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DIRECT MEASUREMENT OF THE ENERGY SPECTRUM OF AN INTENSE PROTON BEAM

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Abstract

A time-resolved magnetic spectrometer has been used to measure the energy spectrum of an intense (0.5 TW/cm^2) proton beam. A thin (2400 Å) gold foil placed at the focus of an ion diode Rutherford scattered protons by 90° into the spectrometer, reducing the beam intensity to a level suitable for magnetic analysis. The scattered beam was collimated by two 1 mm diameter apertures separated by 12.3 cm. The collimated protons were deflected in a 12.7 cm diameter, 6.65 Kg samarium-cobalt permanent magnet. The deflected protons were recorded simultaneously on CR-39 and eight 1 mm^2 by 35 μm thick PIN diodes. A Monte Carlo computer code was used to calculate the sensitivity and resolution of the spectrometer. Data taken on Proto-I show a 150 keV to 250 keV wide proton energy spectrum at each instant in time.

Introduction

One of the most important measurements that can be made on an intense ion beam is a time resolved measurement of the energy spectrum. This measurement allows the determination of the current density, power density, current, and voltage of the beam as a function of time.

A straightforward method of measuring the energy of a charged particle is to observe its deflection in an applied magnetic field. However, to make such an energy analysis, it is necessary to collimate the beam. This has been the major source of difficulty in the use of particle analyzers in the measurement of intense beams. These difficulties have occurred because an intense beam, upon striking the input apertures of the analyzer, can turn the edges of these apertures into a plasma. This plasma will start to move during the pulse, closing off the apertures and causing large dE/dx losses. Another problem in using particle analyzers is that the beamlet selected by the aperture system may be of such high current density that it will blow up in crossing the analyzer field from space charge forces.

In an effort to overcome these difficulties, we have used Rutherford scattering from a thin target to reduce the particle flux of an intense beam to a level suitable for charge particle analysis. Since Rutherford scattering is an elastic process, protons will lose little energy in scattering from thin, high Z foils.

A magnetic spectrometer with a Rutherford scattering foil has recently been used to make a time resolved energy spectrum measurement of an intense proton beam. The proton beam was generated with the applied B field magnetically insulated ion diode coupled to Sandia's Proto I accelerator.[1] This proton energy spectrum measurement is the first ever of an intense ion beam.

Experimental Configuration

A schematic of the experimental arrangement used to make the proton energy spectrum measurement is shown in Fig. 1. The magnetic spectrometer is mounted vertically into the applied B field diode and is operated in the vacuum chamber at diode vacuum.[2] The 4.5 cm radius diode generates an intense proton beam that is directed radially inward from the cylindrical anode surface. This beam then enters a gas cell through a 2 μm thick mylar window located just behind the cathode rings and is ballistically focused to the center of the diode. The gas cell is nominally filled with 6 Torr of Argon gas.

Located at the center of the diode is a gold Rutherford scattering foil mounted at an angle of 45° to the vertical axis. The thickness of each foil was measured by an Inficon crystal thickness monitor and varied from 2300 Å to 2600 Å during the course of the experiment. The gold was mounted on a 2 μm mylar backing for strength. The target holder in which the foil was placed was designed to accept protons from a sector of the cylindrical anode surface that had 90° azimuthal and ±15° vertical extent (referenced to the midplane of the diode). Protons which Rutherford scattered through an average angle of 90° then passed through a second 2 μm thick mylar gas cell output

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window and into the collimator. The collimator consisted of two 1 mm diameter apertures separated by 12.3 cm. The apertures were fabricated from brass and had edges that were 0.5 mm thick to minimize collimator edge scattering.

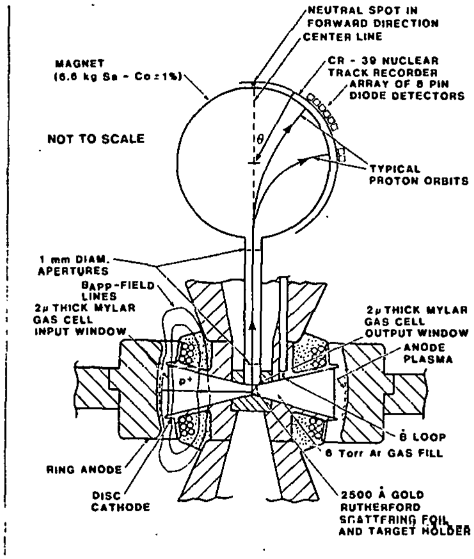

Fig. 1. Schematic of experimental arrangement used to make intense proton beam spectra measurements.

The collimated beam then entered the magnetic region of the spectrometer. The magnetic field was produced by a samarium-cobalt permanent magnet which had a field value of 6.65 Kg uniform to within ±1% over the entire volume of the magnet. The fringe field region extended less than 3 mm from the magnet's edge and was measured with a Hall probe. The magnet had 12.7 cm diameter circular pole pieces separated by 3.2 mm. Typical proton orbits through the magnetic field are shown in Figure 1.

Upon exiting the magnetic field, the deflected protons were recorded on either the nuclear track recording media CR-39 or on eight 1.13 mm diameter by 35 μm thick PIN diode nuclear detectors. The PIN diode detectors were located behind the CR-39 strip and viewed the protons through 3 mm diameter holes drilled through the CR-39. CR-39 records protons through a polymer radiation damage mechanism induced by the ionization energy loss of the protons striking it. The CR-39 is etched in a solution of sodium hydroxide which preferentially etches along the proton damage region to make the proton tracks visible under a microscope. The number of proton tracks per unit area were counted with a computer aided microscope system.

The PIN diode detectors are standard solid state nuclear detectors.[3] One electron-hole pair is formed in the detector for every 3.6 eV of energy deposited. The PINS used in this experiment had rise times of 450 ps and FWHM widths of 1.1 ns as measured by single 5.6 MeV ^{241}Am alpha particles. However, the long cables and the biasing network degraded the system response time to 3.2 ns FWHM. The PINS had an entrance dead layer thickness of 0.5 μm.

A small number of the protons passing through the spectrometer charge exchange and became neutral. These neutrals pass through the spectrometer in the forward direction undeflected and are recorded in the CR-39. This provided a fidicual mark for all measurements of proton deflection in the experiment.

Data Analysis

A Monte Carlo computer simulation of the experiment was used to study the sensitivity and resolution of the spectrometer. The simulation generated protons uniformly on a 90° sector of the anode which had ±15° vertical extent. Each proton is tracked through a 2 μm mylar window and a gas cell filled with 6 Torr argon gas to an interaction point in the gold foil (6% of the interactions occur in the 2 μm mylar backing the gold). After Rutherford scattering, the proton enters the 2 μm mylar entrance window at the front of the magnetic spectrometer. The proton is then tracked through the spectrometer to a detecting surface at the position of the CR-39 strip and the PIN array. For each segment of the proton trajectory, multiple scattering, ionization energy losses, and energy straggling are taken into account. For protons that hit the PIN array, the response of the pin is computed including a small correction for a 0.5 μm dead layer at the front of the PIN. The time-of-flight from the anode to the detector is computed for each proton. This is used to timeshift the raw PIN signals.

The PIN diode response functions calculated with the Monte Carlo are shown in Figure 2. The energy resolution is dominated by the geometry of the experiment at high energies, but energy straggling becomes significant at about 1.5 MeV and dominates the resolution below 1.0 MeV.

The distribution of proton tracks recorded on the CR-39 in the direction perpendicular to the magnetic deflection (Y coordinate) is shown in Figure 3. Each data point represents the number of tracks counted inside a 115 μm x 160 μm area. The error bars indicate the statistical uncertainties. Also shown in Fig. 3 is a Monte Carlo calculation of the Y distribution. The overall magnitude depends on the proton beam intensity, so the calculated distribution was scaled by a constant to match the data near Y = 0.

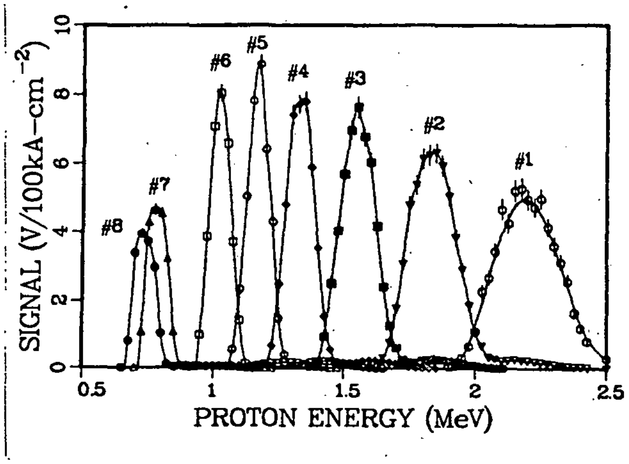

Fig. 2. PIN diode response functions.

The good agreement with the shape of the measured Y distribution demonstrates that the experimental geometry is well understood and that proton scattering from the collimator edges and the pole pieces of the magnet is negligible. This also experimentally verifies the calculated energy resolution of the spectrometer at high energies, where geometrical effects dominate the resolution.

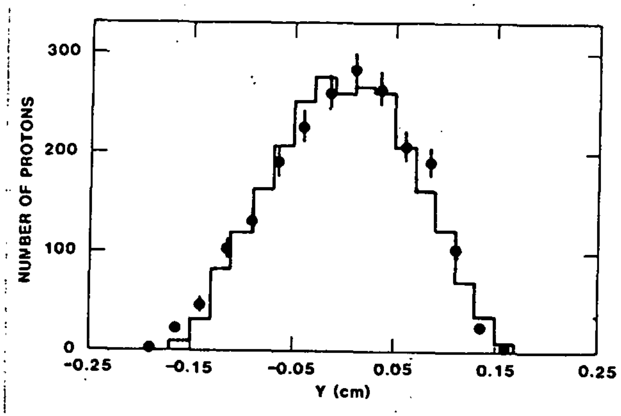

Figure 3. Y distribution of protons on CR-39 from Proto I shot #3957.

The time integrated energy distribution was determined from the CR-39 data using

$$\frac{dN_p}{dE} = \frac{\rho(\theta)}{S(\theta)\left(\frac{dE}{d\theta}\right)} \qquad (1)$$

where the angle θ is defined in Fig. 1. The track density ρ is the number of protons hitting the CR-39 per unit angle along the circular arc of the detector plane. The spectrometer sensitivity $S(\theta)$ and $dE/d\theta$ were calculated using the Monte Carlo. The overall weighting function $f(\theta) = (S\ dE/d\theta)^{-1}$ varies slowly over the range of interest (25% maximum variation).

The time resolved proton energy spectrum was determined from the PIN data using the response functions shown in Fig. 2 and the Sandia developed Unfold Operator Code (UFO).[4] The time integrated PIN signals were used to determine a time integrated proton energy spectrum to compare with the CR-39 data.

Above 1 MeV, the spectromer is sensitive to protons hitting a spot on the gold foil with a diameter of less than 1.6 mm. Aluminum K_α measurements indicate that the beam spot size is 2.6 mm FWHM, so in this analysis we assume that the beam intensity is uniform over the sensitive area of the foil. We correct the data by a geometrical factor to present proton intensity, current density, and power density in terms of a cylindrical surface at the focus onto which the full 360° beam is incident.

Results

The signals from the eight PIN diode detectors from Proto I shot #3957 are shown in Figure 4. These signals have been corrected for time-of-flight between the anode and the detector surface. The signals overlap much more than the PIN response functions, indicating a broad proton energy spectrum at each instant in time.

The time integrated proton energy spectrum is shown in Fig. 5. The agreement in both shape and magnitude between the CR-39 measurements and the PIN diode measurements provided an important consistency check on the data analysis.

The time resolved energy spectrum is shown in Figure 6. After making small corrections for the time response of the spectrometer (not shown in the plot), these data show a proton energy spectrum at each instant in time with a width of 150 keV to 250 keV FWHM.

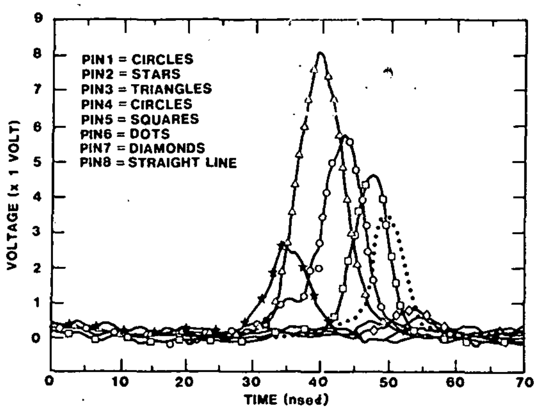

Fig. 4. Multi-plot of the signals from the eight PIN diode detectors from Proto I shot 3957.

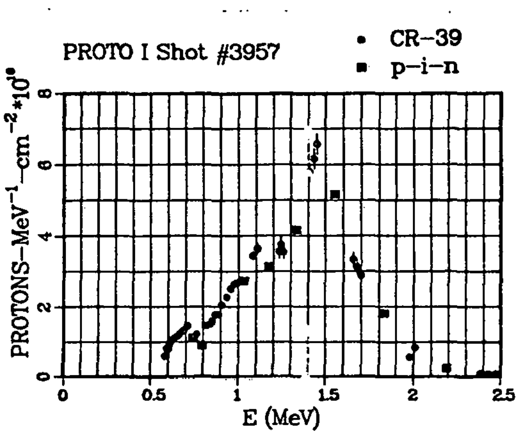

Fig. 5. Time integrated proton energy spectrum from CR-39 data and time integrated PIN data for Proto I shot 3957.

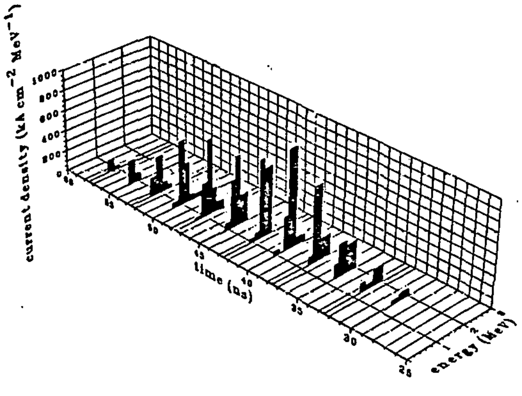

Fig. 6. Time resolved proton energy spectrum from Proto I shot 3957.

The mean proton energy, current density, and power density can be computed from Fig. 6 and are shown in Fig. 7-9.

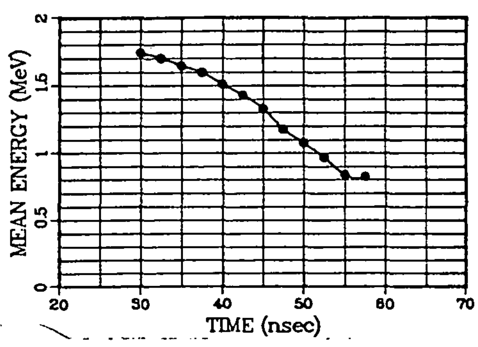

Fig. 7. Plot of mean proton energy versus time from Proto I shot 3957.

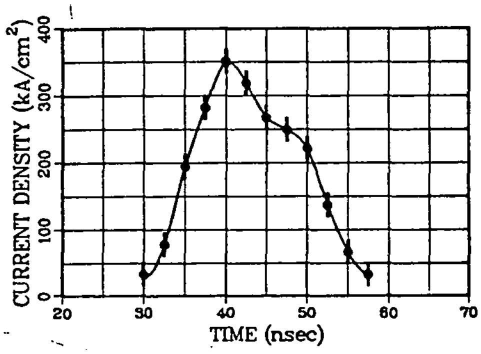

Fig. 8. Plot of proton current density versus time from Proto I shot 3957.

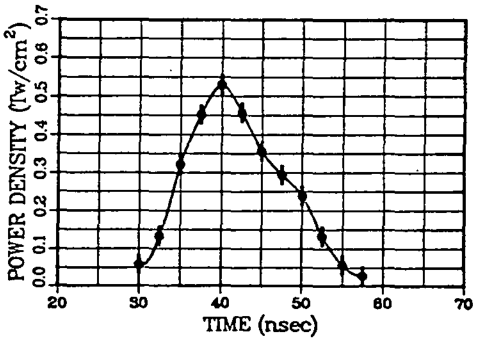

Fig. 9. Plot of proton power density versus time from Proto I shot 3957.

Acknowledgements

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