DESIGN OF A COMPACT, HIGH-RESOLUTION ANALYZER FOR LONGITUDINAL ENERGY STUDIES IN THE UNIVERSITY OF MARYLAND ELECTRON RING*

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Abstract

Retarding-potential energy analyzers have long been used for energy spread measurements in low-energy beams. In addition to energy spread and energy profile measurements, a high-resolution analyzer can be used to reconstruct the longitudinal phase space. This is useful for our experimental studies of longitudinal physics topics, such as dispersion, space charge waves, and longitudinal focusing. A previous energy analyzer designed at the University of Maryland demonstrated high-resolution measurements of a 5 keV electron beam [1]. Motivated by the need to characterize the 10 keV electron beam of the University of Maryland Electron Ring, we have improved on the design of the earlier analyzer, increasing its high voltage breakdown threshold and vacuum performance. Results of high-voltage testing and particle optics simulations of the new design are presented.

MOTIVATION

Space charge forces have strong effects on longitudinal beam dynamics [2]. Our investigation of longitudinal physics at high space charge in the nonrelativistic regime motivates the creation of instruments to measure the particle distribution at high energy resolution.

Space charge applies fields to the ends of the beam, accelerating the head and decelerating the tail, causing longitudinal expansion. To counter this, longitudinal focusing fields can be applied; the effect of these fields on the beam's energy profile is important for accurate focusing [3].

When space charge is combined with the effect of perturbations on the beam, we see space charge waves. In the linear regime, subject to relatively low-amplitude perturbations in charge density, these effects manifest as sinusoidal waves [4]. With larger perturbations, nonlinear effects become significant, as illustrated by observations of solitons on the UMER beam for high induced perturbation currents [5]. Again, the energy profile associated with space charge waves is of interest, particularly for accurate simulation work [6].

Longitudinal perturbations of a particle beam can cause unwanted modulations in beam current and energy, reducing beam quality. Longitudinal perturbations created at sub-relativistic speeds at the source of the beam are preserved, becoming frozen in as the beam reaches relativistic speeds. This makes study of the longitudinal physics of high space charge beams applicable to the problem of designing high quality beams in general.

DESIGN OF ANALYZER

At relatively low energies, it is possible to measure the energy distribution by applying a retarding potential to a wire grid in the path of the beam. When the grid is held at a given potential (such as 10 kV), it will reject particles with kinetic energy below the corresponding energy threshold (10 keV), and allow those above the threshold to pass. By collecting the particles which pass through the grid, we can measure the portion of the beam above the threshold energy. By scanning the grid potential across a broad range of voltages, we can create an energy profile for the beam and reconstruct its energy distribution.

The grid only affects longitudinal velocity: velocity parallel to the plane of the retarding mesh is not measured, and can cause particles to be deflected by the grid even if their total kinetic energy is above the nominal threshold. To compensate for this, a focusing scheme is required. It is desirable to focus the beam with a high voltage cylinder, analogous to the charged plate of an einzel lens. With the proper choice of focusing cylinder voltage, we can greatly improve the energy resolution of the analyzer [7].

Practical Considerations

The original version of this analyzer design, designed for a 5 keV beam, suffered electrical breakdown problems around 6 kV, precluding use of it with the 10 keV UMER beam. The analyzer must hold a steady DC voltage to operate. Even minor fluctuations in voltage make it unsuitable for use, and any breakdown over the voltage range of interest is unacceptable. This mandated a redesign of the analyzer to handle voltages up to and including 12 kV, to provide a margin of error.

To make this possible, the old design was modified as shown in Figure 1, increasing the vacuum gap between the focusing cylinder and the grounded outer housing, and using fewer ceramic rings for structural support. The main ceramic rings now employ a scalloped surface to further discourage arcing by increasing surface path length.

The essential design concept of the instrument remains the same, but the modified design can withstand considerably higher voltages without arcing. A series of Poisson Superfish simulations were performed to optimize the high voltage engineering of the device, which reduced the peak electric fields by an order of magnitude.

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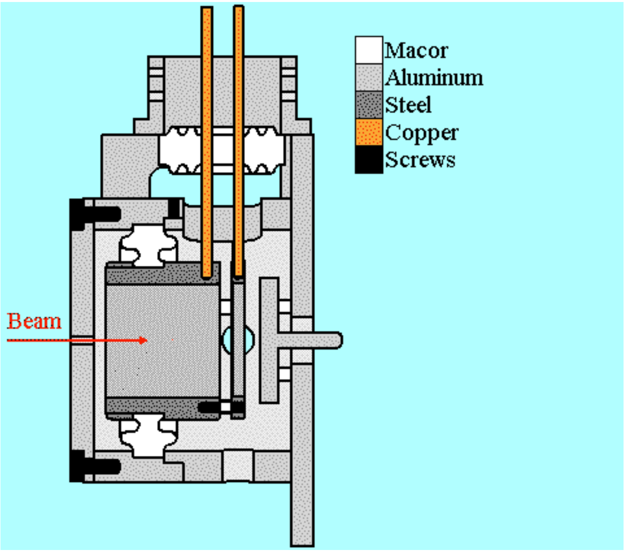

Figure 1: Cross-section of the new energy analyzer design. In order for the beam to experience axisymmetric fields, the aperture is concentric with the focusing cylinder and the grid.

TESTING AND SIMULATION

High voltage tests were done on the old analyzer design under typical vacuum conditions (~10^{-8} Torr) to test its performance. The old design broke down at 6 kV. After substantial high voltage conditioning, the breakdown threshold rose to 10 kV: still too low for operation in UMER. During breakdown, increases in chamber pressure by an order of magnitude were observed, indicating vaporization of material due to arcing.

After construction of the redesigned analyzer, it was tested in a similar arrangement. The new design reached voltages of up to 14.7 kV without arcing. This voltage was held for periods of up to thirty minutes with no sign of electrical breakdown. This is expected to be adequate for study of beams in UMER in the 8-12 keV range.

Energy Resolution in Simulation

The energy resolution of the new energy analyzer hardware is a key question. In the ideal case, with perfect focusing, no space charge, and an ideal grid, the energy acceptance of the analyzer would be a step function: all electrons above the grid potential would pass, while all electrons below it would be blocked. In practice, we expect continuous variation of acceptance through a range of energies. The size of this range limits the energy resolution of the device, and thus the resolution of measurements of the beam distribution in longitudinal phase space.

Without focusing, particles that enter the analyzer off-axis will have a higher effective threshold energy than those moving along the axis. Even if the particle's kinetic energy exceeds the value required for a particle moving parallel to the axis, its velocity in the z-direction may be too low to reach the grid, causing it to be rejected.

The focusing cylinder is used to minimize this effect as far as possible. For optimal choice of focusing voltage, particle trajectories entering the device off-axis will be bent so as to approach the grid while pointing parallel to the axis. This reduces the effect of angular spread on a particle's ability to pass the grid and be recorded as part of the signal from the device.

Using the ion optics code SIMION [8] to model the path of electrons through the device, it was found that best resolution occurs at a bias voltage of ~170 V (i.e. grid at -10000 V and cylinder at -9830 V). This setting has been found to be valid throughout the 8-12 keV range the analyzer is designed to investigate.

In Figure 2, we see that as the bias voltage moves away from this optimal setting, particles require higher energy to pass through the grid when entering the device at larger angles off-axis. This imposes a resolution limit dependent on the angular spread of the beam. At a 170 V bias, this limit is minimized to a value of less than 1 eV in the 8-12 keV range, even for angle values as large as eight degrees. This gives the device a ~1 eV resolution over an energy range of 4 keV.

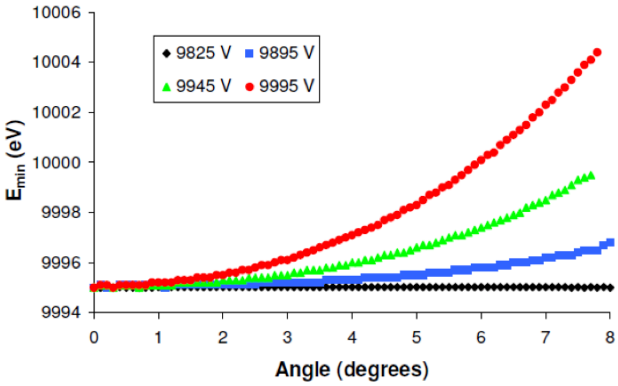

Figure 2: Plot of the minimum energy at which electrons pass the grid, as a function of the angle off-axis with which they entered the analyzer. Each curve corresponds to a different cylinder voltage setting in the simulation. Note that minimum energy grows more quickly for the larger cylinder voltages.

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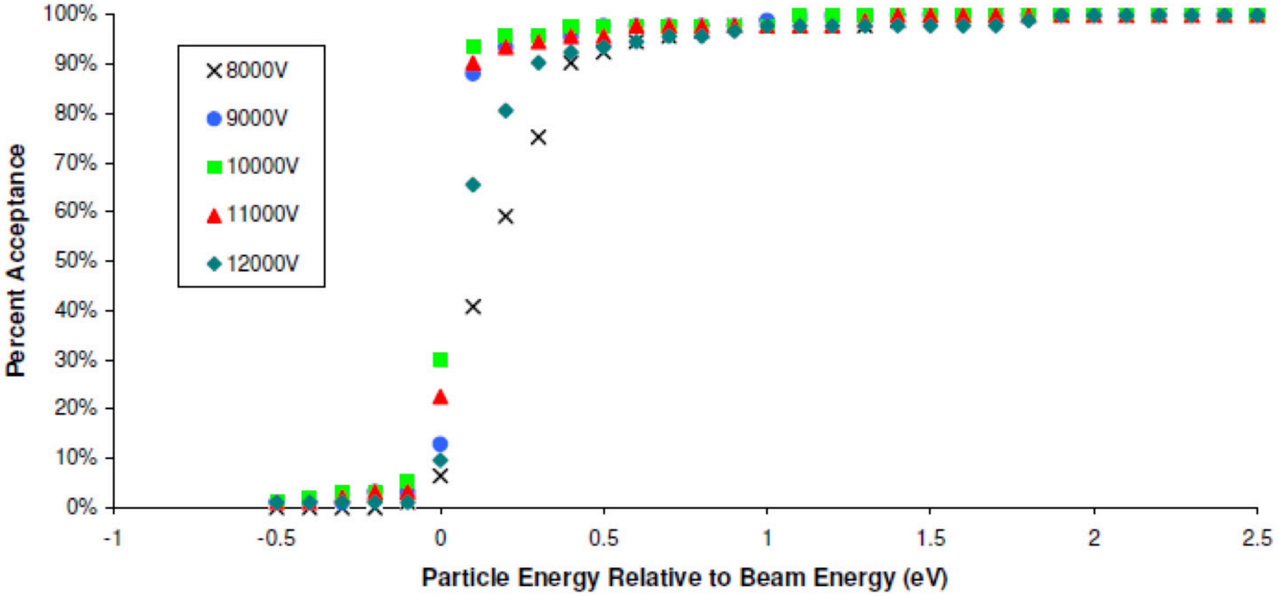

Figure 3: Plot of the acceptance of the analyzer when examined across an 8° half-angle spread, for beam energies ranging from 8-12 kV, with a fixed potential difference of 170 V between the grid and focusing cylinder voltages.

The energy spread between low and high acceptance values is a figure of merit for energy analyzer resolution. At the low end of this energy range, the analyzer rejects nearly all incoming particles; at the high end, nearly all particles pass through the grid and reach the collector. The wider the range, the worse the resolution, as the analyzer is less able to distinguish between particles of different energy values within the range.

Above is a plot of acceptance in these terms, simulated for a wide angular spread of up to 9°, representing a worst-case scenario for the angular divergence of the beam. This simulation was run for beam energies between 8 and 12 keV in 1 keV increments. In each case, simulation concentrated on behaviour in a narrow range around the voltage value listed in the legend. On the horizontal axis, we have the difference between the electron's kinetic energy and the grid's ideal threshold energy (8000 eV for a -8000 V grid, and so on).

Figure 3, taken at the 170 V bias voltage identified earlier, shows a sharp transition from very low acceptance to very high acceptance at 10 keV. As the beam energy moves away from 10 keV, the transition becomes less sharp. This is particularly notable at the more extreme values of 8 and 12 keV. This is because the 170 V bias setting was selected for optimum focusing at 10 keV specifically; the ideal focusing voltage is somewhat dependent on particle energy.

However, in all cases we observe that the transition region is less than or roughly equal to 1 eV in size, even for the extreme angular spread scenario considered. Therefore, we predict an energy resolution of ~1 eV from this device over the 8-12 keV range.

CONCLUSION

In summary, the original variable-focusing analyzer for UMER has been redesigned and improved for higher-voltage operation, to be compatible with the 10 keV UMER beam. Empirical high voltage testing of the new equipment confirms that it can handle the voltages required for operation in UMER. Simulations of the new design indicate resolution of approximately 1 eV over the 8-12 keV range of operation.

Installation of the energy analyzer is planned for summer 2011, pending design and construction of the mount and actuator for the device.

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