FAIR high intensity beam dynamics

Space charge and impedance effects in SIS-18/100

Topics:

- Space charge limit and related beam loss: Optimized working point
- Optimization of RF manipulations with space charge and beam-loading
- Transverse resistive wall and kicker impedances
- Transverse coherent beam instabilities with space charge
- Transverse Schottky noise with space charge

People involved:

O. Chorniy, G. Franchetti, I. Hofmann, R. Hasse, V. Kornilov, S. Paret, A. Parfenova, O. Boine-Frankenheim
GSI, Darmstadt, FAIR accelerator theory

B. Doliwa, L. Hänichen, Th. Weiland, TU-Darmstadt, TEMF

A. Al-khateeb, W. Daqa, University Irbid, Jordan

G. Rumolo, H. Damerau, E. Metral, F. Zimmermann, CERN

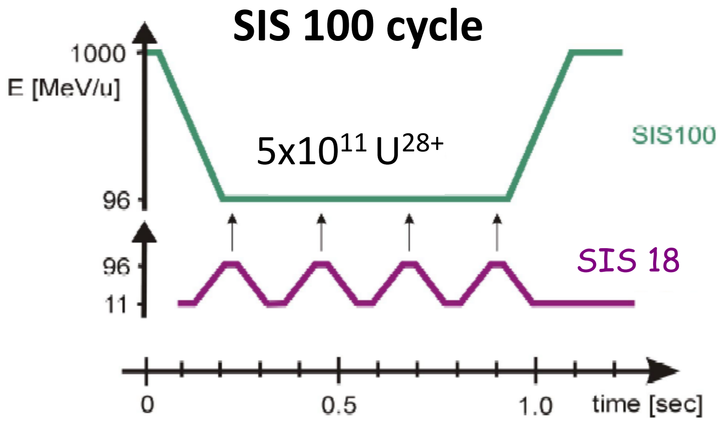
Required FAIR beam intensities

Heavy ions

	SIS-18 today*	After upgrade (2009)	After upgrade (to SIS 100)	SIS 100
Reference ion	U^{28+} / U^{73+}	U^{73+}	U^{28+}	U^{28+}
Maximum energy	0.2 / 1 GeV/u	1 GeV/u	0.2 GeV/u	2.7 GeV/u
Maximum intensity	5x10^{9} / 3x10^{9}	2x10^{10}	1.5x10^{11}	5x10^{11}
Repetition rate	0.3 Hz	1 Hz	2.7 Hz	0.7 Hz
Bunch length	> 100 ns	50 ns	-	60 ns

FAIR specific beam dynamics challenges:

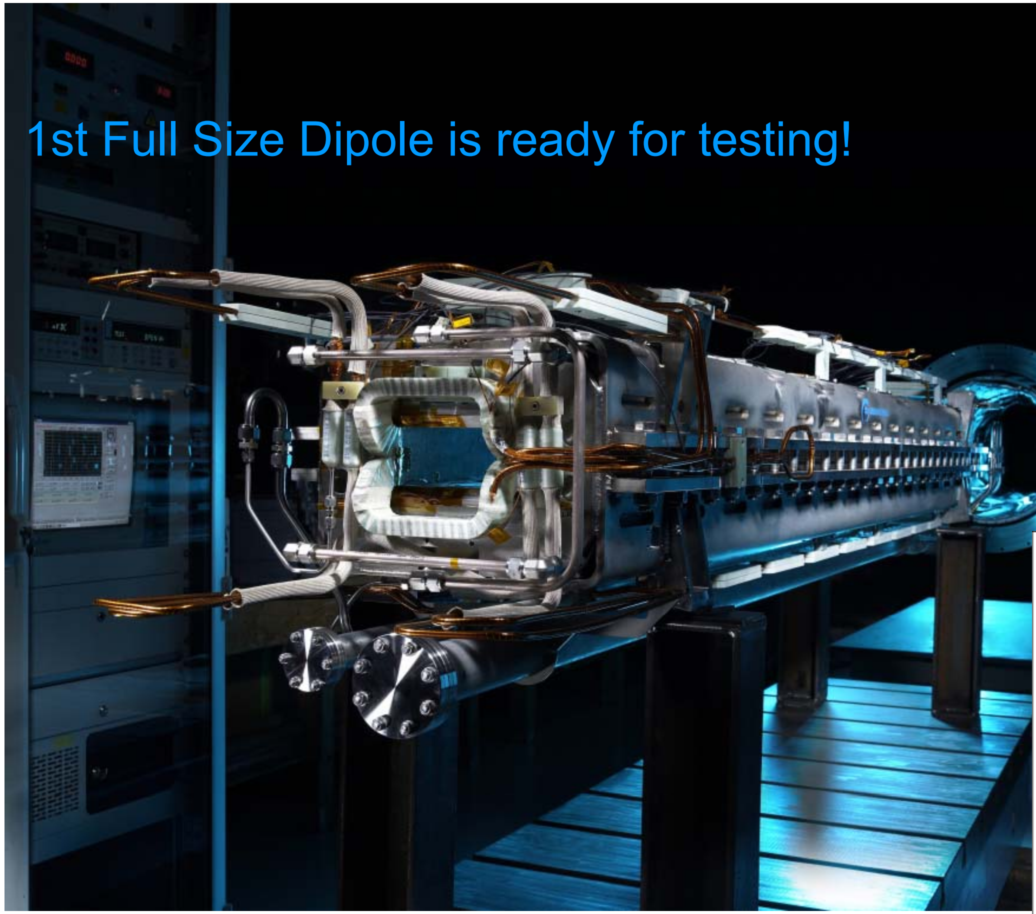
- Intensities at the ‘space charge limit’
- High beam quality (weak or lost Landau damping)
- Long accumulation time (1 s) in SIS-100
- Bunch compression



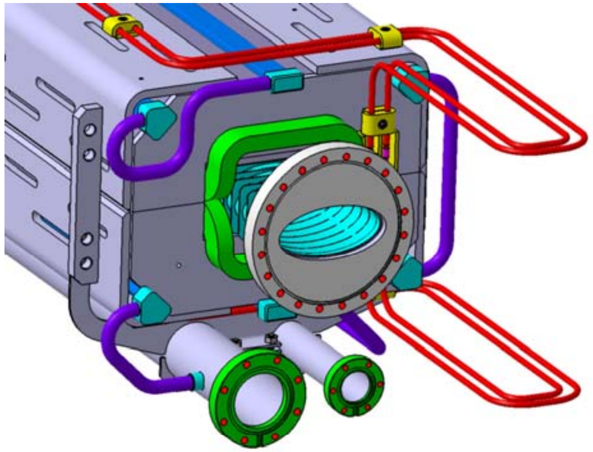
SIS 100 dipole magnets

Field quality

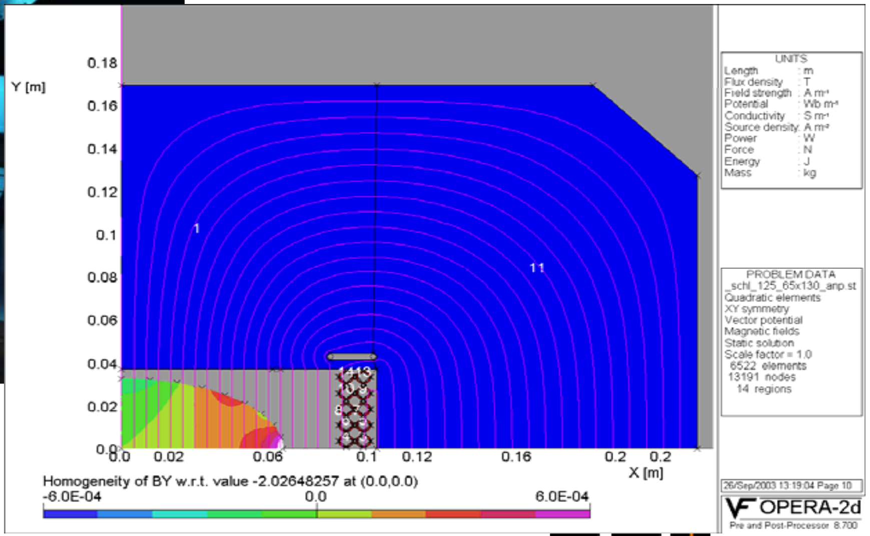
Superconducting magnet with 4 T/s and B_{max}= 1.9 T



Dipole magnet with elliptical beam pipe



2D/3D field calculations

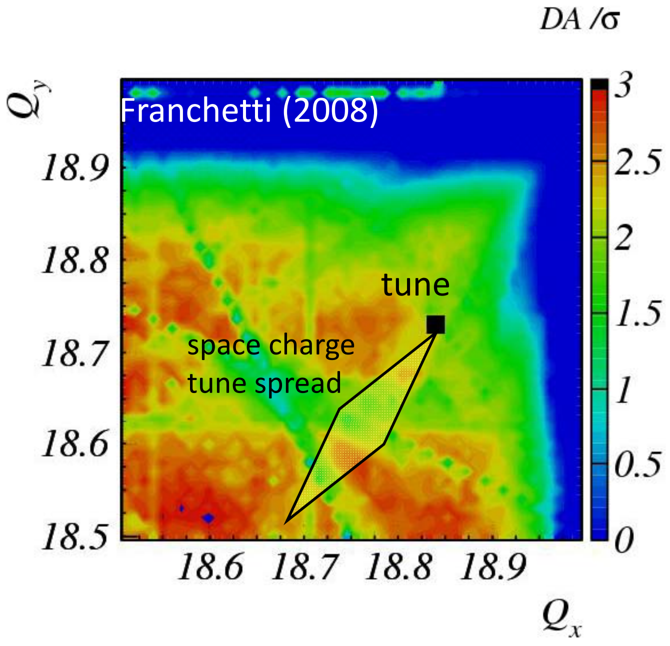


P. Spiller talk !

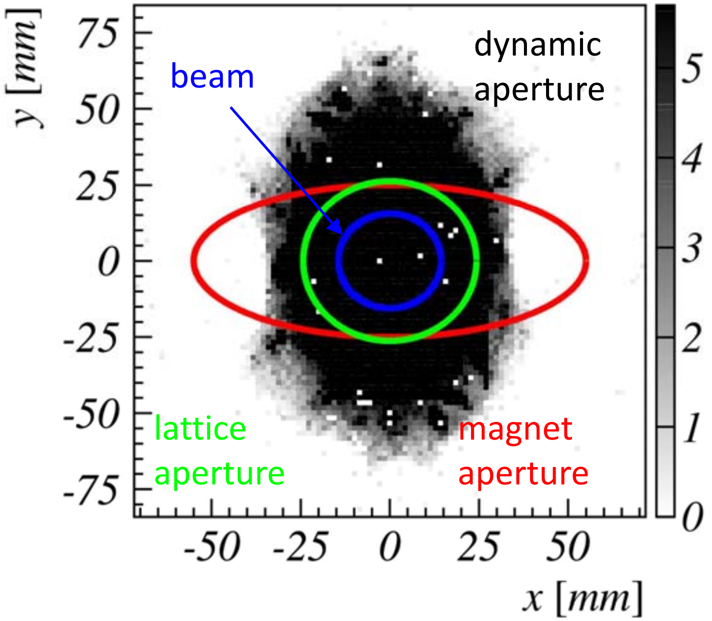
SIS-100 field quality and beam loss

at injection energy 0.2 GeV/u

Simulation scan of the **SIS-100 dynamic aperture**



SIS-100 transverse apertures at injection (0.2 GeV/u)



Long-term (up to 1 s) 3D particle tracking studies with 'frozen' space charge indicate a space charge limit at 3×10^{11} U^{28+} (design 5×10^{11}).

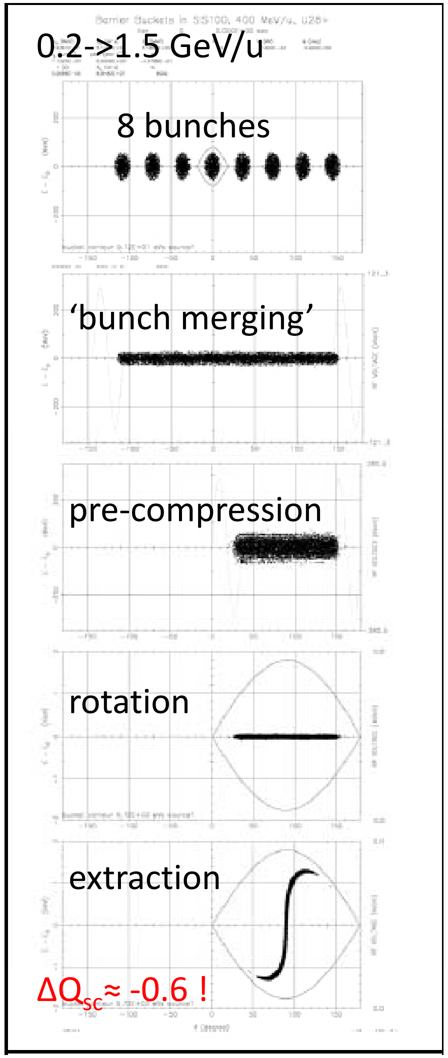
G. Franchetti et al. EPAC 2006
G. Franchetti, SIS-100 technical design report (2008)

High intensity challenges for SIS-100:

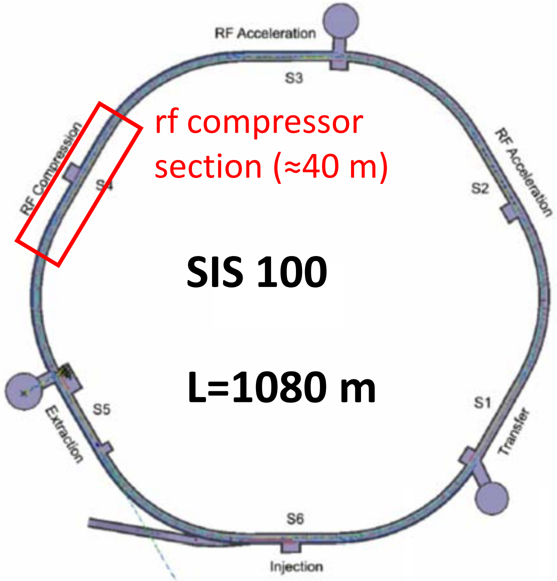
- Long time scales up to 10^6 turns (1 s)
- Space charge tune shift of $\Delta Q_{sc}=-0.25$
- 'Thick' medium energy beams (2/3 filling factor)
- Optimized working point for < 5 % loss.

SIS-100 bunch compression

Single bunch formation



rf bunch compressor
loaded with 20 MA cores



RF compression systems in SIS 100:

	#cavities	**Voltage [kV]**	**Frequency [MHz]**	**Concept**
Barrier rf Pre-compressson	2	30	1.5 (h≈10)	MA
Compression	16	600	0.4-0.5 (h=2)	MA (low duty)

Final bunch parameters:

	Particles/bunch	**bunch length**
1.5 GeV/u U^{28+}	$5x10^{11}$	60 ns
29 GeV/u p	$2\text{-}4x10^{13}$	50 ns

SIS-100 bunch pre-compression

barrier rf bucket with beam-loading and space charge

Longitudinal space charge impedance:

$$\frac{Z_l^{sc}}{n} = \frac{igZ_0}{2\beta_0\gamma_0^2} \approx i200\,\Omega$$

Haissinski equation for the matched bunch form:

$$\lambda(z) = \lambda_m \exp\left(\frac{qV_0 Y(z)}{m^* L v_{rms}^2}\right)$$

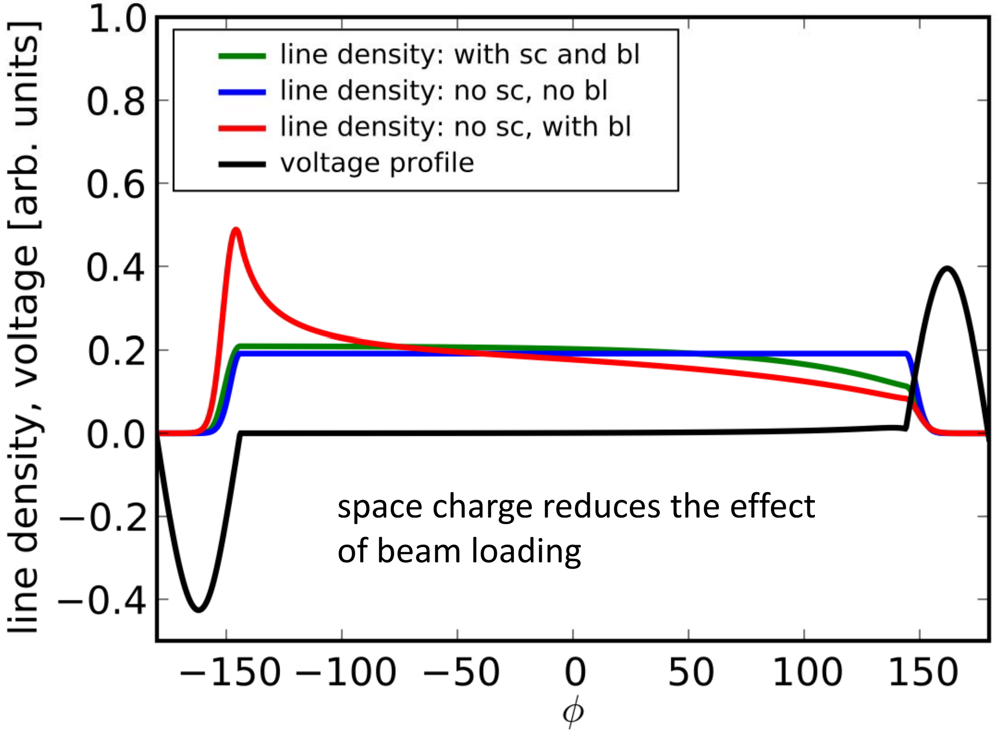
Between barriers (no rf:)

$$\lambda(z) = \lambda_m \exp\left(\alpha_s \lambda + \alpha_r \int_0^z \lambda dz\right)$$

with $\alpha_s \propto \frac{Z_l^{sc}}{n}$ $\alpha_r \propto R_s$

$$\lambda(z) = \frac{\lambda_m}{1-\alpha_s(\lambda-\lambda_m)-\alpha_r\lambda_m z}$$

	# cavities	R_s/cavity [kΩ]	Q_s	f_{res}
acceleration	20	3	10	$10f_0$
barrier	2	1	0.4	1.5 MHz
compression	16	1	2	1.5 MHz



space charge reduces the effect of beam loading

Barrier Bucket Pre-Compression in SIS-100

Non-adiabatic barrier rf phase ramp:

T=100 ms T_{s0}> 100 ms

(ramp time) ('synchrotron period')

Space charge factor:

$$\Sigma = \frac{c_s}{v_{rms}} > 1$$

Cold fluid equation (Rumolo et al. 1999):

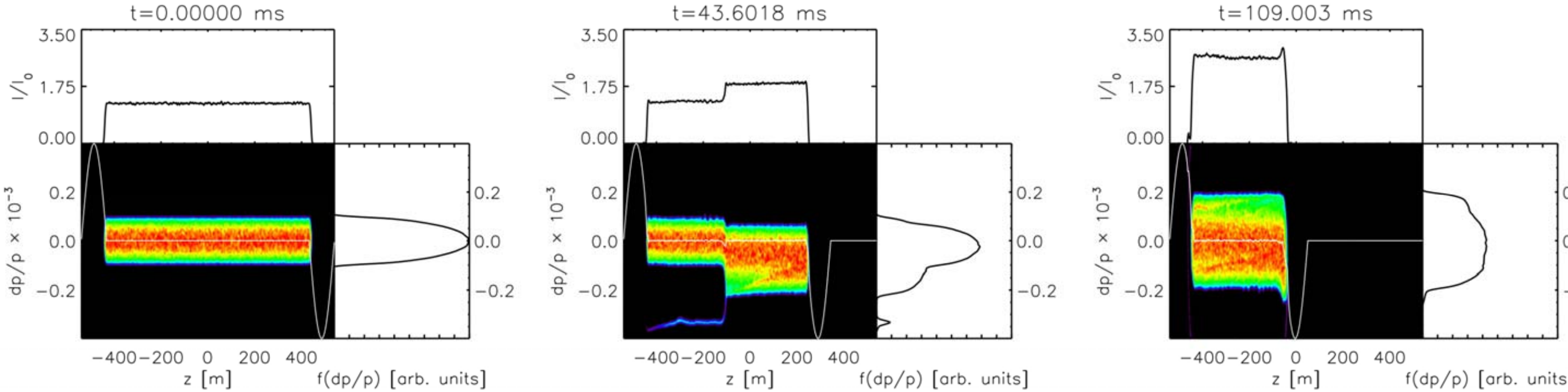
$$\frac{\partial\lambda}{\partial t} + \frac{\partial}{\partial z}(\lambda u) = 0 \qquad \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial z} + \chi\frac{\partial\lambda}{\partial z} = 0$$

with $\chi = \frac{qX_s\beta_0 c}{2\pi m^*}$ $\frac{Z_{sc}}{n} = -iX_{sc}$

'speed of sound': $c_s \approx \sqrt{\lambda_m \chi}$

Shock compression:

The barrier acts like a piston moving with velocity v in a gas, creating a shock wave of speed c_s>v



The shock compression is dilution-free !

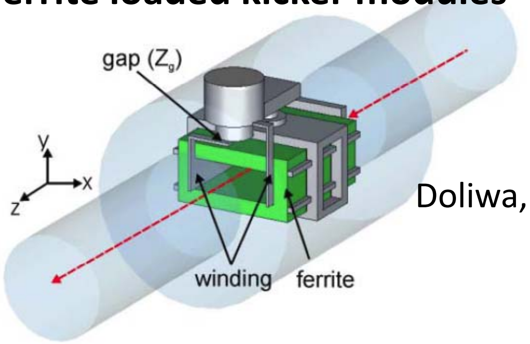
Oliver Boine-Frankenheim, CARE-HHH 24.11.2008

Transverse impedances in SIS-18/100

Specific SIS-18/100 impedance issues:

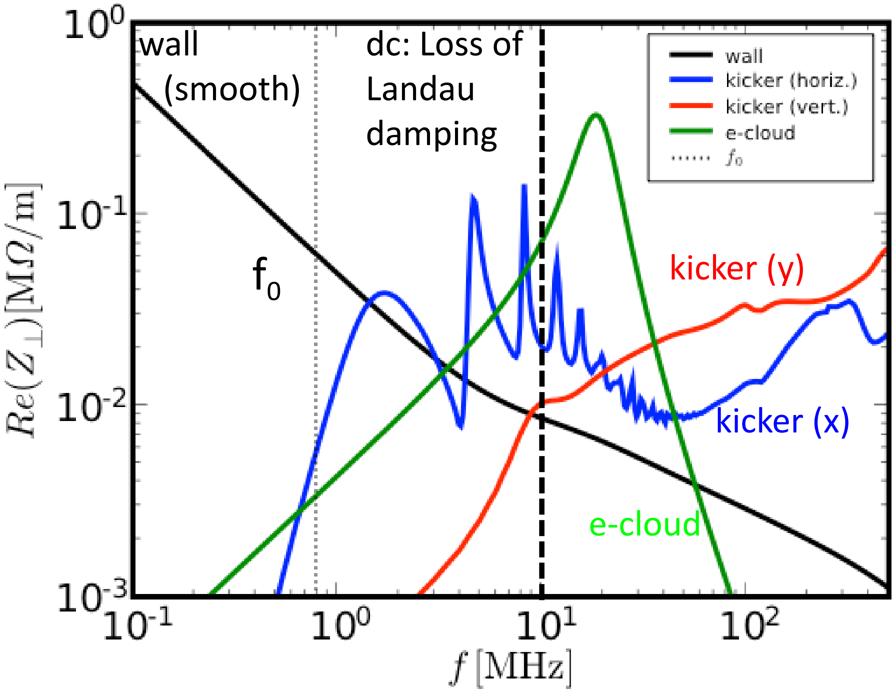
- Low frequencies and beam energies
- Thin (0.3 mm) stainless steel pipe (**optional** corrugated)
- Ferrite or magnetic alloy loaded ring components
- Distributed collimation system

Ferrite loaded kicker modules



Doliwa, Weiland (2006)

SIS-18 transverse impedance spectrum (200 MeV/u)



'Space charge impedance': $Z_\perp^{sc} = -i\frac{Z_0 R}{\beta_0^2\gamma_0^2}\frac{1}{b^2} \approx -i10\ \mathrm{M\Omega/m}$

e-clouds ?:

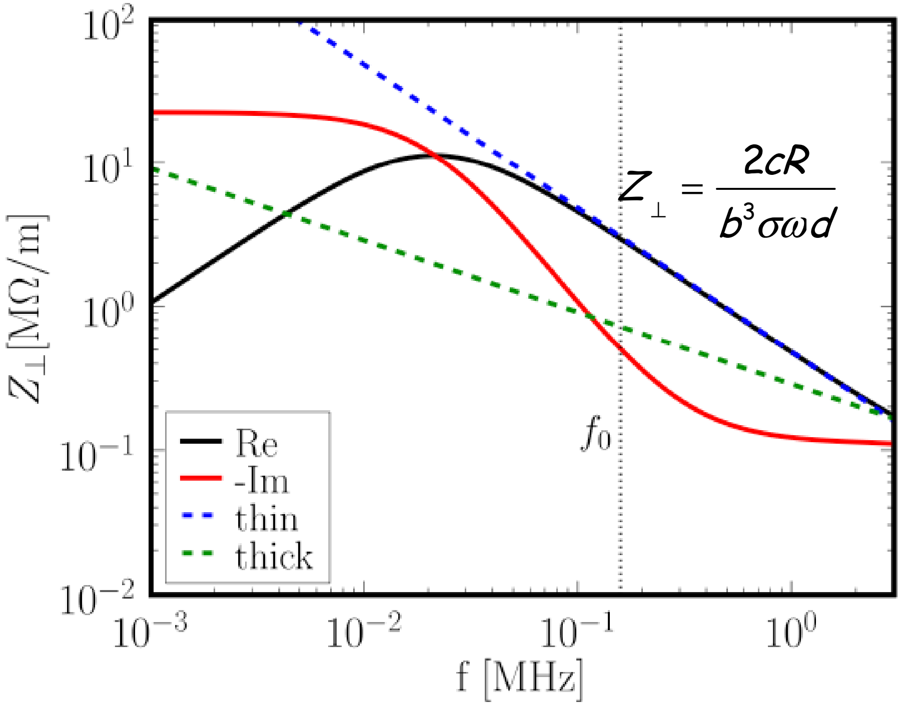
- electrons from residual gas ionization and beam loss.
- e-accumulation: survival rate in bunch gaps ?
- transv. 'impedance': Ohmi, Zimmermann, PRL (2000)
- long. impedance: Al-khateeb et al. NJP (2008)

Resistive (thin) beam pipe in SIS-100

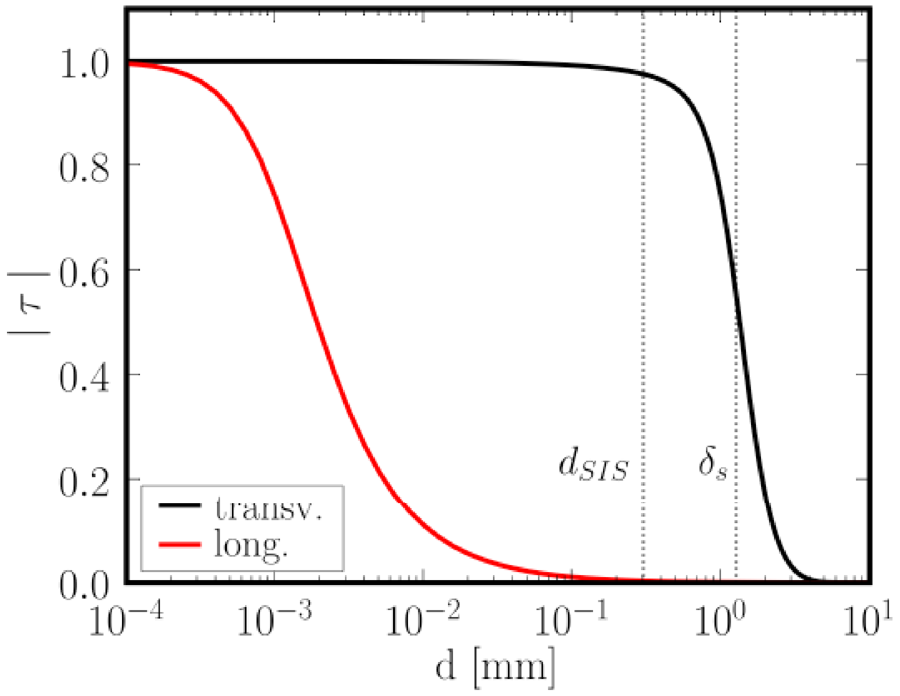
Transverse impedance and shielding

In SIS-100 the thin (0.3 mm) beam pipe is the dominant transverse impedance contribution !

SIS 100 transverse resistive wall impedance (200 MeV/u)



Transmission coefficient !



Transmission: Structures behind the pipe might contribute !

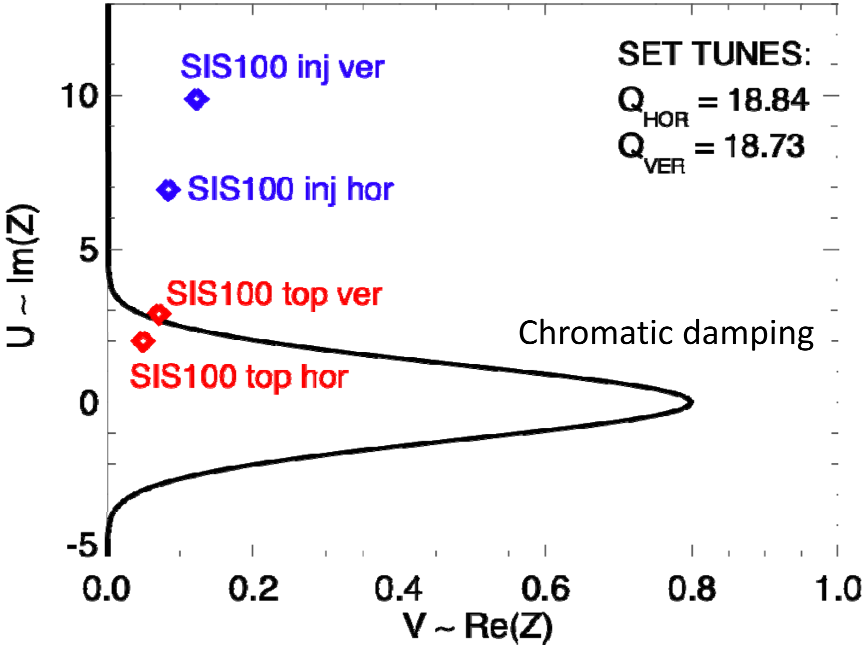
SIS-18: Measured growth rate of the resistive wall instability agrees with impedance formula.

Al-khateeb, Hasse, Boine-F., Daqa, Hofmann, Phys. Rev. ST-AB (2007)

Transverse Impedance Budget with Space Charge

coasting beam stability boundaries (from dispersion relation)

$$Z_\perp = Z_\perp^{rw} + Z_\perp^{sc} \qquad Z_\perp^{sc} = -i\frac{Z_0 R}{\beta_0^2\gamma_0^2}\left(\frac{1}{a^2} - \frac{1}{b^2}\right)$$



Specific issues for SIS-100:

- Long time scales (up to 1 s)
- Image current and space charge effects
- Long bunches and ‘dc-like’ barrier rf beams

Potential cures:

- octupoles and nonlinear space charge
  (Kornilov et al. PRST-AB 2008)
- feedback systems

Challenges:

- Octupoles and dynamic aperture
- 3D space charge and image current effects

Head-tail instability in SIS-100 (talk by V. Kornilov this Monday afternoon):

-Sacherer’s formula predicts head-tail modes with 70 ms growth rate in SIS-100 !

-3D simulation studies including: resistive wall impedance, image currents, space charge, nonlinear rf.

-’Mode coupling regime’: $\Delta Q_{\mathrm{incoh}}^{\mathrm{sc}} > \Delta Q_{\mathrm{coh}}^{\mathrm{sc}} > \nu_s$ (ν_s: synchrotron tune)

TWO SIMULATION TOOLS

V. Kornilov

our strategy on the way to a correct description of the effects relevant in SIS-100 for the Head-Tail instability: two different tools

PATRIC

(development at GSI)

short-term simulation:
resolve betatron oscillations

impedances Z(ω) [add. W(s)]

self-consistent 3D space charge

coasting / long bunches

Coasting beam modes: comparison with analyic dispersion relation
Schottky noise: comparison with analytic theory.

HEADTAIL

(joint work with G.Rumolo)

long-term simulations:
once per turn

wake fields W(s)

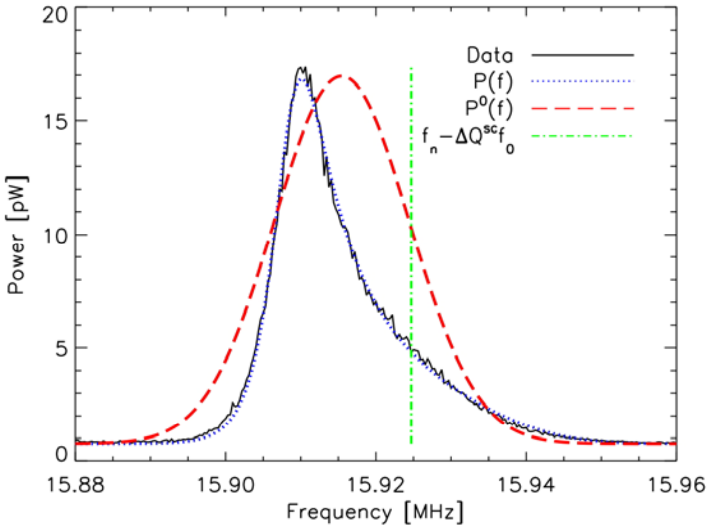
beam-beam kick

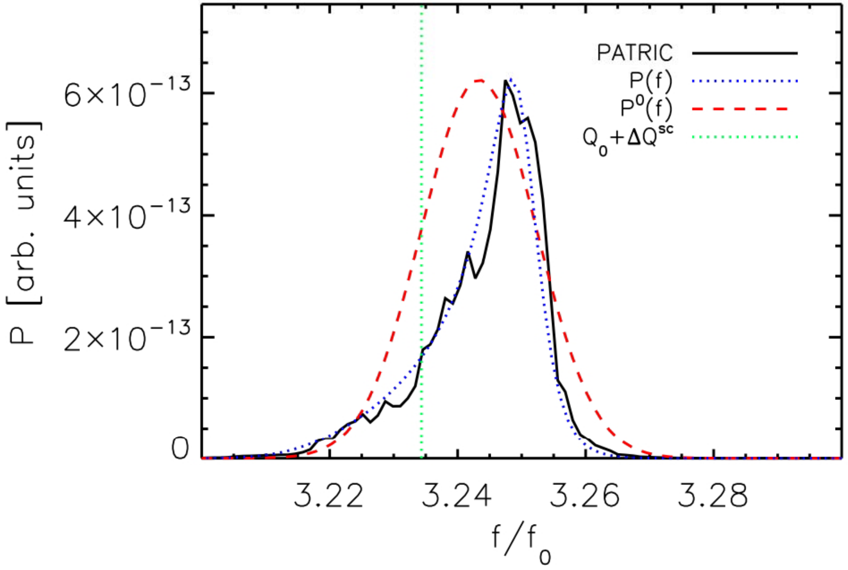
short bunches

Head-Tail modes: consistency with the Sacherer theory was confirmed in the recent work (E.Metral,G.Rumolo,R.Steerenberg,B.Salvant,PAC'07)

Schottky noise measurement in SIS-18

coasting beam with space charge


Measured lower sideband (n=75)


Upper sideband (PIC Simulation)

Transverse Schottky signal:

$$d(t) = \sum_{j=0}^{N} x_j(t) I_j(t)$$

coasting beam coherent betatron lines:

$$\Omega_n = (n \pm Q_0)\, f_0$$

Low intensity Schottky band: $P^0(\Omega)$

Modified Schottky band (analytic approach):

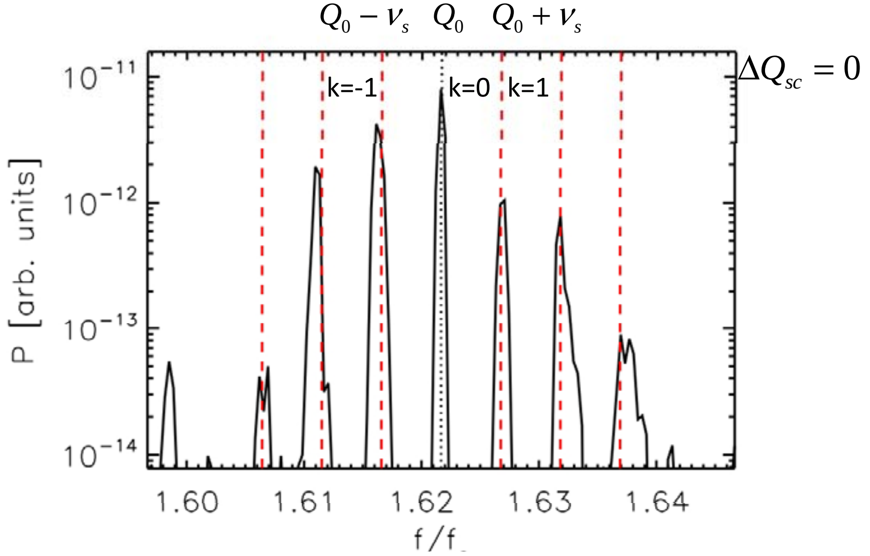
- Assuming linear space charge (KV-dist.)
- Dispersion relation D(z) with space charge:

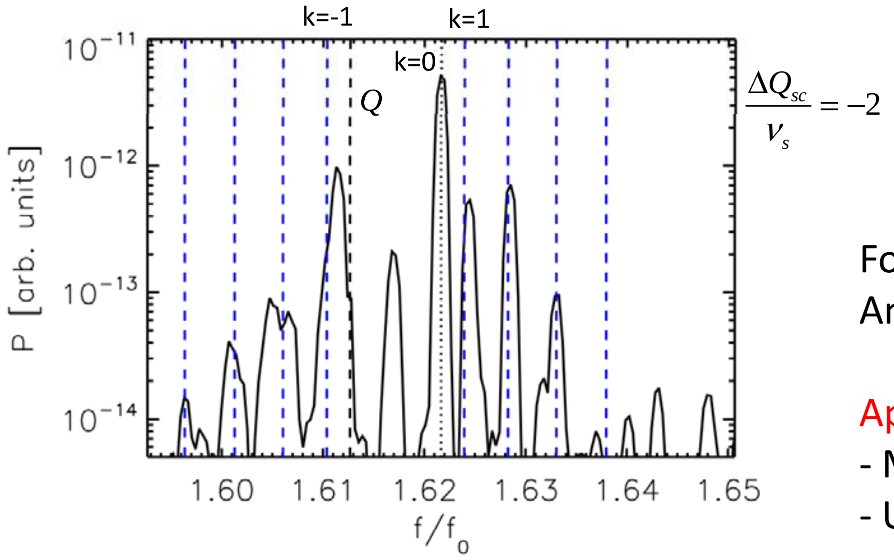
$$\varepsilon(z) = 1 - D(z) \qquad P(z) = \frac{P_0(z)}{|\varepsilon(z)|^2}$$

Comparing the measured Schottky bands with P(z) we can obtain the space charge parameter.

Boine-Frankenheim, Kornilov, Paret, PRST-AB (2008)

PATRIC simulations of transverse Schottky signals with space charge





Shift of head-tail modes with space charge

M. Blaskiewicz, Phys. Rev. ST Accel. Beams 1, 044201 (1998)

for a barrier air-bag distribution.

For k≠0: $$\Delta Q_k = -\frac{\Delta Q_{sc}}{2} \pm \sqrt{(\Delta Q_{sc}/2)^2 + (k\nu_s)^2}$$

$\Delta Q_{sc} = \nu_s$ $$\Delta Q_k = -\frac{\Delta Q_{sc}}{2} \pm k\nu_s$$

ΔQ_{sc} ? ν_s $$\Delta Q_k = \frac{(k\nu_s)^2}{\Delta Q_{sc}} \approx 0, \quad \text{for} \quad k > 1$$

$$\Delta Q_k = -\Delta Q_{sc}, \quad \text{for} \quad k < 1$$

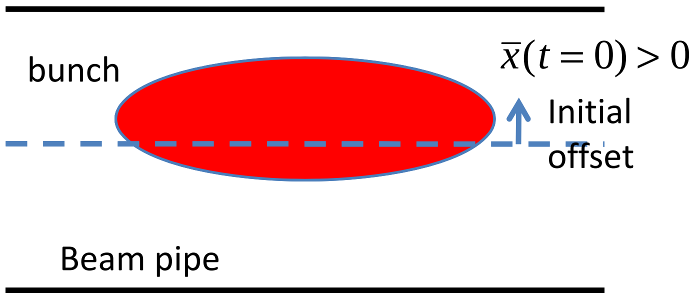
For barrier air-bag: code benchmaking
Analytic results apply for realistic bunches (e.g. elliptic).

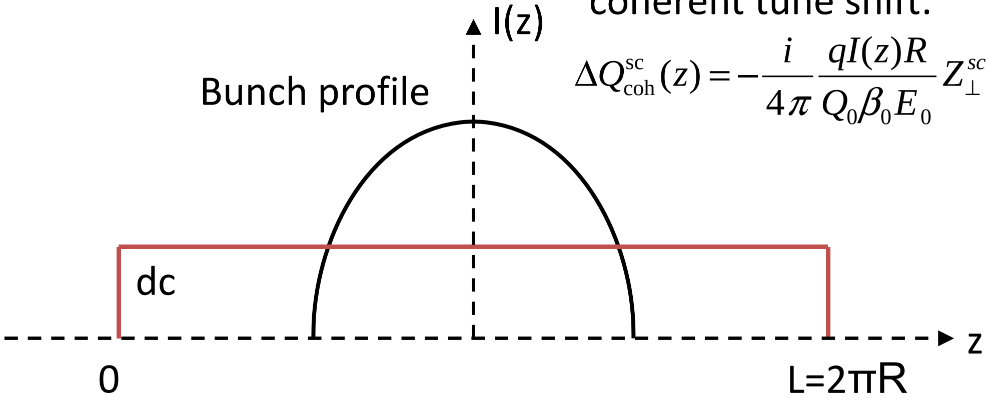
Application:
- Measure space charge tune shifts in bunches
- Understand thresholds for head-tail instabilities

Decoherence with image currents and space charge

3D simulation studies with space charge and impedances

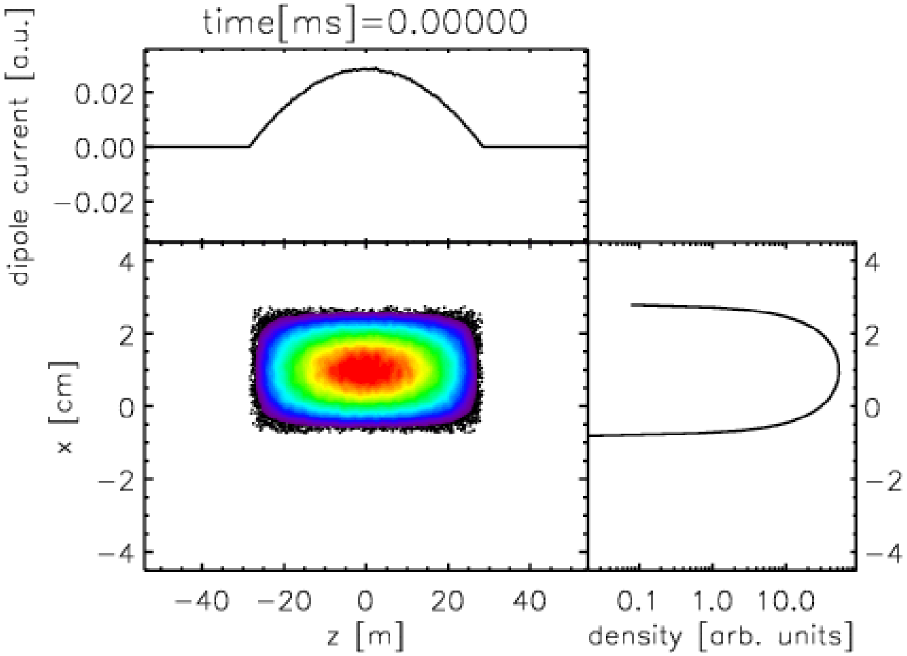
Injected bunch in SIS-100 with a transverse offset.





coherent tune shift:

$$\Delta Q^{\mathrm{sc}}_{\mathrm{coh}}(z) = -\frac{i}{4\pi}\frac{qI(z)R}{Q_0\beta_0 E_0} Z^{sc}_{\perp}$$



Coherent and incoherent tune spread along the bunch:

$$\Delta Q_{\mathrm{coh,incoh}}(z) = \Delta Q^{\mathrm{max}}_{\mathrm{coh,incoh}}\left(1-\frac{z^2}{z_m^2}\right)$$

Interplay of space charge and image currents:

-mode coupling (due to image currents)

-persistent bunch modes

-halo formation !

Summary

Work performed in the framework of the CARE-HHH network activity.

- Long-term particle tracking studies for SIS-100 including ‘frozen’ space charge for different working points: Beam loss estimates.
- Analysis of space charge and beam-loading effects in barrier rf buckets: Optimized pre-compression scheme with space charge.
- Transverse impedance spectrum in SIS-18/100 from analytic and from simulation models.
- Transverse impedance budget for dc-like beam and for bunches including space charge.
- Experimental and simulation studies of transverse Schottky noise and decoherence with space charge.