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FEASIBILITY OF SLOW-EXTRACTED HIGH-ENERGY IONS FROM THE CERN PROTON SYNCHROTRON FOR CHARM

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Abstract

The CERN High Energy Accelerator Mixed-field (CHARM) High-energy Ions for Micro Electronics Reliability Assurance (CHIMERA) working group is investigating the feasibility of delivering high energy ion beams to the CHARM facility for the study of radiation effects to electronics components engineered to operate in harsh radiation environments, such as space or high-energy accelerators. The Proton Synchrotron (PS) has the potential of delivering the required high energy and high-Z (in this case, Pb) ions for radiation tests over the relevant range of Linear Energy Transfer (LET) of $\sim 10-40$ MeV cm^2 mg^{-1} with a >1 mm penetration depth in silicon, specifically for Single Event Effect (SEE) tests. This contribution summarises the working group's progress in demonstrating the feasibility of variable energy slow extraction and over a wide range of intensities. The results of a dedicated 5.4 GeV/u Pb ion beam test are reported to understand the performance limitations of the beam instrumentation systems needed to characterise the beam in CHARM.

INTRODUCTION TO CHIMERA

The CHIMERA working group at CERN is studying the feasibility of exploiting the PS to provide Very High Energy (VHE), > 100 MeV/u heavy ion beams for space applications, such as the qualification of active semiconductor components and boards. Lead ions are available for exploitation in the CERN accelerator complex within the framework of the LHC heavy ion programme [1]. Combined with the recent renovation of the East Area during Long Shutdown 2 (LS2) [2], the CHARM facility offers a unique opportunity to increase the limited availability and accessibility of beam time in Europe required for breakthrough research and innovation in the field. The CHIMERA activity falls inside the scope of the collaboration between CERN and the European Space Agency (ESA) who are supporting the study. A proposal has also been recently submitted to the European Union's HORIZON programme call "Strategic autonomy in developing, deploying and using global space-based infrastructures, services, applications and data 2021" under the name High-Energy Accelerators for Radiation Testing and Shielding (HEARTS) [3]. The objective of the proposal is to facilitate 2 – 3 weeks of heavy ion beam time annually as of 2023, for both CERN internal users, and external academic and industrial users.

The focus of the working group last year was demonstrating the feasibility of variable energy operation of both the slow extraction system in the PS and the network of transfer lines that transport the beam to the CHARM facility. In parallel, other studies also continued to understand the performance of instrumentation to characterise the ion beam in CHARM, to control the intensity in the transfer line with a collimation system and FLUKA [4, 5] studies to understand pollution from fragmentation of the beam as it passes material on the beam line, such as interceptive beam instrumentation devices and vacuum windows.

VHE HEAVY ION BEAM REQUIREMENTS

The PS is capable of delivering slow extracted VHE heavy ion beams suitable for mimicking the effects of galactic cosmic rays with a kinetic energy range of $\sim 70-5400$ MeV/u in spills of a few 100 ms in length. Due to the non-linear variation of the LET as a function of range in silicon, the lower end of the PS's energy range is most attractive for Pb ($\lesssim$ 1000 MeV/u), see Fig. 1.

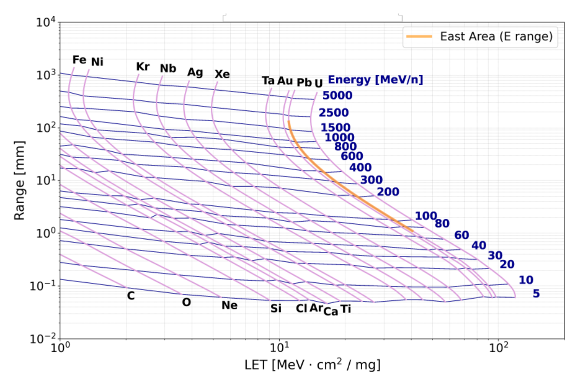

Figure 1: Range in silicon vs. LET for different heavy ions and the energy range of Pb available at the East Area [6].

The beam specification is summarised in Table 1, highlighting the main challenges at the PS including (i) guaranteeing the wide-range of beam energy and LET, (ii) providing reproducible spills at the relatively low beam intensities required to respect SEE testing standards and (iii) delivering a uniform beam distribution over a range of different test devices.

SLOW EXTRACTION AND BEAM TRANSFER DEVELOPMENTS

Building on the experience of first slow extraction tests of ions to the East Area before LS2 [7–9], regular machine

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Table 1: Beam specifications for a VHE heavy ion test facility for space applications at CERN PS

Parameter	**CHIMERA spec.**
Ion species	lead (Pb)
Kinetic energy [MeV/u]	70 - 5400
LET [MeV cm^2/mg]	10 - 40
Beam spot area	up to 20×20 cm^2
Beam spot homogeneity [%]	uniform, ±10
Average flux [ions/cm^2/s]	10^2 - 10^5
Spill length [ms]	~ 400
Spill uniformity [%]	±20

development studies were performed in 2021, starting with protons and culminating with a dedicated two-day Pb-ion run at the end of the year.

Electrostatic Septum Limitation

The electrostatic extraction septum cannot be used for partially stripped ions because of the presence of 50 μm thick aluminium foils installed in the high field region to avoid residual gas ionised by the circulating beam provoking high spark rates. The foils strip the ion beam and cause the entire beam to be lost in the machine before being extracted. Instead, the electrostatic septum was bypassed by turning off its local extraction bump and the partially stripped ions are extracted directly over the magnetic septum. The additional beam loss and induced radioactivation from the degraded extraction efficiency can be neglected at the low intensity of the ion beam. In the framework of heavy ions for LHC, studies are ongoing to investigate the acceleration of fully stripped ions, however, stable regulation of the main power converters at the already very low injection energy in the PS first needs to be demonstrated.

Dedicated External Beam Dump

The East Area renovation included the installation of a dedicated external beam dump that could be used in parallel to operation for slow extraction studies with low intensity proton or ion beams. Although limited by radiation protection reasons to approximately 2×10^{11} protons per spill, the external dump still allowed the studies discussed in this contribution to advance at a quicker pace than before LS2.

Variable Energy Slow Extraction & Transfer

It is envisaged to prepare a set of PS cycles with a range of different extraction energies and to provide full energy variability by installing degraders in CHARM. Even the setup of a few cycles at different energies will add a significant overhead to an already busy operational schedule. Dedicated studies were performed in 2021 to better understand and operate the slow extraction cycle. The control of the tune in the PS is complicated at high energy because the integrated dipole and quadrupole components of the combined function main magnets saturate differently as the current of the main power supply is increased. As a consequence, when approaching saturation the machine does not scale with momentum and non-linear corrections are needed using auxiliary circuits called the Pole Face Windings (PFW), which also provide the additional degrees of freedom needed for both tune and chromaticity control.

A low intensity pilot bunch of a few $\times 10^9$ protons could be accelerated through transition to flat-top in a bare machine (without PFW). When the machine is ramped gently on a flat-top plateau at a kinetic energy of 23 GeV the tune is observed to vary. The same measurement repeated on the proton injection plateau with a lower kinetic energy of 2 GeV showed no such variation and demonstrated that the machine scales linearly when the main units are operated far from saturation. Additionally, a slow droop of the tune was observed on both injection and extraction plateaus, which was attributed to the presence of eddy currents coming from a range of different sources. Correcting and adjusting these non-linear effects are required in every cycle. In 2021 empirical corrections were applied using the PFW to keep the tune and chromaticity of the extracted (on-resonance) particles constant throughout the spill [10, 11] on the operational proton cycle.

The scalability of the machine when the main magnets are not in saturation is a good result for CHIMERA, which will help the setup of most irradiation campaigns requested at the lower end of the energy spectrum ($\lesssim$ 1000 MeV/u). To this end, an important effort has been made to incorporate the transfer functions: $\int B_n(t)dL \rightarrow I(t)$ of as many magnetic circuits as possible into the control system. However, it is still to be understood how quickly a new cycle can be set-up by scaling an optimised cycle with momentum.

The situation is similar in the transfer lines but easily compensated with magnetic measurements and non-linear transfer functions available for all magnets installed during renovation. The main difficulty encountered in the transfer line was hysteresis effects of the switching dipoles and regulating the magnets at very low currents.

Low energy slow extraction was demonstrated on the injection plateau for protons (2 GeV) and Pb ions (70 MeV/u). The 2 GeV proton beam was transferred to the external beam dump by scaling the transfer line with momentum, however the 70 MeV/u Pb-ion beam was not observed at the dump; probably due to energy straggling in the vacuum window or due to the very low currents in the transfer magnets, which may limit the lower energy range available to CHIMERA without the additional use of energy degraders.

Intensity Control Techniques

Different techniques for adjusting and reducing the intensity are being investigated. Collimation in the transfer line is being investigated as a way of controlling the intensity but suffers from the drawback that it strongly couples intensity with beam size and distribution. A good variability could be achieved simply by adjusting the sweep of the tune through the third-integer resonance and extracting only a fraction of the circulating beam, before dumping the remaining beam internally. The lower range of the achievable beam intensity

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accelerated to flat-top is limited by the need for the RF system to operate in closed-loop. Future studies will investigate acceleration in open loop or by accelerating in closed-loop with a higher intensity pilot bunch that could be disposed of by fast extraction before slow extraction commences. The lowest intensity that can be delivered by LEIR and Linac3 needs to be understood. Noise excitation techniques will also be investigated to extract very slowly and in a controlled manner.

Transfer Line Studies

It was difficult to achieve a good transmission between the PS and the experimental target in CHARM using the quadrupole settings from the MAD-X model after the East Area renovation; the settings had to be adjusted and optimised empirically. After a campaign of optics measurements (kick response and quadrupole strength scans) exploiting the available Beam TV (BTV) screens the problem was identified as a wrong assumption in the MAD-X model of the initial beam parameters slow extracted from the PS. The likely cause is the strong effect of the fringing fields in the second half of main unit 62 seen by the extracted beam as it leaves the synchrotron [12]. Instead of being focused, the extracted beam is defocused with a strength thrice that experienced by the circulating beam. Unfortunately, the stray fields change as the main unit saturates and do not scale with energy. To combat this issue the BTVs have been fitted with filter wheels to avoid the saturation observed on the measured profiles and allow accurate measurements of the beam parameters at extraction to use as input for the MAD-X model. Additional beam loss monitors will also be installed to help with transfer line setup. All transfer line magnets can be operated and controlled in normalised magnetic strengths from the optics model. Other developments now allow for a readout of the beam size and position in the transfer line throughout the spill. In addition, the available instrumentation has been interfaced with CERN's generic steering program (YASP) so that steering corrections can be computed and applied online, which will vastly speed up the setup of the lines at different beam energies.

Beam Spot Size and Distribution

The transfer line optics model including the characterisation of the extracted beam parameters will be exploited to design the final focus for CHIMERA, most likely with the installation of higher-order multipole magnets to create a uniform distribution over a large area [13].

Safe Transport of Low Energy Primary Beams

Before the recent East Area renovation there was a small but non-zero probability that low energy primary beams could enter and be transported by the secondary magnets into the secondary experimental area. The East Area is now designed with a safety feature to ensure that primary beams cannot enter the secondary zone thanks to a forced vertical production angle. This is important as it means that the rest of the East Area can continue operation in parallel to low energy proton and ion operation to CHARM, without the need to consign the power converters in the secondary areas.

2021 HEAVY ION TEST CAMPAIGN

The approval for sending low energy ion beams to CHARM in parallel to proton operation was not complete before the start of the short two-day heavy ion test campaign on 13 - 14 November 2021. Nevertheless, a successful campaign was carried out with Pb^{54+} ions extracted at an equivalent rigidity to the nominal proton beam with a kinetic energy of 5.4 GeV/u. The scaling of the transfer line to match the rigidity of the fully stripped Pb^{82+} beam downstream of the first vacuum window was validated and the extracted intensity was varied by over a wide range from $\sim 10^6 - 10^9$ ions per spill. Once the extraction and transfer was setup the main focus was on beam characterization of the beam instrumentation systems, in terms of intensity and profile. A fast extracted ion beam was provided for calibration studies using a fast beam current transformer (fBCT).

At the lowest intensity achieved of $\lesssim 10^6$ ions per spill, the secondary emission monitors (XSEC and XION [14]) showed good linear behaviour, however further work is needed to calibrate the absolute intensity as problems were encountered with the fBCT. It was difficult to adjust the intensity with the tune sweep at very low intensity whilst maintaining a spill length of 400 ms. The spill quality monitor (BCCGA, N2 gas scintillator [15]) could have provided the diagnostic needed but was overlooked and will be investigated further in 2022. At $> 10^6$ ions per spill there was no well-defined linear relationship between the different secondary emission devices. The Multi Wire Proportional Chamber [16] showed promising results but could not profile the lowest intensity beams with good resolution, however the gas intensity was not optimised and the signal level could be increased in the future.

SUMMARY AND OUTLOOK

The effort driven by the CHIMERA working group towards low intensity, variable energy slow extracted ion beams has improved our understanding of the PS slow extraction cycle and led to the development of tools that are already making operation easier. The feasibility of slow extraction down to injection energy has been demonstrated and efforts are ongoing to improve the magnetic reproducibility of the PS and its magnetic measurement system, as well as to better understand and compensate the dynamic eddy currents, all of which affect the slow extraction cycle. Although more work is needed to understand and quantify the operational resources needed for variable energy extraction at even lower intensities, the objectives for 2022 remain ambitious with the goal of attempting a first pilot run of a high-energy ion SEE test campaign at CHARM over two weeks in November 2022, including external users from ESA. Future efforts will concentrate both on calibrating and optimising existing beam instruments for the low intensity, variable energy ion beams, as well as installing dedicated beam instrumentation.

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