Beam Dynamics
for SIS100 of FAIR and
for the Future Circular Collider (FCC)

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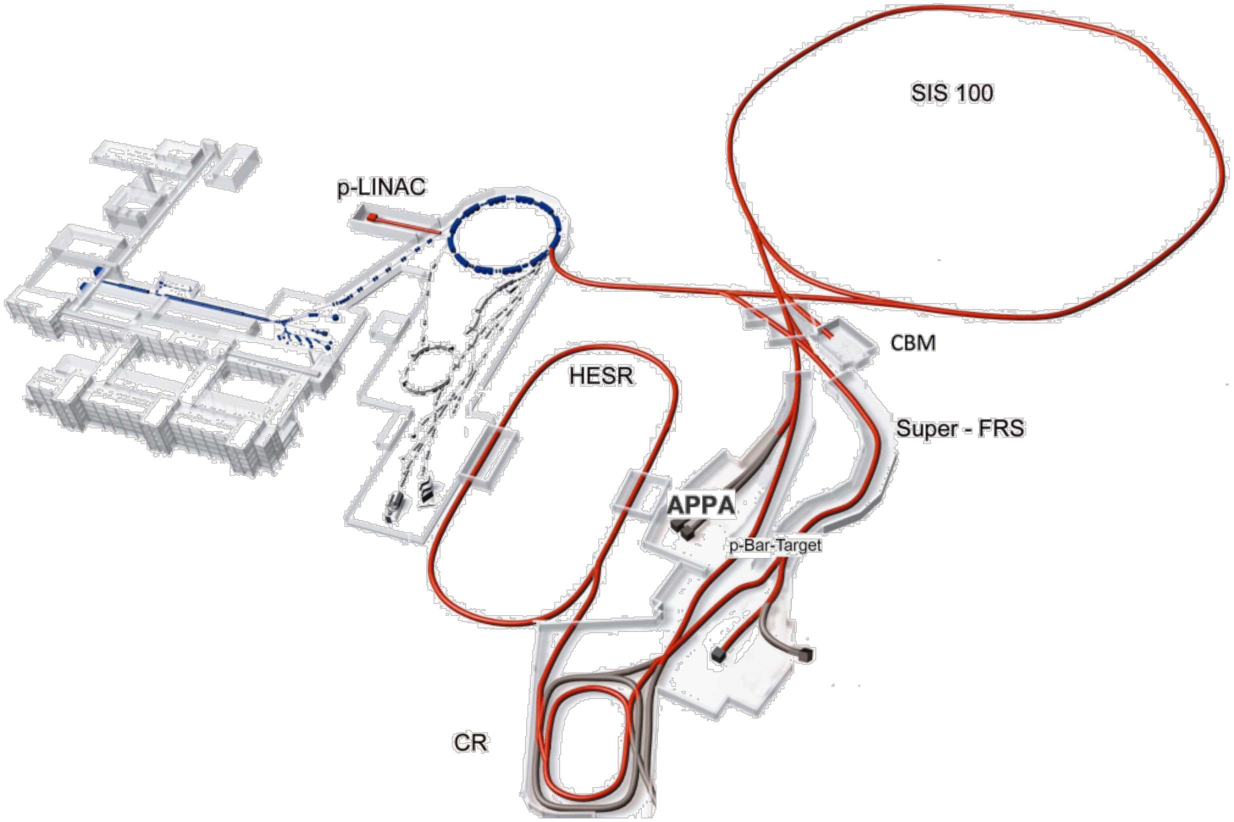
FAIR Project

- NUSTAR
  - R^3B
  - HISPEC/DESPEC
  - MATS
  - LASPEC
  - ILIMA
  - EXL
- APPA
  - SPARC
  - HEDGEHOB
  - BIOMAT
- CBM-HADES
  - CBM
  - HADES
- Antiprotons
  - PANDA

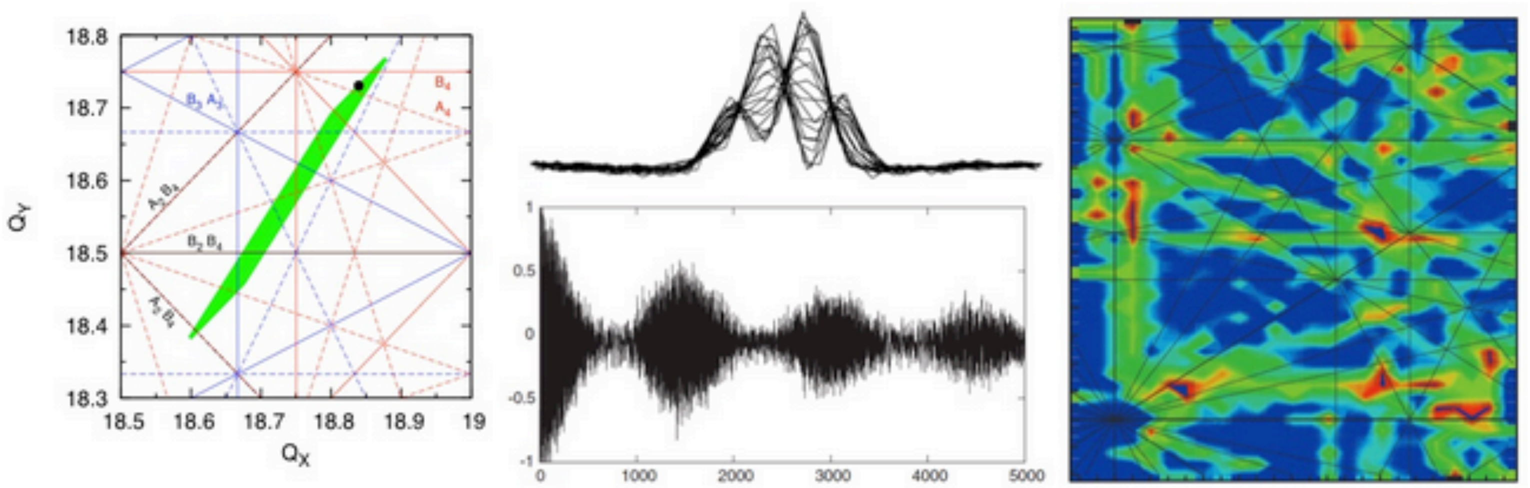
The SIS100 synchrotron is the
central accelerator of the FAIR Project:
Beams of high intensity, high energy, short/long pulses,…



Working Package SIS100 Beam Dynamics

https://wiki.gsi.de/foswiki/bin/view/SIS100BD/WebHome

SIS100 Beam Dynamics



- Instabilities & Mitigation
- Main magnet field quality assessment & sorting
- Beam-loss / emittance simulations
- Resonance correction
- Slow extraction
- Impedances
- RF manipulations and stability
- Bunch compression, transition crossing

The SIS100 Synchrotron

$$E \propto B_{dipole} \times \rho_{bending}$$

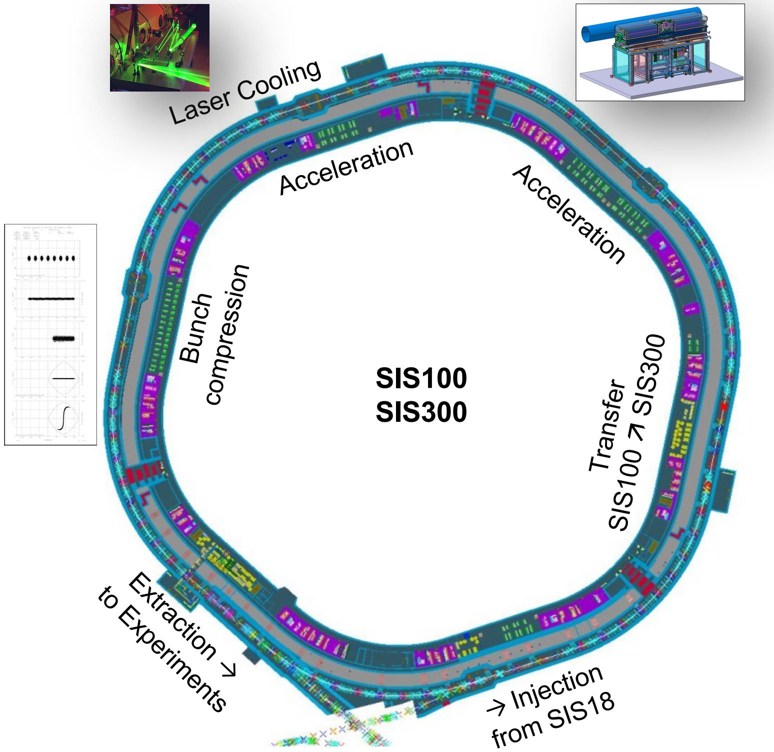
SIS18: 18 Tm
U^{28+} 0.2 GeV/u
Protons 4 GeV

SIS100: 100 Tm
U^{28+} 1.5 GeV/u
Protons 29 GeV

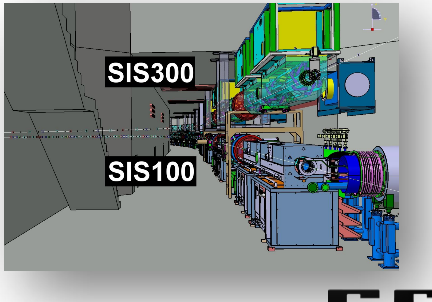
Aerial photo of the construction site taken on May 25, 2014 (photo: Jan Schäfer for FAIR)

The SIS100 Synchrotron

- Length: 5 x SIS18 length (= 1 083.6 m)
- Reference ion operation: U^{28+}
  - Control vacuum pressure
  - “Charge Separator Lattice”
- Protons
  - Variable γ_t-optics
  - Fast γ_t-jump
- RF system
  - State-of-the-art bunch manipulations: Bunch merging & compression, Barrier buckets
- Versatile extraction modes
  - Fast kicker system
  - Slow extraction



Images courtesy of M. Konradt / J. Falenski



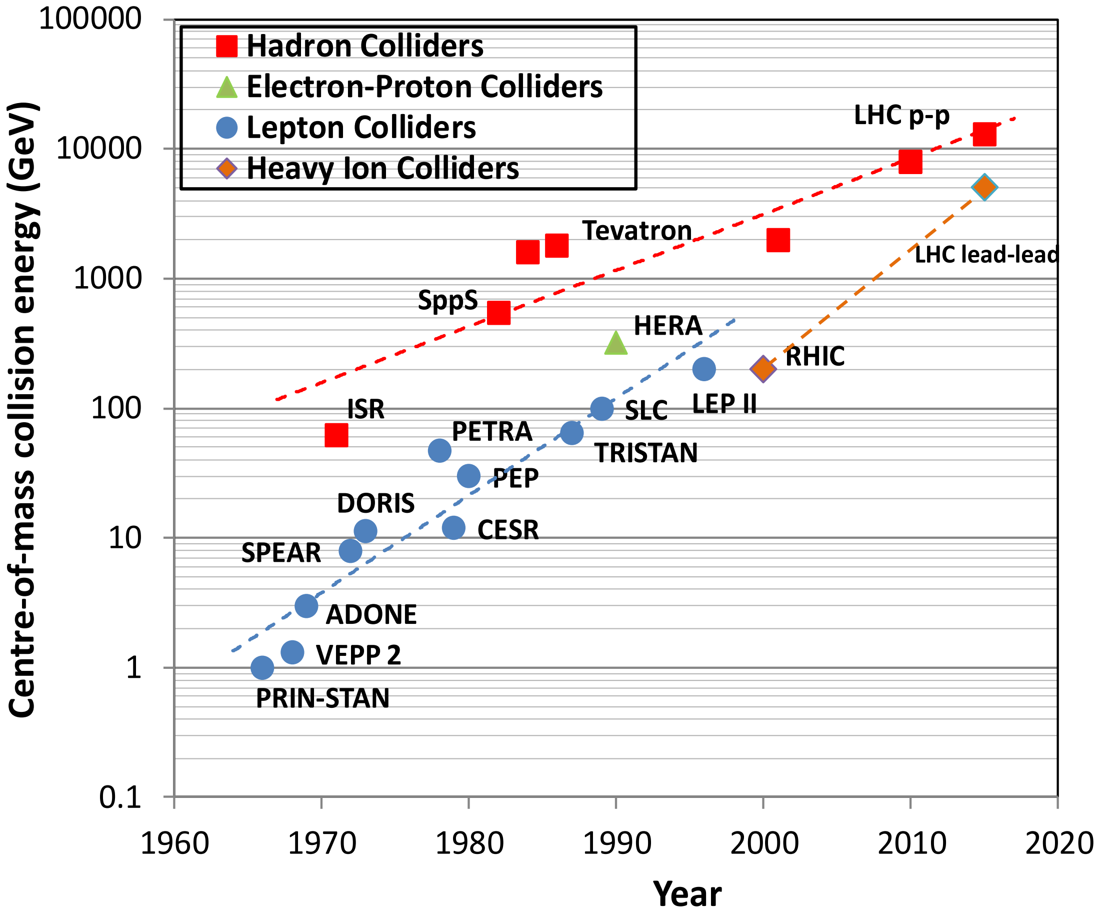
C.Omet, EuCARD-2 XRING Workshop, March 2017

The FCC Study

High Energy: Need for a next-generation accelerator

Since 60s, colliders are major discovery machines

- Higgs Boson
- Dark Matter
- Dark Energy
- Matter ↔ Antimatter
- Gravity
- Uncharted territory in the energy scale
- and much more…



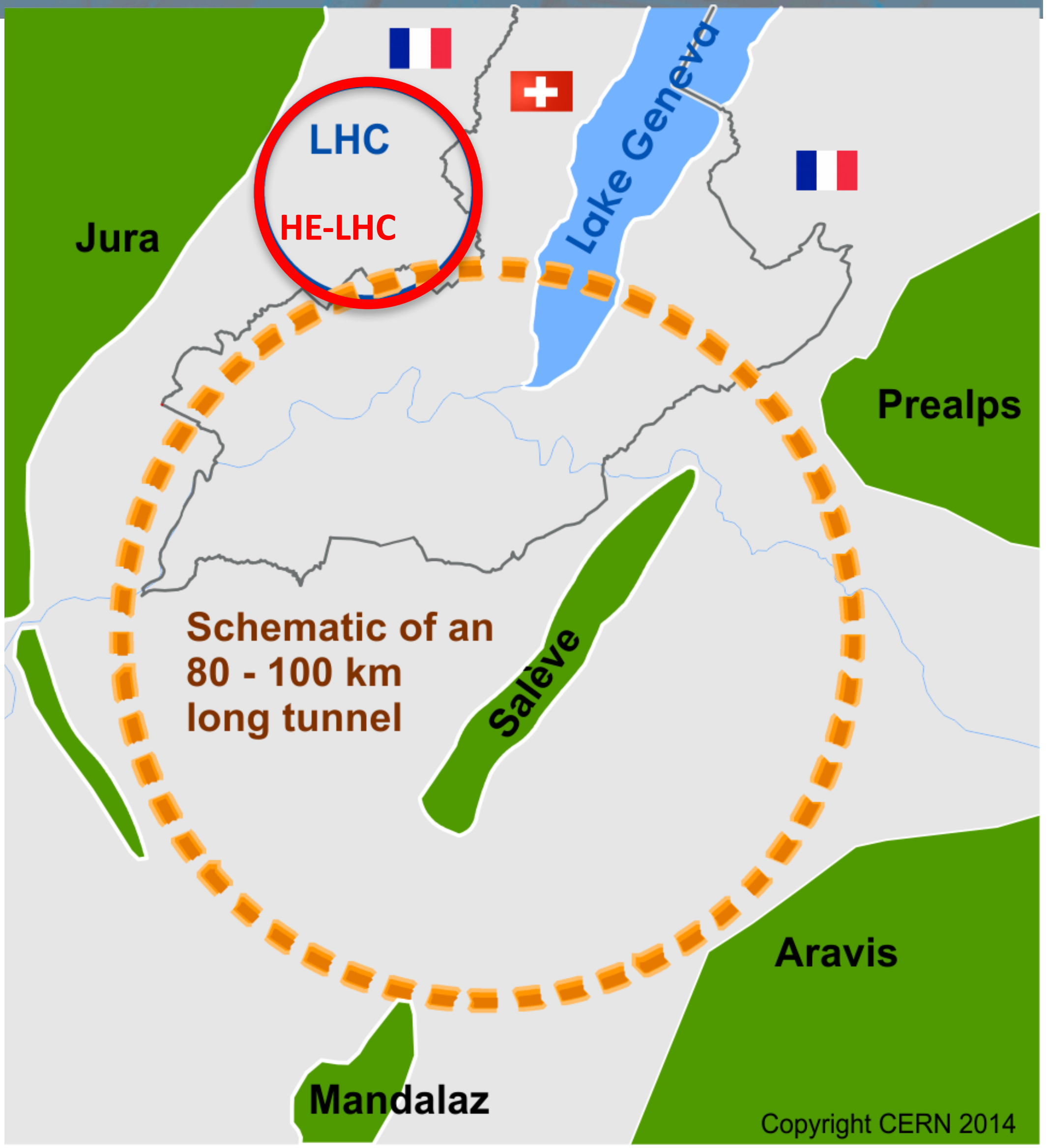
The FCC Study

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)** → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*),** as a possible first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology



F. Zimmermann, EuCARD-2 XRING Workshop, March 2017

CERN Accelerators

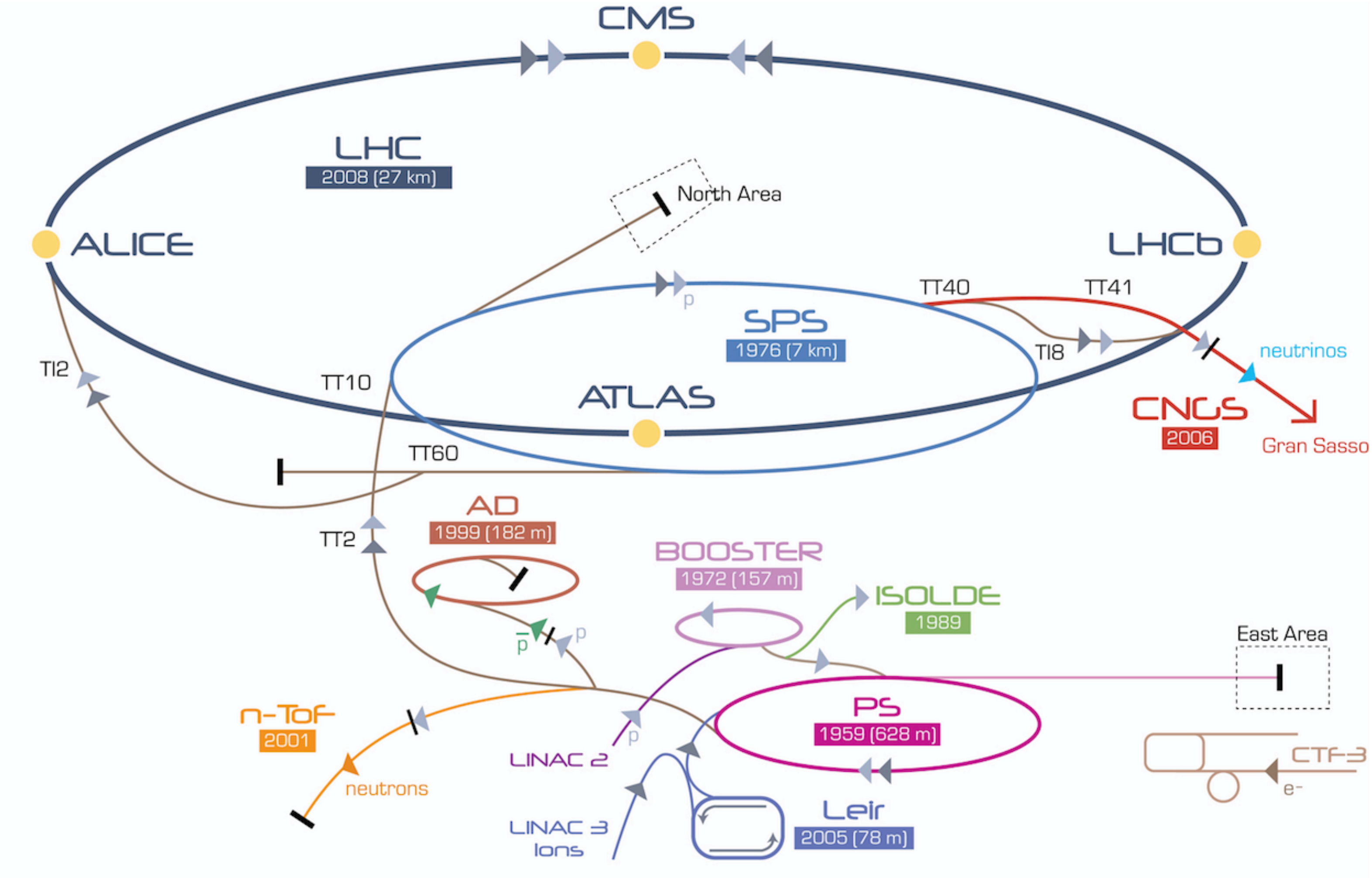
Linac 4
(160 MeV)

PS Booster
(157 m, 2 GeV)

PS
(628 m, 26 GeV)

SPS
(6.9 km, 450 GeV)

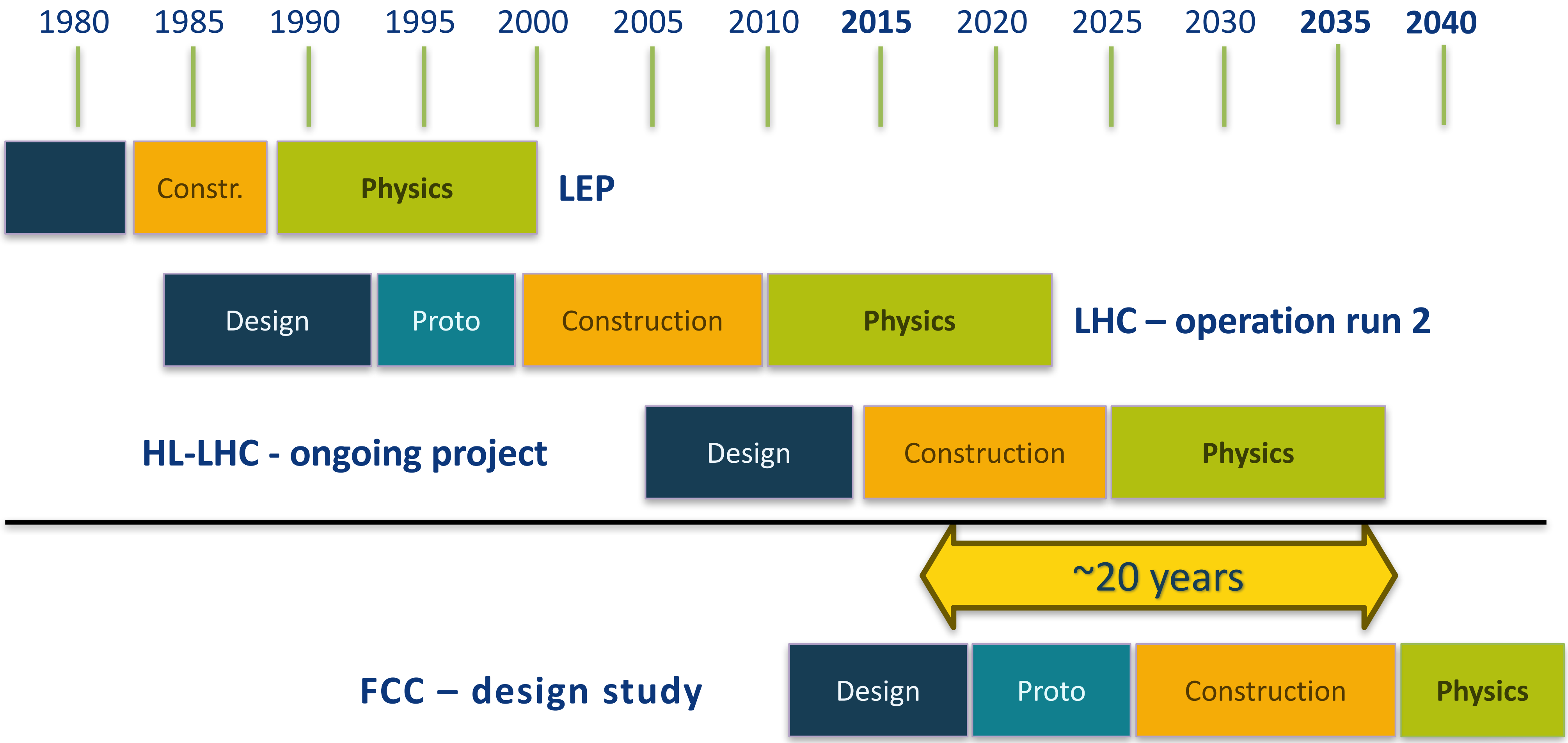
LHC
(27 km, 3.3 TeV)



Boosters for the FCC at CERN

(there are other options, in China, etc)

CERN Colliders & FCC



1980 1985 1990 1995 2000 2005 2010 **2015** 2020 2025 2030 **2035** **2040**

Constr. **Physics** **LEP**

Design Proto Construction **Physics** **LHC – operation run 2**

HL-LHC - ongoing project Design Construction **Physics**

~20 years

FCC – design study Design Proto Construction **Physics**

F. Zimmermann, EuCARD-2 XRING Workshop, March 2017

	SIS100 (ions)	SIS100 (p)	FCC-hh
C	1083.6 m	1083.6 m	100 km
Q_x	18.8	10.4	107.3
E_K	0.2→1.5 GeV/u	4→29 GeV	3.3→50 TeV
f_0	156→255 kHz	272→276 kHz	3 kHz
T_0	6.4→3.9 μs	3.7→3.6 μs	0.3 ms
Bunch length	340 ns	160 ns	1.2 ns

Very different scales of:
Length, Time, Frequency…

Stability of single-particle motion

Resonances

SIS100 Tune Diagram

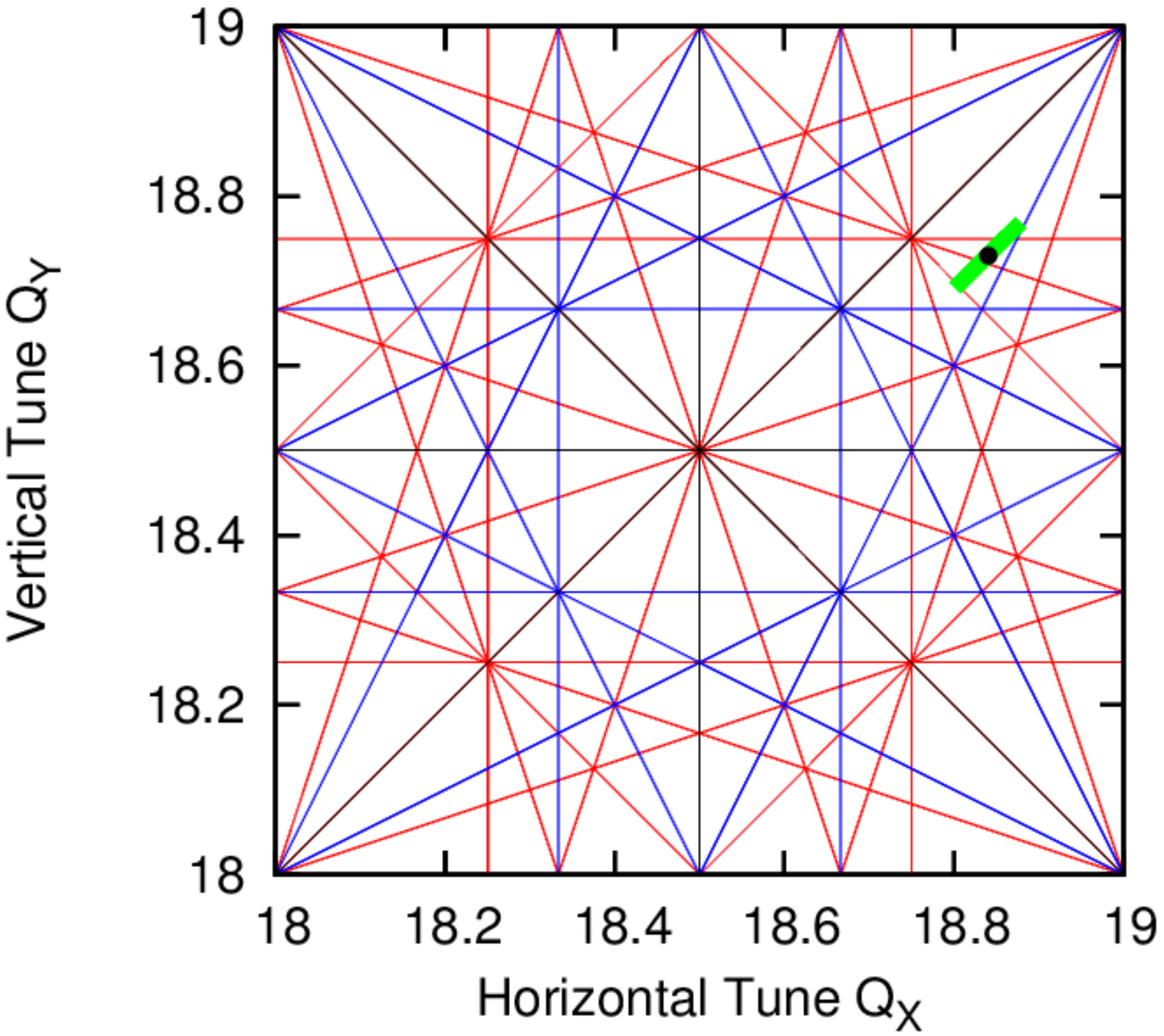
TUNE:
Number of oscillations during one turn around the ring

Here: Transverse Oscillations

Resonances:
$kQ_x + mQ_y = n$
2nd order, 3rd order,
4th order, …

SIS100, Operation type
Heavy ions, fast extraction
$Q_{X0} = 18.84$
$Q_{Y0} = 18.73$

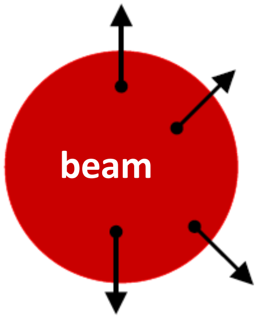
There are tune shifts (ΔQ) and tune spreads



Space Charge

Self-field space charge

Related to beam center
(moves with the beam)

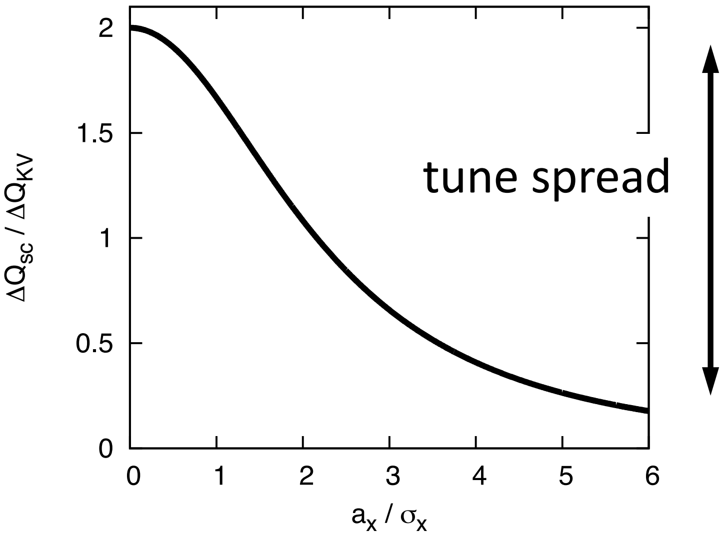


Space-Charge Tune Shift

$$\boxed{\Delta Q_{sc} = \frac{\lambda_0 r_p R}{\gamma^3 \beta^2 \varepsilon_\perp}}$$

$Q = Q_0 - \Delta Q_{sc}$

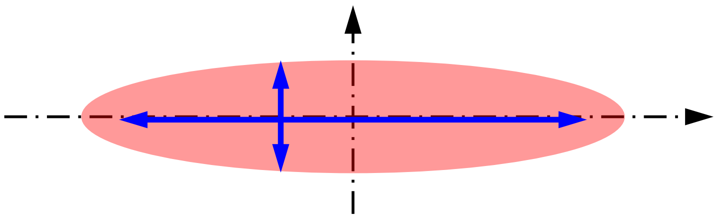
changes the individual tunes Q_{inc},
does not shift collective tune Q_{coh}



High Beam Intensity, Low Energy
→ Strong Space-Charge

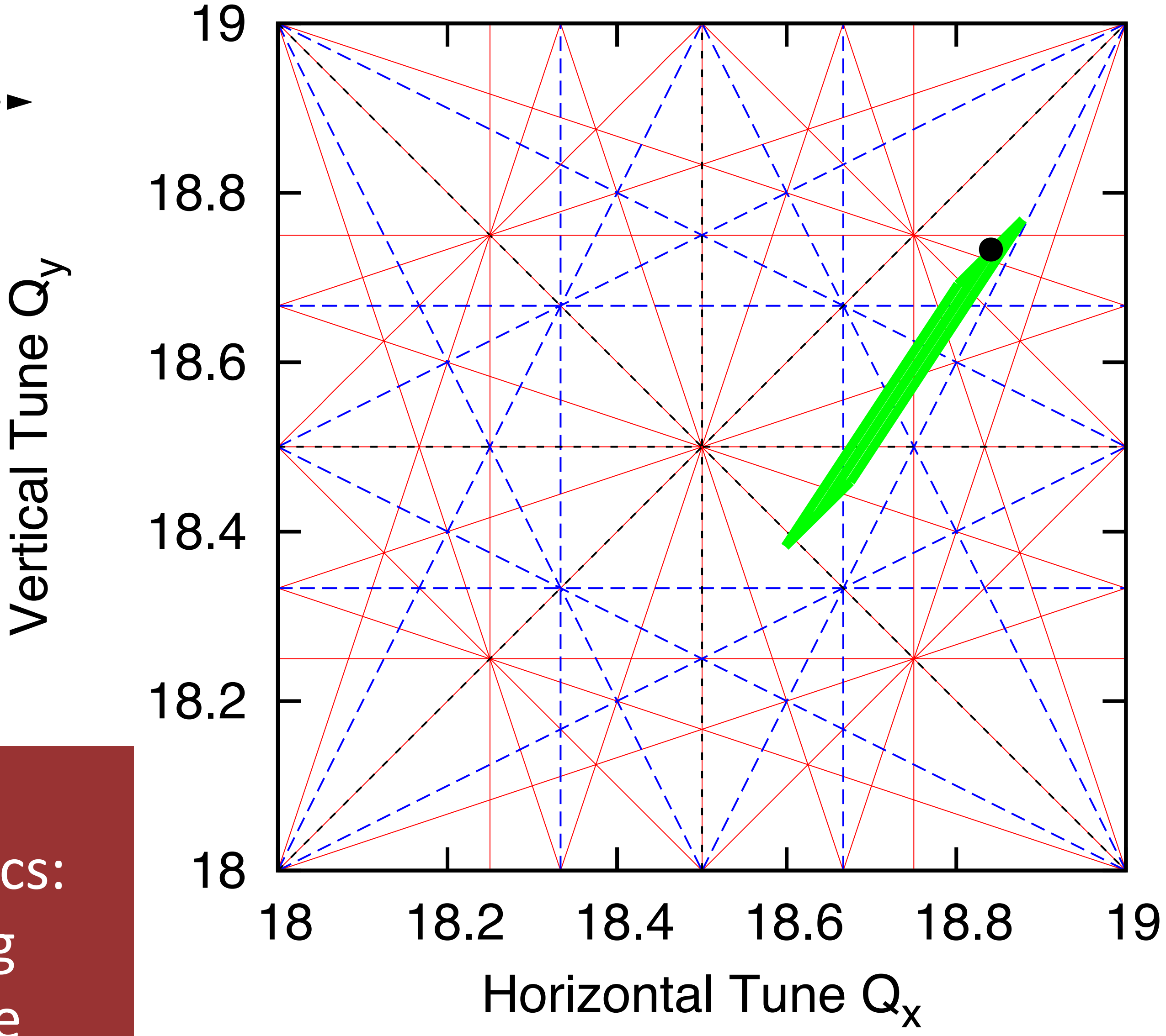
Space-Charge is an internal interaction:
Very different from other forces

Space Charge in SIS100



$f_{longitudinal} \approx 1.5$ kHz
(T ≈ 600 us, Q≈0.005)

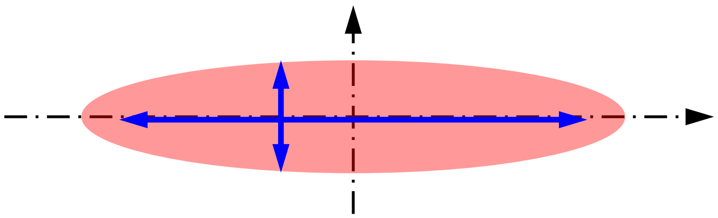
$f_{transverse} \approx 5$ MHz
(T ≈ 0.2 us, Q≈19)



Challenge for
SIS100 beam dynamics:
Resonance crossing
due to space charge

Vladimir Kornilov, GSI Accelerator Seminar, January 25, 2018

Space Charge in SIS100



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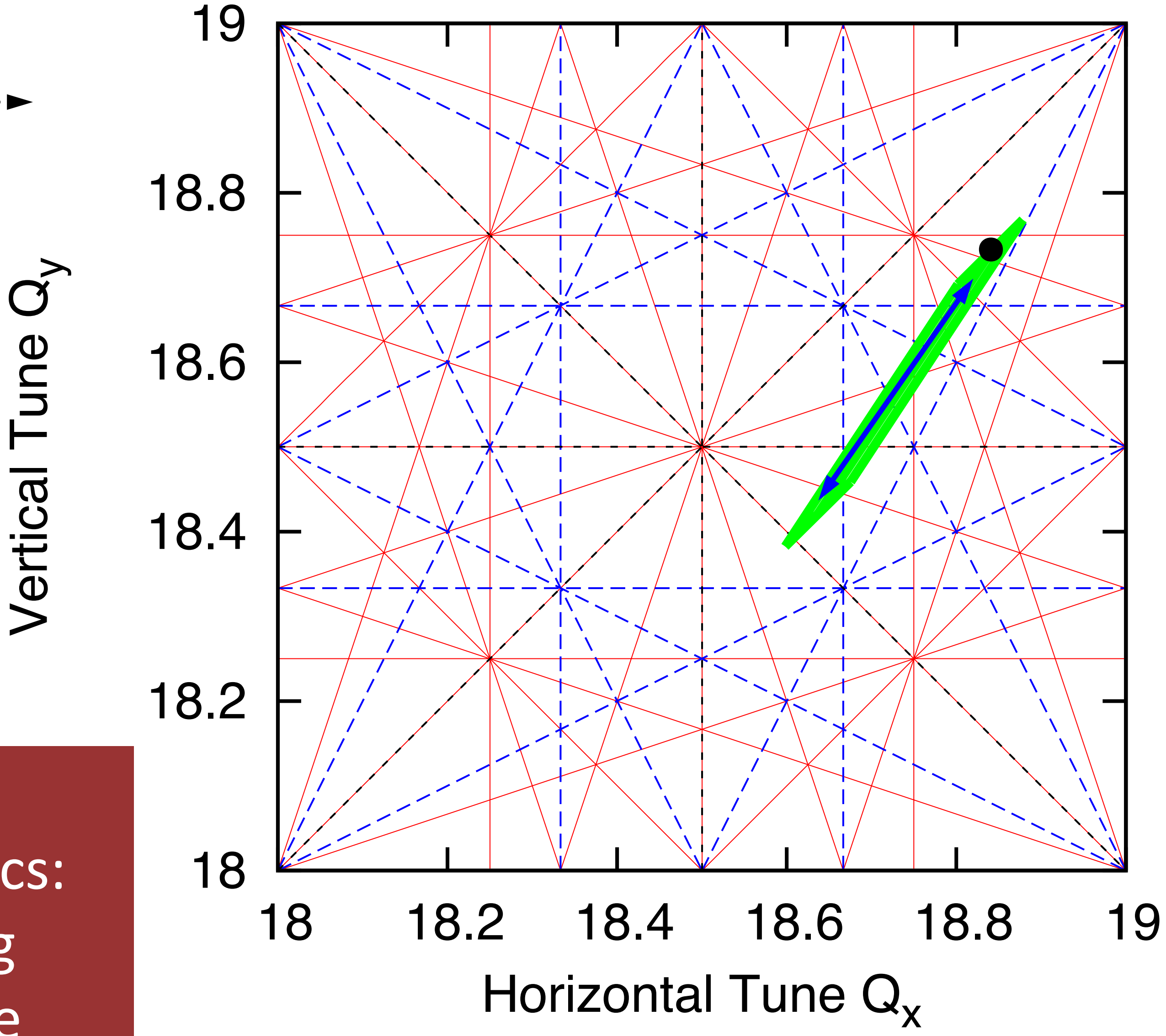
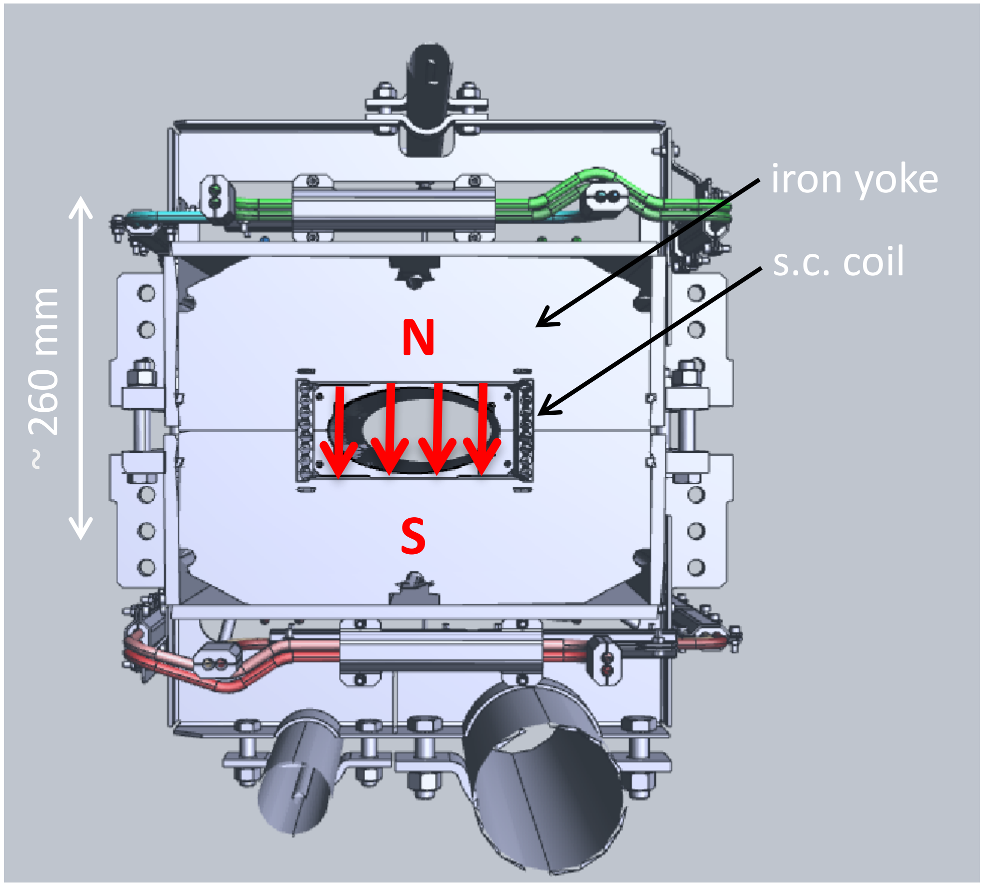
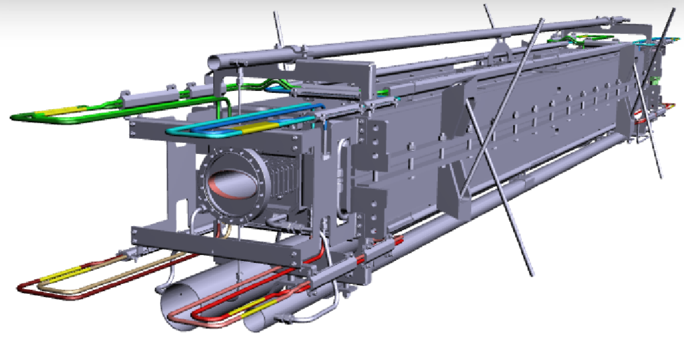


Challenge for
SIS100 beam dynamics:
Resonance crossing
due to space charge

SIS100 Dipole Magnets

Superconducting (U^{28+}) fast magnets





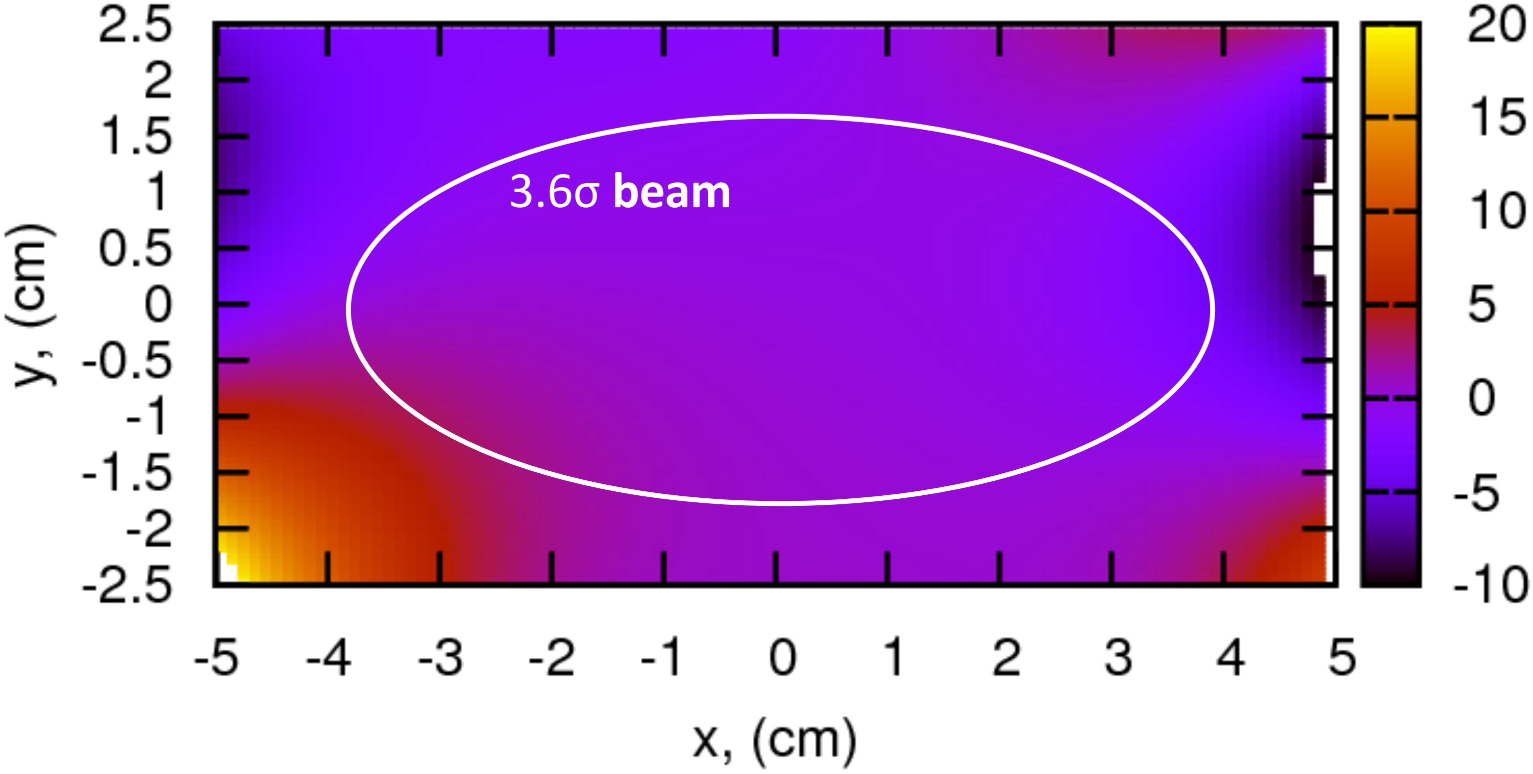
P. Spiller, Status of the FAIR Synchrotron Projects, IPAC2014

E. Fischer, MAC12, November 2014, GSI Darmstadt

Dipole Magnets: Field Quality

An example for the measured field

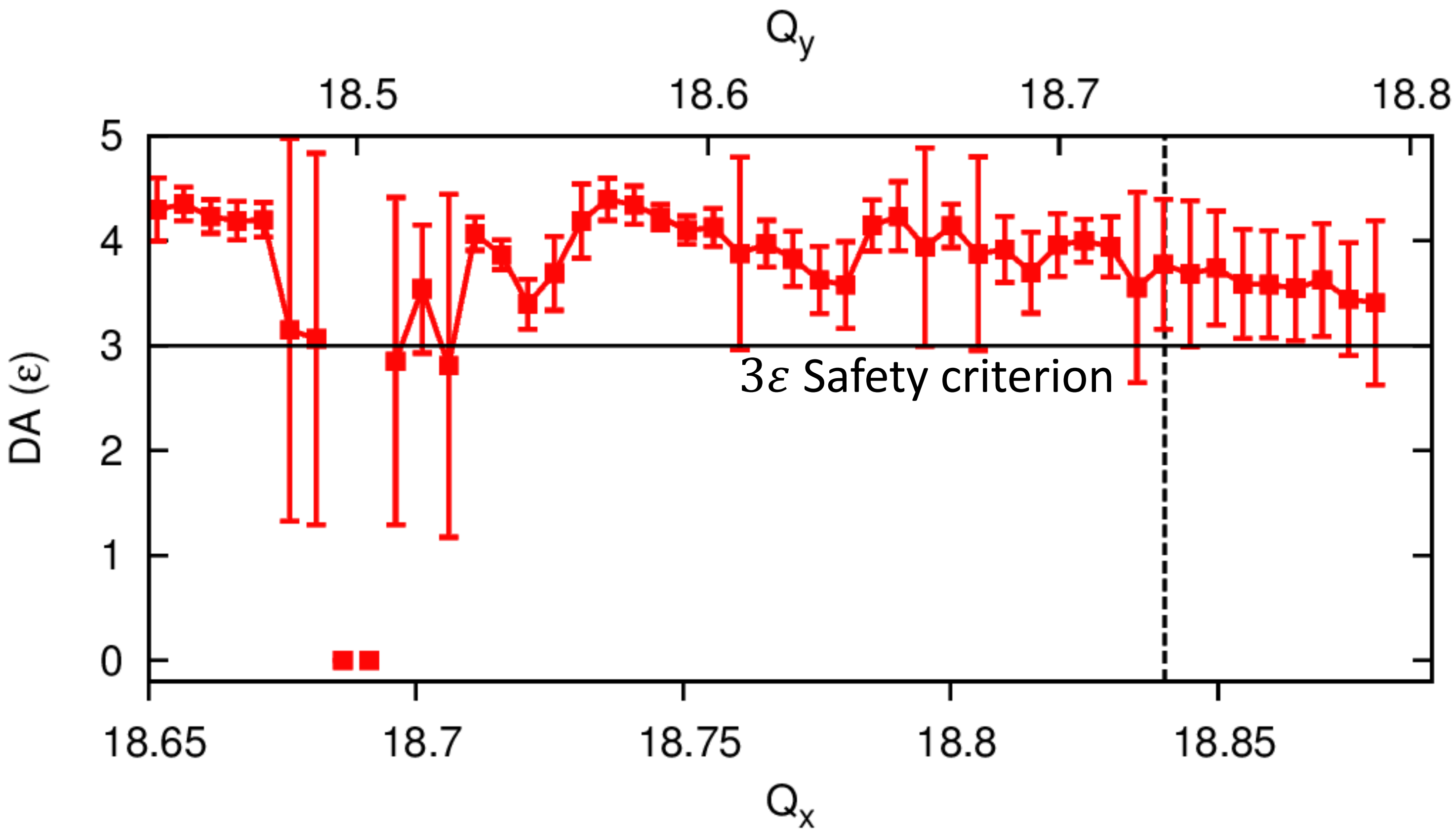
$\Delta|B|\,/\,B_0$, 1 unit = 10^{-4}



Detailed magnetic field measurements for SIS100 Dipole Magnets:
SCM Group, F.Kaether, C.Roux, A.Mierau, G.Golluccio, et al.

Particle motion simulations

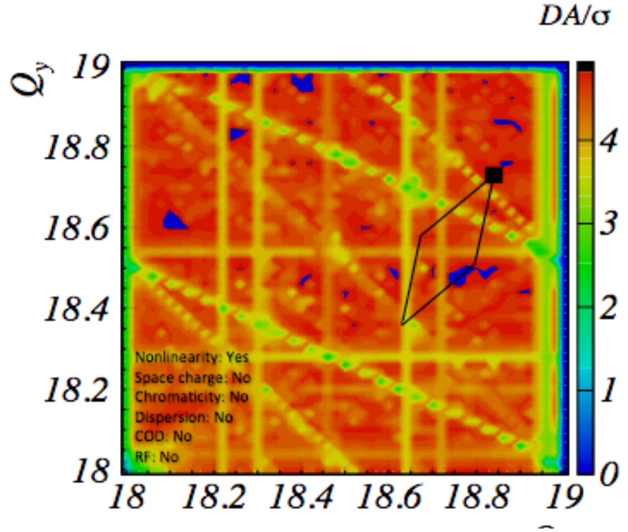
Particle tracking simulations (MADX code):
Dynamics Aperture for single-particle stability

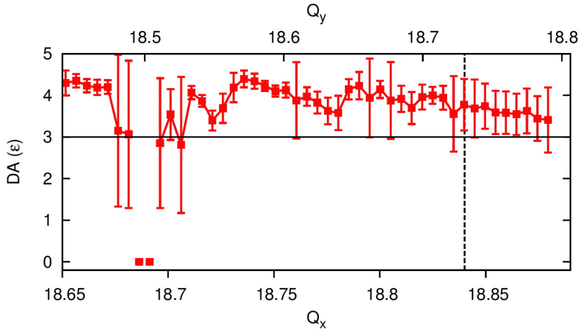


V. Kornilov, SIS100 FoS dipole: beam physics aspects
11th Machine Advisory Committee (MAC), Darmstadt, May 26-27, 2015

SIS100 Main Magnets

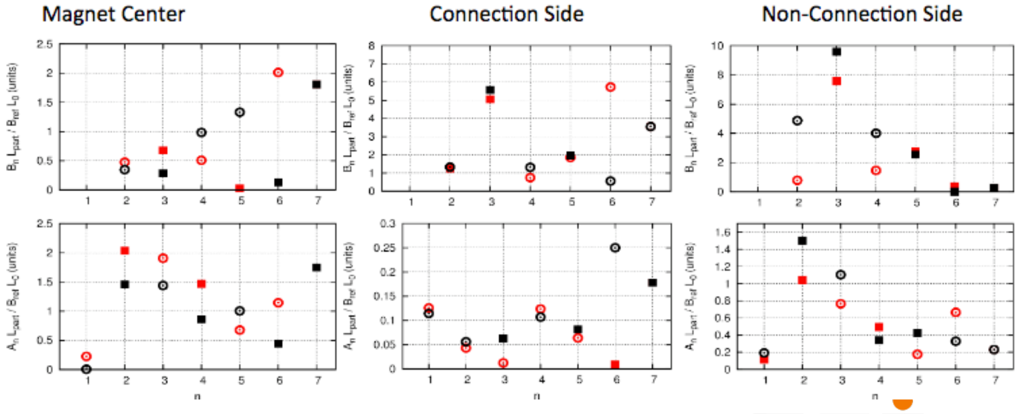
In the past: data from magnet computer models.
Now: the new database of the SIS100 magnets from measurements





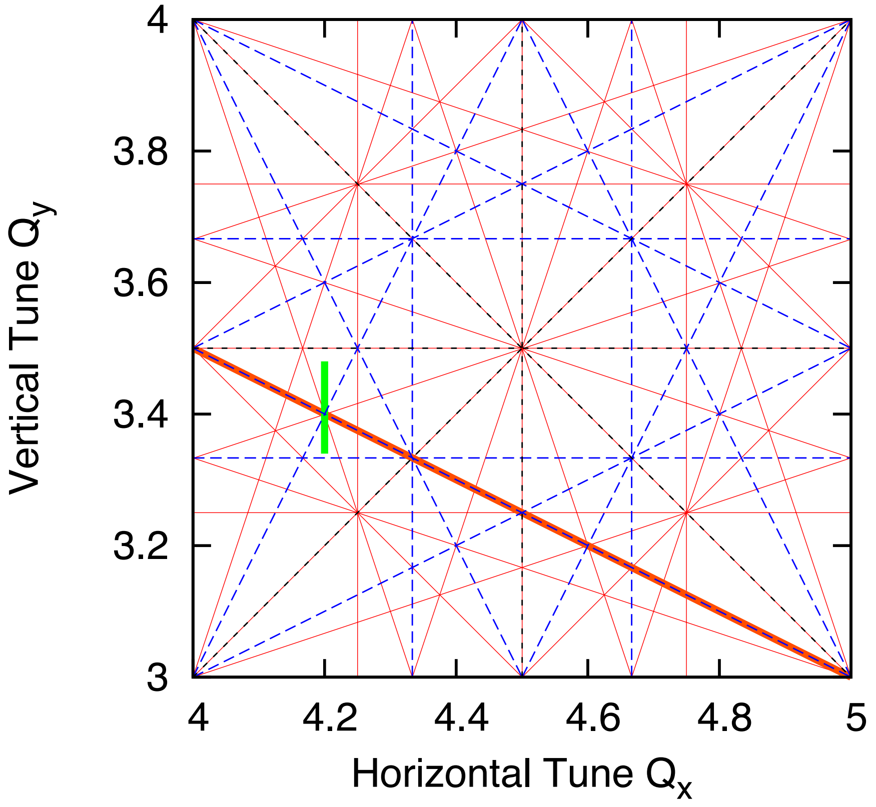
G. Franchetti, MAC5, May 2011
V. Kornilov, MAC11, May 2014

Magnet Center		Connection Side		Non-connection Side	
$B_2 = 0$ $dB_2 = B_{2FoS} \times 1.0$	$A_2 = A_{2FoS}$ $dA_2 = A_{2FoS} \times 0.25$	$B_2 = 0$ $dB_2 = B_{2FoS} \times 1.0$	$A_2 = A_{2FoS}$ $dA_2 = 0.2$ unit	$B_2 = 0$ $dB_2 = B_{2FoS} \times 1.0$	$A_2 = A_{2FoS}$ $dA_2 = A_{2FoS} \times 0.5$
$B_3 = B_{3FoS}$ $dB_3 = B_{3FoS} \times 0.5$	$A_3 = A_{3FoS}$ $dA_3 = A_{3FoS} \times 0.25$	$B_3 = B_{3FoS}$ $dB_3 = B_{3FoS} \times 0.25$	$A_3 = A_{3FoS}$ $dA_3 = 0.2$ unit	$B_3 = B_{3FoS}$ $dB_3 = B_{3FoS} \times 0.25$	$A_3 = A_{3FoS}$ $dA_3 = A_{3FoS} \times 0.5$
$B_4 = 0$ $dB_4 = B_{4FoS} \times 1.0$	$A_4 = A_{4FoS}$ $dA_4 = A_{4FoS} \times 0.25$	$B_4 = 0$ $dB_4 = B_{4FoS} \times 1.0$	$A_4 = A_{4FoS}$ $dA_4 = 0.2$ unit	$B_4 = 0$ $dB_4 = B_{4FoS} \times 1.0$	$A_4 = A_{4FoS}$ $dA_4 = 0.2$ unit
$B_5 = B_{5FoS}$ $dB_5 = A_{5FoS} \times 1.0$	$A_5 = A_{5FoS}$ $dA_5 = A_{5FoS} \times 0.5$	$B_5 = B_{5FoS}$ $dB_5 = B_{5FoS} \times 0.5$	$A_5 = A_{5FoS}$ $dA_5 = 0.2$ unit	$B_5 = B_{5FoS}$ $dB_5 = B_{5FoS} \times 0.5$	$A_5 = A_{5FoS}$ $dA_5 = 0.2$ unit
$B_6 = B_{6FoS}$ $dB_6 = B_{6FoS} \times 0.25$	$A_6 = A_{6FoS}$ $dA_6 = A_{6FoS} \times 0.25$	$B_6 = B_{6FoS}$ $dB_6 = B_{6FoS} \times 0.25$	$A_6 = A_{6FoS}$ $dA_6 = 0.2$ unit	$B_6 = B_{6FoS}$ $dB_6 = B_{6FoS} \times 0.5$	$A_6 = A_{6FoS}$ $dA_6 = 0.2$ unit
$B_7 = B_{7FoS}$ $dB_7 = B_{7FoS} \times 0.25$	$A_7 = A_{7FoS}$ $dA_7 = A_{7FoS} \times 0.25$	$B_7 = B_{7FoS}$ $dB_7 = B_{7FoS} \times 0.25$	$A_7 = A_{7FoS}$ $dA_7 = 0.2$ unit	$B_7 = 0.2$ unit $dB_7 = 0.2$ unit	$A_7 = A_{7FoS}$ $dA_7 = 0.2$ unit



Resonance Compensation

Resonance compensation using the Magnet Correctors
(2nd, 3rd, 4th order, skew and normal Magnets)



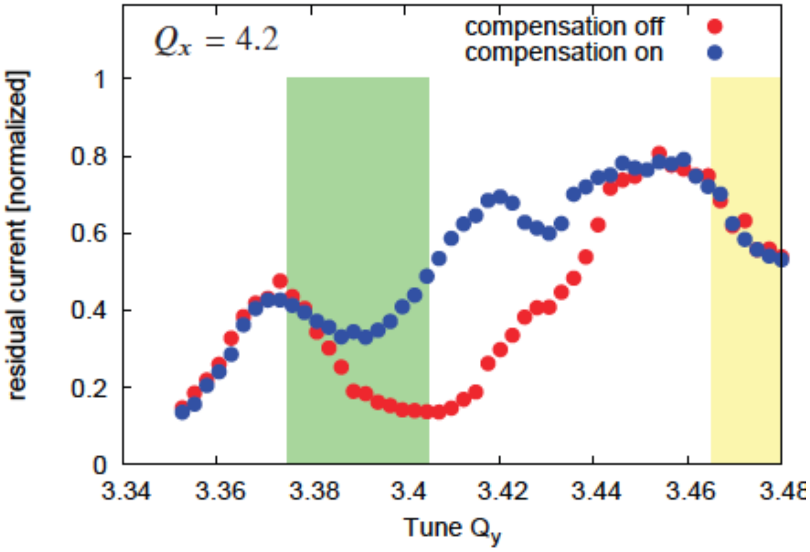


Figure 3: Beam survival for a bunched beam stored for 1 second as function of Q_y. The blue curve is obtained for the partially compensated third order resonance, whereas the red curve is measured for the naked machine.

G.Franchetti, et.al., IPAC2015

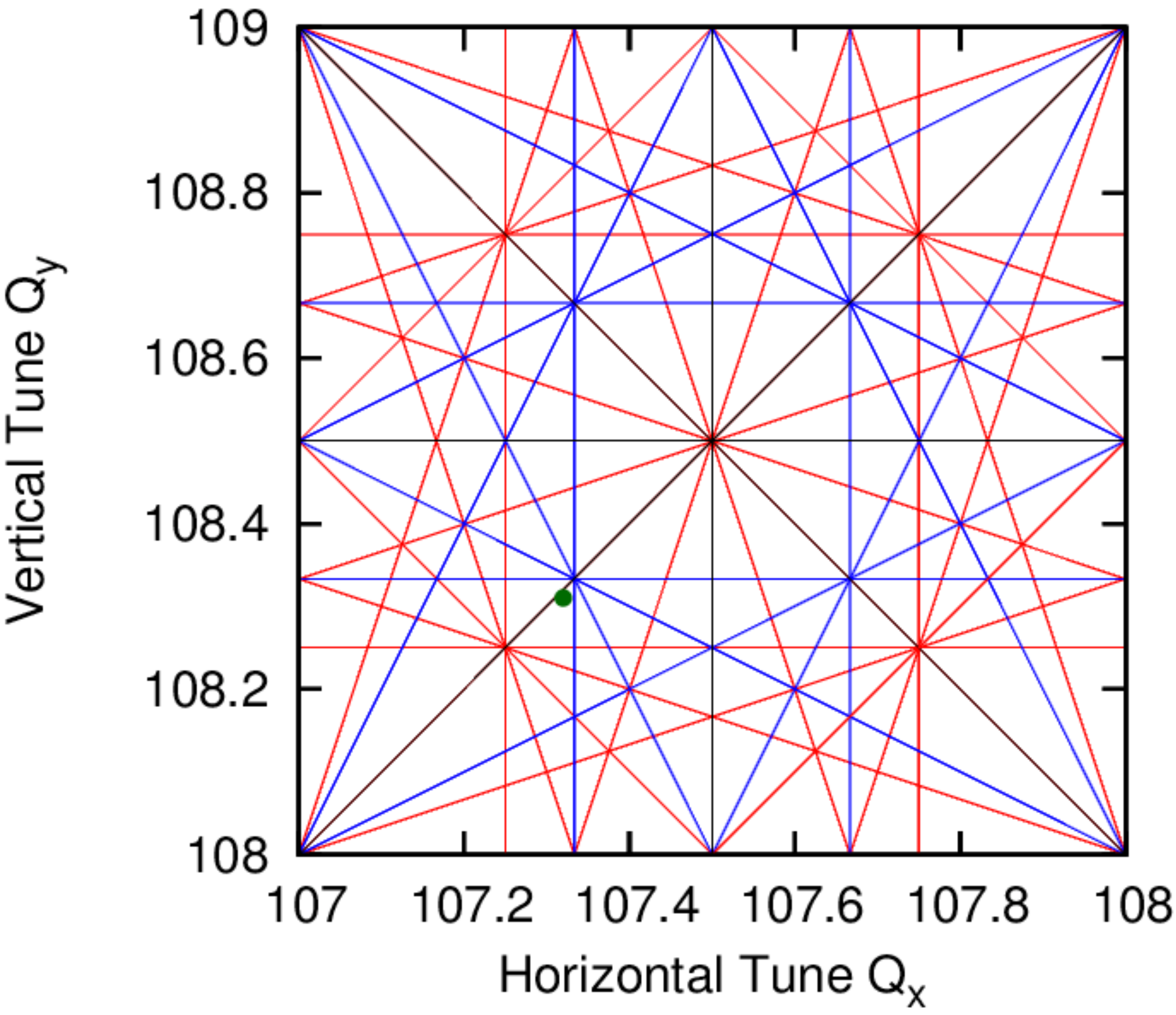
Experimental proof & experience at SIS18

FCC-hh Tune Diagram

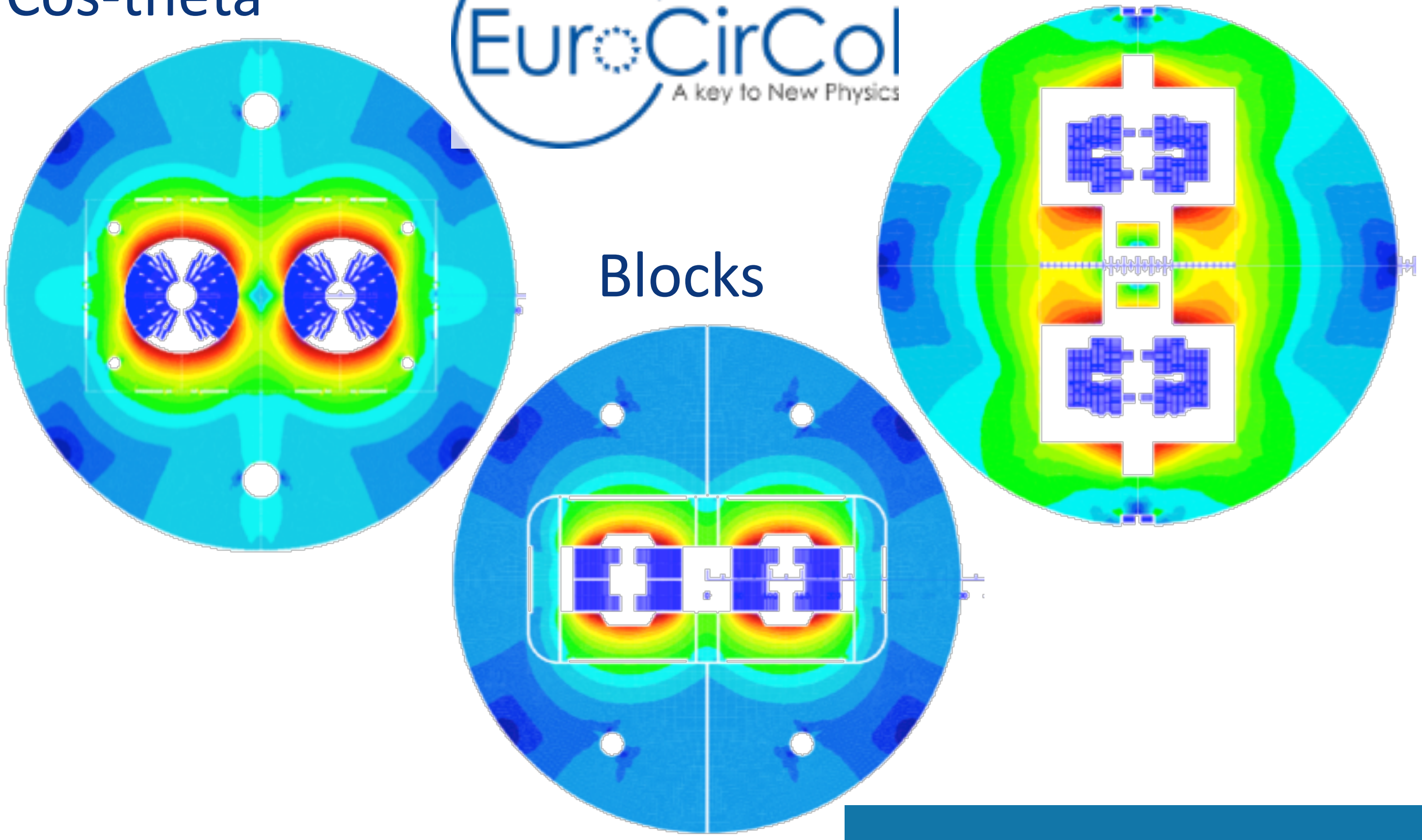
Q_x=107.32
Q_y=108.31

FCC tune shifts:
0.2×10^{-3}

Long-time storage (hours). Very low-loss requirements.

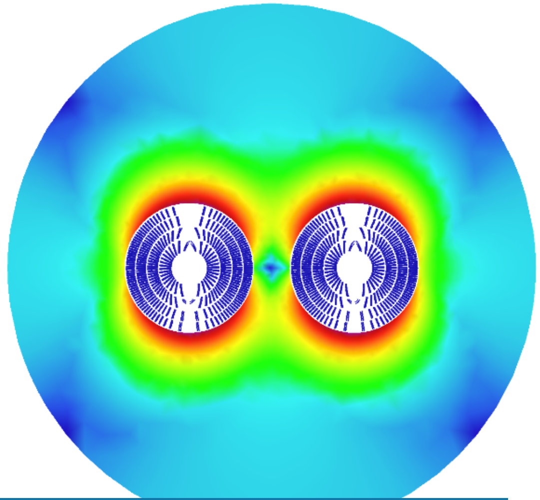


FCC Dipole Magnets



Swiss contribution
via PSI

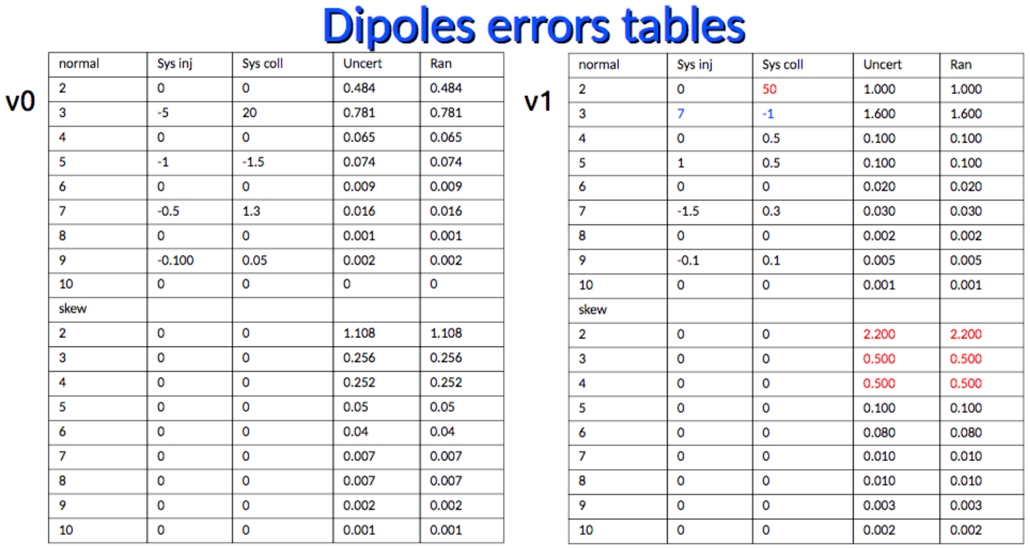
Canted
Cos-theta



16 T dipole options and plans
prototype production by 2025

The U.S. Magnet Development Program Plan

Particle motion simulations



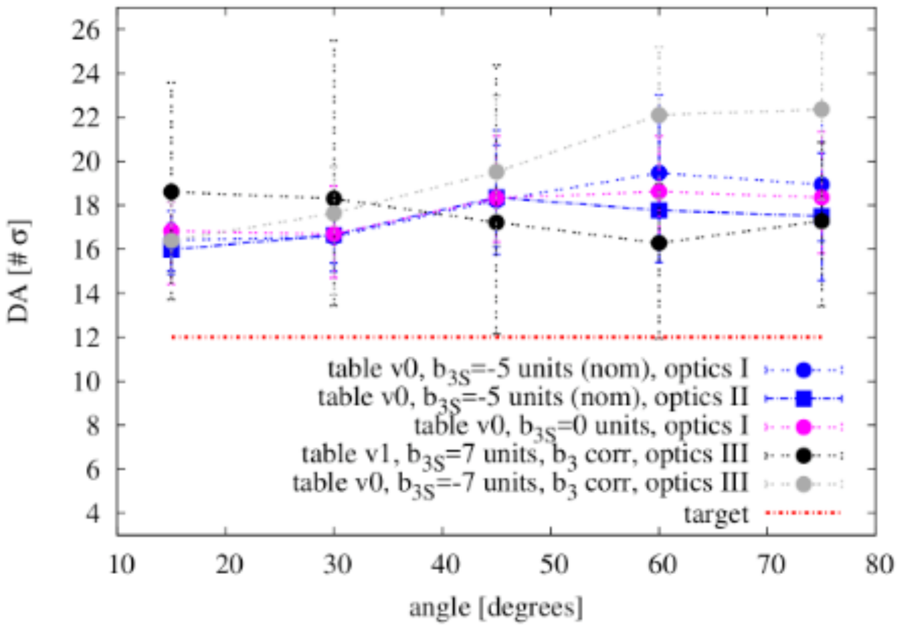
Dipoles errors tables

v0

normal	Sys inj	Sys coll	Uncert	Ran
2	0	0	0.484	0.484
3	-5	20	0.781	0.781
4	0	0	0.065	0.065
5	-1	-1.5	0.074	0.074
6	0	0	0.009	0.009
7	-0.5	1.3	0.016	0.016
8	0	0	0.001	0.001
9	-0.100	0.05	0.002	0.002
10	0	0	0	0
skew				
2	0	0	1.108	1.108
3	0	0	0.256	0.256
4	0	0	0.252	0.252
5	0	0	0.05	0.05
6	0	0	0.04	0.04
7	0	0	0.007	0.007
8	0	0	0.007	0.007
9	0	0	0.002	0.002
10	0	0	0.001	0.001

v1

normal	Sys inj	Sys coll	Uncert	Ran
2	0	50	1.000	1.000
3	7	-1	1.600	1.600
4	0	0.5	0.100	0.100
5	1	0.5	0.100	0.100
6	0	0	0.020	0.020
7	-1.5	0.3	0.030	0.030
8	0	0	0.002	0.002
9	-0.1	0.1	0.005	0.005
10	0	0	0.001	0.001
skew				
2	0	0	2.200	2.200
3	0	0	0.500	0.500
4	0	0	0.500	0.500
5	0	0	0.100	0.100
6	0	0	0.080	0.080
7	0	0	0.010	0.010
8	0	0	0.010	0.010
9	0	0	0.003	0.003
10	0	0	0.002	0.002



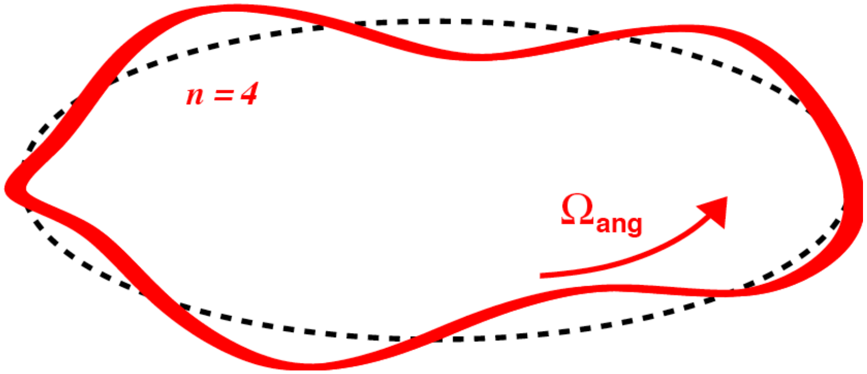
B. Dalena, et al, FCC Week 2017

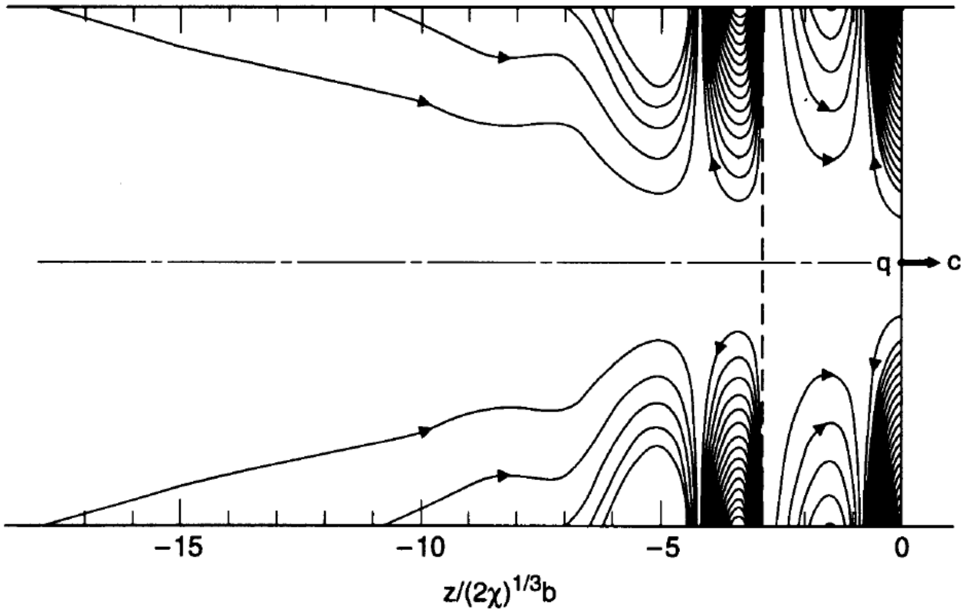
Stability of collective beam motion

Instabilities, Impedances

Collective Oscillations

Collective (coherent) beam motion



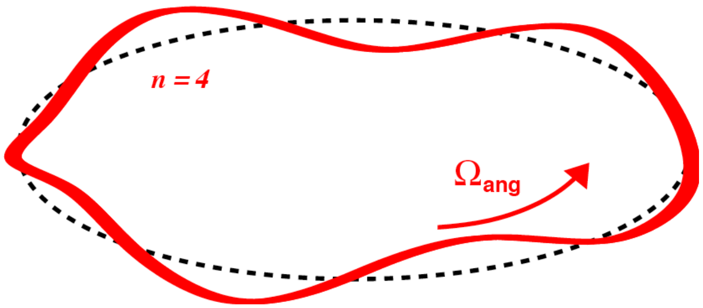


Coasting beam (unbunched).
Normally a beam is grouped
into bunches

Electromagnetic fields
due to the facility:
E ~ Impedance × Beam Current

Unstable Oscillations

small initial perturbation ***⟨x⟩***



produces

excitation force

$$G \propto Z^{\perp}_{\text{ext}} I_0 \langle x \rangle$$

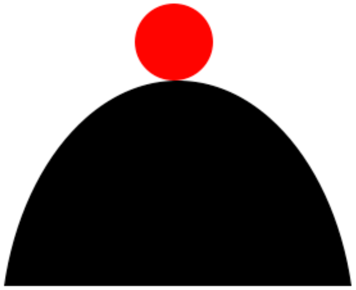
forced oscillations (eigenmode)

the perturbation is amplified

⟨x⟩ × (1+Δ)

reinforcing mechanism

Unstable System



Exponential growth: instability

$$\langle x \rangle (t) = x_0 e^{\mathrm{Im}(\Omega) t}$$

Instabilities in SIS18

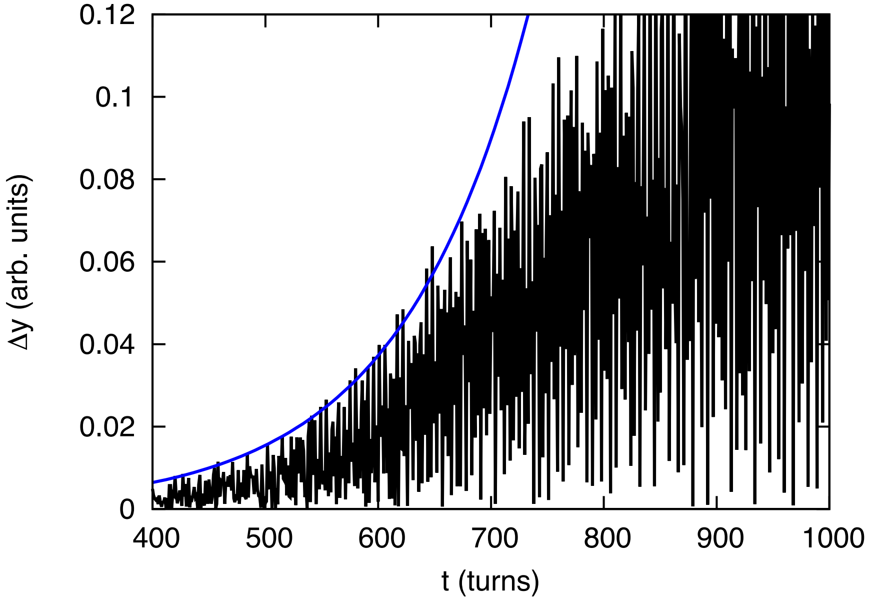
For tunes above $Q_y \approx 3.79$:
strong collective oscillations,
fast beam loss

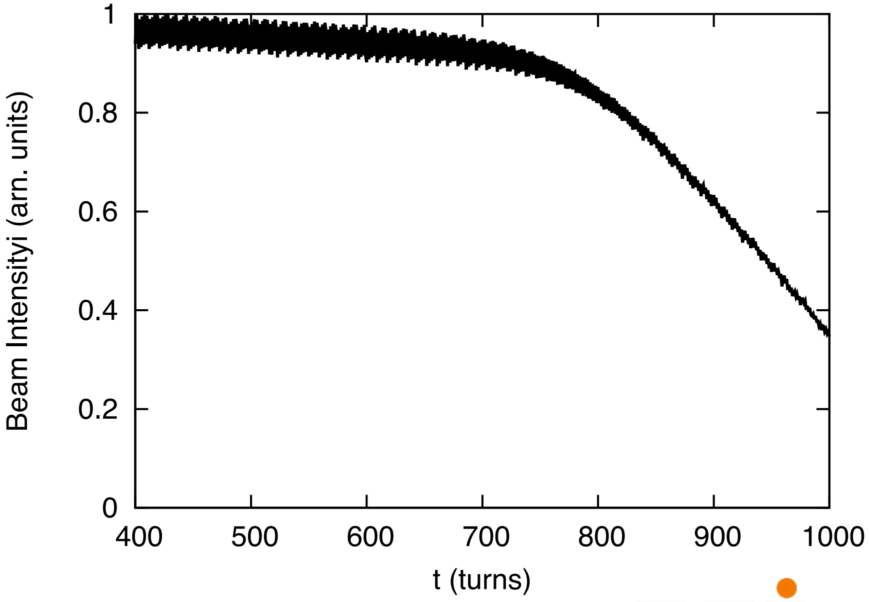
exponential growth with
$\tau = 0.11$ ms

$$A(t) = A_0 \exp\left\{\frac{t}{\tau}\right\}$$

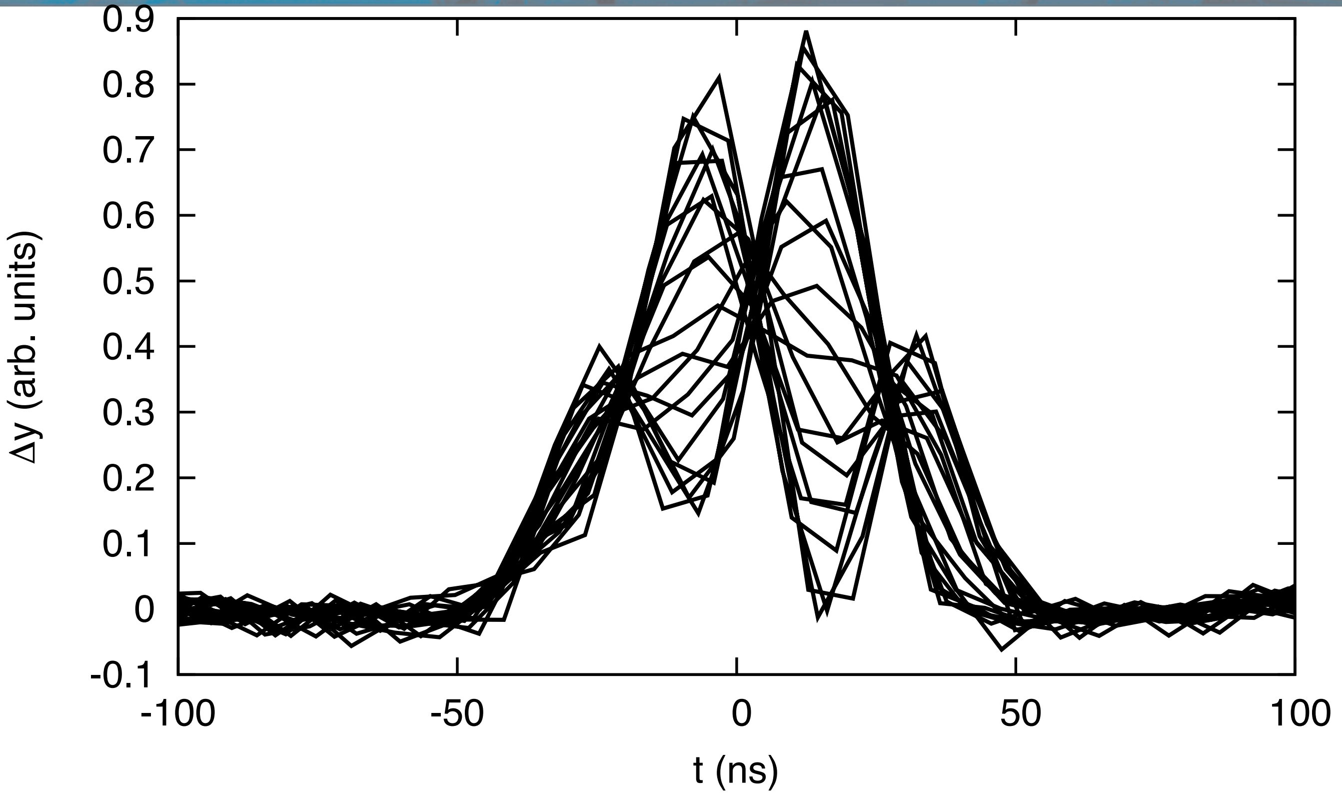
1 turn = 0.989 us

Kornilov, 2016, 2014,2008





Instabilities in SIS18



Head-Tail instability in SIS18

- development of Transverse Feedback System for SIS18 and SIS100
- design of an octupole magnet set for SIS18 (role of space charge)
- understanding the impedances in SIS18 → SIS100

Instability Drive vs. Damping

$$\Delta\Omega = \Delta\Omega_{\mathrm{Re}} + i\gamma_{\mathrm{drive}} + i\gamma_{\mathrm{damping}}$$

change the parameters of the driving mechanism

use and enhance the damping mechanisms

How to cure instabilities

Reduce the impedances, change the beam/machine settings,…

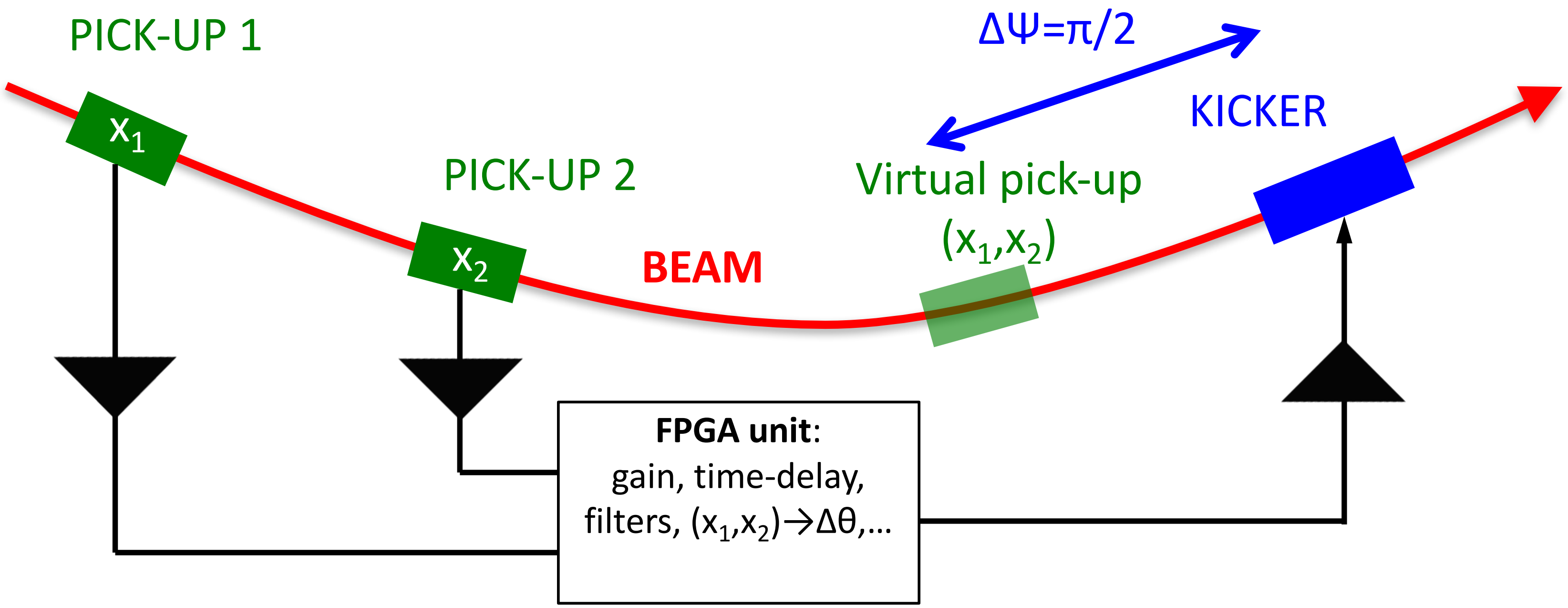
Active cures: feedback systems

Passive mitigation: octupole magnets

Feedback Systems

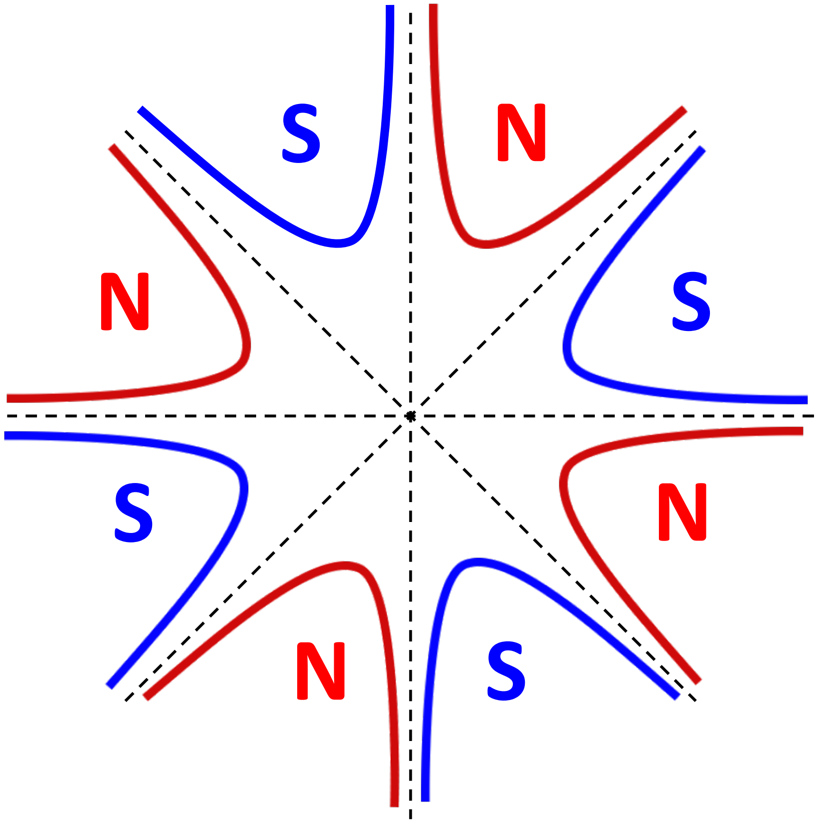
Essential for operation in many accelerators

Foreseen in FCC and in SIS100



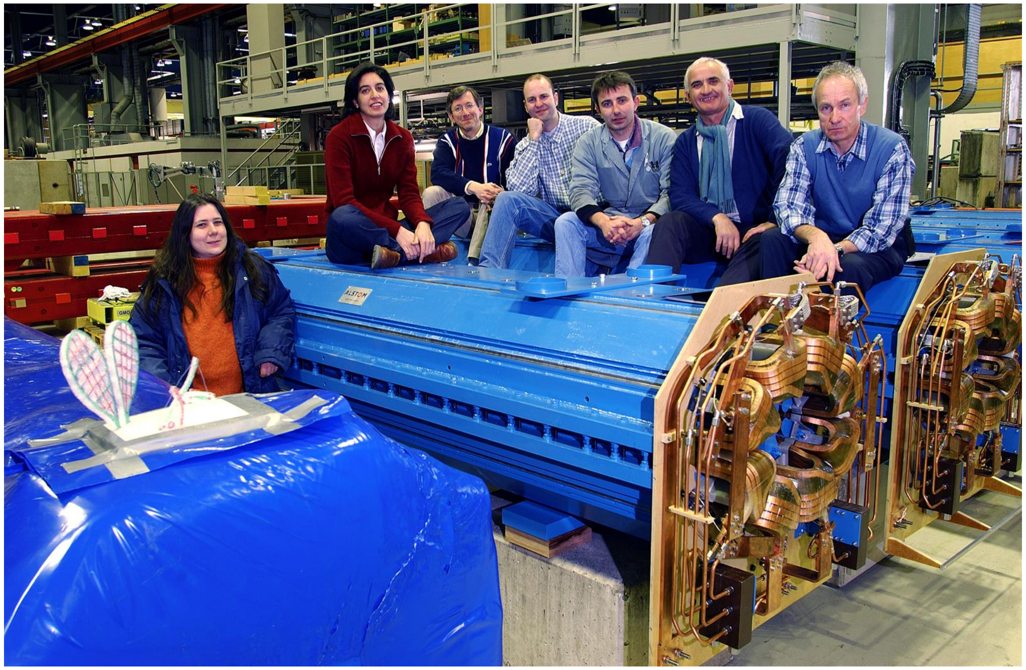
V. Kornilov, General Specifications for the Transverse Feedback System, GSI Project report 2014

Octupole Magnets



Schematic yoke profile
of an octupole magnet

LHC: 168 dedicated octupoles
for Landau damping



Dispersion Relation

L.Laslett, V.Neil, A.Sessler, 1965
D.Möhl, H.Schönauer, 1974
J.Berg, F.Ruggiero, CERN SL-96-71 AP 1996

$$\Delta Q_{\mathrm{coh}} \int \frac{1}{\Delta Q_{\mathrm{oct}} - \Omega/\omega_0} J_x \frac{\partial \psi_\perp}{\partial J_x} dJ_x dJ_y = 1$$

complex coherent tune shift for the beam without damping

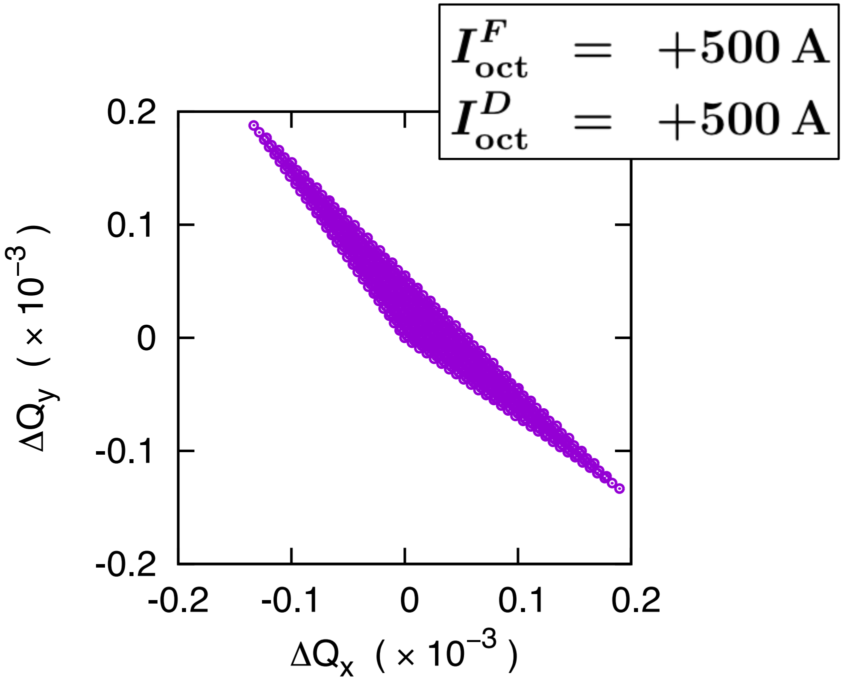
The solution: collective mode frequency Ω for the given impedance and beam

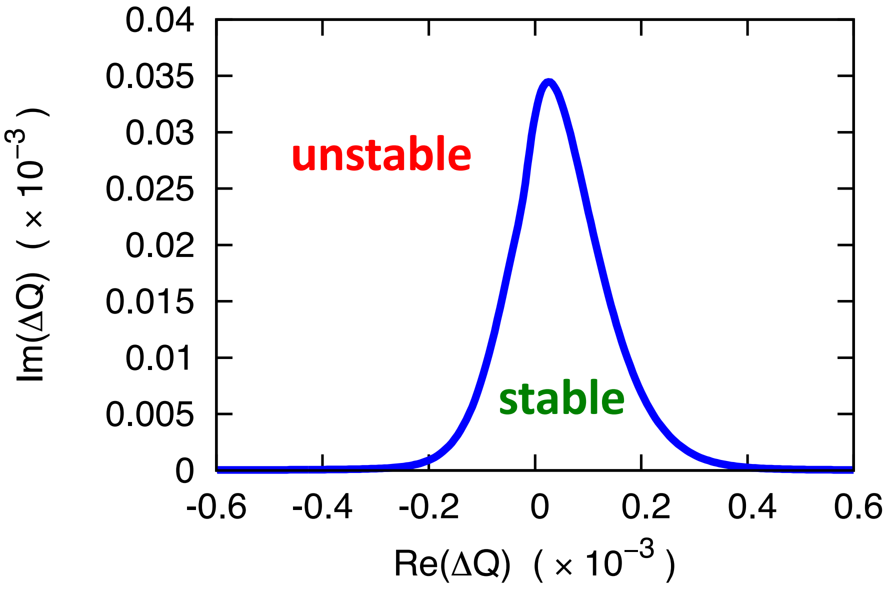
Octupole
Tune shifts:

$$\begin{aligned}
\Delta Q_x &= \left\{\frac{3}{8\pi}\sum \hat\beta_x^2 \frac{O_3 L_{\mathrm{m}}}{B\rho}\right\} J_x - \left\{\frac{3}{8\pi}\sum 2\hat\beta_x \hat\beta_y \frac{O_3 L_{\mathrm{m}}}{B\rho}\right\} J_y \\
\Delta Q_y &= \left\{\frac{3}{8\pi}\sum \hat\beta_y^2 \frac{O_3 L_{\mathrm{m}}}{B\rho}\right\} J_y - \left\{\frac{3}{8\pi}\sum 2\hat\beta_x \hat\beta_y \frac{O_3 L_{\mathrm{m}}}{B\rho}\right\} J_x
\end{aligned}$$

This dispersion relation has been used for the planning of the LHC octupole scheme.

Transverse Stability





FCC-hh

For the ΔQ_{coh}–Damping as in LHC:
508 Advanced-technology octupoles.

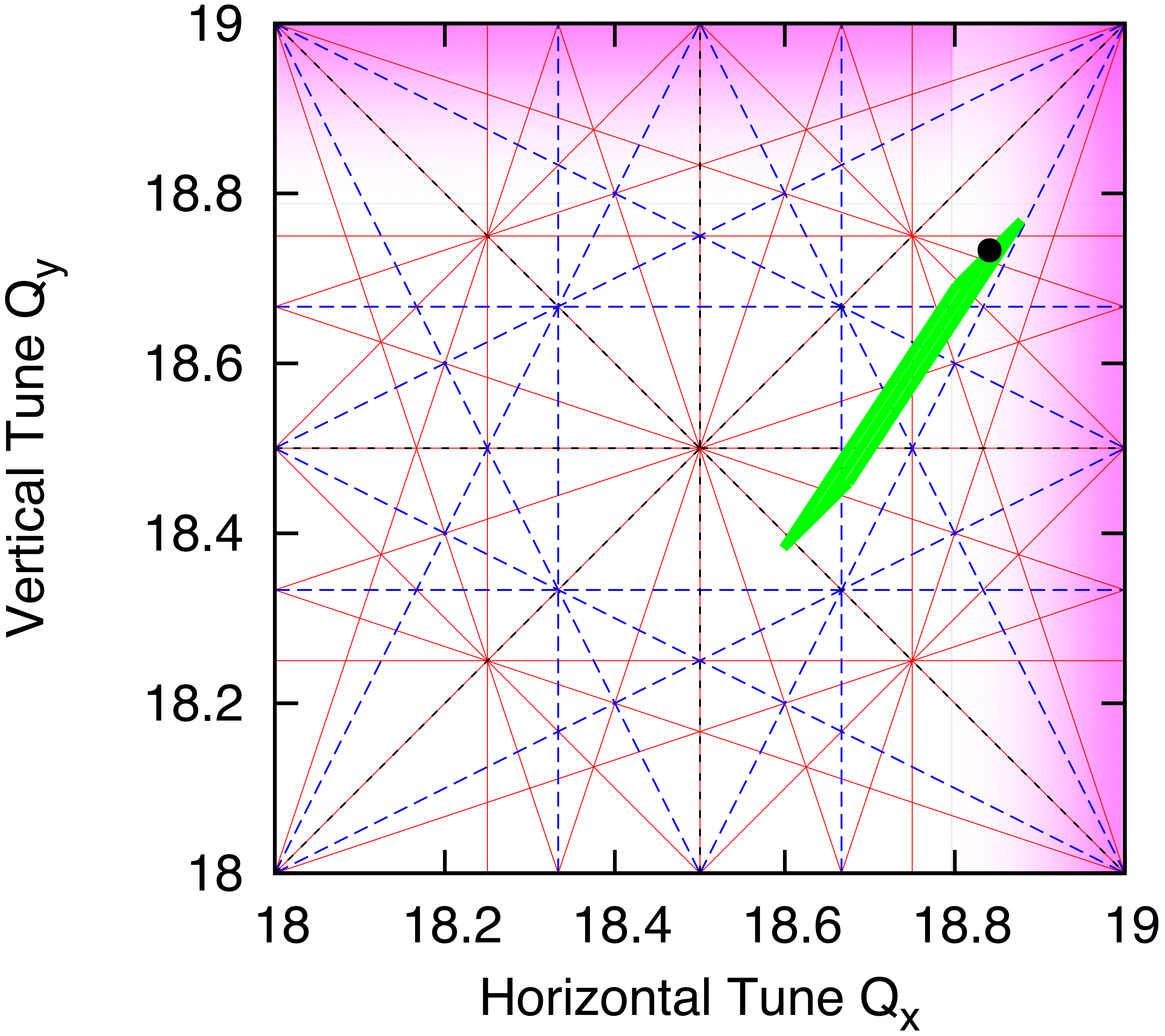
V.Kornilov,
FCC Week 2017, Berlin

Our contribution to the FCC Study

Instabilities in SIS100

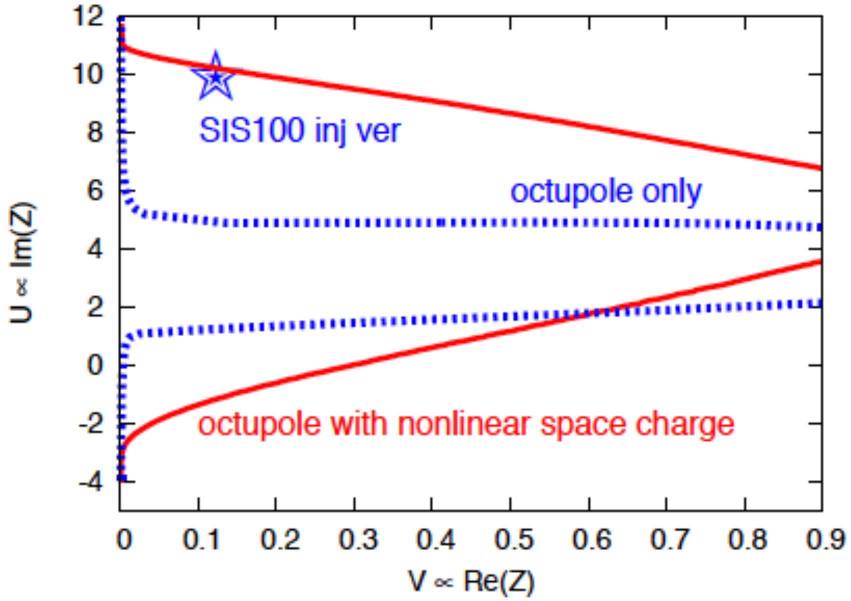
Ion Fast extraction
Working Point
Q_x=18.84 Q_y=18.73

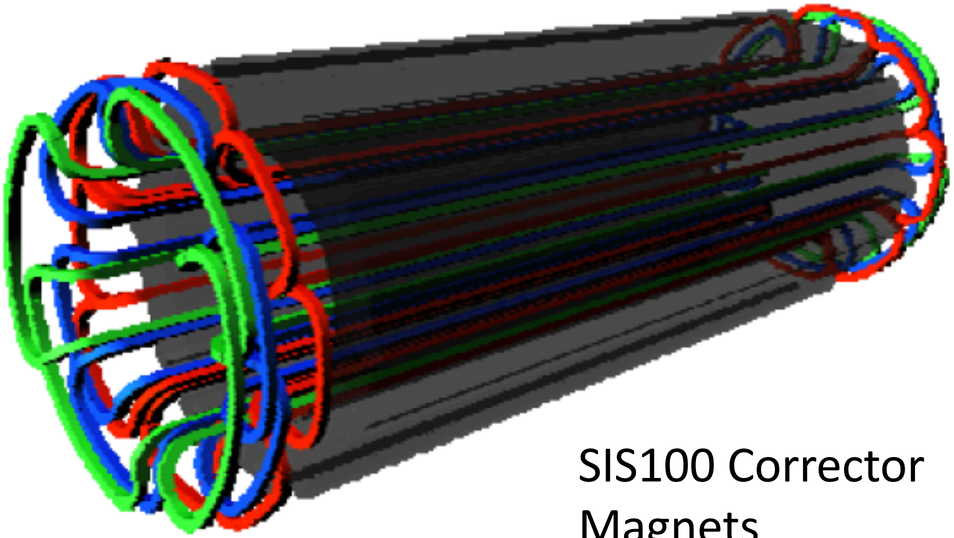
Tunes below integer:
head-tail instability
driven by the
resistive-wall
impedance



Instabilities in SIS100

Octupoles Magnets in SIS100





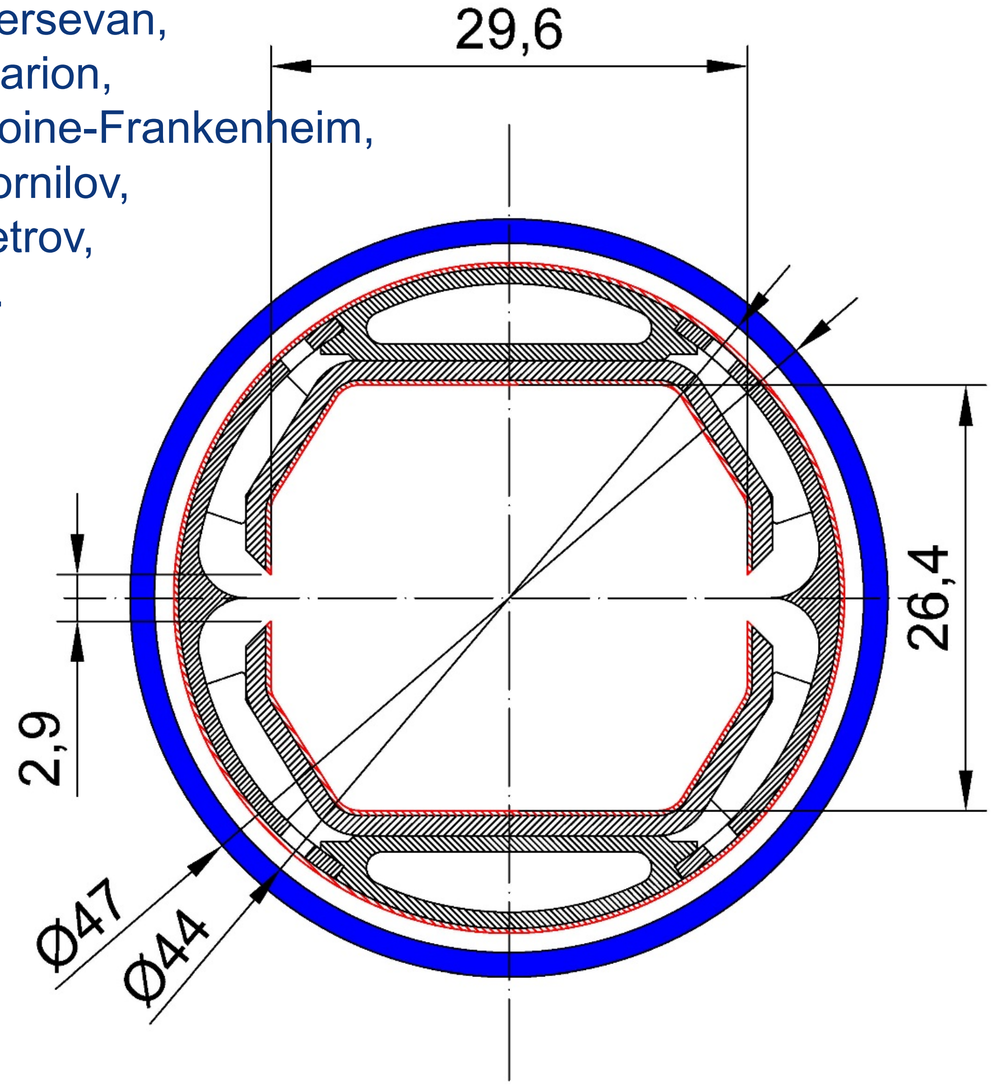
SIS100 Corrector Magnets

V. Kornilov, O. Boine-Frankenheim, I. Hofmann, Transverse Collective Instabilities in SIS100, GSI-Acc-Note-2008-006, GSI Darmstadt (2008)

Beam Pipe

FCC Beam Pipe

R. Kersevan,
C. Garion,
O. Boine-Frankenheim,
V. Kornilov,
F. Petrov,
et al.



F. Zimmermann, EuCARD-2 XRING Workshop, March 2017

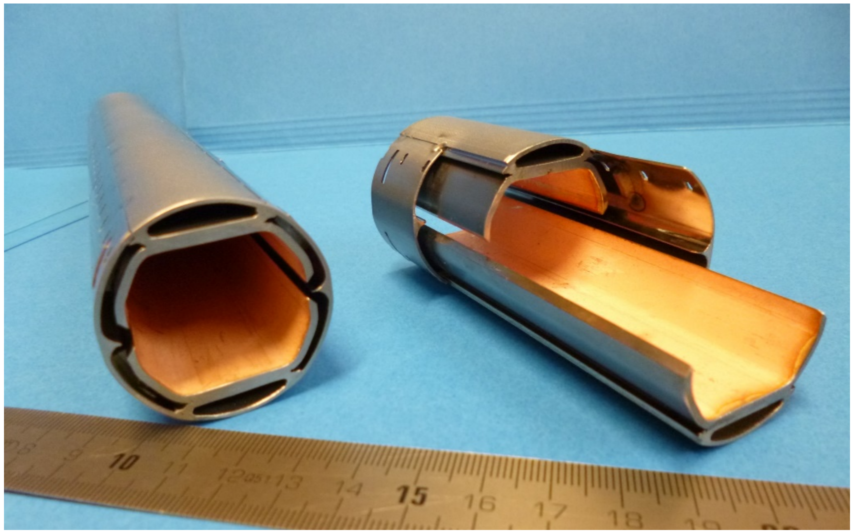
FCC-hh: ≈5 MW Synchrotron Radiation emitted in cold arcs

beam screen at 40—60 K

(LHC at 5—20 K)

slits & wedge capture and hide photons

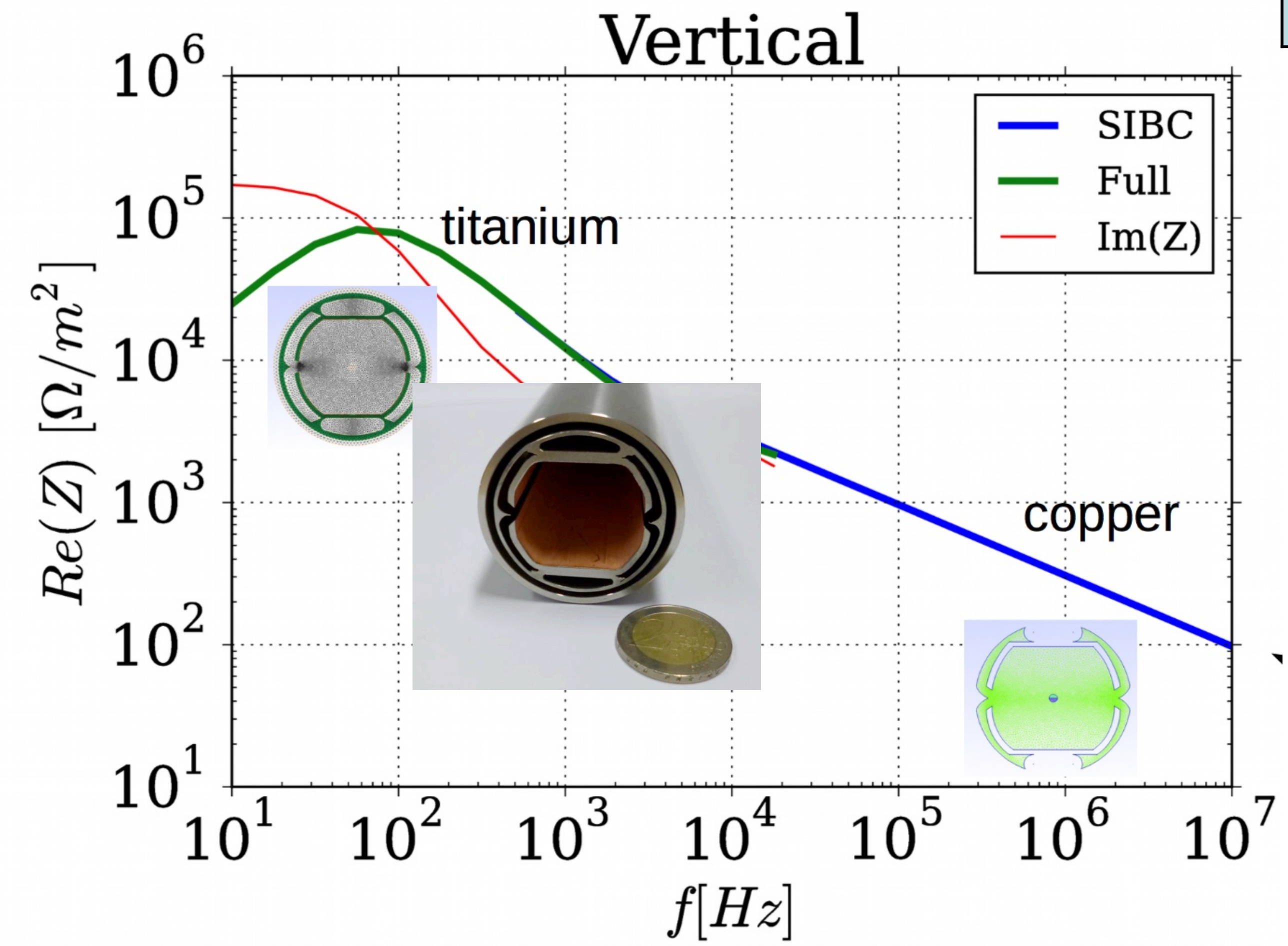
surface treatment



FCC Beam Pipe

FCC-hh Task 2.4,
TU Darmstadt, O.Boine-Frankenheim et al.

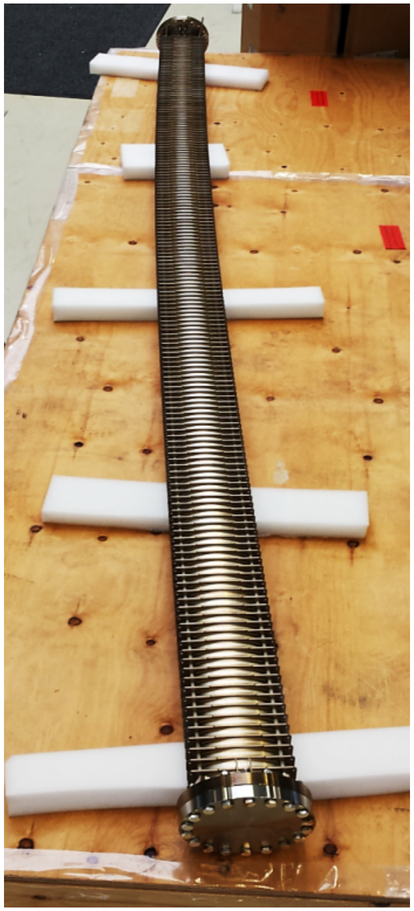
Beam pipe	
Material	Cu, Ti
Cu thickness [µm]	**300**

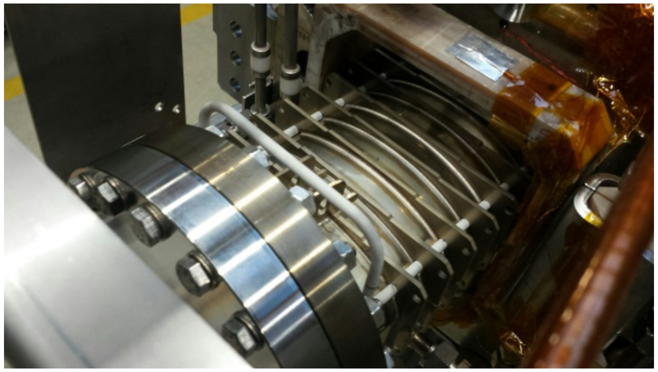


Beam pipe impedance and the resulting instabilities are an input for the feedback systems and for the passive mitigation (octupoles)

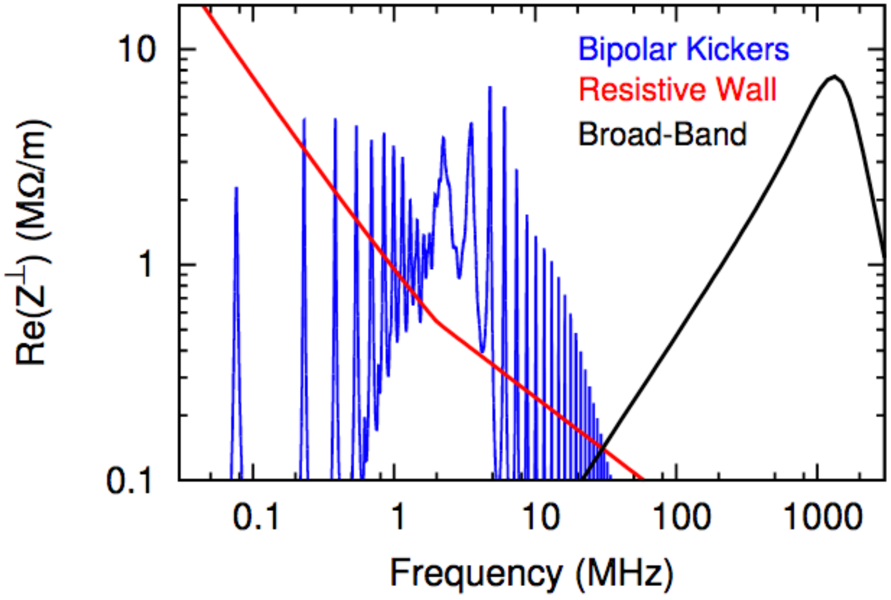
SIS100 Beam Pipe

Dipole chambers. Curved, thickness 0.3 mm (eddy currents), special stainless steel, cooling tubes, stability ribs.





S. Wilfert, et al, March 2017. GSI Vacuum Systems.



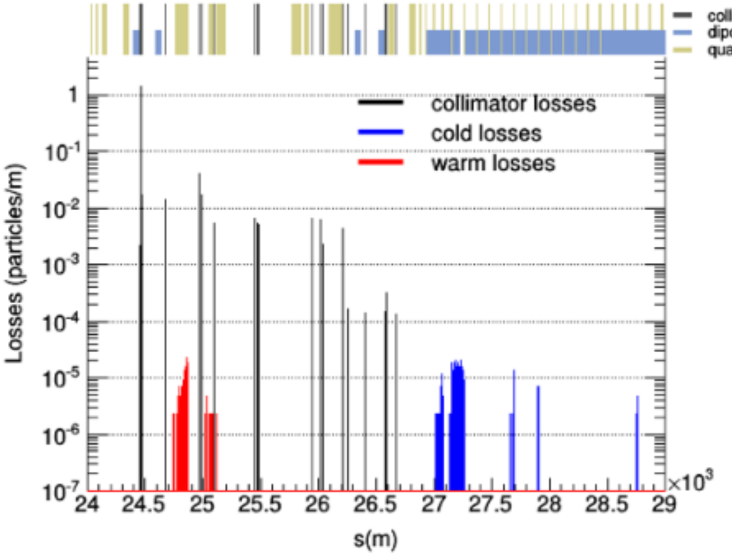
V. Kornilov, Coupling Impedances in SIS100, Project report 2015.

Machine Protection

FCC Machine Protection

stored energy 8.4 GJ per beam

- at least one order of magnitude higher than for LHC, equivalent to A380 (560 t) at nominal speed (850



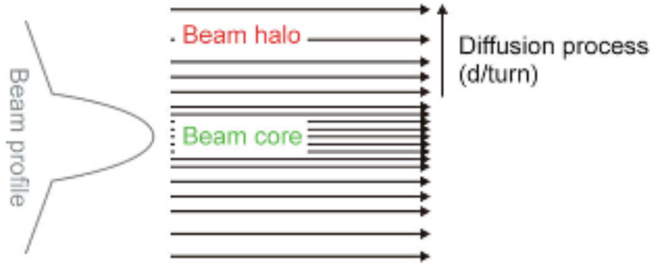
- collimation, control of beam losses and radiation effects (shielding) are of prime importance.
- injection, beam transfer and beam dump all critical

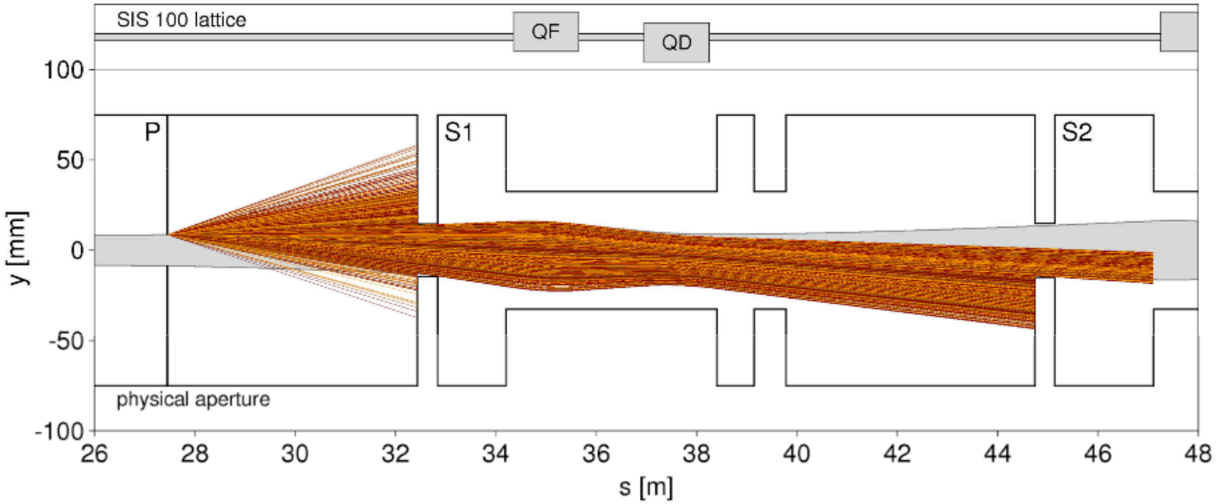
Beam Dynamics studies for the design and efficiency of the collimation system

F. Zimmermann, EuCARD-2 XRING Workshop, March 2017

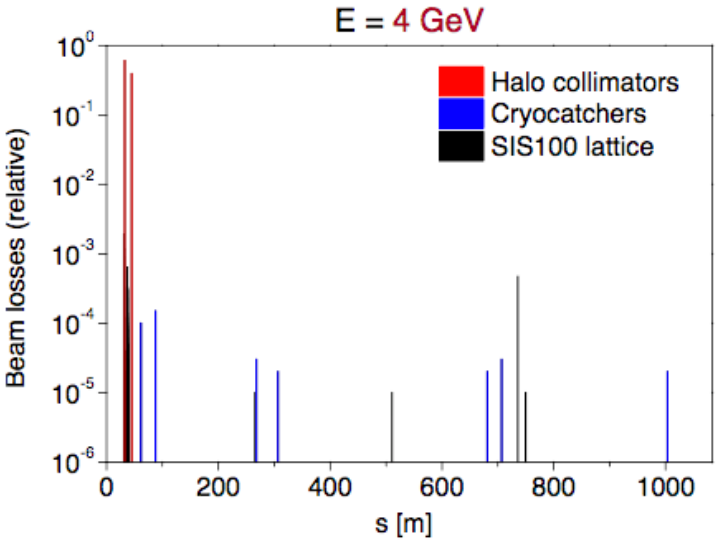
SIS100 Collimation

SIS100 Halo Collimation System





Beam Dynamics studies for the design and efficiency of the collimation system



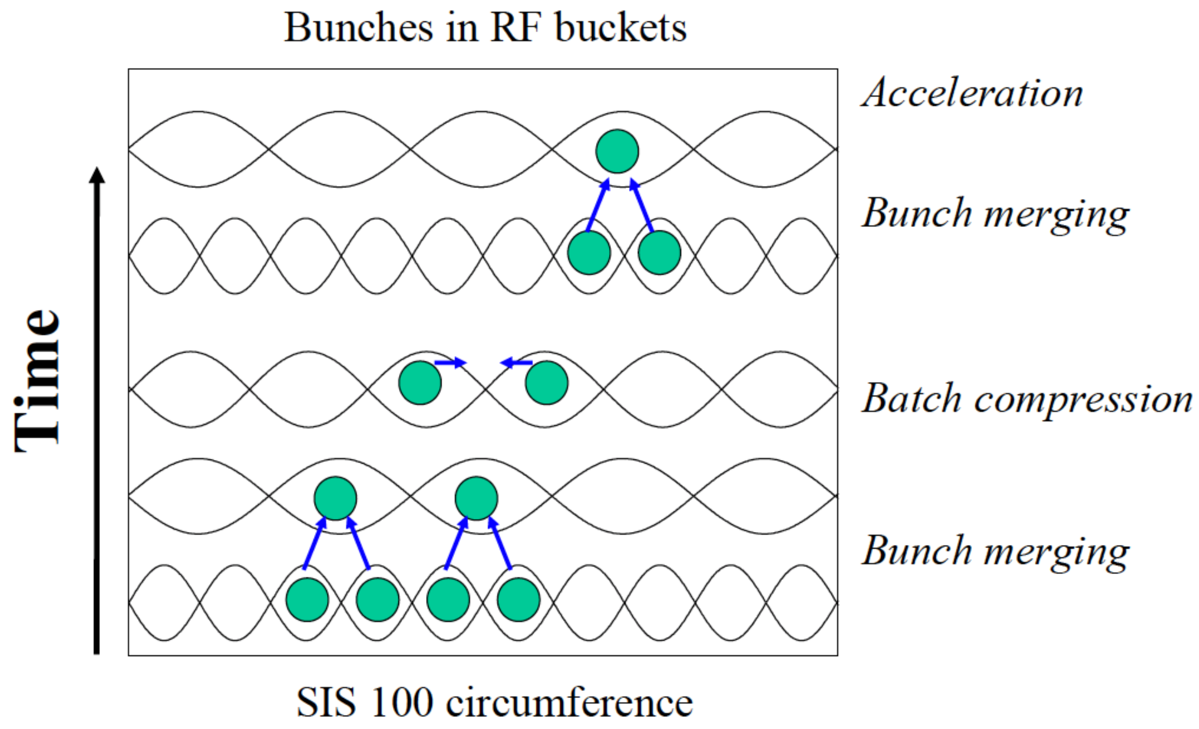
Primary collimator: thin foil
Secondary collimators: bulky absorbers

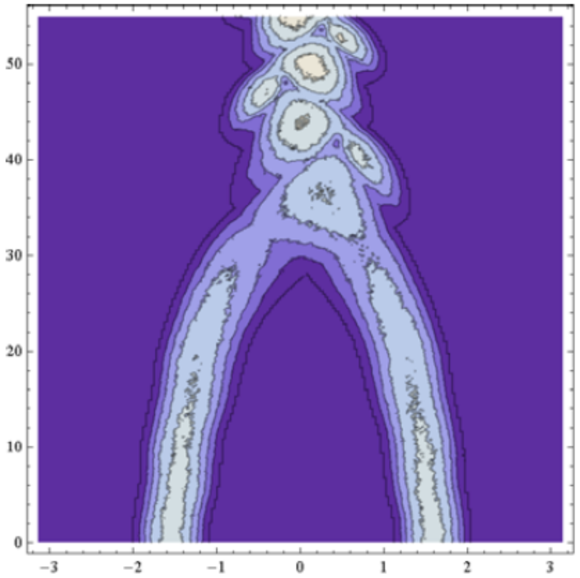
I.Strasik, SIS100 Beam Dynamics Meeting, May 2015

RF Systems

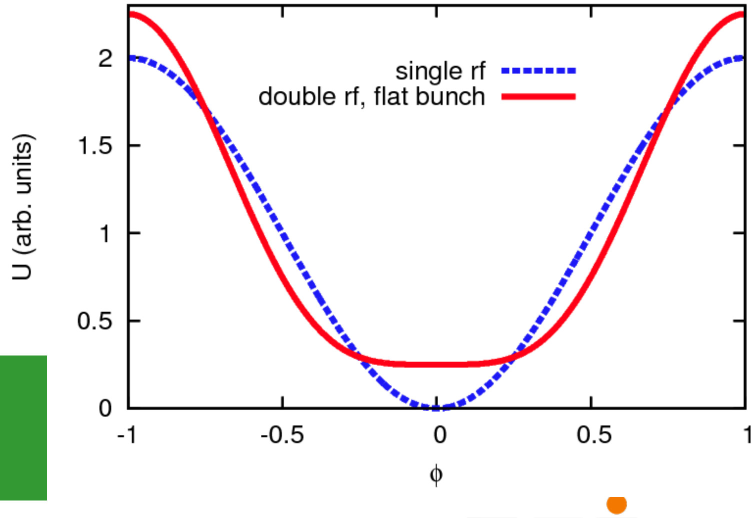
SIS100 RF Cycles

Complex RF manipulations for different operation cycles





A. Chorniy, SIS100 Beam Dynamics Meeting, May 2012



Usage of the Dual RF for better beam lifetime and stability

Dual RF for SIS100

Beam time in SIS18:

$^{124}Xe^{43+}$ ions

12 June 2016

$N_p = 2\times10^9$

$E_K = 6.81$ MeV/u

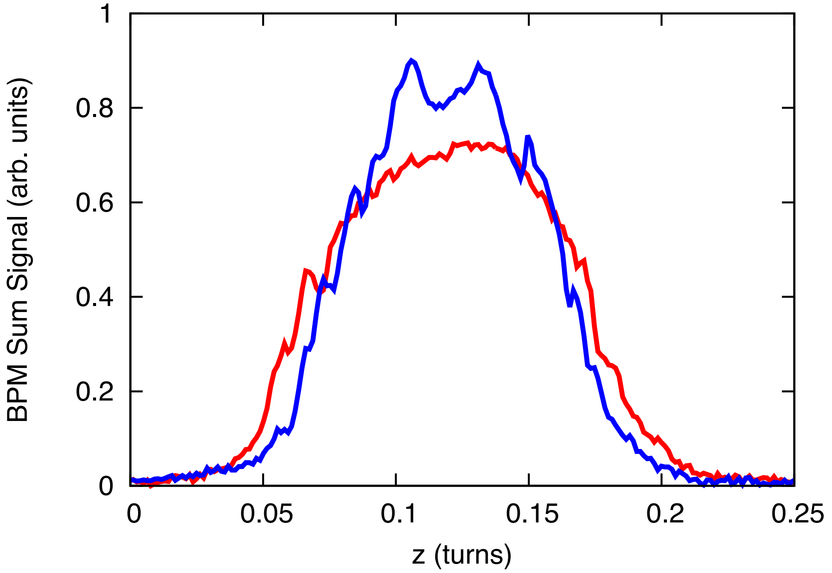
MA h=4 V=2.2kV

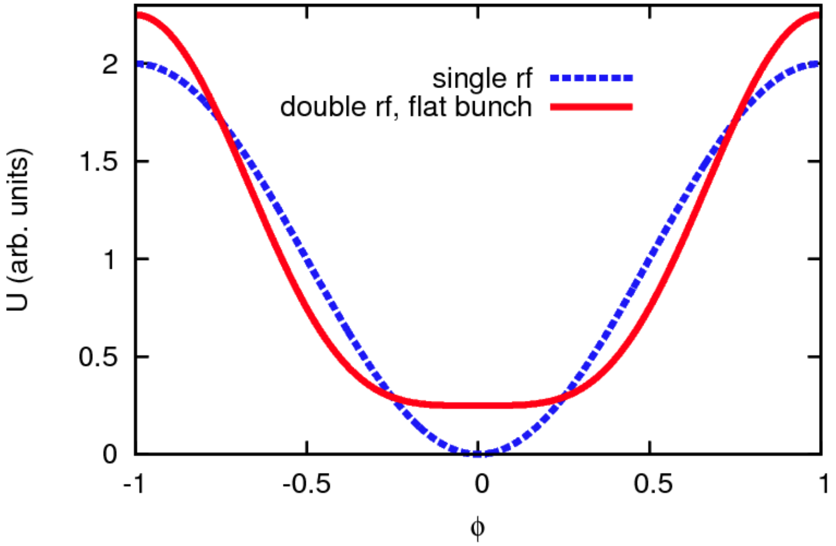
F h=8 V=1.1kV

$\Delta Q_{sc} \approx -0.12$ (vert)

$\Delta Q_{sc} \approx -0.06$ (hor)

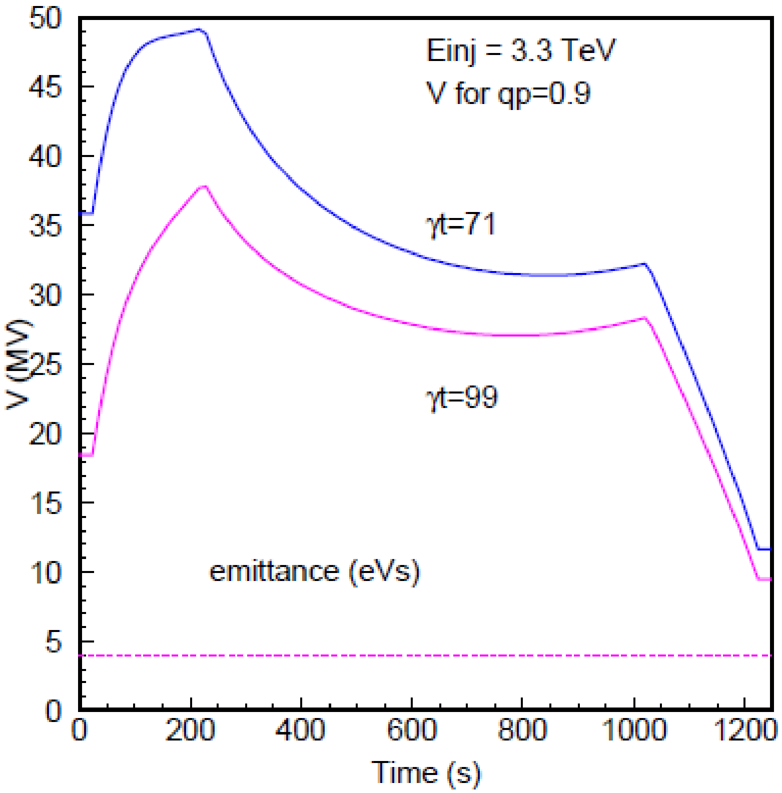
V. Kornilov, SIS18 Beam Time 2016





RF Studies for FCC

Planning and design of the RF System



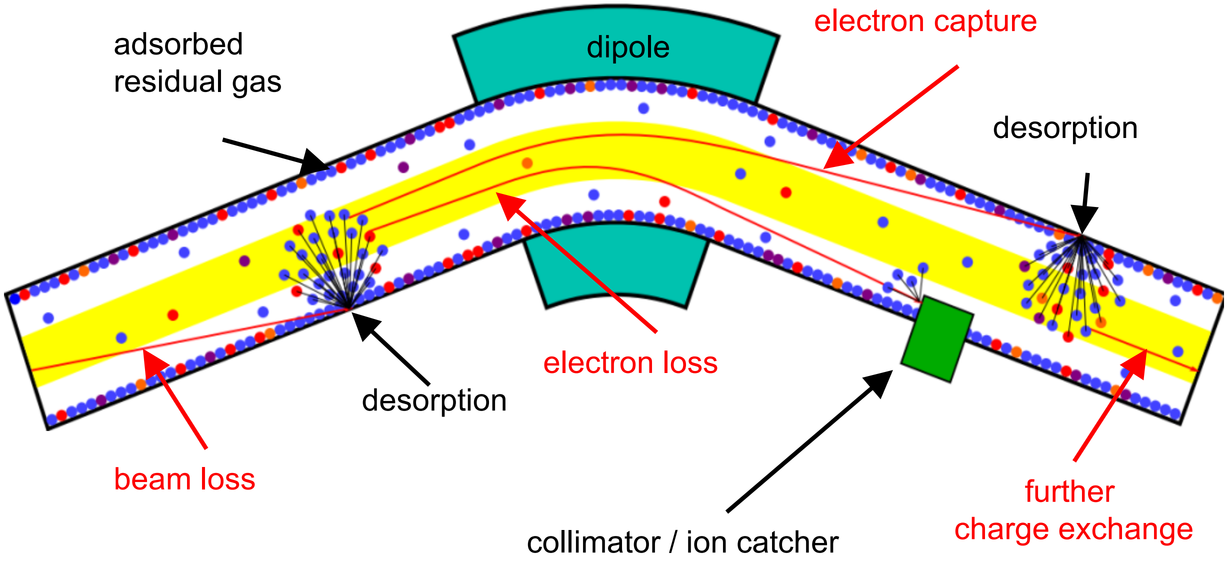
RF Voltage during the ramp

E. Shaposhnikova, FCC Week 2017

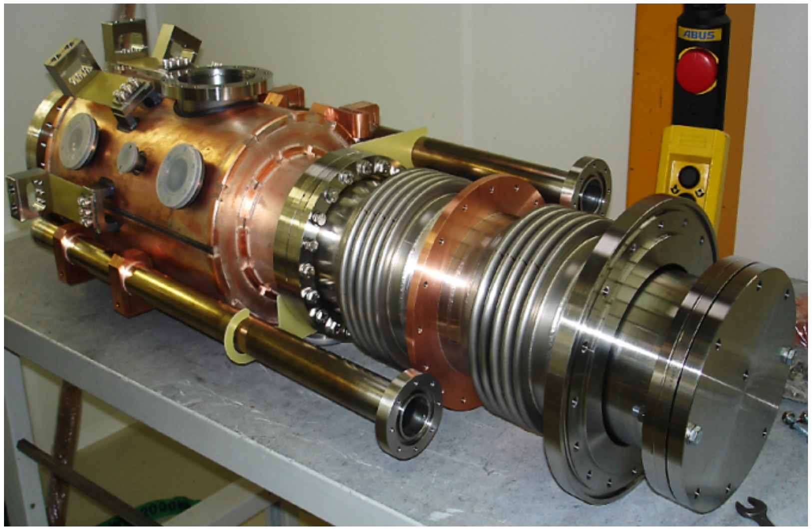
Non-Common
FCC—SIS100
Beam Dynamics Issues

Dynamic Vacuum in SIS100

Higher Intensities due to low charge states.
Stable vacuum is a critical issue.



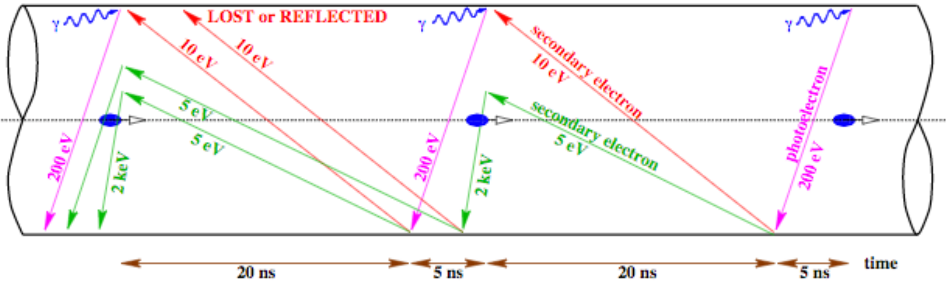
L. Bozyk, C. Omet, D. Ondreka, et al



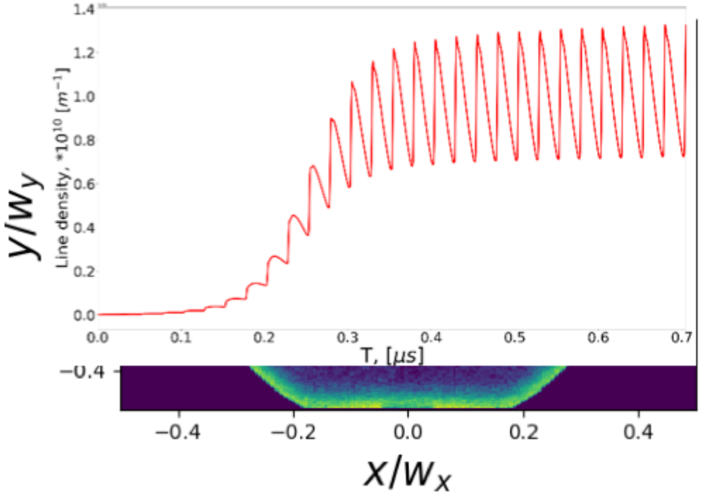
Pre-Series SIS100 Cryocatcher

Electron Clouds, Beam-Beam in FCC

Electron Coulds

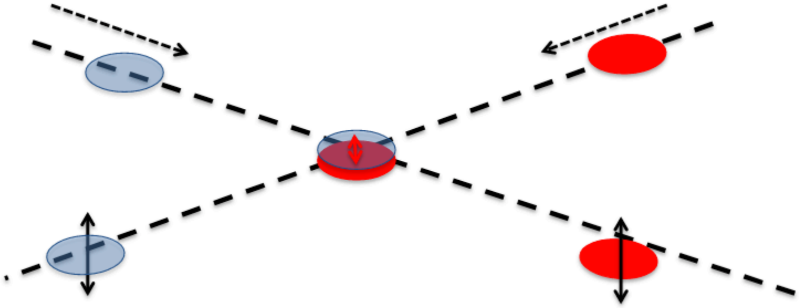


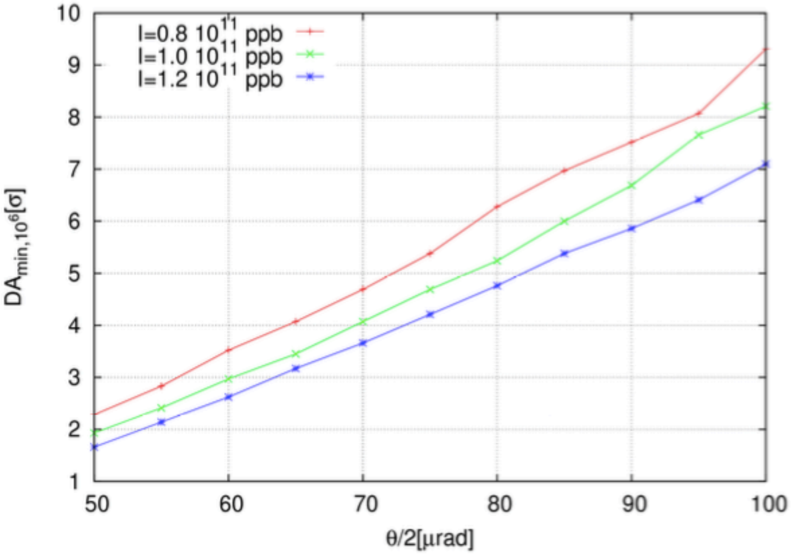
Electron Cloud Buildup



O.Boine-Frankenheim, FCC Week 2017

Beam-Beam

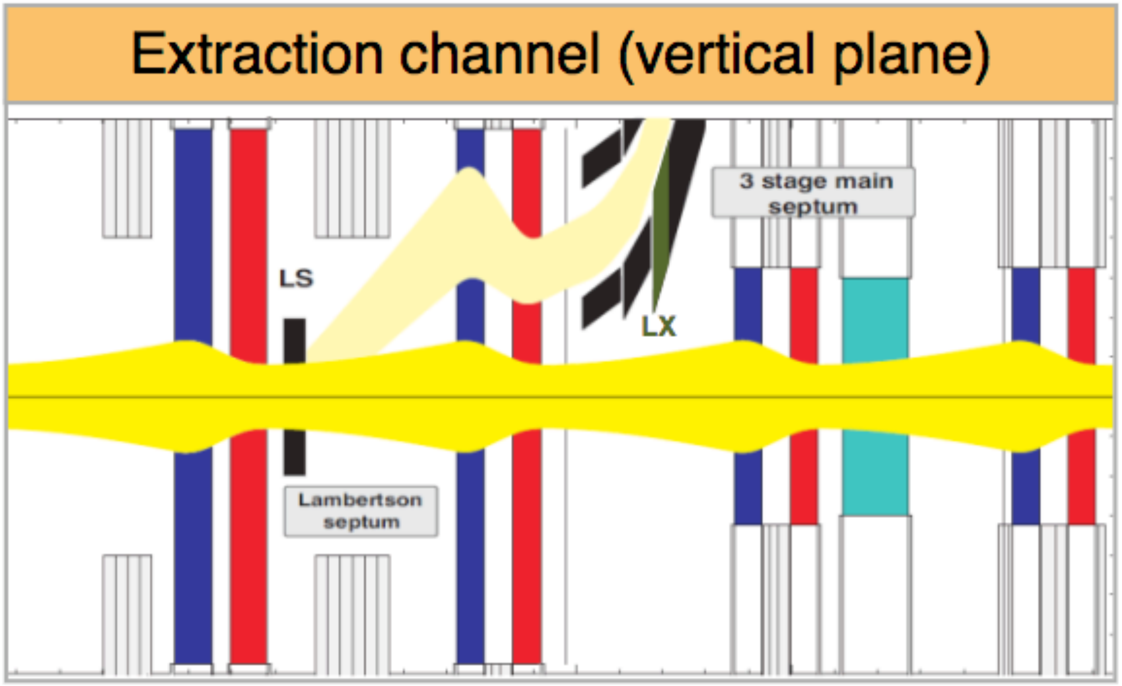


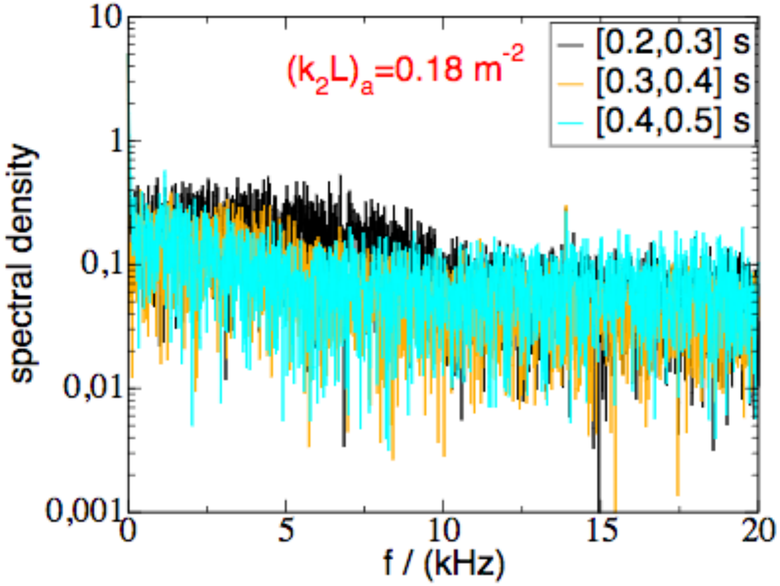


T.Pieloni, FCC Week 2017

Beam Extraction from SIS100

Dedicated devices for slow extraction.
Fast extraction system.
Emergency extraction system.


Extraction channel (vertical plane)



D. Ondreka, November 2017
S. Sorge, November 2017

Challenging issue: spill quality of the slow extraction, 1-10 sec

Summary

- Field quality (Dynamic Aperture), Resonances & Correctors
  - SIS100: resonance crossing due to space-charge
  - FCC: very low loss requirements for long storage (hours)

- Collective Instabilities: Impedances, active cures (feedback), passive mitigation (octupoles)
  - SIS100: space-charge
  - FCC: electron clouds, beam-beam

- Machine Protection

- RF Manipulations and Stability

- Non-Common beam dynamics issues (U^{28+} in SIS100, collider FCC)