MODELING OF MULTITURN INJECTION AT SIS-18 FOR A TRAIN OF UNILAC MICROBUNCHES

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Abstract

Multiturn Injection is an essential tool for achieving high beam intensities in synchrotrons. At SIS-18, a significant increase in the intensity of the uranium beam is foreseen, by several orders of magnitude, up to 1.5×10^{15} ions per injection cycle, prior to acceleration and extraction to SIS-100. Under these conditions, any beam losses during injection become critical, both in terms of beam lifetime and the risk of damaging injection system components, in particular the electrostatic septum. Usually, the optimization of the multiturn injection is carried out considering only the process of injecting one transverse slice of UNILAC macroparticles per turn. We present here a three-dimensional modeling of the injection process, which takes into account the longitudinal structure of the injected beam, namely the train of microbunches, and evaluates differences from previous approaches.

ONE- AND TWO-PLANE MULTITURN INJECTION

In this study, we focus on the well implemented process of multiturn injection in one transverse plane, which has been subject of extensive research in the past [1–3], as well as the process of two-plane multiturn injection, which optimizes the painting of the phase space in both transverse planes and is subject of recent studies [4, 5]. In both cases, the transverse trajectory of the closed orbit center is excited via four steerer magnets, performing a local orbit bump, which enables collecting the beamlets injected outside of the electrostatic septum (ES). This accumulation process is also referred to as phase space painting.

Local Orbit Bump Decrease Functions

The bump amplitude is shaped by an initial maximum $u_{B,\max}$ and a decrease rate per turn, given by a decrease function f. For this work a linear decrease function f_1 is chosen for the one-plane MTI, based on the real bump decrease curve of the SIS18, and an exponential decrease function f_2 for the two-plane MTI, based on the current benchmark of two-plane multiturn injection studies at GSI [4], with $f_1 = u_B(i_t) = u_{B,\max}(1 - \frac{i_t - 1}{j})$, with u being the generalized transverse coordinate standing for x or y correspondingly, i_t the turn number and j being the number of turns until the orbit has decreased back to zero amplitude. For the purpose of this work we set j to the number of injection turns i_{inj}. For the two-plane MTI the decrease function is $f_2 = u_B(i_t) = b_u + (u_{B,\max} - b_u)\frac{1-e^{\tau_u(N_u - i_t)}}{1-e^{\tau_u N_u}}$ with b_u the plateau value the function approaches after N_u turns and τ_u is the exponential decay coefficient defining the shape and steepness of the curve.

Simulation Prerequisites

The injection coordinates of the bunches are set by $X'(s_{\text{inj}}) = X(s_{\text{inj}})[-\alpha_x(s_{\text{inj}})/\beta_x(s_{\text{inj}})]$, where $\alpha(s_{\text{inj}})$ and $\beta(s_{\text{inj}})$ are the Twiss parameters at the longitudinal injection location s_{inj}. For the purpose of this work we implemented a one-plane MTI simulation code in Fortran 2018, utilizing the MICROMAP library for beam initialization and tracking. The SIS18 lattice was used as a representative synchrotron lattice. The code initializes a beamlet at the longitudinal injection point at each turn and performs the corresponding local orbit bump. The particle coordinates are tracked throughout the injection process. Losses are checked at every calculation step, also for $i_t > i_{\text{inj}}$ to check for after-injection losses with $i_{t,\text{1P}} = 100$ and $i_{t,\text{2P}} = 30$. The fixed simulation settings are shown in Table 1. Simulations are performed for two different tune sets “Q1” (Qx=4.238, Qy=3.422) and “Q2” (Qx=4.290, Qy=3.290).

Table 1: Shared simulation settings for multiturn injection in this work for SIS18-lattice with U^{238}_{28+} ions. *)$\Delta p/p$ value is scaled by a Gaussian random value, range [-1, 1].

Parameter	Value	Unit	Description
N_p	100	[1]	Particles per beamlet
i_{inj}	22	[1]	injected beamlets
ϵ_x (injection)	6	[mm-mrad]	Emittance, x-plane
ϵ_y (injection)	6	[mm-mrad]	Emittance, y-plane
Distribution	Gauss(3σ)	[-]	Beam-Distribution
$\Delta p/p*$	$2.5 \cdot 10^{-3}$	[-]	Momentum Spread
E_{nuc}	11.4	[MeV/u]	Energy per nucleon
$\alpha_x(s_{Septum})$	-1.3862	[rad]	Twiss α, x-plane
$\beta_x(s_{Septum})$	14.919	[m]	Twiss β, x-plane
For 2-Plane MTI:			
θ	45	[deg]	Septum tilt angle
$\alpha_y(s_{Septum})$	-0.66484	[rad]	Twiss α, y-plane
$\beta_y(s_{Septum})$	10.517	[m]	Twiss β, y-plane

MODELING OF MICROBUNCH TRAIN

In regular MTI simulations, the injected particle bunches are often modeled as a single beam slice per turn, where a number N_p of particles is distributed transversely over the phase space area of the slice, in the exact same longitudinal position s. In this work, we want to model the longitudinal extension of the beamlets as a train of beam slices, in the following also referred to as “bunches” that are injected with a certain time delay Δt after one another. The ratio $\Delta t/t_{rev}$ corresponds to $i_s/i_{s,max}$, with i_s being the number of calculation steps between injections and $i_{s,max}$ the maximum number of calculation steps within one turn and t_{rev} the revolution time of a particle at injection energy.

Injection Efficiency

For the purpose of this work, the injection efficiency η is defined as the ratio of the number of particles which survive until the end of the simulation $N_{p,\text{end}}$ and the number of particles that were set to be injected in total, respectively the number of particles $N_{p,\text{inj}}$ initialized throughout the simulation: $\eta = \frac{N_{p,\text{end}}}{N_{p,\text{inj}}}$.

Equidistant vs. Fixed-Distance Bunch Injection

The model shown in this work contains two approaches of injecting a number i_b of bunches longitudinally across the length of the accelerator within one revolution: Equidistant injection (EQ) of i_b bunches per turn, and injection of i_b bunches per turn with a fixed distance (FX) of i_s calculation steps. Figure 1 shows a schematic view of both models. In the EQ model i_s is calculated by $i_s = \text{int}(i_{s,max}/i_b)$. In the FX model i_s is a direct input for the code. Bunches are initialized every i_sth step as long as the number of bunches within one turn does not exceed i_b. The bunch frequency at the end of the transfer channel of the UNILAC is $f = 36.136\,\text{MHz}$ [6]. With $T = 1/f \approx 27.8\,\text{ns}$. The distance Δs is equal to vT, with v being the velocity $v = \beta c$. Taking into account a relativistic β of 0.156, which corresponds to the injection energy of 11.4 MeV we get $\Delta s \approx 1.3\,\text{m}$. The length l_s of SIS-18 is 216.72 m, thus Δs is $\approx 1/167$ of the complete accelerator circumference. The local orbit bump will be updated at every calculation step. A larger number of calculation steps leads to a smoother bump curve, but also increases the computation time. To find a trade-off between precision and calculation time while keeping the condition of $i_{s,max}$ being an integer multiple of $l_s/\Delta s$, a total number of 336 calculation steps per turn is chosen, injecting bunches at every second step as an equivalent of an injection every $\Delta t = \Delta s/v_p$ with v_p being the velocity of the particles. This leads to a minimum distance between bunch centers of $\approx 1.29\,\text{m}$. Whilst the bunches are injected, the bumper flank is updated at every calculation step, decreasing slightly, leaving all bunches with a slightly different oscillation amplitude around the corresponding center of the closed orbit.

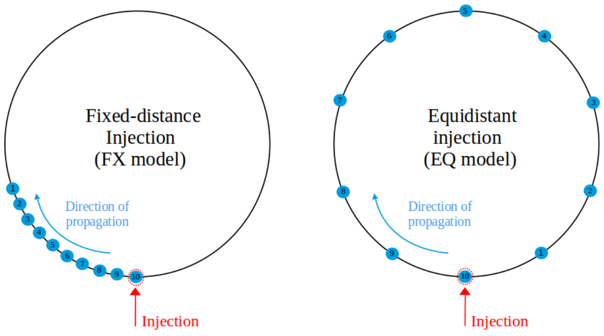

Figure 1: Schematic comparison of fixed-distance injection and equidistant injection for an example number of 10 beam bunches.

RESULTS AND DISCUSSION

This work evaluates a total of 16 simulation runs with different parameter settings. Table 2 summarizes the results, showing the efficiency for single-bunch injection ($i_b = 1$), the maximum achieved efficiency η_{max} with the corresponding number of injected bunches, as well as the gain in efficiency relative to the single-bunch case. The results are visualized in Fig. 2 for the one-plane MTI and in Fig. 3 for the two-plane MTI. Each plot shows the injection efficiency η as a function of the number of injected bunches i_b for the two bunch distribution schemes (FX and EQ), with and without momentum spread ($\Delta p/p$), as defined in Table 1.

Table 2: Simulation results with the highest efficiencies η simulated, displaying the maximum efficiency η_{max} for all simulation models (1P/2P:1-plane/2-plane, FX/EQ: fixed-distance/equidistant injection, tunes(Qx/Qy): Q1(4.238/3.422),Q2(3.290/4.290), and the corresponding bunch numbers with (d1) and without (d0) $\Delta p/p$ and the maximum gain in efficiency in percentage points).

Model	$\eta_{(i_b=1)}$[%] (d0 | d1)	η_{max}[%] (d0 | d1)	i_b**[1]** (d0 | d1)	$\Delta\eta_{max}$ [pt.] (d0 | d1)
1PEQQ1	59.59 | 57.73	60.67 | 58.71	5 | 3	1.08|0.98
1PFXQ1	59.59 | 57.73	60.08 | 58.55	167 | 2	1.41|2.08
1PEQQ2	65.32 | 59.68	66.73 | 61.76	18 | 57	0.99|0.82
1PFXQ2	65.32 | 59.68	66.33 | 61.45	168 | 168	1.01|1.76
2PEQQ1	82.23 | 79.32	82.75 | 80.94	85 | 3	0.52|1.62
2PFXQ1	82.23 | 79.32	82.72 | 80.63	90 | 4	0.64|1.71
2PEQQ2	74.68 | 73.14	75.32 | 74.85	85 | 3	0.54|1.31
2PFXQ2	74.27 | 72.86	75.19 | 74.38	90 | 4	0.92|1.51

The results show that the efficiency is generally lower for simulations with momentum spread, which can be attributed to chromaticity and dispersion effects, which increase the effective emittance of the bunches and lead to enhanced particle losses at the ES, which acts as a collimator in this setup. For the one-plane MTI, it can be observed in Fig. 2 that the efficiencies of the FX and EQ models are identical for $i_b = 1$ and $i_b = i_{b,\text{max}} = 168$. In these cases, the bunches occupy identical positions in the ring for both injection schemes. For intermediate values $1 < i_b < i_{b,\text{max}}$, the FX model consistently produces lower efficiencies than the EQ model for both sets of tunes. Tune set Q2 that has equal fractional tunes ($q_x = q_y = 0.29$), which corresponds to an operational working point in SIS18, shows higher efficiencies for the one-plane MTI compared to the tune set with identical fractional tunes (see Fig. 2). For the Two-Plane MTI simulated in this work, the FX model has a higher gain in efficiency for $i_b > 1$ compared to $i_b = 1$ for tune Q1, but the maximum efficiency is lower than for tune set Q2, which has different fractional tunes in x and y. Although only the final efficiency is evaluated, the underlying behavior is governed by the phase advance sequence $\mu_{x/y}(i) = i \cdot 2\pi q_{x/y}/i_b$ during the injection process, with i being the number of injections and q the fractional tune.

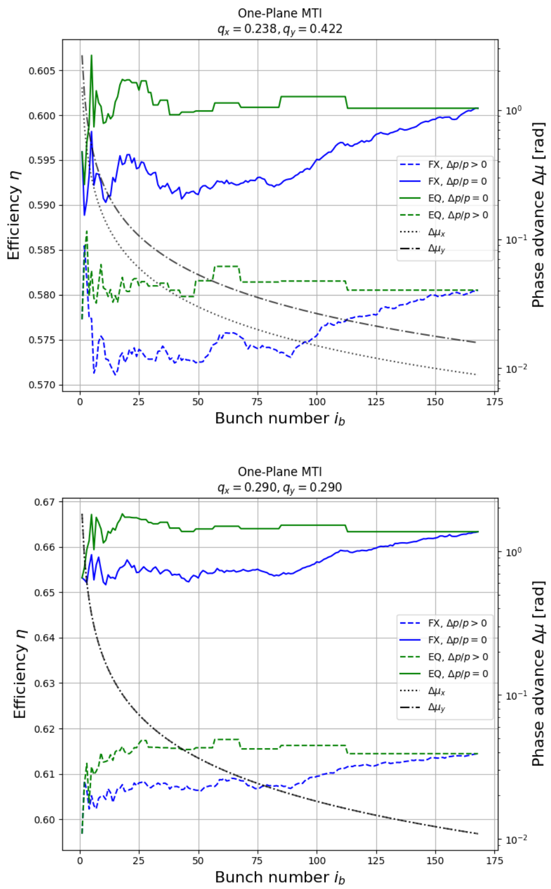

Figure 2: Comparison of FX- and EQ-bunch models with 1-plane-MTI for two different tune sets: Injection efficiency η vs. number of bunches i_b with and without $\Delta p/p$. The black lines show the phase advance between injections.

For all tune sets, the FX model is generally less efficient than the EQ model. This difference is more pronounced for the one-plane MTI but remains visible in the two-plane results shown in Fig. 3. In all figures, the efficiency curves for the EQ model exhibit a plateau at larger values of i_b. This behavior is caused by the discretization of the injection scheme due to the finite step size of the simulation. Within certain ranges of i_b, the number of simulation steps between successive injections remains constant, resulting in a fixed $\Delta s_{\mathrm{min}} = 1.29$ m. This limits the resolution of the curves and can be improved by increasing the number of calculation steps, at the cost of additional computation time. It should be noted that the number of particles per injected bunch (N_p) is kept constant across all simulations. As a result, simulations with larger i_b involve a higher total number of tracked particles. Consequently, the same absolute number of particle losses corresponds to a larger relative loss in simulations with smaller i_b compared to those with larger i_b.

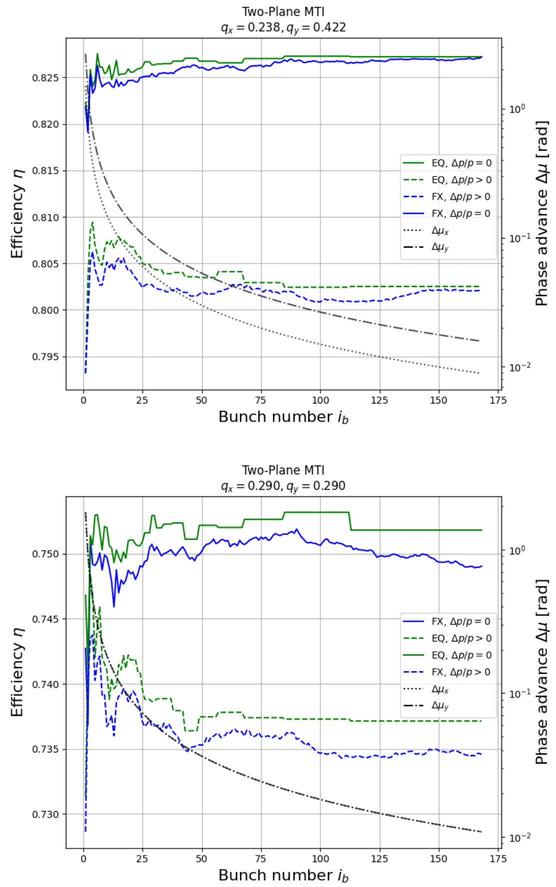

Figure 3: Comparison of FX- and EQ-bunch models with 2-plane-MTI for two different tune sets: Injection efficiency η vs. number of bunches i_b with and without $\Delta p/p$. The black lines show the phase advance between injections.

OUTLOOK

A beneficial extension of this work will be the inclusion of transverse and longitudinal space charge effects as well as a tune scan for optimal efficiency.

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