EUROPEAN RADIATION FACILITIES AND TEST METHODS

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1. Introduction.

The increased usage of modern complex component technologies and the thrust to use 'commercial' technologies wherever possible in space systems, gives rise to the need for radiation test facilities well suited to component testing and test methods which clearly define how such testing is to be performed.

In the past, much testing has been carried out on an 'ad hoc' basis, using test methods which have been constrained by the facilities used as well as cost and time. Component measurements are frequently curtailed due to difficulties in working at a site remote from the 'home' laboratory and the practical difficulties in working with research irradiators or high energy accelerators do not always allow the components to be exposed under the required conditions (e.g. dynamically operating, DC biased etc.).

The situation in Europe up until the early 1990s was that Total Ionizing Dose testing was carried out following MIL 883 Method 1019 with various modifications to suit particular circumstances and Single Event Effects testing was largely a research type activity heavily constrained by the capabilities of the accelerators used. At the same time there was strong cooperation with various US authorities such as Sandia Labs , JPL and Aerospace Corporation as well as a number of cooperative test campaigns at such facilities as Berkeley and BNL. By this means, at least informally, a degree of standardisation in testing was achieved.

In 1993 ESA set up the 'Space Hardness Assurance Working Group' which is a small group of technical experts from space agencies, space system manufacturers, component manufacturers and academia. The first task of this group was to finalise and issue the total ionizing dose test method SCC 22900 and the second task was to issue a companion test method for single event effects, SCC 25100. In addition, there was extensive discussion of 'user requirements' for test facilities which were then reflected in the ESA sponsored developments taking place at the Paul Scherrer Institute, Switzerland for the Proton Irradiation Facility (PIF) and the Universite Catholique de Louvain, Belgium for the Heavy Ion Facility (HIF).

2. Test Facilities.

2.1 ESTEC Total Ionizing Dose Facility.

The ESTEC total ionizing dose facility was installed in 1988 and was reloaded in 1995 to the original nominal 2000 Curies of Co-60. The source is housed in a Nordion Gammabeam 150C collimated irradiator giving a 30° beam angle. Using a collimated source allows test and monitoring equipment to be used in the source room (with protection by lead bricks) close to the device under test. A dedicated laboratory (Fig 1) was built to house the source and the control/measurement equipment. Being a new facility we were able to make a design which incorporated all the features necessary for space component testing. The source room is approximately 7m long and 2.5 m wide with 3 large feed-through pipes in the side wall for cables. From the source room we have approximately 10 m of large bore plastic piping which runs under the floor to the LSI tester in the main laboratory. 64 wires with line drivers and receivers allow complex devices be exercised by the LSI tester while being irradiated. Radiological protection aspects were a major consideration and the shielding walls were designed for 6000 Curies. In practice this results in no measurable radiation in the control room which, nevertheless, is treated as a controlled area. The length of the source room was chosen to give at least a factor of 100 on dose rates available. In practice this has resulted in 0.8 rad/min on the end wall and 32 rad/min at 1 from the source with 1% uniformity over an area 30 x 30 cm.400 rad/min is available at the exit of the collimator but, of course, the area is much reduced. Dosimetry is of major concern in component testing and a range of techniques are used. Routine dosimetry is performed using a Nuclear Enterprise 'Ionex Dosemaster' with two 0.6 cc ion chambers. A 600 cc ion chamber is also available for low dose rate testing. Overall accuracy of this system is 5%. Field uniformity is monitored using a Keithley "Tracker' which has one central ion chamber and 4 ion chambers on a 20cm square grid. Thermo-Luminescent Dosimeters type TLD200 are used with a Harshaw 3500 reader reader when the dose at specific locations needs to be recorded. TLDs are also used when any radiation testing is performed 'off-site'. All dosimetery systems are periodically calibrated by authorized laboratories and a full dose mapping of the source room has been carried out using reference alanine dosimeters from the National Physical Laboratory, UK.

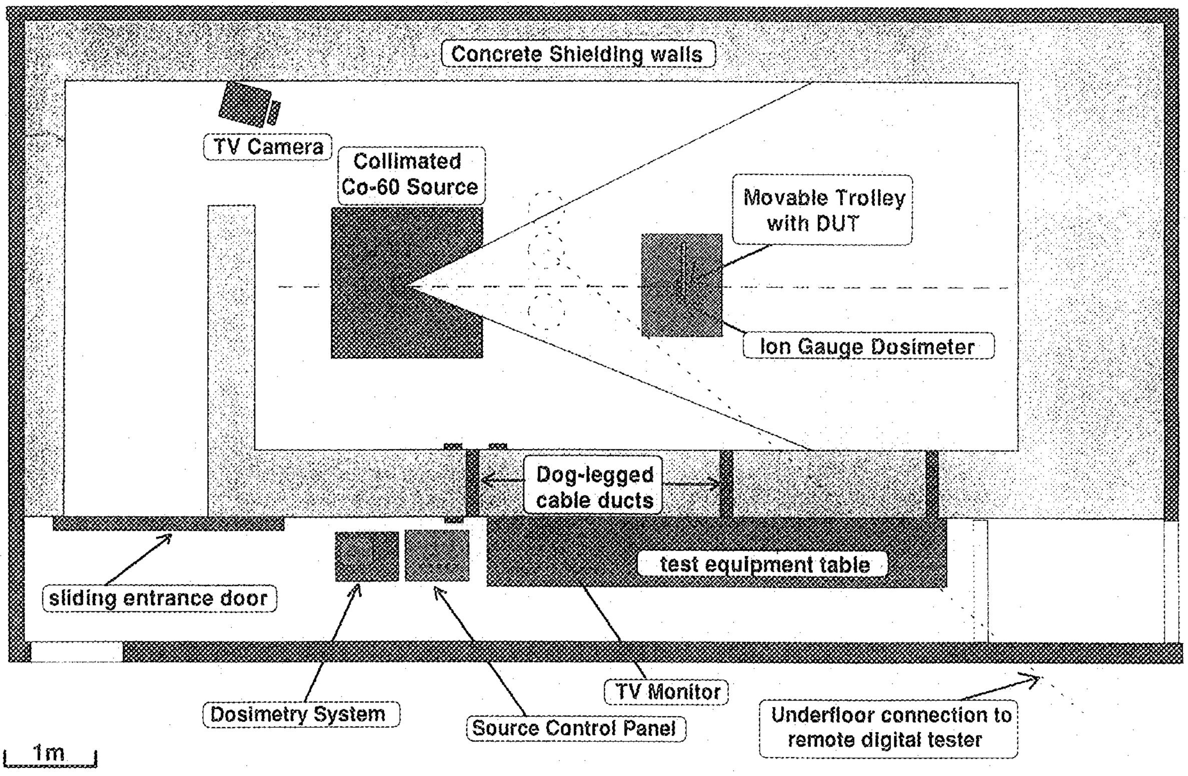

Fig 1. The ESTEC Co-60 Facility

2.2. *The Proton Irradiation Facility (PIF)*

The Proton Irradiation Facility (PIF) 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 microamperes into the experiment hall.

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%.

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. The schematic of the PIF is given in Fig 2. 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.

The key element of the PIF is the energy degrader which 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-1mm} (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. Fig 3 shows a Solar Flare spectrum generated using this technique.

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.

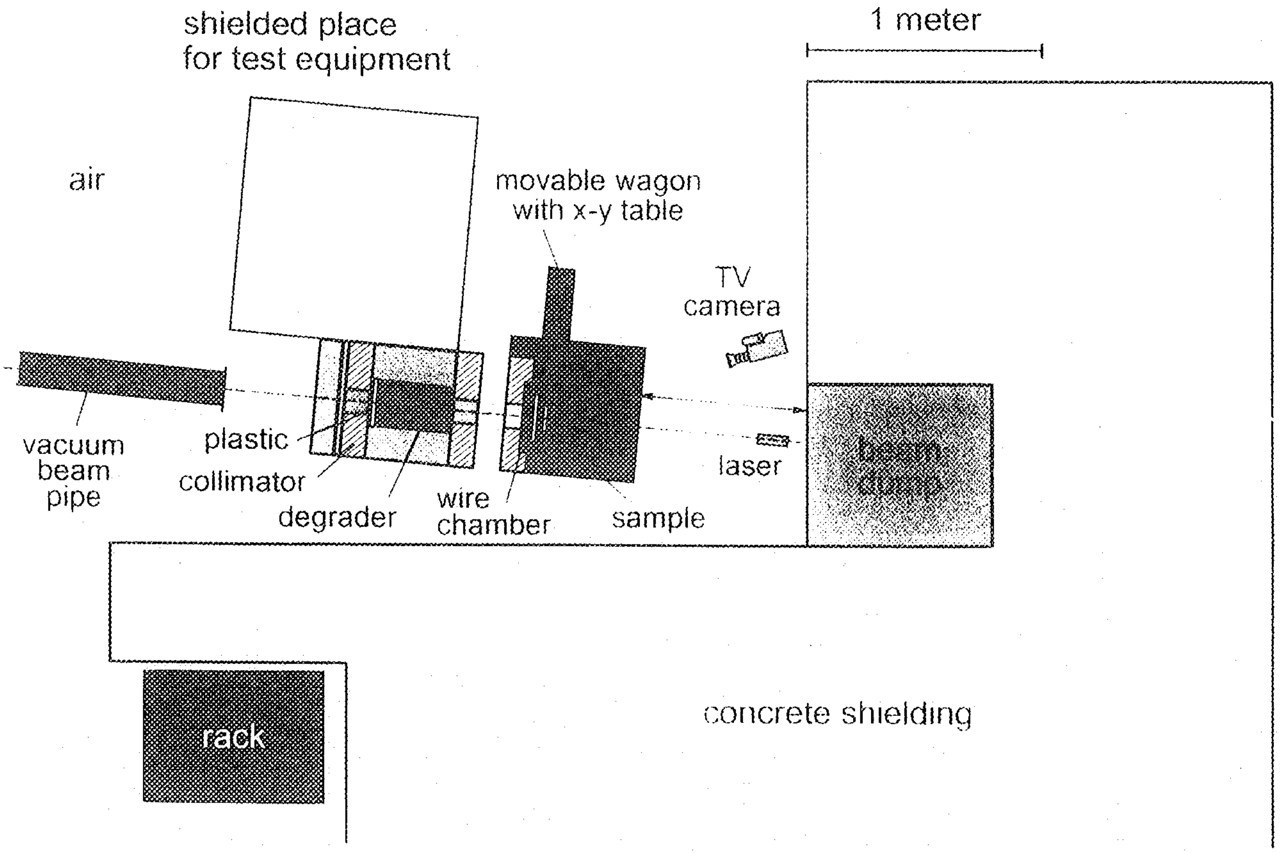

Fig 2. Schematic of the PIF.

THE 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, BaF2).

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.

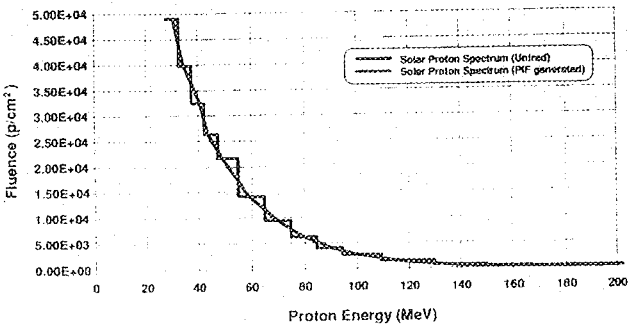

Fig 3. Solar Flare generation on the PIF.

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 microamps.

* 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%.

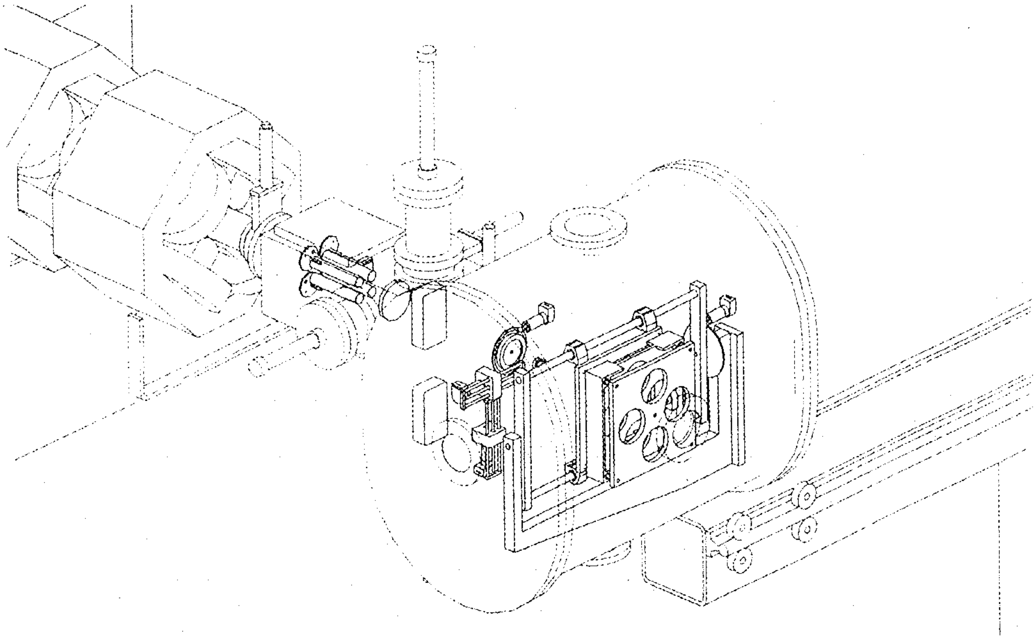

Fig 4. Schematic of the HIF vacuum chamber and dosimetry box.

2.3 The Heavy Ion facility (HIF).

2.3.1 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.

Fig 4 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.

2.3..2 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.

2.3.3 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.

2.3.4 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 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.

2.3.5. Test chamber

The test chamber 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.

2.3.6. 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.

Coktail # 1 :

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

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

M / Q = 4,94	Primary Energy [MeV]	DUT Energy [MeV]	Range [µm Si]	LET [Mev cm2 / mg]
$^{84}\mathrm{Kr}^{17+}$	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]
$^{12}\mathrm{C}^{3+}$	82,5	79	130	1,67
$^{16}\mathrm{O}^{4+}$	110	105	104	2,9
$^{40}\mathrm{Ar}^{10+}$	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.

- **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.

2.3.7 *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 5 gives the results obtained using a 16 Mbit DRAM and clearly shows excellent correlation.

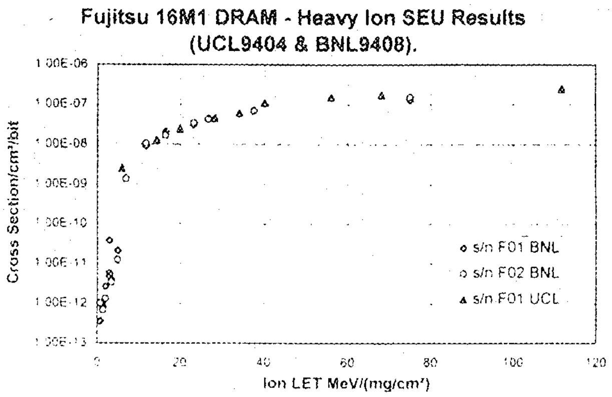

Fig 5. Results of correlation tests using 16 Mbit DRAM

3. *Test Methods.*

3.1 *Total Dose Steady State Irradiation Test Method, SCC22900, Issue 3.*

The basic aim of setting up SCC 22900 was to provide a test method 'tailored' to the requirements of the space environment (low dose-rate), the constraints of testing at remote facilities (transport of devices) and the extent of radiation testing required during the different phases of component assessment (evaluation, qualification and procurement). An experimental verification programme covering MOS and bipolar technologies using both MIL 1019.4 and SCC 22900 test methods was carried out by Matra Marconi Space under ESA contract. The aims of this programme were to validate various assumptions made in SCC 22900 concerning dose rates, sample sizes and annealing tests. The results of the study were :

- Sample sizes should be maintained (2 lots with 10 samples from each for evaluation tests, 10 samples for procurement verification test, with a possible reduction to 5 for well known technologies).
- Dose rate 'windows' should be maintained, possibly removing any restrictions on the lowest rate.
- For MOS technology SCC 29900 provides a conservative estimate of survivability in the space environment and there is a good possibility of extrapolating very low dose rate behaviour from annealing tests.
- For linear bipolar devices we found enhanced degradation at low dose rates and it may be that the maximum dose rate for testing these technologies should be constrained to abour 300 r/hr.
- For linear bipolar technologies no correlation was found between annealing and low doe rate behaviour which means no extrapolation from annealing beahviour to space environment is possible.

We will continue collecting data from the application of SCC 22900 and may consider a re-issue in the light of experience later this year.

3.2 *Single Event Effects Test Method and Guidelines. SCC 25100.*

SCC 25100 differs from SCC 22900 in that it was felt that some sort of tutorial material (guidelines) was needed to accompany the test method, since this is a comparatively new field of component testing.. The guidelines were largely derived from several years of ESA experience using different facilities. For the Test Method itself, we found that one of the greatest difficulties was to avoid making it 'facility specific' . This was achieved by putting details of the the various facilities into the guidelines which form part of the same document and can be referred to directly. The salient features of SCC 25100 are :

- To be used for both heavy ion and proton testing.
- To require the generation of a full response curve from threshold to saturation.
- A minimum sample size of 3.
- Extended data reporting on devices tested including die photograph, dimensions and technology details.
- Extended details of exposure conditions including ion specie and charge state, energy and dosimetry techniques.

The Test Method was issued in October 1995, consequently there is not yet much 'user feedback' . As with SCC 22900 we will collect data arising from application of the test method as well as comments from users.

4. *Acknowledgements.*

A survey paper of this nature is the result of a great deal of effort on the part of many people and I would especially like to acknowledge the ESTEC team of R. Harboe-Sorensen, B. Johlander and R. Nickson as well as our cyclotron colleagues G. Berger of Louvain and W. Hajdas of PSI.