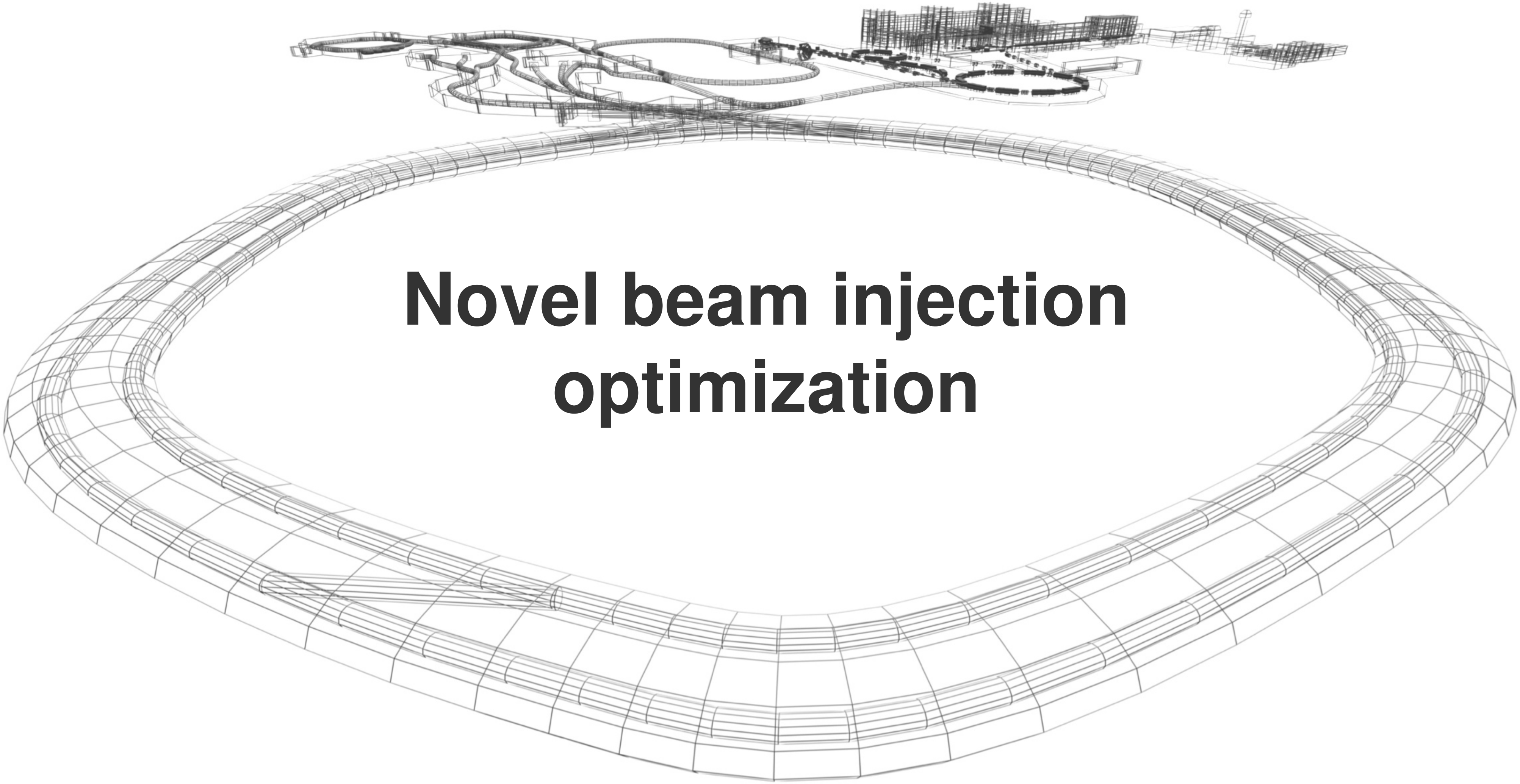
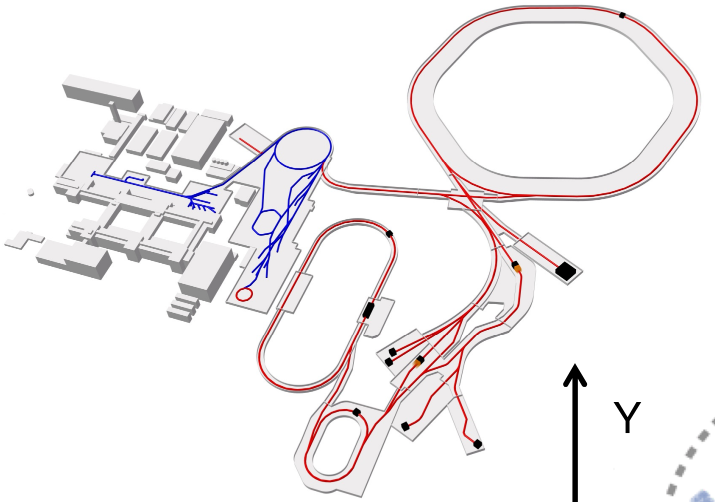


Novel beam injection optimization

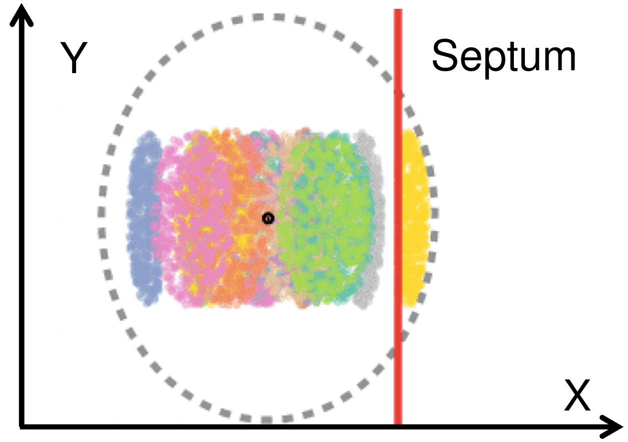
Dr. Sabrina Appel, Accelerator Physics Department, GSI, Darmstadt

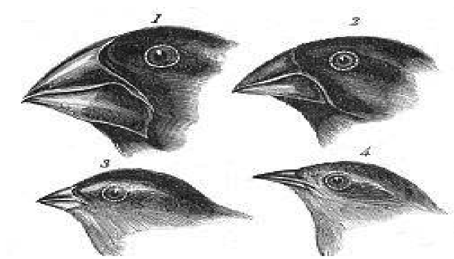
Outline

- **Multi-Turn Injection**
  - SIS18
  - Intensity limitation

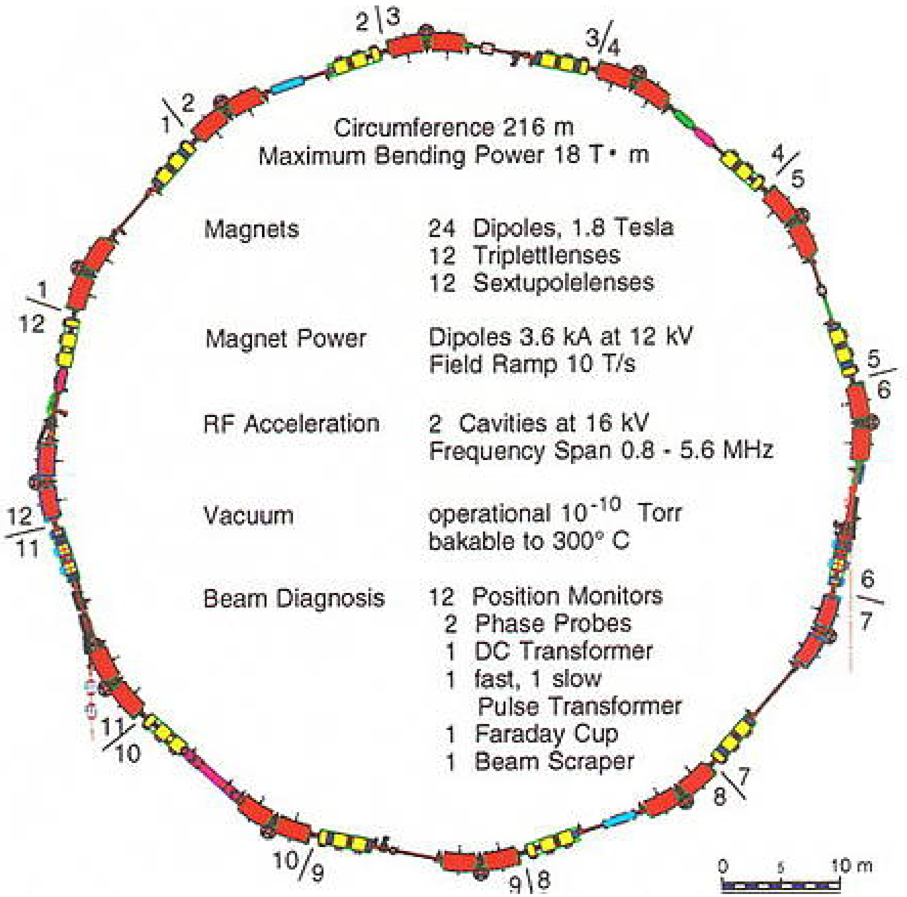


- **Optimization**
  - Algorithms
    - Genetic Algorithms
    - Particle swarm algorithms
  - Technical solution
    - EMTEX
    - Skew quadrupoles

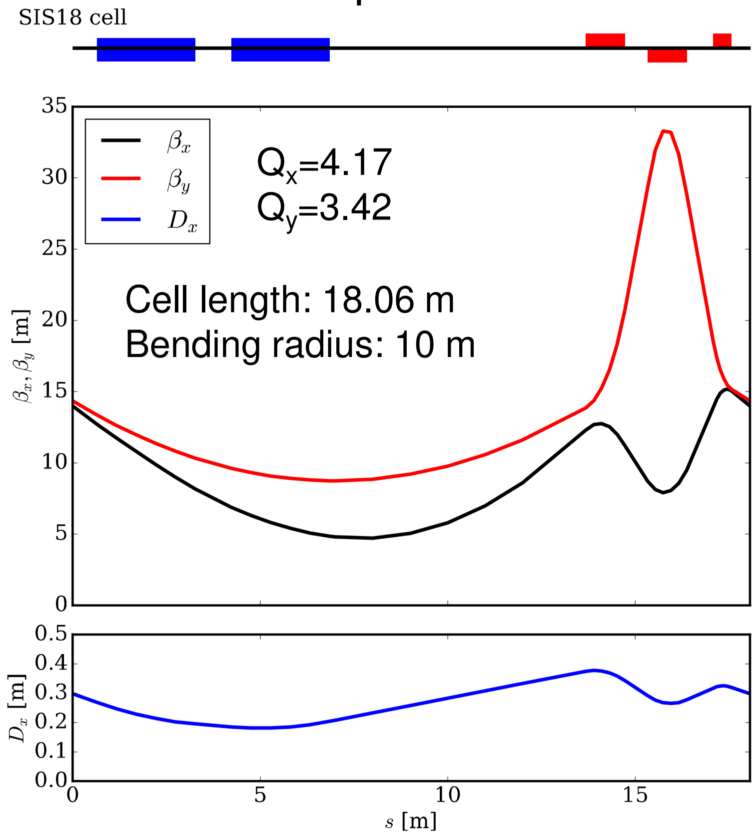




SIS18 (SchwerIonenSynrotron)



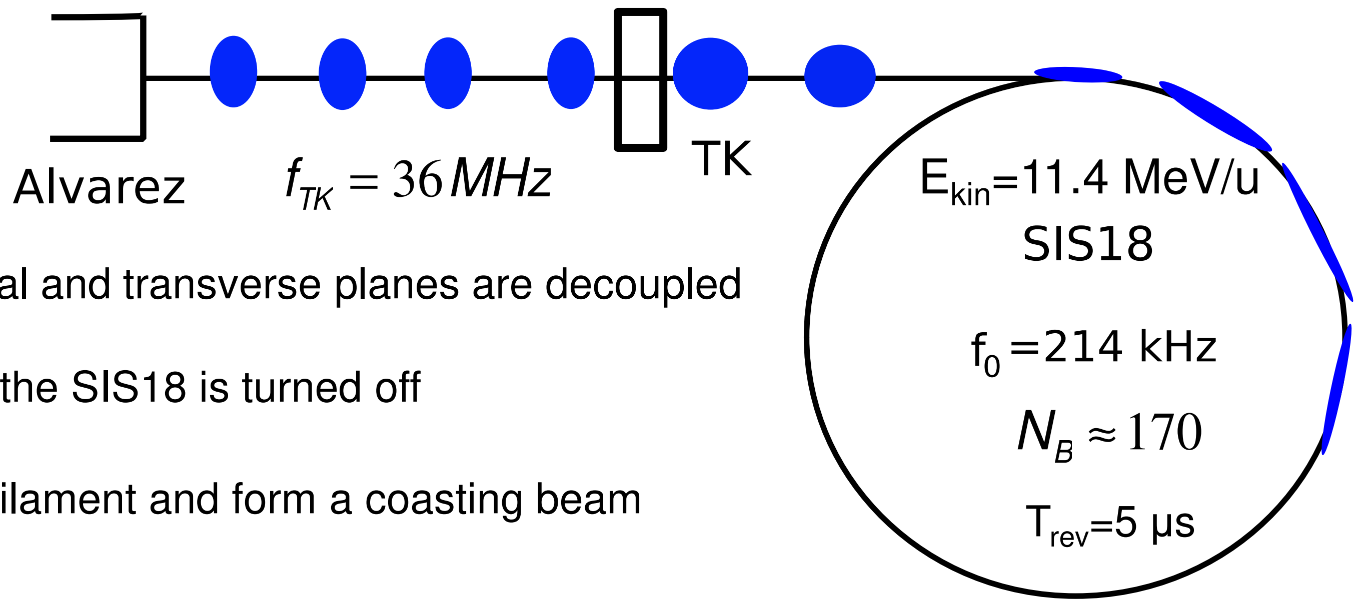
Triplet lattice



On the ramp a dynamic change-over from triplet to doublet focusing is foreseen

Doublet focusing→ less quad strength -> easier beam extraction and chromaticity correction

Overview injection into SIS18



We assume that the longitudinal and transverse planes are decoupled

During MTI 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

$$\Delta p / p \leq 10^{-3}$$

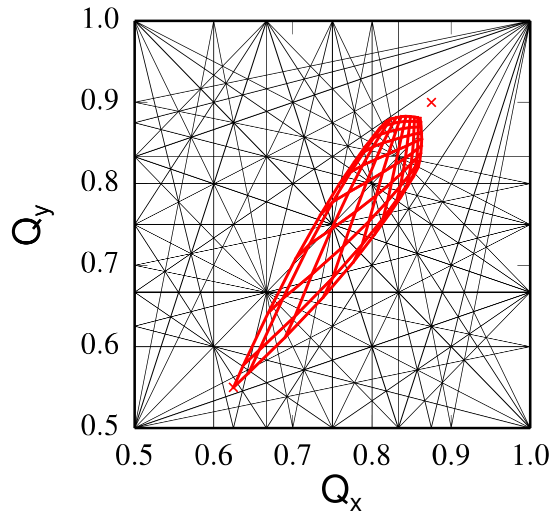
(equivalent parabolic distribution)

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

$$\epsilon_x = 150 \text{ mm mrad} \quad \epsilon_y = 50 \text{ mm mrad}$$

(equivalent K-V distribution)

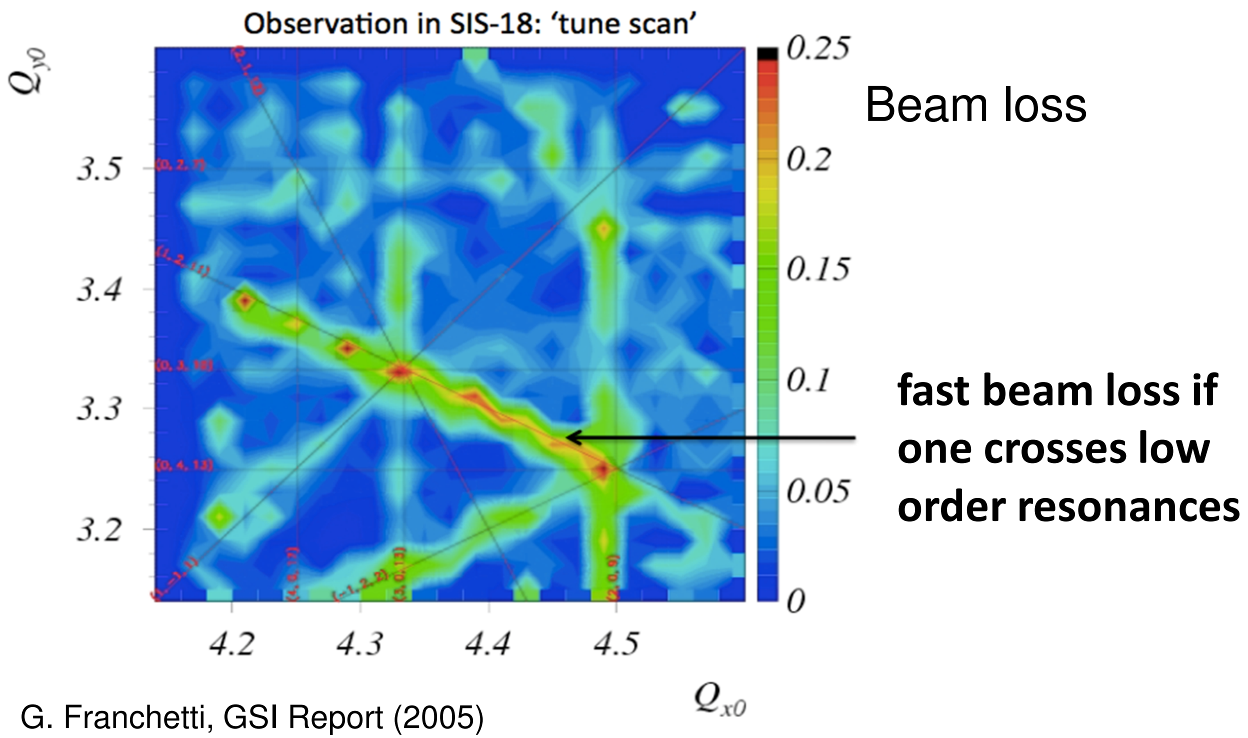
Intensity limit: Space charge



The (incoherent) transverse space charge force is the main intensity limiting effect in the FAIR synchrotrons

Tune shift: $\Delta Q_y^{sc} \propto -\frac{q^2}{m}\frac{N}{B_f}\frac{4}{\varepsilon\beta_0^2\gamma_0^3}$

Intensity limit: $|\Delta Q^{sc}| \lesssim 0.1-0.5$

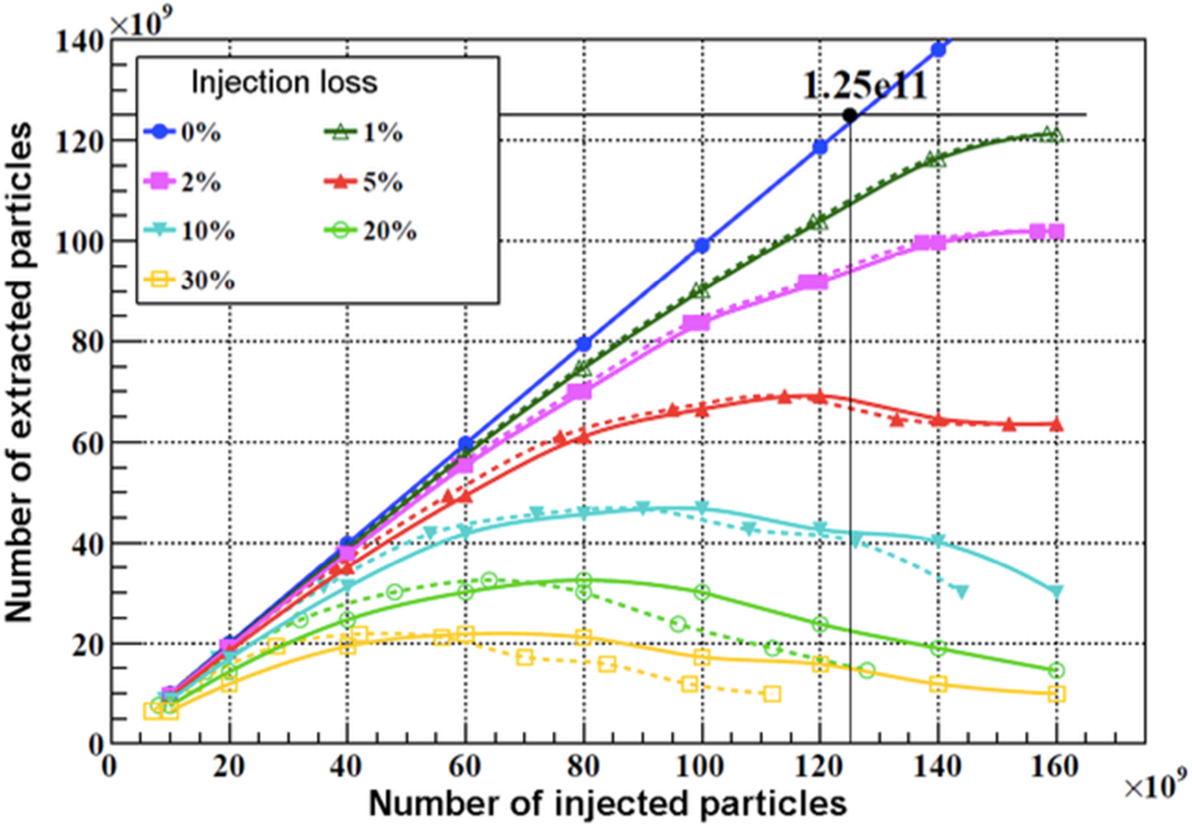


G. Franchetti, GSI Report (2005)

Intensity limit: Dynamic vacuum

For intermediate charge state ions, the loss-induced vacuum degradation is another important key intensity-limiting factor.

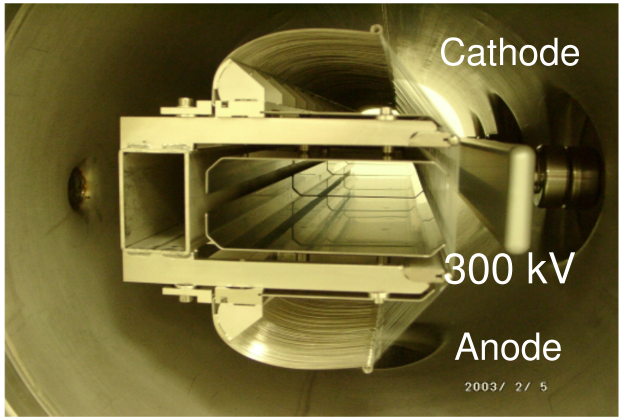
Results of STRAHLSIM simulations for the desired SIS18 booster operation with different (uncontrolled) initial beam loss.

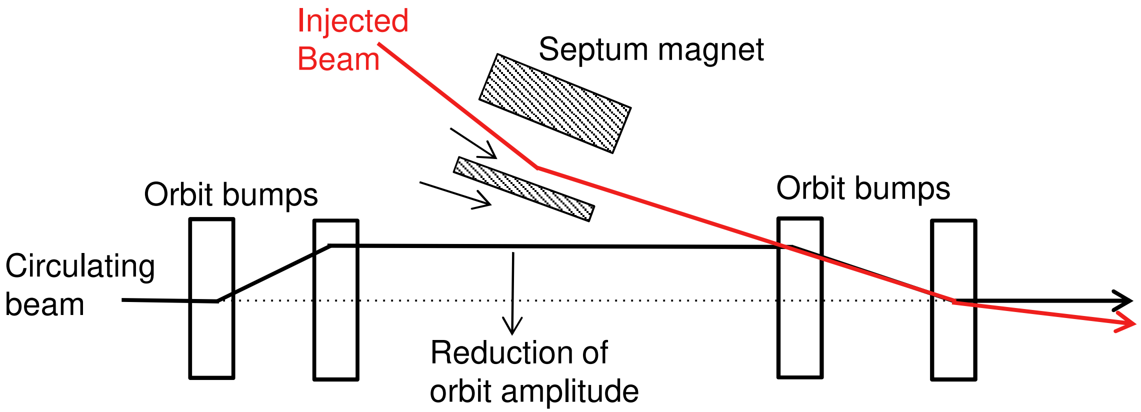


P. Spiller {SIS18} upgrade: Status, Present and Expected Performance Low Charge State Heavy Ion Beams. MAC, (2013)

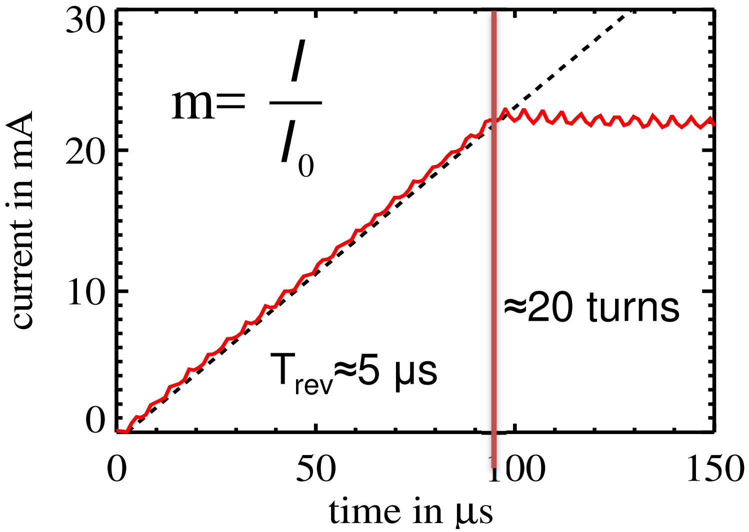
Multi-turn injection (MTI) into SIS18

SIS18 electrostatic injection septum





Measured MTI performance in SIS18



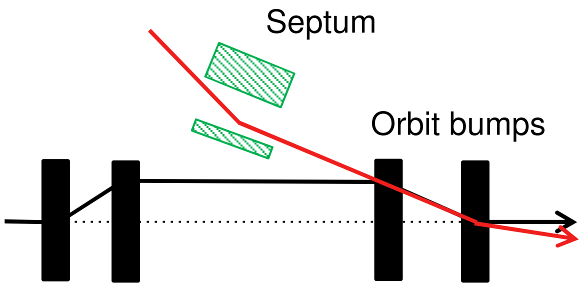
SIS18 flexibility in providing a broad range of ions allow only Liouvilian injection schemes

MTI has to respect Liouville's theorem: Injected beams only in free space

The beam from linac is injected until machine acceptance is reached and maximize intensity

Loss at septum and acceptance should be as low as possible due to loss induced dynamic vacuum

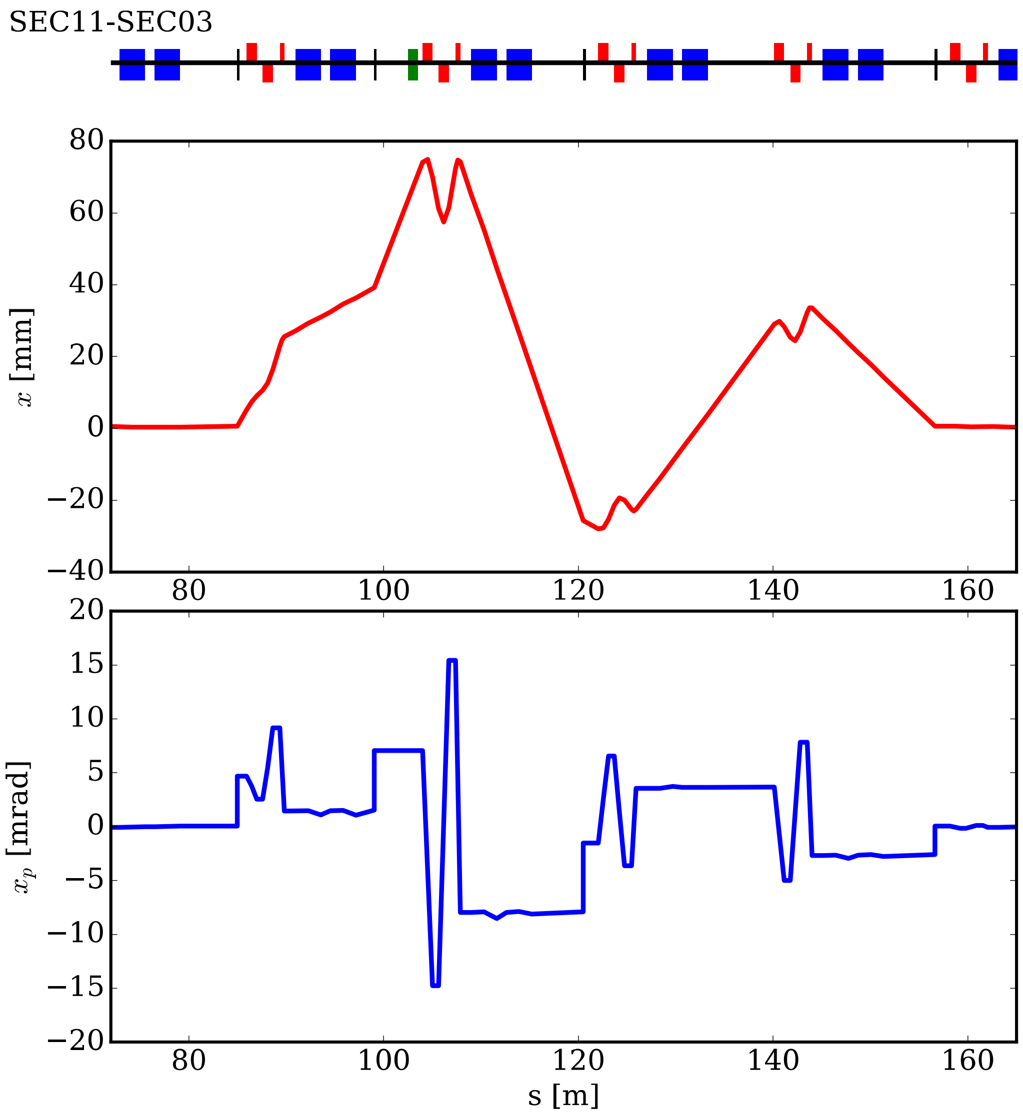
Overview injection into SIS18



No distortion outside injection region

Degrees of freedom position and angle of closed orbit at septum

An analytical solution is known
See: C.J. Gardner, Booster technical note no. 197, 1991



MTI into SIS18: Model

MTI has to respect Liouville's theorem:
Injected beams only in free space

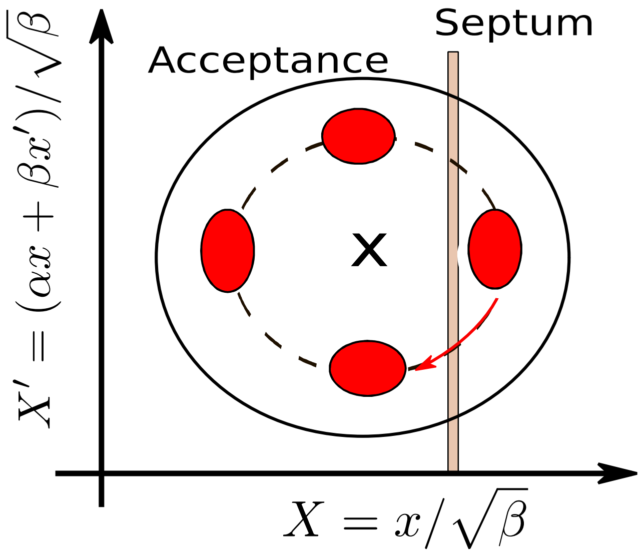
Loss of ions at the septum due to the betatron oscillation

Loss minimization at septum $Q_x \neq$ integer

Injected beam into upright ellipses $\frac{\alpha_0}{\beta_0} = -x'/x$

Mismatch of lattice function to adapt to ring curvature $\frac{\beta_0}{\beta_i} = (\frac{\epsilon}{\epsilon_i})^{\frac{1}{3}}$

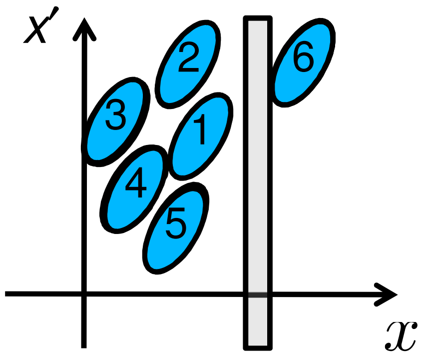
Linear orbit bump reduction $\Delta x = \frac{1}{4}(2a + d_c)$



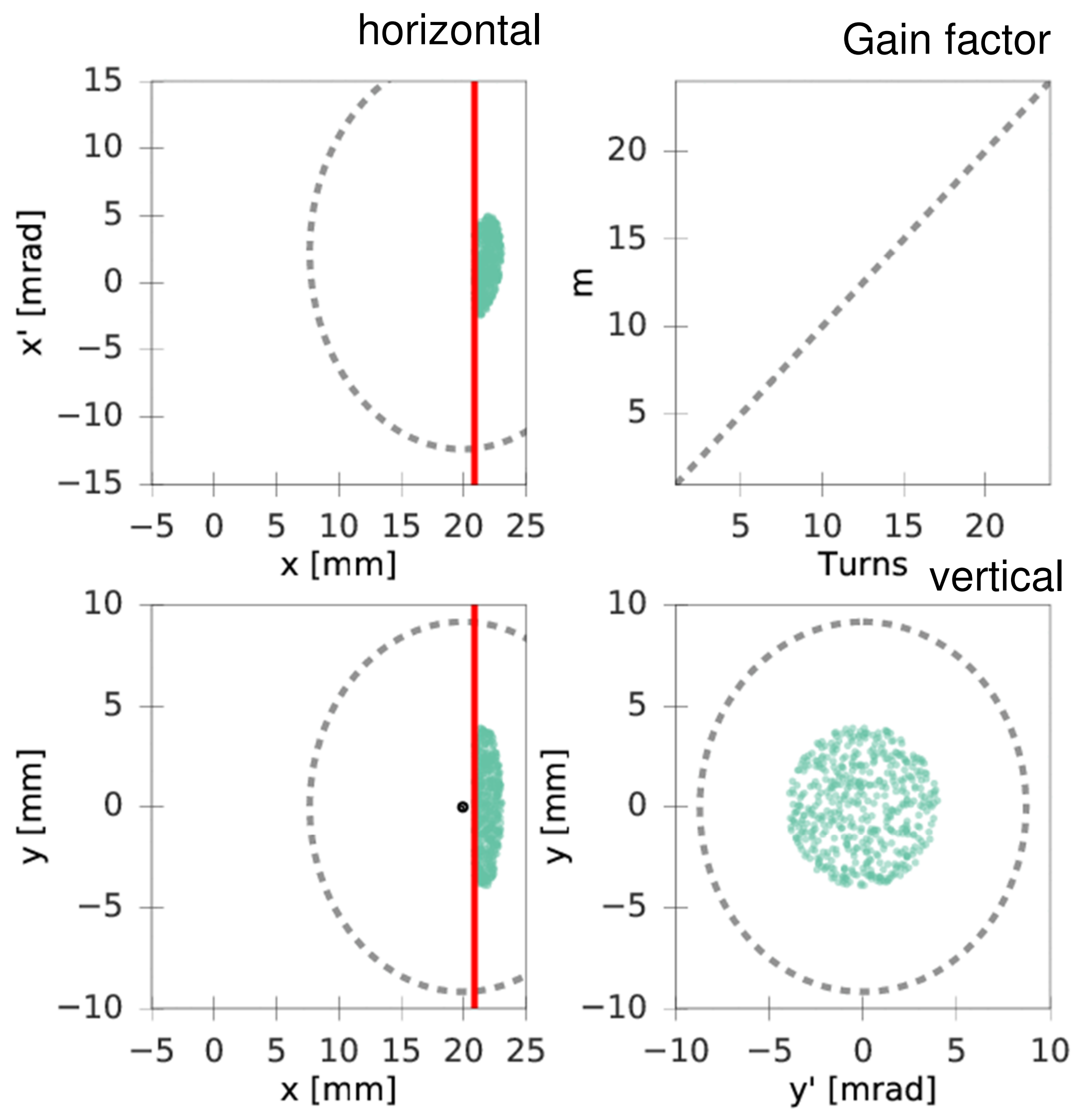
Imagined best optimum injection scheme has the smallest dilation and the lowest loss at the septum.

➔ Contradicting

Betatron oscillation and orbit bump reduction
➔ free phase space



Multi-turn injection into SIS: Movie



Acceptance

Septum

Normalized coordinates

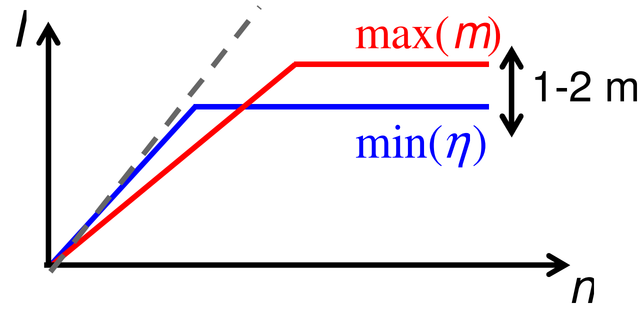
15 turns injection
with 15% loss

MTI into SIS18: Model

- **Multi-objectives:**
  - stacked current (maximize) $I = mI_0$
  - beam loss (minimize) $\eta = \frac{I_{loss}}{nI_0}$
  - emittance ε_x

output

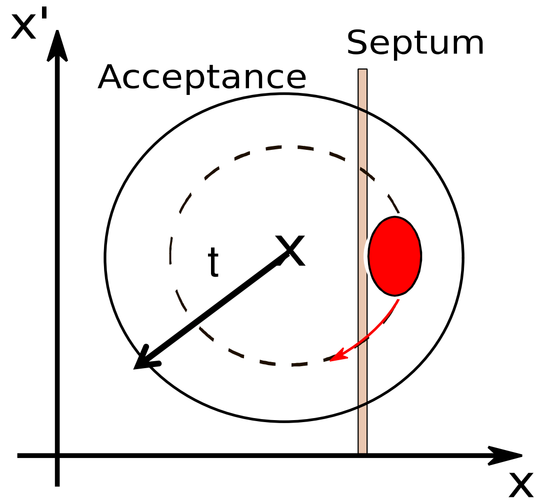
$m = (1-\eta)n$



- **Constraints:**
  - Position of septum x_s
  - Machine acceptance A
  - Closed orbit (bumper kick) $\phi_i(Q_x)$

Model in simulation code

- **Parameters:**
  - Position of incoming beam at septum x_c, x_c', M
  - Initial bump amplitude and its decreasing x_0, x_0', τ
  - Injected turns n
  - Horizontal tune Q_x
  - Horizontal emittance ε_x
  - Skew strengths k



Multi-turn injection into SIS: Optimization problem

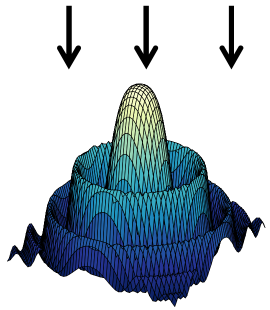
The analytically description characterize:
Incoming beam position and this mismatch

Loss minimization at septum: tune
Linear orbit bump reduction: tune + size

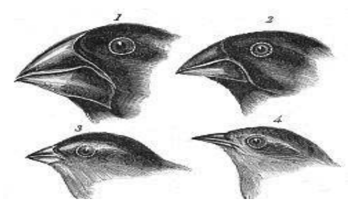
Unfortunately the MTI model is underrepresented:
A few variables can be choose freely from a value range

Discover by trial and error optimum settings or perform parameter scans

Scan

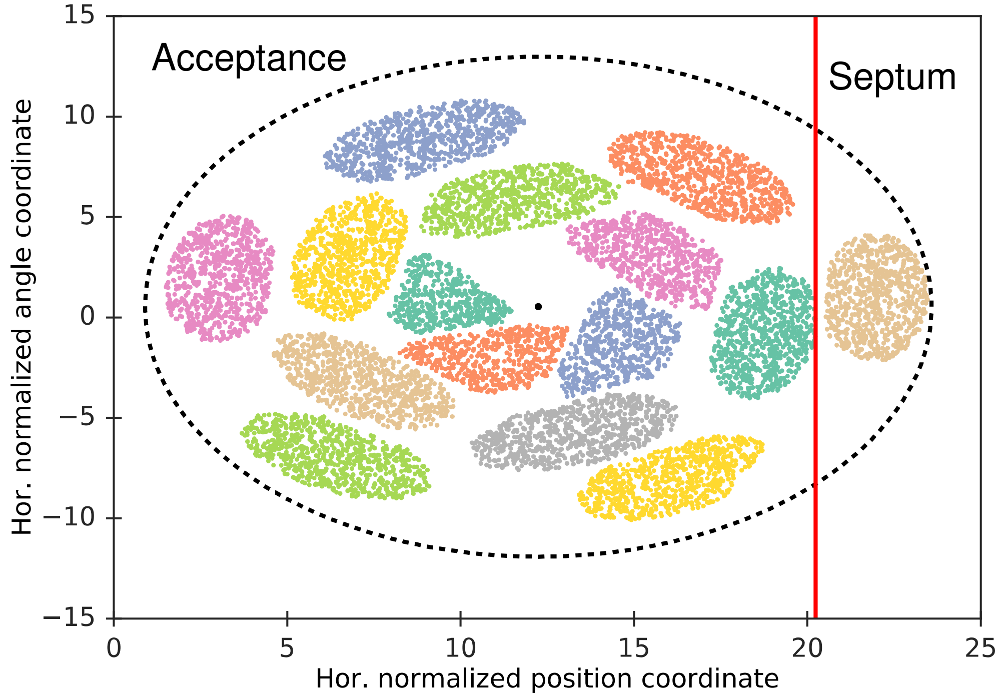


New approach is the use of genetic algorithms (GA) and particle swarm (PA)

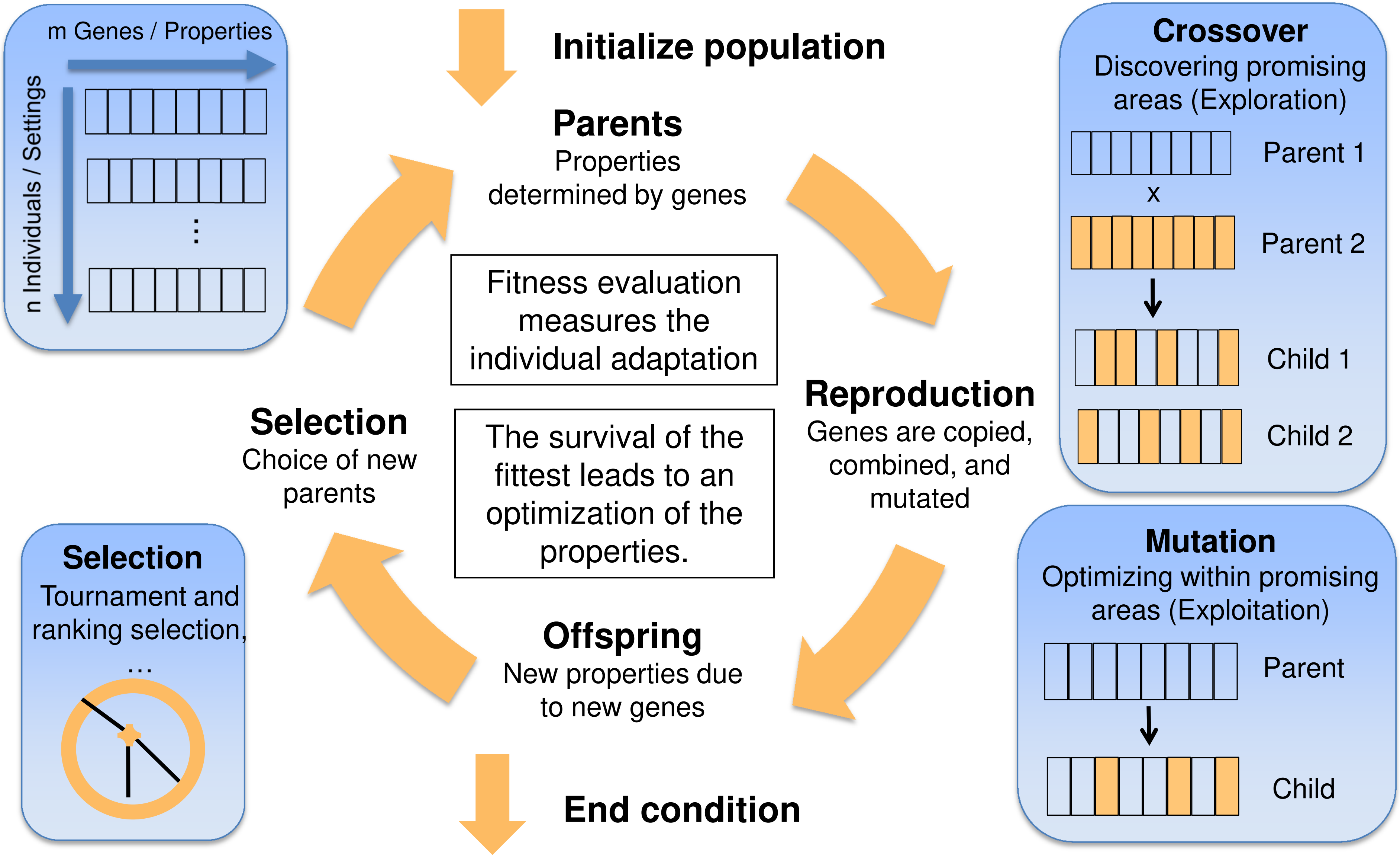


Darwin Finches
J. Gould,
Voyage of the
Beagle

GA optimized MTI



Genetic Algorithms



Particle swarm algorithms

Inspiration from the "graceful but unpredictable choreography of a bird flock"

Position

$$x_i(t+1) = x_i(t) + v_i(t+1)$$

Velocity update

$$v_i(t+1) = wv_i(t) + r_1C_1(P_i^l - x_i) + r_2C_2(P^g - x_i)$$

Inertia | Local search | Global search

x_i Each individual particle position refers to a point in the variable space

w Inertia weight reflects effect of particle current motion

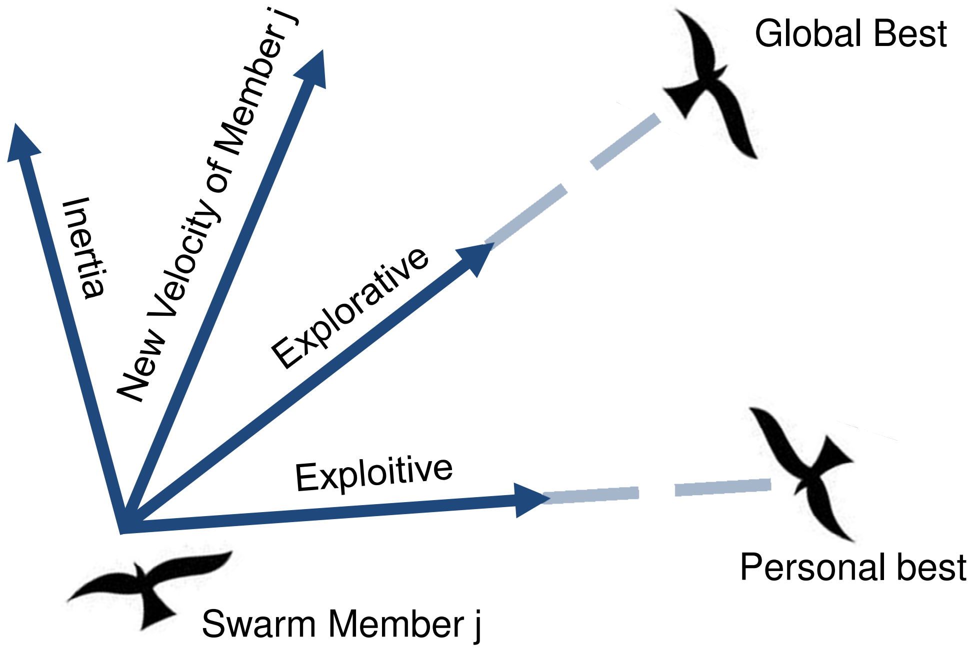
P_i^l Personal best; analogous to "nostalgia"

C_1 Cognitive parameter is contribution of particle personal experience

P^g Global best is the best position ever for entire swarm

C_2 Social parameter reflects publicized knowledge or social norms

r_1, r_2 Stochastic elements of the algorithm

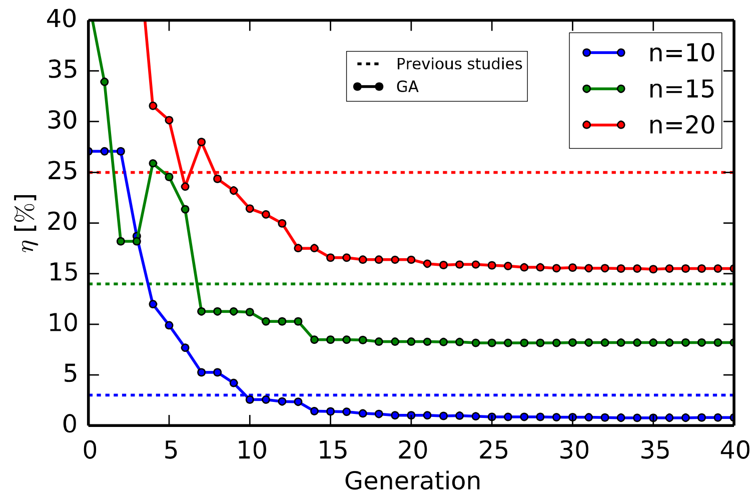


Multi-turn injection into SIS18

Optimization of loss

Genetic algorithms can improve MTI

Especially for longer injection GA discovers a much better solution

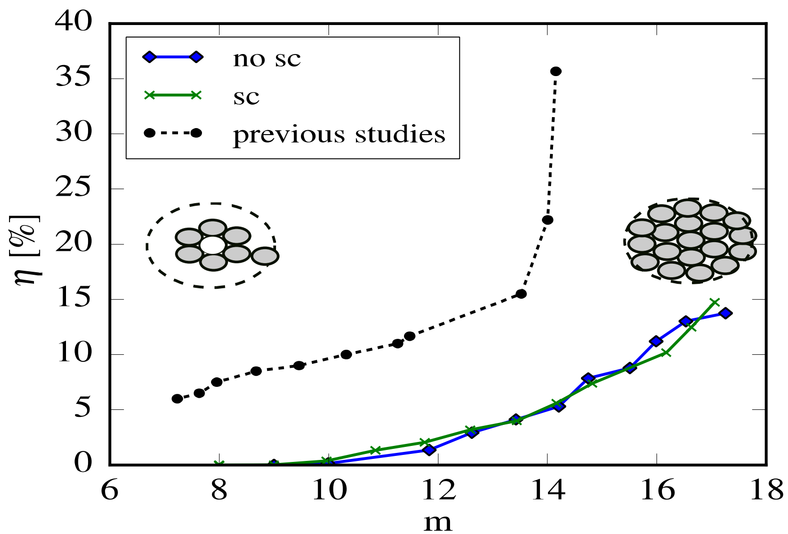


Optimization of loss and gain factor

Dependence of gain factor on loss

Loss-free injection could be found

Space charge results in a similar PA front, but with different injection settings



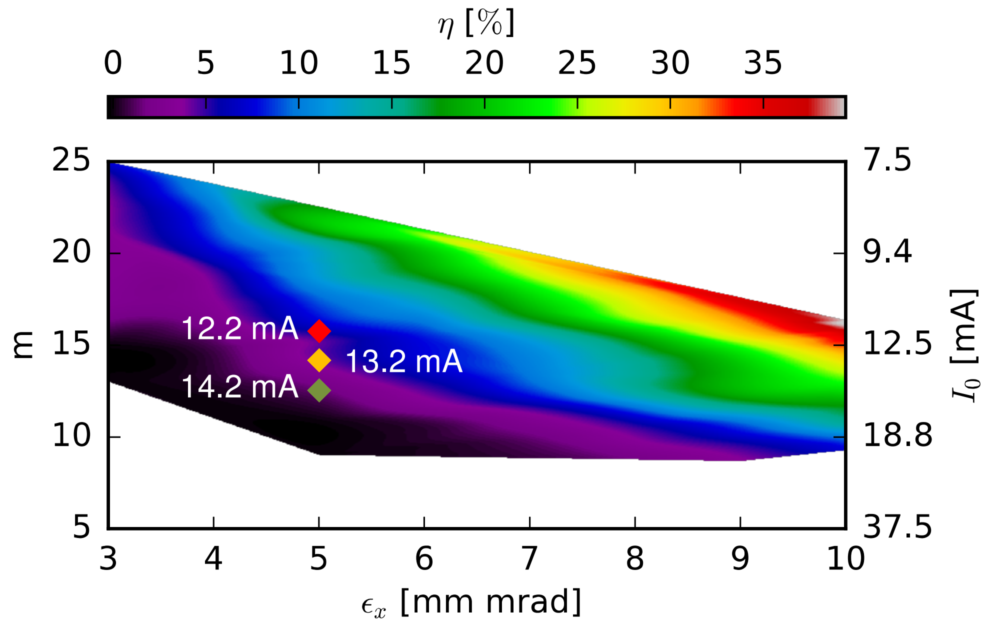
Multi-turn injection into SIS18

Optimization of loss, gain factor and beam emittance (injector)

Dependence of interface parameter

$$B = \frac{I}{\varepsilon} \qquad m(\eta) = \frac{N}{I} q f_0$$

allows to define a frame, in which the required beam parameter can be matched at best for a high performance



This crucial information gives more flexibility for the injector upgrade layout.

New Alvarez DTL provide requirement beam brilliance (including errors)

S. Appel et al: Nucl. Instrum. Methods A 852 (2017), pp. 73-79

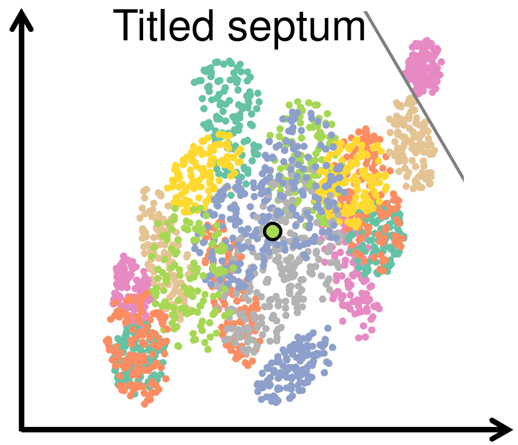
A. Rubin, Beam dynamics design of the new FAIR post-stripper linac, GSI Accelerator Seminar, 14.05.17

Multi-turn injection

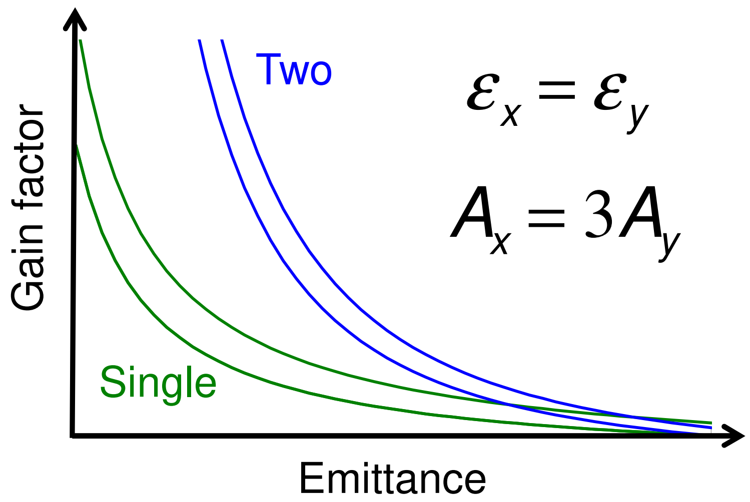
Smaller beam emittance increase MTI performance

Available acceptance limited MTI performance

Besides the horizontal phase space, the vertical one can also be exploited, which can lead to higher gain factors



- Titled septum or skew quadrupoles



$$\varepsilon_x = \varepsilon_y$$

$$A_x = 3A_y$$

Single plane: $m = \frac{A}{d\varepsilon}$ $\quad d \approx 1.5 - 2$

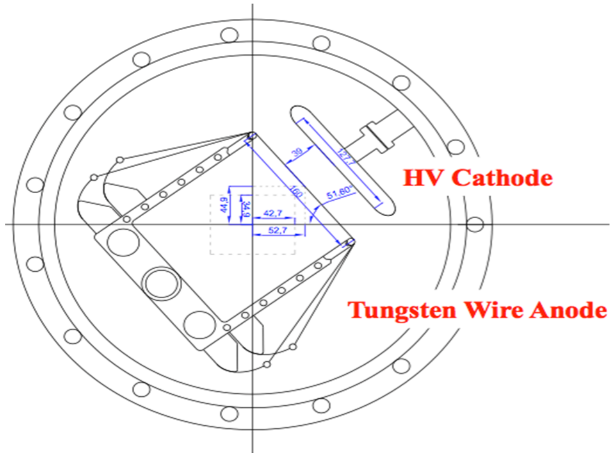
Two plane: $m = \frac{A_x A_y}{d\varepsilon_x \varepsilon_y}$ $\quad d \approx 8 - 10$

G.H. Rees in Handbook of accelerator physics and engineering

Multi-turn injection (Two plane)

Titled septum

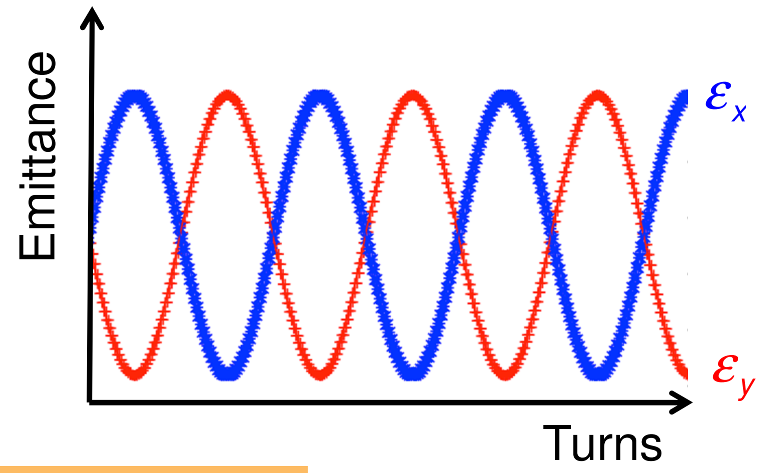
Need new technical development
Titled septum and magnets in transfer line
Coordinate rotation system
Four additional bumpers (vertical)



BRing of HIARF project

Skew quadrupoles

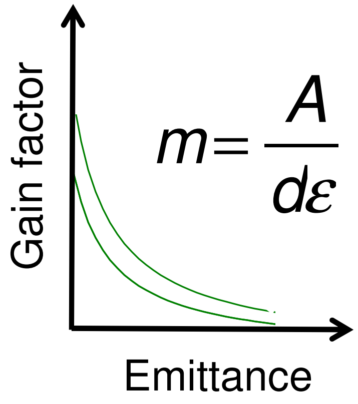
Using installed skew quadrupoles
Linear coupling of hor. and ver. phase space
Skew strength should be swift off after injection



Which gain factors can be reached for a given beam emittance and loss for SIS18?
For conventional, skew and titled septum injection?

Injector brilliance depending

EMittance Transfer EXperiment (EMTEX)



One consequence of single-plane MTI is that the required horizontal injection emittance is very demanding; to the other plane not.

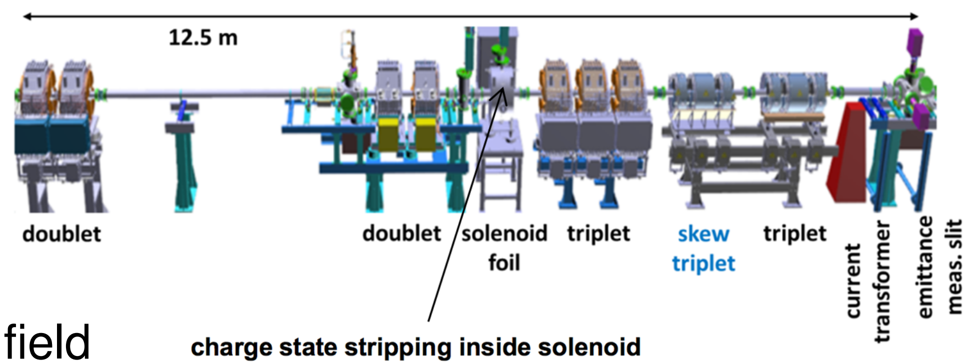
Re-partitioning of the injected beam emittances: round-to-flat transformation would increase the injection efficiency

Repartition with constant emittance product:
Effective solenoid exit fringe field + skewed quadrupole triplet

Twiss-parameters are preserved

Beam flatness amount is controlled by solenoid field

EMTEX Beam line



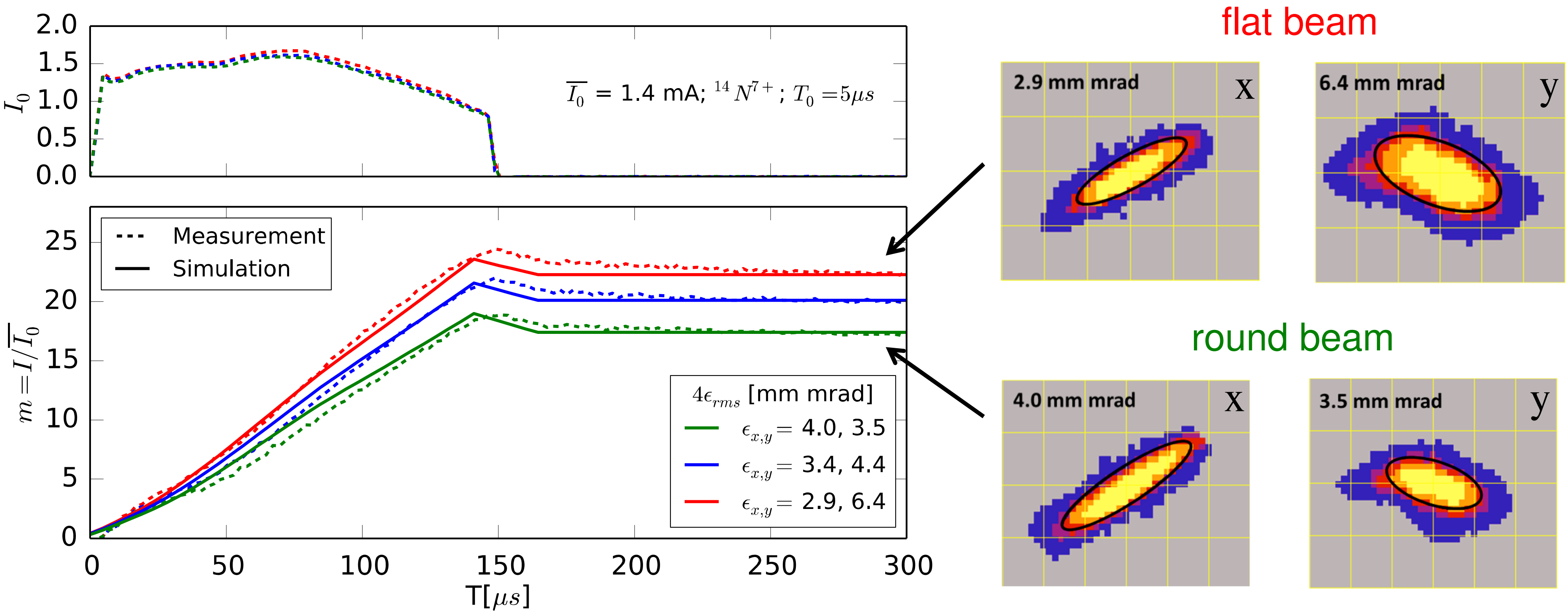
The effective solenoid exit fringe field is created by changing the ion charge state

L. Groening: Phys. Rev. ST Accel. Beams 14 064201 (2011)
C. Xiao et al: Phys. Rev. ST Accel. Beams 16 044201 (2013)
L. Groening et al: Phys. Rev. Lett. 113 264802 (2014)
S. Appel et al: Nucl. Instrum. Methods A 866 (2017), pp. 36-39

Injector brilliance depending

EMittance Transfer EXperiment (EMTEX)

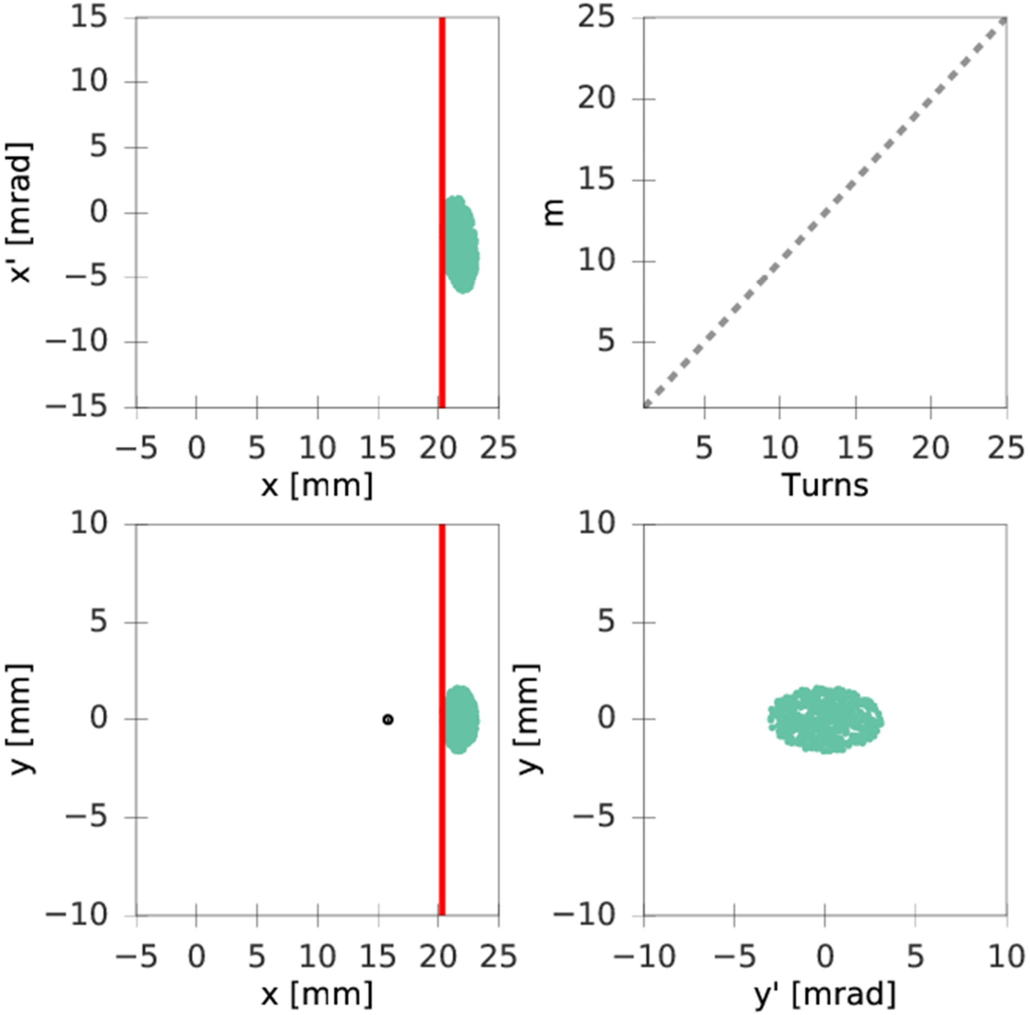
MTI performance has been measured as a function of the amount of beam flatness



Excellent agreement between simulation and measured injection performance was achieved thanks to fast adjustment of the beam flatness without changing other beam parameters.

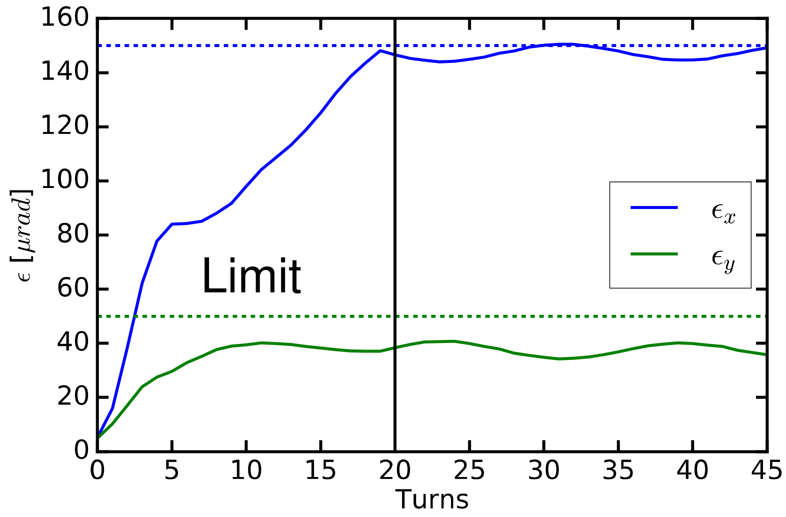
Multi-turn injection with skew quadrupoles

With linear coupling the injection loss could reduce from 15% to 1-5% for n = 20



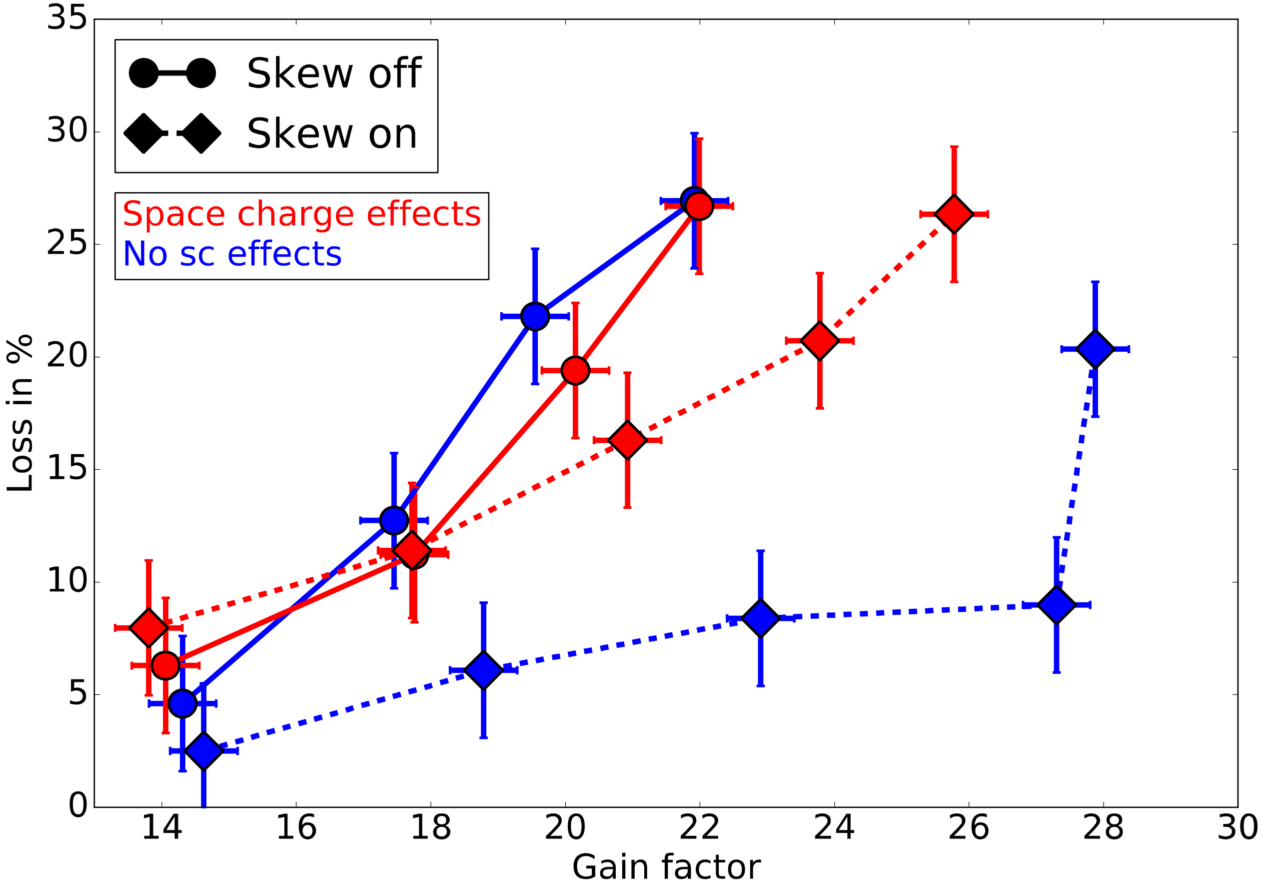
Coupling parameters: $Q_x : 4.17,\ Q_y : 3.22,$ $k : 0.0141/m,\ \delta : -0.05$

Emittance development



Multi-turn injection with skew quadrupoles

The injection performance can increase with linear coupling
Unfortunately, space charge effects lower the beneficial effect



Summary and Outlook

Evolutionary Optimization

- ✓ MTI setting for a loss-free or low-loss injection were identified
- ✓ Range of optimum brilliances for all ions species can be defined (shown for U^{28+})
- ○ Online optimization of MTI (GA, PSA or derivative-free algorithm)

EMTEX

- ✓ Injection optimization through generation of flat ion beams
- ○ Application for intense beams (e.g. U^{28+})

Two plane MTI

- Skew
  - ✓ The injection performance can increase with linear coupling
  - – Unfortunately, space charge effects lower the beneficial effect
- ○ Corner septum

Thank you for your attention