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ENHANCING BEAM INTENSITY IN SIS18 BY A TWO-PLANE MULTI-TURN INJECTION APPROACH

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Abstract

The existing synchrotron SIS18 will serve as an injector for the FAIR (Facility for Antiproton and Ion Research) complex in booster mode operation. FAIR requires high-intensity beams, placing stringent demands on increasing beam currents in SIS18. Operational experience has shown that significantly increasing beam intensity in SIS18 necessitates both a higher current from UNILAC and improved injection efficiency into SIS18. Currently, injection into the SIS18 synchrotron is performed using conventional multi-turn injection (MTI) in the horizontal plane.

To significantly enhance beam intensity in SIS18, we propose implementing a two-plane multi-turn injection scheme. This method aims to boost beam intensity to the desired levels (e.g., uranium beams exceeding 1.5 x 10^{11} per cycle), even within the current capabilities of UNILAC. This paper discusses how MTI gain can be increased with high efficiency through a two-dimensional technique of painting Lissajous-like patterns in horizontal-vertical phase space using an inclined electrostatic septum. Simulation examples are presented, illustrating the characteristics of the beam created in SIS18 and the potential effects of space charge forces.

INTRODUCTION

The main objective of serving SIS100 with the required intensity of 5×10^{11} U/cycle demands the extraction of 1.5×10^{11} U/cycle from SIS18 at a repetition rate of 2.7 Hz [1]. The so far provided intensities and qualities of the Uranium beams provided for injection into SIS18 enables stacking of intensities far below the space charge limit. In order to significantly increase the number of particles of Uranium beams, the charge state for acceleration in the SIS18 should be "lowered to U^{28+}. Achieving required intensity presents significant challenges, particularly concerning the stabilization of the dynamic vacuum and the control of charge exchange processes, both of which scale exponentially with increasing beam intensities. To address these challenges, several technical measures have been proposed, such as cryogenic inserts in the ion catcher system. Over the past decade, the completed upgrade program, which encompassed all major technical systems of SIS18, has enabled stable acceleration of 4.5×10^{10} U/cycle at a high repetition rate [2]. Long-term operational experience with SIS18 has shown that substantial particle losses occur during multi-turn injection (MTI) [3,4], significantly contributing to dynamic vacuum instability. This, in turn, leads to additional uranium beam losses during capture into the RF bucket and subsequent acceleration in SIS18. To improve the dynamic vacuum, it is highly desirable to minimize—or even completely eliminate—particle losses during injection into SIS18 while simultaneously achieving a uranium beam intensity of more than 1.5×10^{11} U/cycle. Both simulations and operational experience indicate that the existing MTI scheme in the horizontal plane cannot fulfill this requirement without significant losses at the septum magnet. However, preliminary theoretical studies suggest that the required intensities for the FAIR project [5,6], with minimal particle losses, could be achieved by implementing MTI in both transverse planes. This innovative approach has the potential to optimize phase space utilization and reduce beam losses, thereby enhancing injection efficiency and improving the stability of the dynamic vacuum in SIS18.

To date U^{28+} particles from the high current UNILAC are injected into the SIS18 by a one dimensional multi-turn technique in the horizontal plane [7]. At present, the UNILAC delivers current 3.5 mA of U^{28+} beam at the energy of 11.4 MeV/u [8], which correspond to 3.7 x 10^9 particles for one turn (t=4.7 µs) in the SIS18. After UNILAC upgrade it is planned that injection current will be 15 mA or 1.56 x 10^{10} per one turn with injected horizontal emittance less than 5 mm·mrad [9].

LAYOUT OF THE TWO-PLANE MTI

To realize a two-plane MTI, the beam at the position of the electrostatic septum (ES) must be injected between the septum wire and the cathode, which may be oriented at an angle between 40° and 50° with respect to the vertical, as shown in Fig.1. The bump orbit must be formed in close proximity to the septum wires, with a maximum displacement from the reference orbit of 70 mm in the horizontal and 20 mm in the vertical plane.

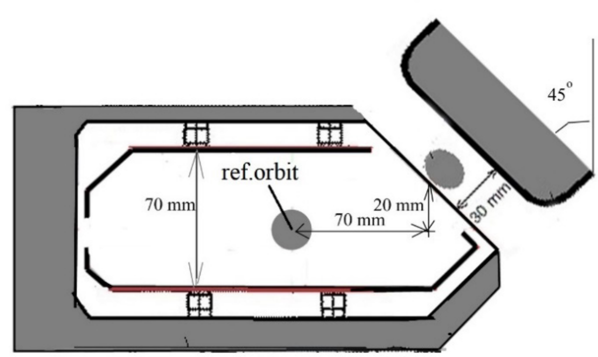

Figure 1: Schematic of the injected beam at the ES, showing displacement in both horizontal and vertical planes.

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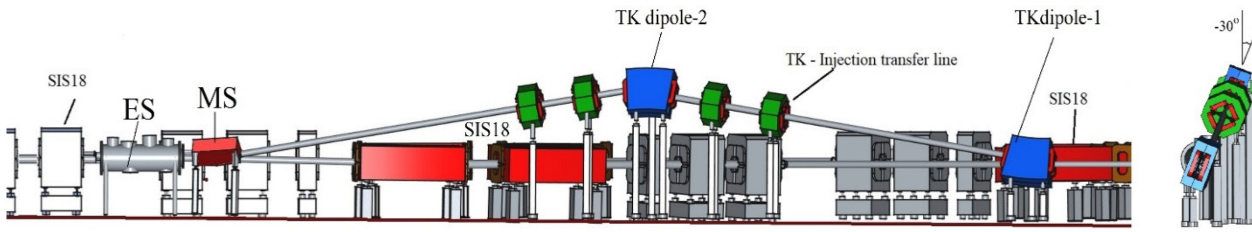

Figure 2: Layout of the TK transfer line with proposed dipole and quadrupole magnet arrangement for two-plane MTI.

The bump orbit at the ES is generated using four horizontal and four vertical bumper magnets. The four horizontal bumper magnets currently used for single-plane MTI can also be utilized for the two-plane configuration. Their positions remain unchanged within the existing SIS18 setup. An additional set of four vertical bumper magnets is required and may be installed in close proximity to the horizontal bumpers.

The section of the TK transport line upstream of the ES, which currently consists of the septum magnet (MS) and four quadrupole magnets, must be reconfigured to allow beam transport in both the horizontal and vertical planes, while remaining compatible with the existing TK beamline extension from UNILAC as shown in Fig.2. The MS must be tilted to match the angle of the ES wires, enabling simultaneous injection in both planes. Two additional dipole magnets - with deflection angles of +9.5° (TK dipole-1) and −18.2° (TK dipole-2) - need to be installed. These dipole magnets, along with the four quadrupoles, should be arranged within a plane inclined at −30° with respect to the vertical, as depicted in Fig. 2.

CALCULATED PERFORMANCE OF TWO-PLANE MTI INTO SIS18

An analysis of the proposed two-plane MTI into SIS18 was carried out using the simulation code 2PMTISIS18 (2 Plane Multi-Turn Injection for SIS18). The code has been employed to study particle accumulation, losses, emittance growth, the phase-space distribution for varying tune, bump settings, injection duration, initial particle distribution, emittance and intensity. The space charge is included in the code and numerically evaluated using an approximate frozen space charge model.

In the simulations, the SIS18 lattice is assumed to be linear, including only dipole and quadrupole elements. This is a reasonable approximation, as only 20–55 beamlets are stacked during a maximum of 100 turns, and the sextupole magnets present in the ring are relatively weak. Chromatic effects of the magnets are included in all simulations. During MTI, the RF cavities of the accelerator are switched off and no acceleration takes place, so the longitudinal beam dynamics are neglected. To minimize beam losses on the ES, an optimal choice of betatron tunes Q_x and Q_y, as well as a proper design of the bump orbit reduction functions $b_{x,y}(n)$, is essential.

Bump Orbit at the ES

Bump orbit reduction as a function of time is one of the critical parameters for MTI. It significantly influences both the stacking efficiency and particle losses on the backside of the ES. In the presented simulations, a nonlinear reduction of the closed orbit $b(n)$ over turn number n was studied using an exponential decay function defined by:

$$b(n) = b_f + (b_i - b_f)\left(\frac{1-exp(\tau(N_{max}-n))}{1-exp(\tau N_{max})}\right), \qquad (1)$$

where N_{max} is the number of required turns to move the orbit from initial b_i to the final b_f position and τ is a shaping parameter that defines the slope of the curves.

After the final turn is injected, the beam should be deflected away from the septum as quickly as possible to prevent further losses. However, emittance growth will still occur slightly due to nonlinear effects as the beam evolves toward a stationary state.

SIMULATION RESULTS

MTI into SIS18 was studied for the parameters listed in Table 1. For the given betatron tunes, the bump orbit reduction functions $b_{x,y}(n)$, calculated using Eq. (1), were optimized to enable the injection of the maximum number of beamlets while minimizing particle losses at the ES.

Table 1: Parameters of MTI for SIS18

Parameters	Value
Circumference, m	216.6
Magnetic rigidity, Tm	4.15
Acceptance hor/ver, mm·mrad	150 / 50
Ion species	U^{28+}
Injection beam energy, MeV/u	11.4
Ion current (U^{28+}), mA	3.5 - 15
Number of particles per turn	(3.7–15)x10^9
Emittance hor/ver, mm·mrad	< 5
Betatron tunes, Q_x / Q_y	4.23 / 3.36
b_i , hor/ver, mm	70 / 15
b_f , hor/ver, mm	22 / 0
N_{max} hor/ver	100 / 50
τ , hor / ver	0.06 / 0.05

In the first stage, the simulations were carried out without considering space charge effects, assuming injected horizontal and vertical emittances of 5 mm·mrad. In the subsequent analysis, taking into account the influence of space charge depending on the injection current, the optimal betatron tunes were identified near Q_x/Q_y = 4.28/3.40. Corresponding parameters for the bump orbit reduction were then generated to minimize particle losses. Fig. 3 shows the simulated injection efficiency for 55 beamlets

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under conditions with and without space charge effects for two injection current scenarios: 3.5 mA and 15 mA. As shown in Fig. 3, major losses begin to appear after 25 turns, when space charge effects become significant.

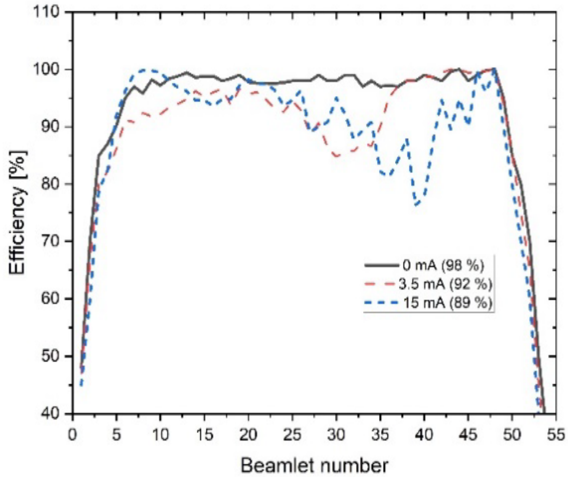

Figure 3: Simulated injection efficiency for 55 beamlets with and without space charge effects for injection currents of 3.5 mA and 15 mA.

Fig.4 illustrates particle accumulation as a function of turn number. For an injected current of 3.5 mA from UNILAC, more than 1.1×10^{11} uranium particles can be injected into SIS18 within horizontal and vertical emittances of ε_x =200 mm·mrad and ε_y =25 mm·mrad, respectively. The total beam loss is 8.8% for 45 injected beamlets.

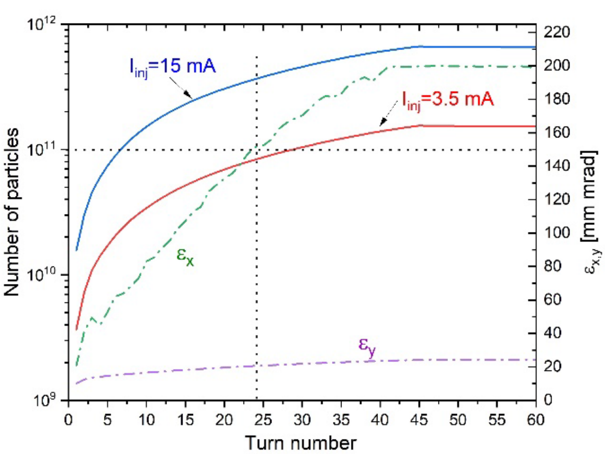

Figure 4: Number of accumulated particles and beam emittance as functions of turn number for a 3.5 mA and 15 mA injected uranium beam.

By optimizing the number of injected beamlets, the loss fraction can be minimized. Table 2 summarizes the simulation results for beam losses. In the most realistic scenario, the dynamic aperture of SIS18 can accommodate approximately 25 turns, corresponding to a horizontal acceptance of 150 mm·mrad. In this case, the expected number of injected uranium particles ranges from 8.5×10^{10} to 3.5×10^{11} depending on the current delivered from UNILAC. Importantly, total beam losses remain below 3.1%, representing a substantial improvement over single-plane MTI.

Table 2: Simulated Beam Losses for Different Numbers of Injected Beamlets and Two Injection Current Scenarios

Injected current	3.5 mA	15 mA
Injected beamlets	**Loss,%**	**Loss ,%**
20	3.0	2.5
25	3.1	2.7
45	8.8	9.3
55	14.6	16.9

It is important to note that the above results for specific betatron tunes do not represent the only possible configuration. To obtain a comprehensive understanding of the operational window for two-plane MTI, simulations were performed across a horizontal tune range of Q_x = 4.0 to 4.5 and a vertical tune range of Q_y =3.0 to 3.5. Fig. 5 presents a map of injection efficiency for 45 injected beamlets. Multiple tune islands can be identified, within which the injection efficiency remains close to 94%, assuming fixed bump orbit parameters.

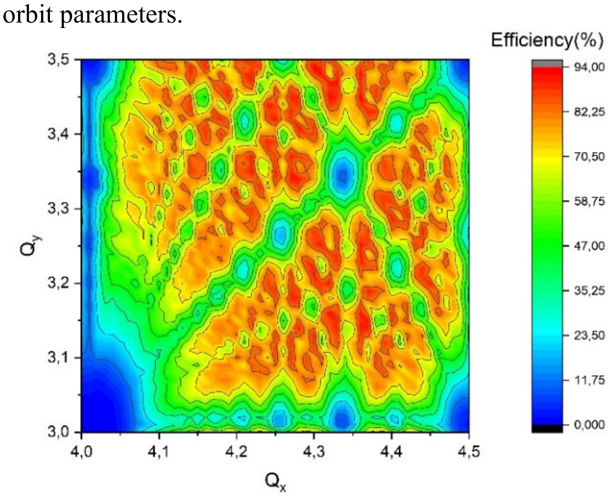

Figure 5: Map of injection efficiency as a function of horizontal and vertical betatron tunes for 45 beamlets.

A key factor in optimization is the expected beam intensity per injected turn. Based on this parameter, the bump orbit reduction function must be selected to maximize injection efficiency and particle accumulation. Further theoretical studies are required to validate the two-plane injection approach under realistic machine conditions.

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