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PRODUCTION OF SLOW EXTRACTED BEAMS FOR CERN'S EAST AREA AT THE PROTON SYNCHROTRON

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Abstract

Since the upgrade and renovation of CERN's East Area during the Long Shutdown 2 (LS2: 2019 - 2021), demand has increased for slow extracted beams at the CERN Proton Synchrotron (PS). The East Area is a multi-user facility carrying out a diverse experimental physics programme. It requires a wide range of slow extracted beams to be delivered by the PS. This contribution summarises gained understanding, progress and improvements made since LS2 in the slow extraction (SX) of both proton and ion beams. Furthermore, it describes the production of low intensity, variable energy heavy-ion beams for the collaboration between CERN and the European Space Agency (ESA), striving to establish a novel and flexible, high-energy, heavy-ion radiation test facility.

INTRODUCTION

The CERN PS has been in operation since 1959 and provides slow extracted beams to experiments in the East Area. During its annual physics run, it sends 24 GeV/c proton spills to two targets and a radiation test facility at a rate of approximately one spill every 10 seconds, using a SX method based on a third-integer betatron resonance. The beam is extracted from the ring towards three transfer lines to feed either two North production targets in front of the secondary lines T9 and T10/T11, or the primary T8 line for the IRRAD and CHARM irradiation facilities [1], as shown in Fig. 1.

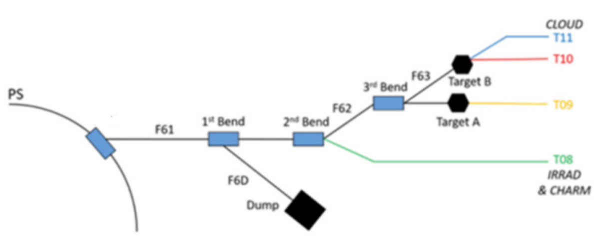

Figure 1: Schematic layout of the East Area beamlines.

The East Area was renovated during LS2 with new instrumentation, redesigned beamline configurations, renewed beam optics, new powering schemes and energy recovering power supplies, which significantly reduce the energy consumption [2]. Following this renovation, demand by the user community has increased and proposals were made to improve the extraction process. These include increasing the intensity per pulse for T8 (currently $60 \cdot 10^{10}$ protons) and exploring lower momentum and longer spills (currently 400 ms, 24 GeV/c) for the North targets.

CHIMERA[1], a work package within HEARTS[2], a joint effort between CERN and ESA, has transformed the 130 m long T8 line into a versatile high-energy, heavy-ion radiation testing facility. To successfully extract ion beams, a more comprehensive understanding and knowledge of the extraction process is necessary. This is because the process involves much lower energies and intensities than those used for protons. Additionally, irradiation of space components requires improved management of the accelerator settings through the control system to enable rapid adjustments to the desired extraction energy.

To a large extent, the SX has remained unchanged since its renovation by Steinbach et al. in the early 1990s [3]. While the spill quality for 24 GeV/c protons was satisfactory, there was still room for improvement. This contribution outlines the various operational adjustments made in 2022, including the creation of new controls settings. The lower energy ion beams used by CHIMERA greatly benefited from these modifications, as the simplified setup process at varying energy levels, resulting from the new parameters, significantly facilitated their operation.

SLOW EXTRACTION DESCRIPTION

The PS ring is made of 100 combined-function, normal conducting magnets used for both bending and focusing the beam. Each main unit (MU) is composed of two alternating gradient half-units: one focusing and one defocusing. The MUs are also equipped with additional compensation coil circuits: the figure-of-eight loop (W8L) and the pole face windings (PFW), which provide quadrupolar and sextupolar component corrections without significantly altering the dipole field [4]. The W8L is used during the acceleration ramp but is deactivated during SX. In contrast, before the start of the SX, the current of the PFWs is adjusted to provide the correct initial betatron tune and negative chromaticity. At flat-top, the debunched beam is pushed through resonance by a gradually increasing field in the MUs.

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At the 24 GeV/c flat-top, an initial horizontal tune of about 6.2 is set with the MUs and PFWs. Two dedicated quadrupoles (QSE) are used to set the horizontal tune just below the third-integer resonance. The resonance is driven by three sextupoles (XSE). A DC electrostratic septum (SEH23) is located more than two betatron wavelengths upstream of the first thin magnetic septum (SMH57), which deflects the beam towards the extraction magnetic septum 61 (SMH61), situated a quarter of a betatron wavelength further downstream. A local bump (BSW57) is created by four dipoles and is common to both magnetic septa. Figure 2 illustrates the SX layout used since the early 1990s.

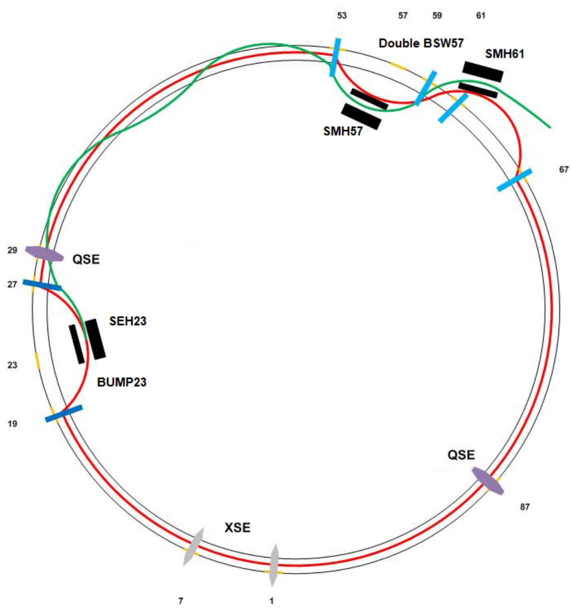

Figure 2: Schematic layout of the SX and its elements.

OPERATIONAL IMPROVEMENTS

Cycle Modifications

In 2022, several modifications were introduced to the cycle, including the insertion of a flat section in the magnetic field at 24 GeV/c prior to the extraction ramp. This was done to facilitate the RF phase jump for the bunch rotation, performed just before debunching to increase the momentum and tune spreads, under stable conditions, as opposed to during an accelerating ramp.

To avoid overshoots observed during the spill, power converter pulses have been advanced in time and modified to incorporate shallower ramps and smoother transitions between ramp and flat-top.

One of the most significant changes relates to the PFW and W8L configurations. The EAST cycles are used in conjunction with another high-intensity bunch for the n-TOF experiment[3], referred to as the TOF parasitic bunch. Both TOF and EAST are similar up to 20 GeV/c, which is the extraction momentum for TOF. However, eddy currents arise when the W8L goes to zero upon reaching 24 GeV/c, with a significant impact on the SX spill. The cycle has hence been modified to bring the W8L to zero earlier, i.e., at 20 GeV/c after extracting the TOF bunch. These modifications have resulted in a significant improvement in the stability of the extracted beam position and size.

[3] The neutron time of flight facility is a pulsed neutron source coupled to a 200 m flight path, for which the PS sends a short high-intensity 20 GeV/c proton bunch, sharing the same PS cycle.

New Settings Management

The LHC Software Application (LSA) is a common CERN framework based on a database that centralizes all hardware information, such as calibration curves, to calculate the required current I for a given magnetic field. An important effort has been made to incorporate the transfer functions for all transfer line magnets, and the settings of the various magnets are now defined in strength, normalized by the beam momentum.

All functions for magnets now use the new LSA beam-oriented normalized strength parameters. The constant strength is transformed into a current function derived from the beam momentum function. Each PS power converter is automatically scaled with any change of momentum to maintain a constant effect on the beam.

As the beam is pushed through resonance with a ramp on the MUs and negative chromaticity, the momentum of the extracted particles gradually increases during the spill. The new LSA parameters ensure that the strength for each machine element remains constant throughout the duration of the spill.

These changes have clearly improved the horizontal beam position stability and beam shape in the various beam lines. A horizontal tail is still present in the T8 line, but is likely to be caused by scattering of the beam through air regions (30 m), vacuum windows, and beam instrumentation, creating a tail of low-energy particles observable in the horizontal plane.

New settings have also been put in place to control the first bending magnets in the transfer line in a more flexible way, which enables a dynamic, pulse-to-pulse change of the beam destination. As a result, the East Area dump can now be used in parallel with physics. Although radiation protection constraints limit the dump usage to approximately $7 \cdot 10^9$ protons per second (lower than the nominal proton beam intensity of $6.6 \cdot 10^{10}$ p/s) [5], it enables SX studies for low-intensity proton and ion beams and tests of various energy extractions at a much faster pace than prior to LS2.

ION IRRADIATION ACTIVITY IN CHARM

The ion irradiation activity in the CHARM (CHIMERA/HEARTS) facility aims to explore the feasibility of providing high-energy ion beams to internal and external users for research on radiation effects on electronic components intended for extreme radiation environments, such as space or high-energy accelerators. The PS can deliver the high-energy and high-Z (specifically, Pb) ions necessary for radiation testing across the relevant

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Linear Energy Transfer (LET) range of approximately ~10–40 MeV·cm^2·mg^{-1}. This range allows for a penetration depth of over 1 mm in silicon, making it suitable for Single Event Effect (SEE) tests [6].

Electrostatic Septum Limitation

For the SX of partially stripped ion beams, such as the Pb54+ used in recent years, the electrostatic extraction septum cannot be used. This is due to the presence of aluminum foils installed to prevent residual gas ionized by the circulating beam from entering in its high-field region, which could cause increased spark rates. However, these foils would also strip the ion beam, resulting in the entire beam being lost within the machine before extraction. To circumvent this issue, the electrostatic septum is bypassed by disabling its local extraction bump, allowing the partially stripped ions to be extracted directly by the two magnetic septa. The additional beam loss and induced radioactivation from the reduced extraction efficiency is acceptable due to the low the intensity of the ion beams.

Reducing the Beam Energy

The PFW and W8L are highly non-linear components and represent a noticeable exception in the new settings management framework. Indeed, for several reasons beyond the scope of this contribution, the PFWs/W8L functions lack the normalized strength beam parameter, meaning that they are not inherently linked to momentum. In other words, no automatic calculation of the PFW/W8L functions is performed when the SX energy is changed.

However, acceleration without the PFW/W8L is possible with low extraction momentum, low-intensity beams, and no transition crossing. At low energy, fine-control of the tune can instead be achieved through the low energy quadrupoles (LEQ), which are not employed during the 24 GeV/c operational proton SX.

The conducted tests have shown that at low fields, without the use of PFW and with the implementation of the new settings management, the machine's scalability is excellent. This represents a significant achievement for CHIMERA, which used several kinetic energies per nucleon during the 2022 short run: 2, 1, 0.75, and 0.65 GeV/u. It has been demonstrated that setting up a new cycle is now remarkably quick, achieved simply by changing the cycle's magnetic field at flat-top.

Flux Control

To achieve the ion flux range of 10^3–10^5 ions/cm^2/s required by external users, a robust SX technique capable of manipulating the flux at different energies in a repeatable manner was needed. Various intensity reduction methods were explored and compared, leading to the selection of an amplitude-driven SX scheme called RF-knockout (RFKO). Controlled by an oscillating dipole RF field on the transverse feedback system, RFKO increases the beam's emittance and diffuses the particles into the unstable region, as depicted in Fig. 3, resulting in significant amplitude growth and enabling the particles to jump SMH57's septum blade.

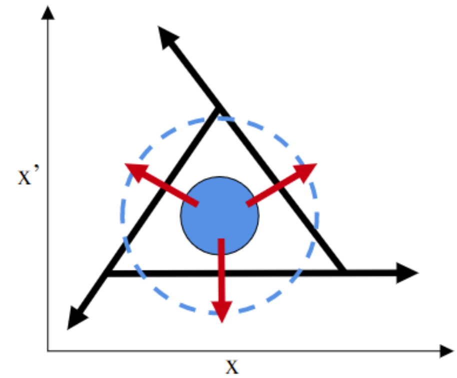

Figure 3: The emittance growth diffuses the particles from the stable triangle to the unstable region.

RFKO simplifies the operation for beams of different kinetic energies compared to a tune-driven SX, as the flux is primarily controlled by the strength and duration of the RF chirp [7]. Typical ion spills obtained thanks to RFKO are shown in Fig. 4.

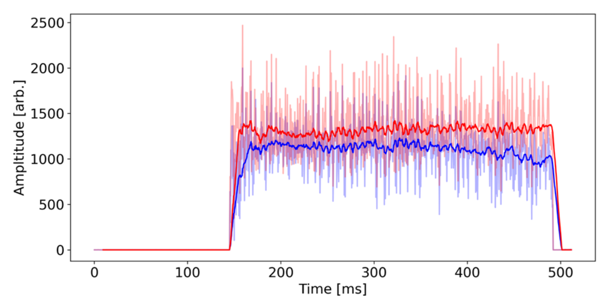

Figure 4: Spills obtained with the RFKO technique, from two different devices on the same gas scintillator

CONCLUSION

In 2022, several improvements were made to the EAST cycles, driven by the significant progress in understanding SX on the 24 GeV/c proton beam. New LSA parameters are now employed to maintain machine consistency throughout the SX, with the exception of the highly non-linear PFW, which makes maintaining the optics during extraction challenging. However, for low-energy ion cycles used for CHIMERA, PFW usage can be avoided, and the machine has proven to be highly scalable in this configuration. Thanks to the new cycles and LSA parameters, as well as techniques like RFKO for extracting very low intensity, the process of changing the energy and intensity of the extracted beam has been greatly simplified.

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