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The Holifield Radioactive Ion Beams Facility (HRIBF) - getting ready to do experiments

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Abstract

The conversion of the HHIRF facility to a Radioactive Ion Beam facility started in 1994. In this ISOL type facility the Cyclotron has been re-fitted as a driver providing high intensity proton beams which react with the target from which the radioactive products are extracted and then accelerated in the Tandem Electrostatic Accelerator to the desired energy for nuclear science studies.

Facilities for nuclear physics experiments are at different stages of development: A Recoil Mass Spectrometer (RMS) with a complement of detectors at the focal plane and around the target is used primarily for nuclear structure studies. A large recoil separator combining velocity and momentum selection, with its complement of focal plane detectors, will be dedicated to measurements relevant to nuclear astrophysics. The Enge Split Pole spectrograph is being re-fitted for operation in a gas filled mode, making it a more versatile tool for nuclear reaction studies. With the new experimental equipment being commissioned and the prospects of running experiments with low intensity radioactive beams a significant effort to develop equipment for beam diagnostics is underway. Some of our efforts and results in developing beam diagnostic tools will be described.

1 Introduction

The possibilities and promise to nuclear science research that can can be realized when using radioactive ion beams has been the subject of numerous conferences and symposia and was recently summarized in a white paper following an "all hands" meeting in Columbus, Ohio [2]. Presently, HRIBF is the only ISOL type facility in operation in North America capable of providing proton rich radioactive beams accelerated to energies in excess of few MeV/A [1]. The layout of the facility is shown in Fig. 1 and indicates the placement of several experimental facilities. The RMS - a large recoil mass spectrometer - which is now fully operational [3]. The DRS - a recoil separator based on velocity

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and momentum selection - is in its final stages of commissioning [4, 5]. The Enge Split Pole spectrograph is being re-fitted for work with low pressure gas filling. The UNISOR isotope separator facility is presently used for testing RIB production schemes and ion-source design using proton beams from the 25MV Tandem Accelerator. The general purpose beamline is in use for studies of beam diagnostic devices which will be discussed later. The first RIB experiment performed at the HRIBF was also performed in this beamline [8].

2 Experimental facilities at HRIBF

2.1 The Recoil Mass Spectrometer

The RMS - Recoil Mass Separator was commissioned during 1995-96 and is now fully operational. The RMS combines a momentum separator and a mass separator and is planned as a large filter for nuclear structure measurements using both in-beam and decay studies. The layout of the spectrometer appears in Fig. 2 where some parameters of the device are listed. The momentum separator refocuses the products at the achromatic focus. The momentum acceptance is determined at the dispersion plane of the first stage ("Fingers Region"). The focus at the achromat is weak, allowing for higher acceptance values at the mass separator stage. A complement of detectors exists around the target station as well as at the focal plane of the mass separator: Five clusters (Clovers) and six single Ge high resolution photon detectors surround the target chamber. The focal plane is equipped with a thin, two-dimensional position sensitive detector ($10cm \times 30cm$) facilitating A/Q identification of the recoil products reaching the focal plane. Mass spectra obtained during a first test run with 210 MeV ^{58}Ni beam on ^{60}Ni target are shown in Fig. 3 - the 1:450 number quoted in Fig. 2 was derived from this spectrum. The spectrum shown in Fig. 3 is an inclusive spectra and shows very little non-recoil (or beam) background. Following this thin detector, one can position a gas-filled ionization chamber for Z identification, or a double-sided Si Strip detector used to catch recoil products and study their proton or alpha particle decays [9]. Future plans call for the addition of BGO shields around the Ge detectors surrounding the target and a charged particle "ball" surrounding the target as well as some additional capabilities at the focal plane.

2.2 The Daresbury Recoil Separator (DRS)

The Astrophysics end station is centered around the DRS [5] - the Daresburry Recoil Separator [7] which was shipped to ORNL in 1994, where it was reinstalled by members of the RIBENS [6] collaboration and HRIBF staff. Figure 4 shows the separator which combines velocity and momentum selection to separate beam from reaction products recoiling to zero degrees. Some reactions which the astrophysics group plans to measure with this device are shown in the top left corner of that figure. Also shown in this figure are the additions to

the target station and the focal plane region. The focal plane assembly [7], built at Daresbury UK, consists of a position sensitive foil + microchannel detector assembly and a 30 cm deep gas-filled ionization chamber. The specifications for this spectrometer are shown on the right - the specified (0.3%) resolution in A/Q can be realized if the position resolution along the dispersive plane is kept below 3 mm. Required beam rejection in these typical experiments is between $10^{10} - 10^{12}$. A combination of position along the focal plane, energy, and energy loss measurements can provide additional background rejection, along with time-of-flight (to be added later).

In one of the first commissioning experiments, a Polypropylene target was bombarded with 8 MeV ^{12}C ions. The device was tuned for transmission of ^{13}N recoils that were cleanly separated from scattered beam particles in the ionization chamber at the focal plane. The level of beam rejection achieved here was approximately 3×10^{-11}. In the future, plans call for new commissioning runs with reactions that exhibit a higher counting rate then the one realized in this test. Under such more favorable conditions, fine tuning of the DRS elements and careful placement of slits will result in even better beam rejection.

Future plans call for surrounding the target area with an array of silicon strip detectors, and a high efficiency array of photon detectors. The addition of a high density differentially pumped gas target and a gas jet target will result in enhanced capabilities crucial for measuring processes such as proton and He capture at low energies.

2.3 Other experimental stations

The Enge Split Pole Spectrograph (SPS) is being re-fitted for measurements with low pressure gas filling. This approach has been pioneered by B. Cohen [10] and used more recently by Rehm and collaborators [11]. The presence of dilute gas along the particle's trajectory causes all the products deflected through the magnet to aggregate along trajectory of only one charge state. Position (momentum), time-of-flight (velocity) and energy signals for the reaction products will be used for identification. Position will be measured with a gas-filled position sensitive avalanche counter [15], [11] (PSAC) and energy with a plastic scintillation counter placed behind the PSAC. Time-of-flight through the magnet will be measured using the anode signal of the PSAC as start and signals from secondary electrons emitted from a thin foil hit by the reaction products will provide the stop.

The UNISOR isotope separator is now dedicated to ion source testing and the development of radioactive beam production targets. No utilization of the Spin Spectrometer is planned at present. The station labeled general purpose beamline is presently used for studies of diagnostic equipment and for detector tests. It has also been used in the first RIB experiment [8] performed at the facility - studies of coulomb excitation of ^{69}As.

3 Beam Diagnostics at HRIBF

Several tools for beam diagnostics and profiling have been developed at HRIBF during the past two years. Implementation of beam diagnostics at radioactive beam facilities introduces some new dimensions. The beam itself is often only a small part of what gets accelerated. Isobars are not easy to separate, except in very few low mass cases, hence the need to identify the presence of particular species in the beam. A second requirement is the need to be able to localize (profile) beams over a large range of intensities (low intensities in particular) and to do so with minimum contamination imparted to the apparatus.

To detect the presence of a certain radioactive species is often the purview of a careful experimenter. However, at the facility, a moving tape is used to sample the beam at several critical stations between the ion source and the Tandem. The beam is implanted on a moving tape which is transferred to an off-line high-resolution gamma-ray detector. The gamma-ray energies from the daughter nucleus following the decay of the beam are used to identify the radioactive products. One such device is installed at the exit of the RIB injector, and another one will be installed past the Isobar Separator magnet and before the 90 degree bend into the Tandem. Such a device interferes with the beam delivery but is a necessary tool in such a facility. Physical separation of isobars is a daunting task because some are too close in mass to separate, even with the large isobar separator magnet.

We are presently working on the development of a variety of devices for beam diagnostics. Some are designed to aid the operator in steering the beam inside the tandem accelerator. Other devices are designed to measure beam profile and can be used by the operator or the experimenter for locating and steering the beam. A list summarizing the different devices and their range of applicability is shown in Table 1

Device	Effect on Beam	Sensitivity	Usage
Phosphor + CCD camera	Stops	$10^4 - 10^{10}$	Tandem, Beamline
2-D PSAC	Transmits	$10^0 - 10^5$	Beamlines
Plate + Channeltron	Stops	$10^3 - 10^9$	Tandem, Beamline
Foil + MCP	Transmits	$10^0 - 10^7$	Beamlines
Res. Gas Sampling	Transparent	$10^1 - 10^{11}$	Beamlines

Table 1: **List of Devices for Beam Profiling**

3.1 Phosphor and sensitive CCD camera

The first device listed is an old standard in beam diagnostics except for the fact that a phosphor of high brightness and good durability was used (a 5% Cr doped Alumina - $Al_2O_3 : Cr$) in conjunction with a sensitive CCD camera. [1] The combination of this CCD camera and the Cr doped Alumina phosphor

[1] The camera is a CCD B/W camera Model SE360S from ELMO Mfg. Corp. [12]

provides an extended sensitive range as quoted in Table 1 (see also Ref. [13]). The tests of the above mentioned combination were performed with a 120 MeV ^{32}S beam [14].

3.2 Dual Position Sensitive Avalanche Counter - PSAC

The second device listed in Table 1 is also a newer and improved version of a device used before [15]. The PSAC is a position sensitive avalanche detector in which a plane made of individual sense wires hooked to a delay line is used to measure the position of the discharge in the counter. In this version, the cathode and the anode planes were defined by closely spaced thin wires [16]. The detector has one cathode plane and two anode planes with two position sensing wire planes placed between the cathode and anode planes. These two position sensing planes record positions in two perpendicular directions. This arrangement results in decreased energy loss suffered by the particles passing through the detector at the cost of some transmission losses (usually a few percent).

3.3 Detection of Secondary Electron Emission generated by the beam hitting a metal plate

The third device on the list was introduced to aid the tandem operators in tuning low-intensity beams through the accelerator [17]. This device and schematics of the signal processing from it are shown in Fig. 5. In this device, secondary electrons emitted from the plate, which is placed in the beam's path, are counted in a Channeltron (an electron multiplier). Measurements with 12 MeV ^{35}Cl have shown the output to be proportional to the beam current (see Fig. 6).

As shown in Fig. 8, the measured rate also depends strongly on the direction of the voltage gradient between the emission plate and the Channeltron entrance. There are two "levels"shown in Fig. 8: The "normal" mode in which electrons are accelerated off the plates into the Channeltron and the so called "ion mode" in which electron emission is hindered by the opposing bias. These levels differ by almost two orders of magnitude giving the device an enhanced dynamic range. The device is used in "ion mode" for more intense beams (up to few pA) where it can be calibrated and then switched to "normal mode" for very low intensity beams. A solid plate rather then a foil is used here because it is more robust and can be repeatedly inserted (by remote mechanism) into the beam path.

3.4 Beam Profile and Timing measurement by recording secondary electron emission from foils using a Microchannel plate detector.

The device mentioned in the previous paragraph operates on the principle of detecting secondary electrons emitted following interaction of the beam with

a thin foil. The thick plate has been replaced by a thin foil which allows for transmission of the incident beam. The Channeltron has been replaced by a Microchannel plate detector, providing the added ability to read out the position of the beam's incidence on the foil as well as giving a fast and accurate time readout. The detector is made of individual multipliers each a few tens of microns in size and is therefore capable of resolving hits on its front face with detail of that order of magnitude. The ultimate resolution of the whole device, however, depends also on the transport of the electrons from the collision site (where the beam hit the foil) to the detector. The type of device that could provide good timing and two-dimensional profiles of the passing beam is shown in Fig. 9 (see Ref. [18]).

The main impediment to accurate transport of secondary electrons from the collision site to the Microchannel plate is the transverse velocity component of the secondary electrons being emitted from the foil. Fig. 9 shows two schemes of minimizing the smear in position signals, as recorded at the face of the microchannel plate due to the transverse motion of the electrons exiting the foil. Both methods have some limitations. In the case of electrostatic acceleration, we face the problem of spontaneous emission of electrons from the foil in the presence of a strong electric field gradient perpendicular to the foil near its surface. The magnetic confinement requires a strong homogeneous magnetic field which is not trivial to supply. Studies are underway now to determine which method would serve us best. The microchannel plate provides very fast signal output and we have been able to get sub-nano-second timing from this detector in two different experiments even in the presence of high rates of incident particles (in excess of 10^6p/s). The position readout can be a bit more complicated. A resistive layer is placed at the exit of the microchannel and the charge produced at the microchannel plate anode is collected on the resistive layer and read out from four extreme corners of the resistive layer. By comparing the charges arriving at the four extreme positions on the resistive layer, a position signal is derived. Figure 10 shows the setup used in the first tests of this device. This figure also shows the signal processing scheme that was used to decode position in the presence of high rates of incidence. Only the signals for which an interesting event occurred are converted and stored. We use charge integrating ADCs with a 50 ns wide gate, supplied by a coincidence between the microchannel anode signal (delayed) and the final detector (i.e. the experiment). Figure 11 shows results of the alpha particle test with the setup shown in Fig. 10. The bottom displays are the two-dimensional position spectra with selected regions ("gates") drawn in. The second row shows position spectra projected with these gates (x is the direction along which the foil tilts - i.e. the three peaks represent different distances between start and stop detectors). Obviously, the position resolution (5-6mm FWHM) is mediocre but timing resolution is about 0.5 ns FWHM. Note that the two spectra in part c correspond to time projections for the two regions gated in Fig. 11 a. The two peaks in the position spectrum shown in Fig. 11 b correspond to the Y positions projected from one of the gates shown in Fig. 11 a.

3.5 Residual Gas Beam Profile Sampler

The last device mentioned in Table 1 is probably most suited for studies with radioactive beams. It is a sampling device, [19] i.e. it does not record every beam particle, only a random sampling of them. It is, however, non invasive, and could be used to monitor the beam position during an entire experiment. In this device, beam position is sampled by atomic collisions between the beam and the residual low pressure gas in the detector's volume. It operates by recording the position of arrival of the recoiling ions from this atomic collision. The position of the ion that drifted toward the electrode provides information only on one dimension transverse to the beam trajectory (see [20] and references therein). In our device, the second dimension is provided by recording also the electron arrival time. The electrons drift in the opposite direction, but they move very fast. Therefore the time difference between the electron and ion arrival times is proportional to the ions' drift time and therefore to its mass to charge ratio as well as to the distance which it had to drift. The device is shown in Fig. 12. In it the electrons and the positive ions produced in ionizing collisions between the beam particles and the residual gas molecules in the evacuated beam pipe are swept toward the opposite electrodes. The ion drift time depends on its position of formation and its mass to charge ratio. To retain maximum sensitivity to position, it is important to know and even regulate the residual gas contents. This can be accomplished with a combination of good pumping and controlled injection of known gas, if needed. Figure 13 shows drift times measured after pumping down the system and introducing two different components to the residual gas mixture. Water vapor (which would result in ionization into H+ and HOH+) and nitrogen gas (resulting in ions of $N_2^+, N^+, and N^{++}$) were injected in these trials. Figure 14 shows the dependence of the recorded drift times on mass to charge ratio of the ions. These data also serve as good calibration benchmarks. It is clear that if we maintain a nearly pure N "atmosphere" we could sample positions over a range exceeding two inches - more than enough for our purposes.

This beam profile sampler has been tested with stable beams and used in conjunction with a Coulomb excitation experiment done with ^{69}As beams at the HRIBF facility [8, 21]. Figure 15 shows the horizontal position signal obtained with 4 pA (about 10^7p/s) ^{48}Ti beam. The structure seen in the peak shape reflects granularity associated with the discrete elements used for position decoding in this case. (charge pickup strips - 1 mm pitch). Note the paucity of background in this spectrum.

Figure 16 show a two-dimensional plot of the beam profile obtained with ^{69}As beam at intensities near 10^5 particles per second. We used a nitrogen leak and ran with ambient pressure near 4×10^{-5} torr maintained throughout the experiment. The data shown were accumulated in less then one minute. The Y position was derived from the N_2 drift time, and a biased TAC was used to amplify the region around that peak. As can be seen from the two orthogonal projections of the beam profile in Fig. 17, the resolutions in X and Y are comparable and the beam spot in this experiment was about 2-3 mm in

diameter.

4 Acknowledgement

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[6] The RIBENS (Radioactive Ion Beams for Explosive Nucleosynthesis Studies) collaboration includes scientists from: ORNL, Yale, University of North Carolina Chapel Hill, Tennessee Technological Univ., Ruhr-Univ. Bochum, University of Liverpool, Univ. of Edinburgh, Colorado School of Mines, Univ. of Bombay, and Louisiana State Univ.

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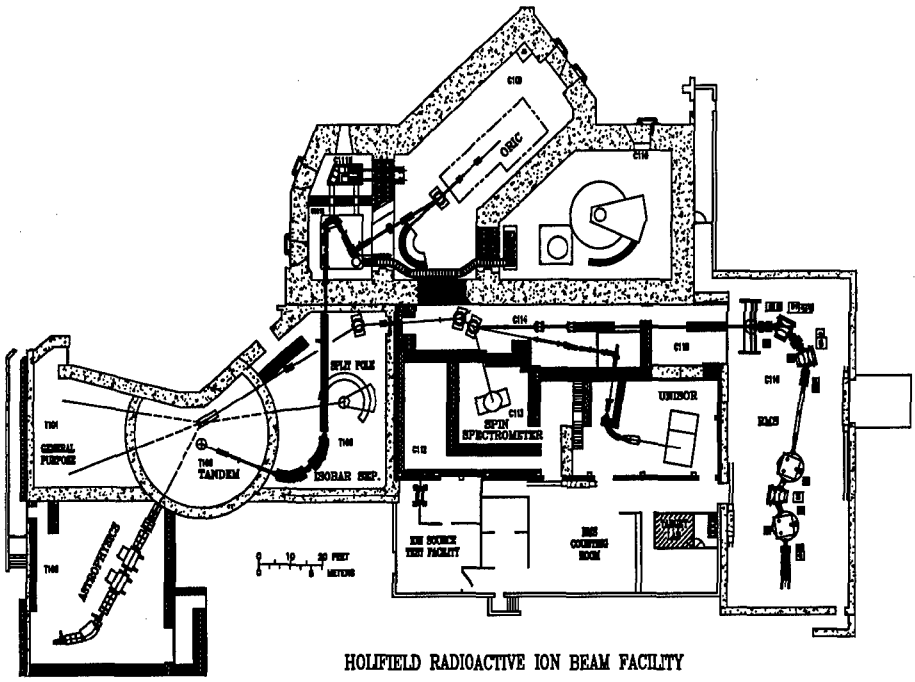

Figure 1: Layout of the HHRIF facility - the two major experimental areas are new to the facility.

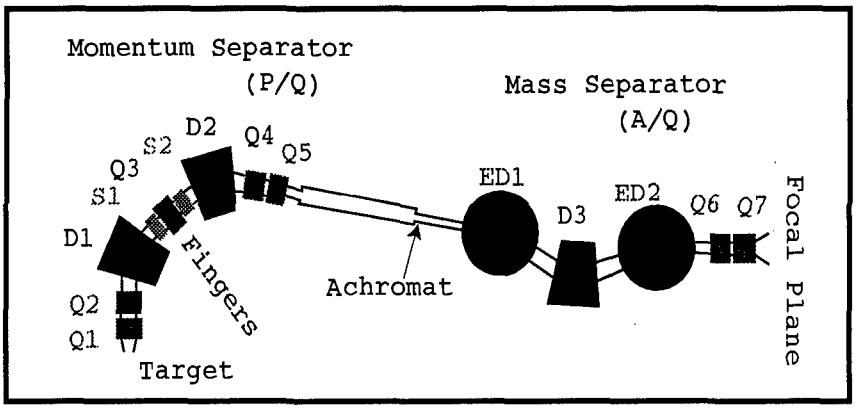

Figure 2: Layout of the Recoil Mass Spectrometer Facility

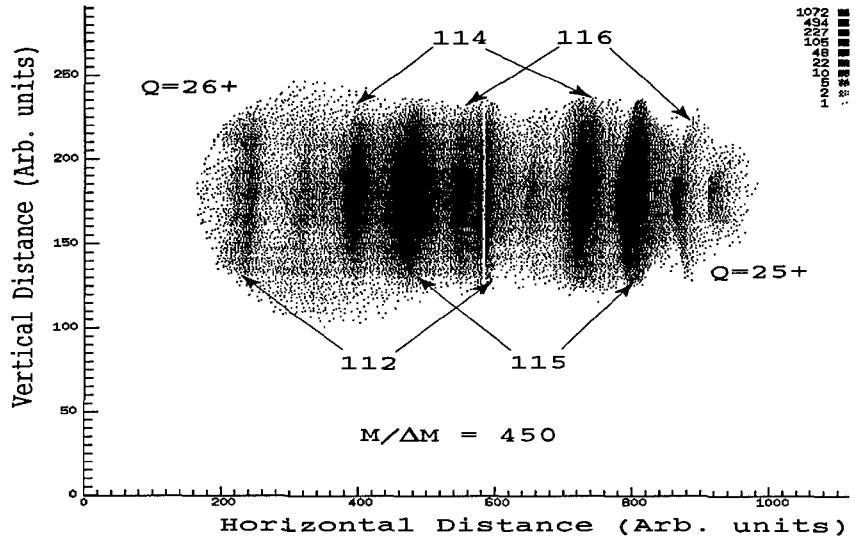

Figure 3: Mass (A/Q) spectrum at the RMS focal plane for evaporation residues from the $^{58}Ni + ^{60}Ni$ reaction.

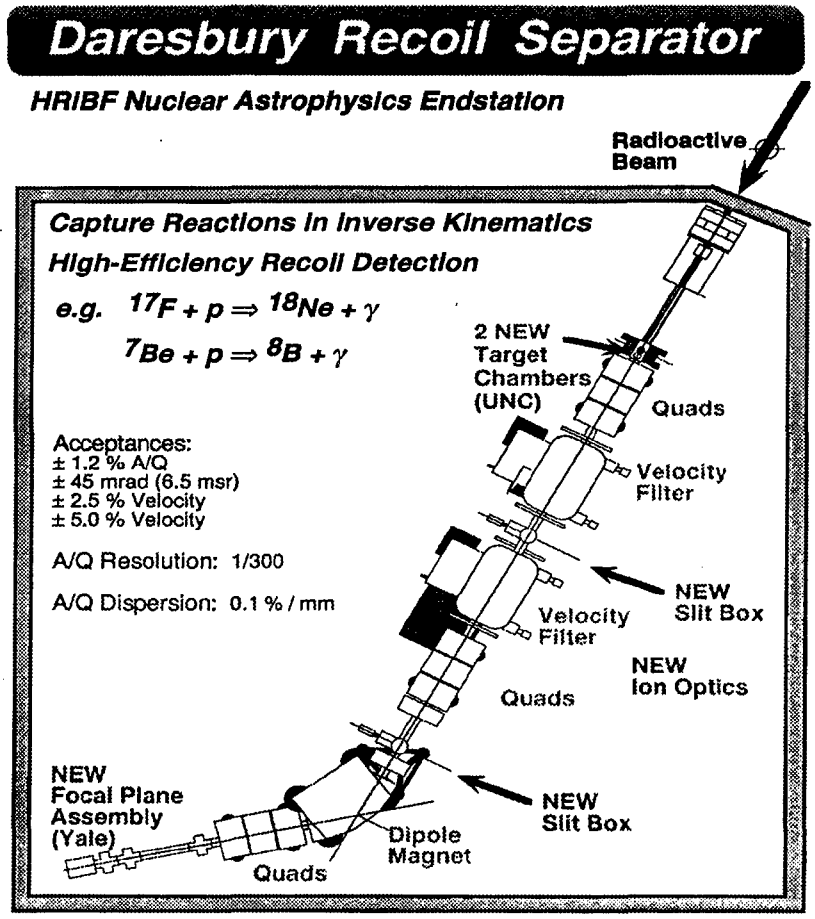

Figure 4: Layout of the DRS at HRIBF.

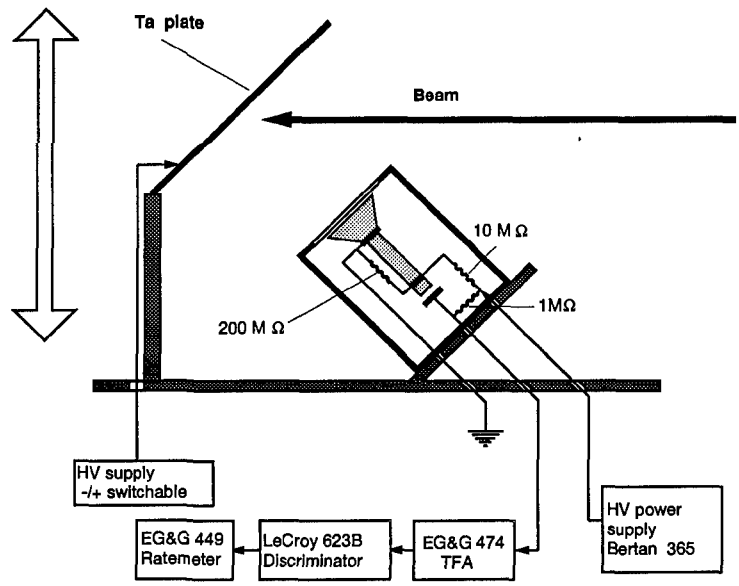

Figure 5: Beam intensity monitor based on secondary electron emission from a solid plate.

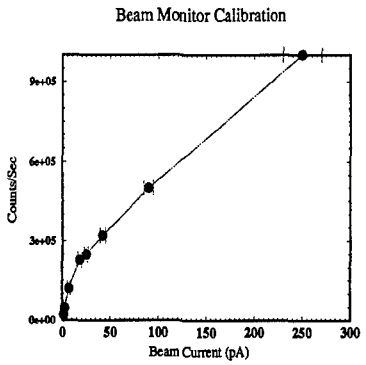

Figure 6: Calibration Curve for beam intensity based on secondary electron emission - Full Range.

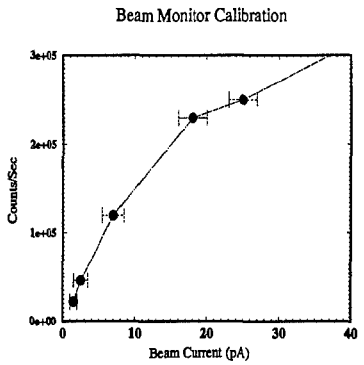

Figure 7: Calibration Curve for beam integrator based on secondary electron emission - Low intensity region.

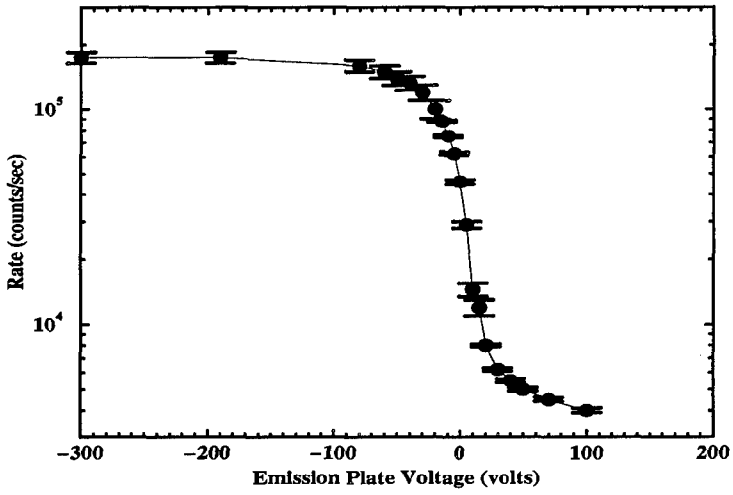

Figure 8: Measured yields from the Channeltron as a function of voltage applied to the emission plate. The beam intensity was kept the same throughout the test.

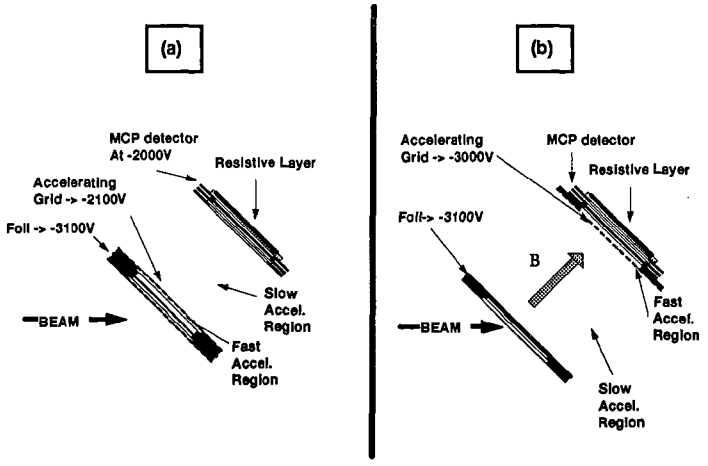

Figure 9: Two solution for containing the lateral spread in electron trajectories as they move from the foil to the Microchannel plate. (a) Prompt electrostatic acceleration and (b) confinement to spiral trajectories in a magnetic field.

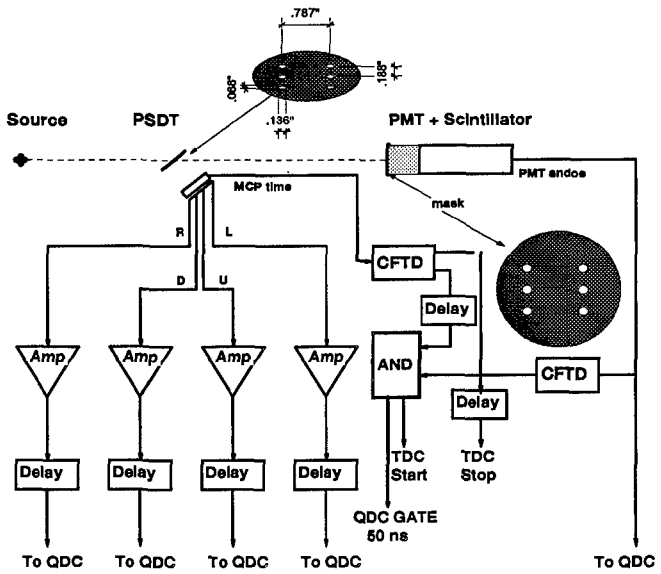

Figure 10: Test setup of a PSDT based on prompt acceleration of the electrons. Note the distortion of the mask at the foil surface.

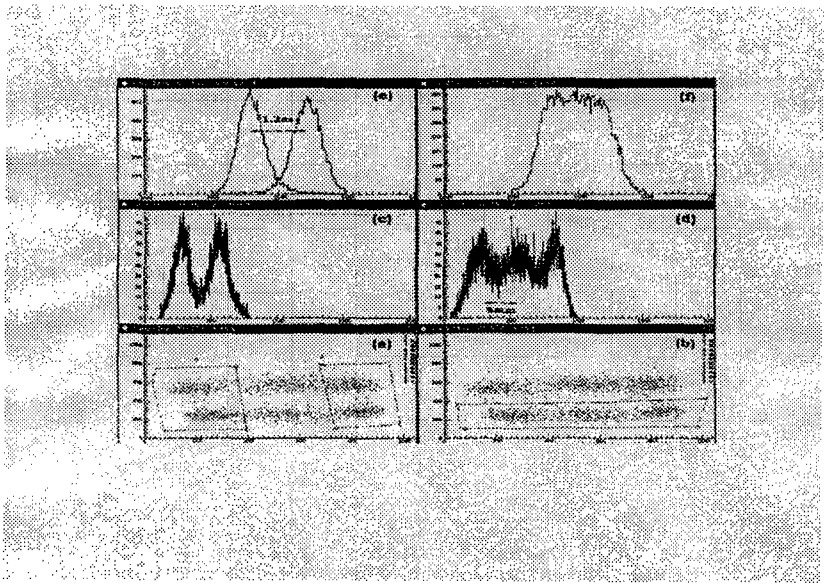

Figure 11: PSDT test results.

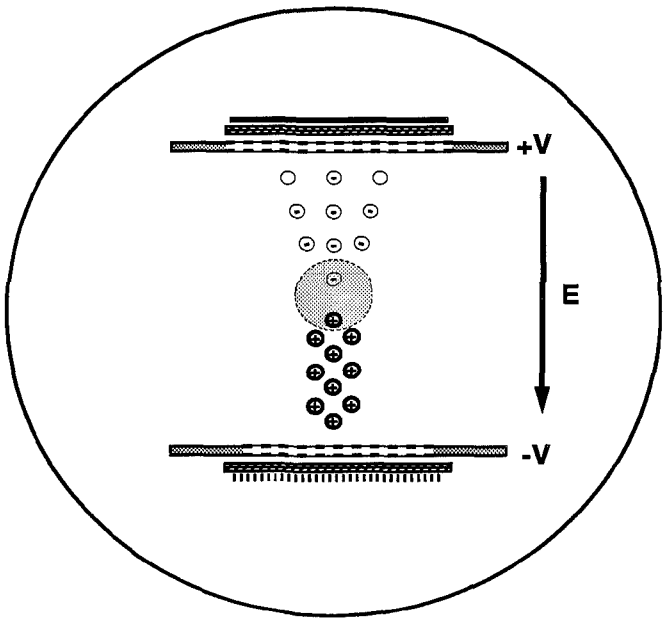

Figure 12: Principles of Detector. Residual gas ion and electron pairs formed in collisions with beam particles are swept vertically in the direction of an applied electric field. Microchannel electron multipliers amplify the signals and provide timing and position signals for the positive ion hits and timing only for electron hits.

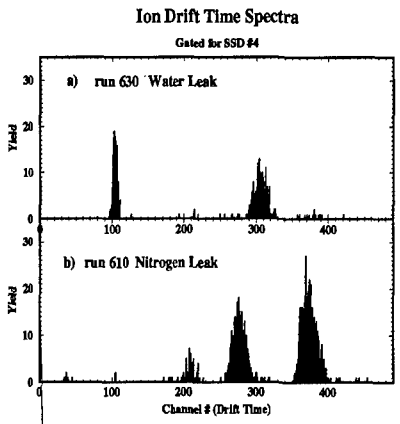

Figure 13: Spectra showing ion drift times for two cases: in a) a H_2O leak and in b) a N_2 leak were introduced.

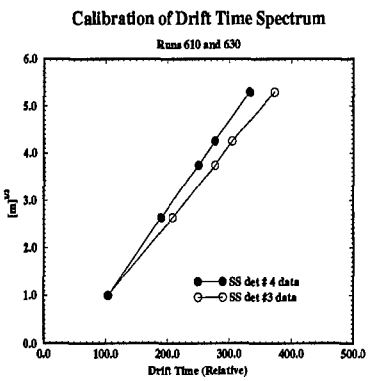

Figure 14: A calibration curve showing drift time vs. the square root of the mass of the accelerated ion. The ions identified were H, N(doubly charged), N(singly charged), H_2O and N_2.

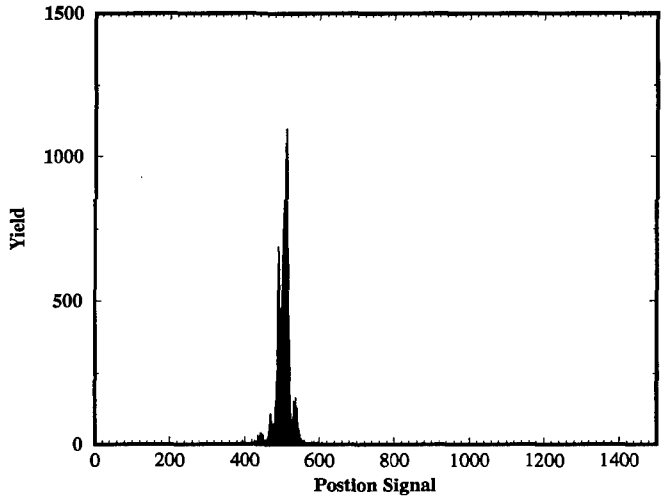

Figure 15: Horizontal projection of beam spot obtained with 4 particle pA of 160 MeV ^{48}Ti beam.

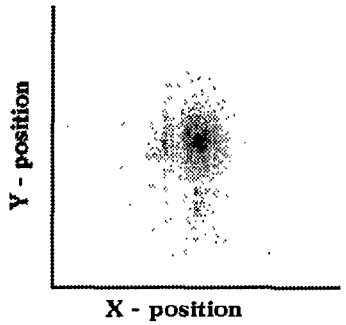

Figure 16: Two-dimensional beam profile obtained with a beam of 10^5 ^{69}As ions per second.

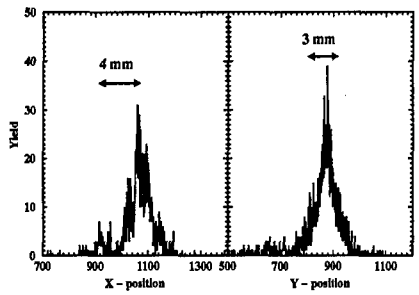

Figure 17: Horizontal and vertical projection of beam spot obtained with a beam of 10^5 ^{69}As ions per second.

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