The use of particle accelerators for space projects

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Abstract. With the introduction of CMOS technology radiation effects in components became an important issue in satellite and space mission projects. At the end of the cold war, the market of radiation hard (RadHard) components crashed and during the 90’s their fabrication practically stopped. The use of “commercial-off-the-shelf” (COTS) components became more common but required increased evaluation activities at radiation test sites. Component manufacturers and space project engineers were directed towards these test sites, in particular, towards particle accelerators. Many accelerator laboratories developed special beam lines and constructed dedicated test areas for component evaluations. The space environment was simulated at these test sites and components were tested to levels often exceeding mission requirements. In general, space projects environments were predicted in respects to particle mass and energy distributions with the expected fluxes and fluences. In order to validate this information in tests, concepts like stopping power, linear energy transfer, ion penetration ranges etc. have to be understood. The knowledge from the component structure also defines the way of irradiation. For example, the higher ion energies resulting in much deeper ion penetration ranges allow successful reverse side irradiation of thinned Integrated Circuits (ICs). So overall increased demands for radiation testing attracted the European Space Agency (ESA) to the JYFL-accelerator laboratory of the University of Jyväskylä, Finland. A contract was signed between ESA and JYFL for the development of a “High Penetrating Heavy Ion Test Site” [1]. Following one year development, this test site was commissioned in May 2005. This paper addresses the various issues around the JYFL laboratory with its accelerator and radiation effects facility as the focal point in service of component evaluations for the space community.

1. Introduction

In addition to the crash of the RadHard market, also a “technology revolution” in the physical size of COTS components occurred. Now the line widths go below 100 nanometers, the operating voltages are reaching the one volt limit and the evolution of the efficiency follows Moore’s law [2] (number of transistors in memories quadruples every third year). The COTS components are small in physical size, their power consumption is low, the memory capacities are large and processors fast, they represent the latest design and their reliabilities are tested in every day’s applications. All these properties are useful for satellite electronics, but the only problem is their radiation performance.

To find out the radiation durability of components the space project engineers turned to the accelerator and nuclear physicists, who have a long experience with creation and measuring particle radiation and using particle accelerators. They also have basic research knowledge and information available about the behavior of energetic ions and their effects in materials.

In simulating space radiation environment the beam modification and dosimetry play an essential role. On the contrary to the usual nuclear physics experiments the beam intensity, or preferably
particle flux, is very low. New processing techniques also require penetrating ions, which means new challenge for the accelerator and ion source physicists to develop more energetic beams. In order to validate the test the spectroscopic properties of the beam like the ion identification, beam purity and energy must be defined in each individual test run. The parameters like homogeneity, flux and fluence must also be calibrated and monitored during the irradiation.

Yet another demand came from the project engineers. In order to keep the project costs low the tests should be performed in as short time as possible. A typical test campaign includes several different ions and all the calibration procedures have to be repeated for each individual beam. Also, the component selection typically includes many samples, which have to be irradiated in vacuum conditions. Therefore, time saving procedures and solutions are crucial questions in modifying the accelerator and building the irradiation facility for the use of space projects.

2. Space radiation environment

In figure 1 the origins of space radiation and the relevant particle radiation components are given. The most important particle source Sun emits, besides of neutrons and electrons, 70% protons, 28% helium, 1.5% carbon, nitrogen and oxygen, and 0.5% all other elements. Because Sun cannot create heavier nuclei than oxygen, the existence of all other elements are the evidence that the Sun is not a first generation star but formed in a region where more massive, violent stars once lived.

Cosmic rays coming outside of the solar system can have energies up to $10^{20}$ eV and are the debris from the nova and supernova detonations in Milky Way or other galaxies. Trapped particles in the two Van Allen belts consist of electrons and protons. According to their dominating abundances the inner belt is called proton belt and the outer one electron belt.

The stars over eight times more massive than Sun can create heavy particles like e.g. iron. Iron is the heaviest one, whose abundance in space is significant enough to cause single event effects (SEU) in spacecraft components. In figure 2 relative abundances of elements are given.
3. Sample preparation

In figure 3 a simplified sketch of a memory cell transistor is given. A fast charged particle plunges into a transistor and creates an ionization column of electron hole pairs along its track. The accumulation of this charge to the sensitive depletion region can cause errors like e.g. a bit flip, transient spike or a latch-up in the transistor. Also heavy recoils followed by nuclear interactions caused by protons can create enough extra ionization causing similar effects, see figure 3.

The electronic circuit is typically processed on a substrate of standard thickness of 300 microns. Adding up a typical process thickness of the depletion region and both the prompt and diffusion charge collections depths (funnel length) the radiation sensitive area thickness is much less than ten microns.
Figure 3. Principles of error creation in a component caused by a charged particle and proton [3].

Obviously, in order to reach the sensitive area, the component’s package has to be removed first. In plastic encapsulated devices this can be done either by etching or mechanically grinding. If the bonding is made on the sides of the die the irradiation of the sensitive area can be performed directly from the front side. Today, many components and practically all modern memories are assembled with the bond pads in the centre and the lead frame on top of the die. This is shown in an x-ray picture of an SDRAM-memory chip of figure 4. In this case the direct, front side irradiation is not possible. There are two ways to proceed, i.e. to use re-bonding or back thinning methods.

Figure 4. X-ray of Hitachi 256-Mbit SDRAM in 54-pin TSOP (plastic package). The centre bonding and the lead frame can clearly be seen [3].
In the re-bonding method the package has to be opened very carefully. Then one has to remove the lead frame and re-bond the bare die to the test board. This method allows the front side irradiation, but is not very reliable. Roughly one out of ten memories only survives this procedure.

In the thinning method the package and the die is thinned from the backside. This can be done mechanically, but one has to avoid going too close to the sensitive area. Alternative choices are dry plasma etching or laser ablation. A safe distance to stop the process is, when 50 microns is left to the front surface. Thinning method is reliable, but needs irradiation from the back and therefore higher ion penetration. Techniques involved in this method are treated in a recent paper of Courtade et al. [5].

4. **Bragg curve behaviour**
Let us suppose that a heavy energetic ion with a certain charge state enters the component’s surface. If the entrance velocity overcomes the Bohr’s velocity of the atomic electrons of the target, the ion becomes fully stripped. This is described in figure 5.

![Bragg curve behaviour](image)

**Figure 5.** The Bragg curve behaviour of the ionising particle. The approximation does not include the effects originating from the de-excitations of the atoms.

By traveling in silicon the ion slowly looses its energy via Coulomb interactions with target electrons and forms the ionization column as was shown in figure 3. This coulombic energy loss is called linear energy transfer, LET. It reaches the maximum at the so called Bragg peak. There the ion fills its orbits and, as a neutral atom, gets closer to the target nuclei and rapidly slows down via the nuclear interactions with them.

A term, which obeys this Bragg curve behavior, is stopping power S. In figure 5 it is approximated with the sum of coulombic and nucleonic terms LET and NIEL, respectively. NIEL is an acronym of Non-Ionising Energy Loss. Because ionizing causes single event effects (SEEs) and non-ionising interactions displacement damages in the silicon’s crystal lattice the LET and NIEL are the terms commonly used within the space community.

LET can be given in units of energy per distance [MeV/μm], but most often the unit [MeV/(mg/cm²)] is used. The penetration distance in material depends on the mass of the ion and its energy as is discussed later.

5. **Requirements of space projects**
In order to test the durability of the component in radiation exposure the error cross section needs to be determined as a function of LET. The measurement principle is described in figure 6. By increasing LET and monitoring SEE cross section the threshold and saturation points of error creation can be defined. To be able to compare the components the cross section has to be normalized to the total fluence of particles in cm².
The LET values are varied by changing ions with different masses. The mass variety should cover the threshold and saturation points evenly. Together with the proper LET values the sufficient ion ranges have to be taken into account. As is obvious (see figure 5), the sensitive region of the component should be located before the maximum of the Bragg peak. Two examples are depicted in figure 7, where the LET curves as a function of penetration depths for two sets of ions with same energy per nucleon are given.

These kinds of set of ions are called “ion cocktails”. In the front side irradiations the minimum range is at 33-40 microns for the ions in the low energy 3.6 MeV/amu cocktail. The LET curve starts to turn down after 10 microns except for xenon, in which the drop starts immediately after hitting the surface. If one must confine to the back thinning method the sufficient penetration depth has to be doubled when thinning the component to 50 microns. This is satisfied with the 9.3 MeV/amu cocktail of figure 7.

The spectrum, which defines the ion and beam purity, has to be measured before irradiation. The ion flux and fluence as well as the beam homogeneity are monitored during the irradiation. Adequate
beam uniformity is ±10% with a sufficient area of about 4 cm$^2$. Also, the test board or component changes should be fast procedures including easy fixing system of the DUT (device under test). Proper cabling and feed-through flanges equipped with several standard type connectors are also mandatory. The test chamber needs effective pumping capacity for a few minutes’ evacuation down to ~10$^5$ mbar.

Most effective way to shorten the test duration is to minimise the time of the beam changes. With the cocktail beams the ion change takes only few minutes. In addition to this, the increased need for back-side irradiations is a challenge for accelerator laboratories to develop more energetic cocktails for the use of space projects as discussed later.

6. Requirements of SEE accelerator facilities

6.1. European SEE accelerators

Following nine accelerator laboratories facilitating a space irradiation station were introduced in a “Thematic Meeting on European SEE Accelerators”, which was hosted by JYFL accelerator laboratory of the University of Jyväskylä, Finland [7], in May 2005 (c = cyclotron, t = tandem, p = provides only protons):

- BIBER, Berlin, Germany (c)
- CPO, Orsay, France (c,p)
- GANIL, Caen, France (c)
- HIF, UCL Louvain-la-Neuve, Belgium (c)
- PIF, PSI, Villigen, Switzerland (c,p)
- IPN, Orsay, France (t)
- RADEF, Jyväskylä, Finland (c)
- SIRAD, Padova, Italy (t)
- TSL, Uppsala, Sweden (c)

Three of the laboratories, HIF, PIF and RADEF, are the contract radiation facilities of European Space Agency ESA. Most of the SEE accelerators are cyclotrons, equipped with electron cyclotron resonance (ECR) type ion source(s). Cyclotron in combination with ECR provides the ability to accelerate ion cocktails.

Ion cocktails are mixtures of ions with almost identical mass-to-charge (m/q) ratios. The operation of ECR is based on microwave frequency heating of elements. Several elements can be simultaneously fed into the ECR, where the microwave power ionises atoms by stripping electrons from their orbits. Magnets confine the electron-ion plasma and positive ions are pulled to the injection line. From there the ions are injected into the cyclotron for the acceleration. Cocktail ions accelerate along the same paths and in order to separate ions the cyclotron is utilised as a mass analyser by shifting its RF frequency and/or the trim coils in the extraction. The mass separation is based on a slightly different mass excess between different nuclei (m/q • A/q). Therefore, only fine tuning is needed to change ion species inside the cocktail. This makes the fast beam change possible.

In the following two subsections the JYFL accelerator laboratory and its RADEF facility are introduced and used as an example about issues, which have to be taken into account in utilising the accelerator for SEE ground tests of space components.

6.2. The JYFL accelerator and the ECR ion sources

The JYFL K-130 cyclotron is a sector-focused accelerator of ion beams from hydrogen to xenon. It is equipped with two ECR ion sources (6.4 GHz [8] and 14 GHz [9]) designed for high-charge-state heavy ions and a multicusp ion source for negative light ions. The K=130 value describes the bending limit of the cyclotron’s main magnet. The energy of the beam can be given by $E = K \cdot q^2/A$, where q is the charge state of the ion and A is its mass number.

Because of the q$^2$-proportionality the development of high charge states in ECR is crucially important when increasing the beam energy. The use of RADEF facility started in 1998 [10] by
utilising the low energy, low penetration cocktail depicted in left part in figure 7 and listed in table 1. The highest charge state was 22+ for the $^{132}$Xe beam of 475 MeV. Also the MIVOC (Metallic Ions from Volatile Compounds) technique, developed in the laboratory [11], allowed one to use metallic ions (iron was produced from ferrocen) in cocktails.

### Table 1. The low energy (3.6 MeV/amu) cocktail.

| Ion   | Energy [MeV] | Range [μm] | LET | Surface |
|-------|--------------|------------|-----|---------|
| $^{12}$C$^{2+}$ | 43           | 51         | 3   |         |
| $^{30}$Si$^{5+}$   | 108          | 38         | 11  |         |
| $^{54}$Fe$^{9+}$   | 194          | 33         | 27  |         |
| $^{84}$Kr$^{14+}$  | 302          | 39         | 40  |         |
| $^{132}$Xe$^{22+}$ | 475          | 40         | 69  |         |

In order to satisfy the increased demands to perform reverse side irradiations ESA placed a contract with JYFL. The contract was started with an upgrade phase by implementing a second frequency to laboratory’s 14 GHz ECR ion source. The results from the first test with a new Travelling Wave Tube Amplifier (TWTA) connected to the laboratory’s ECRIS-II are given in figure 8.

![Figure 8. Performance of the JYFL ECRIS-II ion source in single and double frequency heating modes [12].](image)

As demonstrated in figure 8 the production of highly charged ion beam with ECR ion source can be improved by using the two-frequency heating. TWTA has a frequency range of 10.75-12.75 GHz and a maximum power of 400 W. With double frequency mode the performance of the JYFL ECRIS-II improved significantly. Figure 8 shows the extracted currents of xenon beams of different charge states for a single 14 GHz klystron and double frequency heating of 14 GHz klystron and 11.39 GHz from TWTA. The improvement factor for the 136-xenon beam current increased more than seven times larger with double frequency heating for the charge state of 32+. It is also promising to note that the factor increases drastically with the increasing charge state.

The developed high-penetration cocktail is shown in table 2.

### Table 2. The high-penetration (9.3 MeV/amu) cocktail.
In table 2 three LET values are calculated with SRIM [6]: LET at surface, at a distance of 50 microns and at the Bragg peak in silicon. Also, the distance of the Bragg peak is tabulated. It is worth to note, that in the case of reverse side irradiation the distance of the sensitive region from the thinned backside has to be taken into account in the determination of the LET value. Another thing is that in the preparation of samples the flatness of the thinning and the accurate measurement of the device thickness are extra demands, which are not needed in the front side irradiation.

As was stated before, for the rapid change of the ions the m/q ratios of the cocktail ion species should be close to each other. On the other hand, if they are too close they cannot be resolved. Therefore, it is important to know the mass resolution of the cyclotron. In figure 9 a mass spectrum of different close lying ions is measured. Ions shown in the spectrum were injected simultaneously in the cyclotron and were extracted by slightly changing the magnetic field. The result was that the mass resolution of 0.3 ‰ was accurate enough to resolve the individual ions. Even with the 0.2‰ resolution Ar and Fe ions can be seen as separate peaks. The resolutions of different ions in the high penetration cocktail are shown in the last column in table 2. The values are normalized to nitrogen, which acts as a buffer gas. As can be seen the cocktail components are far enough from each other and can easily be separated. This guarantees the purity of the individual beams. This is proved in figure 10, where the spectra of different cocktail components are measured with a scintillator/PMT detector. As is seen the peaks can easily been identified and the spectra are clean.

| Ion  | Energy [MeV] | Range [μm] | LET\textsuperscript{a} Surface | LET\textsuperscript{b} 50 μm | LET\textsuperscript{c} Bragg | Range\textsuperscript{c} Bragg | m/m |
|------|--------------|------------|--------------------------------|----------------|----------------------------|-------------------------------|-----|
| \textsuperscript{15}N\textsuperscript{4+} | 139         | 202        | 1.8                           | 2.1            | 5.9                        | 198                           | 0.0 |
| \textsuperscript{20}Ne\textsuperscript{6+} | 186         | 146        | 3.6                           | 4.4            | 9.0                        | 139                           | –   |
| \textsuperscript{30}Si\textsuperscript{18+} | 278         | 130        | 6.4                           | 7.8            | 14.0                       | 120                           | -0.9 |
| \textsuperscript{40}Ar\textsuperscript{12+} | 372         | 118        | 10.1                          | 12.6           | 19.6                       | 105                           | –   |
| \textsuperscript{56}Fe\textsuperscript{15+} | 523         | 97         | 18.5                          | 24.3           | 29.3                       | 77                            | -5.6 |
| \textsuperscript{82}Kr\textsuperscript{22+} | 768         | 94         | 32.1                          | 39.2           | 41.0                       | 69                            | -7.1 |
| \textsuperscript{131}Xe\textsuperscript{35+} | 1217        | 89         | 60.0                          | 69.2           | 69.2                       | 48                            | -2.6 |

\textsuperscript{a} Ne and Ar ions form slightly different cocktail \textsuperscript{b} in [MeV/(mg/cm\textsuperscript{2})] \textsuperscript{c} in [μm]
Because the TWTA is able to amplify multiple carrier signal it is possible to feed with two oscillators providing signals with different frequencies (the frequency range 10.75 – 12.75 GHz). This was tested in co-operation with the Finnish Air Forces which borrowed another microwave oscillator for the experiment. Figure 11 shows preliminary results for $^{129}$Xe$^{30+}$ ion beams with different heating modes. Natural xenon (26 %) was used in tests. The 3-frequency heating improves the intensity by 20 – 40 % for high charge states. Again, the effect increases with the charge state. The results shown in figure 11 are recently published in [12].

A multiple frequency heating is a way to further develop the cyclotron’s capability to accelerate more energetic and higher penetration cocktails. Preliminary measurement indicate that with 3-frequency heating the stripping of xenon up to 37+ charge state can be achieved. The $^{129}$Xe$^{37+}$ ion is already identified. To take the 37th atomic electron out from xenon means that there are 17 electrons left. This corresponds to a jump over a shell formed by 18 electrons (“argon configuration”). An increase of 251 eV in extraction energy was needed after the 36th electron. For comparison, the corresponding energy increase to extract the 36th electron after the 35 previous ones is only 13 eV. Therefore, after this main shell crossing it follows again lower jumps, which might make more stripping possible.

However, it was also discovered that adequate intensity of the $^{56}$Fe$^{15+}$ beam can be produced by sputtering the biased disk, which is made of stainless steel. The biased disk voltage of -150 V or higher gives an appropriate sputter yield for the irradiation tests. Consequently, the iron beam is presently produced with the JYFL 14 GHz ECRIS together with krypton and xenon (table 2). The details of the procedure are given in [13].

6.3. The RADEF station
In figure 12 a panorama photo and a schematic picture from the RADEF beam lines is shown.
The heavy ion line includes beam modification elements, like a tantalum diffusion foil (2 μm thick) and x-y wobblers. They make the beam homogeneous. Because the foil reduces also the energy its use is avoided especially for the heaviest beams. Beam tuning elements are a set of collimators, Faraday cup and a beam viewer equipped with a CCD camera. They are used by the cyclotron operator when tuning the intense beam into the chamber.

Schematic pictures of the dosimeter system are shown in figures 13 and 14. The system includes four scintillation crystals equipped with photomultipliers. The detectors are fixed behind the aluminium plates, which are used to limit a certain shape and area from the beam. Fixed collimator apertures in the plates limit the counting area to 0.5 cm² for each scintillator (see figure 14). The detectors are used as counters during the irradiation. They also collect the energy and beam purity spectra before the irradiation. A position sensitive avalanche counter is located behind the detectors. It can draw an accurate picture from the beam profile and acts also as an absolute beam flux counter.
The DUT is attached in a standard plate, which will be fixed in a linear movement table located in the chamber as is described in figure 15. The x-, y-, z-table can be tilted. The plate is also water cooled (hoses not shown in the picture). The DUT positions are determined with a CCD camera equipped with a telescope and located at the upstream end of the beam line. The coordinates are written in the computers memory. Standard cabling with connectors and feed troughs from the chamber to a connector panel outside the chamber and to the user site increase the easiness of the use.
The proton line locates beside the heavy ion line. This makes it possible to perform proton test during the same test campaign. Protons are taken into air and a degrader system is used for changing the energies. Both solutions make the proton testing fast and easy.

The absolute proton flux is defined with particle detector(s) at the DUT position and relative current is measured with a biased ionisation chamber located at the end of the beam tube. The current is monitored during the irradiation and used to determine the flux and fluence (see figure 12).

7. Conclusion
New demands caused by increased SEE test activity of space components and new processing techniques have necessitated space projects to utilise particle accelerators. It has challenged ion source physicists to push the developing work of the ion sources to the highest charge states by keeping in mind the advanced ion cocktail requirements. The work done with the 14 GHz ECR ion source of the JYFL K=130 cyclotron has produced the new high penetration cocktail with an energy of 9.3 MeV/amu. This means the increase in energy from 475 MeV to 1217 MeV for its heaviest component, $^{131}$Xe. Compared to Xe in the old cocktail the charge state has increased from 22+ to 35+. Even more stripping and, consequently, higher penetrating cocktails are possible as proved by identifying the $^{129}$Xe$^{37+}$ ion in a cocktail spectrum measured with the new detector system of the laboratory’s RADEF facility. Commercial reasons also necessitate the development of mass analysing properties of accelerators for fast separation of different ion species. Better than 0.3‰ mass resolution was measured for the JYFL K=130 cyclotron, when using the trim coil separation. Tests to apply the RF frequency separation have recently started. The flexibility and time saving performances are needed also in irradiation facilities. The crucial points are the fast beam calibration and component changing methods as well as proper monitoring of different beam parameters. These were explained more detail when the development of ESA-RADEF irradiation station to facilitate European space projects was introduced.

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