A HEAVY ION MICROBEAM FACILITY USING MICRON RESOLUTION DETECTORS FOR 3 GEV/NUCLEON BEAMS *

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Abstract

In this paper we will discuss the technical issues related to creating microbeams of heavy ions (e.g. iron) at energies higher than at existing microbeam facilities (up to 3 GeV/nucleon) and related to developing an electronic position sensitive detector for heavy ions with a position resolution better than 1 micrometer. The experimental requirements define microbeams to be beams which will have a sufficiently small diameter to localize the ions to a single cell.

1 INTRODUCTION

The ability to place discrete numbers of particles in defined cellular and extracellular locations is now possible by using microbeam irradiation facilities. Such facilities permit heavy-ion radiobiology to address specifically the impact of signal transduction between cellular compartments as well as issues related to intercellular communication at limiting low fluences where not all the cells in a population have been traversed by even a single particle. Higher energy heavy ion microbeams will permit investigations of an important unanswered question: whether neurons that survive traversal by high charge, high energy (HZE) particles develop changes as a late consequence of the damage they incurred. Therefore, these low-fluence studies promise to aid in our understanding of the consequences of exposure to high-LET (Linear Energy Transfer) radiation such as encountered in the space radiation environment, in which a large amount of energy is transfered within the small distance of single cells.

During a long-term space flight mission, it is estimated that virtually no cell receives more than one Fe ion traversal in 3-year Mars mission scenario [1, 2, 3]. Thus the use of the microbeam will aim to produce data for direct input into the analysis of human health risks during long-term space flights exposures involving exposure to low fluences of charged particles.

2 MOTIVATION

HZE particles transfer their energy to biological organisms through high density ionization and excitation along the particle track. This characteristic, microscopically non-uniform dose delivery is expected to induce complex DNA damage and mutagenesis, in contrast to relatively uniform dose delivery in gamma-rays or electron beam irradiation.

Using conventional track segment irradiation methods and sophisticated ion track detecting techniques, the position of the target cells and the ion tracks can be measured together. However, this approach is not practical because all responses of many cells which do not contribute to the aim of the irradiation experiment must be measured. An alternative is to control each ion hit so that the irradiation experiment is not a random Poisson process. A heavy ion microbeam can be used to selectively irradiate individual cells which can be analyzed afterward to determine what changes have occurred to that cell and to its non-irradiated neighboring cells and to look for pathways other than DNA damage, i.e., damage to the cell membrane or cytoplasm.

In order to study the neurotoxicity of single ion particle exposures on human neural cells, we plan to use a cell system based in the use of human post-mitotic hNT neurons derived a teratocarcinoma cell line (NT2). The NETera2/ci.D1 (NT-2) cell (Stratagene) is a human teratocarcinoma cell line that is induced by treatment with retinoic acid to commit irreversibly to a neural phenotype. These cells (hNT-2) are permanently post-mitotic and develop functional dendrites and axons. Since large quantities of NT-2 cells can be generated and maintained in a fully differentiated state for weeks, these cells provide a unique opportunity to study the induction of DNA damage and its cellular consequences in two different neural developmental stages; 1) Assay for cell viability: Direct visualization of damaged cells will be done using the Live Cell/Dead Cell assay (Molecular Probes) employing two fluorescent probes; 2)Assay for apoptosis induction: Apoptotic in exposed culture cells will be identified morphologically by conventional fluorescent staining with Hoechst 33358. Cell with condensed or fragmented chromatin will be scored.

3 PARTICLE BEAM DEFINITION AND PARAMETERS

The AGS Booster has operated since 1991 as an injector of protons and heavy ions into the AGS. It is a 201.78 m circumference separated function alternating gradient synchrotron which can operate up to a maximum rigidity of 17 Tm. The lattice consists of 6 superperiods, 24 cells. It operates near the betatron tunes of $\nu_x = 4.82$ and $\nu_y = 4.83$. The acceleration rates are 8.9 T/s up to 7.5 Tm and 1 T/s for going up to 17 Tm. The Booster Application Facility (BAF) will operate as a beam-line that branches from the AGS Booster. BAF will employ heavy ion beams of many different ion species and at beam energies ranging from 0.04 to 3.07 GeV/nucleon with beam intensities from

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10^4 to 10^9 ions/cycle [4]. Beam will be delivered to BAF as a slow constant current over 0.5 to 1 second. This is achieved by using a third integer resonant extraction system [5]. In the extraction system a thick septum magnet is used which bends the beam out of the Booster by 143 mrad. At the entrance to this magnet there will be a stripping foil/collimator mechanism which will strip off all remaining electrons on the ions and provide vertical jaw collimation for intensity control. Table 1 shows the operating parameters for typical ions for BAF. Intensities as low as 10^3 ions per pulse will be available to experimenters through collimation. Table 1 summarizes the operating parameters for Booster BAF operation.

Table 1: SEB Operating Parameters for Typical Ions

Ion	Charge in Booster	K.E. Range (GeV/nucl.)	Est. Inten. [10^9 Ions/pulse]
p	1	0.10...3.07	100
28 Si	14	0.09...1.23	4
56 Fe	21	0.10...1.10	0.4
63 Cu	22	0.10...1.04	1
197 Au	32	0.04...0.30	2

The beam line for BAF is approximately 250 feet long, ending with a 20 ft. x 20 ft x 10 ft. high experimental area. The beam line is designed to be achromatic and through the use of octupoles can create a highly uniform transverse beam image on the targets [6].

Through the combination of vertical collimation and the use of wire stripping foils it is expected that beam intensities down to 1000 ions/second and beam emittances on the order of $\epsilon_x = 2.3 \times 10^{-8}$ pi-m-rad and $\epsilon_y = 7.9 \times 10^{-8}$ pi-m-rad can be achieved. The main difficulty in achieving micro-beams is not in being able to get down to low intensities, but to get the beam spot to be defined within a 10 micrometer area. Given the above emittances we would require $\beta_x = 0.004$ m and $\beta_y = 0.001$ m at the target location. Figure 1 shows the un-collimated normal phase space at the entrance to the thick septum after a full aperture foil.

One approach for getting the extremely small beams at the desired flux is to use crystal channeling technology [7]. Crystal extraction and collimation techniques are an established technology and crystals could be used either as part of the transport, or to make cleaner collimation of final beam [8]. Nevertheless, getting a beam confined to the level of 10 μm is a challenge using crystals.

Neutron contamination may be a significant problem. This requires that we design neutron absorbing shielding between the collimator and the target samples. The use of crystals in the beam transport may help control and possibly eliminate the background secondary particles. The use of shielding in the design is still important to ensure the environment at the target samples is as clean as possible.

A final consideration is ensuring we don't get multiple hits on cells. Since the target samples will have to be moved (or the beam moved on the target samples) we must ensure no particles arrive until the sample is ready. This can be
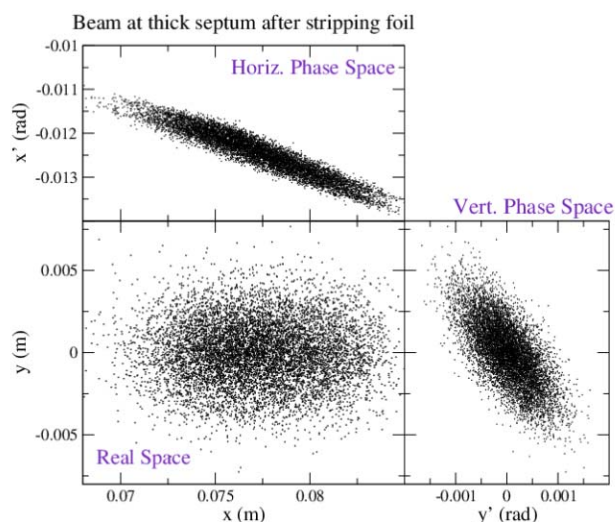

Figure 1: Phase Space after a thick foil at entrance to thick septum

accomplished using sets of kicker magnets and scintillator detectors (for single particle detection), such that once a particle is detected exiting the first kicker magnet, it is shuttered on, preventing any further passage of particles. The second kicker would shutter off once the sample was in the ready state, thus allowing a particle to pass through undeflected. A second scintillator would be used to determine whether more than one particle made it though the shutters. Since the velocity of a 3 GeV proton is 97 % that of the speed of light, the time to travel 200 feet is about 200 nsec. With a flux of 100 particles/sec, it is possible to fire a set of fast kickers such that we only allow a single particle through at a time, in a very controlled manner.

4 SILICON DETECTOR WITH SUB-MICRON RESOLUTION FOR HEAVY IONS

A novel detector which we propose here based on a concept (patent pending [9]) developed at BNL has the necessary properties to provide a position resolution better than 1 micron. The concept is based on interleaved pixel electrodes arranged in a projective $x - y$ readout, which makes possible position encoding with a moderate number of readout electronic channels. A fine position resolution in the sub-micron range is achieved by determining the centroid of the charge collected on pixel electrodes with a granularity in the range of 5-6 microns. This electrode granularity does not pose difficult demands on the lithography and the fabrication technology. In further discussions, we refer to this concept as a "strip" detector, as it combines the two-dimensional position resolution of a pixel electrode geometry with the simplicity of the projective readout of a double-sided strip detector. It also has a unique advantage

of being able to achieve sub-micro resolution based on our simulation and current understanding.

To achieve fine resolution in the sub-micron range, we take advantage of the natural diffusion process of drifting charges with respect to the pixel spacing. In order to get both X and Y position resolution, it is necessary that χ is greater or equal to the pixel pitch p, i.e. $\chi \geq p$. For a typical high resistivity ($6\mathrm{k}\Omega - \mathrm{cm}$) n-type substrate Si detector with a thickness of $200\mu\mathrm{m}$, the full depletion voltage is 23 volts. At an operating bias of V=25 volts, the maximum standard deviation of the charge (due to lateral diffusion) distribution from the center if the track is:

$$\chi = d \cdot \sqrt{\frac{2kT}{eV}} = 9.1\mu\mathrm{m} \qquad (1)$$

The pitch of our detector should therefore be less than $10\mu\mathrm{m}$ to provide charge interpolation with better than one micron resolution in two dimensions. This is possible since 1) the charge cloud is spreading over 9 or more pixels due to the diffusion, and 2) the signal is large with very small fluctuations for good position interpolation.

Fig. 2 shows the design layout of an $8.5\mu\mathrm{m}$ pitch interleaved strip detector. The mask layout for the first prototype of strip detectors with different types and pitches is now being tested.

The entire detector process technology, including the simulation of processing and device, mask design, oxidation, chemical etching, photo-lithography, and the double-metal process is available in the Semiconductor Detector Development and Processing Lab (SDDPL) in BNL's Instrumentation Division. Instrumentation Division's SD-DPL is the only facility in DOE's national labs that has the state-of-art semiconductor device processing technology and has been fabricating prototype detectors (micro and mm strip detectors, pixel detectors, Si drift detectors, etc.) for various Institutions/experiments (RHIC, AGS, FNAL, LANL, JHU, UCD, CERN, etc.) around the world.

For detector readout, a 16-ch low capacitance low noise pre-amplifier shaper developed in BNL's Instrumentation Division will be used.

We have produced a prototype $8.5\mu\mathrm{m}$ pitch interleaved strip detector. The widths of X and Y strips are in the order of $2 - 3\mu\mathrm{m}$. The electrical testing (interconnection quality, I-V and C-V characteristics, etc.) are underway at BNL. Charge collection and position resolution testing using focused laser and electron beam are planed for late 2002.

5 CONCLUSIONS

Although the technical issues related to constructing a high energy micro-beam facility are challenging, they are not insurmountable. We are strongly encouraged by these initial investigations and by the experimental motivations for having such a facility.
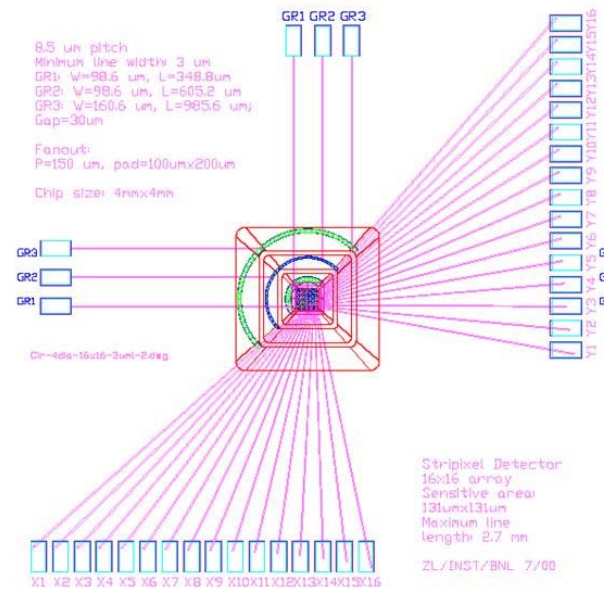

Figure 2: The prototype design layout of the novel strip detector with two dimensional position sensitivity and micron resolution (8.5 μm pitch)

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