TECHNISCHE UNIVERSITÄT DARMSTADT

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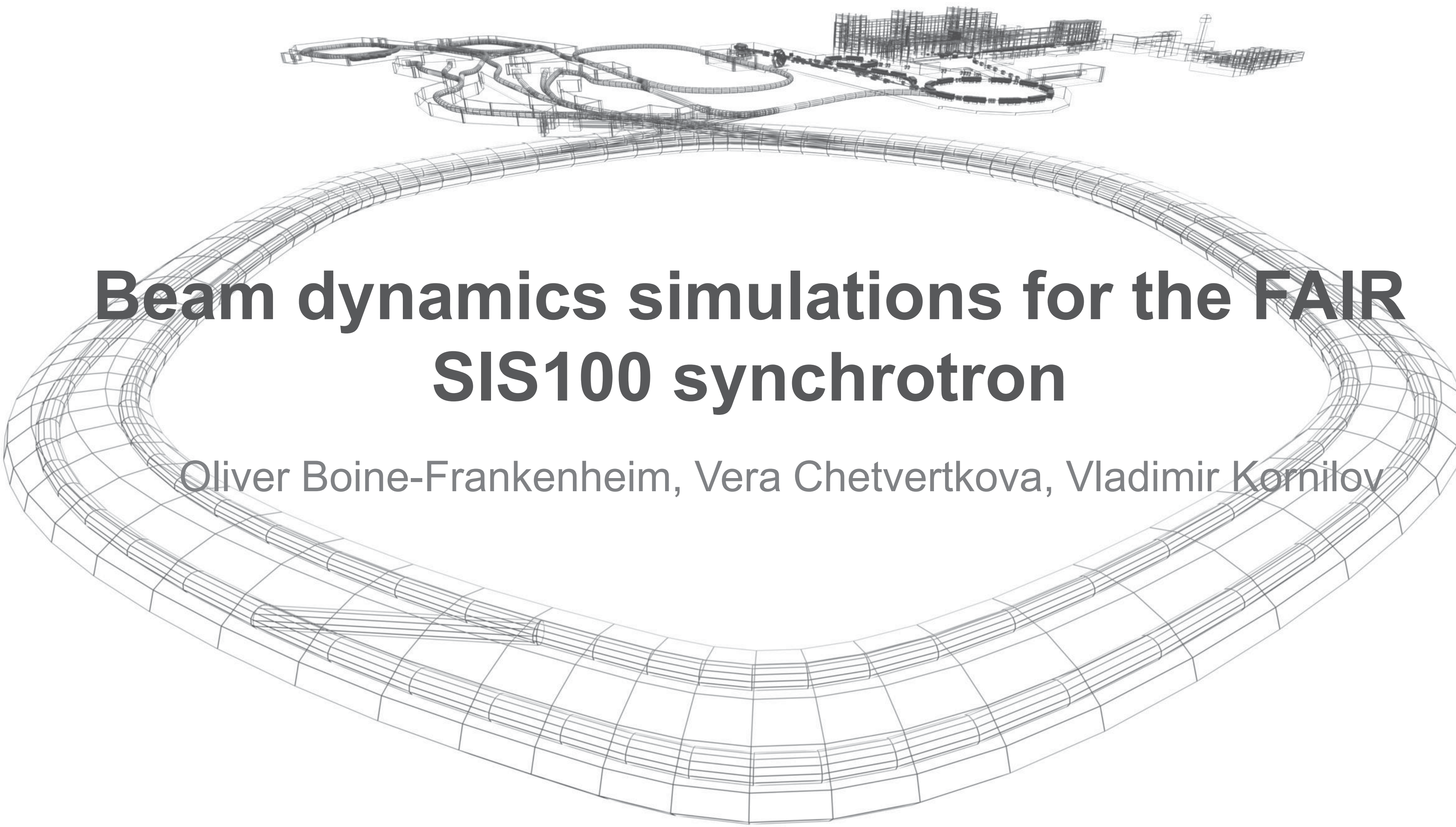


Beam dynamics simulations for the FAIR SIS100 synchrotron

Oliver Boine-Frankenheim, Vera Chetvertkova, Vladimir Kornilov

FAIR main facts

a new facility for research with anti-protons and heavy-ions.

Primary ions: Protons-Uranium

Max. energy: 100 Tm

Max. beam intensity on target: 10^{11}/s (15 kW)

Beam intensity/quality limitations:

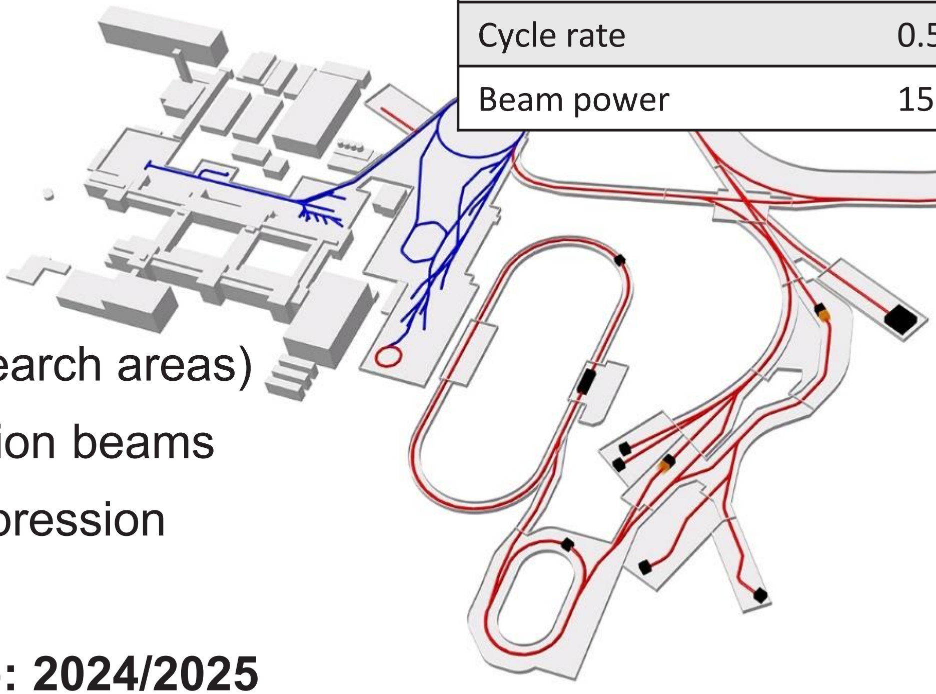
- Sources, injection (Liouville), cycle times
- space charge / resonances
- lifetime
- activation

Unique features:

- Parallel operation (serves 4 research areas)
- Intense and high-energy heavy-ion beams
- Slow extraction and bunch compression
- Storage rings and beam cooling

Start/end commissioning (day-1): 2024/2025

	SIS-100
Reference primary ion	U^{28+}
Reference energy	1.5 GeV/u
Ions per cycle	3E11
Bunch length	60 ns
Cycle rate	0.5 Hz
Beam power	15 kW

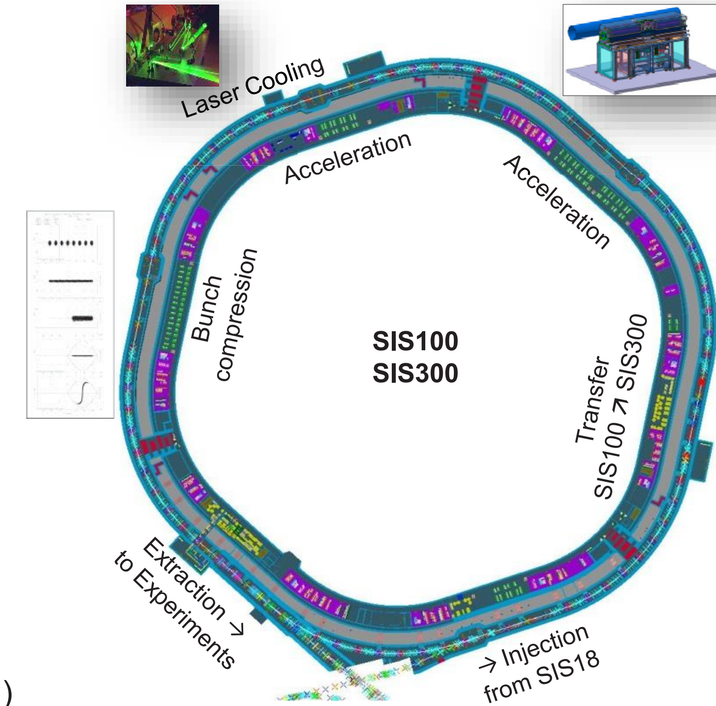


FAIR@GSI

https://youtu.be/wSN7jIoV5nM

The SIS100 synchtrotron

Aerial photo of the construction site taken on May 25, 2014 (photo: Jan Schäfer for FAIR) (2014, before start of construction)

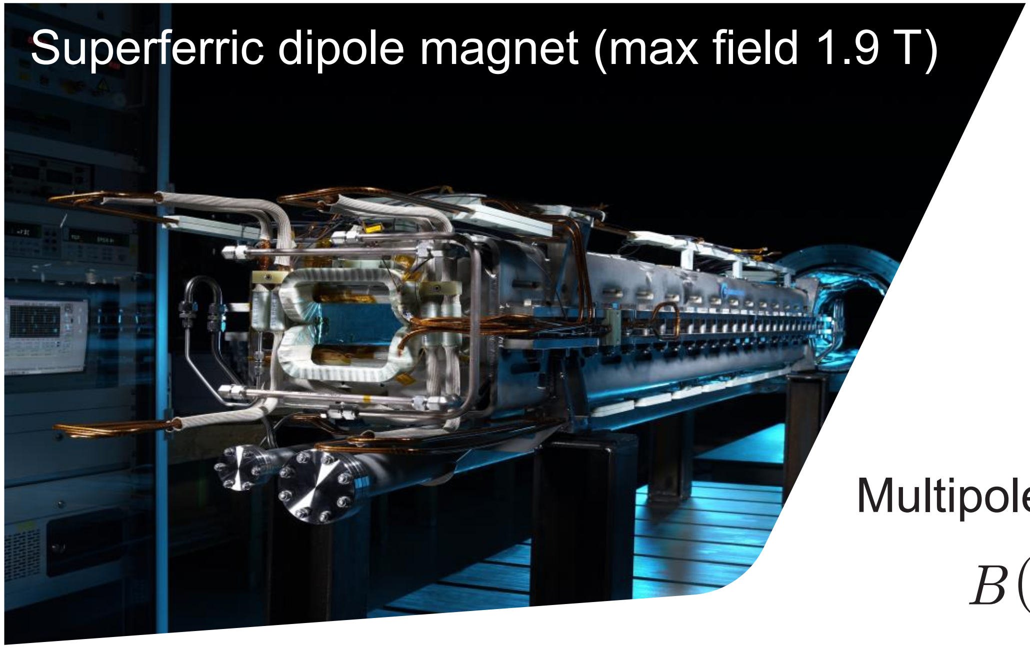


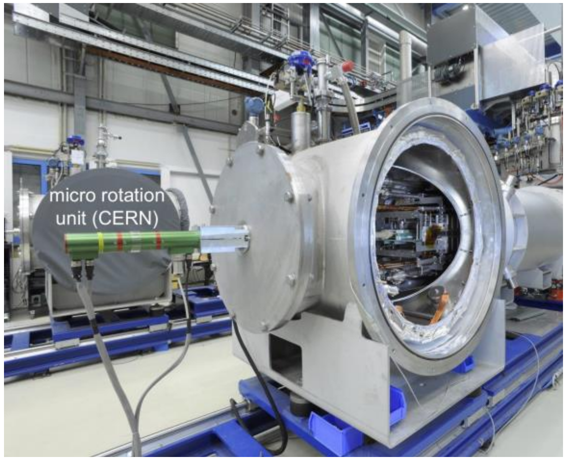
Images courtesy of M. Konradt / J. Falenski

- Circumference: 1 km
- Rigidity: 100 Tm
- Fast ramping superferric ‘nuclotron’ magnets (4 T/s)
- Cycle rates of up to 1 Hz (1 s accumulation after injection)
- Slow extraction (over seconds) or fast extraction (single compressed bunches)

SIS100 Machine model and simulations

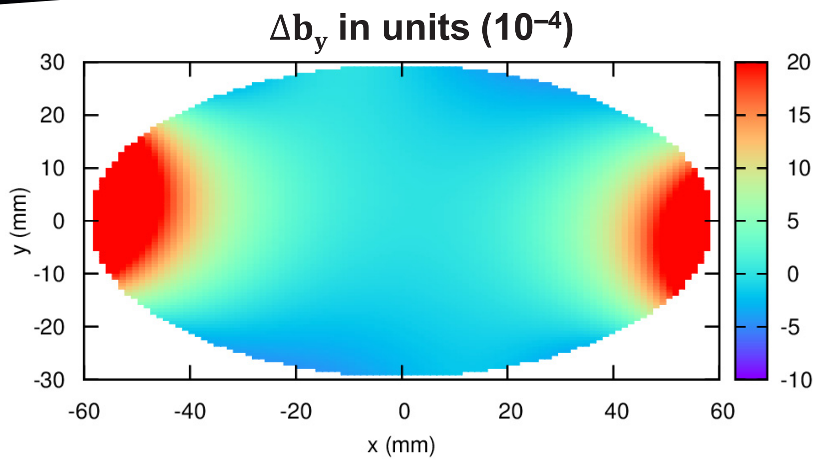
Superferric dipole magnet (max field 1.9 T)

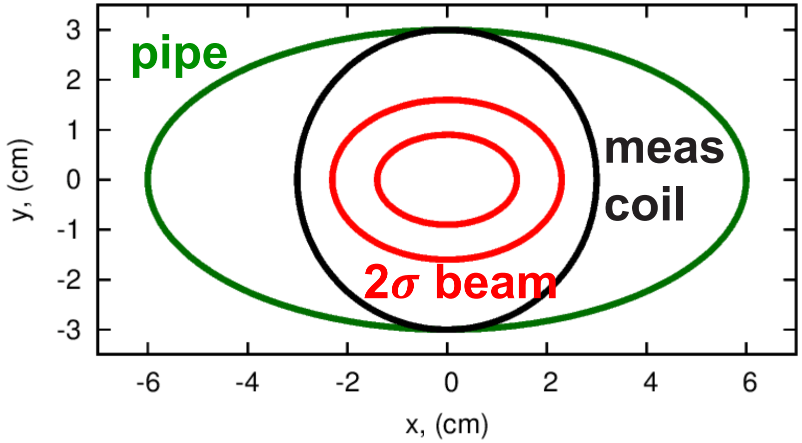




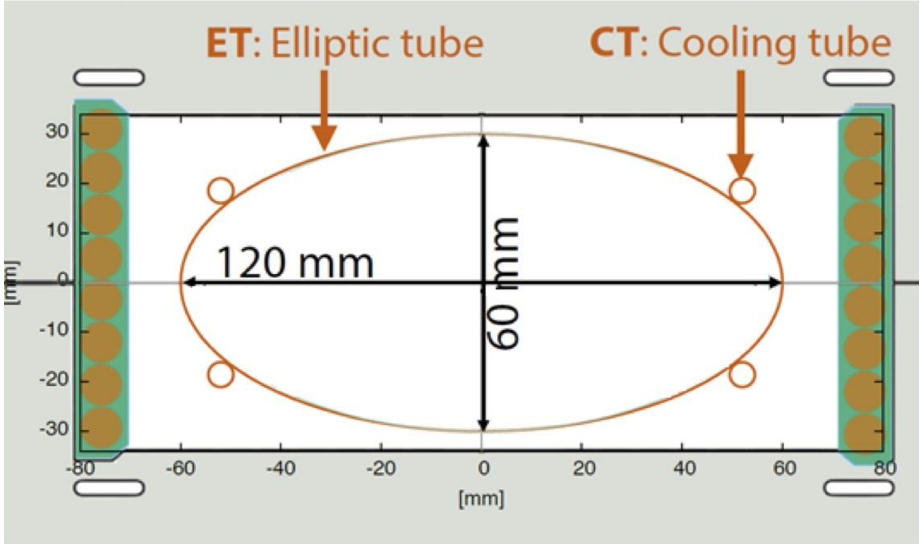
Multipoles from measurements with rotating coils

$$B(z) = B_y + iB_y = \sum_{n=1} C_n \left(\frac{z}{R_c}\right)^{n-1}$$

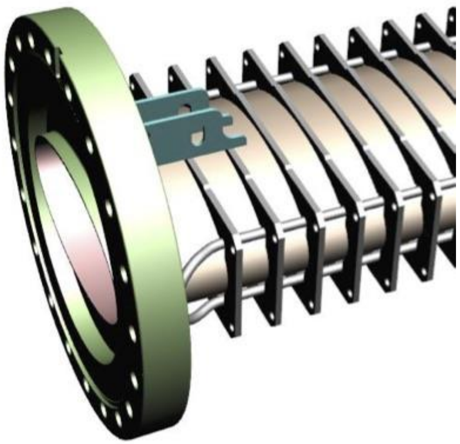




Dynamic effects: Eddy currents and beam pipe



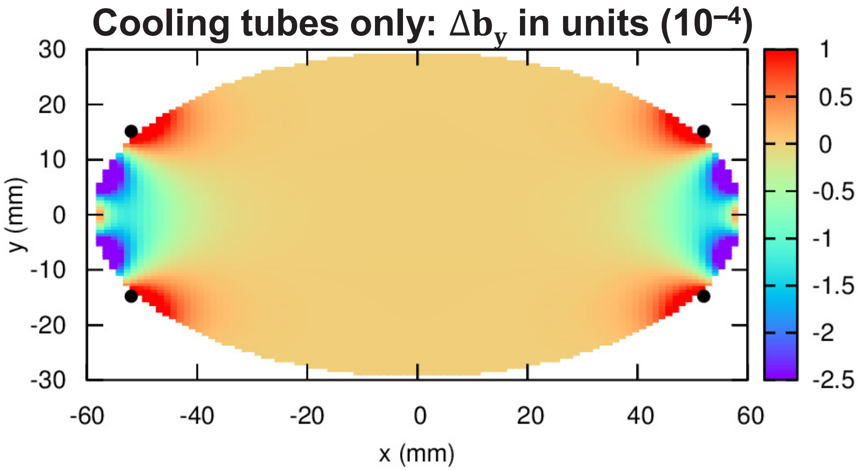
Cooling pipes to keep pipe wall at 10 K



Magnet field distortion due to cooling pipes during fast ramping (4 T/s)

The thin (0.3 mm) stainless steal pipe is also the main transverse impedance source for beam instabilities !

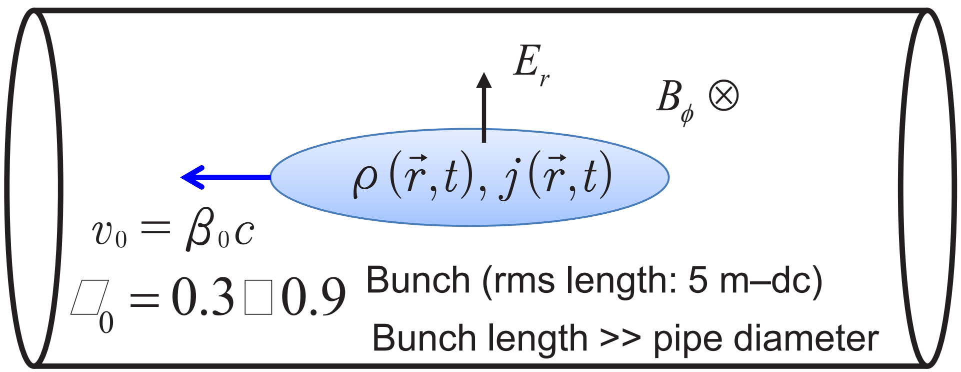
Impedance/instability/damping simulation studies are not part of this talk.



(Transverse) space charge force in SIS100

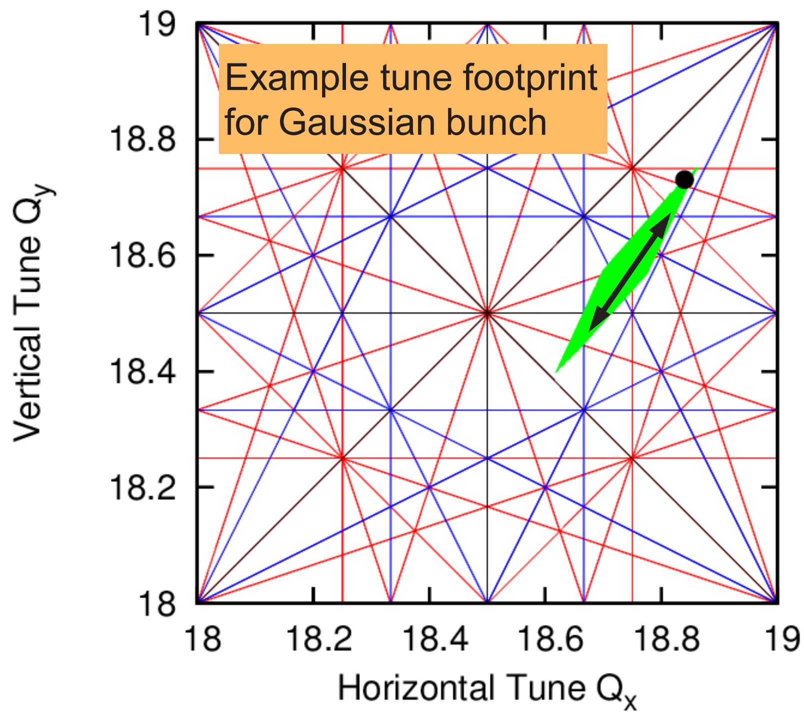
$$\varepsilon_0 \nabla \cdot \vec{E} = \rho$$

(in the rest system of the beam)



The transverse space charge force is one of the main intensity limiting effect in in the FAIR synchrotrons !

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



Space charge tune shifts in SIS100: 0.2 – 0.4 (> 0.5 during bunch compression)
Time scales: 1000-10^6 turns (1 ms - 1 s)
Tolerable **e**mittance growth < 10 %, Beam loss (a few %)
Simulation challenge: Control numerical errors/emittance growth ! Performance !!!!

Particle Tracking Codes used for SIS100

Elegant (M. Borland)
- **3D static nonlinear space charge kicks**
- Pelegant for parallel tracking
- For flexible, also for longitiudinal tracking
- Script input

V. Kornilov (2018)

pyPATRIC:
- 3D particle tracking with **self-consistent 2.5D space charge solvers**
- MADX maps, arbitrary rf bucket forms
- Automatized parameter scans.
- **python/numpy implementation**
- Optional: **gridless space charge solvers**

O. Boine-Frankenheim, W. Stem, NIMA 2018

py-orbit
(A.Shishlo, S.Cousineau, J.Holmes, S.Appel)
http://sourceforge.net/projects/py-orbit/
- Teapot tracking
- **3D static space charge kicks**
- **2D/2.5D self-consistent space charge**
- MPI
- C++ sources / Python interface

Y. Yuan, O. Boine-F., I. Hofmann, PRAB 2018

MAD-X (L. Deniau, F. Schmidt, et al.)
https://github.com/MethodicalAcceleratorDesign/MAD-X
- Thin lens / PTC tracking
- **3D static space charge kicks**
- Fortran/C sources, Script input

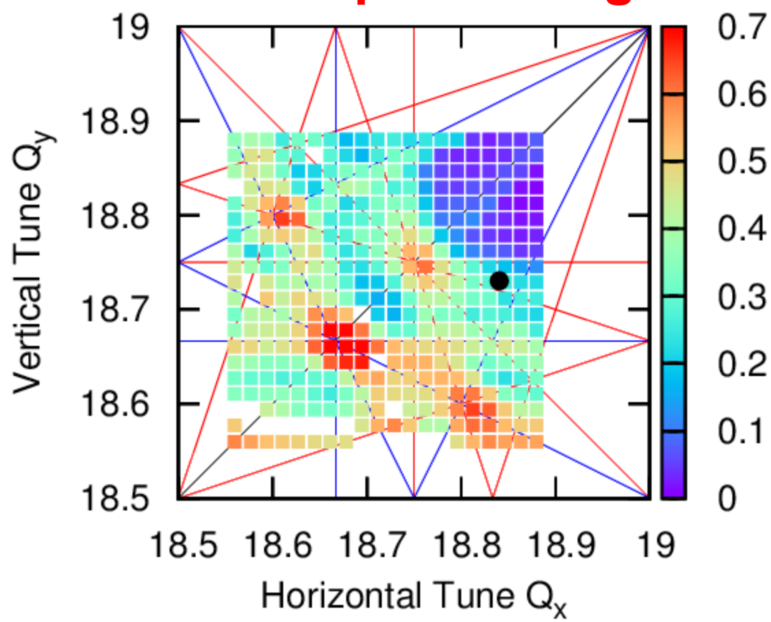
V. Chetvertkova (2018)

Example: Tracking with static 3D space charge

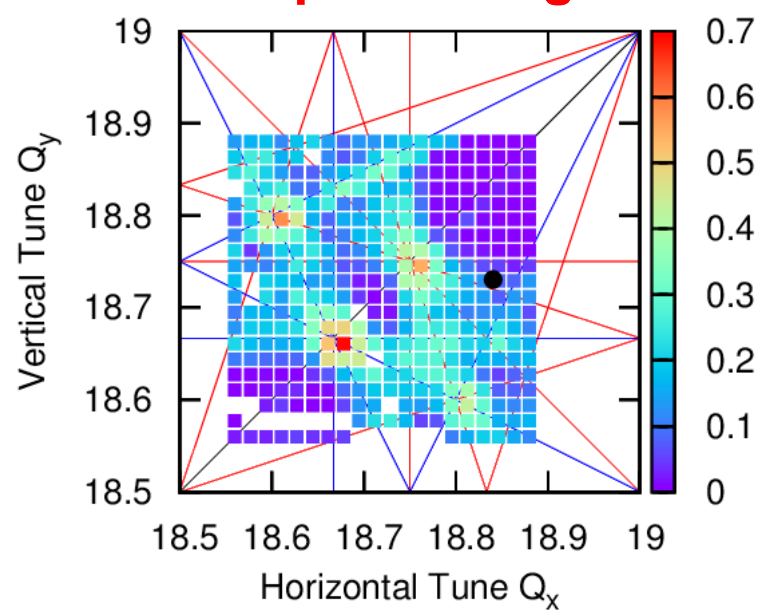
- U^{28+} bunch at the injection energy (200 MeV/u) in SIS100
- Space-charge tune shifts: vertrical ΔQ_{sc}=0.3, horizontal ΔQ_{sc}=0.2
- **Elegant:** 3D static “frozen” nonlinear space-charge kicks
- Field errors in the main dipole magnets and in the main quadrupole magnets.
- Beam loss after 20k turns (130ms)
- Lines: black (2nd order, quadrupole), blue (3rd order, sextupole), red (4th order, octupole)

V. Kornilov (2018)

With space charge



No space charge



Self-consistent (grid-based) tracking: PIC for beams

The present “production code” for beam quality/loss predictions.

integration step
(4D, for simplicity)

$$\begin{pmatrix} x_j \\ x'_j \\ y_j \\ y'_j \end{pmatrix}_{n+1} = \mathcal{M}(s_n, s_{n+1}) \begin{pmatrix} x_j \\ x'_j + \Delta x'_j \\ y_j \\ y'_j + \Delta y'_j \end{pmatrix}_n$$

(map/kicks from PTC or Teapot)

$$\rho(x,y,s) = Q' \sum_j^M S(x - x_j)$$

(favorite interpolation scheme)

$$\epsilon_0 \nabla \cdot E = \rho(x,y,s)$$

(favorite Poisson solver)

$$Q' = \frac{Q}{L}$$

(macro particle charge)

$$x'' = \frac{qE_x}{m\beta_0^2 c^2 \gamma_0^3}$$

(space charge kicks)

Artificial emittance growth depending on the ratio of real N to macro-particles M

Growth rate: $\nu \propto \frac{N^2}{M}$

For example: Boine-Frankenheim, Hofmann, Struckmeier, Appel, NIM A (2015)

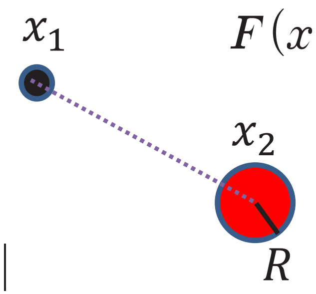
Because of noise and performance issues „frozen“ or „adaptive“ sc kicks are used.

However, this might be justified only for weak space charge and Gaussian distributions !
(Example: Bunch compression with strong space charge in SIS100)

(Fast) gridless space charge solvers

$$F_1 = \sum_{j=1}^{M} F_{12}$$

(sum over all macroparticles)



$$F(x_1) = \frac{qQ'(x_1 - x_2)}{2\pi\epsilon_0\gamma^2 |x_1 - x_2|^2}$$

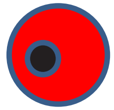
Direct particle-macroparticle force

$$Q' = \frac{Q}{L}$$

Potential: $\phi(x_1) = \frac{Q'}{2\pi\epsilon_0\gamma^2}\sum_{j=1}^{M} \ln|x_2 - x_1|$

Smoothed „cloud“ macroparticles:

$$F_{12} = \begin{cases} \dfrac{qQ'(\boldsymbol{x}_2 - \boldsymbol{x}_1)}{2\pi\epsilon_0\gamma^2 |\boldsymbol{x}_2 - \boldsymbol{x}_1|^2} & |x_2 - x_1| > R \\ \dfrac{qQ'}{2\pi\epsilon_0\gamma^2 R^2}(x_2 - x_1) & |x_2 - x_1| \leq R \end{cases}$$



Advantages:

- Underlying (multi-particle) Hamiltonian
- No ‚grid heating‘, but (smooth) ‚collisions‘
- Controlled noise smoothing (shapes) !
- Cylindrical pipe with image charges.
- Fast Multipole Method

Disadvantages:

- Complex pipe boundaries

Greengard and Rokhlin, *A Fast Algorithm for Particle Simulations*, J. Comput. Phys. (1997)
Zhang and Berz, *The fast multipole method in the differential algebra framework,* Nucl. Instr. Meth. A (2011)
FMMLIB2D: Gimbutas and Greengard, *Simple FMM Libraries for Electrostatics …*, Comm. Comput. Phys. (2015)

Tests: (Single-particle) Symplecticity

R. Ruth, A Canonical Integration Technique,1983; E. Forrest, Geometric Integration for Particle Accelerators, 2006

$$\boldsymbol{x}_2 = M_{1,2}(\boldsymbol{x}_1)$$

Mapping of particle coordinates from position "1" to position "2"

$$M^T S M = S$$

Symplecticity condition
M: Jacobian or transport matrix

$$S_{2D} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Symplectic matrix

Symplectic error [2]: $\left\| M^T S M - S \right\| = \eta$

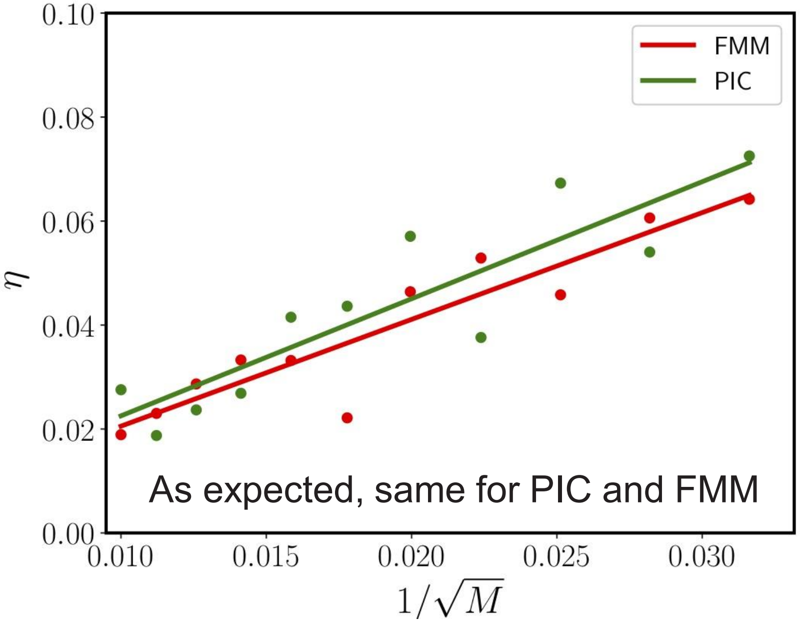
$$\begin{pmatrix} x_j \\ x'_j \\ y_j \\ y'_j \end{pmatrix}_{n+1} = M(s_n, s_{n+1}) \begin{pmatrix} x_j \\ x'_j + \Delta x'_j \\ y_j \\ y'_j + \Delta y'_j \end{pmatrix}_n$$

(sector map without space charge)

$$x_j^{n+1} = \sum_{i=0}^{6} M_{j,i} x_i^n \quad j = 1,6, \quad n = N, N+5 \quad \Rightarrow \quad M_j$$

Reconstruction of the individual particle transport matrix M for one cell with space charge [1]

Simplectic error for FODO (PIC vs. FMM)



[1] A. Luccio,N. D'Imperio, *Eigenvalues of the One-Turn matrix,* BNL (2003)
[2] M. Titze, ICFA-HB 2016

How to test multi-particle symplecticity in a tracking code ?

Conclusions

- The FAIR SIS100 construction is progressing ! The focus of beam dynamics simulations is now on the characterization of the magnets and the identification of optimum parameter windows for high-intensity operation.
- Also for the purpose of benchmarking, several codes are employed, with different tracking implementations and space charge models/solvers.
- Self-consistent space charge solvers are required for realistic predictions ! At present they are employed only for short-term simulations (< 10k turns) because of performance/noise issues.
- Gridless space charge solvers based on the Fast Multipole Method are very promising in terms of flexibility and performance for 2.5D or 3D tracking with self-consistent space charge.
- Gridless solvers are „closer“ to a Hamiltonian multi-particle system for which fluctuations follow the „well-known“ IBS theory. Therefore the numerical errors might be easier to predict and to control (cloud shapes).
- More difficult to add complex beam pipe geometries for image contributions !