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BEAM DELIVERY OF HIGH-ENERGY ION BEAMS FOR IRRADIATION EXPERIMENTS AT THE CERN PROTON SYNCHROTRON

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Abstract

Heavy-ion single event effect (SEE) test facilities are critical in the development of microelectronic components that will be exposed to the ionizing particles present in the hostile environment of space. CHARM High-energy Ions for Micro Electronics Reliability Assurance (CHIMERA[1]) and HEARTS[2] have developed a high-energy ion beam capable of scanning a wide range of Linear Energy Transfer (LET) at low intensities to study ionization effects on space-bound technology using CERN's Proton Synchrotron (PS). This contribution describes the extraction and transport of low-intensity lead ions at multiple energies to the CHARM facility at the East Area of CERN. Furthermore, it discusses the implementation of a Radio Frequency Knockout (RFKO) technique that streamlines beam extraction and enhances particle flux control and reproducibility across different energies, thereby improving performance and reliability in SEE testing.

BEAM PRODUCTION AND ACCELERATION

The process of delivering high-energy ion beams for irradiation experiments at the CHARM facility begins with the production of lead (Pb) ions in Linear Accelerator (LINAC) 3. These ions are then injected into the Low Energy Ion Ring (LEIR), followed by the PS, where they are accelerated to the desired kinetic energy using RF cavities and appropriate dipole bending strengths. Once the target kinetic energy is reached, the ion beam is extracted using slow extraction and transported through the F61 and T8 transfer lines to the CHARM facility located in the East Area [1], where the irradiation experiments take place.

Development Progress

Considerable efforts have been dedicated to streamlining the process of modifying magnet strengths in the F61 and the T8 transfer lines, aiming to reduce the operational challenges associated with operating the irradiation facility at different beam energies [2]. Discontinuing the use of Pole Face Windings (PFW), which are employed to control the tune at high energy in the PS, was critical to facilitating energy changes via scaling, as they are strongly non-linear. At low energies, the PS combined function magnets scale linearly with rigidity, with non-linearity at high energies stemming from the different levels of saturation of the K0 and K1 components. For kinetic energies below 2 GeV/u, PFWs are turned off during momentum selection resonant slow extraction, and tune control is achieved through Low Energy Quadrupoles (LEQ) and Quadrupoles for Slow Extraction (QSE). The QSE are maintained at a constant value, used to approach the third-integer tune, while slow extraction is enabled by a gradual ramp applied to the LEQ.

To control the primary beam's kinetic energy, an algorithm (makerule) has been implemented to automatically scale the magnets in the F61 and T8 transfer lines and the extraction septa according to the PS magnetic field (and thus kinetic energy (E_{kin})). This improvement was achieved through two main steps. First, the transfer functions were updated using the latest magnetic measurements for the dipoles and quadrupoles installed in the transfer line. Second, the magnets were upgraded to support Pulse-to-Pulse Modulation (PPM). With these modifications, the beam's E_{kin} can be adjusted by changing the PS's Main Units (MUs) strength at flat-top, eliminating the need for manual steering of the transfer line for each new energy. This significant upgrade, which allows for continuous energy selection, contrasts with previous runs where no other beam could be sent during hand-scaled test. Furthermore, the Pb ion beam used (isotope A=208) is accelerated as a partially stripped ion in the PS, retaining 28 electrons. It becomes fully stripped during extraction when interacting with the vacuum window separating the PS's vacuum from the F61 transfer line leading to the East Area. The change in rigidity $B\rho$ before and after the stripping process on the vacuum window (from 54+ to 82+) requires two different makerules depending on the magnet's position. Some limitations were observed at low energy, where the two magnetic septa, SMH57 and SMH61, required manual steering and did not scale well. This issue may arise from bypassing SEH23 (due to aluminum foils which would strip the beam), which is used in the nominal proton slow extraction, causing the beam to get closer to the inside of SMH57, where it might hit the blade. Nevertheless, this development has enabled the capability of performing continuous energy scans, where the energy delivered to the Device Under Test (DUT) is changed with each shot, as shown in Fig. 1.

Energy Loss and Straggling

A detailed FLUKA model has been developed to accurately describe the material budget seen by the beam (vac-

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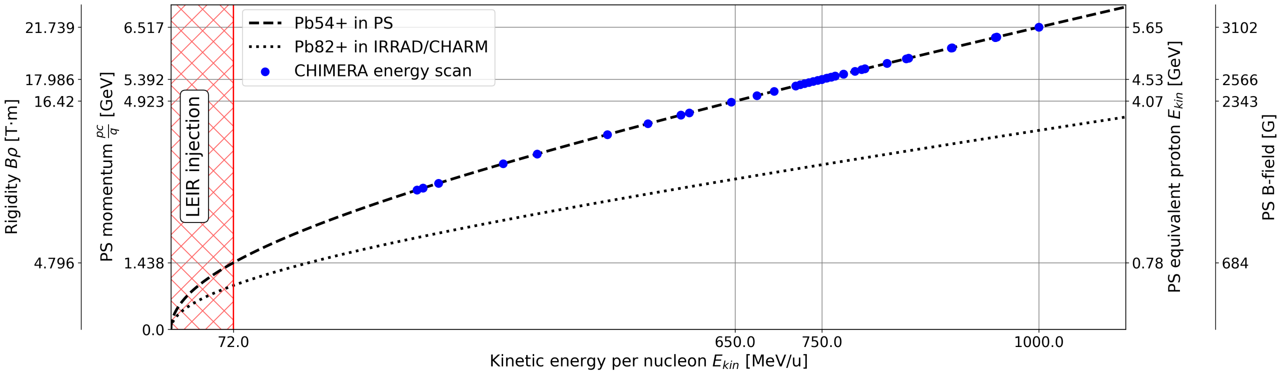

Figure 1: Lookup table for the Pb ion beam flat-top in the Proton Synchrotron (PS). The magnetic field required for acceleration to three different energies (1000, 750, and 650 MeV/u) as well as energy scan measurements to the East Dump is shown.

uum windows, instruments, and air molecules, etc.) along the transfer line [3]. This allows for estimating the energy loss due to straggling, as shown in Table 1. However, further studies are needed to fully understand the transport of low-energy beams. It is unclear why the beams are transported through the transfer line, even though the bending magnets in the transfer line have only been scaled to the primary PS energy, without correction for energy loss due to straggling.

FLUX ADJUSTMENT

Chromatic Driven Slow Extraction

Accurate flux control is crucial for the irradiation of electronic components. Four different techniques were examined to reduce the intensity of the extracted beam. The first three techniques use a chromatic slow extraction, where the spill extraction rate is controlled by the speed at which the beam's tune approaches the resonant tune via chromaticity. In these techniques, it is beneficial to increase the beam's momentum spread, usually through a bunch rotation, so that a smaller part of the beam enters the resonance at a time. However, setting up the bunch rotation for different energies is challenging. Therefore, a voltage jump was used as an alternative to increase the momentum spread, which increases the size of the RF bucket and scales well with different energies.

The first flux control technique involved reducing the tune speed at which the beam approaches the resonance by adjusting the ramp on the LEQ. The second flux control technique involved using the bump in section 23 to collimate and reduce the beam intensity on the external aperture before extraction. An increase in bump height leads to a decrease in flux, but unfortunately, it correlates the momentum spread of the beam via the dispersion at the collimation location. The third flux control technique also uses the bump in section 23, but parks the beam close to the aperture and collimates the beam by blowing up its emittance using Transverse Feedback (TFB) excitation, also lowering the beam's flux proportionally to the blow up gain applied. This maintained a roughly constant transverse beam emittance and reduced the correlation with momentum. However, these three techniques required extensive setup time to achieve a homogeneous spill and do not scale well at different energies. Additionally, they also suffered from machine drift, jitter and material activation, prompting the investigation of the amplitude growth slow extraction technique.

Amplitude Driven Slow Extraction

To achieve a wide range of ion fluxes for irradiation experiments, the slow extraction technique known as Radio Frequency Knock-Out (RFKO) was tested and implemented during the November 2022 run. In this technique, the emittance growth of the ion beam, see Fig. 2, is induced by a transverse dipole RF-field resonantly exciting the beam at its horizontal betatron frequency. The ramp applied to the LEQ is removed and the tune is kept constant.With a Frequency Modulated (FM) chirp, this process allows for a more precise control over the extraction rate of the ion beam compared to the chromatically driven techniques and scales well with energy.

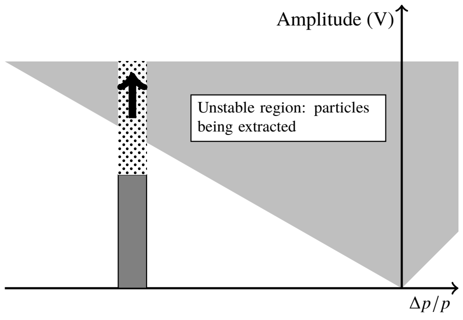

Figure 2: In RFKO, transverse stochastic noise or coherent RF excitation at an integer fraction of revolution frequency is used to excite the beam and induce growth in its betatron amplitudes.

Adjusting Beam Intensity

In RFKO, the beam intensity can be controlled by adjusting the amplitude of the RF field on the TFB, the length and range of the chirp FM, and its repetition rate. By tuning these parameters, average ion fluxes between 10^3 and 10^5 ions/cm^2/s were achieved during a single spill of 360 ms. Higher fluxes can be achieved by spatially focusing the beam on the DUT. Intensity control using RFKO proved to be easier and more reproducible compared to other techniques, provided that the chirp FM range was sufficiently large to cover the tune variation coming from the reproducibility of the PS.

Challenges in Flux Control and Reproducibility

Achieving stable and reproducible beam flux across a wide range of intensities is crucial for irradiation experiments. One of the main challenges in maintaining a stable flux lies in the large difference in the magnetic hysteresis of the PS magnets that occurs when different cycles are played. To address this issue, careful programming of the supercycle composition is necessary to minimize perturbations and ensure stable flux.

Another challenge is the reproducibility of the East Area transfer lines. While spill-to-spill intensity repeatability is not critical for radiation effects testing, it is still desirable. A potential improvement for future runs would be to implement a degauss cycle on the switching magnets of the East Area transfer lines, which should help to mitigate hysteresis problems.

Beam Characterization and Irradiation Experiments

The high-energy ion beams were used for irradiation experiments in collaboration with the European Space Agency (ESA) during the five-day November 2022 run, where three primary kinetic energies were selected, see Table 1. This beam selection allowed for a wide range of Linear Energy Transfer (LET) values to be explored, which is critical for accurately characterizing the radiation response of electronic components and designing robust systems for space and other radiation environments.

Table 1: Kinetic energy used during the ESA November 2022 run at flat-top in the PS and the effect of straggling to the kinetic energy and LET at the DUT [3].

E_{kin}^{PS} [MeV/u]	$E_{kin}^{DUT\,\dagger}$ [MeV/u]	$LET^{DUT\,\dagger}$ [$\mathrm{MeV \cdot cm^2/mg}$]
1000	605	13.2
750	300	18.2
650	140	26.6

† FLUKA simulation.

The run included testing all four DUTs (one diode and three SRAMs [4]) sequentially for all energies and performing a degrader scan.

SPILL TIME PROFILE

The spill time profile analysis was performed on data collected during the November 2022 run, employing different instruments such as the diode, gas scintillator, secondary emission monitors, and ionization chambers. Higher gain values on the TFB excitation signal led to a rapid extraction of the beam in the initial milliseconds, while lower gain values resulted in a gradual increase in beam intensity throughout the spill. Intermediate gain values (around 0.15) produced a uniform, rectangular spill profile, indicating constant intensity during the spill, see Fig. 3.

The beam time structure showed a frequency structure with slow and fast frequencies present. The RFKO technique generated a spectral line at 1 kHz due to the software's maximum chirp repetition rate limitation. Furthermore, fast spill structures were observed at the fractional tune of the third integer (128-139 kHz depending on the energy), which corresponds to the revolution frequencies for the different beam energies.

Additionally, the analysis showed that for a particular TFB gain, the spill shape remained the same for different energies, but that there was a slight variation in intensity. This could be attributed to factors such as the supercycle composition or inadequate scaling of the septa SMH57 and SMH61 to different energies.

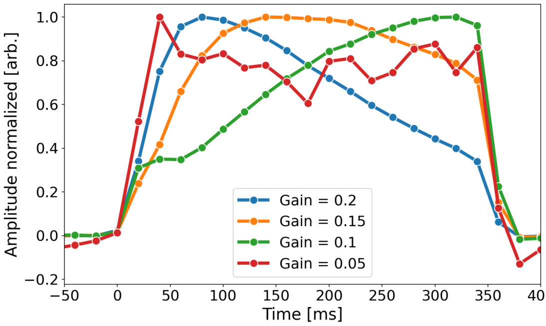

Figure 3: Average spill profile observed on XSEC70 with the 750 MeV/u beam at different RFKO gains.

SUMMARY AND OUTLOOK

Significant work has been performed to streamline the extraction of ions at variable kinetic energy and flux, improving the radiation testing of electronic devices. Additional studies could benefit from using a signal generator to modify the excitation voltage during the spill [5], allowing the extraction of a constant beam intensity and dampening of the excitation frequency seen in the spill. To address the higher frequencies induced by the revolution frequency, one idea to consider is injecting more bunches around the machine and attempting to debunch the beam over a longer duration. This approach would help mitigate the impact of low frequencies and improve the beam time structure.

In addition, increasing the spill duration to around 1 second could potentially be achieved by utilizing the full B-field flat top of the PS. This would allow for longer, low-intensity spills that are preferable for slow SEE acquisition systems. For higher energies and chromatic extractions, longitudinal RF-noise extraction will be investigated in the future.

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