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PROPOSAL FOR A NEW LEIR SLOW EXTRACTION SCHEME DEDICATED TO BIOMEDICAL RESEARCH *

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Abstract

A proposal is here presented for a new slow extraction scheme for the Low Energy Ion Ring (LEIR) in the context of the feasibility study for a future biomedical research facility at CERN. The new slow extraction system is based on the third-integer resonance. Two resonance driving mechanisms have been studied: the quadrupole-driven method and the RF-knockout technique. Both were made compatible with the tight constraints imposed by parallel operation of LEIR as heavy ion accumulator and care was taken to maximize the use of the available hardware.

INTRODUCTION

In parallel to its on-going operation for LHC and SPS fixed-target physics experiments, an additional secondary use of LEIR as accelerator for a biomedical research facility has been proposed [1-2]. This facility would complement the research beam-time available at other laboratories for studies related to ion beam therapy, radiation protection, and detector instrumentation. The LEIR synchrotron has a circumference of around 80 m and is composed of four 13 m-long straight sections (SS) numbered 10 to 40 and four 90° bending magnets. It is foreseen to adapt the adjacent South Hall as a new biomedical experimental area, as shown in Fig.1.

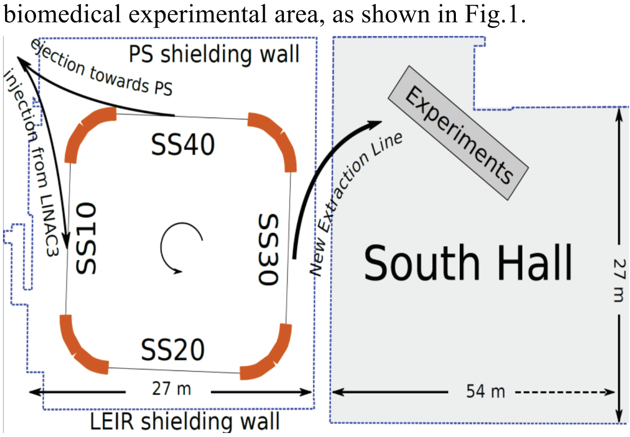

Figure 1: Schematic view of LEIR and the adjacent areas with possible locations for experimental endstations.

Given the space constraints in the LEIR lattice and its position relative to the South Hall, a slow extraction from SS30 is technically simpler to implement than a fast extraction and has the advantage of providing more flexibility to accommodate the variety of extracted beam characteristics desired by future users.

The extraction methods considered in this study are: the quadrupole-driven method (Q-D) and the RF-knockout extraction (RF-KO) [3]. In the former, the working point of the machine is slowly moved towards the resonant tune. It represents the simplest implementation in LEIR, since only the quadrupole settings are varied during extraction. However, the resulting intensity is strongly affected by tune ripple and extracted beam transverse properties vary along the spill. An RF-KO system was studied as a potential upgrade. It is based on transverse excitation of the stable beam by band-limited noise, while the machine parameters stay constant. The feasibility of these two methods will be assessed with simulations.

DESIGN CONSTRAINTS AND METHODOLOGY

MADX-PTC [4] was used to study the extraction optics and to perform single particle tracking. Data analysis scripts were implemented in Python, partly based on and extending *PyAccel*, a library for synchrotron design written by U. Dorda (DESY).

In the machine model, the orbit correctors are assumed to produce point-like kicks and the sextupolar components from the pole-face winding (PFW) of the main dipoles are modelled as thin pure sextupoles. The septa are modelled as point-like orbit correctors at the centre of their longitudinal position in the lattice. The effect of (non-linear) coupling between the two transverse planes has been neglected and tracked particles were placed on the reference path in the vertical plane. A diagram of the iterative workflow for the tracking study is shown in Fig.2 and the interested reader will find the full description of each step in [5].

For Q-D, the extracted beam phase space characteristics change through the spill. Indeed, as the tune approaches resonance, large emittance particles will be extracted before small emittance particles. To simplify operations (and to avoid dynamic adjustments of the closed orbit bump and resonance excitation strength), the parameters for the sextupoles and closed orbit correctors have been fixed to values compatible with all extraction emittances. The lattice is therefore matched in terms of sextupole excitation and closed orbit correction for an intermediate extraction tune and emittance. These settings are then imposed for tracking the various extraction emittances and momentum offsets, and only the tune is changed via the quadrupole gradients. To obtain all extreme positions

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of the extracted beam segment during the spill for Q-D, extraction of on and off-momentum particles is simulated at the same tune/emittance. Therefore, the lattice tune is offset by the chromatic tune shift of off-momentum particles.

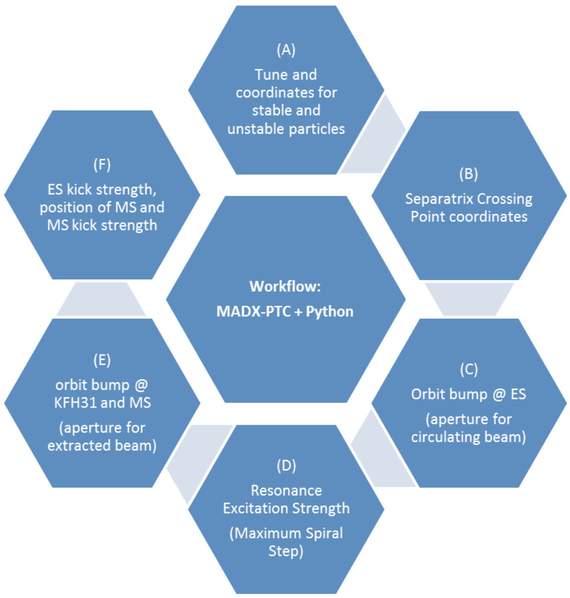

Figure 2: Workflow for simulating the extraction of a particle with a given momentum and extraction emittance.

For RF-KO, the lattice tune is fixed and characteristics of the extracted beam are constant throughout the spill. For non-zero chromaticity, off-momentum particles will be extracted at emittances slightly higher and lower than the on-momentum particles.

RESULTS

A fully stripped carbon ion beam ($^{12}C^{6+}$) is assumed for this study (q/A≈1/2), as this is suitable for injection into LEIR and a very similar charge-over-mass ratio can be achieved for most elements of biomedical interest (H to Ne). A normalized RMS emittance of 1.05 µm is assumed for the circulating beam in both transverse planes. For extraction, two sets of extracted beam parameters describe the superposition of all particles extracted over the whole spill. The lowest considered kinetic energy of 20 MeV/u corresponds to the highest emittance beam (5 µm, rms physical emittance) and the highest relative momentum spread ($1.8\cdot10^{-4}$, rms). The highest considered kinetic energy of 440 MeV/u corresponds to the lowest emittance beam (1 µm, rms physical emittance) and the lowest momentum spread ($0.4\cdot10^{-4}$, rms). This allows proving the feasibility of the extraction systems for the most extreme beam conditions, under the assumption that the current power supply and water cooling of the main bending magnets will be exchanged in order to extend the maximum beam rigidity from the present 4.8 Tm to the design limit of 6.7 Tm.

The tunes at extraction are placed close to the 5/3 resonance in the horizontal plane and at 2.735 in the vertical plane (close to the tunes used for heavy ion operation). This setup is characterized by a superperiod of 2 with two dispersive straight sections and two non dispersive straight sections.

Extraction Elements

The use of a PFW in bend 40 for resonance excitation was found to be the optimal solution in terms of resonance excitation strength (up to 51 $m^{-1/2}$ at the highest beam rigidity) and phase, based on the desired septa positions: it corresponds to a virtual sextupole placed at –70° [120°] average phase advance to the entrance of the electrostatic septum (ES), which is the optimal angle for the given setup. The two sextupole families in the ring are used to adjust the chromaticity and do not contribute to resonance excitation.

The ES, which had been in use in the former LEAR, is still available and could be re-installed. It is used to create a minimum orbit separation of 10.2 mm between the circulating beam and the extracted particles at the entrance of the first magnetic septum (MST). A spare injection septum of LEIR (SMH11) would be available for this use. It could provide a kick of 56 mrad and its entrance can be placed at -51 mm. The second magnetic septum (MSE) provides a stronger kick of 104 mrad. As this element cannot be recuperated elsewhere, its characteristics have been defined for this purpose: the apparent thickness is 22 mm and the maximum integrated magnetic field is 840 mT·m [5].

Aperture

The new extraction system must not affect other LEIR uses and ideally, be capable of working in between LHC injection pulses without moving equipment. Thus, the position of the ES and MST needs to be compatible with the current aperture limitation for heavy ion operation. The beampipe, going from the ES, through a quadrupole-sextupole doublet section and the KFH31 kicker, up to the MST (see Fig.3), has to be enlarged up to ±84 mm in the horizontal axis, in order to house both the circulating and the extracted beam. In addition, an extraction beampipe has to be accommodated through the KFH3234 kicker tank. Because of these constraints, an elaborate orbit bump is needed in SS30. In addition to the existing orbit correctors in SS20, bend 20 and bend 30, two new orbit correctors (OC), providing up to 70 mT·m, are needed to create the required orbit offsets at the entrance of the ES, at KFH31 and at the entrance of the MST.

Quadrupole-Driven Extraction

The chromaticity sextupoles were matched to achieve a horizontal chromaticity of +8.9 (corresponding to close to the magnet limits for the highest extraction energy) and a vertical chromaticity of -4.5 (close to the natural chromaticity). Such a high horizontal chromaticity is beneficial to reduce the instantaneous horizontal extracted emittance (Hardt condition [3]) and to expand the range of tunes over which the beam is extracted, thus reducing the effect of the tune ripple and improving the beam quality.

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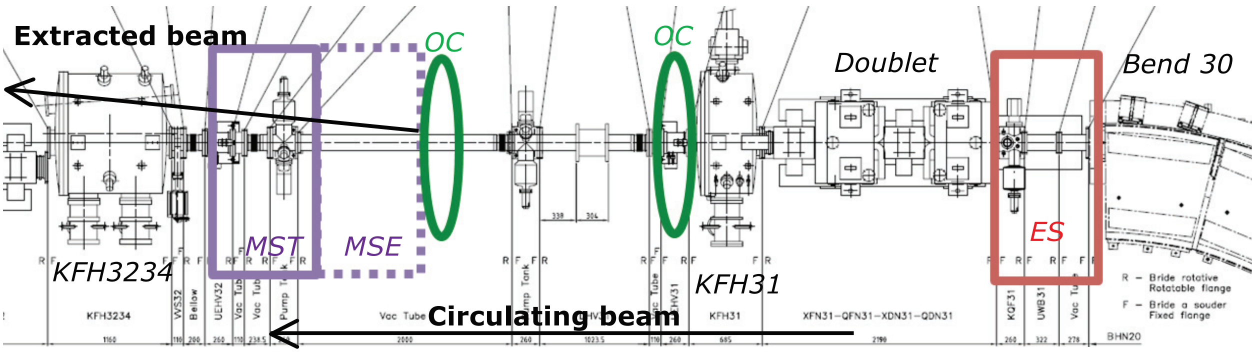

Figure 3: Position of elements in SS30.

The chromaticity has, however, only a minor effect on the phase space area occupied by the beam throughout the spill, and a horizontal chromaticity closer to the natural one could also be employed if instabilities arise.

The ES was placed at -50/-46.4 mm (entrance/exit) and the closed orbit in SS30 was adjusted accordingly. The summary of the results of the tracking is given in Tab.1.

Table 1: Q-D Extraction Beam Parameters

Kinetic Energy [MeV/u]	**20**	**440**
Momentum Offset [‰]	± 0.9	± 0.2
Physical Emittance [µm]	0.1-25.0	0.1-5.2
Spiral Step [mm]	0.6-7.0	8.3-9.2
Average lattice tune distance to resonance	-4.8e-3	-2.6e-3
Resonance Excitation [$m^{-1/2}$]	30	35
ES kick [mrad]	7.3	3.9

RF-Knockout Extraction

In this case, the horizontal chromaticity is set to 0.9 to extract all momenta at the same time and with similar emittances. The ES was placed at -49/-45.8 mm (entrance/exit). The closed orbit in SS30 was adjusted accordingly. The results of the tracking are summarised in Tab.2.

Discussion

The most critical aspects in the design are the aperture available for off-momentum particles in the MST (where the dispersion is at its maximum) and the slope of the ES blade (if only one beam energy is requested by the experiment, the slope can be optimized for this energy, but not if an experiment requests fast switching between energies). This effect is more prominent for the Q-D since the phase space area occupied by the extracted beam at the ES entrance (for all configurations) is larger than in the case of RF-KO.

Table 2: RF-KO Extraction Beam Parameters

Kinetic Energy [MeV/u]	**20**	**440**
Momentum Offset [‰]	± 0.9	± 0.2
Physical Emittance [µm]	26.1-29.1	6.2-7.0
Spiral Step [mm]	0.7-8.5	9.4-10.6
Lattice tune distance to resonance	-2.8e-2	-6.8e-3
Resonance Excitation [$m^{-1/2}$]	80	40
ES kick [mrad]	6.4	3.4

CONCLUSION

The feasibility of implementing a slow extraction system based on the third integer resonance in LEIR was proven by tracking the most extreme beam conditions with MADX-PTC. Compatible solutions, for both Quadrupole-Driven and RF-Knockout extraction, were found in terms of: resonance excitation, the closed-orbit bump required by aperture constraints and the extraction septa. An electrostatic and a thin magnetic septum can be recuperated from spare components at CERN, a thick magnetic septum and two orbit correctors have to be manufactured additionally. To allow the extracted beam transit, the beampipe of a quadrupole-sextupole doublet section has to be enlarged and the extracted beam has to pass through the tank of one of the fast kickers.

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