SIS18 Injection: Parameter studies on MTI with space charge and longitudinal aspects

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Outline

- Introduction to the injection process into the SIS18 (specific aspects)

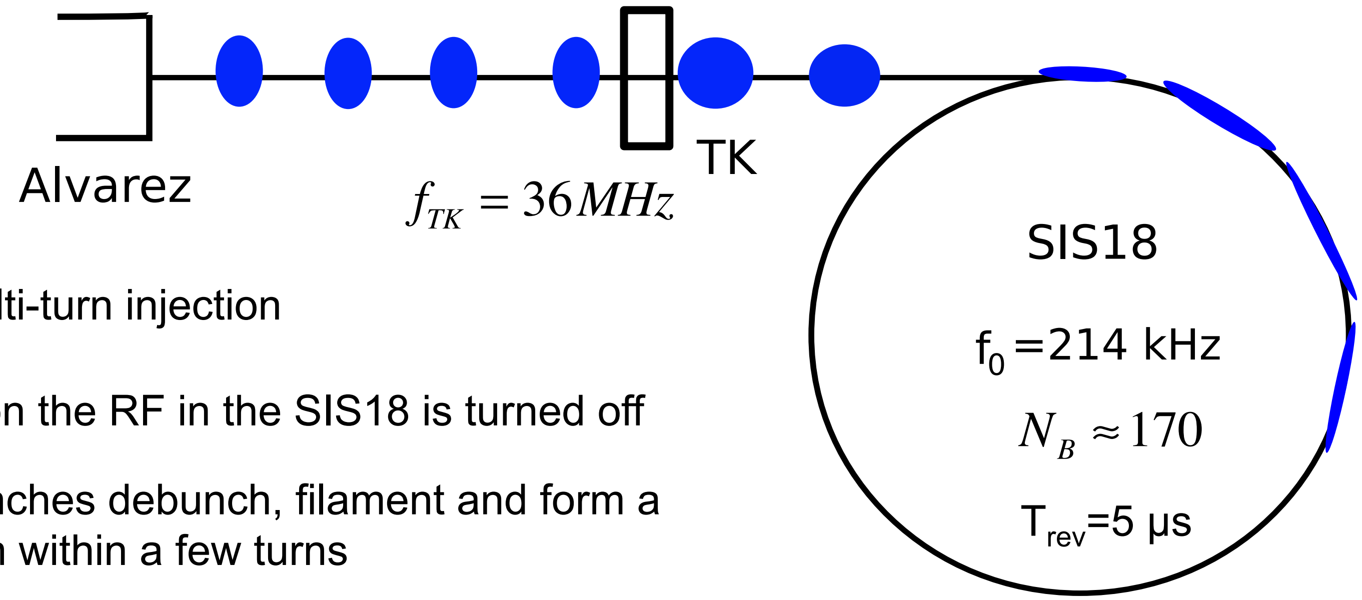
- Longitudinal aspects

- Multi-turn injection model and parameter studies
    - UNILAC emittance, horizontal tune and effect of space charge

- Summary and Outlook

Overview injection into SIS18

- We assume that the longitudinal and transverse planes are decoupled



- Horizontal multi-turn injection

- During injection the RF in the SIS18 is turned off

- The micro-bunches debunch, filament and form a coasting beam within a few turns

- Final full momentum spread after injection should be within the rf bucket area

$\Delta p / p \leq 10^{-3}$ (equivalent parabolic distribution)

- Transverse beam size (4 rms physical emittance) should be within the machine acceptance

$\epsilon_x = 150$ mm mrad $\epsilon_y = 50$ mm mrad (equivalent K-V distribution)

Longitudinal beam quality
Debunching of the micro-bunches

- Debunching in the SIS18:

- The space charge energy of the micro-bunches is transformed into incoherent thermal momentum spread

$$\Delta_f = \sqrt{\Delta_i^2 + \frac{2K_L}{\eta^2 z_{m,i}}}$$

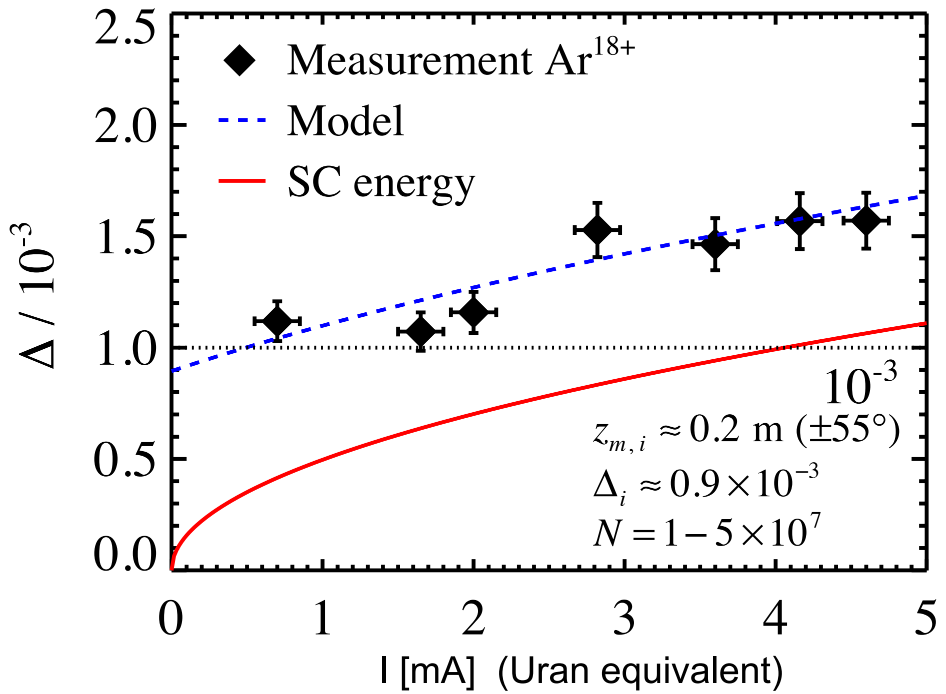
- Longitudinal perveance $K_L \sim gNZ^2 / A$

- The geometry factor describes the influence of the transversal beam distribution on the longitudinal motion $g = 1 + 2\ln\frac{b}{a}$

- See for more information:
S. Appel, O. Boine-Frankenheim, Phys. Rev. ST Accel. Beams 15, 054201 (2012)

Longitudinal beam quality
Debunching of the micro-bunches

- Measured momentum spread in SIS18 after injection (dc beam)



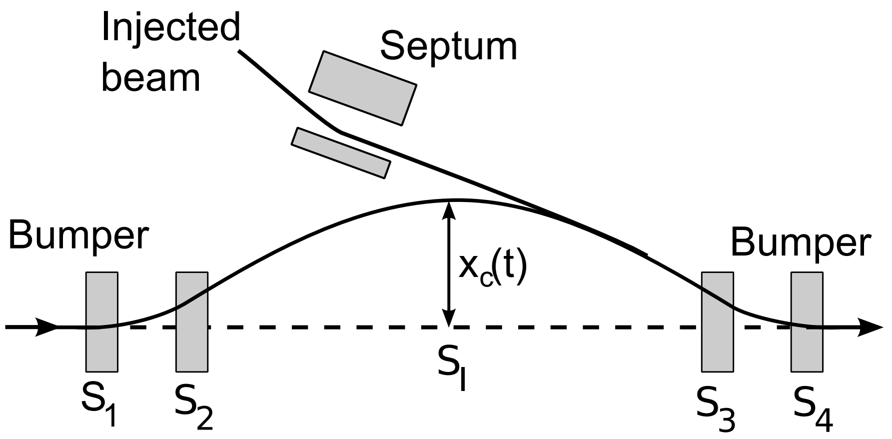
$$\Delta_f = \sqrt{\Delta_i^2 + \frac{2K_L}{\eta^2 z_{m,i}}}$$

Minimum momentum spread given by SC

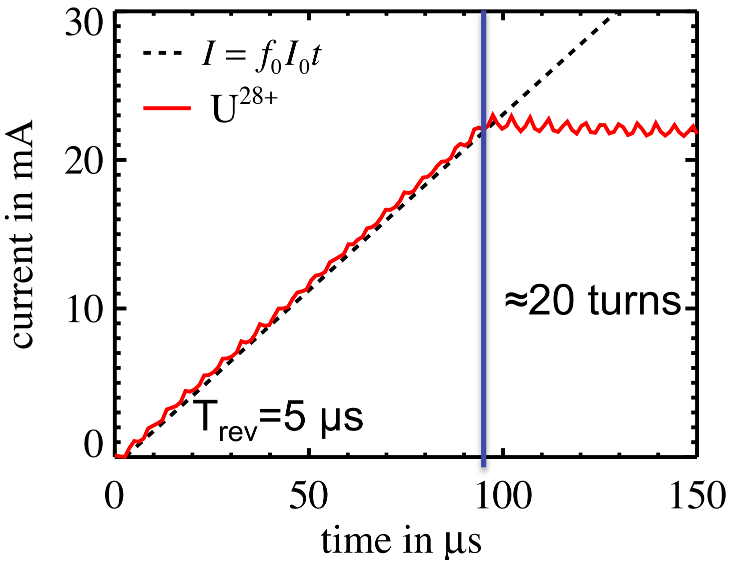
- Since the SC effect depends on the initial micro-bunches length, the micro-bunches are stretched in the TK (further optimization might be possible)

- Space charge and the initial momentum spread from UNILAC are the main sources of the momentum spread in SIS18!

Horizontal multi-turn injection into SIS18

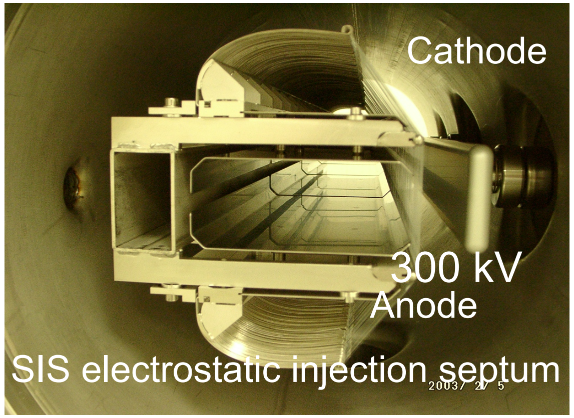


Measured MTI performance in SIS18 (low intensities)



- Beams are stacked until machine acceptance is reached

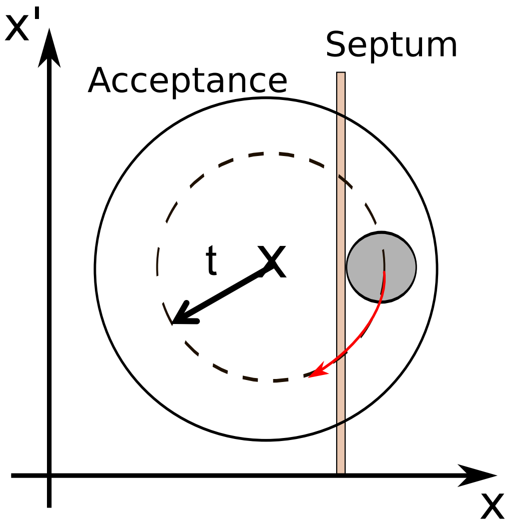
- Loss should be as low as possible (activation, damage, vacuum)



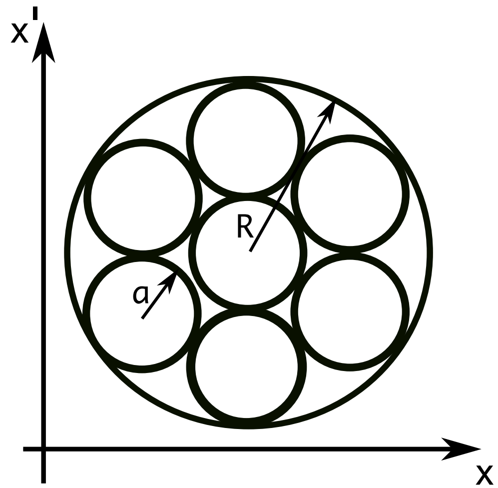
For U^{28+} : N~10^{11} in $\epsilon_x \approx 150$ mm mrad within 30% loss

Multi-turn injection
Model and quality parameters

- To achieve high intensity the beams should be packed as compact as possible



End of injection
(optimal)



- Loss of particles at the septum due to the betatron oscillation, if the orbit is not reduced fast enough

- Loss maxima $Q_X n = \text{integer}$

- Quality:

  - Intensity $N = n_s N_0$ n_s: Effectively stacked turns (multiplication factor)

  - Loss $\eta = \frac{n - n_s}{n}$ n: Injected turns

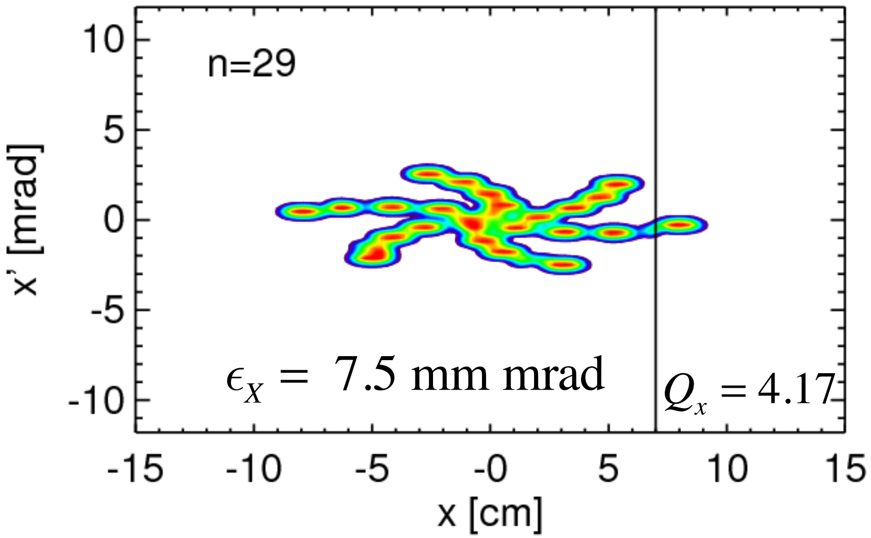
- MTI model implemented in the tracking codes PATRIC (GSI) and pyORBIT (Oak Ride Lab.)

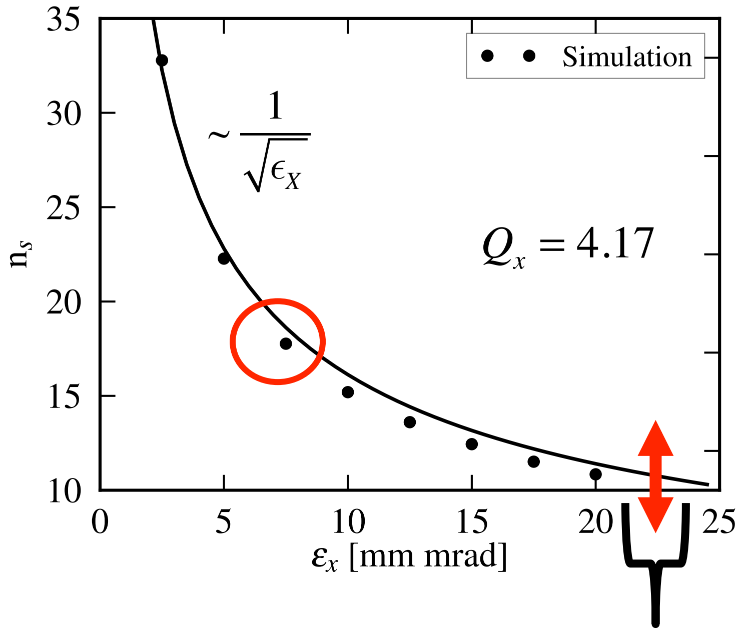
- Both codes include a 2D space charge solver

MTI: Emittance and tune dependency
Simulation results

- Animation of MTI (Horizontal phase space)

- Acceptance limitation due to septum
- No optimization for loss





- Arm formation given by fractional tune

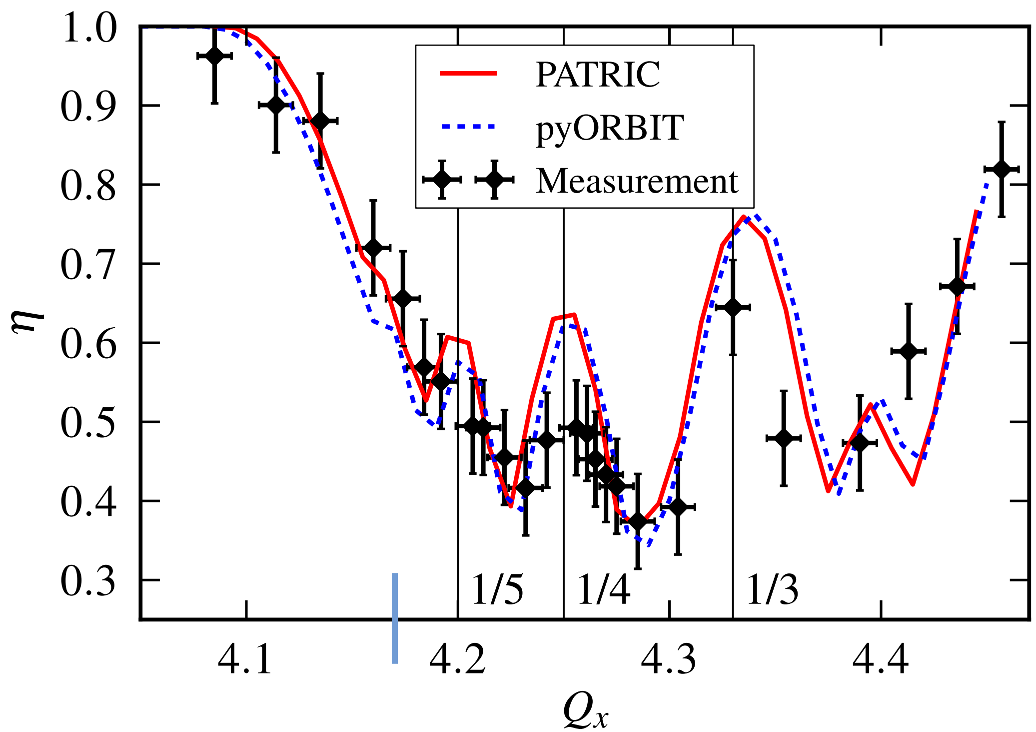
$$m \sim Q_f^{-1}, \text{ if } 0 < Q_f \leq 0.5$$

- Orbit bump reduction
- Horizontal tune
- Position of beam center

- MTI efficiency depends very strongly on the initial emittance and fractional tune!

MTI simulation studies

Comparison between experiment and simulations (low intensity)



- Measurement results provided by Y. El-Hayek, GSI

- No space charge effects

- In the simulation the same parameters were used for the bump reduction and the measured emittance as in the experiment

- In this measurements the loss for Q_x=4.17 is larger as generally (optimization possible)

- The loss maxima are located at the same fractional tunes $Q_X n = \text{integer}$

- Measurements and simulations are in good agreement for the first time for the SIS18 injection

MTI simulation studies
Space charge effects for FAIR design intensities

- Space charge affects the betratron motion of the individual particles

- Therefore also the injection efficiency

- With space charge the maxima of the efficiency are shifted

$$(Q_x + |\Delta Q_{sc}|)n = integer$$

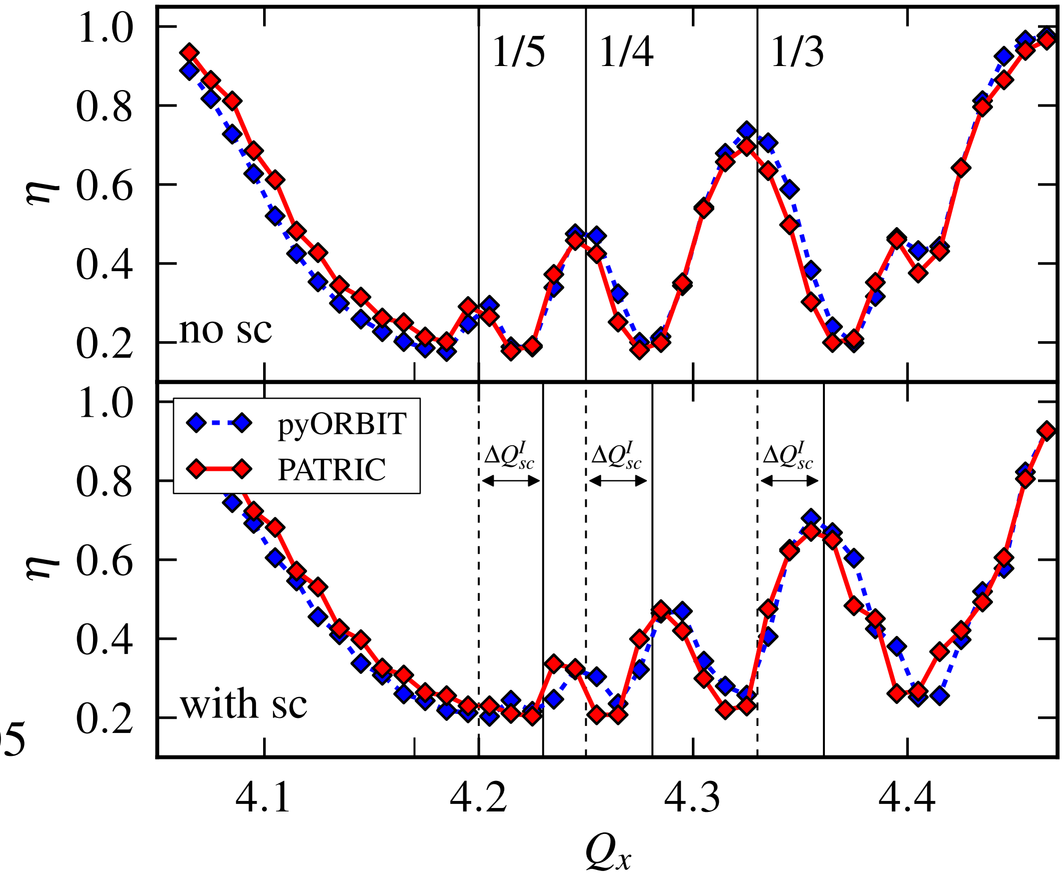
- Space charge tune shift

$$\Delta Q_x^{sc} = -\frac{r_p}{\pi}\frac{Z^2}{A}\frac{N}{\beta^2\gamma^3}\frac{g_f}{B_f}\frac{1}{\epsilon_x + \sqrt{\epsilon_x\epsilon_y}}$$

Changes during injection

- Mirco-bunch

$$\Delta Q_{x,y}^{sc} \approx -0.05$$



- In the most cases:

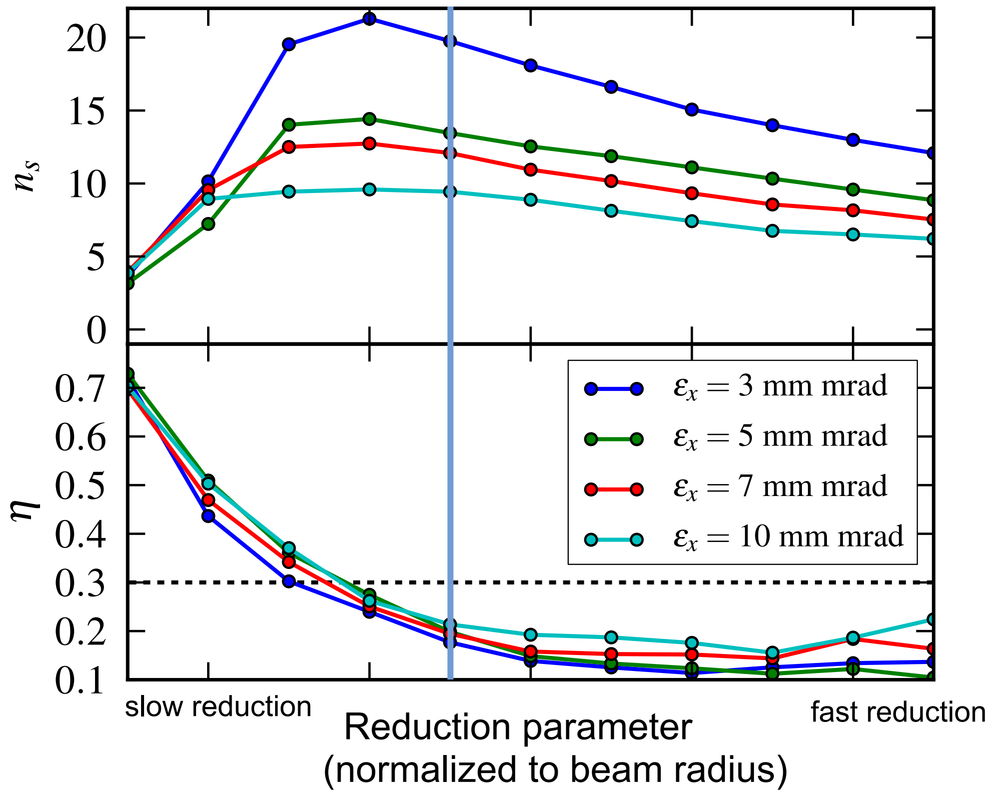
  The increase of intensity and emittance compensate each other and the shift is nearly the space charge shift of the micro-bunches

- For Q_x= 4.18 a beam loss minimum for low and high intensity beams exists (FAIR currents)

Optimization of intensity and loss (quality)

- Goal (After we found the optimum tune):
Find best compromise between compact packing and loss by varying the speed of bump reduction

- Simulation parameters: A_h = 150 mm mrad, Q_x= 4.17



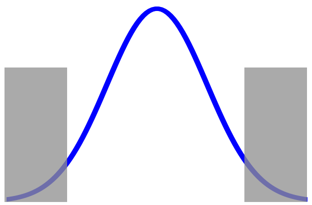
- Current and brilliance for the linac with 2×10^{11} U^{28+} particles stored in SIS18

$$N_{linac} = N_{SIS} / n_s$$

ϵ_x mm mrad	*I* mA	*t* µs	*B (norm.)* mA / (mm mrad)
3	10	140	3.3 (21)
5	15	80	3.0 (19)
7	16	75	2.3 (15)
10	20	60	2.0 (13)

Effect of collimation in the TK (before injection)

- Scraped-off beam edges of Gaussian distribution



- Note: Quality parameters includes the scraped-off particles

Intensity $n_s = \frac{N}{N_0}$ Loss $\eta = \frac{n - n_s}{n}$

- Non collimation (blue line):

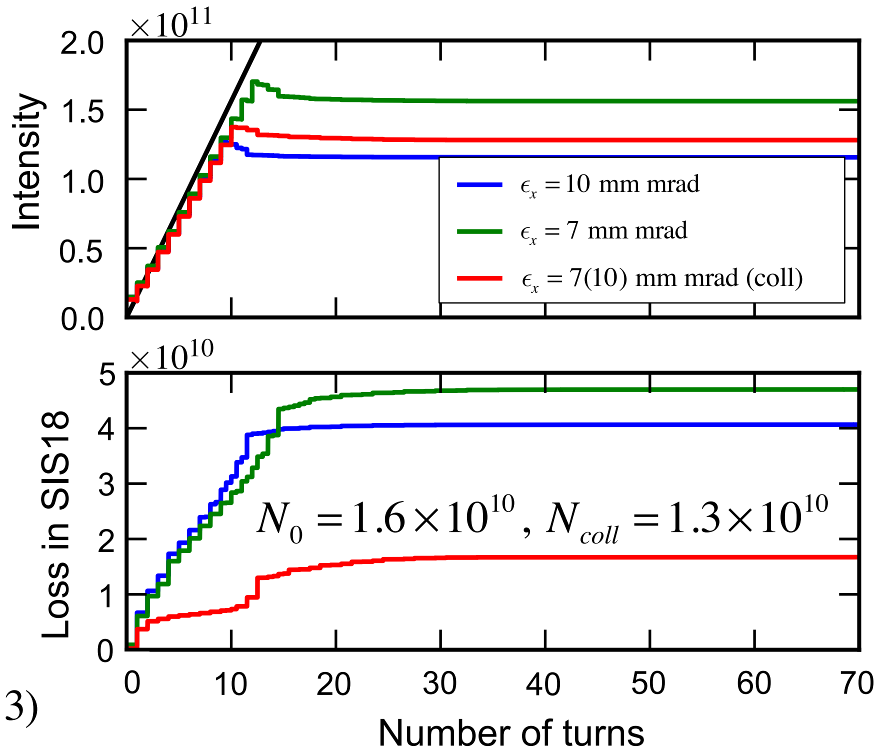
$\epsilon_x = 10$ mm mrad, $n_s = 7$, $\eta = 0.3$

- Collimated (red line):

$\epsilon_x = 7(10)$ mm mrad, $n_s = 7.6$, $\eta = 0.29$ $(\eta_{SIS18} = 0.13)$

- Loss in the SIS18 could be reduced
- Similar intensity could be injected

- Intensity is reduced by ~ 20% and emittance by ~ 30%



Summary and Outlook

Longitudinal:

- Space charge is one important source of the ‘initial’ momentum spread in SIS18!
- For high intensity beams the momentum spread could be larger than the rf bucket area
- Stretching of the micro-bunches in the TK could help (limited by the available bunchers)

Transverse:

- MTI quality (intensity + loss) depends very strongly on the initial emittance and hor. tune!
- Space charge leads to a tune shift of the beam loss maxima
- For Q_x= 4.18 a beam loss minimum for low and high intensity beams exists (FAIR currents)
- Current and brilliance required in order to achieve the FAIR parameters are be shown

Outlook:

- The MTI model and micro-bunch parameters (long. + trans.) from UNILAC with space charge must be verified accurately with measurements
- Dependence of the MTI efficiency on initial beam distribution should be studied more accurately
- Possible influence of skew quads on the MTI efficiency