Heavy-Ion Beams for Single-Event Research
at Brookhaven - Present and Future

BNL--45359

DE91 004800

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* Supported by the U.S. Department of Energy under Contract Number DE-ACO2-76CHOOO16, and an interagency agreement with NASA-Goddard Space Flight Center (GSFC), Naval Research Laboratory (NRL), National Security Agency (NSA), United States Army Strategic Defense Command (USASDC).

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Abstract

Since low energy nuclear physics research was discontinued at Brookhaven and replaced by a relativistic heavy ion program, large blocks of time became available at the Tandem Van de Graaff Facility for technological applications and for research in other areas. The main technological application has been the single event upset (SEU) testing of microelectronic devices and this activity has been steadily increasing over the last few years. The ion beam requirements for this type of work are discussed and a description is given of methods used for satisfying these requirements at the Brookhaven facility. Available ion species, energies, ranges, LETs and beam intensities, purity and uniformity are discussed. Characteristics are summarized of a sophisticated and extremely user friendly test chamber and associated hardware and software installed at Brookhaven by a coalition of government agencies and made available for general use. The possibility is mentioned of extending SEU testing to higher energies by using heavy ion beams from a Booster synchrotron now under construction and from the existing large Alternating Gradient Synchrotron (AGS). Finally a brief discussion is given of compatibility with other programs and of future availability of low and high energy heavy ions for SEU testing at Brookhaven.

* Supported by the U.S. Department of Energy under Contract #DE-ACO2-76CH00016, and an interagency agreement with NASA-Goddard Space Flight Center (GSFC), Naval Research Laboratory (NRL), National Security Agency (NSA), United States Army Strategic Defense Command (USASDC).

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Introduction

The uninterrupted and progressive miniaturization of micro-electronic devices is the main reason that more and more powerful computers become available for all types of applications. This is particularly true and particularly important for space applications where weight and size are at such a premium. But it is also mainly in space where deleterious effects of ionizing radiation on these devices become increasingly serious as the sensitive volumes shrink leading to reductions in the critical charges that are sufficient for the production of "bit-flip" errors (soft errors) or of hard errors, latchups and power transistor burnouts. Such events produced by the passage of single ionizing particles through micro-electronic devices are called "Single Event Upsets" (SEU). It is important to study these events in the laboratory, under controlled conditions and at relatively high repetition frequencies to characterize and select existing devices and to gain a better understanding of the phenomena involved, in order to arrive at improved designs for new devices and systems.

A wide spectrum of atomic masses and energies extending to many hundred MeV per nucleon characterize the primary and secondary radiation components encountered in spacecraft. The linear energy transfer (LET) values and the corresponding specific ionization values are however limited by the fact that these quantities reach maxima at relatively low heavy-ion energies which are at most two to three MeV per nucleon for the heaviest ions [1]. It is therefore sufficient, at least in principle, to provide ion beams for testing at energies sufficient to reach or to approach these maximum LET points. The Tandem Van de Graaff Facility at Brookhaven provides heavy ions which exceed these maximum LET energy values for most of the elements of the periodic table and which, as can be seen in Fig. 1, approach the maximum LET values for the heaviest elements such as gold to within a few percent.

SEU testing at the Brookhaven Tandem Van de Graaff Facility was initiated in 1984 by a team from the Jet Propulsion Laboratory (JPL) [2]. More recently, a coalition of U.S. government agencies in collaboration with Brookhaven National Laboratory has developed a dedicated SEU testing facility which operates at this accelerator and which is available for general use. These agencies are the National Security Agency (NSA), the National Aeronautics and Space Adminis-

tration (NASA), the Naval Research Laboratory (NRL) and the Army Strategic Defense Command (USASDC).

In the following sections we give a brief description of the design and operation of this facility [3] and then summarize the possibilities of utilizing existing and planned relativistic heavy-ion accelerators at Brookhaven to perform SEU tests at higher energies in the future.

The Single Event Upset Test Facility

The heavy ions used for SEU testing are generated using an upgraded model MP Tandem Van de Graaff accelerator [4] which is operated at a maximum terminal voltage of 15 MV. The range of energies and corresponding LET values achievable for a few representative beams are shown in Fig. 1. Many other ions are available and, up to date, about 35 different elements have been accelerated.

A simplified overall diagram of the facility is shown in Fig. 2. Negative ions are generated in a sputter-type ion source (a) [5,6] operated at ~ -150 kV with respect to ground and a first mass selection is performed by means of an inflection magnet (b). This magnet which has a mass resolution of 1/40 is operated at ~ -120 kV and is provided with a hall-probe gaussmeter. Then the ~ 150 keV negative ions are injected into the accelerator contained in the pressure vessel (c) which is filled with insulating gas containing $\sim 50\%$ SF₆, $\sim 40\%$ N₂ and $\sim 10\%$ CO₂ pressurized to about 10 atmospheres. The negative ions are accelerated in an evacuated acceleration tube to the high voltage terminal (d) which can be operated at voltages ranging from ~ 1 MV to 15 MV. In the high voltage terminal the negative ions are converted to positive ions by allowing them to pass through a carbon foil (d) which causes several electrons to be stripped off the ions but which is thin enough (typically ~ 5 $\mu\text{g}/\text{cm}^2$) to cause an almost negligible energy loss. A second stripper foil (e), located at the 75% voltage point, can be optionally used to achieve even higher charge states and consequently higher energy gain during the last stage of acceleration.

A beam-calibrated generating voltmeter located at the wall of the pressure vessel is used to measure the terminal voltage with a precision of 0.1 to 0.2%. The energy of the different charge-

state components emerging from the accelerator is therefore also known to this precision. The highly precise double-focussing magnet (g) used in conjunction with narrow object and image slits (f and h, respectively) is then used to select one of these components and to determine the energy with even greater precision. The field in this magnet is measured by means of a nuclear magnetic resonance probe and the magnetic energy of the selected component is thus determined with a resolution of $\sim 10^{-3}$ and a precision of $\sim 10^{-4}$. In spite of this high resolution, there are occasions in which different charge-state components of some ions can have close enough magnetic rigidities as to cause possible confusion or beam contamination especially when both strippers are used. A number of procedures have been implemented to detect and eliminate these problems.

First a computer search is performed to identify possible known beam contaminants. Charge-state combinations which may generate beams of similar rigidities are then avoided. This computer search can be skipped in the case of well established beams for which extensive experience exists. The next step is to select at least three different charge states by varying the terminal voltage. The measured voltages and beam intensities are then compared with computer predictions and the energies are verified by means of a silicon detector (see below). If no anomalies are encountered the desired beam is deflected in the switcher magnet (j) and is allowed to traverse the multiple scattering foil (k). Some of the ions scattered by this foil enter the silicon surface barrier detector (l), the pulse height spectrum of which is recorded in a multichannel analyzer. Here the energy and purity of the beam is checked making use of the fact that if different charge-state components are present they will have different energies. If a single peak is observed at the correct position the final energy is calculated by making a small correction to take into account the energy loss in the gold foil and the beam is sent into the target room. Here an independent energy and purity check is performed with one of several alpha-particle calibrated silicon surface barrier detector systems (u). Some of these detectors are also partly covered with aluminum foils of different, calibrated thicknesses and can thus be used for precise on-line LET measurements.

The ion flux reaching the part being tested can be adjusted by utilizing ion source controls, a variable aperture at the accelerator entrance, object and image slit settings, scattering foil thickness

selection and beam sweeping amplitude changes. A method useful for reducing the flux to very low values consists of using the carbon stripping foil (i) to generate a charge state distribution and then selecting a weak component of this distribution with the switcher magnet (j). Doing this allows to easily maintain a beam intensity at the regulating slits (h) sufficient for stable accelerator operation.

Beam uniformity at the device mounted on the goniometer stage (z) is achieved by multiple scattering in the foil (k), by two dimensional sweeping with the steerer magnet (m) or by a combination of these methods. The uniformity is monitored and verified by a set of four plastic scintillation detectors (two of which are shown as (r) and (s) in Fig. 2) surrounding the useful part of the beam and by a fifth detector (t) which can be rotated into the central, on-axis position. These five detectors are provided with precisely machined collimators of identical area. Usually the counting rate in the central detector is somewhat higher than the average of the other four and a corresponding automatic correction is applied to the fluence as measured by the outer detectors. Another correction is applied to take into account the divergence of the beam while traveling from the plane of the detectors to the location of the tested device.

During a prolonged measurement, the central detector is periodically and automatically rotated into the beam, the correction factor is updated and if it becomes too large the users and the operators are alerted. The flux and uniformity are constantly monitored in the diagnostic chamber (p) and displayed numerically and graphically in a specially designed PC based system [7] which is located in the control room and which also provides alarms when the flux or other parameters fall outside selected limits. A somewhat similar system had been previously developed at Brookhaven by a team from JPL. [8]

The beam can be intercepted by a faraday cup (q) and by the "parts shutter" (v). The beam is collimated by a variable and rotatable iris (x) which is adjusted so as to avoid bombarding parts adjacent to the one under study. By maintaining the plane of the iris parallel to the test board the illuminated area on the board remains constant when both planes are rotated. For some tests, other than normal incident is chosen to vary the "effective" LET value.

The entire target-room system is computer controlled and partly automated with user-friendly menu-driven software. The system can "remember" and reproduce the positions of a large number of devices on the board. The information is fed into the system by positioning each device with the aid of a joy-stick and by pressing a pushbutton. To aid in the location of the devices a light beam, which is almost collinear with the ion beam, is generated with the laser (n) and reflected by the mirror (o). The collimated light spot on the device is then observed on a monitor connected to the television camera (y). Once the test board information has been entered, a test sequence can be set up by selecting desired fluences and effective LET values. After entering the number of upsets for different LET values the system provides on-line display of the single event upset cross-section curves and documentation in the form of plots, printed tables and information recorded on floppy discs. Good examples of such data can be found in reference 9.

If the chamber needs to be opened the total vacuum cycle time is less than five minutes. The large number of chips that can be simultaneously installed and the fast, totally automated vacuum system add to the unprecedented testing efficiency which is achieved with this system.

Possible future use of higher energy heavy ion accelerators for SEU testing

As can be seen from Fig. 1 almost the entire range of charged-particle LET values can be reached at the Brookhaven Tandem Facility. There are, nevertheless, important reasons why tests with higher energy heavy ions are also desirable. One practical advantage is that at higher energies it becomes unnecessary to remove the plastic lid which protects most devices. This "delidding" procedure is often difficult and risky. Also, at higher energies the passivation-layer thickness is no longer a concern in terms of the uncertainties introduced by an unknown energy loss at lower energies. More importantly, the testing can become more realistic since the energy spectrum of heavy ions in space extends to many hundreds of MeV per nucleon. At such energies events are possible where the ions traverse devices at all angles including edge-on incidence, where more than one device is traversed by the same ion or where a primary ion generates a shower of many secondary particles which impinge simultaneously on several different devices. When studying

effects of primary radiations at these high energies, extreme care is required to avoid spurious events from possible lower energy, higher LET, beam contaminants.

There are several existing and planned coupled heavy ion accelerators at Brookhaven [11] which could be used for such tests. As can be seen from Fig. 3 a very wide range of energies and ion masses will be available. Of particular interest for SEU testing are the ions from the Booster synchrotron [10], the construction of which is now almost complete. There is an excellent overlap between the ion-species and energies available from this accelerator and the most important components of the cosmic-ray heavy ion particle spectrum. The very weak higher energy fractions can, if necessary, be reproduced by utilizing the Alternating Gradient Synchrotron (AGS). As soon as the Booster is completed in 1991, the entire range of heavy ions will be available at the AGS energies indicated in Fig. 3. However, to make use of the same ion species at the Booster energies, which are of greater interest for these applications, a new experimental facility will have to be constructed. At present the proposal for such a facility is being prepared mainly for radiobiological applications and could be easily extended for SEU testing. The construction could be initiated in 1992 and operation could start in 1994.

The operation of this new facility would be compatible and could operate simultaneously with most of the particle-physics and nuclear-physics programs planned for the AGS and for RHIC [12]. For almost all modes of operation, the Booster, which is a fast cycling synchrotron, could send beam pulses to the new applications facility while the AGS accelerates the previous pulse and before the AGS is ready to accept the next one. The beam species and energies delivered to the Booster Applications Facility could, in general, be different and independent from those delivered to the AGS. The two different beams would originate from the two existing tandem accelerators, one of which would require voltage upgrading and the addition of a short section of beam transport. The magnetic rigidity of the heavy ions sent through the long transfer line to the Booster can always be matched so as to avoid cycling of the beam transport elements. The rigidity matching can be achieved without severe penalties in either final energies or intensities. This is possible thanks to the many possible charge state and energy combinations that can be transported and injected into

the Booster. Once RHIC starts operating, injection will be required only once or twice a day and the remaining time will be available for other activities.

Conclusions

Accelerators originally designed and constructed for nuclear physics and for particle physics research are also useful and important tools in other areas of science and technology. Relativistic heavy ions have been used for many years at the Lawrence Berkeley Laboratory's BEVALAC [13] for applications in such areas as medicine, radiobiology, material sciences, electronics, etc. in addition to the basic physics research for which the facility was developed. Similar activities may in the future be carried out at the Brookhaven's Booster and AGS.

SEU testing in particular is already being performed at the Tandem with a modern, efficient and user-friendly facility which has been carefully engineered and optimized for this application. It is hoped that a facility with similar characteristics will become available at the Booster for complementary and more realistic SEU studies at higher energies.

Acknowledgements

We wish to thank C. Carlson and the Tandem operations crew for their expertise and dedication which are essential for the efficient utilization of the facility. We gratefully acknowledge contributions by I. Feigenbaum, M. Manni, T. Robinson, and G. Westwater who helped to develop and improve many systems and procedures with support from the operations crew.

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FIGURE CAPTIONS

Fig. 1 Beam energies and corresponding LET values in silicon for a few representative beams available at the Brookhaven Single Event Upset Test Facility. Many other beams are also available. More than 35 different elements have been accelerated.

Fig. 2 Simplified schematic diagram of the Brookhaven SEU test facility. Descriptions of the labeled items are given in the text. Not shown in this figure is an injector accelerator which is occasionally used for pre-acceleration of the heaviest ions. Also not shown are a number of faraday cups used for intensity measurements along the beam path and focussing and steering elements used for optimizing beam transmission.

Fig. 3 Maximum beam energies as a function of atomic mass number for existing and planned heavy ion accelerators at Brookhaven. The Tandem Facility is used to provide beams for the Single Event Upset facility described in this paper. Tandem beams up to the mass of silicon are presently directly injected and further accelerated in the Alternating Gradient Synchrotron (AGS). The Booster synchrotron [10] which is being completed will increase this mass-range up to gold and perhaps uranium. The Relativistic Heavy Ion Collider [11] (RHIC) when constructed will provide two counterrotating heavy ion beams at energies of about 100 GeV per nucleon.

Fig. 1

Fig. 2

Fig. 3

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