SIS-100 beam dynamics

Outline:

- beam and intensity parameters
- beam loss studies (-> talk by G. Franchetti)
- beam stability studies: coherent beam instabilities, impedances and cures
- rf manipulations with intense bunches

SIS-100 machine cycle

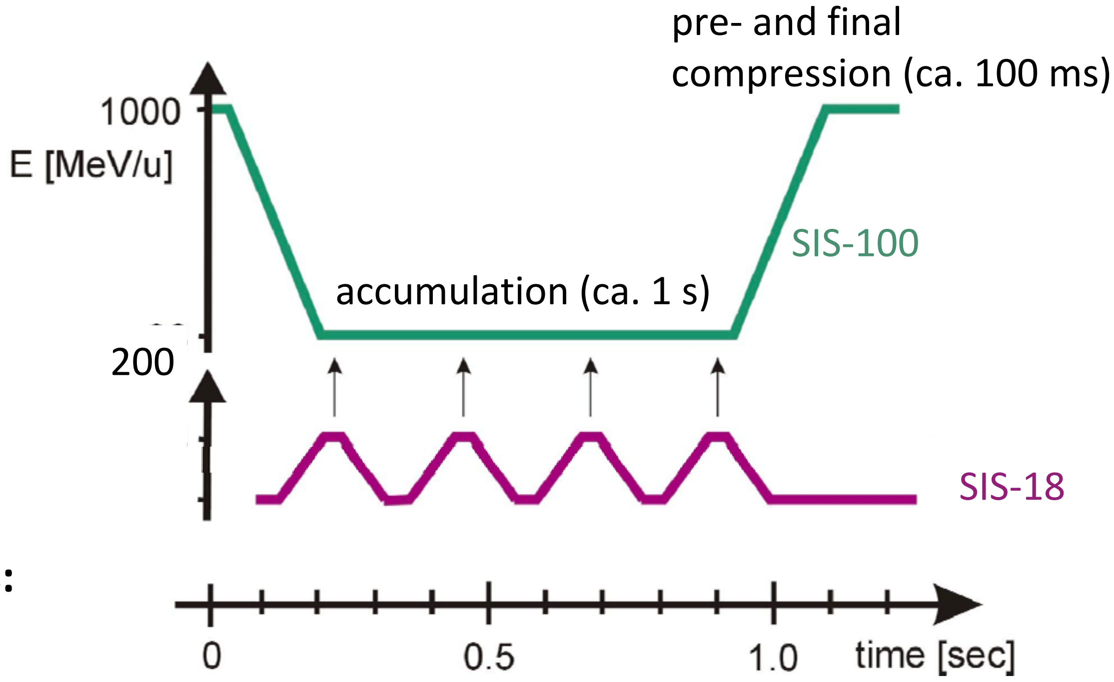
beam dynamics issues

Studies concentrate on:

a) accumulation phase

b) pre-compression schemes

c) fast bunch compression



SIS-100 specific beam dynamics issues:

- Intensities at the ‘space charge limit’
- ‘Thick beams’
- High beam quality (weak or lost Landau damping)
- Long accumulation time (1 s)
- Strong bunch compression (‘extreme’ space charge)

SIS-18/100 beam parameter

FAIR beam parameter booklet, April 2007

space charge tune shift:

$$\Delta Q_y^{sc} = -\frac{NZ^2}{A\beta_0^2\gamma_0^3}\frac{g_f}{\pi B_f}\frac{2}{\left(\varepsilon_y + \sqrt{\varepsilon_x \varepsilon_y}\right)}$$

<u>bunching factor:</u> $B_f = \frac{I_{dc}}{I_{peak}}$

	SIS-18	SIS-100
Ion	U^{28+}	U^{28+}
inj./ext. energy	11.4/200 MeV/u	0.2/1.5 GeV/u
# bunches (inj/ext)	2/2	8/1
# ions (ext)	1.5E11/cycle	5E11/cycle
beam loss / cycle	40 %	10 %
ΔQ_{sc} (inj/ext)	-0.5/-0.06	-0.3/-0.7
$\varepsilon_{x,y}$ (4σ, physical, inj)	150/50 mm rad	50/20 mm mrad
Dilution factor (transverse)	2.5	2.5
Δp/p (2σ, dc, inj)	1E-3	4E-4
Dilution factor	2	2
Bunch length (ext.)		60 ns (10 m)

SIS-100 transverse acceptance:
200/50 mm rad
-> aperture filling factors:
in x: 1/2, in y: 2/3

SIS-100 beam power:
max. 50 kW
10 % distributed loss: 5 W/m

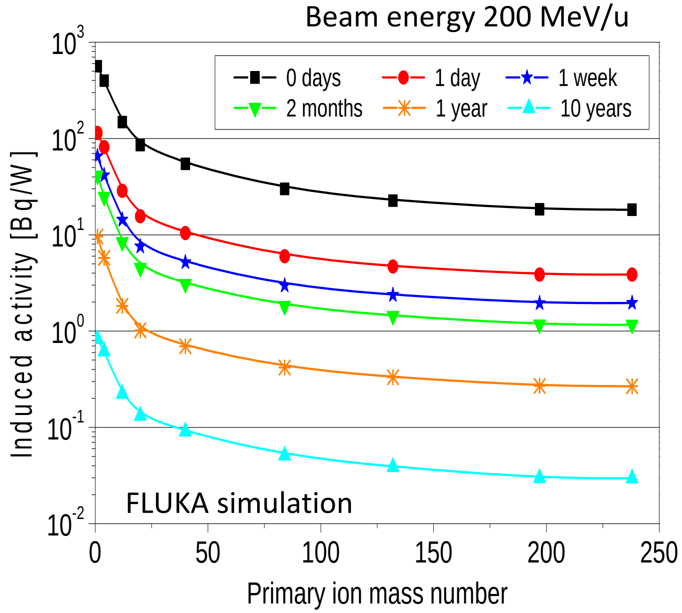
Beam loss budget:
Residual activation induced by heavy ions and tolerable beam loss level

Hands-on maintenance criterium:
1 W/m for 1 GeV proton beams.
5 W/m for 1 GeV/u uranium beam.
58 W/m for 200 MeV/u uranium beam.

Beam loss budget in SIS-100:
desorption (other talks), damage, quenching, activation

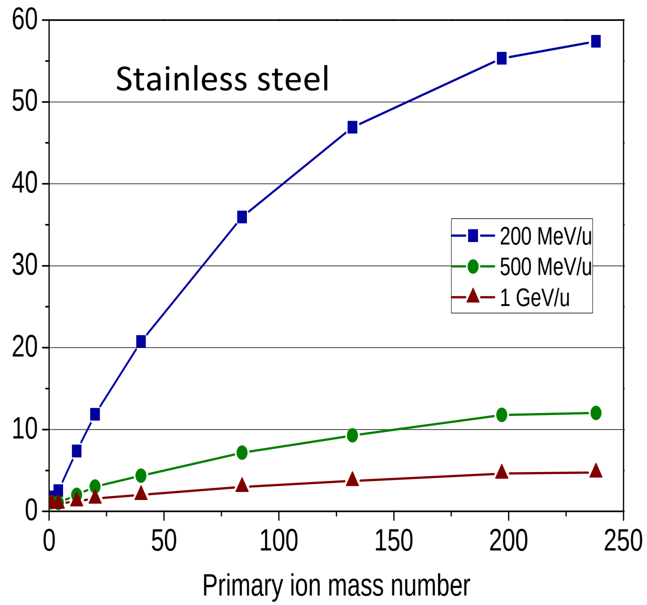
I. Strasik, E. Mustafin et al., **RESIDUAL ACTIVITY INDUCED BY HIGH-ENERGY HEAVY IONS IN STAINLESS STEEL AND COPPER**, EPAC 2008

- Isotope distribution is the same for p and U beams.
- Due to Z^2 dependence of dE/dx heavy ions experience less nuclear interactions than protons -> less activation.



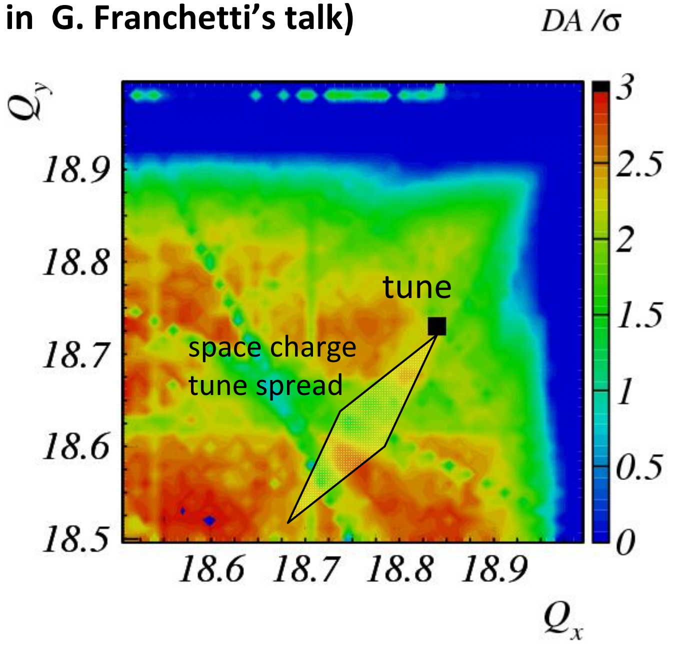
- Tolerable beam loss for heavy ions is higher than for proton beams.

W/m



Beam loss studies (-> G. Franchetti's talk):
Particle tracking including space charge and resonances

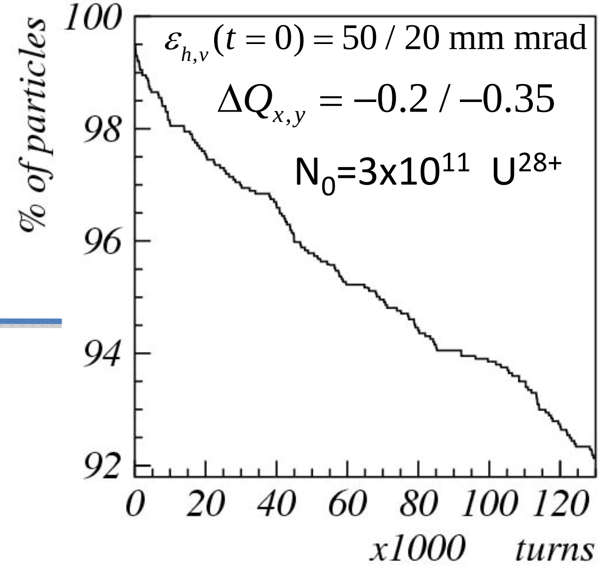
Simulation scan of the **SIS-100 dynamic aperture (details in G. Franchetti's talk)**



Particle tracking studies:

- initial Gaussian beam distribution (cutted at 2.5σ)
- bunching factor B_f=0.33
- natural chromaticity
- multipole errors (+ random fluctuations)
- residual closed orbit distortion
- 'frozen' transverse space charge field

beam loss with space charge



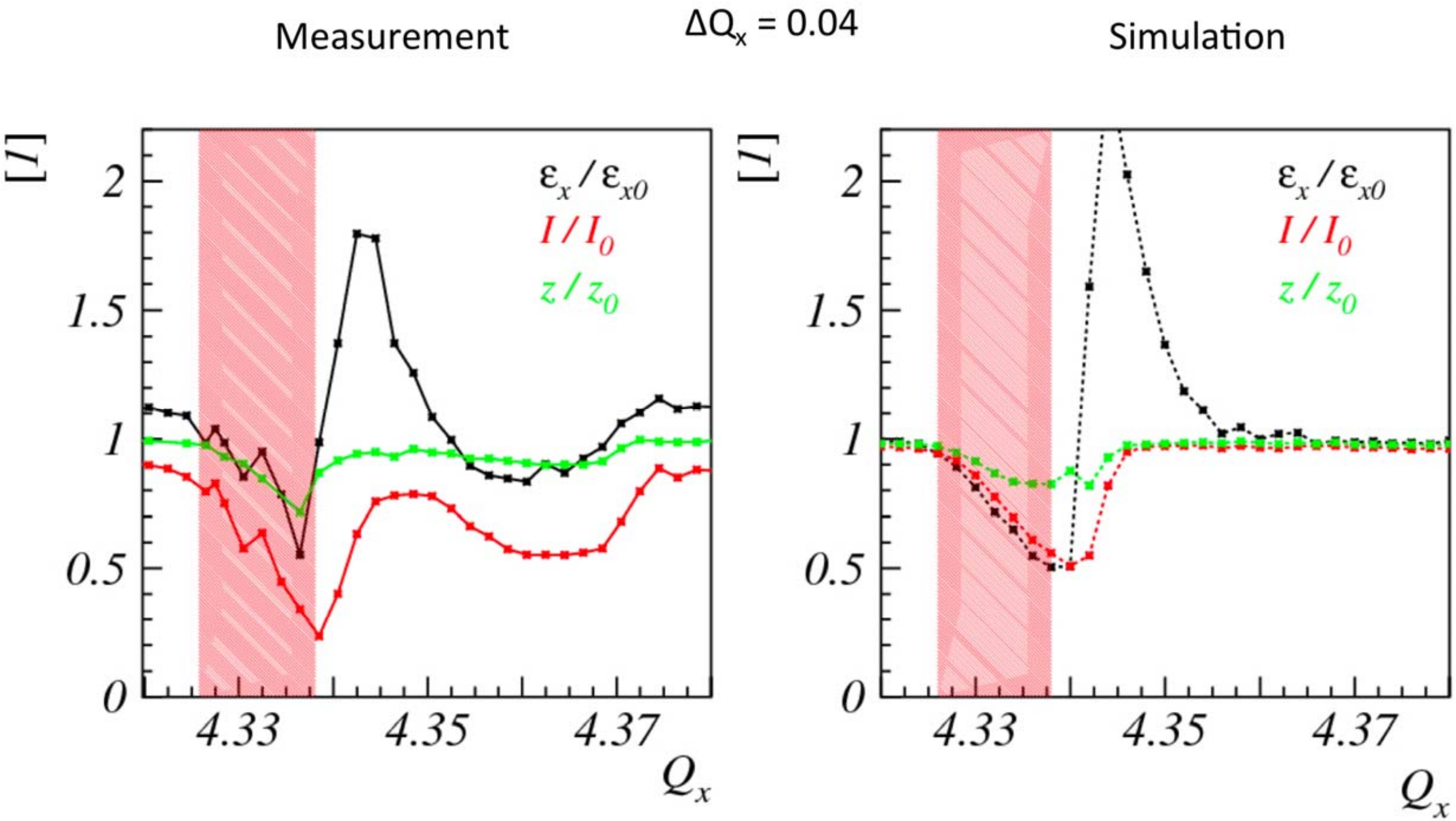
Long-term (up to 1 s) 3D particle tracking studies with 'frozen' space charge indicate a space charge limit at 3x10^{11} U^{28+} (design 5x10^{11}).
Possible solutions: 'Bunch flattening', correction.

G. Franchetti, I. Hofmann, F. Zimmermann, W. Fischer
Incoherent Effects of Space Charge and Electron Cloud
Proc. of 11th European Particle Accelerator Conference, 2008

Code benchmarking: SIS-18 experiments (S317)

Crossing of a 3-order resonance with space charge in SIS-18: Ar^{18+} bunch

Measurements vs. simulation: emittance growth, beam loss and bunch length

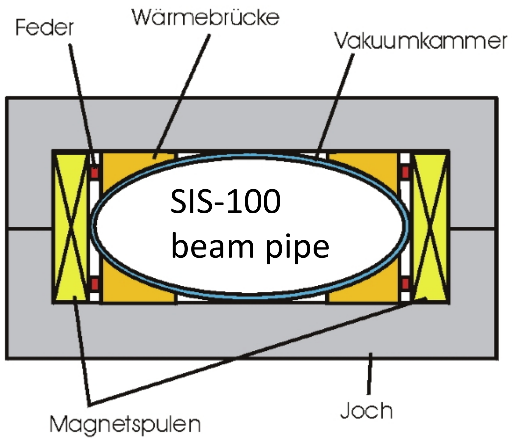


G. Franchetti et al., to be published

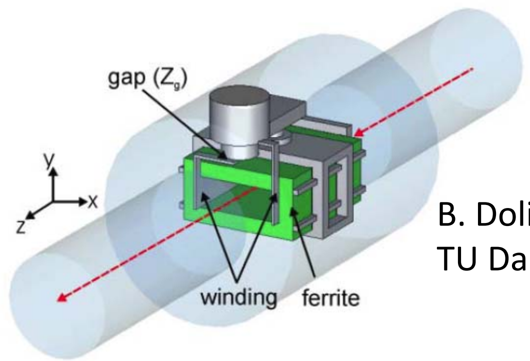
Beam stability: Transverse SIS-100 impedance studies

Impedance studies:

✓ Thin (0.3 mm) resistive beam pipe:

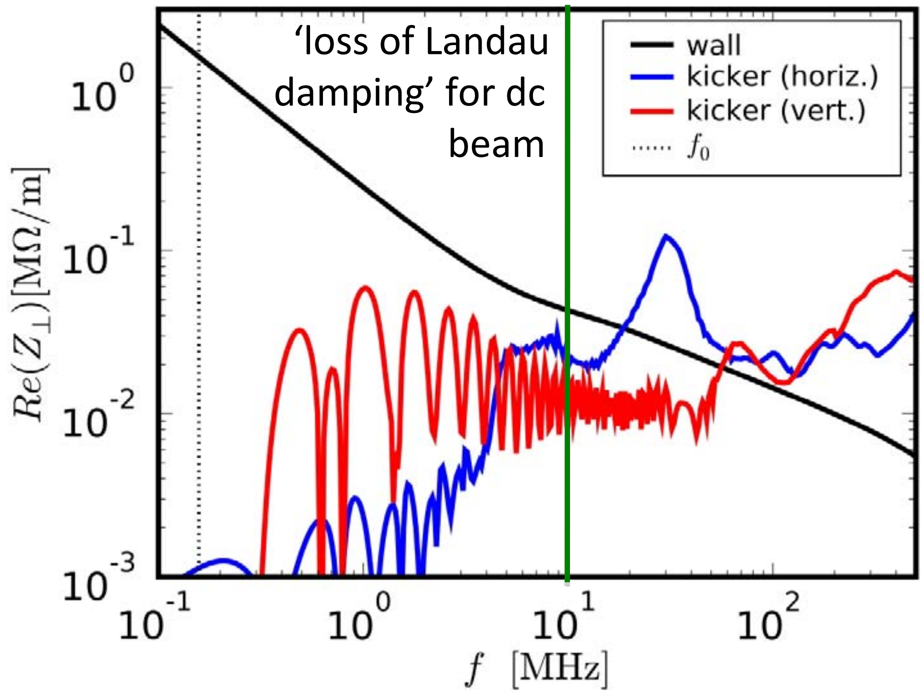


✓ Ferrite loaded kicker modules:



B. Doliwa, Th. Weiland
TU Darmstadt (2007)

Estimated impedance spectrum at 200 MeV/u



Specific SIS-100 impedance issues:

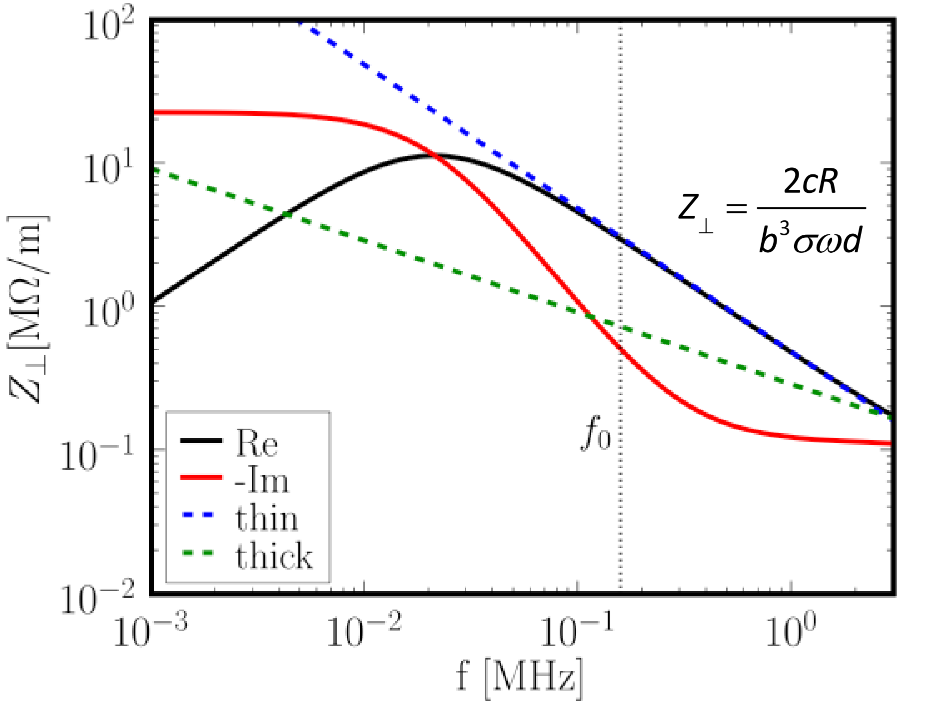
- Low frequencies and beam energies
- Image current impedance: $Z_\perp^{sc} = -i \frac{Z_0 R}{\beta_0^2 \gamma_0^2} \frac{1}{b^2} \approx -i10\ \text{M}\Omega/\text{m}$

✗ Electron clouds (from residual gas ionization), distributed collimator system

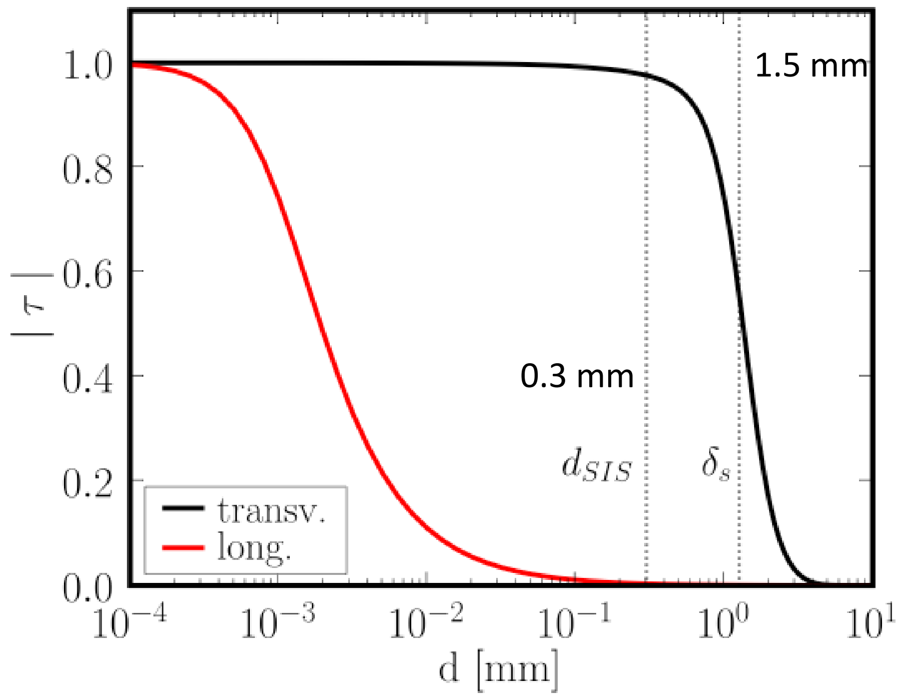
Beam stability: SIS-100 thin resistive wall impedance

Lowest coherent betatron frequency: $f_{\min} = (1 - [Q]) f_0 \approx 0.5 f_0$

Transverse resistive wall impedance (200 MeV/u)



Transmission coefficient !

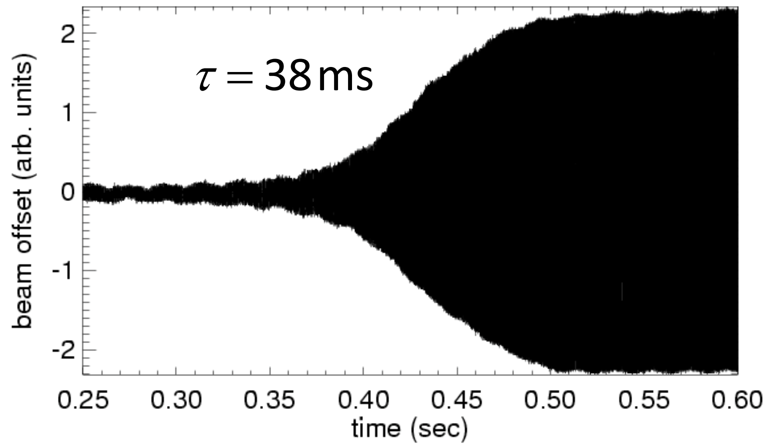


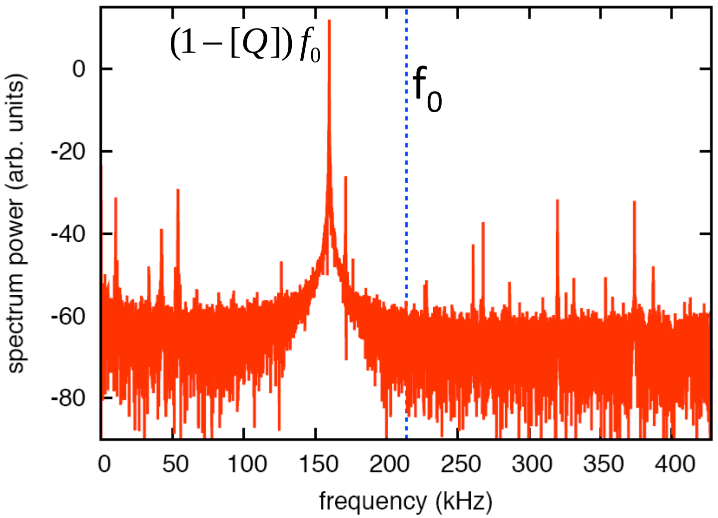
Transmission: Structures behind the pipe might contribute to the impedance !

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

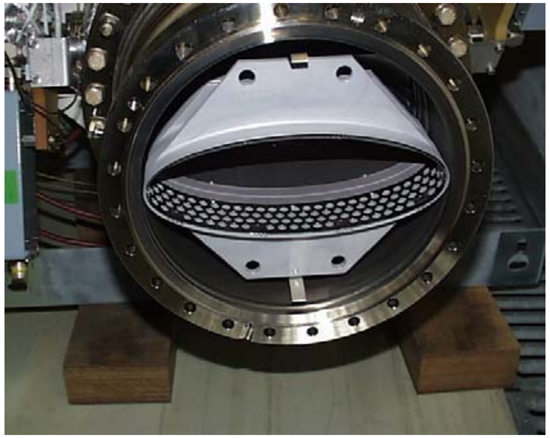
Beam stability: resistive wall instability in SIS-18

Measured instability growth in a coasting Xe^{48+} beam ($N=10^{10}$) at injection energy (11.4 MeV/u)





The **beam pipe in the SIS-18** dipole sections is only 0.3 mm thick (similar to SIS-100).



from the growth rate: $\Re Z_\perp^{rw} \approx 0.45\,\mathrm{M\Omega/m}$

analytic expression: $\Re Z_\perp^{rw} \approx 0.15\,\mathrm{M\Omega/m}$

Analytic theory underestimates the thin wall impedance in SIS-18 by a factor 3.

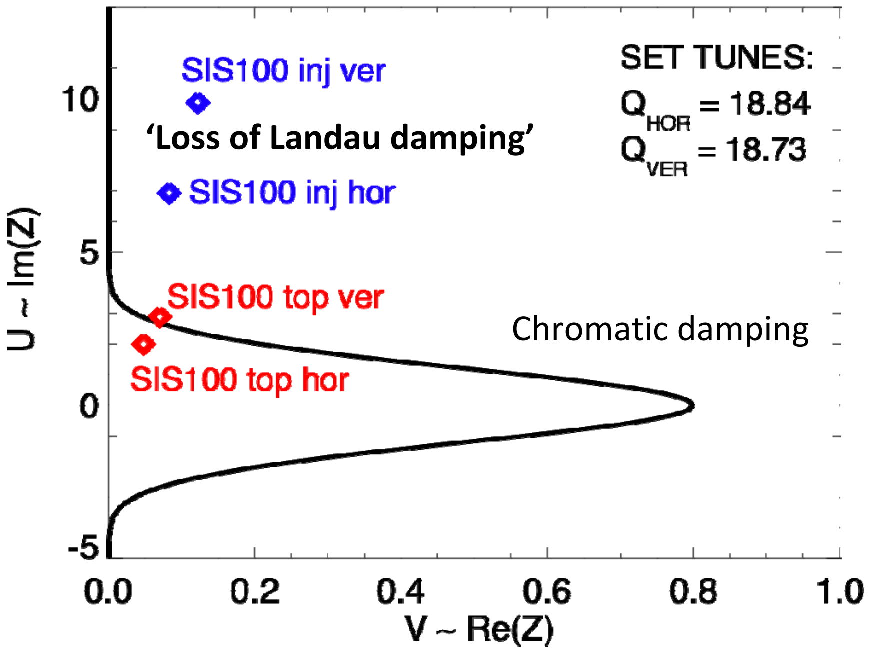
V. Kornilov (2008)

Stabilization of the coasting beam

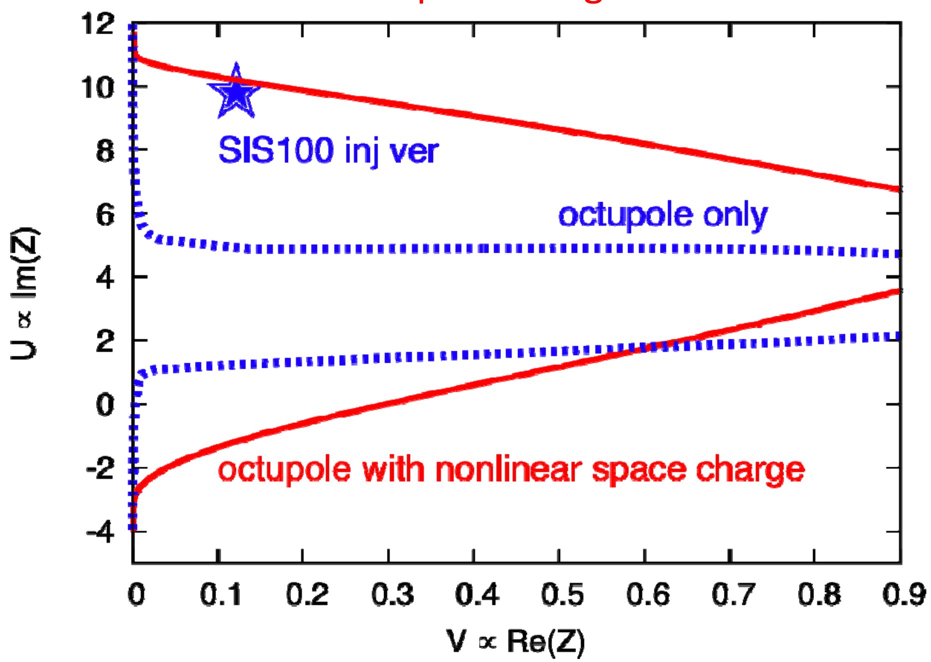
coasting beam stability boundary (from dispersion relation)

V. Kornilov, O. Boine-F., I. Hofmann, PRST-AB 2008

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



Stability boundary including octupoles and nonlinear space charge



The coasting beam resistive wall instability can be damped using the available octupoles.

The effect of the octupoles on the DA is presently being studied.

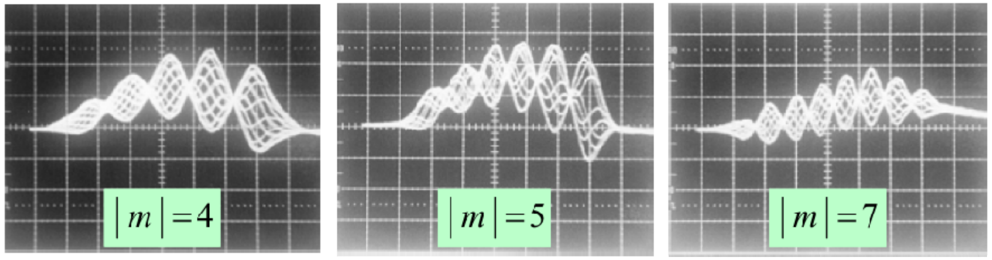
Beam stability: Transverse head-tail instability in SIS-100 caused by the resistive wall impedance

- Sacherer's formula predicts the growth of the head-tail mode m=5 with the rate 70 ms.

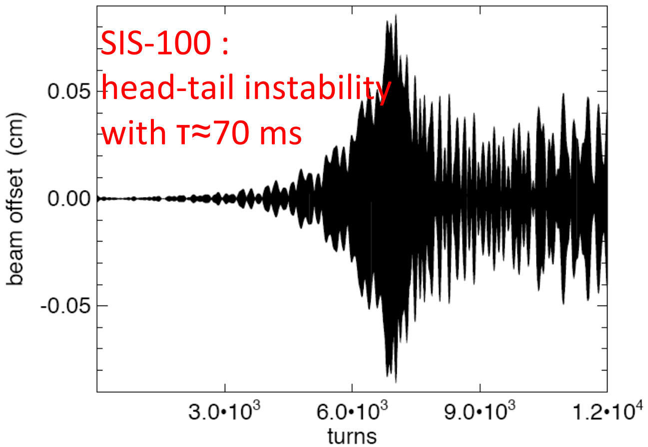
- Specific conditions in SIS-100 (not included in the available theory) are space charge and image currents with $\Delta Q_{\mathrm{incoh}}^{\mathrm{sc}} > \Delta Q_{\mathrm{coh}}^{\mathrm{sc}} > \nu_s$

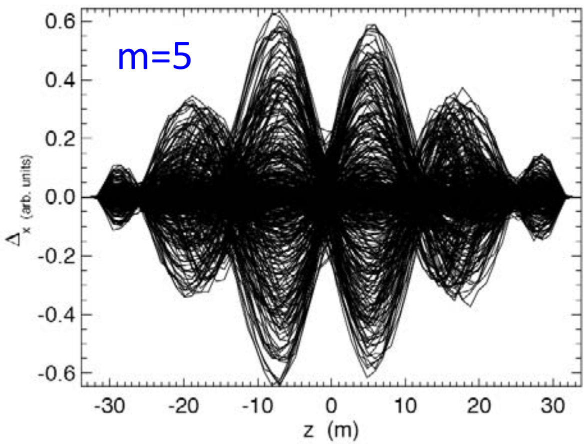
- Simulation and experimental studies (SIS-18 and CERN PS) are pursued to confirm damping mechanisms with space charge.

Head-tail instability in the CERN PS (E. Metral 2007): Results (mode number) agree with theory although space charge is as strong as in SIS-100.



Experimentally validated cures in the CERN PS:
- x-y coupling and octupoles



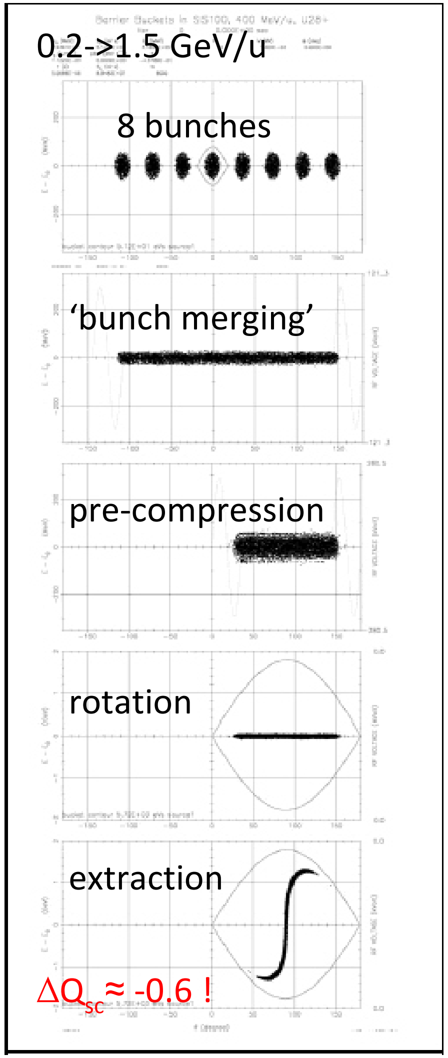


V. Kornilov, O. Boine-F. Proc. of ICFA-HB 2008, Nashville, USA, 2008.

We presently assume that dc and head-tail instabilities can be damped with the available octupoles. In addition a broadband damper system can be installed.

rf manipulations and bunch stability

Single bunch formation in SIS-100:



SIS-100 specific issues:

o longitudinal space charge and broadband beam loading (MA cavities)

o tight budget for longitudinal emittance dilution (factor 2).

SIS-100 longitudinal beam dynamics studies:

✓ Bunch form distortion and bucket area with space charge and beam loading

✓ Effect of rf phase and amplitude modulations and noise

✓ Longitudinal coasting and bunched beam stability

✓ Fast and low dilution pre-compression schemes

✓ Bunch rotation with beam loading

bunch stability: space charge and beam loading

barrier rf bucket before pre-compression

Longitudinal space charge impedance:

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

	# 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

Matched line density
(between barriers ,no rf):

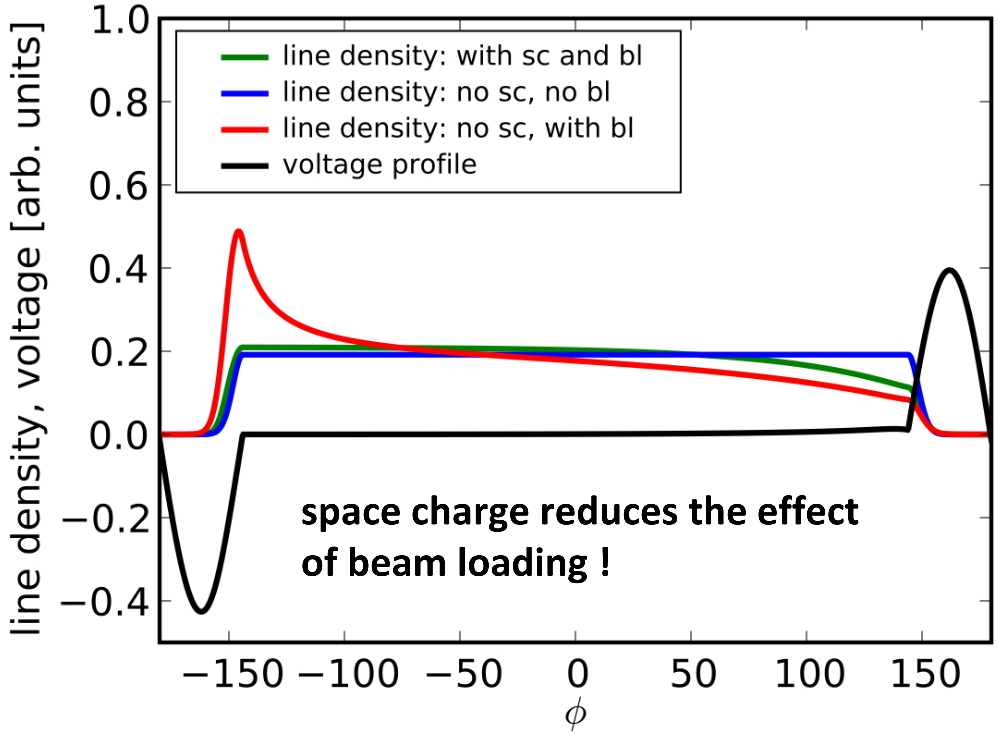
$$\lambda(z) = \lambda_m \exp\left(\alpha_s\lambda + \alpha_r \int_0^z \lambda dz\right)$$

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

Maximum bunch distortion:

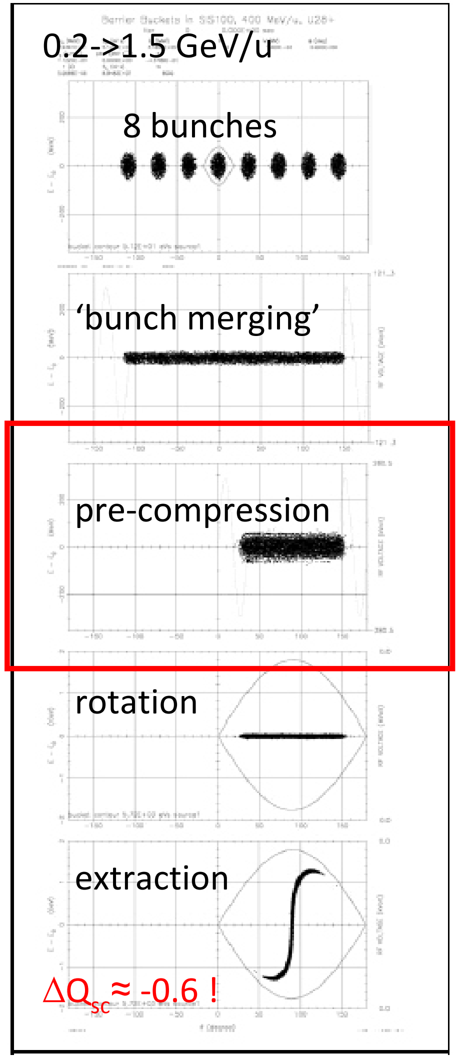
$$\frac{\Delta\lambda}{\lambda_0} \approx \frac{\alpha_r\lambda_0 z_m}{1-\alpha_s\lambda_0} \le 0.1$$

Tolerable: R_s ≈ 0.75 kΩ/cavity



rf manipulations: fast pre-compression

Single bunch formation



Non-adiabatic barrier rf phase ramp:

T=100 ms (ramp time) T_{s0} > 100 ms ('synchrotron period')

Space charge factor: $\Sigma = \dfrac{c_s}{v_{rms}} > 1$

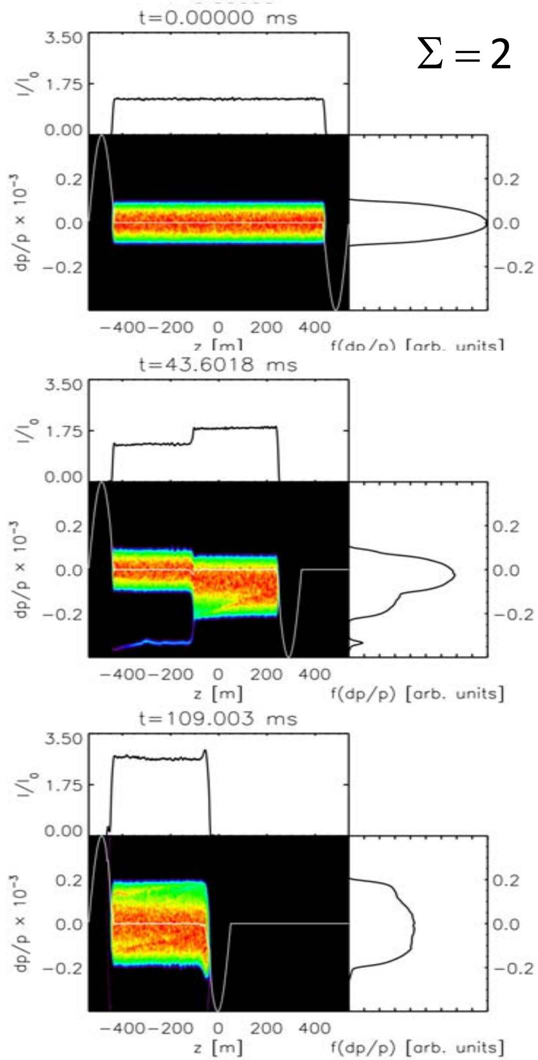
$c_s \propto \sqrt{\dfrac{Z_P^{sc}}{n}}$: speed of space charge waves

$v_{rms} \propto \dfrac{\Delta p}{p}$: incoherent rms velocity

Barrier shock compression:

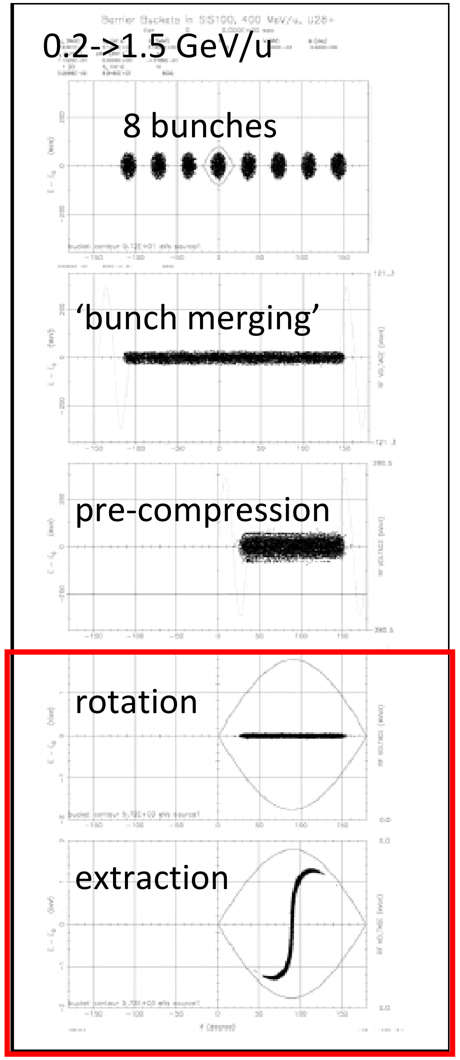
The moving barrier rf pulse launches a shock wave that is reflected from the opposite barrier.

The process is fast and 'dilution-free'.



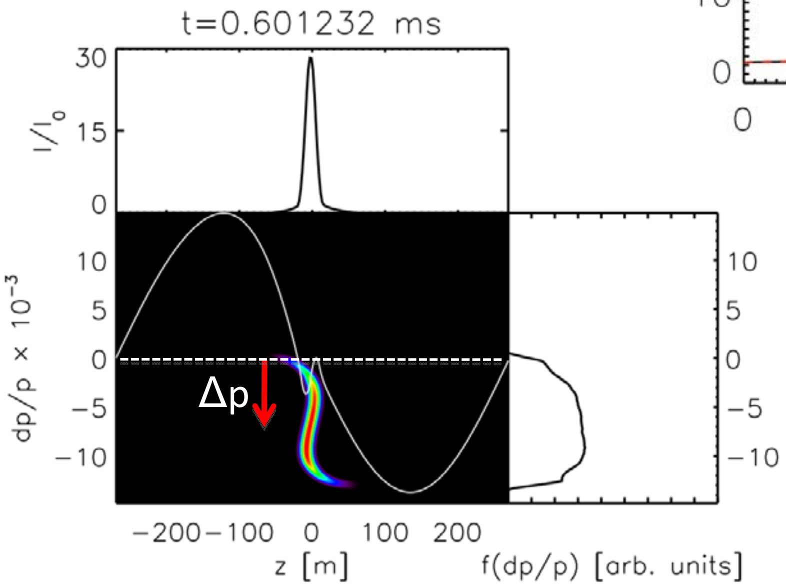
rf manipulations: final bunch compression

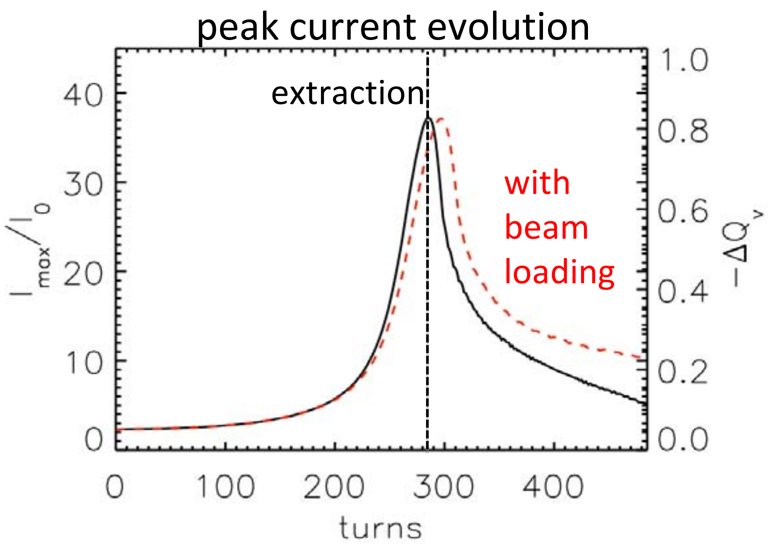
Single bunch formation



	# cavities	R_s/cavity [kΩ]	Q_s	f_{res}
compression	16	1	2	1.5 MHz

- beam loading shifts the final bunch distribution down in momentum.
- compression factor is not affected.
- **Solution:** initial momentum offset or rf phase ramp.





Transverse beam loss/blow-up :

- No indication seen in 3D studies.
- Experiments in SIS-18 this April.
- CERN PS: $\Delta Q_v \approx -1$ reached.

Summary

Beam loss due to resonances and space charge (-> G. Franchetti's talk)**:**

- Elaborate particle tracking and experimental studies have been completed.
- Simulation studies indicate a space charge limit close to 3E11 U^{28+}.
- Strategies for intensity increase: flattened bunches, resonance compensation.

Transverse beam stability and impedances:

- Impedances of ring components have been calculated or simulated (activity still ongoing).
- The thin resistive wall impedance is a main concern for beam stability.
- Transverse space charge causes 'loss of Landau damping'.
- Octupoles are a potential cure for coasting and head-tail instabilities (DA will be checked).
- For more safety: active broadband damping system

Rf manipulations and longitudinal beam stability:

- Space charge compensates the beam loading effect on the bunch form
- Space charge allows for faster barrier compression.
- Beam loading effect during the final compression has to be compensated.
- For longitudinal bunch stability active dampers are needed (-> rf talk).

Collaborations

CERN ABP group (E. Metral, G. Rumolo, F. Zimmermann, F. Schmidt):
beam loss, space charge, impedances, coherent instabilities, electron clouds, MAD-X

CERN RF group (E. Shaposhnikova, H. Damerau):
longitudinal bunch stability, rf manipulations, BTF

FNAL accelerator division (A. Burov, V. Lebedev):
coherent instabilities with space charge

TU Darmstadt, TEMF (Th. Weiland and co-workers):
simulation of impedances

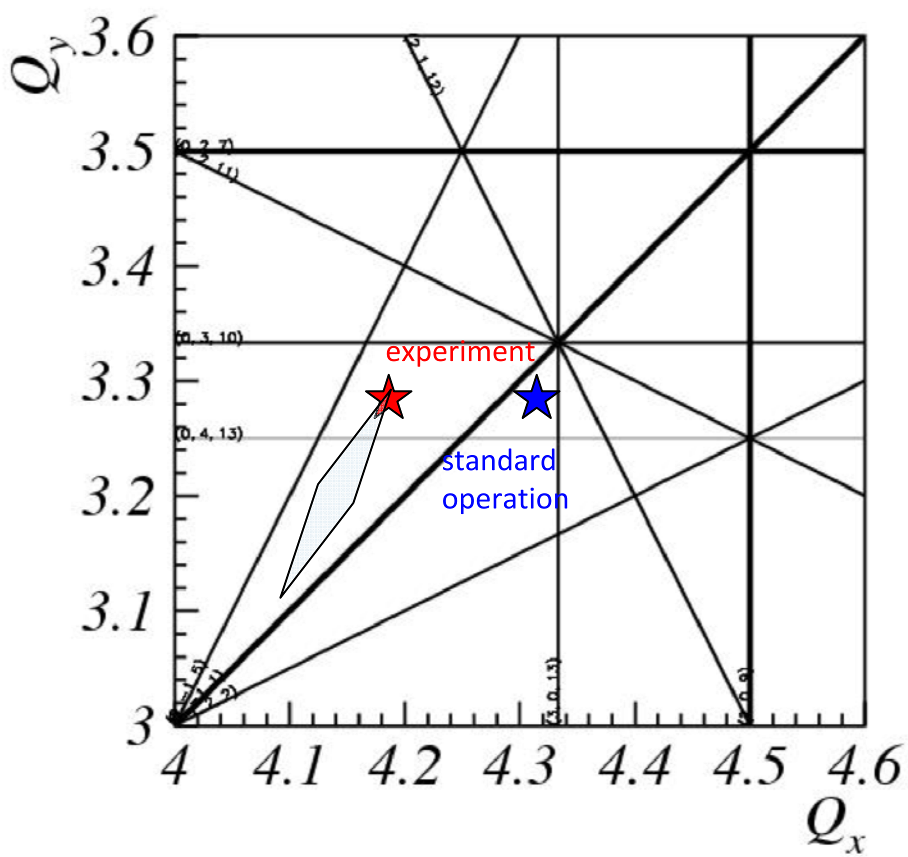
ITEP, Moscow (P. Zenkevich, S. Bolshakov, V. Kapin):
nonlinear beam dynamics, MAD-X

Jarmouk University, Jordan (A. Al-khateeb):
impedance calculations

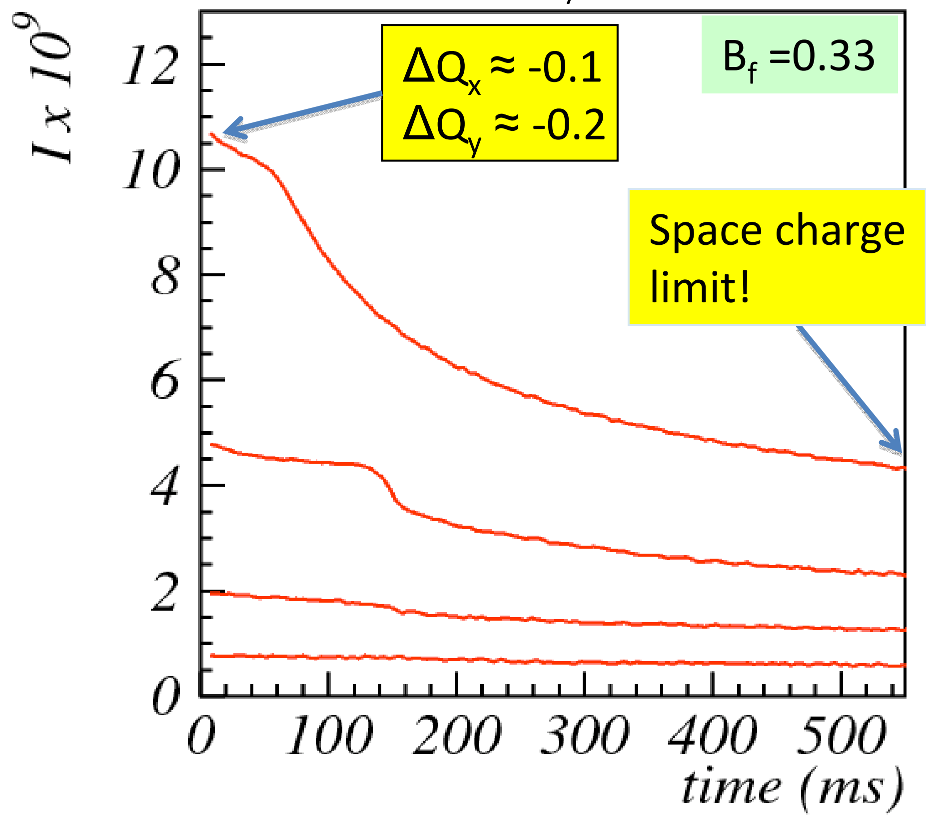
(Last collaboration meeting: 18/19 Feb. 2009 at GSI)

Beam loss studies in SIS-18 for SIS-100 (S317 experiment)

Experiments (08/2008) related to the **space charge limit** for Ar^{+18}: high-intensity working point



Q_x = 4.17, Q_y = 3.24



G. Franchetti, I. Hofmann, W. Bayer, F. Becker, O. Chorniy, P. Forck, M. Kirk, T.Mohite, C. Omet, A. Parfenova, P. Schütt
The S317 experiment on high intensity beam loss and emittance growth, Proc. of ICFA-HB 2008, Nashville, USA, 2008