CONCEPTUAL DESIGN AND PERFORMANCE STUDY OF TWO-PLANE MULTITURN INJECTION FOR HIGH INTENSITY U^{28+} BEAMS IN SIS18

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Abstract

Within the FAIR project, SIS18 is planned to be used as an injector and booster to increase the intensity of ion beams in the SIS100. To achieve higher intensities, a two-plane multi-turn injection scheme for SIS18 is being developed at GSI. The new injection system will allow a substantial increase in the number of accumulated turns with high efficiency, significantly reducing beam losses at the electrostatic septum. This paper presents the conceptual design of the two-plane injection system and the results of studies on the expected properties of the U^{28+} beam delivered from the upgraded UNILAC, including its parameters after collimation in the TK transfer line. Furthermore, the paper discusses the design requirements for the injection line and the anticipated performance of the two-plane injection system in SIS18, taking into account the beam optics of the injection line, collimation effects, and overall injection efficiency.

INTRODUCTION

The upgrade of the injection system in SIS18 is a key prerequisite for achieving the beam intensity goals of FAIR [1]. To overcome the present SIS18 injection limitations, a two-plane multiturn injection scheme is proposed [2]. In this concept, the injected beam is painted simultaneously in both the horizontal and vertical phase space. This approach leads to much higher number of turns, which can be injected with improved efficiency and a reduced space-charge tune shift. The following requirements are imposed on the new beam injection system into the SIS18: for the existing SIS18 h/v acceptance of 150 x 50 mm·mrad the U^{28+} beam intensity must reach $1.5x10^{11}$ ions per injection; formation of a local closed-orbit bump in both planes at the electrostatic septum (ES); implementation of a three-step operating mode of the bumper magnets; capability of nonlinear variation of the bumper magnet fields; the horizontal and vertical emittance of the injected beam delivered from UNILAC should be less than 6 -7 mm·mrad; injection of the maximum possible number of turns with an efficiency of nearly 100%; beam collimation in the injection transport line upgraded for two plane injection. The expected benefits of the two-plane injection system are:

- Multiplication of the injector current of U^{28+} by factor up to 40 (depending on beam brilliance provided by UNILAC and collimation in TK line).
- Increased injection efficiency up to 100%.
- Reduction of peak particle density and space-charge tune shift.
- Extension of the long-term operational flexibility of SIS18 for FAIR.

The conceptual design has been done taking into account: beam performances provided by UNILAC [3]; ion-optical characteristic of the redesigned part of the TK injection line [4]; requirements for bump magnets; ion optical simulations of two plane multiturn injection in SIS18; concept for a new design of the tilted ES.

COMPUTER SIMULATION

The beam injection process was investigated using a multi-particle tracking code [2]. The injection properties were calculated under the condition of quasi-realistic initial beam characteristics, where the particle distribution is obtained by tracking particles through the TK transfer line, which is redesigned for delivering the beam from UNILAC to SIS18 in two planes [4]. Here, the coupling of the Twiss parameters and the effect of the h/v dispersion functions are taken into account in combination with applied beam collimation, as described in Ref. [4]. The simulations demonstrate that, at the SIS18 injection point, a collimated U^{28+} beam with a transverse emittance of approximately 4 mm·mrad (4 rms) in both planes and an intensity of 9 mA can be formed from an initial 15 mA beam delivered from UNILAC with a Gaussian distribution and an emittance of 15 mm·mrad. Representative beam cross-section and phase-space distributions after 30 turns and injection of 22 beamlets are shown in Fig.1 and Fig.2.

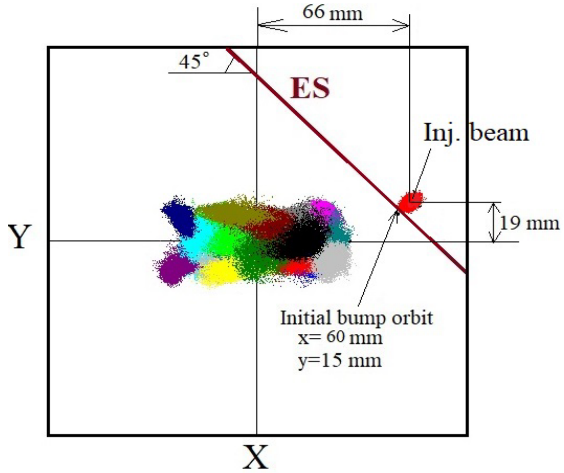

Figure 1: Particle distribution in the x-y plane after 30 turns with two-plane painting injection of 22 beamlets.

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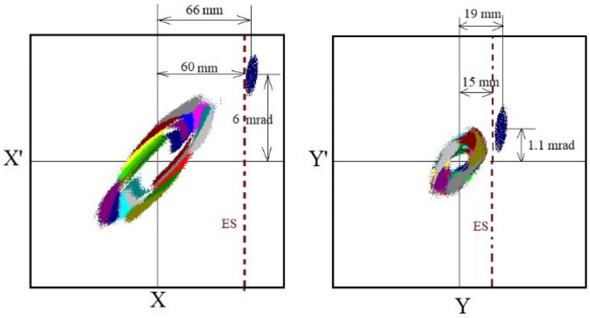

Figure 2: Phase-space portrait of the 22 injected beamlets in SIS18. The dashed lines show the electrostatic septum location at the initial bump deflection point.

Figure 3 presents the calculated evolution of the U^{28+} beam intensity and the 4*rms* emittance in both transverse planes as a function of the number of injected turns. It is theoretically possible to inject 22 beamlets, resulting in 2×10^{11} particles with horizontal and vertical 4*rms* emittances of 145 mm·mrad and 42 mm·mrad, respectively. However, the injection efficiency drops to 92% if the dynamic aperture of SIS18 is limited to 150/50 mm·mrad. For the FAIR requirements, where 1.5×10^{11} uranium particles (corresponding to 150 mA) are needed, calculations show that it is sufficient to inject 17 beamlets with an injection efficiency of 99%. In this case, the horizontal/vertical 4*rms* emittance is 125/40 mm·mrad. For I = 150 mA, space-charge effects remain relatively modest, producing Laslett tune shifts of only $\Delta Q_x'' = -0.04$ and $\Delta Q_Y'' = -0.09$.

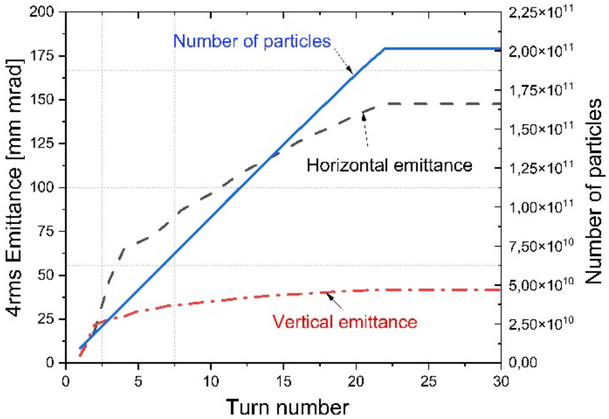

Figure 3: Evolution of the U28+ beam intensity and transverse emittance (4 rms) as a function of the number of injected turns.

BUMP ORBIT

The four horizontal and four vertical bumper magnets must be configured to generate a closed-orbit bump at injection point of the SIS18 a bump orbit offset as shown in Fig 1. The shape of the bump orbit in the SIS18 at beginning of MTI, which is generated by bumper magnets (HB, VB), is shown in Fig.4. For successful multi-turn injection, the closed orbit at ES must decay exponentially from turn to turn [2].

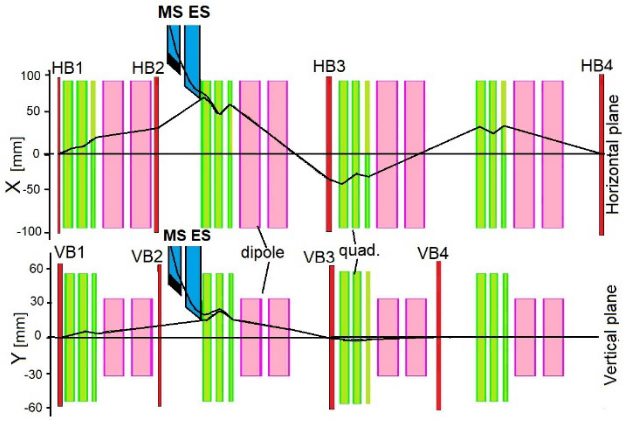

Figure 4: Horizontal (top) and vertical (bottom) closed-orbit bumps in SIS18 generated by the horizontal bumpers HB1–HB4 and the vertical bumpers VB1–VB4, respectively.

The rate of this exponential decay is directly governed by the chosen betatron tunes. A linear or non-linear decay from the maximum to an intermediate value is applied only during beamlet injection. Between injections, the orbit bump must be ramped from zero to maximum as fast as possible. After injection, it drops linearly from the intermediate value back to zero to align the stacked beam with the SIS18 reference orbit. Depending on the injection scheme the fall-off time is ~50-500 µs. The waveform should approximately have a nonlinear shape defined by Eq. (1):

$$I(t) = I_f + (I_i - I_f)\left(\frac{1-\exp\left(\tau\frac{(Tmax-t)}{\Delta t}\right)}{1-\exp\left(\tau\frac{Tmax}{\Delta t}\right)}\right), \qquad (1)$$

where $I_{i,f}$ are the initial and final current, T_{max} is the maximal time to change initial I_i to the final I_f, Δt is revolution time (4.7 µs at E=11.4 MeV/u), τ is a parameter, which defines the slope of the curves. The main parameters of the h/v bumper magnets are summarized in Table 1. For example for parameters given in table 2 the current wave form as function of time is shown in Fig.5 for two bumper magnets (B3, V3), which have the maximum values of required currents.

Table 1: Parameters of Bumper Magnets (HB – Horizontal Bumper, VB - Vertical Bumper)

Parameters	HB	VB
Number units	4	4
Max. bending angle, mrad	6	2.5
Eff. length, m	0.44	0.5
Yoke length, m	0.4	0.4
Max. flux density, T	0.08	0.021
Field homogeneity, δ=ΔB/B	$\pm 5*10^{-3}$	$\pm 5*10^{-3}$
Area of field homog.,h/v, mm	230/90	200/90
Geom. pole gap hight, mm	90	200
Max. coil current, A	5000	3350

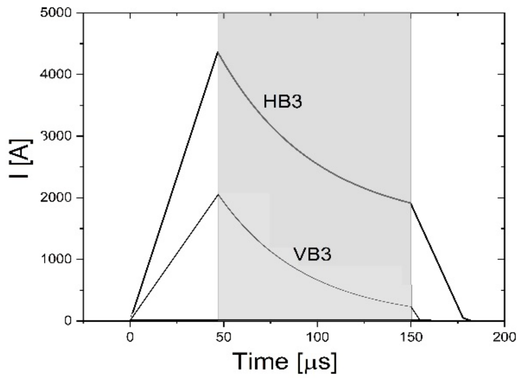

Figure 5: Current wave forms for HB3 and VB3 bumper magnets calculated by Eq.(1) with T_{max}=235 µs as well as τ =0.09 and 0.1 for HB3 and VB3 respectively. Beam injection period is shown in the shaded gray area.

ELECTROSTATIC SEPTUM

The two-plane injection system requires a dedicated electrostatic septum with tilted wires. The distinctive feature of the ES is that both anode and cathode must be inclined at 45° with respect to the horizontal. In Table 2 the required main parameters of ES are given. The new ES is foreseen to be installed in the existing SIS18 injection section, replacing the present ES. The existing magnetic septum MS, currently used for one-plane MTI, can be reused for two-plane MTI after a 45° re-orientation.

Table 2: Main Parameters of ES for SIS18

Parameters	Value
Length, m	1.67
Deflection angle, Degree	2.7
Max. Voltage, kV	250
Operation field, kV/cm	80
Width Anode-Cathode, mm	30
Backable, K	300
Diagnostic	BPM
Protection	Scraper

SENSITIVITY TO INJECTION ORBIT

A reduction in injection efficiency can occur if the injection beam line fails to deliver the required beam centroid coordinates at the SIS18 injection point. Such mismatches lead to particle losses, initially on the outer side of the septum blade during the first passage, followed by additional losses on the inner side as the beam rotates and oscillates in the synchrotron during subsequent turns. To quantify this effect, systematic simulations were performed in which the injection position and angle were varied while keeping all other injection parameters fixed. For example, Fig. 6 (top left) shows the injection-efficiency map as a function of horizontal δx and vertical δy positional deviations from the ideal orbit for the case of zero angular deviations ($\delta x'=\delta y'=0$). The remaining cases are presented in the other panels of Fig. 6. The overall results can be summarized as follows: an injection efficiency above 97 % is maintained provided that the simultaneous mismatch at the injection point does not exceed approximately 2–3 mm in position and 1 mrad in angle in both the horizontal and vertical planes. These tolerances were determined for the injection of 22 beamlets, each with transverse emittances $\varepsilon_x = \varepsilon_y = 4$ mm·mrad (4 rms). These tolerances are expected to be achievable by implementing precise beam steering using two dedicated combined h/v steering magnets installed in the TK9 section of the transfer line. In addition, to ensure accurate control and monitoring of the beam parameters immediately upstream of the electrostatic septum (ES), two beam position monitors (BPMs) should be installed in the TK9 line.

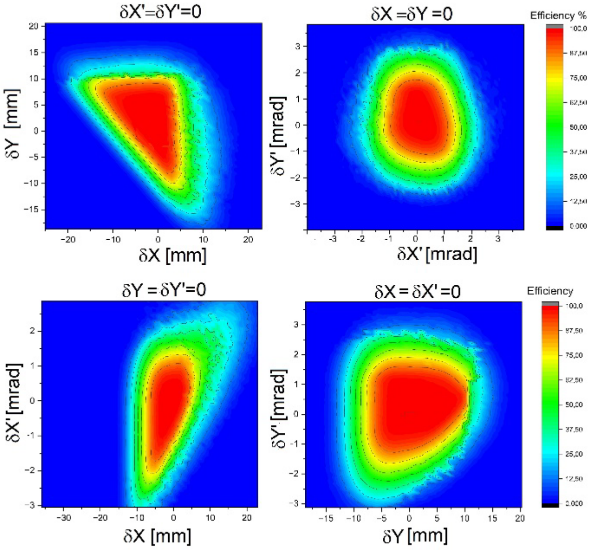

Figure 6: Injection efficiency map versus horizontal and vertical orbit mismatch at the SIS18 injection point.

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