A FAST, COMPACT PARTICLE DETECTOR FOR TUNING RADIOACTIVE BEAMS AT ATLAS*

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Abstract

Radioactive ion beams (RIB) at the Argonne Tandem Linear Accelerator System (ATLAS) are produced either from the in-flight method at 5-15 MeV/u for A < 30, or via reacceleration of fission fragments from the CAlifornium Rare Isotope Breeder Upgrade (CARIBU) at 4-10 MeV/u for 80 < A < 160. These RIB are typically accompanied by contaminant beams >100x more intense. The goal of this work is to develop a fast (>10^5 pps), compact (retractable from the beam line) particle detector capable of A and Z identification to enable accelerator optimization on the exact species of interest. The detector should have an energy resolution of ≤5% and be resistant to radiation damage. A gas ionization chamber supplemented with an inorganic scintillator was chosen as the basic conceptual design. GSO:Ce was chosen as the primary candidate scintillator due to a demonstrated energy resolution of ~3% for 15 MeV/u He and less irradiation induced performance degradation than other candidate materials.

INTRODUCTION

At the Argonne Tandem Linear Accelerator System (ATLAS) we are developing a fast, compact particle detector to aid the tuning of low intensity beam constituents with relatively high intensity (>100x) contaminants. These conditions are regularly encountered during radioactive ion beam production via the in-flight method, or when charge breeding fission fragments from the CAlifornium Rare Isotope Breeder Upgrade (CARIBU). Presently silicon barrier detectors (SBD) are used for mass identification via total energy measurements. However, the total acceptable SBD rate is limited to ~1000 pps, so the signal rate from any minority constituents 100x less intense is typically much too slow to enable meaningful accelerator optimization. In addition, SBDs can tolerate a very limited integrated flux before their performance deteriorates.

The in-flight method of RIB production at ATLAS generally produces beams of interest with energies 5–15 MeV/u and masses less than 30 AMU, while reaccelerated fission fragments from CARIBU, 80 < A < 160, are typically accelerated to energies of 4–10 MeV/u. Our goal is to achieve ~5% energy resolution at a total rate of 10^5 pps over these energy and mass ranges without significant performance degradation after extended use.

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The detector will combine a gas ionization chamber with an inorganic scintillator to generate ΔE and residual E signals and enable the identification of both the Z and the A of the beam constituents. This configuration allows the needed compactness to retract the assembly from the beam path. The conceptual design of the detector and considerations for the selection of the scintillator, photoelectric device, and counting gas are presented in this paper.

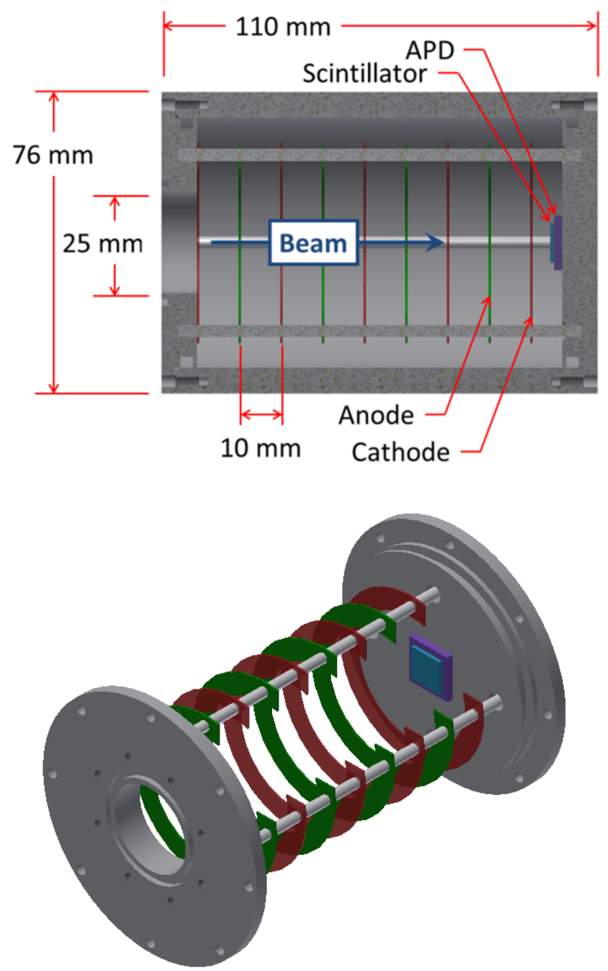

Figure 1: (Upper) A cross section showing the general layout and dimensions of the detector configuration. (Lower) A view of the detector with the vacuum tube removed and the electrodes cut away for clarity.

DESIGN

A hybrid of a gas ionization chamber (IC) supplemented with a scintillator was the chosen conceptual design, shown in Fig. 1. Both the gas and scintillator are fast,

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resistant to radiation damage, and have appropriate resolutions. Silicon detectors cannot maintain their performance at high integrated flux and diamond detectors are not widely available. The ionization chamber will follow the designs of Kimura and Chae [1, 2], whose Tilted Electrode Gas Ionization Chambers (TEGIC) have operated at rates >1x10^5 ions/sec with energy resolution <5%.

The nominal operating pressure of the detector is 1.5 atm or 1100 Torr. The use of the scintillator will eliminate the need to completely stop the ions within the gas and the significant design considerations to operate at higher pressures with thick windows. Even high stopping power gases alone (iC_4H_{10} or CF_4) at 25 C and 1100 Torr do not have enough density to stop the light (A<10) high energy (15 MeV/u) particles in less than ~350 mm, and the use of thick degrader materials could impart significant energy and angular scatter. The target length for a compact design was nominally ~100 mm, and the anticipated window material is Kapton which is available in a variety of thicknesses.

The ATLAS detector electrodes will be spaced closer than either of the two reference TEGIC designs but the smaller electrode area will ultimately result in lower cathode-anode capacitance which is an advantage for higher rates and lower electronic noise. The electrodes will be built from narrow gauge, ø17.5 µm, wire which will sacrifice ~1% transmission per electrode to avoid the additional angular scattering from using metalized mylar foils. The initial detector design will not use tilted electrodes for compactness and simplicity, but the detector response vs. rate will be studied to determine if recombination becomes a significant factor.

The scintillator will give a residual energy signal for particles not stopped in the gas, and enables the flexibility to tune the gas density for the best signal while largely ignoring the gas stopping power. Operating with RIB from CARIBU should be straight forward. The high Z ions will easily stop in the gas, and the good beam quality, <0.2π µm full normalized, will be easily controlled. Light, high energy RIB from in-flight production can have >10x worse quality due to the reaction kinematics and will be more challenging. With appropriate focussing and collimation a clean signal should be achievable given the large restricting aperture diameters (25 mm for the entrance window and 38 mm for the inner diameter of the electrode wire mesh mounting).

SCINTILLATOR SELECTION

The primary criteria for the scintillator selection were the ability of accepting rates >10^5 pps, an energy resolution ≤5%, high radiation hardness, and non-hygroscopicity. Table 1 shows the relevant properties for a number of candidate materials. Organic scintillators were not considered due to higher energy resolution, susceptibility to radiation damage, lower light yield, and non-linearity for heavy charged particles

GSO:Ce was ultimately selected for this detector application. GSO:Ce has good energy resolution (~3% for 15MeV/u ^{3}He [3]), has relatively high light output, is non-hygroscopic, can tolerate rates >10^6 pps, and has the best radiation hardness of any well characterized scintillator by 2-3 orders of magnitude. While the radiation hardness values listed in Table 1 are for low energy γ rays, Kobayashi also studied proton irradiated GSO:Ce [4] and found the onset of performance degradation occurred at ~1.6x106 rad. As an example, for a ø4 mm beam spot at 10^5 pps it would take 12 days and 4 days to accumulate an equivalent dose for 15 MeV/u ^{9}Be and 10 MeV/u ^{12}C, respectively. These estimates ignore the differences between proton and heavy ion radiation damage kinematics, but indicate GSO:Ce can be a robust ion detector.

PHOTOELECTRIC DEVICE

Three photoelectric devices were investigated for this application: a photo multiplier tube (PMT), a PIN photodiode, and an avalanche photodiode (APD). Table 2 highlights the performance of these devices for configurations relevant for this application. The PMT is generally the fastest option with by far the highest gains, but the overall size of the PMT is a big drawback considering the goal of a compact detector system. The typically low quantum efficiencies are also disadvantages which eliminated the PMT as the first choice. Compactness, insensitivity to magnetic fields, and lower complexity are general photodiode features that make these devices better suited for this application. Ultimately an APD was selected, Hamamatsu S8664-1010, due to the device's higher gain (better sensitivity to low light intensities), and typically better radiation hardness.

Table 1: Properties of Candidate Scintillators

Quantity	GSO:Ce	NaI:Tl	BGO	BaF	CsI:Tl	CeF_3
Density (g/cm^3)	6.71	3.67	7.13	4.89	4.51	6.16
Decay constant (ns)	30-60	230	300	0.6/320	980	30
Peak emission (nm)	440	415	480	220/310	530	375
Light yield (relative)	20	100	7–10	5/16	45	4–5
Hygroscopicity	No	Yes	No	Yes	Yes	No
Radiation Hardness (rad) [4]	10^9	10^3	10^{4-5}	10^{6-7}	10^{4-5}	10^6

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Table 2: Approximate Characteristics for Relevant Photoelectric Devices

Quantity	APD	PMT	PIN diode
Gain	10-100	>10^5	1
Quantum efficiency*	75%	25%	85%
Thickness (mm)	~3	>50	~3
Active area (mm^2)	1–100	100–5000	1–1000

*for 440 nm emission peak of GSO:Ce

GAS CONSIDERATIONS

CF_4 will be the primary counting gas due to its fast electron drift velocity, ~13 cm/ms at 3 V/(cm-Torr) [5]. The detector will be designed to operate up to 1100 Torr, but at this pressure and nominal electrode spacing, 1 cm, >3 kV is necessary to achieve the fastest counting. To obviate these higher voltages and comfortably avoid the proportional counting regime up to 90% Ar can be mixed with CF_4 to realize the same high velocity but at ~1 V/(cm-Torr). The addition of Ar can also improve the resolution due argon's lower ion pair production threshold, 26 eV vs. 54 eV for CF_4, and, with the scintillator able to provide a residual energy signal, the stopping power of the gas can be largely disregarded.

DEVICE TESTING

Initially testing of the scintillator and APD will be conducted independently of the gas IC to investigate the radiation hardness of the scintillator for heavy ions and optimize the output signal of the APD with respect to energy resolution and signal to noise ratio. For simplicity these initial tests will use a scintillator with an area equivalent to the active area of the APD, 10x10 mm^2. This scintillator – APD configuration will also be the first used in the full detector assembly with the gas IC. In operation, fully intercepting larger emittance secondary RIBs from in-flight production may become problematic due to this relatively small size. In these cases collimators may be used to constrain the beam size into the gas portion of the detector, or in the future a larger scintillator may be installed. A larger scintillator will in turn require a light guide or a larger photoelectric device in which case a PIN photodiode would likely be used. Once a production model of the IC is finalized it will be fabricated and assembled to test as well. The IC will initially be tested in a fixed position while the insertion mechanism and vacuum chambers are developed.

SUMMARY

Optimizing ATLAS for the delivery of radioactive ion beams requires a detector capable of distinguishing a low intensity species of interest from a high intensity background. The combination of a gas ionization chamber and scintillator will enable incident ion rates of >10^5 ions per second, will be compact, will have energy resolutions <5%, will identify species by both A and Z, and will have the flexibility to operate with wide mass and energy ranges. GSO:Ce was selected as the best scintillator candidate material largely due to its high radiation hardness, fast response time, good resolution, and high light yield. The scintillator will be coupled to an APD, but the relatively small size of the APD may limit the overall detector performance. The high electron drift velocity in CF_4 make it the best counting gas candidate, but Ar may be added to maintain this high velocity at lower pressure normalized electric fields.

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