one or more diagnostics. One possible configuration of the new package includes an off-axis multi-frame dE/dx ion pinhole camera, an off-axis energy-resolved ion movie camera, an off-axis K$\alpha$ X-ray pinhole camera, two on-axis K$\alpha$ X-ray cameras, a K$\alpha$ X-ray PIN array diagnostic, an on-axis Rutherford magnetic spectrograph, an on-axis PIN array time-resolved ion movie camera, an on-axis elliptical crystal spectrograph, an on-axis multi-frame dE/dx ion pinhole camera, a plasma visible spectroscopy diagnostic, off-axis nuclear activation, and neutron time-of-flight diagnostics. (Not all of these are shown in the figure.)

## IMAGING DIAGNOSTICS

Imaging diagnostics are of crucial importance in the study of beam steering, divergence, and focal power intensity. A large variety of

X-ray and ion pinhole cameras, as well as shadowbox arrangements, have been developed to make these measurements on PBFA II.

The two dE/dx multi-frame ion pinhole cameras shown in Fig. 1 were developed to obtain two-dimensional energy density profiles of the PBFA-II ion beam as a function of ion energy both off- and on-axis.[2] The off-axis camera operates by allowing an 80° sector of the ion beam to strike an off-axis gold Rutherford scattering foil (typically 0.25 $\mu$m thick) located at a radius of 3.8 cm. The on-axis camera views a separate 80° beam sector which strikes an on-axis gold Rutherford scattering foil. In both cameras, ions that elastically scatter from the gold are imaged through six baffled pinholes onto six separate areas of a sheet of CR-39 nuclear track detector. Each of the areas is covered by a range filter and records an image with a different lower bound on the ion energy. Subtracting images with adjacent energies results in images with upper and lower energy bounds. Time-resolved images of the beam may be obtained with these instruments if the ion beam is emitted from the diode only as the voltage falls (typical behavior of an applied-B diode) and if the time history of the voltage on target is known (for example, from a magnetic analyzer). A variant of the multiframe dE/dx pinhole camera for imaging protons is a single-frame ion pinhole camera which uses the size of proton tracks in CR-39 to construct images as a function of E.

Another diagnostic system incorporated in the package in Fig. 1 is a series of K$\alpha$ X-ray pinhole cameras and a time-resolved, non-imaging, filtered PIN array K$\alpha$ diagnostic.[3] One pinhole camera views the beam off-axis at a radius of 3.8 cm while two additional pinhole cameras and the filtered PIN array view the beam on-axis. All of these diagnostics operate by viewing K$\alpha$ (M$\alpha$ in the case of a gold target) line radiation emitted when the ion beam strikes titanium, aluminum, or gold targets. The present K$\alpha$ X-ray pinhole cameras used on PBFA II are time-integrated and use film at the image plane. The film is digitized on a scanning microdensitometer and analyzed using the VIDA program.[4] The new time-resolved K$\alpha$ camera, shown in Fig. 2, has a film/scintillator image plane coupled to a $14 \times 18$ element coherent array of 100-$\mu$m-diameter fiber optics. The 2-D array is convoluted to form a 1-D array at the input to the photocathode of a streak camera. Another approach being pursued for time-resolved $K\alpha$ X-ray imaging is an ultra-fast X-ray framing camera, which has eight sealed MCP imaging tubes that are gated sequentially to achieve time resolution. The MCPs are embedded in 4-$\Omega$ transmission lines and can have gate dwell times as short as a few hundred picoseconds.

Also shown in Fig. 1 is the time-resolved PIN array ion movie camera.[5,6] This camera operates by pinhole imaging Rutherford-scattered ions from the on-axis gold target onto an image plane consisting of CR-39 and a 37-element array of 1-mm-diameter PIN diodes arranged in an octagonal pattern. Details are discussed in Ref. 6.

RUTHERFORD MAGNETIC SPECTROGRAPH

One of the most important measurements that can be made on an intense ion beam is a time-resolved measurement of its energy spectrum. This measurement allows the determination of the current density, power density, voltage, and species of the beam as a function of time. The Rutherford magnetic spectrograph that has been constructed to make these measurements on PBFA II is shown in Fig. 1.[7] The spectrograph can be fielded either off- or on-axis; in either case, the radially converging ion beam is allowed to strike a thin gold Rutherford scattering target. Ions that are Rutherford-scattered upward through an average angle of 90° pass through the collimator section of the spectrograph, which consists of a pinhole at the magnet and a slit near the gold scattering foil. The ions then enter a 7.1-kG magnetic field region which is produced by a 30.5-cm Nd-Fe-B permanent magnet. Upon exiting from the field, the deflected ions are recorded on either CR-39 or onto 16 1-mm-diameter PIN detectors. The slit in the collimator system is oriented such that the pinhole forms a 1-D image of the ion beam at the detector plane of the magnet in a direction orthogonal to the direction of magnetic deflection. We plan to use this newly developed 1-D imaging capability of the spectrograph to measure dE/dx in the hot dense plasma formed when the PBFA-II ion beam is allowed to strike an on-axis foil. The experimental configuration is shown in Fig. 3. The center foil is the dE/dx target where the PBFA-II ion beam would be focused. One array of PINS in the magnet's focal plane will be used to measure the time-resolved energy spectrum at the input, while the other array will measure the beam's spectrum at the output. The target ionization distribution responsible for the change in dE/dx will be determined from the K$\alpha$ X-ray satellite spectrum measured with an elliptical crystal spectrograph. Additionally, other X-ray diagnostics viewing the dE/dx target will provide measurements of plasma temperature and density. Previous calculations and experiments have shown that dE/dx may increase as much as a factor 2 under conditions obtainable on PBFA II.

The spectrograph can also resolve ion species: When energy analysis is performed with ion time-of-flight and momentum analysis with magnetic deflection, the ion time-of-flight to a given PIN detector is directly proportional to the ion's mass-to-charge. Once a signal in the time-of-flight spectrum is associated with a given ion mass-to-charge ratio, a full time-resolved analysis of that ion's current density, power density, and mean energy can be obtained. The data of Fig. 4 is an example of the spectrograph's ability to separate protons from lithium ions on PBFA-II shot 2621. The $Li^{+2}$ and $Li^{+3}$ peaks in the data are due to Li ions being stripped to these charge equilibrium states at the 2-$\mu$m-thick mylar gas cell exit window before entering the evacuated region of the spectrograph.

## NUCLEAR REACTION DIAGNOSTICS

Nuclear reaction diagnostics have always been of central importance in the diagnostics of intense ion beams. The most recent reaction schemes on PBFA II use the $^7Li(p,\gamma)^8Be$ reaction to measure the proton beam energy and the $D(^7Li,n)^8Be$ reaction to measure the Li beam energy. In the case of either reaction, a remote sample of praseodymium is activated and then counted in a coincidence counting system. Further details of these activation schemes may be found in Ref. 8. Several new target configurations have developed for both reactions.[9] One particularly useful configuration consists of a Li metal cylinder surrounded on the outside by a thin gold cone so that a correlation between our Rutherford scattering, K$\alpha$ cameras, and activation diagnostics can be established. Finally, neutron time-of-flight is used to monitor neutron production from the reactions $^{7}Li(p,n)^{7}Be$ and $D(^{7}Li,n)^{8}Be$ on almost every PBFA-II shot.

## VISIBLE SPECTROSCOPY DIAGNOSTICS

Visible spectroscopy diagnostics are being used to study the anode plasma ion source in the PBFA-II applied-B diode. This effort is motivated by the need to obtain detailed knowledge of diode physics and by successful measurements on low power diodes.[10] The challenging environment on PBFA II has largely determined the design of our diagnostics. A fiber optic system transports light from the diode to a remote screen room where it is recorded on a streak spectrograph. This alleviates the problems imposed by intense background radiation, mechanical shock, and allows a complete time-resolved spectrum to be recorded on a single shot. The front end of this fiber optic system is illustrated in Fig. 1. HI, CII, CIII, and CIV features have been observed from CH anodes and LiI, FII, and FIII lines have been observed from LiF anodes. Many parameters relevant to the operation of the diode can be obtained from this data, including the plasma density, temperature, and composition, the electric field in the A-K gap, and the hydrodynamics of the anode plasma. For example, the Stark shift of the LiI 2s-2p transition shows that the time-resolved electric field peaks at 7-8 MV/cm, which is the highest field ever measured using the Stark effect. Presently efforts are underway to construct a theoretical diode model which incorporates these measurements.

## FUTURE DIAGNOSTIC SYSTEMS UNDER DEVELOPMENT

Several diagnostic systems are presently under development for future application on PBFA II. These include a new high bandwidth transient data recorder—originally developed at Sandia and now available commercially—which is based on fiber-optic and streak-camera technology.[11,12] The 40-channel system presently consists of 16 directly-modulated 800-nm laser diodes connected over 125-m multimode fiber-optic cables to the streak camera. The streak duration can be set between 2 ns and 1 $\mu$s. The streak image is fiber-optically coupled to a CCD camera with 576(time) $\times$ 384 pixel resolution. The system is controlled, and data are analyzed using a MacIntosh II computer. At 40-ns streak duration, system bandwidth exceeds 0.8 GHz with better than 50:1 signal-to-noise.

Knowledge of the target configuration as a function of time is a necessity in evaluating the performance of inertial confinement fusion implosions. We are presently investigating whether the application of a projective flash X-radiography system will prove useful for making these measurements on PBFA-II targets. Specifically, under study is the development of a 1-2 ns e-beam (bremsstrahlung) source with gated detectors. At issue is the appropriate spectrum, source strength, and material fiducials in the target design. Two codes, IMAGE and RADIM, have been developed for these design studies.

A doppler neutron time-of-flight system is under development for application to PBFA II. This system will make it possible to measure DT target ion temperature by measuring the doppler spread of the 14.1-MeV neutrons emitted from the target. A 40-60 m line-of-sight from the center of PBFA II has been constructed and includes a new building for the neutron detector system.

The ability to measure the PBFA-II ion beam at large radius (>3.8 cm) has always been an important issue. We have developed a Rutherford scattering diagnostic that is contained in a small package and employs a 1-cm-diameter gold Rutherford scattering foil and a 0.5-cm-diameter CR-39 detector. This diagnostic may be deployed (individually or in arrays) on PBFA II at any diode radius up to 12.5 cm.

Finally, we are developing new, high-speed image-processing circuitry that will double the speed of VERA, our CR-39 nuclear track counting system. VERA scans CR-39 for the magnetic spectrograph, Thomson parabola spectrographs, on- and off-axis de/dx ion pinhole cameras, energy-resolved ion movie cameras, and the PIN-diode time-resolved ion movie camera.

SUMMARY

A new, integrated diagnostic package has been developed and fielded to measure the parameters of intense proton and lithium beams generated on Sandia National Laboratories' PBFA-II accelerator. The package enables measurements of the beam's spatial profile (off- and on- axis), the beam charge, the species distribution, the anode plasma density, the anode plasma temperature, the anode-cathode gap **E** field, beam velocity vectors, the beam voltage, and the beam focal power density.

ACKNOWLEDGMENT

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REFERENCES

1]Lockner, T. R. et al., Proc. of the 7th Int'l Conf. on High-Power Particle Beams, Karlsruhe, FGR, W. Bauer & W. Schmidt, eds. (Kernforschungszentrum, Karlsruhe) pp. 311-318 (1989).

2]Stygar, W. A. et al., Rev. Sci. Instrum. **59**, 1703 (1988).

3]Maenchen, J. et al., Rev. Sci. Instrum. **59**, 1706 (1988).

4]Mehlhorn, T. A. et al., Rev. Sci. Instrum. **59**, 1709 (1988).

5]Leeper, R. J. et al., Rev. Sci. Instrum. **59**, 1860 (1988).

6]Stygar, W. A. et al., to be published.

7]Leeper, R. J. et al., Rev. Sci. Instrum. **59**, 1700 (1988).

8]Leeper, R. J., Laser and Particle Beams **7**, 649 (1989) and the references therein.

9]Ruiz, C. L. et al., to be published.

10]For example, see Maron, Y. et al., Phys. Rev. **A41**, 1074 (1990) and the references therein.

11]Chang, J. et al., Rev. Sci. Instrum. **56**, 1861 (1985).

12]Available from Kaman Sciences Corporation, Colorado Springs, Colorado.

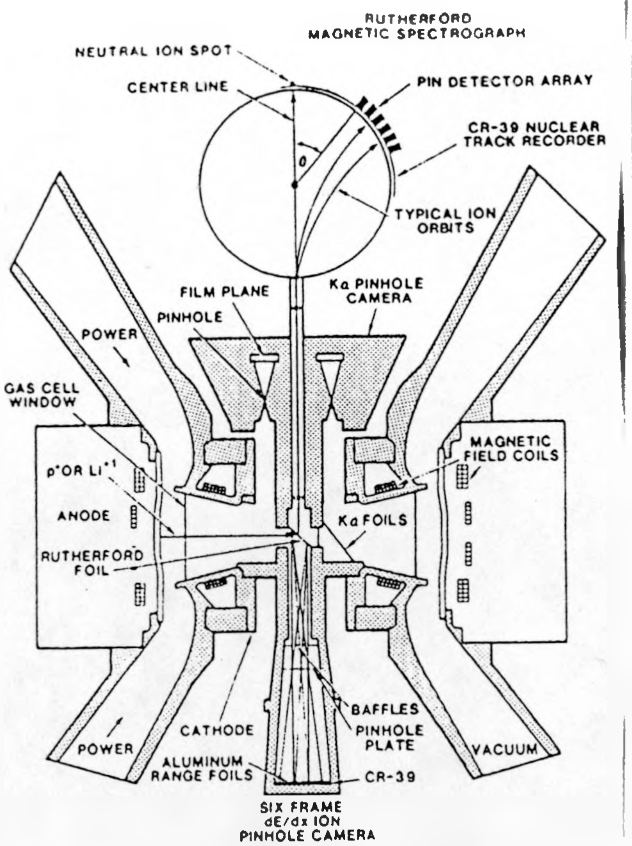


Figure 1. Schematic of experimental arrangement used to make intense ion beam measurements on PBFA II.

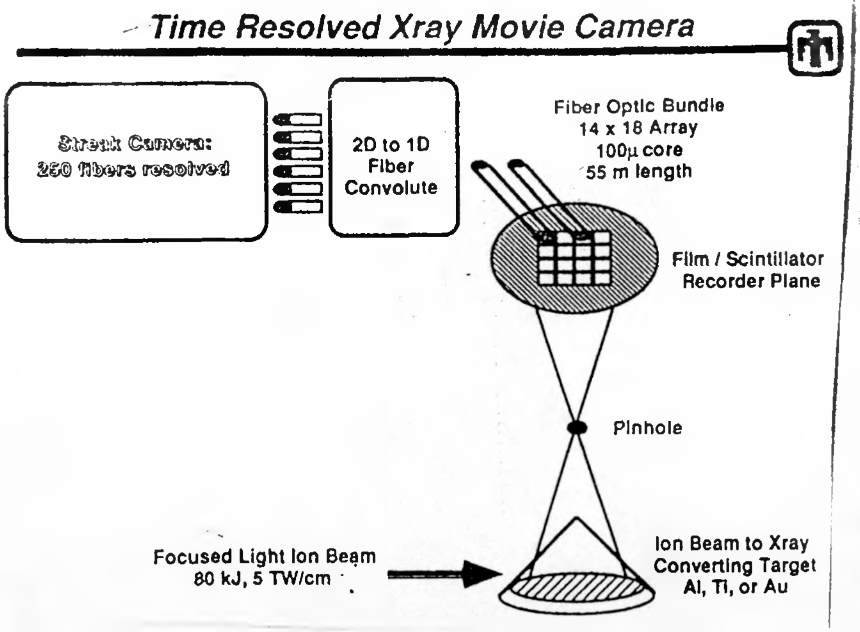


Figure 2. Schematic of time-resolved Kα X-ray pinhole camera.

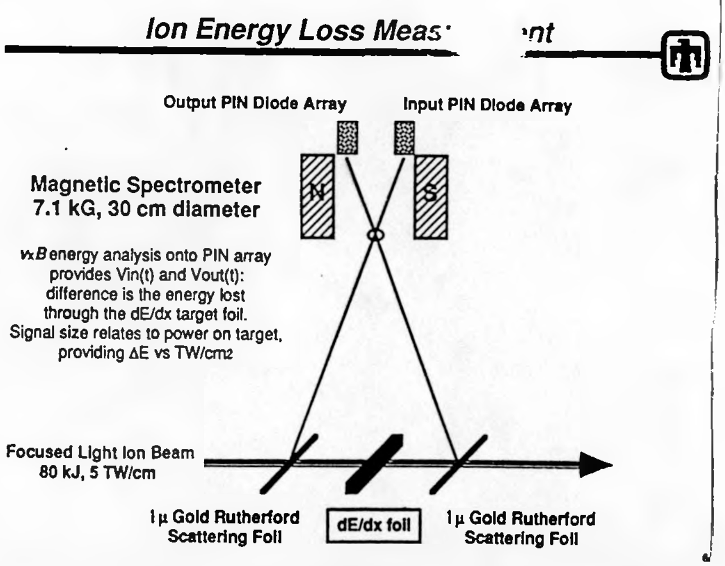


Figure 3. Schematic of the experimental configuration for hot dense plasma dE/dx measurement.

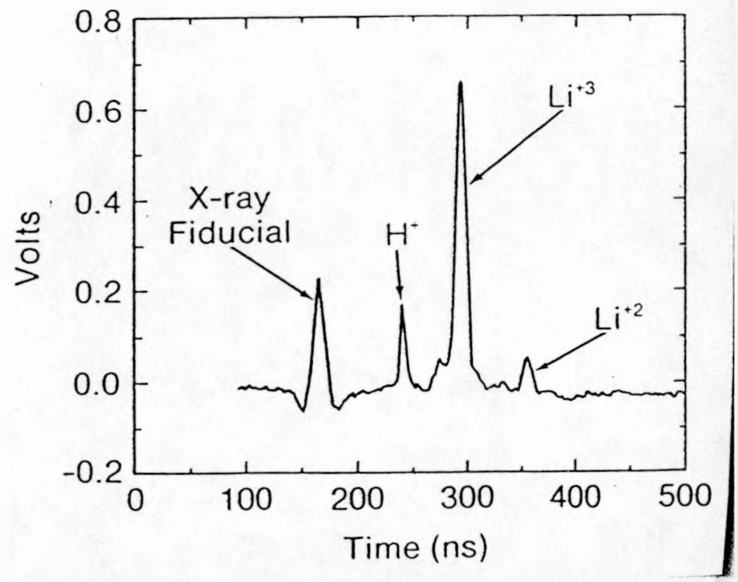


Figure 4. Rutherford magnetic spectrograph PIN detector trace on PBFA-II Shot No. 2621 showing separation of proton and lithium signals.