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CONCEPTUAL STUDY OF MULTI-TURN INJECTION FOR SIS100 AS A LONG-TERM PERSPECTIVE

O. Dolinskyy, Y. El Hayek, D. Ondreka, P. Spiller, GSI, Darmstadt, Germany

Abstract

The SIS100 synchrotron, currently under construction as part of the FAIR project, is designed to play a key role in the delivery of high-intensity ion beams. Reaching the FAIR design intensities for low charge-state heavy ions, e.g. the reference ion U^{28+} will, however, be challenging due to limitations of the existing SIS18 synchrotron serving as injector to SIS100. In the long-term, the integration of a new linear accelerator capable of delivering high-intensity ion beams at energies up to 100 MeV/u would open the possibility of direct multi-turn injection (MTI) into SIS100, bypassing the SIS18. This paper investigates the MTI process for U^{28+} beams, aiming to accumulate up to 5×10^{11} particles per cycle with high efficiency and minimal particle losses on the electrostatic septum. We present a theoretical analysis of horizontal-plane MTI, outline achievable beam performance, and discuss system requirements. Additionally, the proposed layout and parameters of the MTI equipment are detailed.

INTRODUCTION

Currently, the UNILAC and SIS18 at the existing GSI facility form the primary injector chain for the Facility for Antiproton and Ion Research (FAIR) [1]. For the FAIR project, the goal is to accumulate up to 5×10^{11} uranium particles in a single injection cycle into SIS100 [2]. This necessitates an upgrade of the present UNILAC in terms of beam intensity, quality, and high availability, which is presently being implemented [3]. As demonstrated in Ref. [3], the beam dynamics of the completely new Alvarez-DTL will meet the FAIR requirements [4]. In the current FAIR project scenario, partially stripped uranium ion beams from UNILAC are planned to be accelerated in the SIS18 synchrotron from 11.4 MeV/u to 200 MeV/u. The completed upgrade program, which included all major technical systems of SIS18, has so far enabled stable acceleration of 4.5×10^{10} U/cycle at a high repetition rate.

Despite these significant advancements, reaching the FAIR intensity goals remains extremely challenging for SIS18 demanding the extraction of 5×10^{11} U/cycle at a repetition rate of 2.7 Hz. Achieving this target poses significant challenges, primarily associated with stabilizing the dynamic vacuum by minimizing initial losses and controlling charge exchange processes to avoid exponential pressure growth. To address these challenges, additional technical measures have been proposed, such as cryogenic inserts in the ion catcher system [5,6].

However, long-term operational experience has shown that substantial particle losses occur during MTI, significantly contributing to dynamic vacuum instability. Moreover, transverse space charge effects associated with periodic resonance crossing due to the synchrotron motion in the bunched beam at low energies further limit the dynamic aperture, effectively reducing the acceptance for MTI and limiting the achievable beam intensities.

The development of optimized MTI strategies, along with improved vacuum stability and space charge management, is therefore essential for meeting the ambitious goals of the FAIR project and ensuring the reliable delivery of high-intensity uranium beams to SIS100.

A promising alternative approach to increase beam intensity in SIS100 even beyond the FAIR design goals involves bypassing SIS18 entirely. This strategy requires the installation of an additional linear accelerator capable of delivering Uranium beam at energies at least 100 MeV/u, directly connecting the existing UNILAC to SIS100, as illustrated in Fig.1 and discussed in [7]. In this case, MTI in the horizontal plane is proposed for SIS100.

This paper explores the feasibility of implementing MTI in the horizontal plane for the SIS100 synchrotron. Table 1 lists the initial parameters under which MTI was investigated.

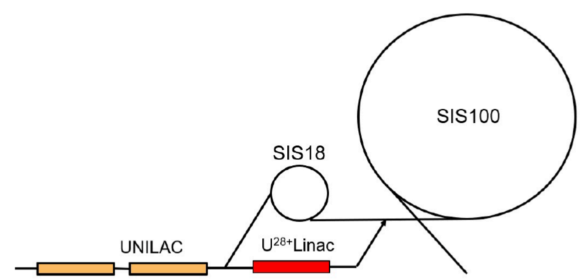

Figure 1: Conceptual layout for a high-intensity heavy ion injector system, showing direct injection from an upgraded UNILAC into SIS100.

Table 1: Parameters of MTI for SIS100

Parameters	Value
Circumference, m	1083.6
Magnetic rigidity, Tm	12
Acceptance hor/ver, mm·mrad	100 / 50
Ion species	U^{28+}
Injection beam energy, MeV/u	100
Ion current, mA	15
Number of particles per turn	2.8×10^{10}
Emittance hor (norm), mm·mrad	< 0.8
Emittance ver (norm), mm·mrad	<2.5
Betatron tunes Q_x / Q_y	18.79/18.73

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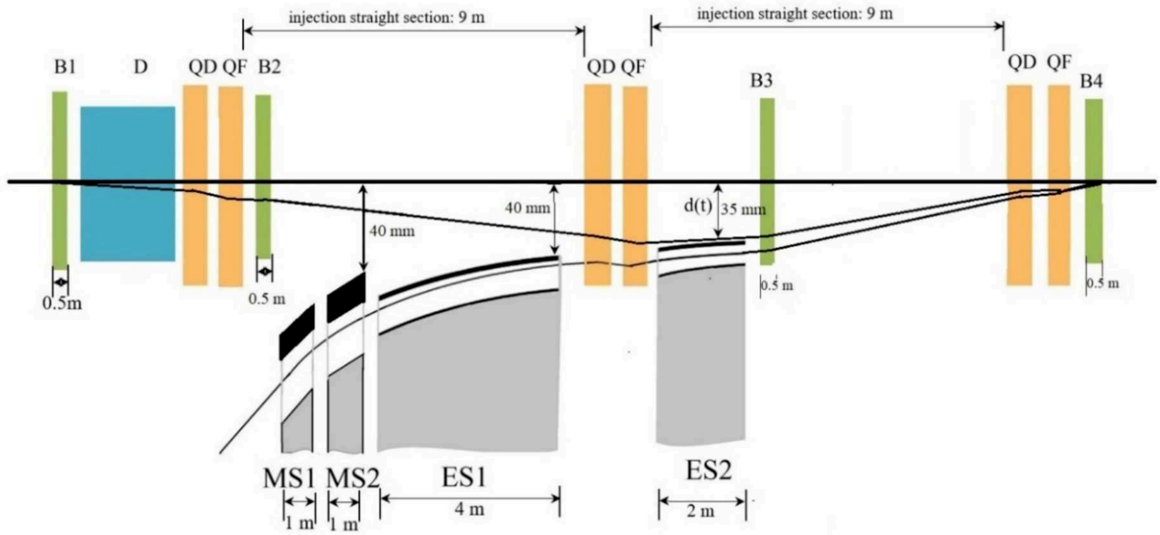

Figure 2: Proposed layout of the multi-turn injection system for SIS100, including two electrostatic septa (ES1, ES2) and bumper magnets (B1–B4).

SIS100 MTI INJECTION LAYOUT

The SIS100 synchrotron has two cells in the straight section dedicated to injection. The proposed MTI layout includes two electrostatic septa (ES1 and ES2) and four bumper magnets (B1–B4), as shown in Fig. 2. The two existing magnetic injection septa MS1, MS2 for single turn injection, may be reused for MTI. The bumper magnets must support programmable kick angle profiles (linear and nonlinear) for beam stacking with minimal losses.

Various injection layouts have been considered for MTI into SIS100. The finally chosen layout matches the following design criteria:

- Sufficient space for installation of four bumper magnets and two electrostatic septa at warm straight sections.
- Reasonable operational parameters for bumper magnets and electrostatic septa at Bρ =12 Tm.

COMPUTER SIMULATION

The MTI into SIS100 has been investigated using a multiparticle tracking code, which was specially developed for this study. The basic features of the injection scheme taking as input from the linac either a KV or Gaussian distribution have been confirmed. The non-linear space charge during injection has been considered. Space charge introduces moderate beam losses (1–5%), which can be further reduced by optimizing the orbit bump program. Gaussian beamlets give the least loss before reoptimisation, mainly because space charge is initially more concentrated into small pockets.

The simulation code was employed to perform tune matching, determine the required bump orbit at ES2, and track particles during injection. As the Rf system of SIS100 does not work during injection, the longitudinal particle dynamic is not considered.

In the simulations, 1000 macro-particles are injected per turn, and the number of injection turns (i.e., bump-pulse duration) is varied to investigate its effect on injection efficiency. To ensure that the injected emittances enter the phase space of SIS100 with optimal filling and minimal dilution, two conditions must be satisfied in the ideal case [8]:

$$\frac{\alpha_i}{\beta_i} = \frac{\alpha_m}{\beta_m} = -\frac{x'_c - x'_o}{x_c - x_o} \;;\quad \frac{\beta_i}{\beta_m} > \left(\frac{\varepsilon_i}{\varepsilon_m}\right)^{\frac{1}{3}} \approx 1 - 0.25, \quad (1)$$

where α_i , β_i, α_m , β_m are the Twiss parameters of the incident beam and the synchrotron at the injection point, (x_c, x'_c) and (x_o, x'_o) represent the coordinates of the incoming beamlets' center and the bump orbit in the ES2 phase space, respectively. Table 2 lists the optimal parameters for the MTI injection scheme.

Table 2: Parameters of a 35 Turns MTI Scheme at ES2

Parameters	Value
Betatron tune, Q_x	18.79
Twiss par. synchrotron, β_m /α_m	12.8 m / - 1.1
Twiss par. inj. beam, β_i /α_i	3.15 m / -0.275
Injected beam position, x_c	37.4 mm
Inj. beam angle, x'_c	3.21 mrad
Bump orbit position, x_o	35 mm
Bump orbit angle, x'_o	3.0 mrad
Injected hor.emittance (100 %)	1.7 mm·mrad
Ele. septum kick angle ES1	10 mrad
Ele. septum kick angle ES2	5 mrad
Bump. kick angle (max)B1-B4	3 mrad

The bump orbit reduction as a function of time is one of the crucial injection parameters. Its influence on the number of particle losses on the septum backside for each beamlet has been investigated using nonlinear closed orbit decrease calculated by formula

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$$d(t) = d_o - \Delta x \cdot \sum_{n=1}^{t} exp(-n \cdot \tau)\,, \quad (2)$$

where n is a turn number, d_o =35 mm is the initial bump orbit displacement at ES2, τ =0.02 is the parameter, which defines the slope of the curves, Δx = 1.6 mm is the initial bumper orbit step displacement. This type of orbit reduction results in a maximum number of beamlets, which can be injected without losses if the fractional horizontal betatron tune is 0.79. Studies show that for given initial beam emittance and chosen horizontal betatron tune the parameter τ must be re-optimized to get a maximal number of injected beamlets without losses. For the selected injection parameters, the maximum number of turns that can be injected into the ring is 35, 20 of which can be injected free of loss. An example of the beam cross section in phase space after stacking of 35 beamlets as the final turn is injected is shown in Fig.3. To minimize space charge effects the vertical beam size had been artificially increased by mismatching the direction of the center of the incoming beamlets at the injection point. In this case for 35 turns at I = 423 mA, space charge effects are relatively small and the Laslett tune shifts are only ΔQ_x =-0.037 and ΔQ_y=-0.056.

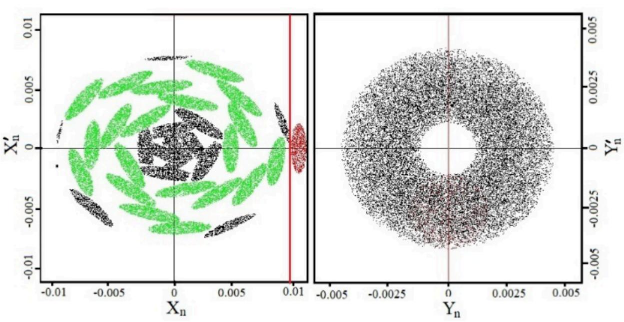

Figure 3: Phase-space stacking of 35 beamlets in SIS100 at the ES2 location. The 20 green beamlets indicate lossless injection. Vertical mismatch of 1.5 mrad is applied.

For each individual beamlet injection efficiency is shown in Fig.4. It is observed that 20 beamlets can be injected with 100% efficiency resulting in lossless injection of 5.6 × 10^{11} uranium particles. Figure 5 illustrates the growth of the accumulated particle intensity and beam emittance as a function of the number of injected turns. The total injection efficiency for this scenario is 81% resulting in a maximum number of 8 × 10^{11} uranium particles within a horizontal emittance of 95 mm·mrad.

For the fixed parameters of the bump orbit reduction at ES2, the conducted analysis shows that over a wide range of betatron tunes, the overall injection efficiency remains constant at the level of 81% (see Fig.6), but the number of lossless injected beamlets varies. Evidently, for betatron tunes around 18.79, the nonlinear bump orbit control program can be generated in such a way as to achieve the maximum possible number of lossless injection turns. To accomplish this, a special optimization procedure for calculation needs to be developed in future studies.

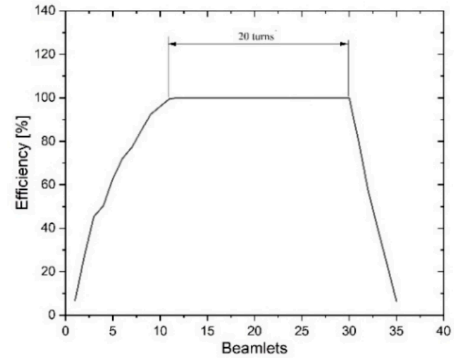

Figure 4: Efficiency of injected beamlets.

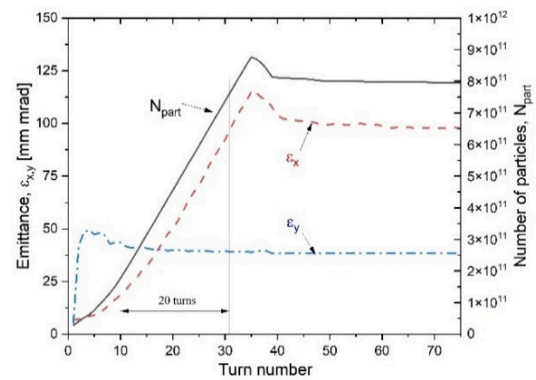

Figure 5: The number of accumulated particles and the corresponding beam emittance as a function of the number of turns. The 20-turn gap indicates the injected turns during which the injected beamlets experience no losses.

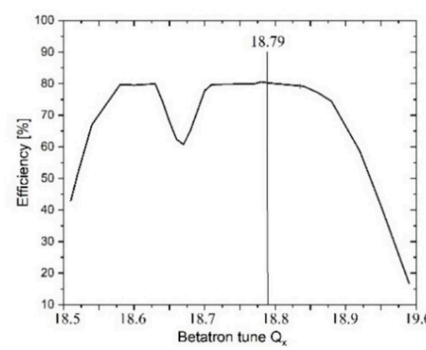

Figure 6: SIS100 MTI efficiency vs horizontal tune.

REFERENCES

[1] P. J. Spiller *et al.*, "Status of the FAIR Project", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 63-68. doi:10.18429/JACoW-IPAC2018-MOZGBF2

[2] P. Spiller, "The FAIR synchrotrons SIS100 and SIS300 and the high energy beam transport system", CERN, Geneva, Switzerland, Rep. CERN-2009-004, CARE-Conf.-08-032-HHH, July 2009.

[3] S. Mickat *et al.*, "Layout of the New FAIR Post-stripper DTL for Intense Heavy Ion Beams", in *Proc. LINAC'18*, Beijing, China, Sep. 2018, pp. 303-307. doi:10.18429/JACoW-LINAC2018-TU2A03

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[4] O. K. Kester *et al.*, "Status of the FAIR Accelerator Facility", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 2084-2087. doi:10.18429/JACoW-IPAC2014-WEPRO060

[5] P. J. Spiller, L. H. J. Bozyk, H. Eickhoff, H. Kollmus, P. Puppel, and H. Reich-Sprenger, "Acceleration of Intermediate Charge State Heavy Ions in SIS18", in *Proc. IPAC'10*, Kyoto, Japan, May 2010, paper MOPD002, pp. 669-671.

[6] L. Bozyk and P. Spiller, "Cryogenic inserts in the room temperature synchrotron SIS18 at GSI", presented at the 16th Int. Accel. Conf. (IPAC'25), Taipei, Taiwan, Jun. 2025, paper THPS058, this conference.

[7] H. Vormann, W. A. Barth, M. Miski-Oglu, U. Scheeler, M. Vossberg, and S. Yaramyshev, "High Current Heavy Ion Beam Investigations at GSI-UNILAC", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 78-81. doi:10.18429/JACoW-IPAC2022-MOPOST012

[8] J. Beebe-Wang and C.R. Prior, "Injection Mismatch for the SNS Accumulator Ring", BNL/SNS Technical Note, Brookhaven National Laboratory, Upton, New-York, no.080, June 2000.