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A STUDY OF THE MASS AND ENERGY
RESOLUTION OF THE E|B CHARGE
EXCHANGE ANALYZER FOR TFTR

BY

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A STUDY OF THE MASS AND ENERGY RESOLUTION OF THE E||B CHARGE EXCHANGE ANALYZER FOR TFTR

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ABSTRACT

The charge exchange diagnostic for TFTR requires simultaneous multispecies (H^+ , D^+ , T^+) analysis of particles in the energy range of 0.5 - 150 keV. The analyzer design chosen to provide this capability employs a wide gap semi-circular region of superimposed parallel electric and magnetic fields to accomplish mass and energy resolution, respectively. Combined with a large area, multi-anode microchannel plate detector, this arrangement will enable the energy distributions of protons, deuterons, and tritons to be measured concurrently as a function of time during each discharge. A computer simulation program for calculating ion trajectories through the analyzer was written that includes a realistic model of the magnetic and electrostatic fringe fields. This report presents the results of a study of the proposed E||B analyzer, and it reveals that the fringe fields are not detrimental to the performance of the analyzer.

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Fig 1

1. INTRODUCTION

Charge exchange diagnostics on the TFTR will require more sophisticated measurement apparatus than were needed on earlier machines. Several factors contribute to this situation, but the primary ones are tritium operation and strong supplemental plasma heating, by injection of 120 keV neutral deuterium (or by hydrogen) beams at power levels up to 20 MW. This results in a multispecies plasma with energy distributions that are usually not the same for each ion component. Consequently, charge exchange diagnostics require mass resolved measurements over a wide range of energies. Tritium operation presents severe neutron and gamma-ray interference to the detectors, and imposes remote maintenance design problems. Furthermore, the limited number of tritium discharges allowed makes multi-shot scanning to acquire, for example, radial profiles unacceptable. This leads to a large number of analyzer units. On TFTR, current plans involve the installation of twenty analyzers, twelve for perpendicular measurement of the ion temperature radial profile (Fig. 1) and eight for tangential measurement of the slowing down energy distribution of beam injection ions (Fig. 2).

A general description of the layout of the charge exchange diagnostic system, including a diagnostic neutral beam for active measurements, has been presented elsewhere.^{1,2} In this report, details concerning the mass and energy resolving characteristics of the E||B analyzer design are examined. Section II presents a brief description of the analyzer concept. The ion trajectory simulation program is discussed in Sec. III, followed by a description of the magnetic (Sec. IV) and electric (Sec. V) field modeling used in the program. Results of the study are presented in Sec. VI and the conclusions in Sec. VII.

II. PRINCIPLE OF OPERATION OF THE E-B MASS/ENERGY ANALYZER

The basic operating principle of the parallel electric and magnetic field analyzer arrangement is described with the aid of Fig. 3.

After reionization of the charge exchange neutrals in the stripping cell, the ions enter perpendicularly into a semi-circular sector of parallel magnetic and electric fields. In these fields, the Lorentz forces

$$m\dot{\underline{y}} = q(\underline{v} \times \underline{B} + \underline{E}) \quad (1)$$

are not coupled. While traversing an arc of 180° due to the magnetic field $\underline{B}$, the ions are displaced parallel to the electric field $\underline{E}$. The time-of-flight

$$t_j = \frac{\pi}{B} \left(\frac{m}{e} \right)_j \quad (2)$$

between entering the field region and arriving at the collector is independent of the initial velocity for any given ion species $(m/e)_j$. The displacement Y_j of the j -th species parallel to the electric field is given by

$$Y_j = \frac{1}{2} \left(\frac{E}{B^2} \right) \left(\frac{m}{e} \right)_j, \quad (3)$$

which is also independent of velocity, so that all particles of a given m/e ratio are displaced along the electric field direction by the same amount. The ion species $(m/e)_j$ entering with velocity v_k is displaced a distance

$$Z_{jk} = \frac{2}{B} \left(\frac{m}{e} \right)_j v_k \quad (4)$$

from the entrance point in a direction perpendicular to $\underline{v}_k \times \underline{B}$. The collection plane thus exhibits parallel columns of analyzed ions, each column containing energy dispersed ions of given (m/e) ratio. The detector is located in the collection plane and consists of a planar channel electron multiplier array (CEMA) as shown in Fig. 4. The CEMA is provided with three rectangular, semi-continuous active area strips, one

corresponding with each of the mass columns for H^+ , D^+ , and T^+ . Each strip is divided into multiple discrete anode elements of width dZ_j . The energy resolution

$$\frac{\Delta E}{E} = \frac{dZ_j}{Z_j} \quad (5)$$

is therefore a function of displacement along each mass column.

A schematic of the prototype E||B analyzer is shown in Fig. 5. The stripping cell and semi-circular magnet pole pieces are evident. To produce the electric field, one pole of the magnet is used as a ground potential electrode while a second, negatively-biased electrode (or deflection plate) is supported on, but electrically insulated from, the opposite pole piece. The ion beam enters near the ground electrode for two reasons. First, this location reduces perturbation of the incoming particle energy due to the electrode potential. Second, this arrangement permits utilization of the full separation of the magnet gap. Even so, adequate spatial separations of the H^+ , D^+ , and T^+ ion species results in a relatively large magnet gap. From the relation for the magnetic field strength B (in gauss),

$$B = 1.25 \frac{NI}{d} \quad , \quad (6)$$

it is evident that to provide a specified field using a set number of coil turns N, the required energizing current I (in amperes) is proportional to the pole separation d (in centimeters). In addition to the sizable magnet power requirements arising from a large pole gap, the associated fringe field might be expected to adversely affect the ion trajectories.

Alternative configurations are possible which reduce the pole separation while preserving the E||B analysis concept. Although a detailed discussion is beyond the scope of this report, two such alternatives will be described briefly. First, some degree of reduction in pole separation can be achieved by requiring that only part of the necessary spatial dispersion of the ion species takes place while the ions are

traveling between the poles. The remainder of the dispersion is realized by allowing the ions to drift some distance on exiting the field region before striking the detector. If the detector plane remains parallel to, but is displaced away from the straight edge of the magnet, the mass columns become parabolic in shape, with lower energies having a greater displacement in the direction of the electric field lines. Linear mass columns may be recovered, however, by tilting the detector plane about an axis which is parallel to the field direction and passes through the "entry point" of the ions into the magnet gap.³ The greatest reduction in pole separation is achieved by applying the electric field after the ions emerge from the magnetic field.⁴ With both of these alternatives, the price for relaxing the magnet effects is a significant increase in the overall dimensions of both the analyzer and the detector to encompass the same energy range. Since the present application requires shielding the interior of the analyzer against stray magnetic fields due to TFTR, increasing the size of the analyzer also leads to more massive enclosure walls.

In the interest of providing the simplest and most compact E¹B analyzer possible for TFTR, it was decided to examine more thoroughly the configuration shown in Fig. 5. Through careful design of the magnet field coils and operation in a pulsed mode for the higher field regimes, the power dissipation requirements can be reduced to at least some degree. This report addresses specifically the effect of the electric and magnetic fringe fields on the performance of the analyzer.

III. ION TRAJECTORY SIMULATION PROGRAM

The program (CENAFOR) to be described here evolved from a Monte Carlo code previously used to simulate ion trajectories in the PLT charge exchange analyzer,⁵ and later for a modification of the PLT system to provide an E¹B field configuration for the PDX thermal analyzer system.⁶ The earlier program, however, was extensively rewritten to account for the different magnetic/electric field

geometry of the TFR system, and to investigate the effect of fringe magnetic/electric fringe fields on the ion trajectories through the analyzer.

The code models the overall charge exchange system from the target to the detector as shown in Fig. 5. For the present purpose, it will be stated without elaboration that this arrangement ensures a spatial and angular distribution of ion trajectories into the analyzer field region. This, in turn, contributes randomly to the distribution of incident particles by the detector surface as will be discussed shortly.

The basic procedure of the Monte Carlo code has been described earlier.⁶ However, a flowchart for the present version is presented in Fig. 6 to assist in the explanation of the new features.

The letters on the flowchart correspond to the points indicated on the analyzer schematic of Fig. 5. Particles are given an initial energy and direction using a random number generator, and enter the analyzer after traversing the 7-meter flight tube (A). Their trajectories are calculated assuming constant velocities until they reach the stripping cell apertures (B and C). Only particles whose displacement from the axis of symmetry of the stripping cell is not larger than the radius of either aperture are allowed to continue into the charge exchange neutral analyzer (CLN) region (D).

Regions D, E, and F correspond to regions where the particles pass through the entrance fringe field, central field, and exit fringe field, respectively, of the magnet and electrostatic deflection plate. Their effects are calculated using the subroutines FRBD and FELD, which are described in Secs. IV and V.

As in Ref. 6, the motion of a particle of mass m , unit charge, and velocity v is governed by $mv^2/R = vB$ in the analyzing magnet. This implies a radius of curvature (in cm)

$$R = \frac{\sqrt{20.7 \text{ mE}}}{v} \quad (7)$$

where E is the kinetic energy in keV, B is in kilogauss, and m is in AMU. The electrostatic plate deflects the particle (unit charge) due to a force $F = E = V/d$, where V is the plate voltage and d is the plate gap. Since the plate and the magnet cover the same region, a distance $l = \pi R$ traveled through the magnet means a total vertical displacement of

$$Y = \frac{l^2 V}{4Ed}$$

$$= 8.51 \frac{mV}{B^2} \quad (8)$$

where d was taken to be 6 cm. The virtue of placing the plate within the magnet is evident here in that Y is independent of energy; for a fixed B and V , the vertical deflection is only a function of the mass m . Thus, B and $E = V/d$ are the only quantities needed to predict the point on the detector plane at which a particle of a certain energy and mass will impact.

In practice, particles will enter the magnet and plate region near the ground plane electrode. In the code, a reasonable value of 9.5 cm was adopted. The boundary conditions require that the magnetic and electrostatic fields do not instantaneously vanish at the edge of the region, and that the flux density increases there as one approaches either pole face or plate. The present simulation code calculates B and E as a function of horizontal and vertical (x and y) position for a more accurate determination of R and Y than was possible in the earlier version. Particles that do not strike the deflection plate and pole piece have their coordinates on the detector plane (G) recorded and plotted. All others are stored in arrays corresponding to the points along the CENA system at which they are lost.

IV. B-FIELD CALCULATIONS IN THE PRESENCE OF IRON BOUNDARIES

A set of FORTRAN subroutines was first written to find the B-field due to a number of conductors in the presence of iron,⁷ which can be called by the trajectory

simulation program to provide B as a function of x and y . The iron region is assumed to be infinite in the z -direction, with symmetry around $x = 0$.

The program first accesses the subroutine SOFIRO (SOLver for Field from Iron boundaries). This subroutine reads the iron and coil parameters from the data file CENADAT. The iron boundaries are then divided into strips (a, b, c, etc. to Fig. 1a), each carrying a current of 1 amp (unit current), and the subroutine FIELD is called. FIELD determines the field due to a current-carrying "ribbon" at a specified point in space, and is used to calculate the tangential field component at the iron boundary just above (or below) each strip. If there are NS strips, the field above (or below) a given strip is determined by that strip and the (NS-1) other strips. The resulting NS X NS field values are stored in the matrix $\underline{A}$.

Subroutine FICOND calculates the fields around conductors (field coils), and by calling it NS times, the tangential field components due to the conductors are computed and stored in the matrix $\underline{B}$. From the boundary condition that the field must be normal to the surface of a material with very high permeability, we have the relation

$$A_{ij} I_j - B_i = 0 \quad . \quad (9)$$

The actual currents I_j in the strips that satisfy this equation are found by calling the IBM/SSP subroutine LLSQ. It uses a least squares method in which the Euclidean norm (or "inner product") of the left-hand side of Eq. (9) is minimized.⁵ The currents are adjusted for finite permeability (μ) by the multiplicative factor MUFAC, where

$$\text{MUFAC} = \frac{1-\mu}{1+\mu} \quad . \quad (10)$$

They are finally stored in an array for access by the subroutine FIBO (Field from Boundaries) when it is called by CENAFOR to calculate the actual B-field.

FIBO calls RIBFLD to get the B-field contributions from the currents calculated by SOFIBO, and FICOND to get the B-field contributions from the conductors. It thus determines the x and y field components (B_x and B_y) at the coordinates (x,y) passed to it by CENA.FOR.

The results we obtain from FIBO are plotted in Fig. 7b, which is an enlargement of the region around the field coil indicated by the dotted line on Fig. 7a. The decrease in density of the field lines reflects the expected variation in the B-field strength with horizontal distance outward from the magnet.

V. ELECTROSTATIC FIELD CALCULATIONS

The electrostatic deflection plate geometry is essentially that of a parallel-plate capacitor in free space, with streamlines and equipotentials as in Fig. 8a.⁹ If we map this into the w-plane and solve for the complex potential Φ (Fig. 8b),

$$z = x + iy = \frac{d}{\pi} \left[\ln w + \frac{1}{2} (1 - w^2) \right] \\ z = \frac{d}{\pi} \left[\ln(u + iv) + \frac{1}{2} (1 - u^2 - v^2) \right] \quad (11)$$

$$\Phi = V_0 + iX = \frac{V_0}{\pi} \ln w \quad (12)$$

Therefore,

$$z = \frac{d}{\pi} \left\{ \frac{i\pi}{V_0} \Phi + \frac{1}{2} \left[1 - e^{2 \left(\frac{i\pi}{V_0} \Phi \right)} \right] \right\} \quad (13)$$

We want to find

$$F = q \\ = \left| \frac{d\Phi}{dz} \right| \quad (14)$$

for particles of unit charge. From Eq. (13),

$$\frac{d\Phi}{dz} = \frac{14}{V_0} \left[\frac{2 \left(\frac{1}{V_0} \Phi \right)}{1 - e^{-\frac{2 \left(\frac{1}{V_0} \Phi \right)}}} \right] \quad (15)$$

$$\frac{d\Phi}{dz} = \frac{V_0/d}{\left\{ \left[\frac{2 \left(\frac{1}{V_0} \Phi \right)}{1 - e^{-\frac{2 \left(\frac{1}{V_0} \Phi \right)}}} \right] \left[1 - e^{-\frac{2 \left(\frac{1}{V_0} \Phi \right)}} \right] \right\}}$$

$$\left(\frac{V_0/d}{\left(1 - 2e^{-\frac{2\pi}{V_0} y} \cos \frac{2\pi}{V_0} x + e^{-\frac{4\pi}{V_0} x} \right)} \right)^{1/2} \quad (16)$$

If we approximate $x + iy$ by

$$x + iy \cong i \frac{d}{V_0} \Phi + i \frac{d}{V_0} x + \frac{d}{V_0} y \quad (17)$$

then

$$E_z = \frac{V_0/d}{\left(1 - 2e^{-\frac{2\pi}{d} x} \cos \frac{2\pi y}{d} + e^{-\frac{4\pi x}{d}} \right)}^{1/2} \quad (18)$$

where the edge of the plate is at $x = 0$. This is the electrostatic field that the subroutine ELFD calculates as a function of x and y .

The electrostatic fringe field along the midplane of the CENA system has a simple form which can be easily derived from Eq. (18). In this case, $y = 3$ cm and $d = 6$ cm in the argument of the cosine term, so that

$$\begin{aligned}
 E_x &= \frac{V_o/d}{\left[1 - 2e^{\frac{2\pi}{d} \cdot x} \cos\left(\frac{2\pi \cdot 3}{6}\right) + e^{\frac{4\pi}{d} \cdot x} \right]^{1/2}} \\
 &= \frac{V_o/d}{\left[1 + 2e^{\frac{2\pi}{d} \cdot x} + e^{\frac{4\pi}{d} \cdot x} \right]^{1/2}} \\
 &= \frac{V_o/d}{1 + e^{\frac{2\pi}{d} \cdot x}} \quad (19)
 \end{aligned}$$

Equation (19) can be expressed in terms of a hyperbolic tangent as follows:

$$\begin{aligned}
 E_x &= \frac{V_o}{d} \left[\frac{e^{-\frac{\pi}{2d} \cdot x}}{e^{-\frac{\pi}{2d} \cdot x} + e^{\frac{\pi}{2d} \cdot x}} \right] \\
 &= \frac{V_o}{2d} \left[1 - \frac{e^{\frac{\pi}{2d} \cdot x} + e^{-\frac{\pi}{2d} \cdot x}}{e^{\frac{\pi}{2d} \cdot x} + e^{-\frac{\pi}{2d} \cdot x}} + \frac{2e^{-\frac{\pi}{2d} \cdot x}}{e^{\frac{\pi}{2d} \cdot x} + e^{-\frac{\pi}{2d} \cdot x}} \right] \\
 &= \frac{V_o}{2d} \left[1 - \frac{e^{\frac{\pi}{2d} \cdot x} - e^{-\frac{\pi}{2d} \cdot x}}{e^{\frac{\pi}{2d} \cdot x} + e^{-\frac{\pi}{2d} \cdot x}} \right] \\
 &= \frac{V_o}{2d} \left[1 - \tanh\left(\frac{\pi}{2d} \cdot x\right) \right] \quad (20)
 \end{aligned}$$

We thus have a convenient analytic expression for modeling the behavior of the electrostatic field as a function of horizontal distance. This analytic form provides

an approximate representation of the magnetic fringe field as well for certain simple magnet models.

VI. RESULTS

The B -field strength was first calculated as a function of horizontal distance from the magnet midplane for several different field coil series. As can be seen in Figure 8, the magnetic field is fairly insensitive to the coil dimensions, so that exact dimensions are not necessary in fabrication of the coil. However, it is also clear that Eq. (19) is not a realistic approximation in that it does not account for the actual nonuniform forces and field coil geometry. Figures 10a and 10b show the magnetic and electrostatic fields ($V = 5$ kV) that each ion species with an energy of 64 keV encounters as it passes through the E/B analyzer, and Figures 11a and 11b are the results for 64 keV particles. The solid, dashed, and dotted lines correspond to protons, deuterons, and tritons, respectively, and in all cases, the field strength is greatest near the ground plane electrode (Sec. III) at the analyzer edge, where the flux density is highest. The fields seen by the entering deuterons and tritons are almost indistinguishable; on Figs. 10 and 11, they actually lie on top of each other above the upper dashed (neutron) lines. This is because the deuterons and tritons differ in mass by only a third, whereas they are two and three times heavier than the protons. The fields approach a constant value toward the center of the analyzer, and are less peaked for particles as they emerge because they are then closer to the midplane of the magnet.

Operating characteristics of microchannel plates are available in the literature,¹⁰⁻¹² and from them we calculated the maximum allowable field strength for the planned CENA geometry. This was found to be ~ 500 gauss, which is about a tenth of its value at the center of the magnet and electrostatic plate assembly. On this basis, it was decided that the detector plane should be at least 5.5 cm away from the pole and plate edge to satisfy this criterion (see Fig. 9).

Maintaining the detector plane parallel to, but displaced 5.5 cm beyond, the exit edge of the magnet is expected to distort the parallel, linear mass column geometry which occurs for exactly 180° deflection in uniform fields as described in Sec. II. From the equations of motion for an ion in a constant electric field,⁶ it is easy to show that beyond the magnet exit, the vertical position $\hat{Y}_j$ of species $(m/e)_j$ is given by

$$\hat{Y}_j = Y_j + 1 + \frac{4s}{\pi z_{jk}} \quad (21)$$

where $s(\text{cm})$ is the distance beyond the "sharp-field" edge of the magnet, Y_j is the vertical position at the magnet edge given by Eq. (3), and z_{jk} is the perpendicular distance between the ingoing/outgoing ion trajectories Eq. (4). Thus for $s > 0$, the lower energy (smaller z_{jk}) ions will exhibit a greater vertical displacement than those of higher energy. This behavior is evidenced in Fig. 12a, which shows the scatter of ions incident on the detector plane at $s = 5.5 \text{ cm}$ for the "sharp-field" case, i.e., no magnetic or electric fringe fields. Also, it can be seen that the vertical width of the scatter distribution for each mass increases with increasing distance along the detector plane. This occurs because the detector plane provides an image through the stripping cell "pin-hole" of the source which has a distribution in space and angle of initial ion trajectories. The distance from the pin-hole to the image plane, of course, increases with increasing distance along the detector plane.

The effect of including the magnetic fringe field (no electric fringe field) is illustrated in Fig. 12b. In general, the vertical deflection is reduced all along each mass column, the reduction being most pronounced at low energies. This occurs due to the fact that no electric field exists in the portion of the particle trajectory through the magnetic fringe field. With decreasing energy, this portion increases, thereby reducing the time the particle spends in the electric field and consequently reducing the vertical deflection.

the matter of particles at the detector plane when both the magnetic and electrostatic fringe fields are included in the calculation is depicted in Figs. 13a and 13b. The first plot corresponds to particle energies ranging from 1.1 to 55 keV (low), and the energy range of the second plot is from 11 to 650 keV (high). The important point to note is that the bulk of each species falls within one centimeter wide strips centered on the detector plane as required by the detector geometry shown in Fig. 1. The results for the low energy range (Fig. 13a) are in good agreement with those obtained with the magnetic fringe field only, as discussed above in connection with Fig. 10a.

Figure 13b shows the dispersion with energy of the detected particles in the high energy range, and it suggests that the resolution provided by detectors eleven centimeters in width (Fig. 4) will vary from about 0.3 keV to 0.6 keV. The associated values for the high energy range (Fig. 13b) are 3 keV and 6 keV. These values are in reasonable agreement with those calculated from the detector geometry according to Eq. (5).

In Fig. 16a, the high energy range well exceeds the 150 keV requirement for the TFTR charge exchange diagnostics. The three mass columns are adequately focused onto the good mass separation. As seen in Fig. 14a, the mass resolution characteristics are preserved at lower energies. Thus the analyzer must only be tuned to cover various energy ranges without loss of mass resolution.

VII. CONCLUSIONS

The results of the simulation program indicate that using the magnet and electrostatic plate specifications for the TFTR-CENA system given in Table I, particles (H^+ , D^+ , T^+) over a broad energy range can be focused onto the detector plane. The design for the channel multiplier array calls for three 1 cm wide strips centered at heights of 1.5 cm, 3.0 cm, and 4.5 cm, and we have demonstrated that

with reasonable plate potentials (about 0.6 kilovolts and 6 kilovolts for the low and high energy ranges), the arrangement will enable the protons, deuterons, and tritons to be mass resolved over an energy range in excess of 0.5 to 150 keV.

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TABLE I

MAGNET AND ELECTRIC FIELD SPECIFICATIONS
FOR THE TFTR CHARGE EXCHANGE NEUTRAL ANALYZER

1. Pole and Plate Dimensions
 - 30 cm diameter semi-circle.
 - 6 cm distance between pole faces.
 - Approximately 5.5 cm distance between plate and ground plane (lower magnet pole face).
2. Field Coils
 - Cross section of approximately 4 cm x 6 cm.
 - Maximum of 14,400 ampere-turns (5.4 kilogauss field).
3. Voltage requirements
 - DC voltage variable up to approximately 6 kilovolts.

Fig. 1. Arrangement of twelve perpendicular analyzers for ion temperature radial profile measurements.

PPPL-793441

PPPL-783808

Fig. 2. Arrangement of eight tangential analyzers for measuring the slowing down energy distribution of beam-injected ions.

Fig. 3. Schematic of E113 analyzer concept.

PPPL-793825

Fig. 4. Geometry of channel electron multiplier array (CEMA).

PPPL-783951

PPPL-793889

Fig. 5. Schematic of proposed TFTR charge exchange neutral analyzer (CENA) system.

TEMA_FPD: Monte-Carlo Code for Calculating
Particle Trajectories in the TETR CENA System

Fig. 6. Flowchart of Monte Carlo simulation program for calculating particle trajectories in the TFTR CENA system (CENA.FOR).

PPPL-793789

PPPL-793929

Fig. 7. Iron boundaries and field coil locations for B-field calculations using FIBO (a) and enlargement of region around magnet field coil showing B-field lines (b).

PHYL-7-3883
Fig. 9. B-Field strength as a function of distance along the pole's longitudinal plane for several different pole dimensions.

PPPL-793885
 Fig. 10. B-field strength (a) and E -field strength ($V = E \cdot d$) (b) as a function of distance as seen by the three ion species (ion energy = 6.4 keV).

Fig. 11. B-field strength (a) and E-field strength ($V = Ed$) (b) as a function of distance as seen by the three ion species (ion energy = 64 keV).

PPPL-793886

Fig. 12. Scatter plot of particles in the detector plane (a) without fringe fields, and (b) with magnetic fringe fields only.

PPPL793928

PML-793884

Fig. 13. Scatter plot (a) and dispersion as a function of energy (b) for both magnetic and electrostatic fringe fields included (low energy range)

PPPL-793890
 Fig. 14. Scatter plot (a) and dispersion as a function of energy (b) for both magnetic and electrostatic fringe fields included (high energy range).