EUROPEAN ACCELERATOR FACILITIES FOR SINGLE EVENT EFFECTS TESTING

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1. Introduction.

Single Event Effects are, by now, well established as a hazard to spacecraft and payloads. These can result in correctable 'soft errors' [1] or destructive latch-up [2] in digital electronics. In addition to these essentially bulk charge collection mechanisms, there is now evidence for oxide effects in a variety of semiconductor technolgies [3], [4].

Single Event Effects are the result of localized ionization along the path of an heavy ion (cosmic ray) or ionization from the products of a nuclear reaction between a proton and the semiconductor material. The charge generated may be comparable with the charge stored by a bistable element in a given state ('one' or 'zero'). In the case that the charge is generated at a sensitive node (see Fig 1) then a change of state will result. Latch-up is the result of charge being deposited in the sensitive region of parasitic devices existing in the bulk of certain integrated crcuit technologies. A parasitic thyristor is created which forms a low impedance path from the power supply to ground.

The testing for single event effects requires the use of accelerator facilities capable of providing a range of ion species and protons. In the case of cosmic ray testing the cross-section for upset of a device is plotted as a function of ion LET and, in the case of proton testing , as a function of energy. For further details of single event effects see for example [5] and [6].

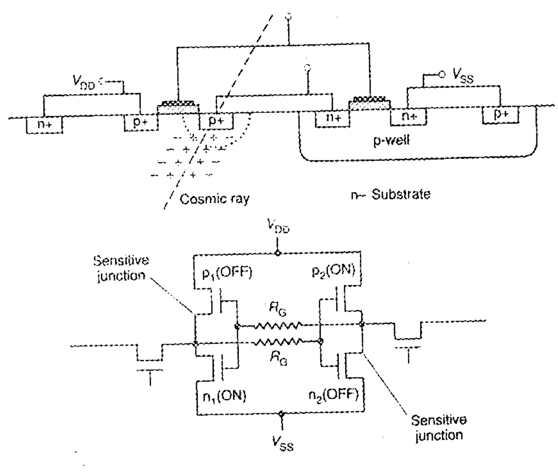

Fig 1. Single event effect mechanism in a CMOS bistable

In 1992 the European Space Agency decided to develop a European centre for proton testing (the PIF) and in 1994 a similar centre for heavy ion testing (the HIF). These two facilities are described in the following.

2. The Proton Irradiation Facility (PIF).

2.1 *General Description*

The Proton Irradiation Facility (PIF) [7] is based on a dedicated beam line shared with the Biomedical Facility and materials irradiation facility PIREX. The beam line is fed from the main 590 MeV ring accelerator by means of an electrostatic beam splitter delivering between 1 and 20 micro-amperes into the experiment hall as shown in Fig. 2.

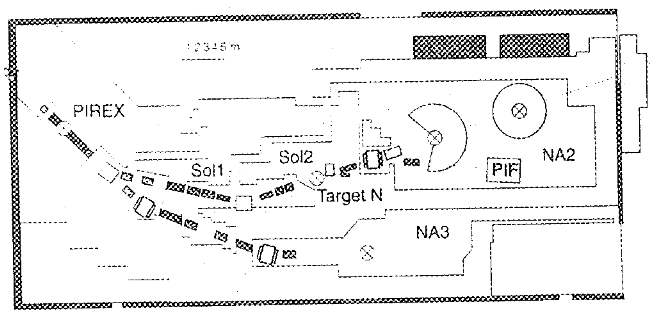

Fig 2. PIF experiment hall (NA).

After the PIREX target station the beam passes through a set of exchangeable copper-graphite blocks (PIREX degrader), reducing its energy and intensity and is guided to the biomedical and PIF areas. The maximum current is limited to 3 nA in order not to activate the experimental area. The PIREX degrader is calibrated for energies into the PIF area of 590, 300, 254, 212, 150, 102 and 60 MeV. The beam line with a sequence of 3 bending magnets make it possible to select the energies with a precision of better than 0.2%. There are two beam stops; the first one, remotely controlled, is mounted at the entrance to the area, the second one is place behind the experimental apparatus of the PIF. The beam is almost parallel and can be focussed to a minimum diameter of about 5 cm (FWHM) using quadrupoles. Energy resolution of the beam at the entrance to the PIF is better than 1%.

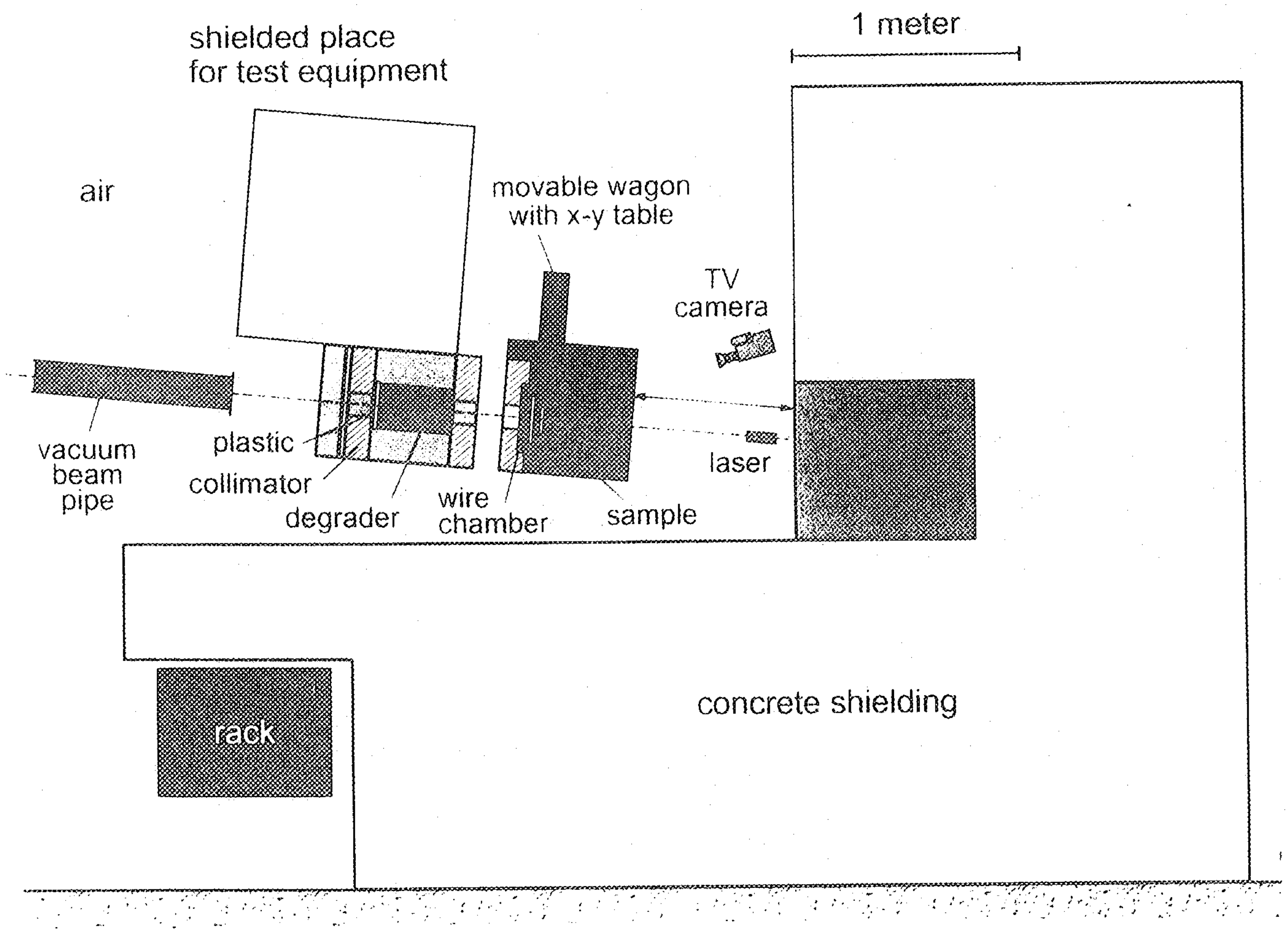

Fig 3. Schematic of PIF installation

The PIF area is fully equipped with various types of cable (coaxial, fibre-optic, RS232, twisted pair, PC extension) to the PIF control room and experimenter cabin. Typical cable lengths into the area are about 60 metres. There are also video cameras in the PIF area for observing experiments during irradiation.

2.2 *Details of PIF*

The schematic of the PIF itself is given in Fig 3. The detailed set-up consists of a system of beam collimators and beam monitoring devices, a computer controlled energy degrader and a movable wagon carrying a remotely controlled X-Y table to hold the test samples. Associated control and user electronics is mounted in a rack behind a concrete wall. Additional electronics with PCs for control and data acquisition are mounted in a PIF control room and experimenter cabin outside, but adjacent to, the experimental area.

2.2.1 *Beam collimating and monitoring*

Beam collimators are used to reduce activation of the apparatus and obtain the desired irradiated area and beam uniformity. The first collimator is placed in the 10 x 10 cm^2 opening of the iron shield in front of the degrader. Another set of collimators can be mounted between the degrader and the sample. The size and arrangement of collimators are matched to the individual requirements of PIF users and various configurations have been established with Monte-Carlo simulations using the GEANT code .

The beam monitoring system consists of the following elements :

- A split four-fold ionization chamber mounted in front of the energy degrader is used to centre the incident beam and monitor its intensity.
- An ionization chamber fixed to the movable wagon monitors the proton flux after the energy degrader.
- A PIN diode (or small area plastic scintillator) mounted directly in front of the sample monitors the beam flux within a small area. The diode essentially does not affect the beam parameters and can be left in the beam for the on-line normalization of the beam flux during irradiations.
- A plastic scintillation counter (10 x 10 mm^2, 2 mm thick) measures single protons. This counter serves for the absolute normalization of the proton flux and, at the beginning of the measurement, to calibrate the PIN diode (or small area scintillator).

- A small X-Y wire chamber is installed permanently on the beam line, behind the PIF degrader. The chamber contains 128 wires in the vertical and 64 wires in the horizontal directions. Spacing between wires is 1 and 2 mm respectively. Beam profiles are monitored on line using an oscilloscope in the PIF control room.The chamber allows rapid centering and (de)focussing of the beam..

2.2.3 *PIF energy degrader*

The local PIF energy degrader reduces the initial proton energy (max 300 MeV) to the required value. In order to continuously cover all energies up to 300 MeV the degrader consists of 8 aluminium slabs with thicknesses of 2^{n-1}mm (where n = 1.8). This allows selection of any degrader thickness between 0 and 255 mm in steps of 1 mm and energy resolution in steps between 3 and 0.8 MeV for the range 30 to 300 MeV. The slabs are driven by compressed air and can be moved in and out of the beam in about half a second. The required configuration (and corresponding energy spectrum) is remotely set using the PIF control PC. In addition to energy lost in the degrader the beam also loses in intensity, undergoes angular and energy straggling and produces secondary particles such as gammas and neutrons. Detailed studies of these problems have been made using the GEANT code and verified experimentally. Results of the simulations for a point-like 300 MeV monoenergetic initial beam are given on Figs 4a and 4b., steps at 127/128 mm correspond to a non-continuous change in the degrader geometry and are confirmed experimentally.

2.2.4 *Movable wagon with sample holder*

The wagon, movable along the beam axis, contains the remotely controlled X-Y table with the sample holder, the final beam collimators and monitors. The sample holder fixed to the X-Y table is fully compatible with the ones used at the Brookhaven National Laboratory and the HIF, for the purposes of standardization and interchangeability. The size of the test board is 25 x 25 cm. and the holder can be rotated in the Z plane to allow irradiation of the sample at different angles of incidence. Accuracy of sample positioning is 1 mm in X and Y directions. For optical monitoring and precision alignment of the sample a laser and mirror system is observed using a video camera.

Depending on the distance between the sample (on the wagon) and the degrader two modes of operation are possible. In the 'high fluence' mode the wagon is placed directly behind the energy degrader. This provides maximum intensity (2.5×10^8 protons/cm^2/sec for 10 microamp split beam). In the 'low fluence' mode the wagon is moved 'down-stream' to give maximum distance between the sample and the energy degrader which, with defocussing, provides an irradiated area of 10 x 10 cm. For larger samples the table can be scanned in X and y under PC control.

2.2.5 *Irradiation procedure*

Irradiations are usually carried out in air. According to experience and user requirements, the monitor detectors are selected for each experiment individually (ionization chambers, PIN diodes, plastic scintillators). The irradiation is controlled through a set of scalers and a PC based data acquisition system. The system monitors the flux of protons, calculates the deposited dose and controls the position of the sample and beam focus parameters. It also allows for setting the beam energy with the help of the PIF energy degrader. This allows fully automated irradiations with arbitrary proton spectra. During data acquisition the most important irradiation parameters (energy, flux, dose, sample position) are updated every second on the computer screen and stored into a file. Alarm signals are provided for occurrences such as low beam intensity or errors in devices under test.

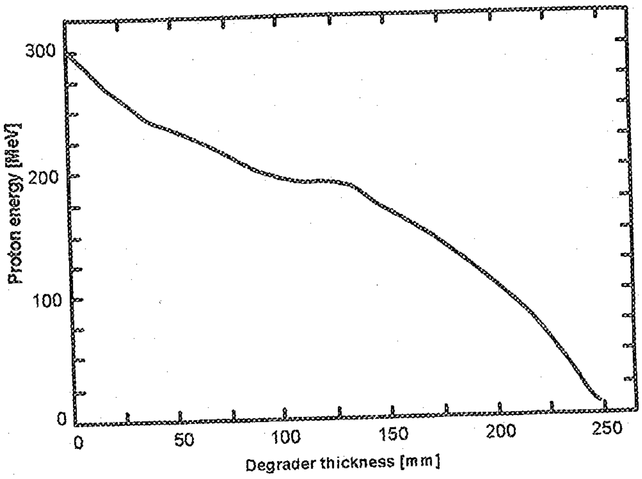

Fig 4a. Energy of protons versus degrader thickness.

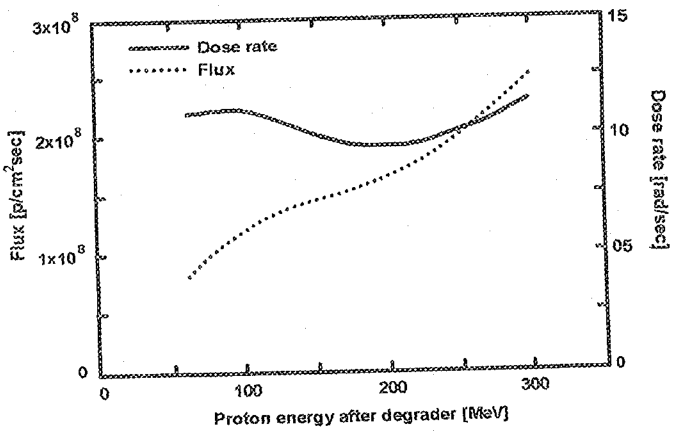

Fig 4b. Proton flux and dose rate at the PIF for 10 microamp beam at the splitter.

2.2.6 PIF experimental programme

The PIF is now in its 4th year of operation and, in addition to the intended purpose of testing for Single Event effects in electronic components it has found wide use in space and terrestrial physics investigations. Typical research activities have included :

- Semiconductor radiation hardness
- Development of monitors and detectors for space application.
- Studies of SQUIDs and CCDs
- Studies of radiation hard packaging for semiconductors.
- Investigation of isotope production rates for atmospheric physics.
- Studies of biological effects for radiation protection purposes.
- Calibration of detectors for high energy physics and space application (BgO, BaF_2).

In performing these experiments over 20 different experimenter groups have been accommodated.

In addition to the application programme there is a process of continuous development in order to improve flexibility and performance. In particular the low energy performance is being continuously improved to cope with the very low thresholds of modern devices.

SUMMARY OF KEY CHARACTERISTICS.

* Standard proton energies (after PIREX degrader) : 590, 300, 254, 212, 150, 102 , 60 and 30 MeV.
* Energies available using PIF degrader : quasi-continuous up to 300 MeV.
* Energy straggling after the PIF degrader for 300 MeV initial beam typically 7.2 MeV at 200 MeV and 15.4 MeV at 50 MeV.
* Upper limit of the beam intensity at 300 MeV : 3 nA (0.5 nA at 50 MeV); the minimum intensity can be set as low as a few protons/sec.
* Maximum flux/dose-rate at the beam centre for 300 MeV 2.5×10^8 protons/cm^2/sec (12 rad/sec) at 10 mictroamps.
* Beam profile at 300 MeV : Gaussian-like with FWHM 2 cm. (will be 1.5 cm FWHM during 1996.
* Irradiated sample area 10 x 10 cm or smaller, depending on collimators and defocussing.
* Neutron background: less than 10-4 neutrons/proton/cm^2.
* Accuracy of flux/dose determination: 5%.

3. The Heavy Ion facility (HIF).

3.1 General Description

The HIF is based on the multi-particle, variable energy, isochronous cyclotron 'CYCLONE' at the Universite Catholique de Louvain, Louvain la Neuve, Belgium. 'CYCLONE' is capable of accelerating protons up to 90 MeV, deuterons to 55 MeV, alpha particles to 110 MeV and heavier ions up to an energy of 110 Q^2/M MeV.The energy range for heavy ions extends from 0.6 to 27.5 MeV/AMU depending, among other things, on the ion's charge state. Ions with the high charge state required for single event work are produced in an external ion source of the Electron Cyclotron Resonance (ECRIS) type. 'CYCLONE' is equipped with two such sources. The ions produced in the sources are accelerated to low energy (± 10 x Q keV) analyzed in Q/M, transported to the cyclotron and injected axially for subsequent acceleration.

3.2 Details of HIF

Fig 5 shows a schematic of the HIF which has a dedicated beam-line terminated in a vacuum chamber which carries the test board for single event experiments. In order to allow a wide range of fluxes (from a few particles/cm ^{2}/sec up to 10^6 particles/cm^2/sec), under control of the experimenter, three additional injector grids were installed on the cyclotron. Two grids are in the injection line close to the ion source and a third grid is close to the cyclotron. These allow attenuation factors of 10 , 100 and 1000, plus any combination of these. For intermediate values the experimenter has access to the RF power of the ion source by means of a control knob.

3.2.1 Ion species

The 'User Requirements' set by ESA were that two different ion cocktails should be available. One should cover a wide range of high LETs (2 - 55 MeV/mg/cm^2) for routine test and characterisation and one covering a range of low LETs
(0.4 - 11 MeV/mg/cm^2)) for research purposes, primarily the study of modern complex devices with very low upset thresholds. In all cases a minimum penetration of 40 microns in Silicon was required. The final 'cocktails' of M/Q = 5 and M/q = 4 are given in Table 1 and were based on 'CYCLONE' experience and capabilities. For the lowest LET a special purpose low LET alpha beam has been developed.

3.2.2 Beam homogeneity

The actual homogeneity is ± 10% over a diameter of 30 mm. This is achieved with a gold foil (1.5 mg/cm^2) placed 7 m in front of the test chamber. Detailed simulations have shown several possibilities for improving homogeneity depending on number of foils, foil thickness, position and beam tuning. These will be investigated during final set-up. The foils are placed on a frame which is activated with a pneumatic jack and has translation movement by DC motor with position read-out by optical encoder.

3.2.3 Beam monitoring

This is an extremely important element in single effects testing as 'drifts' in important beam parameters, not detected by 'before' and 'after' measurements can result in significant error in assessing device behaviour in space.

The HIF monitoring system consists of a 'dosimetry box' placed in front of the test chamber. This box contains :

- A faraday cup (for beam tuning)
- 4 Scintillators
- Parallel Plate Avalanche Counter (PPAC).

The PPAC is checked during calibration by means of a solid state detector (SSD) of 1 cm^2. The user interface will provide warnings in case of uniformity or flux change during irradiation. When a flux warning occurs, after the irradiation and providing the flux is below a preset limit, the system will

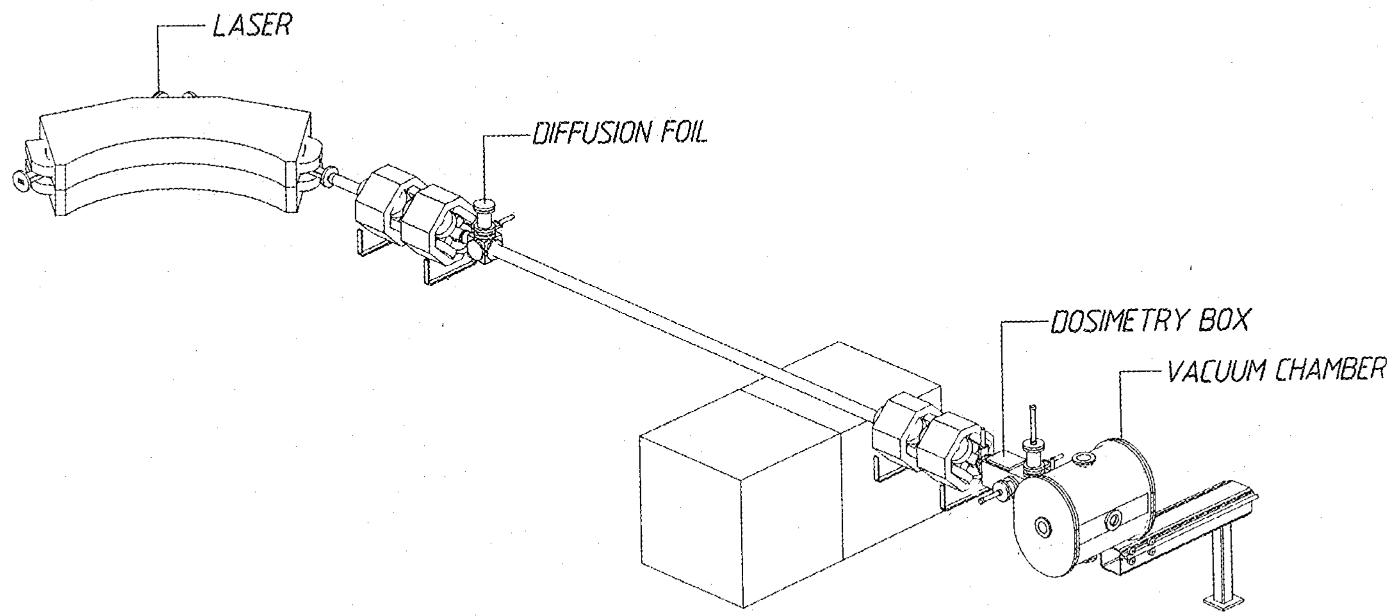

Fig 5. Schematic of HIF installation

automatically place the calibration SSD on the beam axis to verify the flux.
The 4 scintillators are placed at 90° from each other around the beam for uniformity monitoring. This monitoring is required to ensure that no diffusion foil tearing or beam drift occurs during irradiation. Since there is a wide range of flux there is a collimator for each scintillator with holes of 1mm, 4mm and 8 mm diameter. There is also a shutter to protect the scintillators from the alignment laser light. The PPAC is used to measure the total fluence, the count rate is checked using the SSD. A spare PPAC is provided in the dosimetry box and both PPACs are controlled by pneumatic jacks.

3.2.4 Test chamber

The test chamber is shown in Fig 6.and is in the shape of a barrel stretched vertically. One side flange is used to support the calibration and scan detectors. The second flange is used to support the test board frame and feed through connectors. This flange is mounted on a rail system so that it can be moved up to 1 m from the chamber. This allows convenient ' all-round' access to the test board. The test board frame is 25 x 25 cm and compatible with Brookhaven National Laboratory and the PIF. Three mecahnisms are used to position the frame.

- **Translation.** Total movement 264 mm. The movement is performed using a DC motor and the position read using an optical encoder. Translation speed is 20 mm/sec and positioning accuracy is ± 0.5 mm.
- **Rotation.** The board can be rotated through ± 90° with an accuracy of 1°.
- **On-axis translation.** In order to allow precise alignment of a component under test on the rotation axis a very slow translation movement (0.5 mm/sec) is possible along the beam axis. The total stroke is ± 20 mm with an accuracy of 0.5 mm.

Additional features include an iris with motor control from 4 to 60 mm diameter, a camera port, a view port, internal lighting and an on-axis laser diode for precise alignment. The 'pump-down' time for the chamber is 5 minutes.

Coktail # 1 :

M / Q = 5	Primary Energy [MeV]	DUT Energy [MeV]	Range [µm Si]	LET [Mev cm2 / mg]
$^{40}Ar^{8+}$	174	150	42	14,1
$^{20}Ne^{4+}$	88	78	45	5,85
$^{15}N^{3+}$	66	62	64	2,97
$^{10}B^{2+}$	44	41	~80	~1,7

M / Q = 5,07	Primary Energy [MeV]	DUT Energy [MeV]	Range [µm Si]	LET [Mev cm2 / mg]
$^{132}Xe^{26+}$	557	459	43	55,9

M / Q = 4,94	Primary Energy [MeV]	DUT Energy [MeV]	Range [µm Si]	LET [Mev cm2 / mg]
$^{84}Kr^{17+}$	374	316	43	34

Coktail # 2 : M/Q = 4

M / Q = 4	Primary Energy [MeV]	DUT Energy [MeV]	Range [µm Si]	LET [Mev cm2 / mg]
$^{12}C^{3+}$	82,5	79	130	1,67
$^{16}O^{4+}$	110	105	104	2,9
$^{40}Ar^{10+}$	275	259	680	10,9

For special purpose, a low LET alpha beam will be developed:

Ion	Primary Energy [MeV]	DUT Energy [MeV]	Range [µm Si]	LET [Mev cm2 / mg]
α	10	9.2	63	0.4

Table 1. Ion cocktails available.

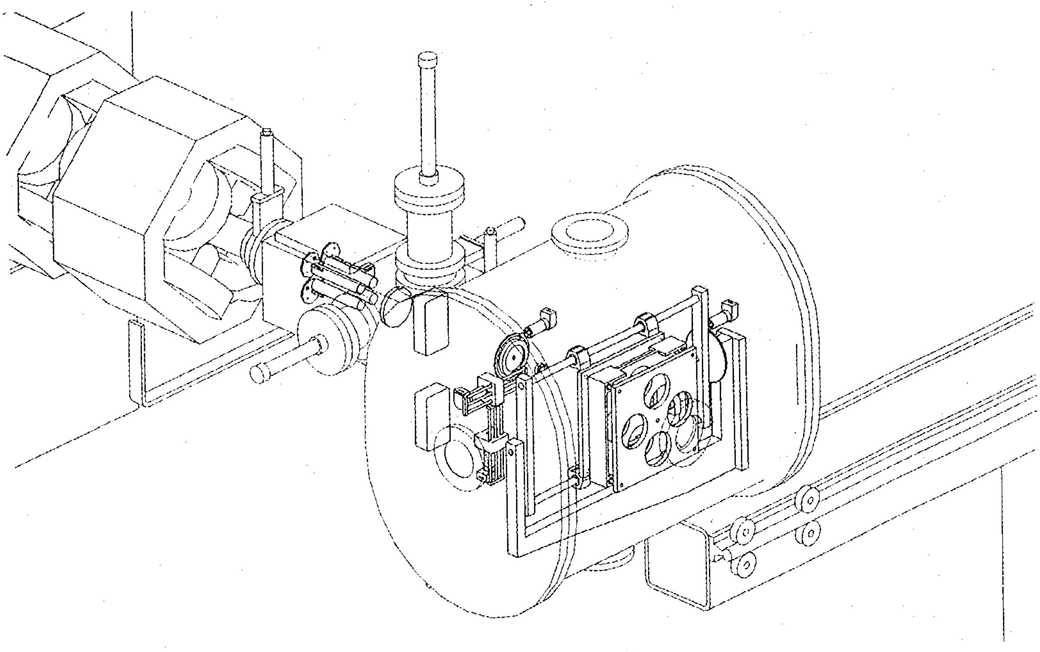

Fig 6. Details of HIF vacuum chamber

3.2.5 User Interface

The user interface is based on a Pentium PC which provides 4 screens and a tool bar. The user has access to 3 screens, the fourth (Operator) being reserved for cyclotron staff. The three user screens are :

- **Board-Position.** This includes motor controls, vacuum control, iris aperture and rotation angle of the test board, board and device selection. The dialog box allows users to edit device positions, recall stored positions , store new boards, verify positions, delete devices from a board or delete a complete board. Up to 10 device positions can be stored per board and users can store as many boards as they need.
A 'Verify' option performs an automatic scan of the device positions from 1 to 10 and pause at each position to await validation. The 'Edit Position' option allows the use of a joystick for repositioning devices.

- **Data-Beam.** This includes beam parameters (ion species, LET, flux, uniformity), run details (run number, effective LET, estimated irradiation time, RUN/STOP), position data (board name, device number and ID, rotation angle, iris aperture), results (number of errors, calculated cross section, deposited dose for the run and cumulative dose, plot of cross-section). The choice of ion species is done with a drop down list. Once the ion and target material has been selected the user interface will display LET and range. For tilting there are two possibilities :

- Prompt for desired angle (automatic calculation of effective LET).

- Prompt for desired effective LET (automatic calculation of the angle).

- **Beam Line.** This includes a beam line bitmap to show the location of each element to the users, vacuum control of the test chamber (vent/evacuate), control of injection grids, beam scan (X, Y, both), laser ON/OFF, calibration SSD IN/OUT.

- **Operator.** The access to this screen is restricted to cyclotron staff and is protected by a password. The screen includes a beam line bitmap, access to the different detectors and the laser, detector biasing, access to all line valves, vacuum control of the test chamber, diffusion air lock and dosimetry box, diffusion foil changing and PPAC swapping.

- **Tool bar.** There is permanent access to a 10 icon tool bar for the most commonly used features of the HIF. These include device at 0°, device at 45°, device at 60°, access to injection grids, scan control, start/stop irradiation, SSD IN/OUT, laser ON/OFF, chamber light ON/OFF, evacuate/vent chamber, shut off the HIF.

3.3 HIF Status

The present situation is that the final engineering development and beam tuning is in progress and the HIF should be ready for commissioning later this year.
Prior to initiating the HIF development a number of studies were carried out on the same beam line using a simpler, less automated facility. One of the main aims of these studies was to establish correlation with another well recognized facility. Brookhaven National Laboratory is one such facility used by many workers in the single event field. Fig 7 gives the results obtained using a 16 Mbit DRAM and clearly shows excellent correlation.

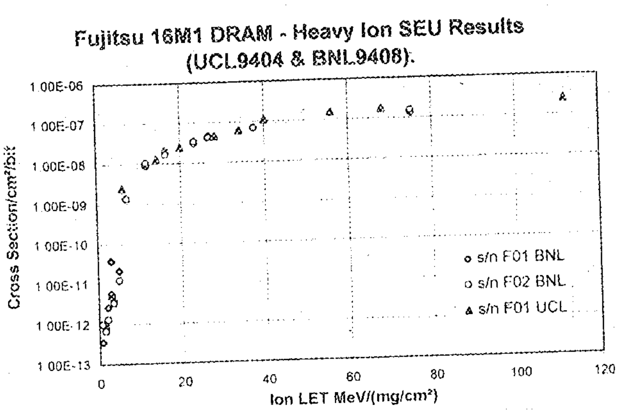

Fig 7. Results of correlation tests using 16 Mbit DRAM

4. *Conclusions.*

Single event effects are an important hazard to spacecraft and payloads. The advances in component technology, with shrinking dimensions and increasing complexity will give even more importance to single event effects in the future.

The ground test facilities are complex and expensive and the complexities of installing a facility are compounded by the requirement that maximum control is to be exercised by users largely unfamiliar with accelerator technology. The PIF and the HIF are the result of experience gained in the field of single event effects testing and represent a unique collaboration between space technology and accelerator experts. Both facilities form an essential part of the European infrastructure supporting space projects.

5. *References.*

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