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## Design of a retarding potential grid system for a neutral particle analyzer<sup>a)</sup>

J. B. Titus,<sup>1,b)</sup> J. K. Anderson,<sup>2</sup> J. A. Reusch,<sup>2</sup> and E. D. Mezonlin<sup>1</sup>

<sup>1</sup>*Department of Physics, Florida A&M University, Tallahassee, Florida 32310, USA*

<sup>2</sup>*Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA*

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The ion energy distribution in a magnetically confined plasma can be inferred from charge exchange neutral particles. On the Madison Symmetric Torus (MST), deuterium neutrals are measured by the Florida A&M University compact neutral particle analyzer (CNPA) and the advanced neutral particle analyzer (ANPA). The CNPA energy range covers the bulk deuterium ions to the beginning of the fast ion tail (0.34–5.2 keV) with high-energy resolution (25 channels) while the ANPA covers the vast majority of the fast ion tail distribution (10–45 keV) with low energy resolution (10 channels). Though the ANPA has provided insight into fast ion energization in MST plasma, more can be gained by increasing the energy resolution in that energy range. To utilize the energy resolution of the CNPA, fast ions can be retarded by an electric potential well, enabling their detection by the diagnostic. The ion energy distribution can be measured with arbitrary resolution by combining data from many similar MST discharges with different energy ranges on the CNPA, providing further insight into ion energization and fast ion dynamics on MST. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4885496>]

### I. INTRODUCTION

The Madison Symmetric Torus (MST) has added two time-resolved neutral particle analyzers, the Florida A&M University compact neutral particle analyzer (CNPA)<sup>1,2</sup> and the advanced neutral particle analyzer (ANPA),<sup>3,4</sup> to its collection of diagnostics. The CNPA, with 25 channels and an energy range of 0.34–5.2 keV, is used for studying the bulk deuterium ion energy distribution and beginning of the non-Maxwellian, fast ion tail.<sup>5</sup> The ANPA, with 10 channels and an energy range of 10–45 keV, is used for studying the energization of the fast hydrogen and deuterium ions during neutral beam injection (NBI).<sup>6</sup> Although the ANPA covers a wide range of energy, the energy resolution is poor and the channels are only relatively calibrated. To further study high energy deuterium ions, a scheme has been developed to exploit the energy resolution of the CNPA on high energy deuterium ions. A retarding potential can be used to decelerate ions into the CNPA's energy range, utilizing the high energy resolution to measure a more accurate ion energy distribution.

Retarding potentials have been used in a variety of analyzers and applications to measure charged particle distributions. Retarding potential analyzers or ion traps have been used aboard spacecraft and satellites to measure atmospheric ion energy distributions.<sup>7,8</sup> Ions above a certain energy threshold, set by a voltage of a set of retarding grids, are detected by a collector producing a current. An ion energy distribution and subsequently an ion temperature are inferred from the current.<sup>9</sup> Other retarding potential analyzers in front of mass spectrometers have been used in chemical physics to

study metastable ions.<sup>10,11</sup> By raising the ground potential of the mass spectrometer, ions are eliminated from detection that have not undergone metastable dissociation, decreasing the noise floor. The system of grids in these retarding potential analyzers provides a good model for decelerating ions into a neutral particle analyzer. To measure ions in a particular 5 keV energy range (the energy range of the CNPA), a specific voltage can be applied to the retarding potential to decelerate the ions so they can be detected. Given the reproducibility of MST plasmas, an ensembled ion energy distribution can be calculated with a minimum of 175 points between 0.34 and 35 keV. This highly resolved distribution may provide insight into fast ion dynamics in high temperature plasmas.

### II. PRINCIPLE OF OPERATION

The well-calibrated CNPA can measure high energy particles by decelerating them on the way into the analyzer. Neutral deuterium,  $D^0$ , that has escaped confinement travels down the vacuum tube at an initial velocity,  $v_i$ . Using a set of grids at different voltages, shown in Fig. 1, an electric potential well can be established between the grids and ground at the vacuum tube that accelerates charged particles. An electric potential well is established between the grids and ground while there is an electric potential “bump” in between them at grid B for electron suppression.

The neutrals are ionized at grid A, where there is an ionizing foil. Grid B is set to a slightly higher voltage,  $V_s$ , to accelerate electrons out of the particle beam to the walls at ground,  $V_g$ , and decelerating the ions,  $D^+$ , to a velocity,  $v_s$ . This suppresses the electrons from recombining with the ions between the retarding potential and the CNPA. It also prevents the potential difference from accelerating the electrons into the CNPA, likely creating x-rays. The ions are brought back to the initial velocity by potential between grids B and C

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<sup>b)</sup>Author to whom correspondence should be addressed. Electronic mail: [jtitus@wisc.edu](mailto:jtitus@wisc.edu)

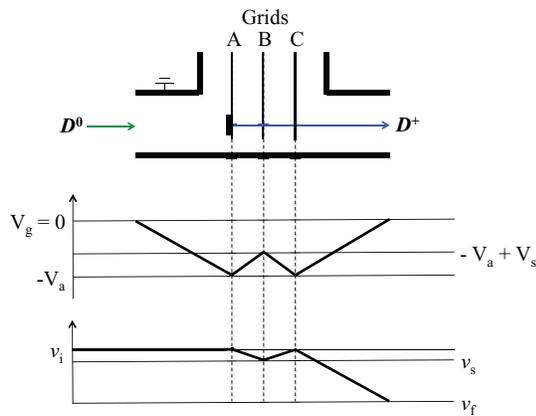


FIG. 1. Principle of the retarding potential grid system in front of a neutral particle analyzer.  $D^0$  refers to the deuterium neutral,  $D^+$  refers to deuterium ions,  $V_g$  is the voltage at ground,  $V_a$  is the power supply applied voltage,  $V_s$  is the applied voltage to suppress electrons,  $v_i$  is the initial velocity,  $v_s$  is the velocity due to the suppression grid, and  $v_f$  is the final velocity.

and are then decelerated to a final velocity,  $v_f$ , between grid C and the end of the flange (at  $V_g$ ). If the stripping cell of the CNPA is disabled, the decelerated ions will be detected at their final velocity, i.e., with an applied voltage of  $-30$  kV, the ions with an energy of  $30.34$  keV will be detected by the CNPA's first channel ( $0.34$  keV).

For an energy distribution of ions, the applied voltage establishes the minimum threshold of energy that ions must have to enter the CNPA. In MST plasmas during neutral beam injection, deuterium ions are known to have energies up to  $40$  keV.<sup>3</sup> Taking a set of discharges while changing the  $V_a$  between shots from  $-5$  to  $-30$  kV in  $5$  kV increments, for example, yields an ensemble ion energy distribution containing  $175$  points between  $0.34$  and  $35$  keV.

### III. APPARATUS

The retarding potential grid system, shown in Fig. 2, is composed of four main parts: two  $30$  kV weldable electrical feedthroughs (I), the three grids (VII), the support system for the wires between the feedthroughs and the grids (III and IV), and the custom four-way vacuum tube (VI). The vacuum structure of the retarding potential is a standard  $6$  in. nipple with two  $2.75$  in. half nipples welded perpendicular to the  $6$  in. nipple, creating a hybrid four-way. The larger  $6$  in. nipple with  $4$  in. tubing is used to fit the electrical feedthroughs, which have a  $1.5$  in. base. These are then welded to a

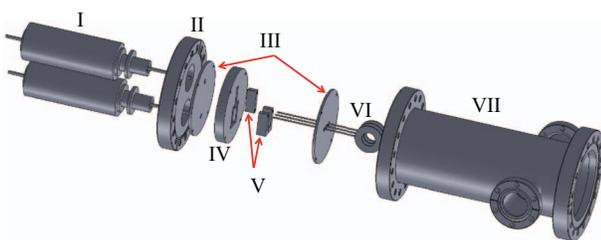


FIG. 2. The exploded schematic of the retarding potential grid system: high voltage feedthroughs (I), custom flange (II), boron nitride caps (III), boron nitride stabilizer (IV), brackets (V), retarding grids (VI), and custom four way vacuum tube (VII).

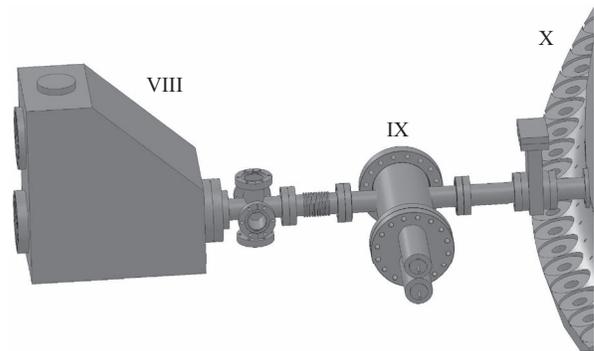


FIG. 3. A drawing of the CNPA (VIII) on MST (X) with the retarding potential grid system (IX).

blank  $6$  in. flange (II). The grids are composed of stainless steel wires mounted on aluminum disks (outer diameter of  $1.26$  in., a through hole diameter of  $0.39$  in. and  $0.5$  in. thick). The feedthroughs are connected to the grid wires with custom aluminum brackets (V). These brackets sit inside a  $4$  in. boron-nitride disk that provides support to the wires and insulates the brackets from each other. Boron-nitride caps are bolted on to each side of the disk, ensuring the brackets are secured to the disk. The carbon stripping foil is placed on grid A at the valley of the electric potential well. A drawing of the CNPA (VIII) on MST (X) with the retarding potential grid system (IX) is shown in Fig. 3.

### IV. SIMULATIONS

Simulations of the electric potential and the effect it has on charged particle trajectories were done with COMSOL Multiphysics. A simulation of the electric potential with grids A and C set to  $-30$  kV and grid C set to  $-29$  kV is shown in Fig. 4. Since the grids are surrounded by ground, the electrical

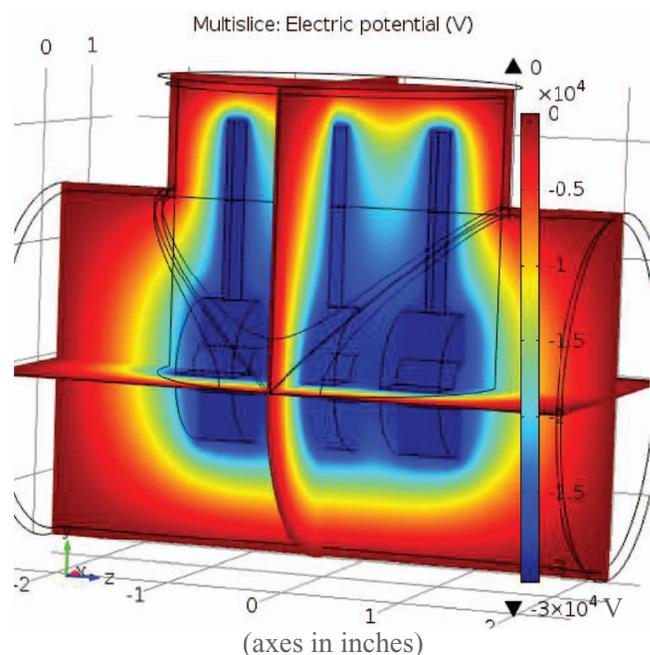


FIG. 4. The electric potential well of the retarding potential (grid A, C  $\sim -30$  kV; grid B  $\sim -29$  kV).

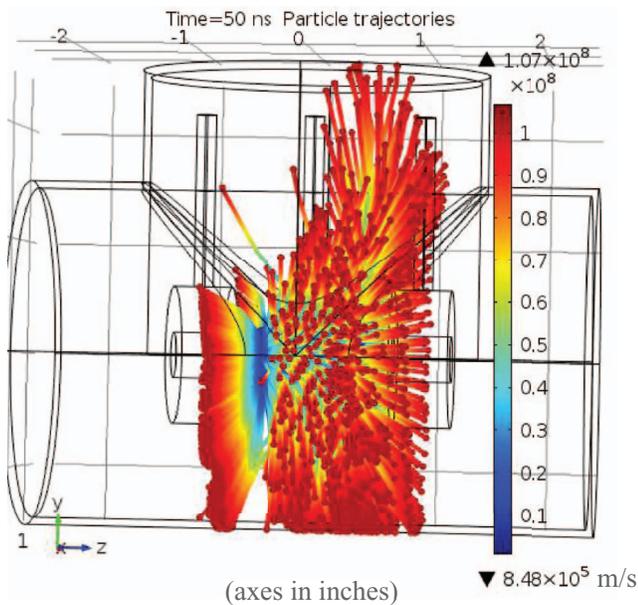


FIG. 5. The electron particle trajectory due to the retarding potential grid system potential well in Fig. 4.

potential decreases to zero within the custom four-way vacuum tube, showing that the particles should only slow down to their theorized values.

The electron and ion particle trajectories with initial velocities that correspond to 35 keV neutrals are shown in Figs. 5 and 6, respectively. The electrons trajectories are shown to get bent perpendicular to the beam of ions or accelerated back toward MST. The ions with velocities over

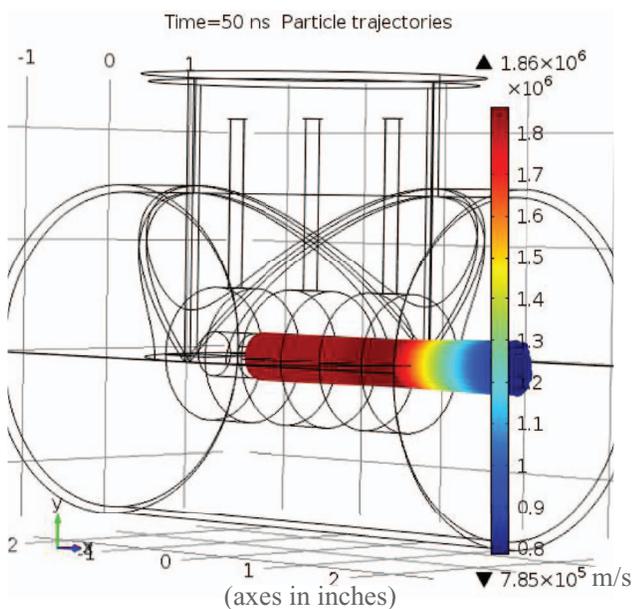


FIG. 6. The ion particle trajectory due to the retarding potential grid system potential well in Fig. 4.

the threshold are shown to decelerate to velocities comparable to 5.0 keV particles. The interaction of the retarding potential grid system happens on the nanosecond time scale and does not affect the timing of the measurements.

The detection efficiency of the system is changed because of the use of a stripping foil, instead of the stripping cell and focusing lens. The detecting efficient is a combination of the efficiency of neutral conversion to ion in the stripping foil and the scattering of the ions in the foil.<sup>12</sup> With the use of large grid mounts and the focusing nature of the lens system, the scattering and the asymmetry effects of the potential well are minimized. Therefore, since the same thickness and density foil used in Refs. 3 and 4 will be used in this system, the detection efficiency for that system would be a good approximation for this system.

## V. CONCLUSION

The deuterium ion energy distribution in MST plasmas is measured from charge exchange neutrals in the energy range 0.34–45 keV by the CNPA and ANPA. The CNPA energy range covers the bulk ions to the beginning of the fast ion tail (0.34–5.2 keV) with high-energy resolution (25 channels) while the ANPA spans the vast majority of the fast ion tail distribution (~10–45 keV) with low energy resolution (10 channels). To gain more knowledge of the energy distribution for ion energization studies, a retarding potential grid system has been designed to be put in front of the CNPA, decelerating the fast ion tail and enabling it to be detected by the low energy, high energy resolution channels.

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