Status of the FAIR project

Vladimir Kornilov
GSI Helmholtzzentrum, Darmstadt, Germany

FAIR project at GSI

July 4th 2017 Official Ground Breaking Ceremony

Area North is under construction.

Tunnel SIS100:

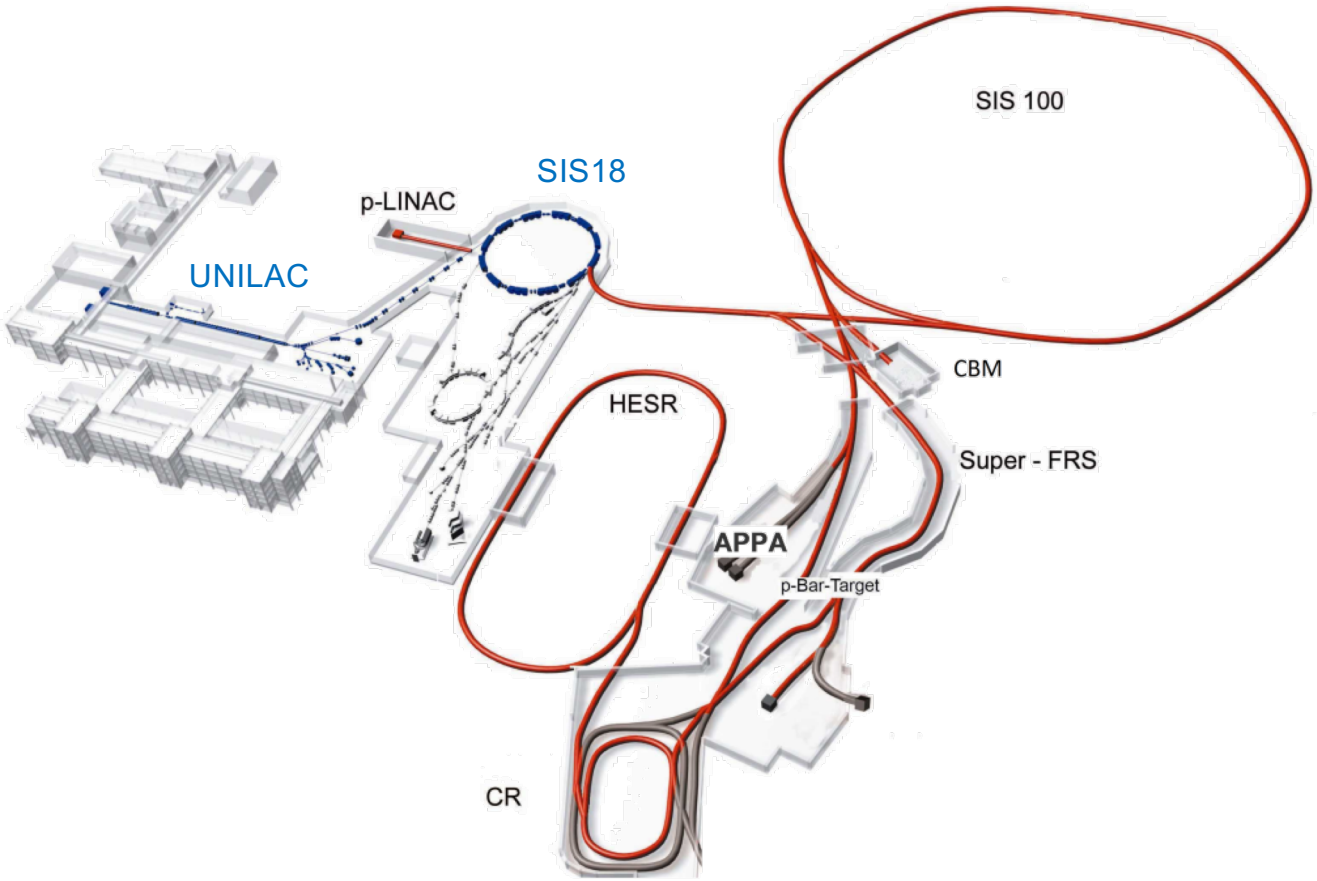
- concrete works for ground slabs
- concrete works for walls and columns
- concrete works for ceilings
- sealing and backfill works

FAIR project: civil construction

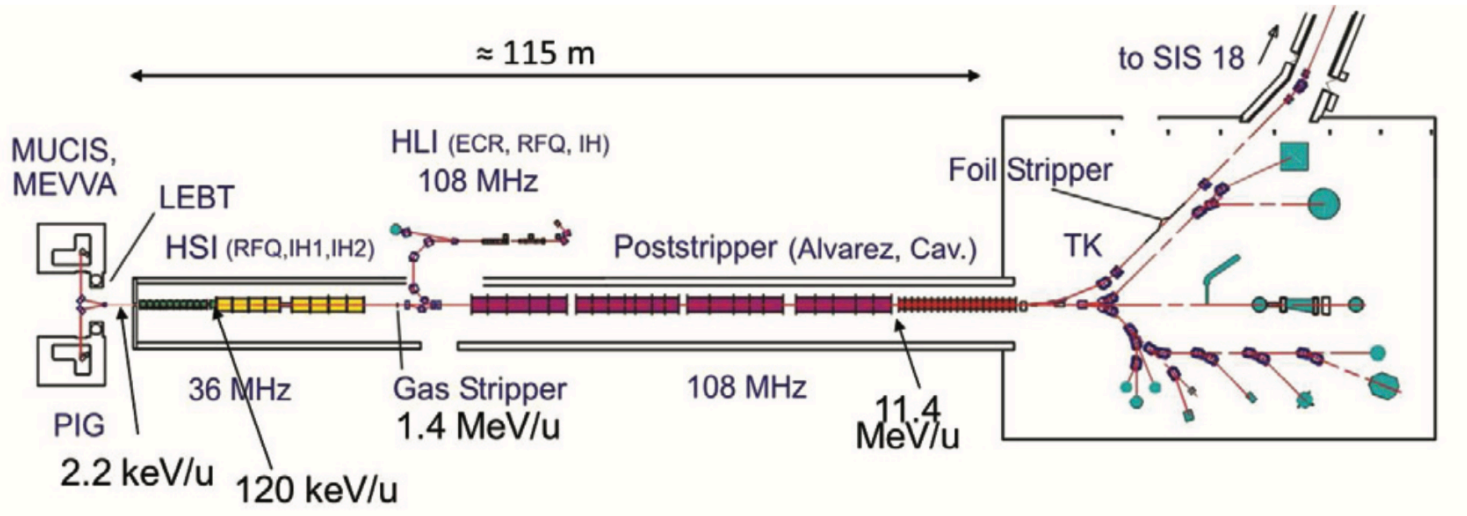
FAIR project at GSI

Four scientific pillars of FAIR:

- APPA.
  Atomic & Plasma Physics
- CBM
  Compressed Baryonic Matter
- NUSTAR
  Nuclear Structure Astrophysics and Reactions
- PANDA
  Antiprotons



UNILAC



L.Groening et al, IPAC2016

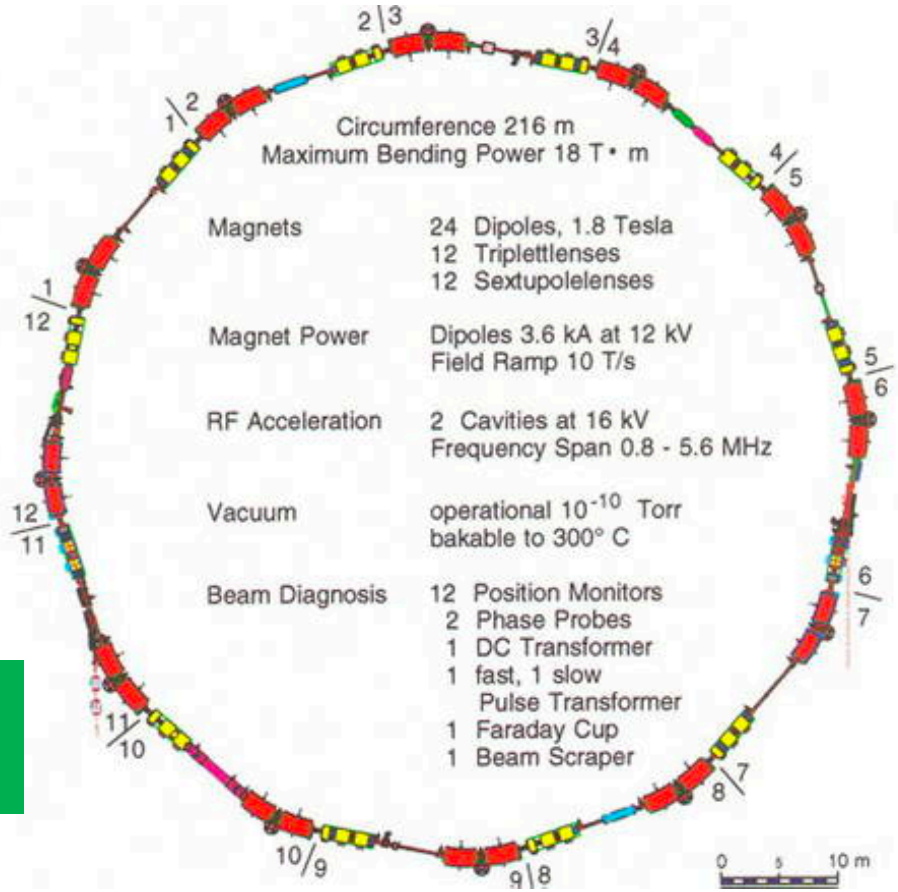
section	features	code
LEBT	multi-q, partial sc-compensation	PARTRAN
RFQ	multi-q, sc, bunches	TOUTATIS (part of TraceWin)
MEBT	sc, bunches	TraceWin
IH-DTL	sc, bunches, KONUS beam dynamics	TraceWin
gas stripper	multi-q, sc, partial sc-compensation, bunches, dipoles	TRACK, TraceWin
Alvarez DTL	sc, bunches	TraceWin
transfer channel	sc, bunches, dipoles	TraceWin

UNILAC is modeled using simulation codes section by section

SIS18 synchrotron

SIS18 as the booster for FAIR

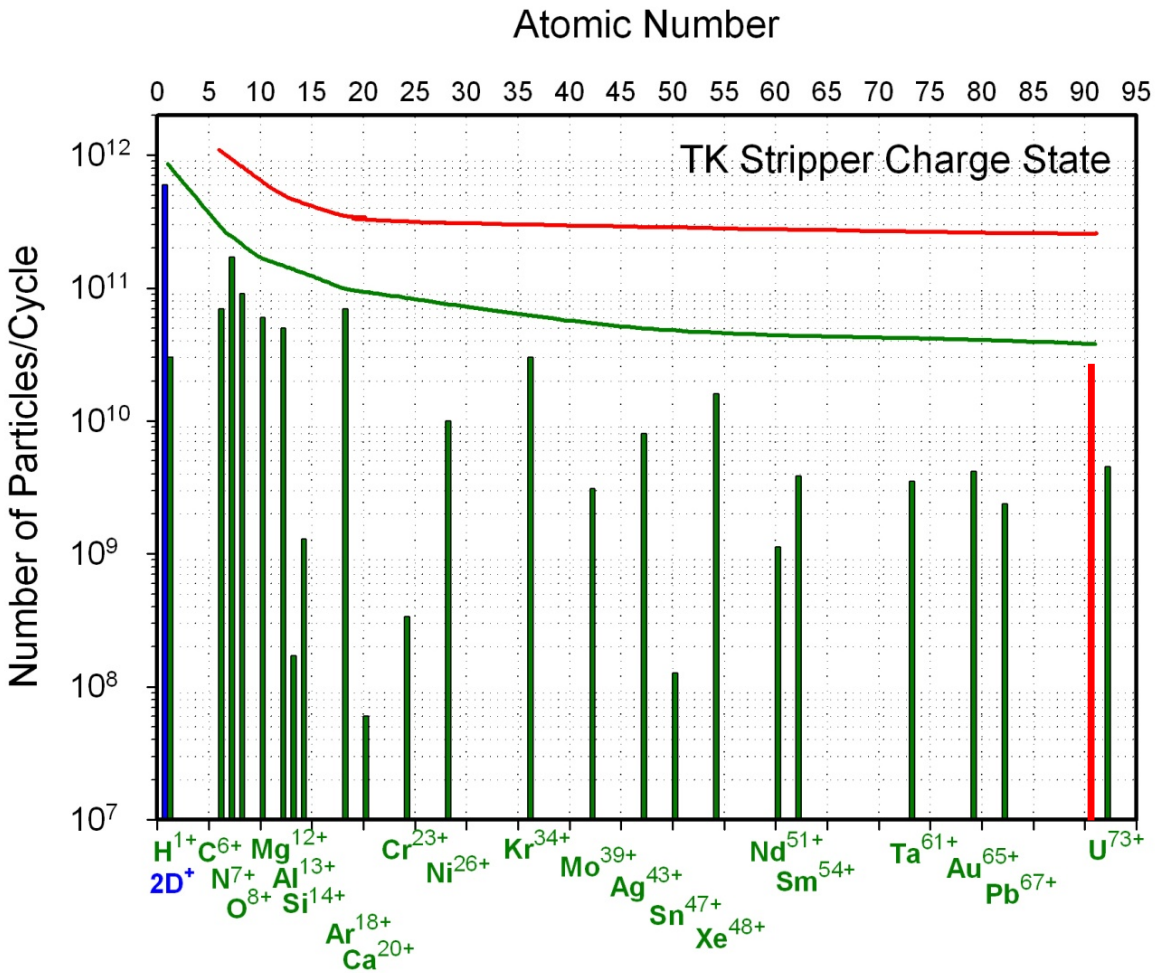
	Protons	Uranium
Number of ions per cycle	5×10^{12}	1.3×10^{11}
Space charge tune spread	Up to 0.5	Up to 0.5
Initial beam energy	70 MeV	11 MeV/u
Final beam energy	4.5 GeV	200 MeV/u
Repetition frequency	2.7 Hz	2.7 Hz



Extensive upgrade program for the beam intensities as the booster for FAIR

The major challenge: life time of U^{28+} and the dynamic vacuum

SIS18 Intensity Limits



Space charge limit for lower charge state ions

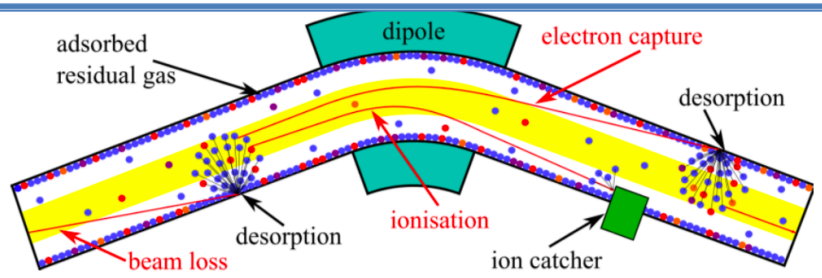
Space charge limit for high charge state ions

(e.g.: $Ar^{18+} > Ar^{10+}$
$U^{73+} > U^{28+}$)

Lower charge state: an order of magnitude higher intensity due to the space charge limit

Heavy-ion synchrotrons

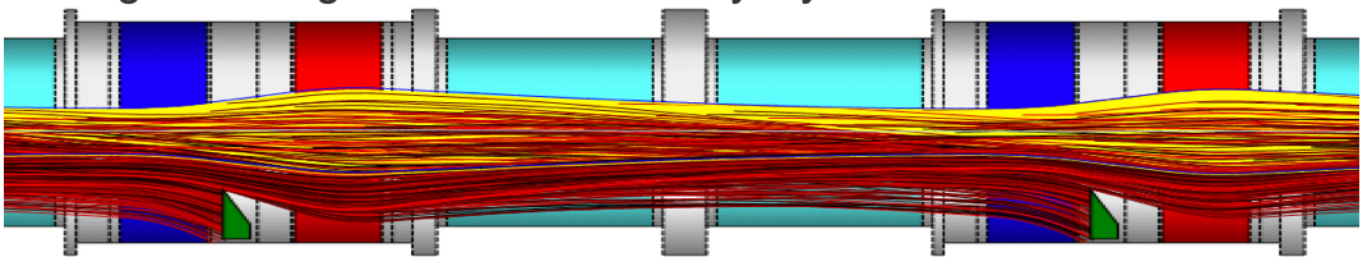
The Dominating Intensity Limitation for Heavy Ion Beams in Synchrotrons is the Interaction with the Residual Gas and thereby generated Charge State Changes. Due to Desorption Processes at High Beam Intensities the Static Residual Gas Pressure becomes the so called Dynamic Vacuum. Ionization in the Dynamic Vacuum is the dominating beam loss mechanism which appears much below the space charge limit.



Ionisation loss drives pressure bumps which itself accelerates the ionisation process.
> Dynamic vacuum instability

P.Spiller, IPAC2018

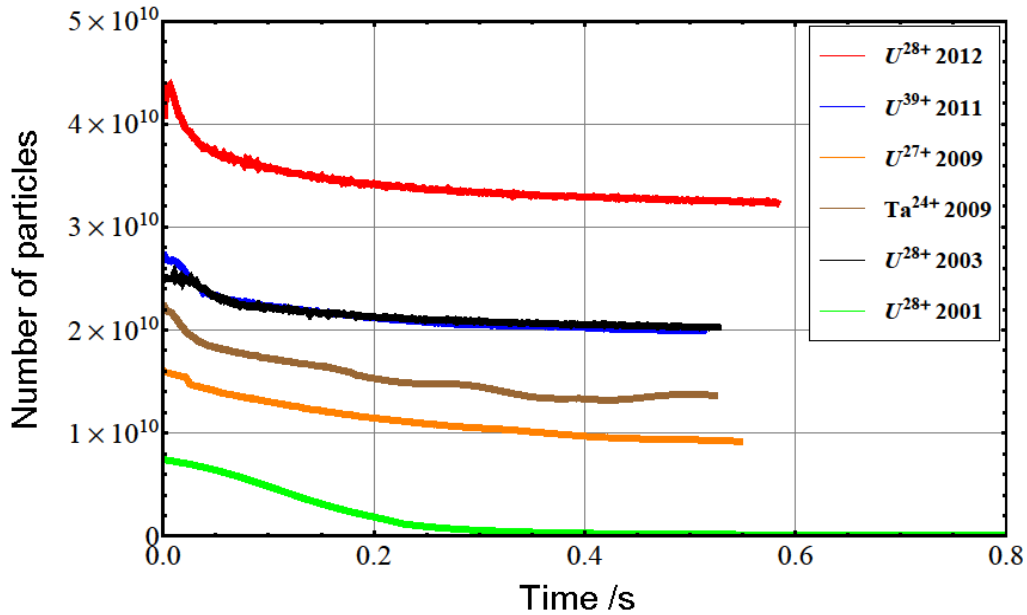
- SIS100 ion catcher system optimized for $U^{28+} \rightarrow U^{29+}$
  - >99% catching efficiency
  - all charge exchange loss is controlled by cryocatcher



SIS18 synchrotron

World Intensity Record for Low Charge State Heavy Ions

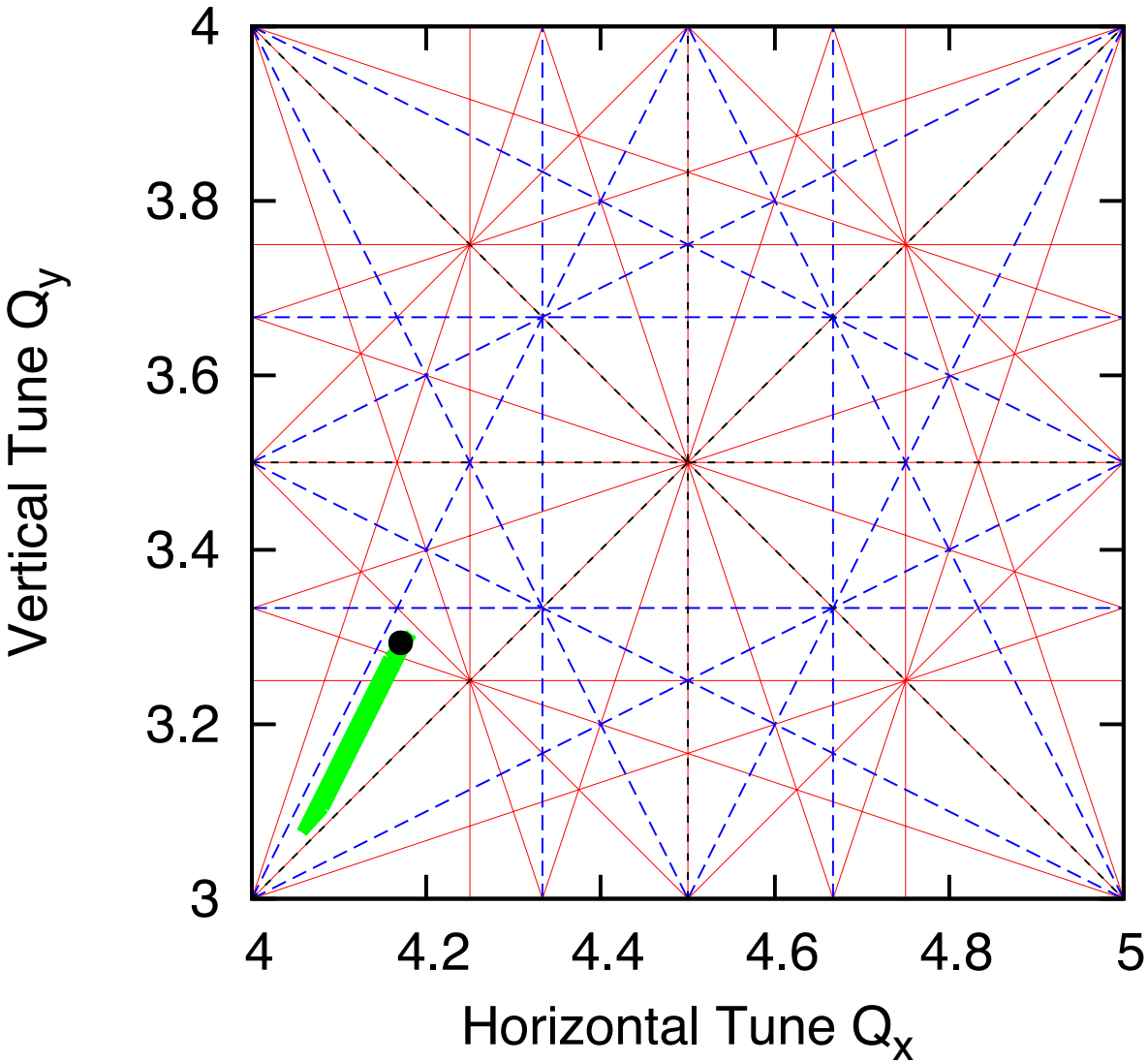
- 3.2 x 10^{10} U^{28+} accelerated and extracted successfully
- further upgrade program
- still a factor of 6 in intensity is missing



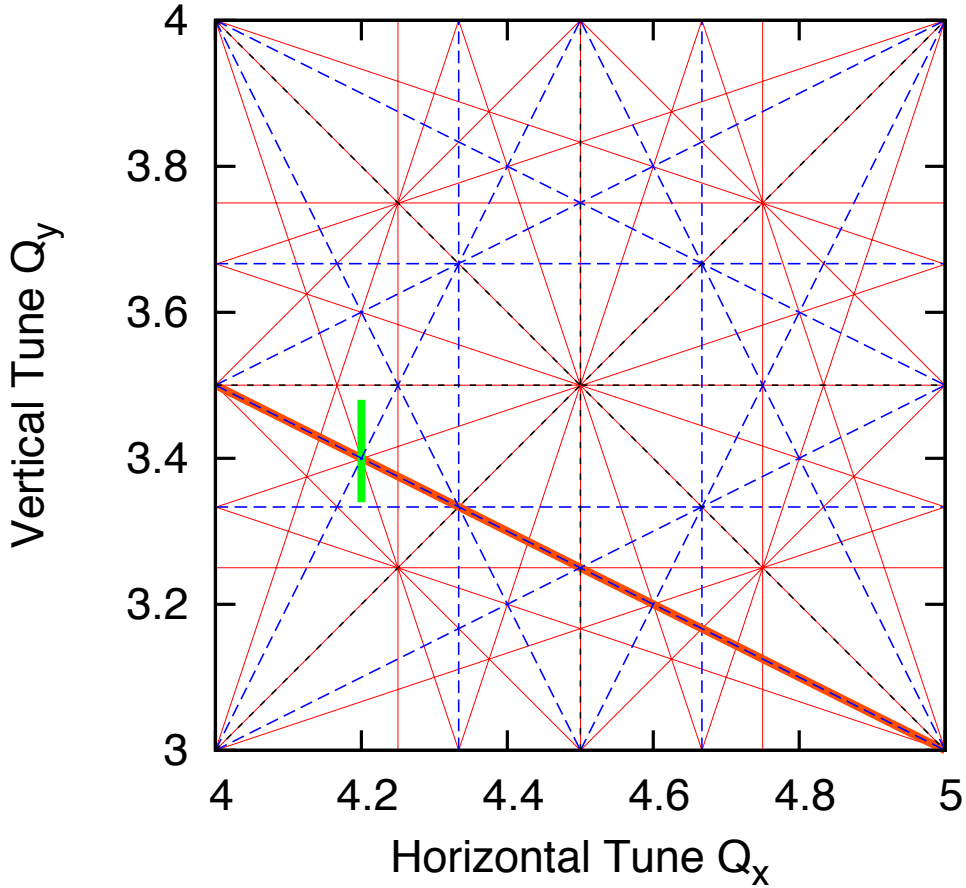
SIS18 High-Current Operation

The present working point • and the space charge tune spread (schematic)

Search for high-current working points (Q_v>3.5?):
Injection efficiency is an issue (presently, the multiturn injection in the horizontal plane)



SIS18 Resonance Compensation



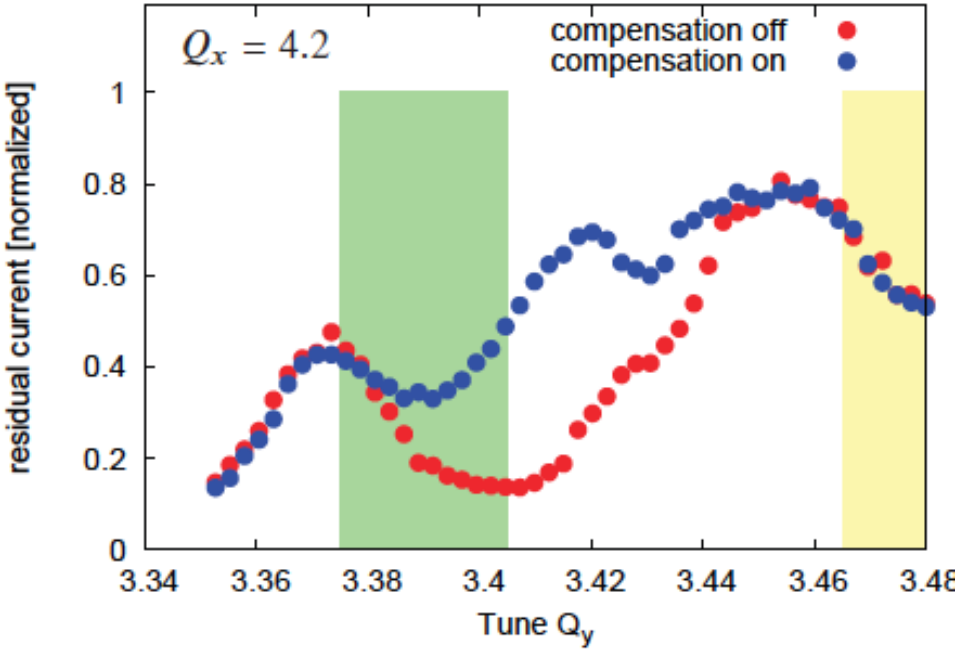


Figure 3: Beam survival for a bunched beam stored for 1 second as function of Q_y. The blue curve is obtained for the partially compensated third order resonance, whereas the red curve is measured for the naked machine.

$Q_x + 2Q_y = 11$
non-structure, sextupole, normal

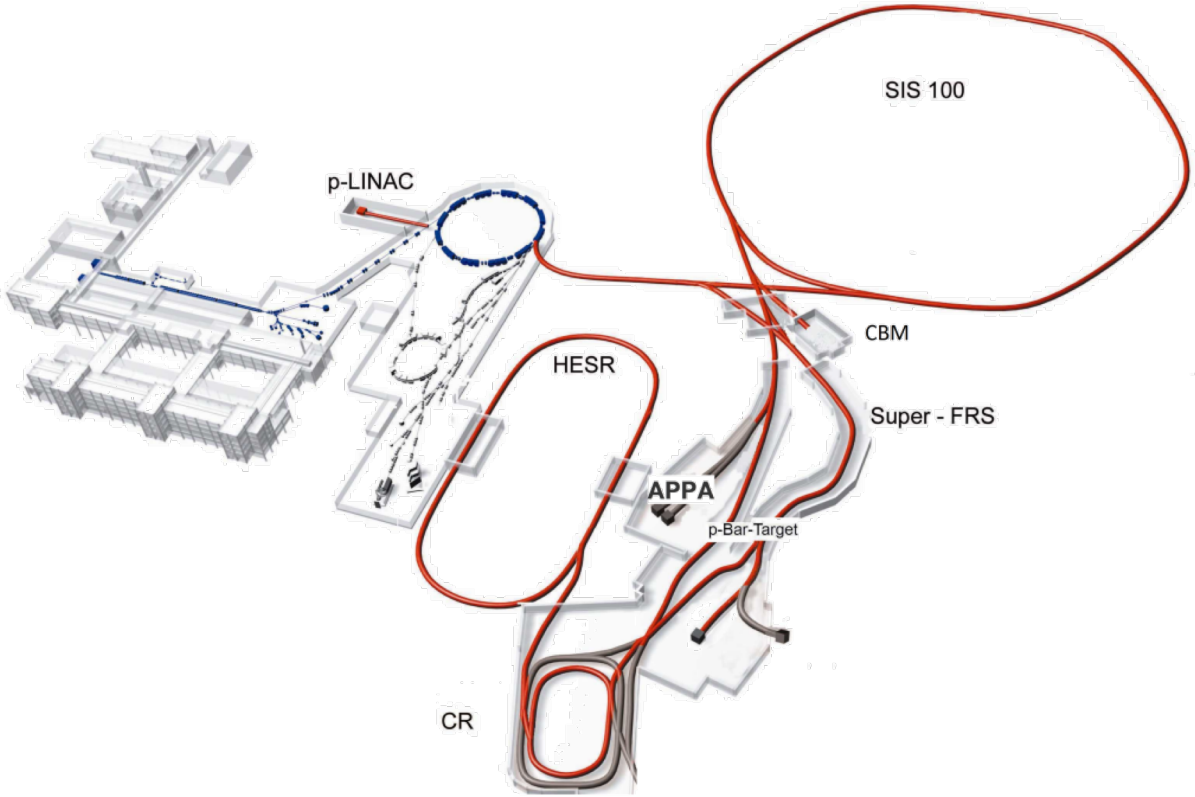
G.Franchetti, et.al., IPAC2015

SIS100: the main accelerator of FAIR

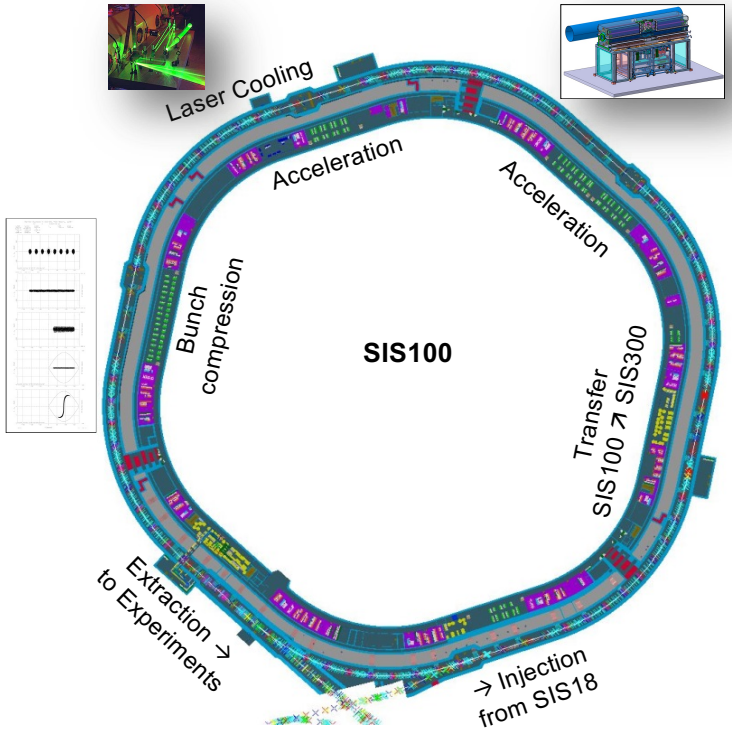
SIS100

- C: 5 x SIS18 = 1 083.6 m
- Ions H−U.
- U^{28+} 0.2→1.5 GeV/u
- p^{+} 4→29 GeV
- High-intensity, low-loss operation
- Coherent instabilities
- Space charge tune spread up to 0.3

- Under construction, commissioning 2025.

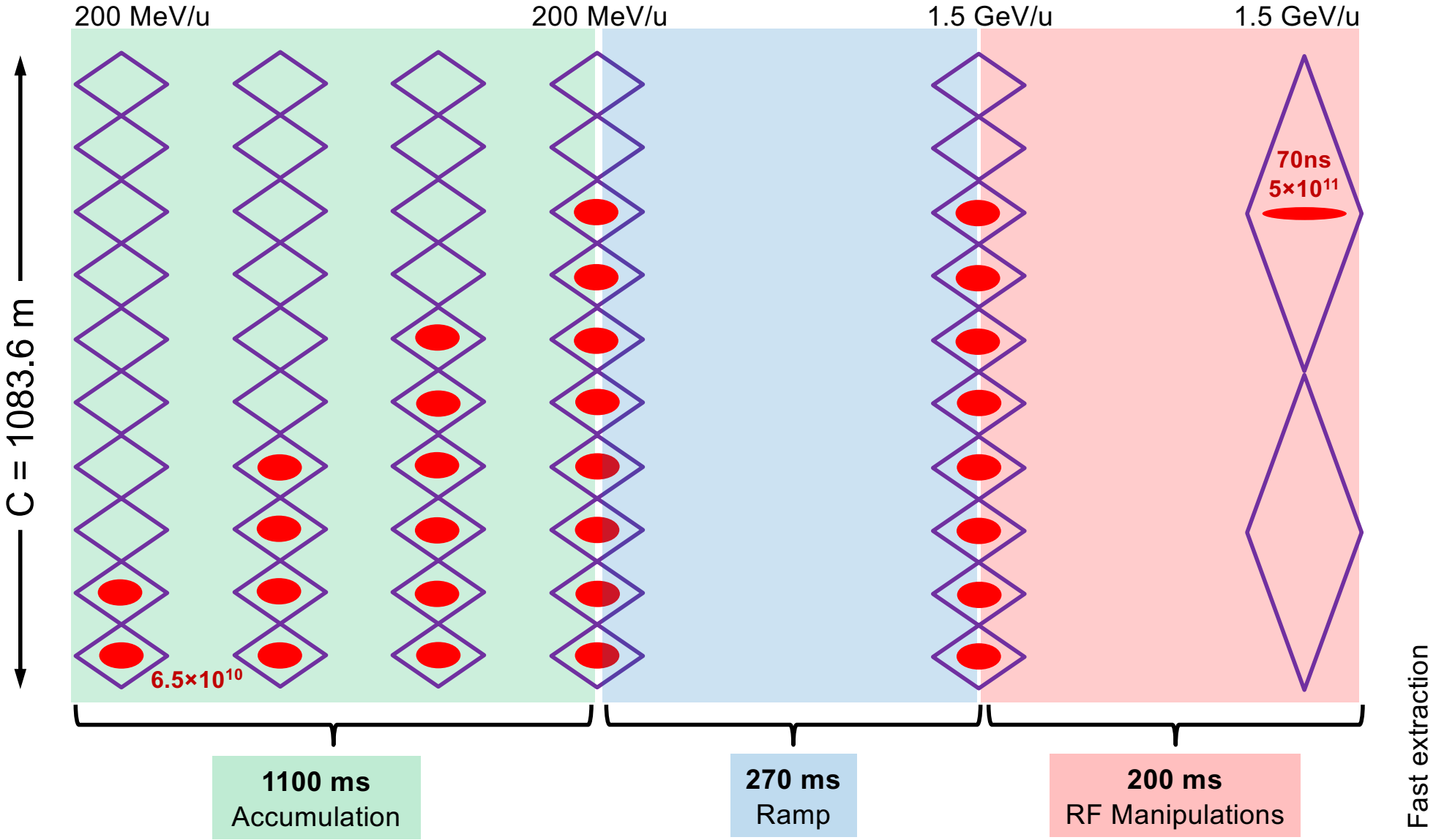


The SIS100 synchrotron

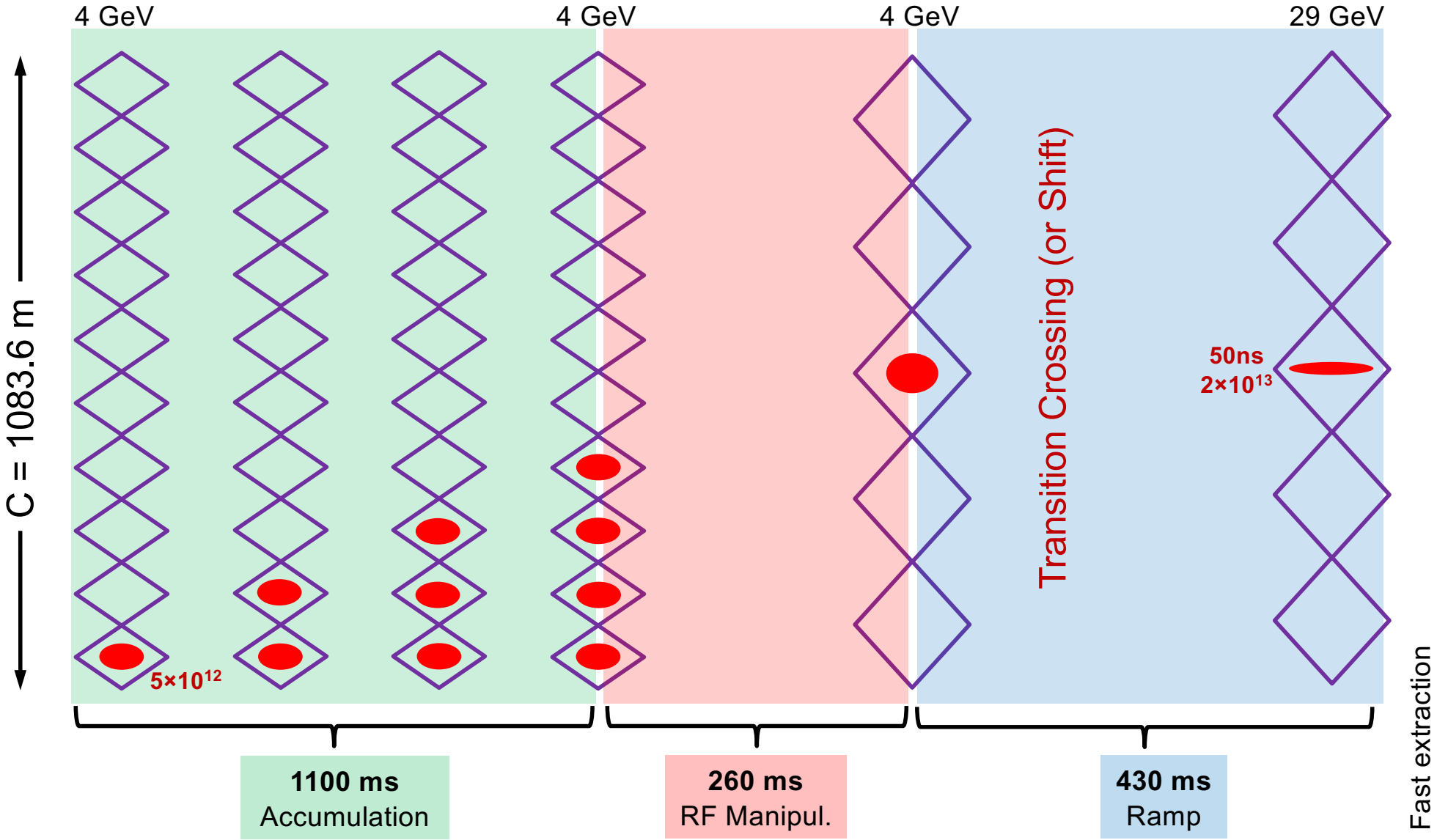


- Fast ramping superferric magnets (4 T/s) with “cool” and thin beam pipe.
- Cycle rates of up to 1 Hz (1 s accumulation after injection)
- Slow extraction (over seconds) or fast extraction (single compressed bunches)

SIS100 Reference Cycle: U^{28+} fast extraction

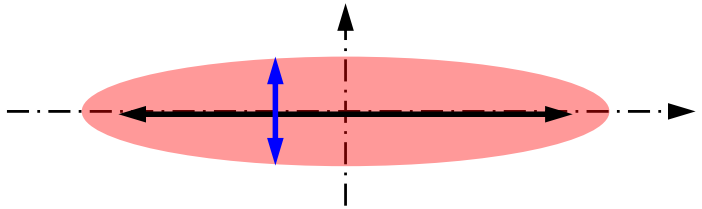


SIS100 Reference Cycle: protons



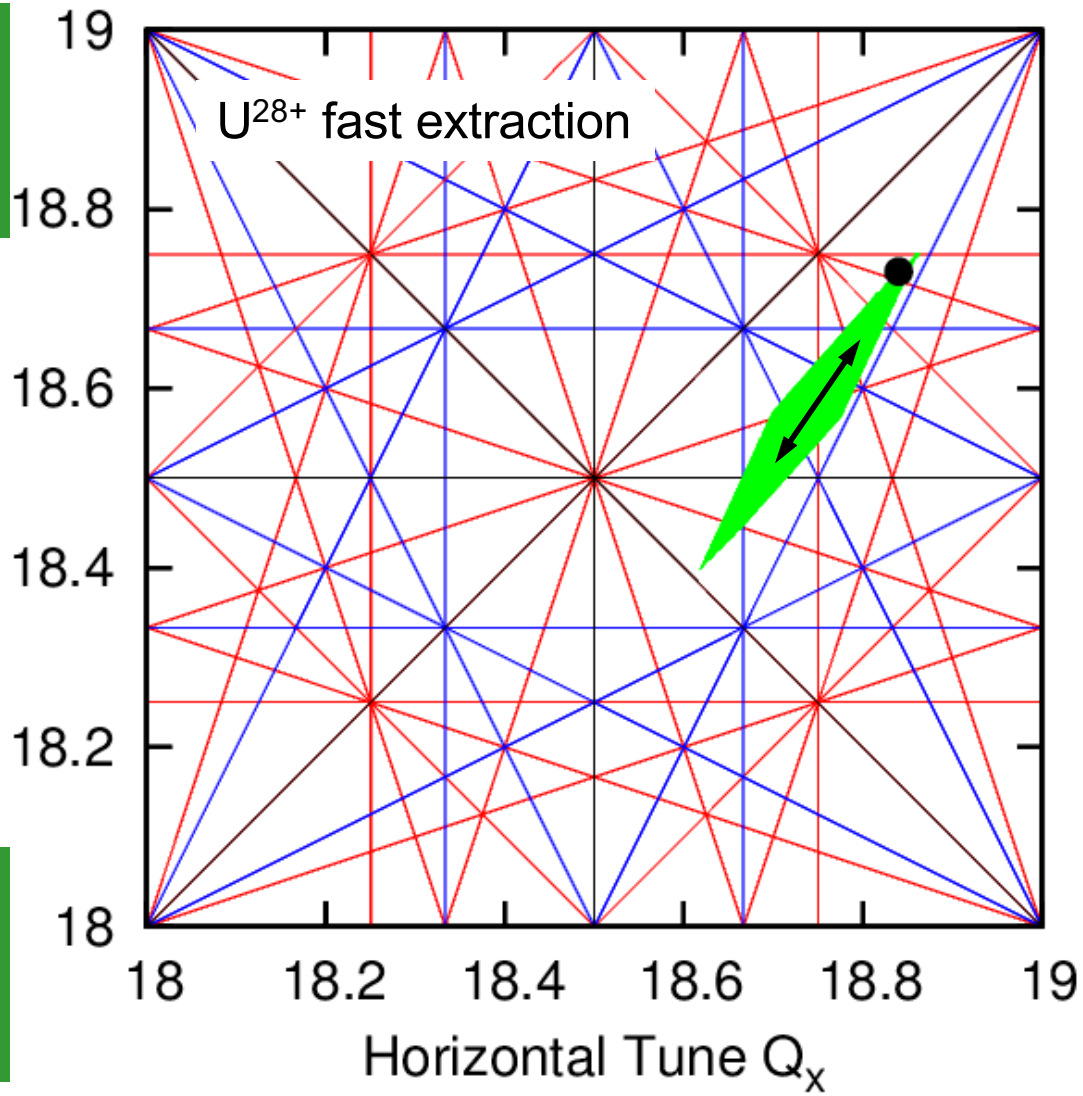
SIS100 Resonance Diagram

Strong effects of space charge for SIS100 beams:
U: 0.3 (injection), 0.07 (after ramp)
p: 0.14 (injection), 0.03 (after ramp)

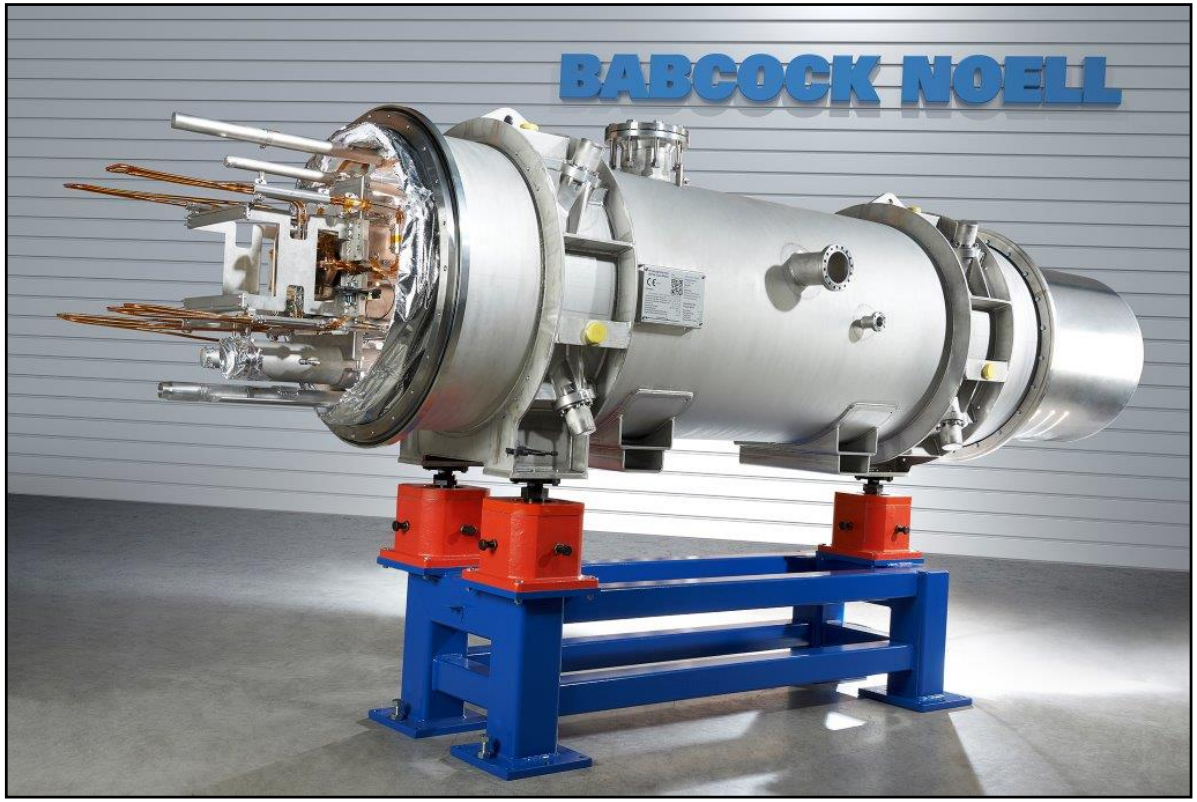


$f_{longitudinal} \approx 1.5$ kHz
(T ≈ 600 us)
$f_{transverse} \approx 5$ MHz
(T ≈ 0.2 us)

Particles cross different resonances while performing synchrotron oscillations.
Errors + Space-charge: a key aspect for SIS100 beam dynamics



SIS100 Dipole Magnets

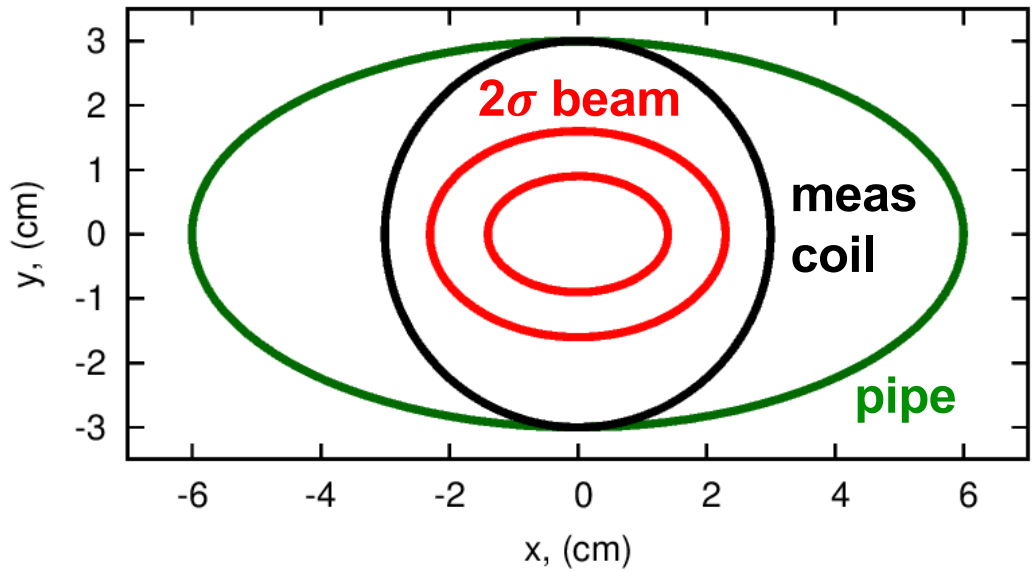


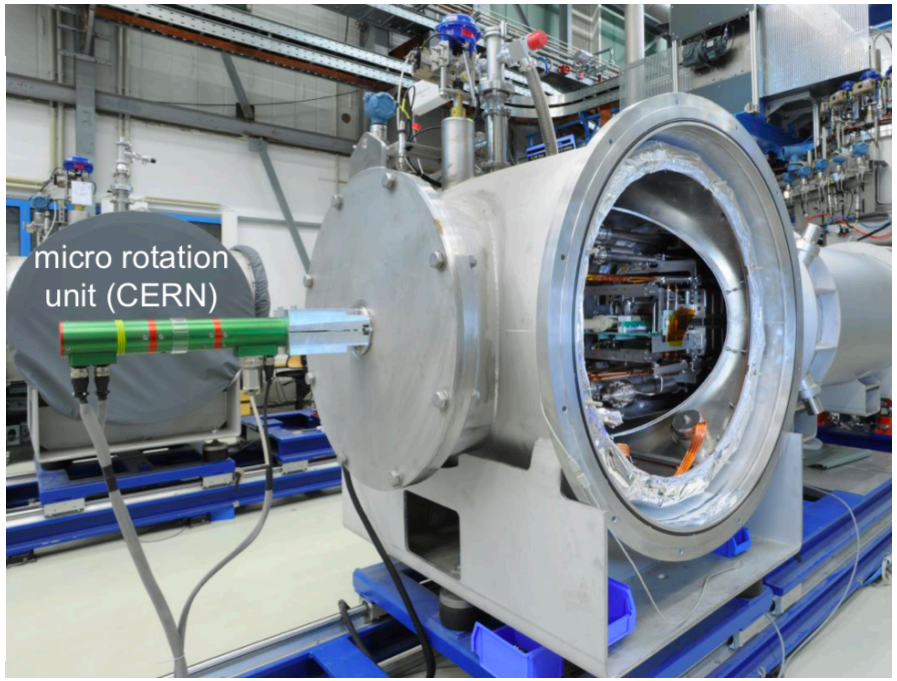
Fast-ramp (4 T/s) superconducting dipol magnets, under series production. Presently, more than a half (54) is delivered and tested.

SIS100 Dipole Magnets

Series B field measurements:

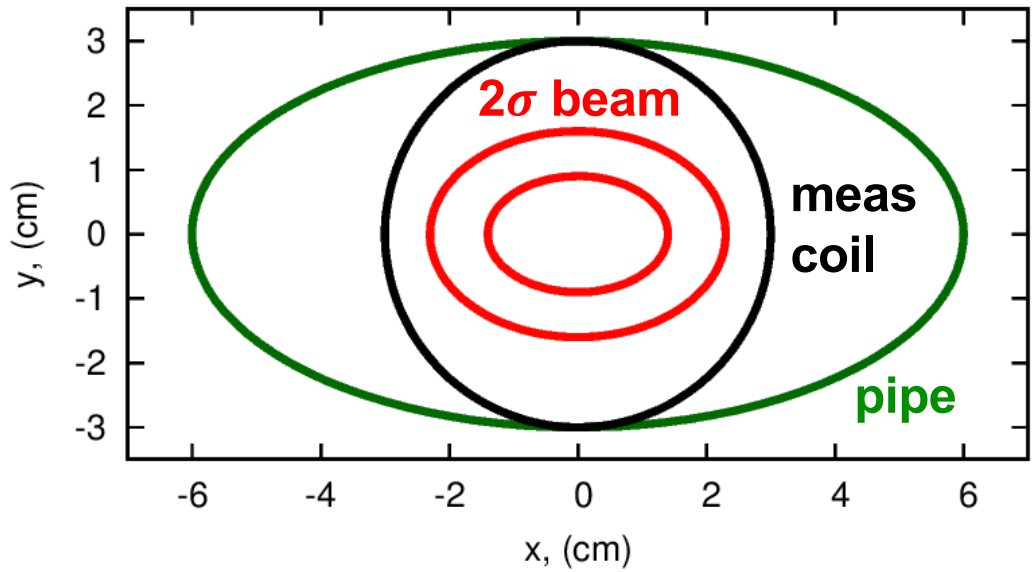
- Rotation coil *R*=30 mm
- 5 positions along the magnet
- Coil on the axis (curved magnet, 3.33°)

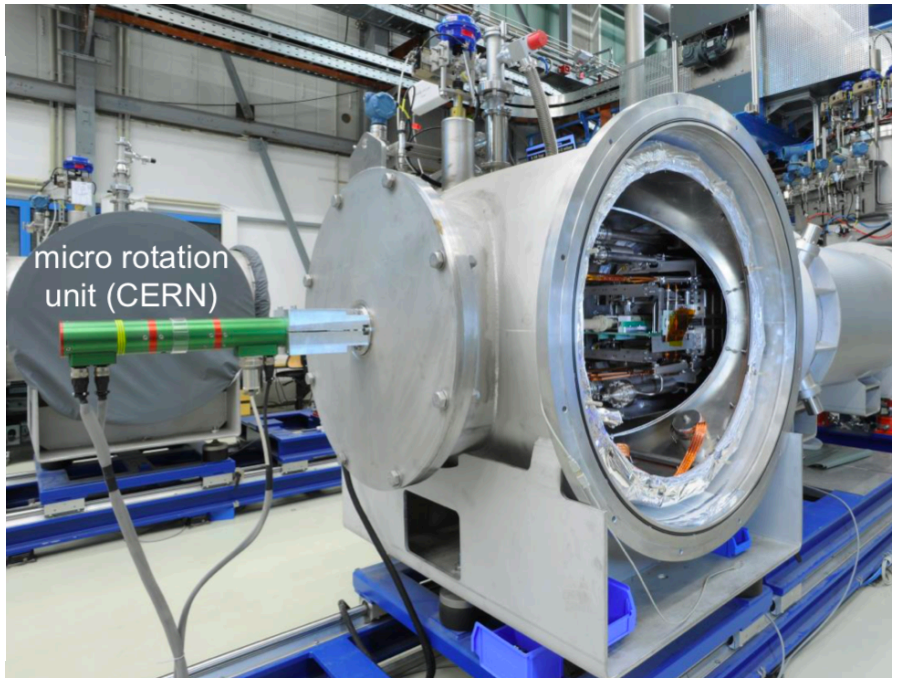




SIS100 Dipole Magnets

B field measurements for the First of Series (FoS) magnet revealed an insufficient field quality (2014)
→ the origins in the mechanic precisions were found, technology was improved (lamination stamping, welding, …)





SIS100 Dipole Magnets

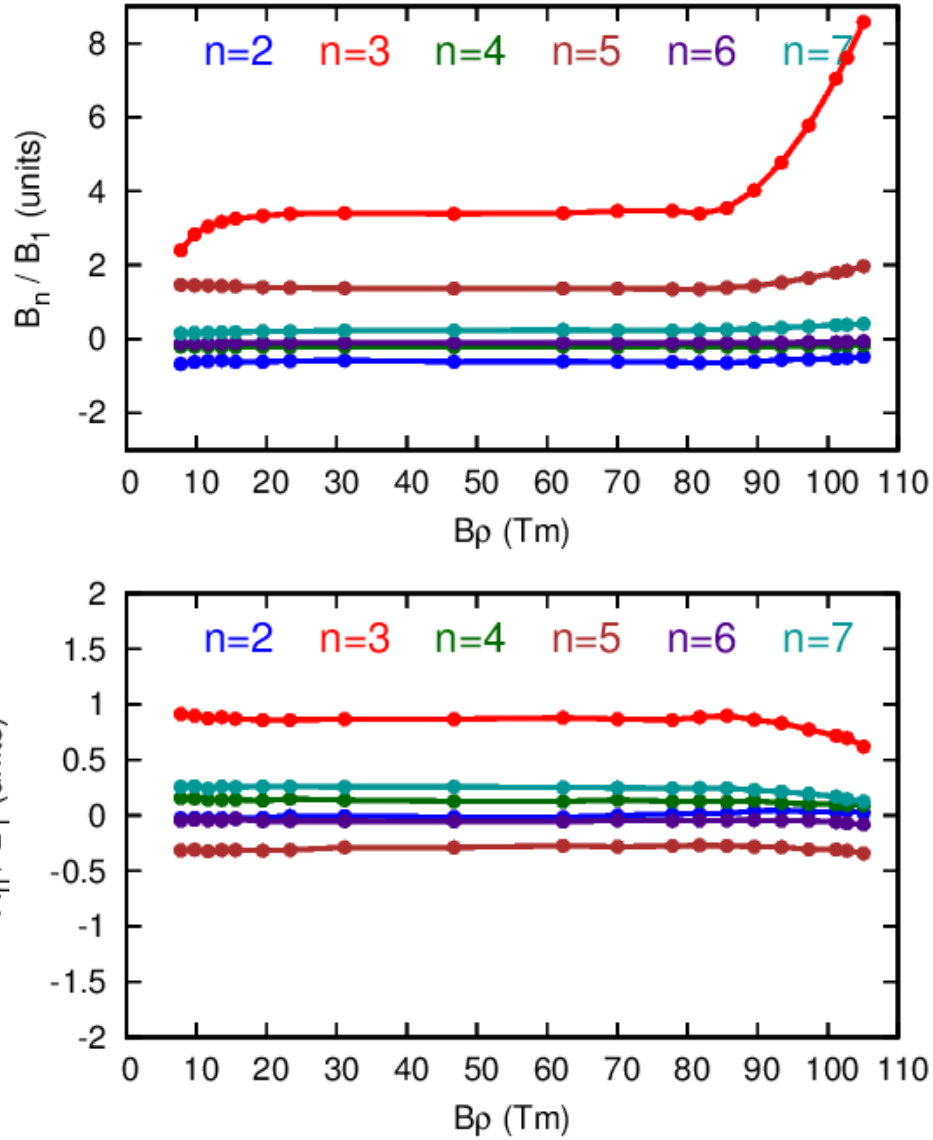
An example for the field measurements for one of the series magnets (data by F. Kaether, et al)

Multipole coefficients of the field errors

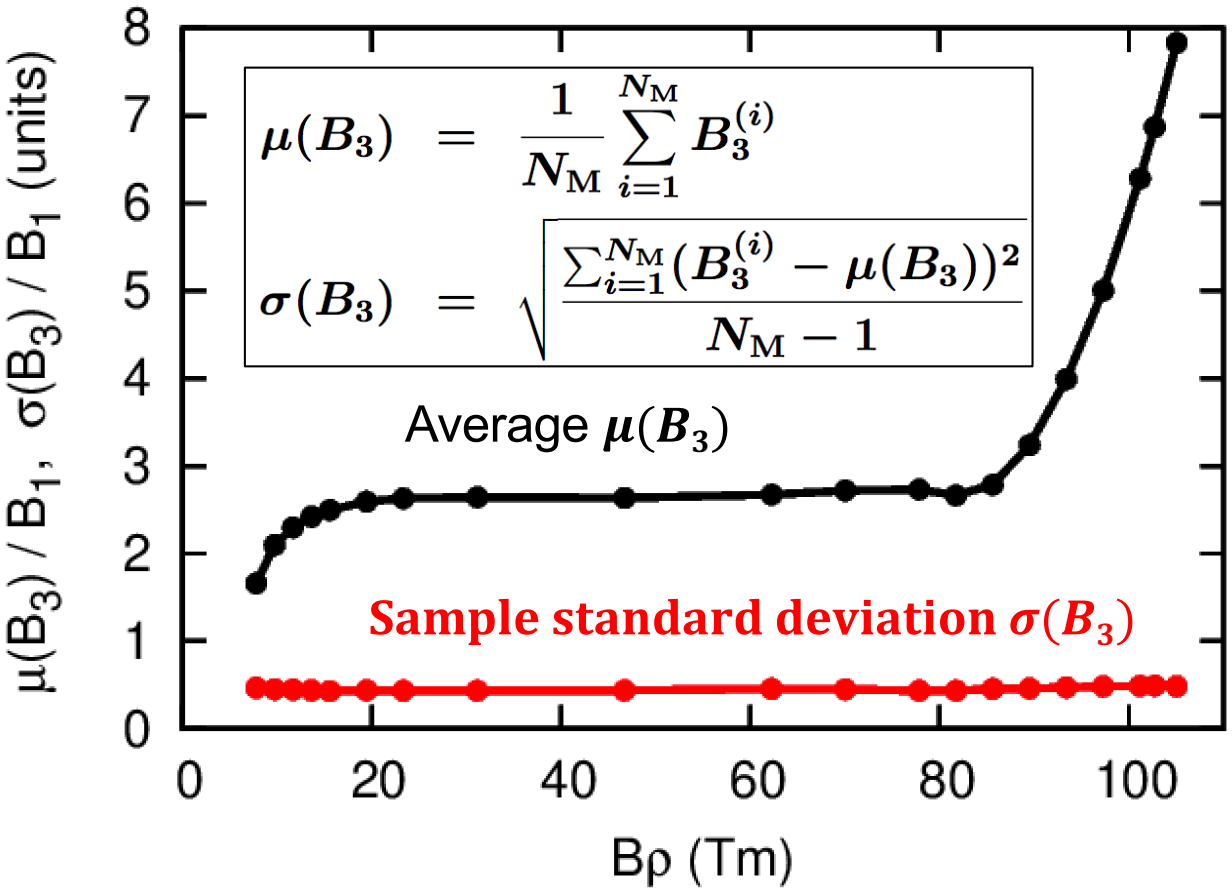
$$B_y + iB_x = (B_n + iA_n)\left(\frac{x+iy}{r_0}\right)^{n-1}$$

B_n normal ; A_n skew
B_1 , A_1 dipole
B_2 , A_2 quadrupole
B_3 , A_3 sextupole
B_4 , A_4 octupole

r_0=30mm, 1 unit = 10^{-4}

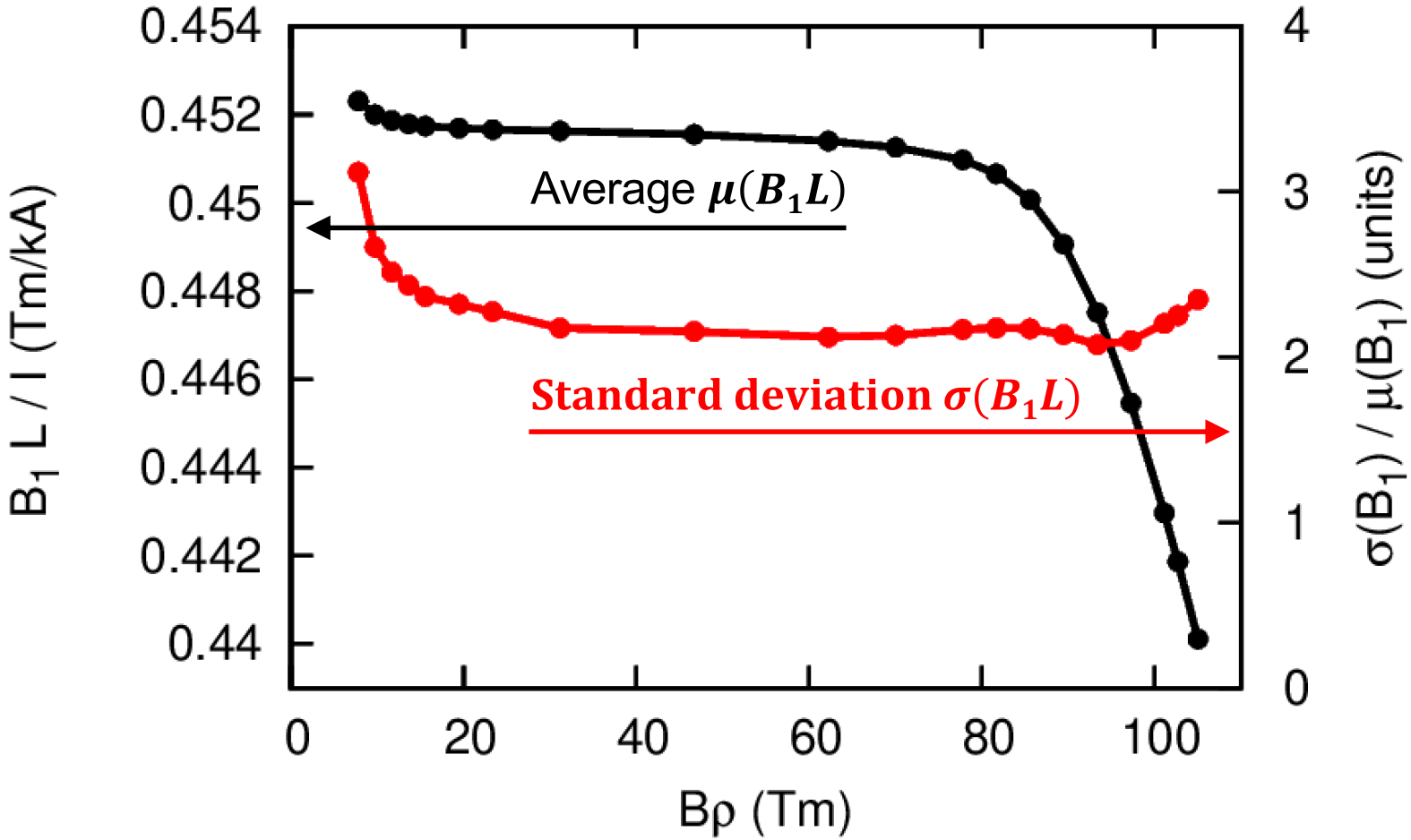


SIS100 Dipole Magnets



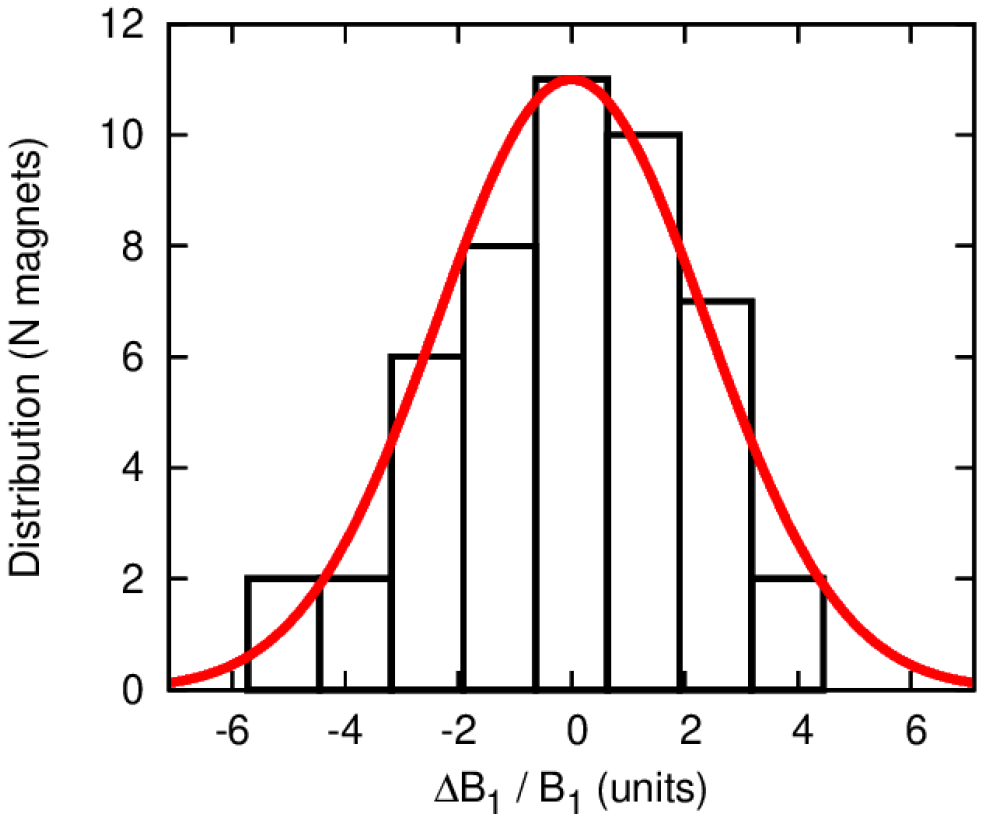
The strongest error component: sextupole.
Very systematic.

SIS100 Dipole Magnets



The total bending field B_1L from the 49 series magnets. Very systematic. SIS100 Closed Orbit correction system covers at least 40 units.

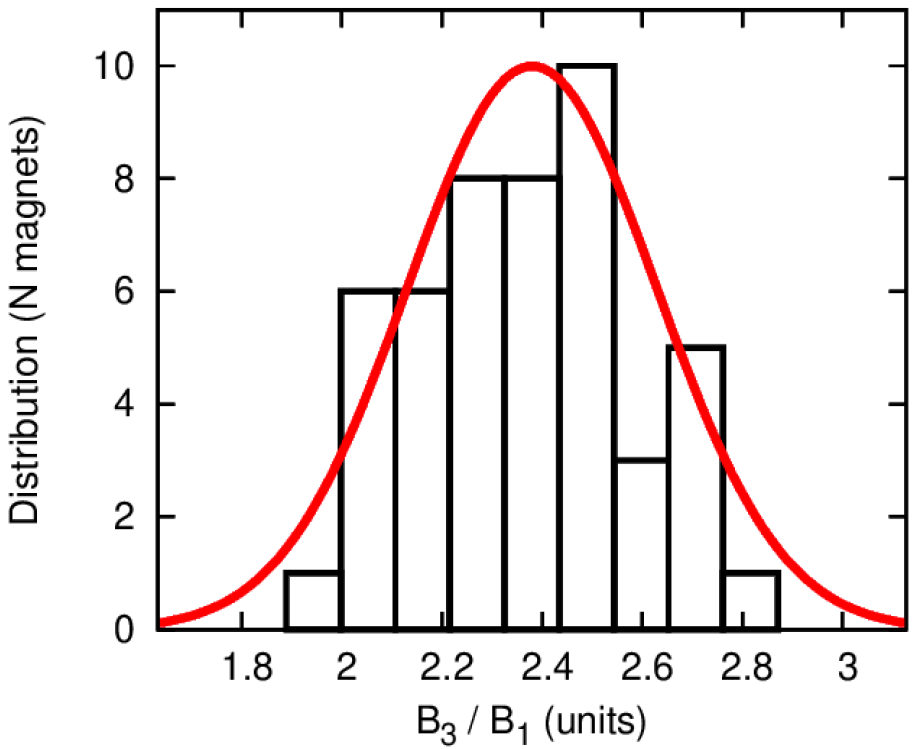
SIS100 Dipole Magnets



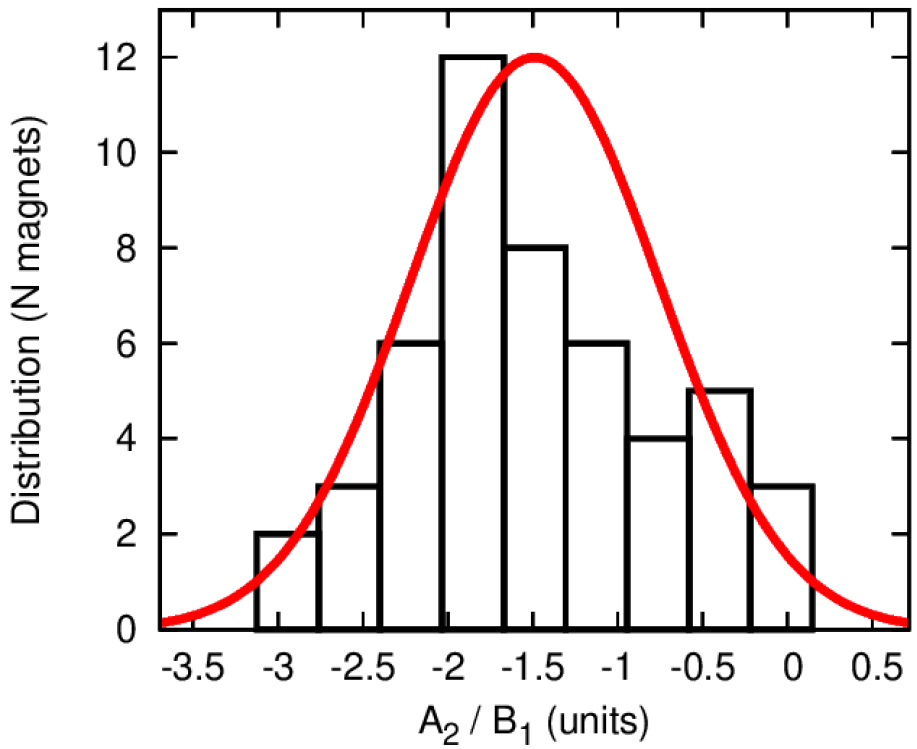
Distribution of the total bending field B_1L from the 49 magnets.
Red line: Gaussian.

SIS100 Dipole Magnets

Normal sextupole



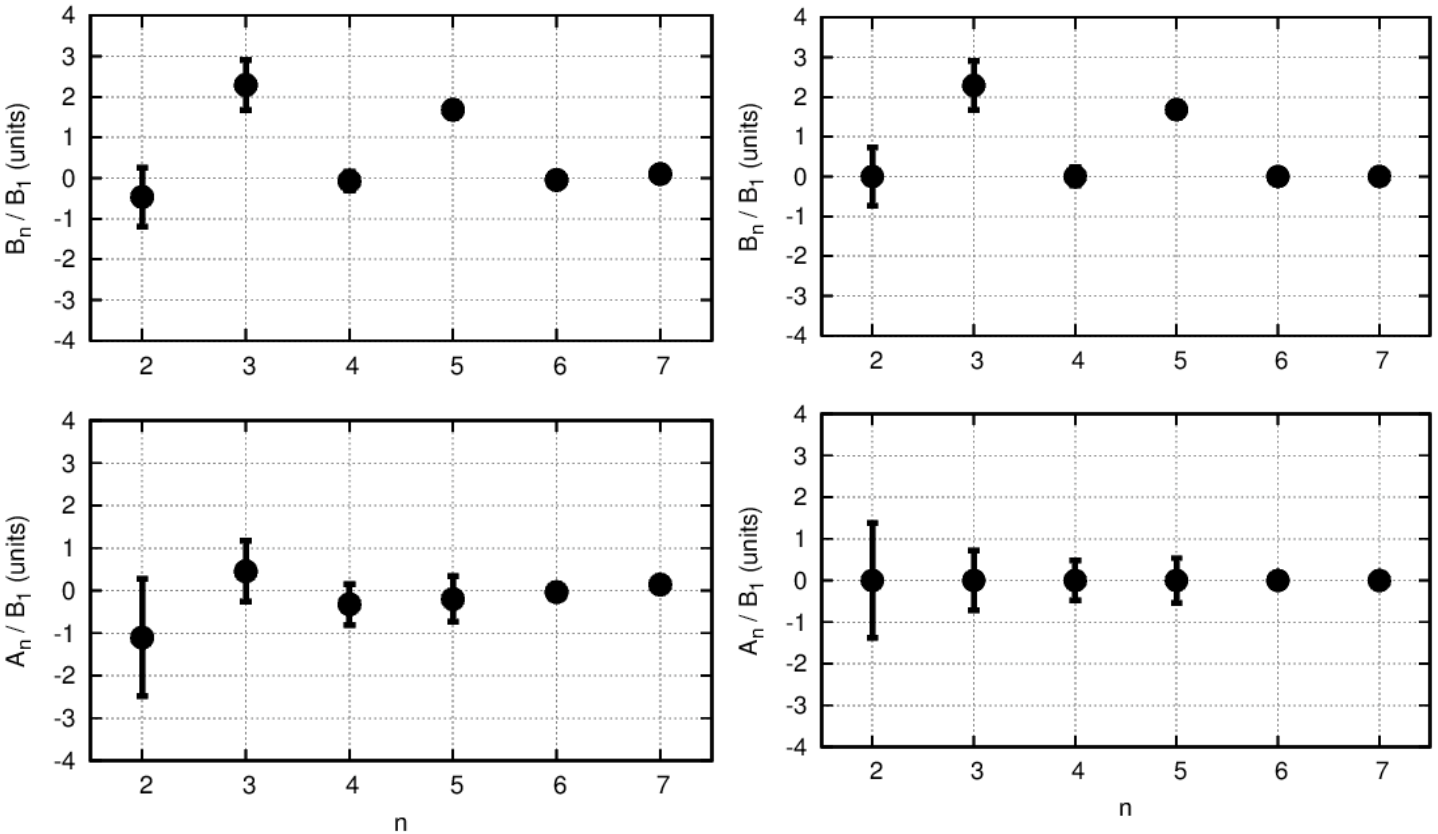
Skew quadrupole



Distribution of the B_3 and A_2 errors from the 49 magnets.
Red line: Gaussian.

SIS100 Dipole Magnet Model

The field measurements of the dipole series provide
the model of the dipole magnets for particle tracking simulations



Assumptions for the magnet model:

1. Only the allowed (B_3, B_5, B_7) systematic components are nonzero
2. The random errors = sample standard deviations

r_0=30mm
Plot: $\pm 2\sigma$ bars
1 unit = 10^{-4}

Results of the measurements

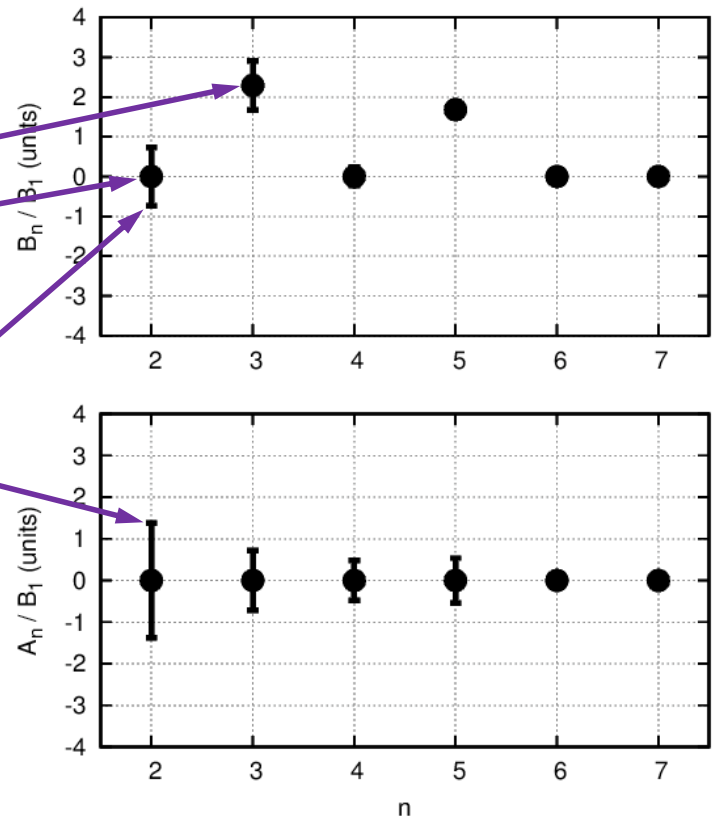
The model used in simulations

SIS100 Dipole Magnet Model

The field measurements of the dipole series provide
the model of the dipole magnets for particle tracking simulations

Fixed values are the systematic components

The bars show the random components, i.e. the amplitude of the Gaussian distribution among magnets



Assumptions for the magnet model:

1. Only the allowed (B_3, B_5, B_7) systematic components are nonzero
2. The random errors = sample standard deviations

r_0=30mm
Plot: $\pm 2\sigma$ bars
1 unit = 10^{-4}

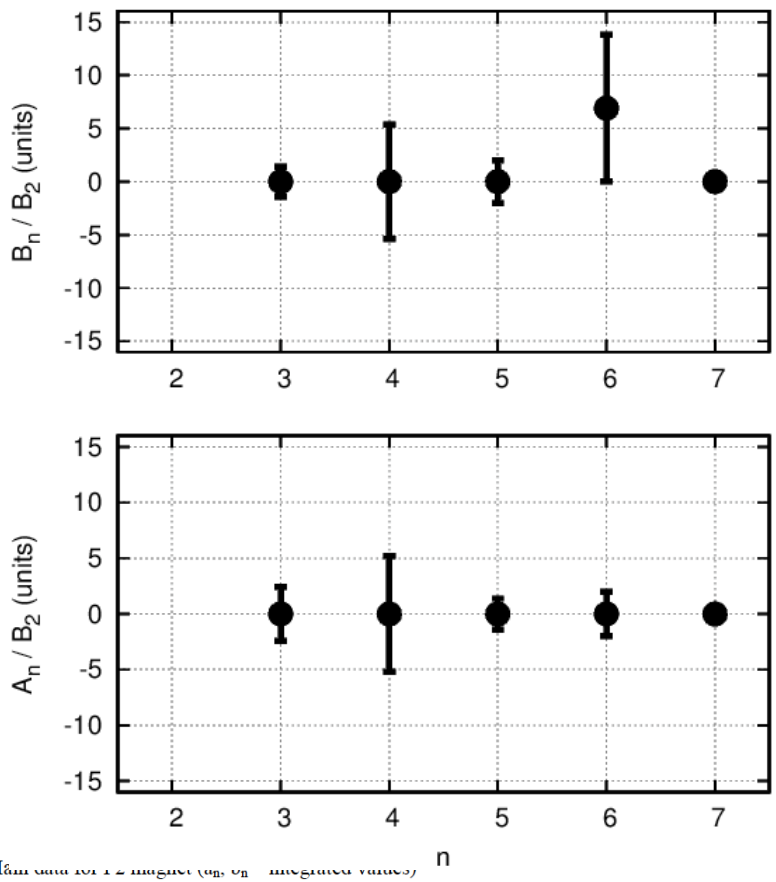
B_n normal ; A_n skew
B_2 , A_2 quadrupole
B_3 , A_3 sextupole
B_4 , A_4 octupole

The model used in simulations,
from the half of the series magnets

SIS100 Quadrupole Magnets

The production of SIS100 main quadrupole sc magnets (166) starts at JINR, Dubna.

Measurements of the B-field for a FoS magnet.



Assumptions for the magnet model:

1. Only the allowed (B_6) systematic components are nonzero
2. The random errors = from the measurement (conservative model)

r_0=40mm
Plot: $\pm 2\sigma$ bars
1 unit = 10^{-4}

Table 1: Main data for FS magnet (a_n, b_n – integrated values)

I [kA]	L_{eff} [mm]	G [T/m]	a_n*10^4								b_n*10^4							
			3	4	5	6	7	8	9	10	3	4	5	6	7	8	9	10
0.9	1243.53	2.687	-0.5	-2.6	0.7	0.8	-0.3	0.3	-0.2	-0.4	-0.6	2.7	0.9	6.9	-0.3	0.5	0.1	-1.0
1.2	1243.37	3.584	-1.2	-2.5	0.4	1.0	-0.3	0.6	-0.3	-0.2	-0.6	2.6	0. 9	6.8	-0.3	0.6	0.1	-1.0
1.5	1243.22	4.480	-1.1	-2.4	0.6	1.0	-0.1	0.5	-0.2	-0.2	-0.6	2.4	0.9	6.9	-0.3	0.6	0.1	-1.0
3	1242.64	8.957	-1.1	-2.4	0.6	1.0	-0.1	0.4	-0.1	-0.2	-0.7	2.1	0.9	6.9	-0.3	0.6	0.1	-1.0

A.Shemchuk, M.Shandov, Report 2018-02-16

Simulations: Code “elegant”

Particle tracking simulations using the code Elegant

M. Borland, "*elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation*" Advanced Photon Source LS-287, September 2000. Y. Wang and M. Borland, "*Pelegant: A Parallel Accelerator Simulation Code for Electron Generation and Tracking*", Proceedings of the 12th Advanced Accelerator Concepts Workshop, AIP Conf. Proc. 877, 241 (2006)

- Nominal U^{28+} bunch during the 1 sec accumulation at the injection energy
- 6D particle dynamics in the complete SIS100 lattice
- Systematic and random errors in the magnets, closed-orbit distortion
- High intensity: frozen nonlinear space-charge model
- Multi-core simulations on the Green IT Cube at GSI

Other code developments for SIS100 (MADX, SixTrackLib with pyHEADTAIL):
Talk V. Chetvertkova on Tuesday, talk A. Oeftiger on Monday.

Other simulation developments at GSI:
Talk G. Franchetti on Tuesday, talk I. Hofmann on Monday

“elegant” simulations

Nonlinear space charge for a Gaussian bunch

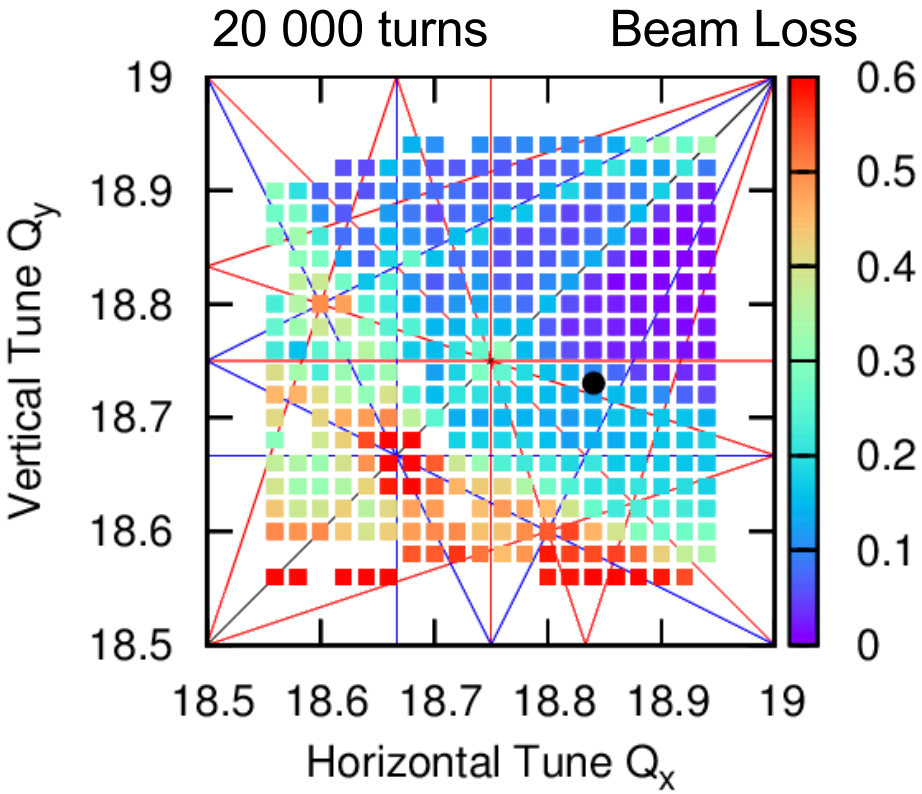
$$\Delta x' = \frac{K_{sc} L e^{-z^2/(2\sigma_z^2)}}{2\sigma_z\sqrt{\sigma_x^2-\sigma_y^2}} Im\left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - e^{-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}} w\left(\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

$$\Delta y' = \frac{K_{sc} L e^{-z^2/(2\sigma_z^2)}}{2\sigma_z\sqrt{\sigma_x^2-\sigma_y^2}} Re\left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - e^{-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}} w\left(\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

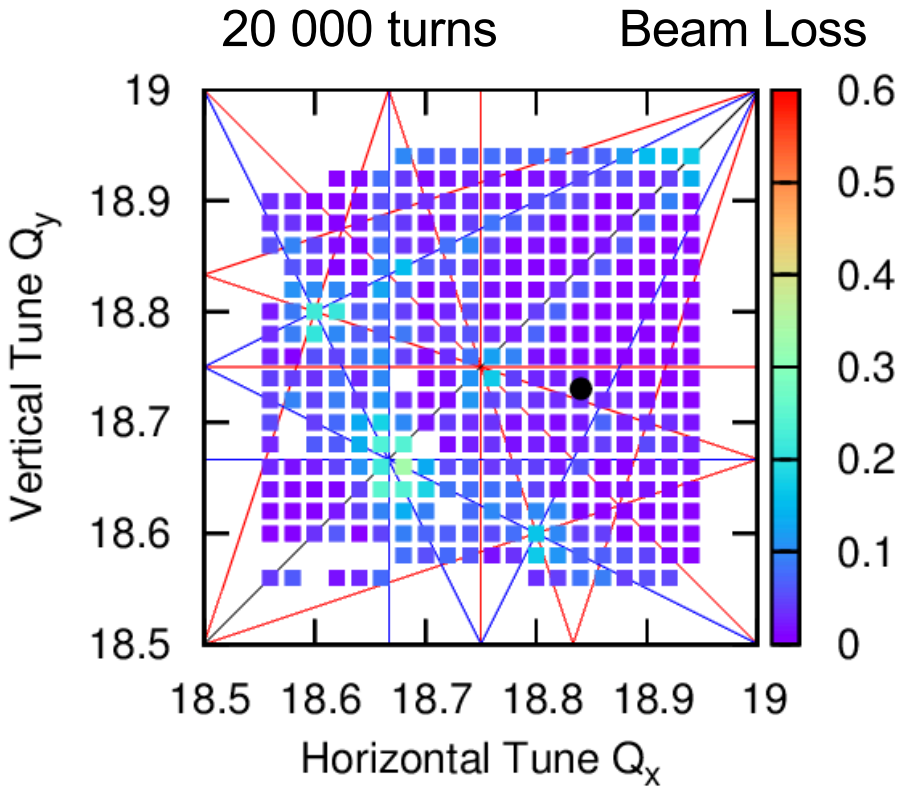
- Dependence of ΔQ_{sc} on the transverse amplitudes
- Effect of the longitudinal profile on ΔQ_{sc} : variation along the synchrotron oscillation
- Effect of the transverse beam size (but not profile)

“elegant“ simulations: Tune Scans

Every square: beam loss (color, 1 is 100%)
after tracking a bunch for 20 000 turns



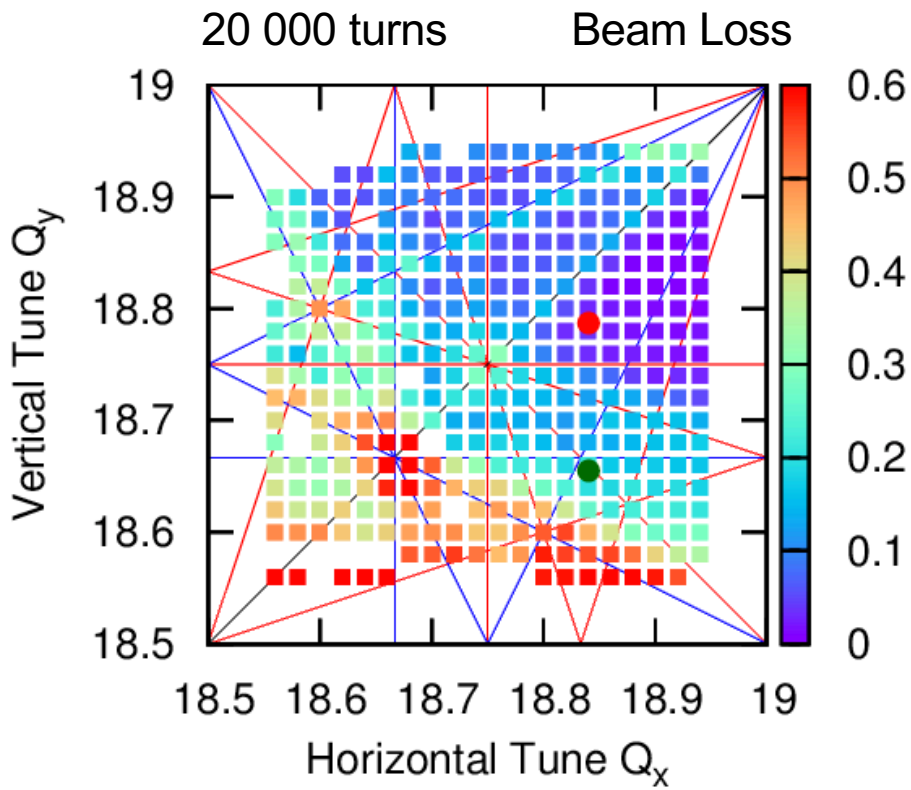
With space charge

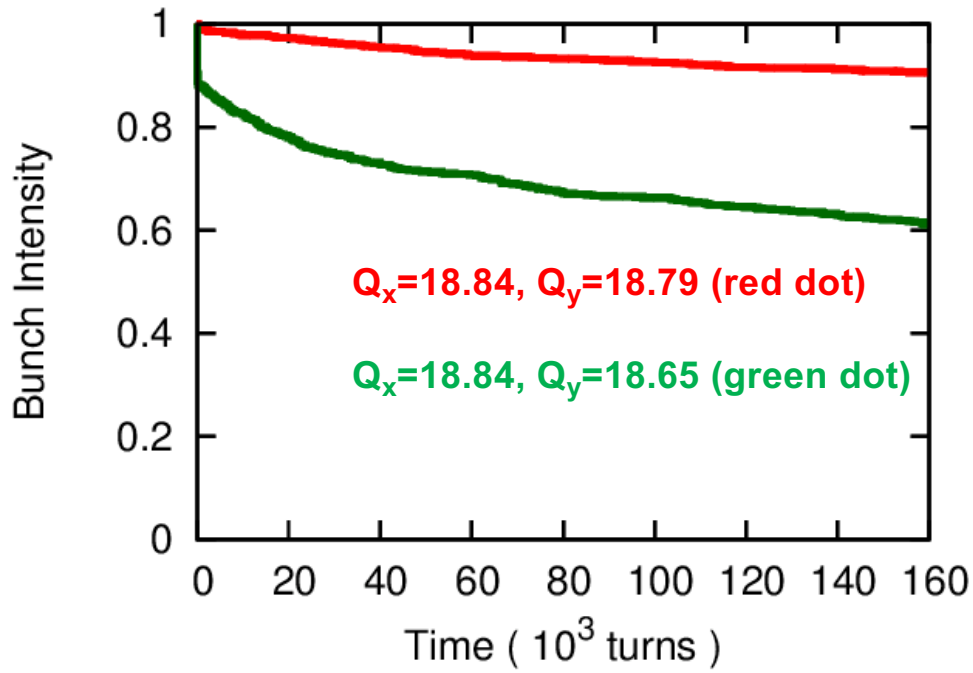


No space charge

“elegant“ simulations for SIS100

There is a good tune area. Longer simulations confirm low losses.





An example for the RIB cycle (1sec, 4 inj × 2 bunches):
first 2 bunches 9% Loss → 5.5% Total Beam loss
160 000 turns = 1 sec.

Correctors in SIS100

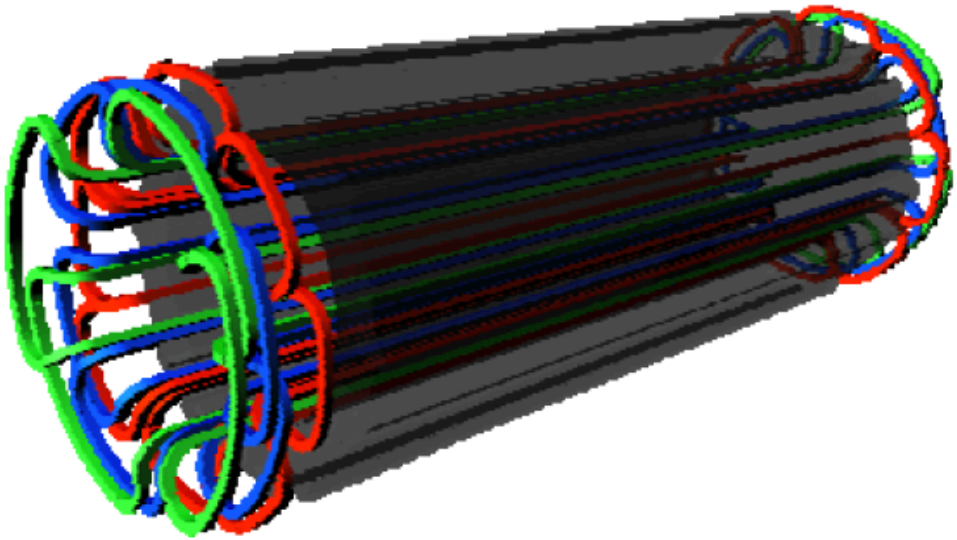
12 Corrector Quadrupoles (**B2**)
0.75T/m, 0.75m

No skew Quadrupoles (~~**A2**~~)

42 ξ−Sextupoles (**B3**)
350T/m^2, 0.5m
(plus 6 Resonance Sextupoles)

12 Correstor Skew Sext (**A3**)
50T/m^2, 0.75m

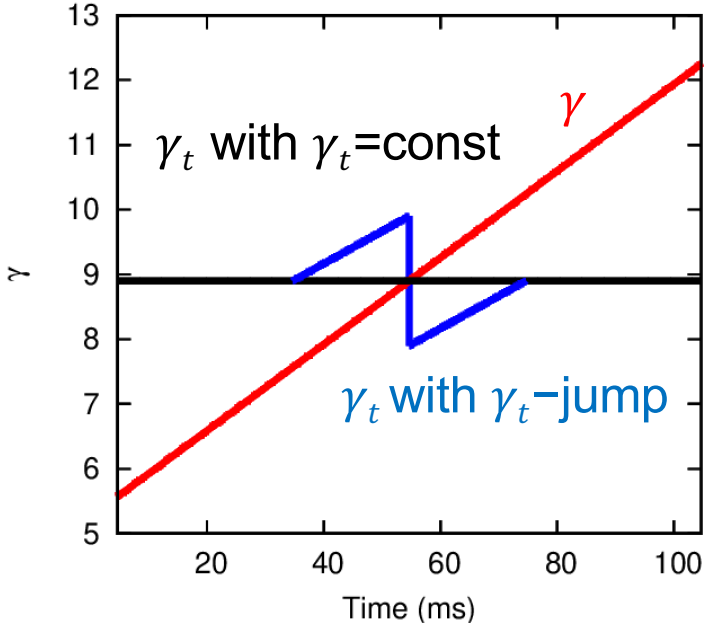
12 Corrector Octupoles (**B4**)
2000T/m^3, 0.75m
Also for Landau damping!

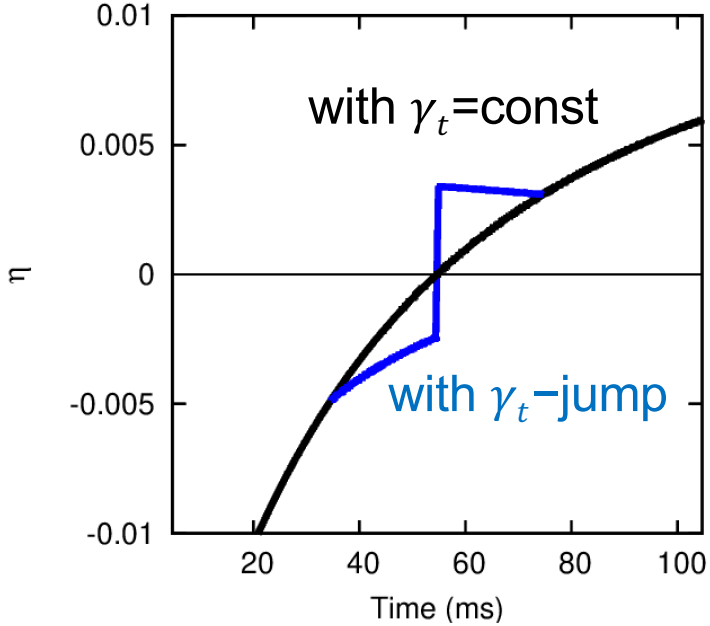


SIS100 Nested
Corrector Magnets (12)

Proton cycle: transition crossing

Without γ_t–jump: small η ($|\eta| < 2.5\times10^{-3}$) for 30 ms.
With γ_t–jump: small η for 0.5 ms.



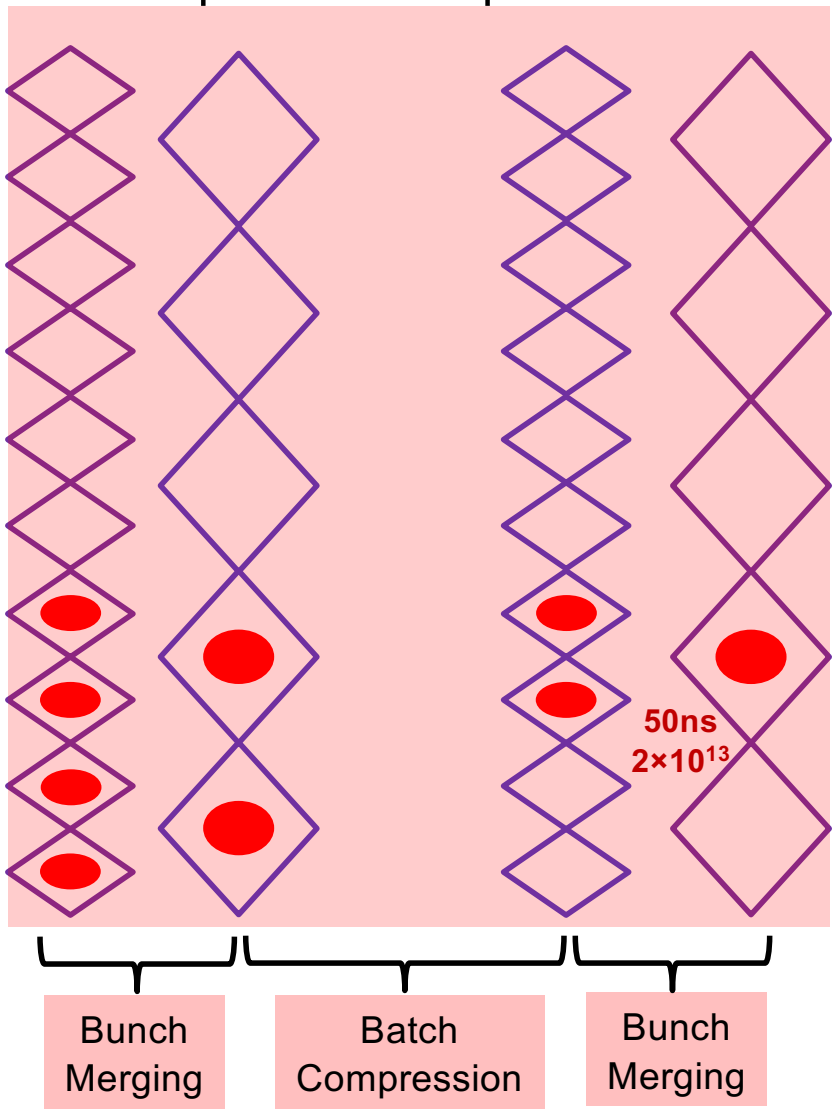


$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$

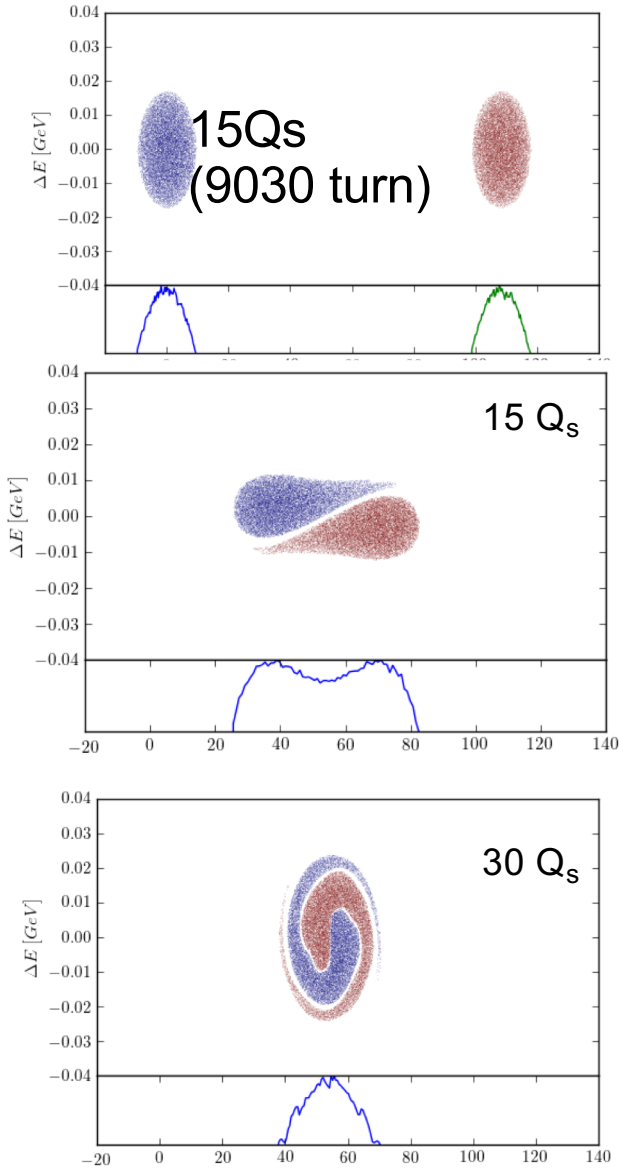
Effects of longitudinal, and transverse space charge for high-intensity proton bunches around transition (T_c=4.5ms)

RF manipulations

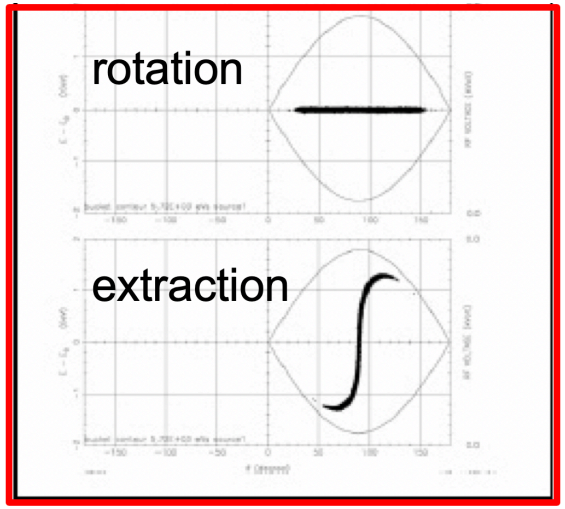
RF manipulations for protons:



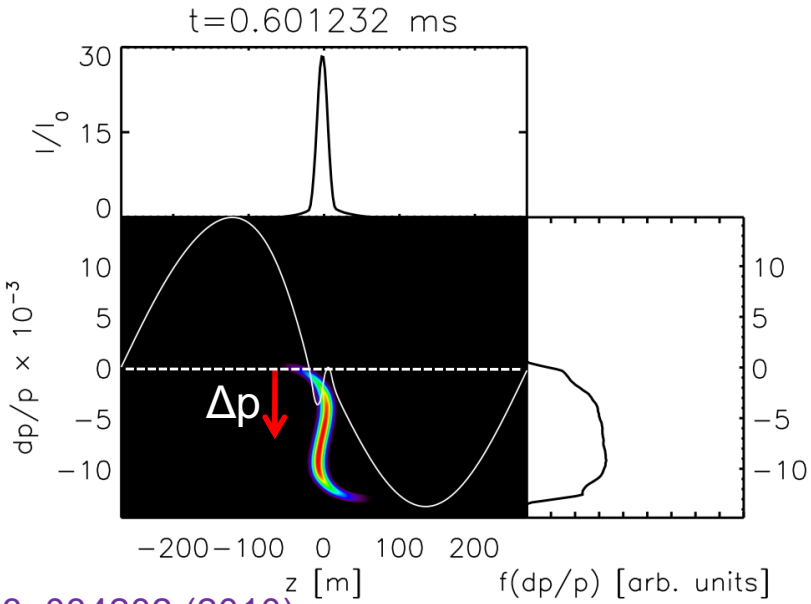
Effect of longitudinal space charge: simulations for the longitudinal emittance preservation and RF scenarios with the high-intensity effects: pyORBIT code (Y.Yuan, GSI, TU Darmstadt).



Reference Cycle: U^{28+} fast extraction



Effect of cavity impedance on the bunch rotation:



magnetic alloy (MA) loaded rf cavities with total: 360 kV (400 kHz)

Large transverse space charge

$$\Delta Q_y^{sc} \approx -0.5$$

(during the last turns)

O. Boine-Frankenheim PRSTB 13, 034202 (2010)

Fast bunch rotation for 70 ns bunch production: 3D space charge problem

Summary

- Large-scale civil construction and component procurement for the FAIR project at GSI in Darmstadt. All components are specified.
- The B-field data from the half of the SIS100 dipole magnets demonstrate a sufficiently good field quality
- The target is as complete as possible knowledge of the SIS100 magnet errors
- In SIS18 and SIS100, space charge is a key aspect of beam dynamics and possibly a beam intensity limitation
- Space charge in SIS100: the 1 sec accumulation, ramp, RF manipulation, transition crossing, short bunch generation (3D)
- Simulation developments using different codes