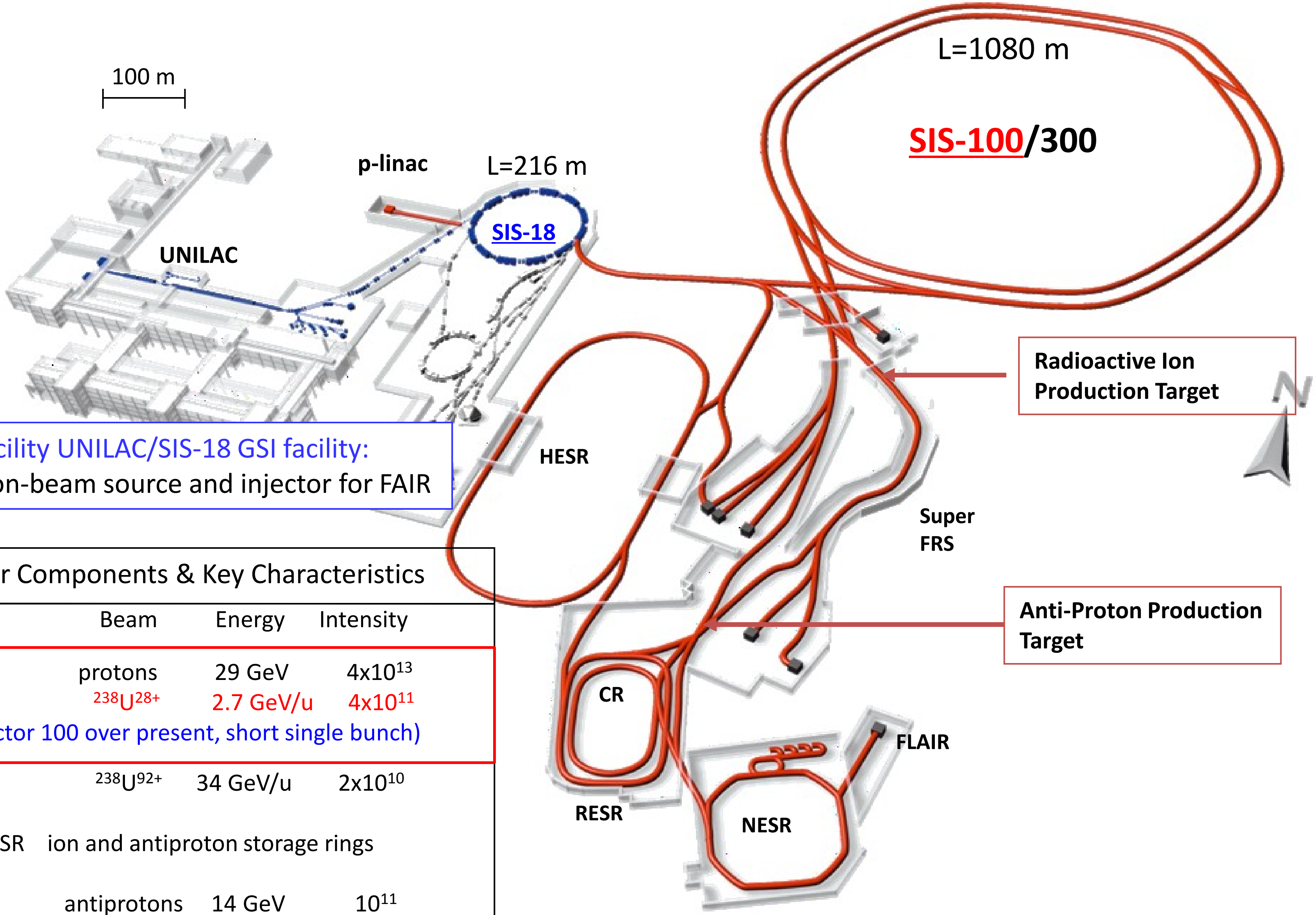
Collective Effects at FAIR

- FAIR beam parameters
- ‘Space charge limit’
- Transverse coherent instabilities
- Impedance sources
- Electron clouds at FAIR

FAIR



Radioactive Ion Production Target

Anti-Proton Production Target

Existing facility UNILAC/SIS-18 GSI facility:
provides ion-beam source and injector for FAIR

Accelerator Components & Key Characteristics

Ring/Device	Beam	Energy	Intensity
SIS-100 Tm	protons	29 GeV	$4x10^{13}$
	$^{238}U^{28+}$	2.7 GeV/u	$4x10^{11}$
(intensity factor 100 over present, short single bunch)			
SIS-300 Tm	$^{238}U^{92+}$	34 GeV/u	$2x10^{10}$
CR/RESR/NESR	ion and antiproton storage rings		
HESR	antiprotons	14 GeV	10^{11}
Super-FRS	rare isotope beams	1 GeV/u	$<10^{9}$

Reference beam parameters

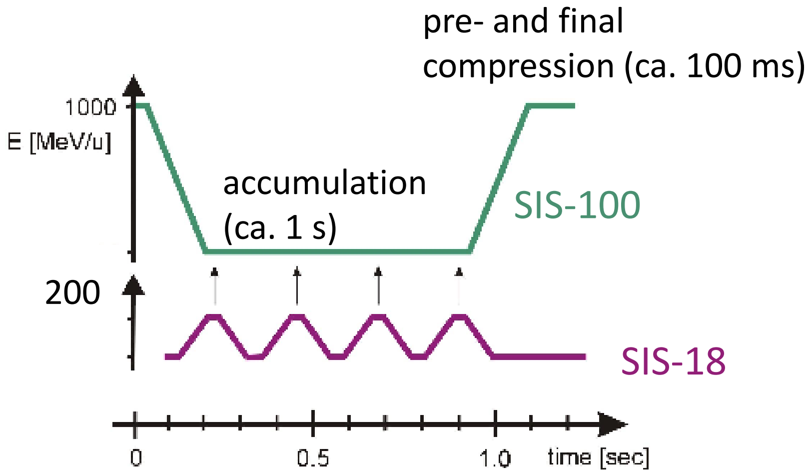
Heavy ions

	SIS-18	SIS-100
Reference primary ion	**U^{28+}**	**U^{28+}**
Reference energy	200 MeV/u	1.5 GeV/u
Ions per cycle	**1.5E11**	**4E11**
cycle rate (Hz)	2.7	0.5

Protons

	SIS-18	SIS-100
Extraction energy	4 GeV/u	29 GeV/u
Ions per cycle	**5E12**	**2E13**
cycle rate (Hz)	2.7	0.2

Design intensities are the expected ‘space charge limits’: ΔQ_y=-0.5/-0.3 in SIS-18/100



FAIR specific operation modes:

- ○ Long (1 s) injection/accumulation plateau
- ○ Single, short bunch (50 ns) at extraction
- ○ Slow extraction (< 1 s) of dc-like heavy ion beams

SIS-18 beam intensities

SIS-18 injection energy: 11.4 MeV/u

$\varepsilon_{x/y} = 150/50 \text{ mm mrad}$ (acceptance)

Increase the 'space charge limit':

- dual rf bucket (h=2/4) - > 2012

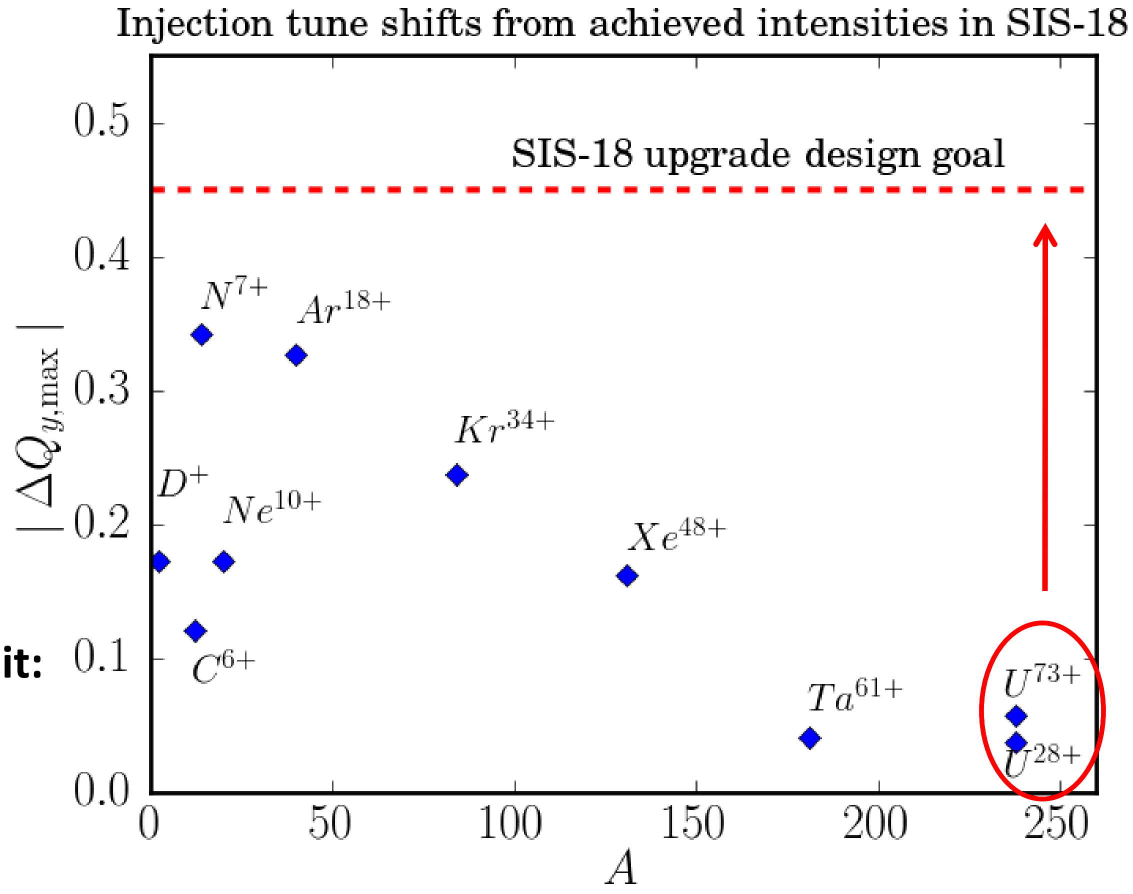
- resonance compensation
(-> G. Franchetti)

Increase the 'vacuum/lifetime' limit:

- distributed NEG coating

- faster ramping (2.7 Hz)

Space charge tune shift: $\Delta Q_y^{sc} = -\dfrac{2NZ^2 g_f}{\pi A \beta_0^2 \gamma_0^3 B_f \left(\varepsilon_y + \sqrt{\varepsilon_y \varepsilon_x}\right)}$



Transverse coherent instabilities expected in SIS-100

Expected coherent transverse instabilities in SIS-100:

- Head-tail at SIS-100 injection (wall impedance)
- Beam-break up of the short proton bunch at extraction (kicker impedance)
- Two-stream instabilities during slow extraction of heavy-ion beams (electron clouds)

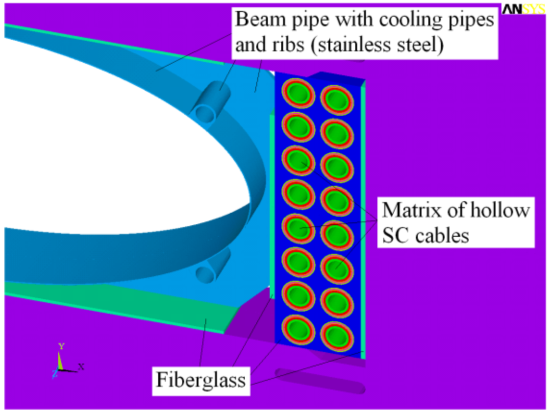
Potential cures:

- Space charge (and octupoles)
- Impedance reduction (wall, kicker)
- Barrier buckets (avoid coasting beams)
- Active feedback systems

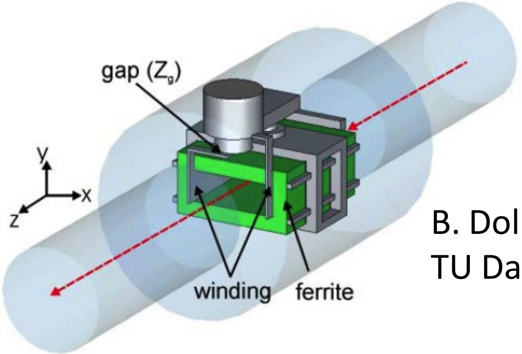
Overview: SIS-100 (transverse) impedance studies

Impedance studies:

Thin (0.3 mm) resistive beam pipe:

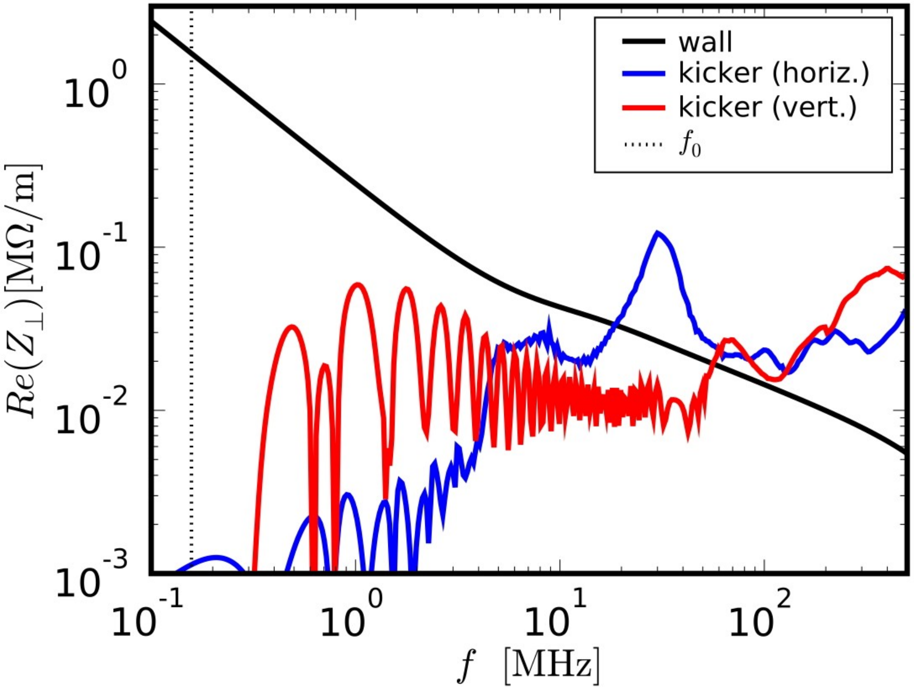


Ferrite loaded kicker modules:



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

Estimated impedance spectrum at 200 MeV/u



Lowest coherent betatron frequency:

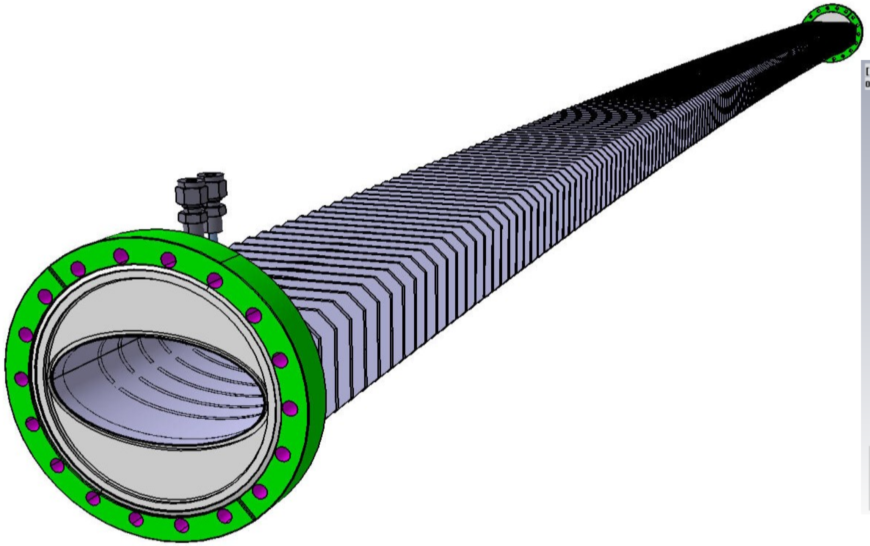
$$f_{\min} = (1-[Q])f_0 \approx 0.5 f_0 \approx 50\,\mathrm{kHz}$$

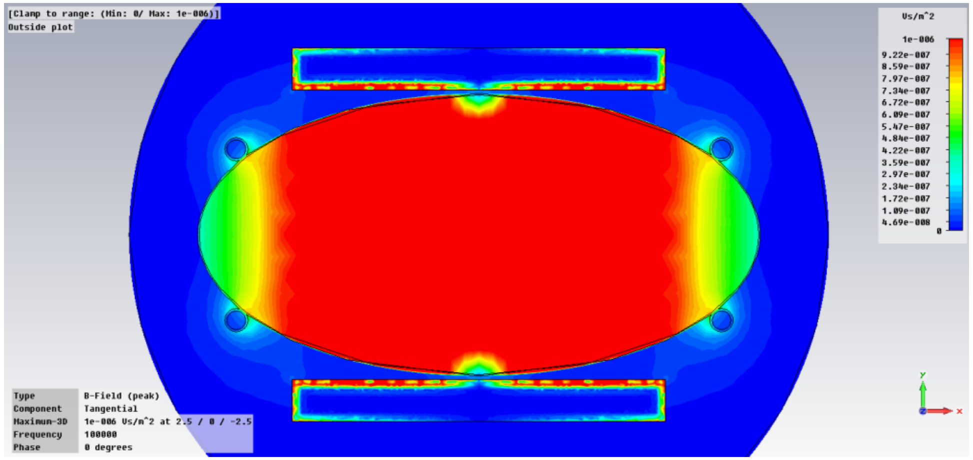
Highest coherent frequency:

$$f_{\max} \approx 100-200\,\mathrm{MHz}$$

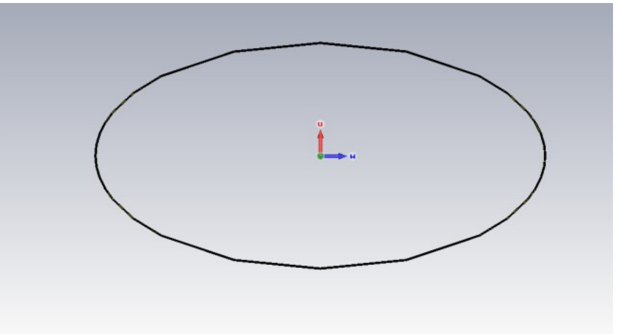
High-frequency broad-band: distributed collimator system, steps,…

SIS-100 beam pipe: CST EM Studio simulations

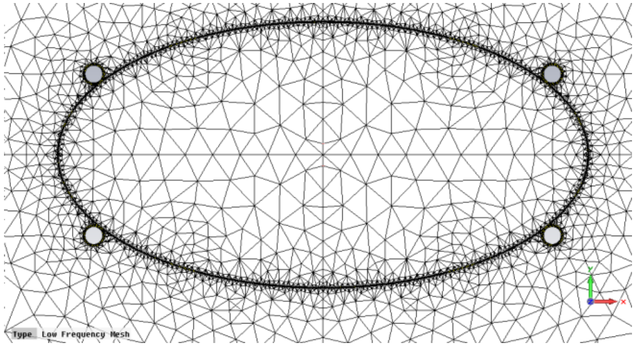




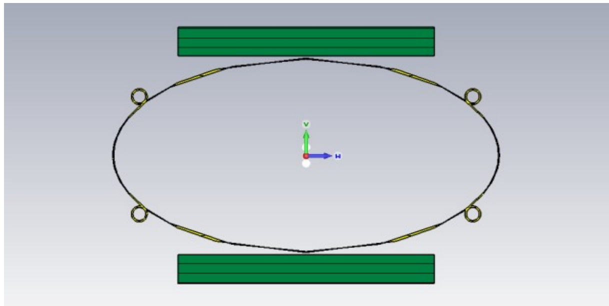
Type B-Field (peak)
Component Tangential
Maximum-3D 1e-006 Vs/m^2 at 2.5 / 0 / -2.5
Frequency 100000
Phase 0 degrees



Stainless steel elliptic pipe (1e6 S/m)



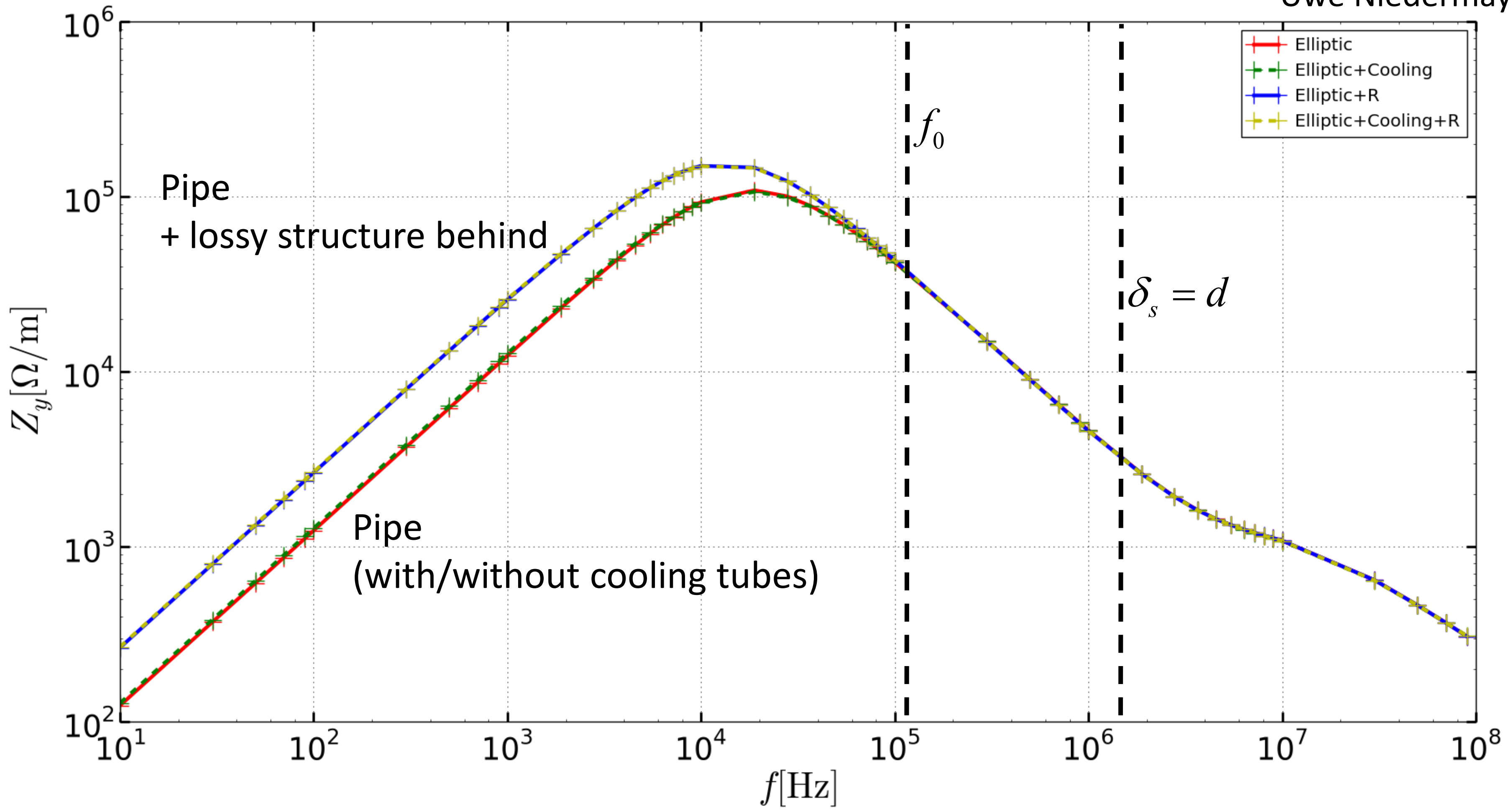
With cooling tubes



Green: Bad Conductor (1e4 S/m) for ‚Worst Case Scenario'

SIS-100 beam pipe: 2D CST results

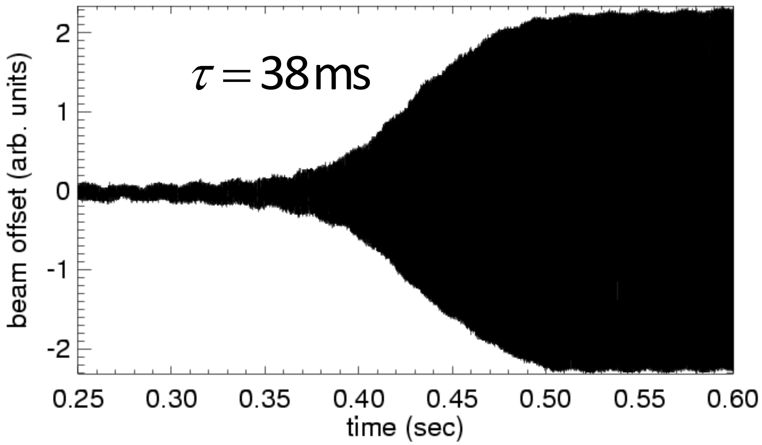
Uwe Niedermayer

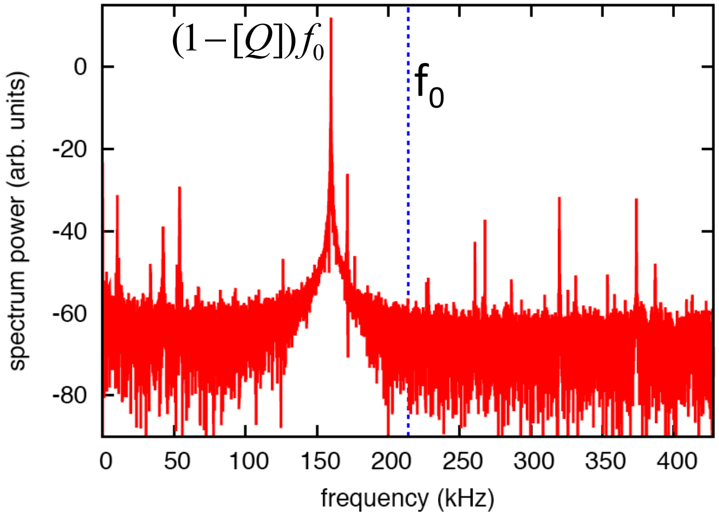


Structures behind seem to not affect the transverse impedance in the frequency range of interest.

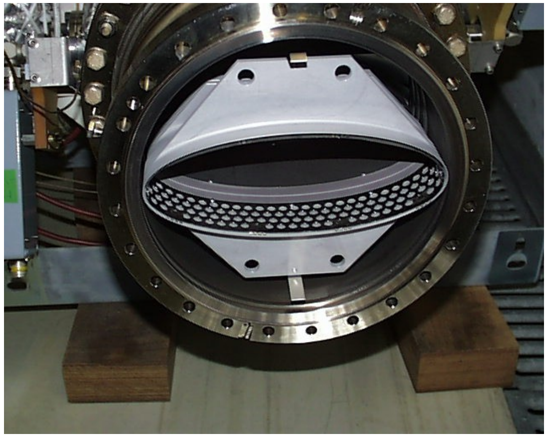
Beam stability: resistive wall instability in SIS-18

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

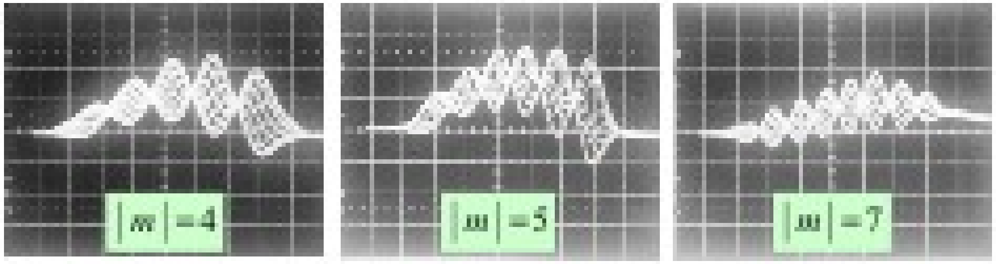
analytic expression: $\Re Z_\perp^{rw} \approx 0.15\,\mathrm{M\Omega/m}$

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

V. Kornilov (2008)

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

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



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

Intensity parameter in SIS-100

Ion	N_b	M	$-\Delta Q_{sc}$	Q_s	z_m (m)
p	$2 \cdot 10^{13}$	1	0.2	0.006	20
U^{28+}	$0.6 \cdot 10^{11}$	8	0.25	0.013	25

space charge parameter: $q = \frac{\Delta Q_{sc}}{Q_s}$

Sacher's theory for U^{28+} bunches in SIS-100 at injection:

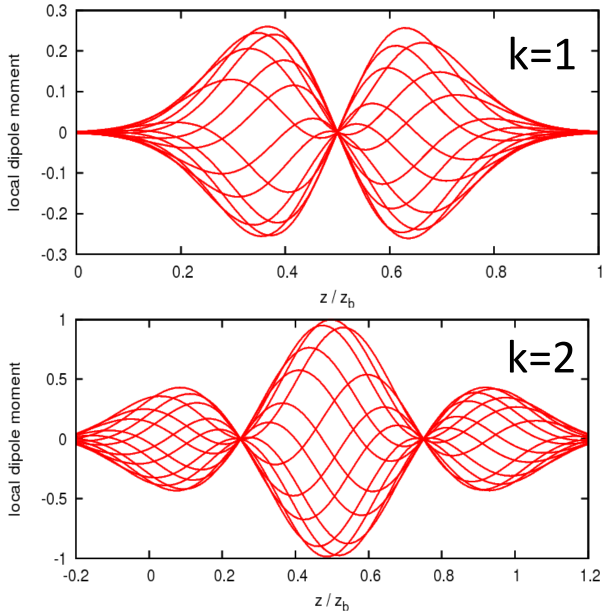
head-tail instability *m*=4 with $t_{inst} \approx 70$ms

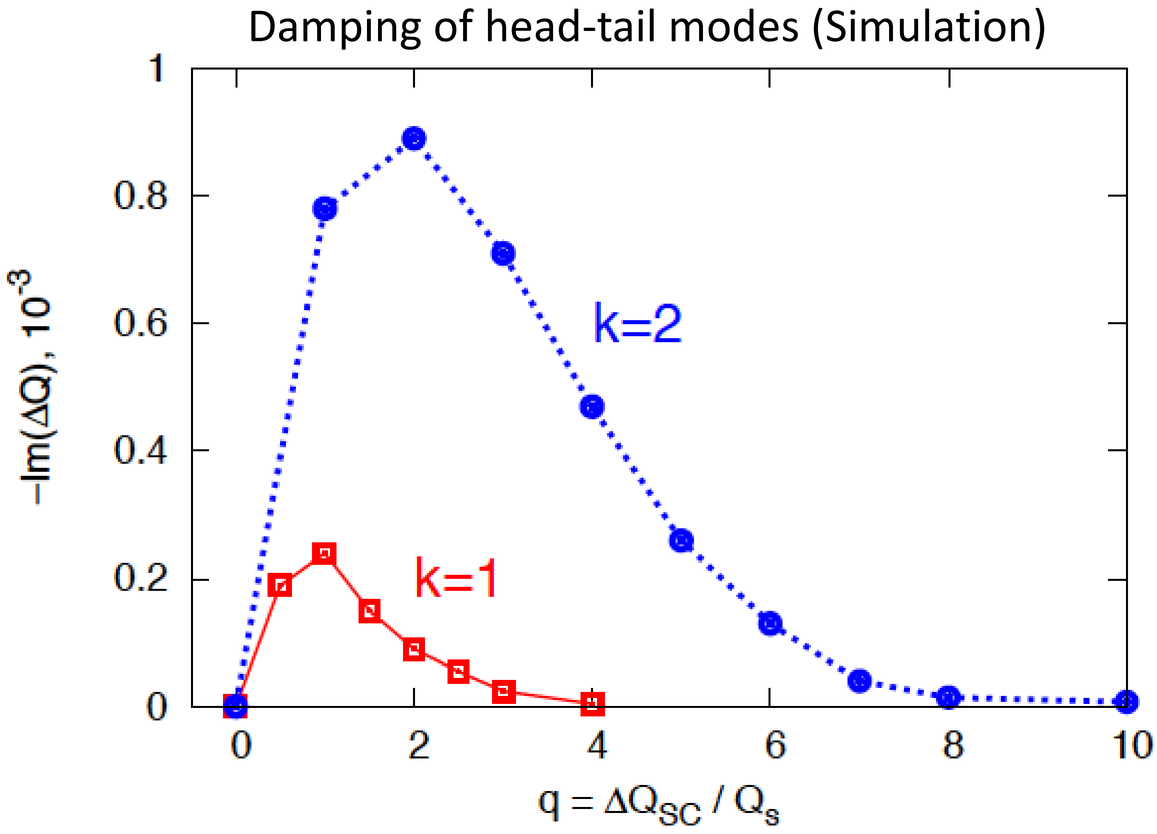
SIS-100: q=10-30

CERN PS: q≈150

Space charge induced ‘intrinsic’ Landau damping

‘Intrinsic’ Landau damping:
Tune spread due to the variation of the space charge tune shift along the bunch.




Damping of head-tail modes (Simulation)

V.Kornilov and O. Boine-Frankenheim, PRSTAB **13**, 114201 (2010)

Beam breakup instability in SIS-100 ?

Proton bunch at extraction:

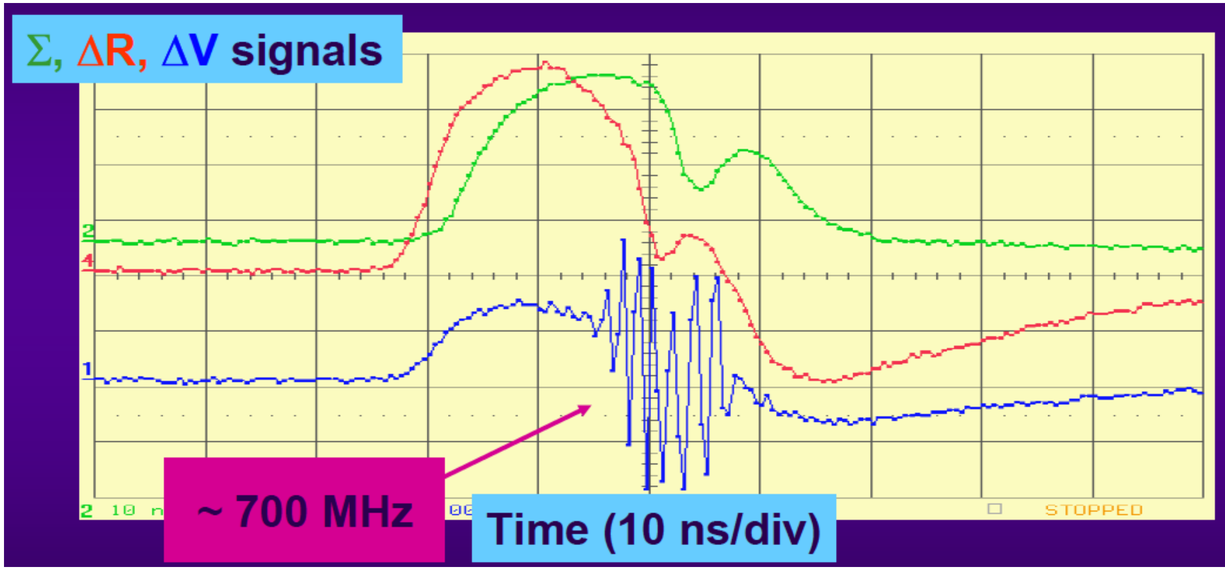
E = 29 GeV (γ=32, γ_t=45)

N = 4x10^{13}

τ < 50 ns

f_s = 10 Hz

Beam Breakup Instability in the CERN PS (near transition)



Σ, ΔR, ΔV signals

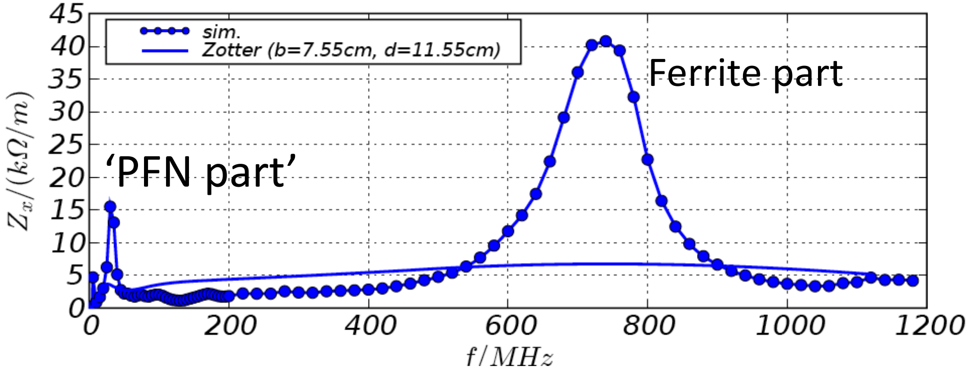
~ 700 MHz

Time (10 ns/div)

R. Cappi, E. Métral, G. Métral, EPAC 2000

The instability was cured by increasing the bunch length: 40ns -> 50ns

SIS 100 kicker impedance



Ferrite part

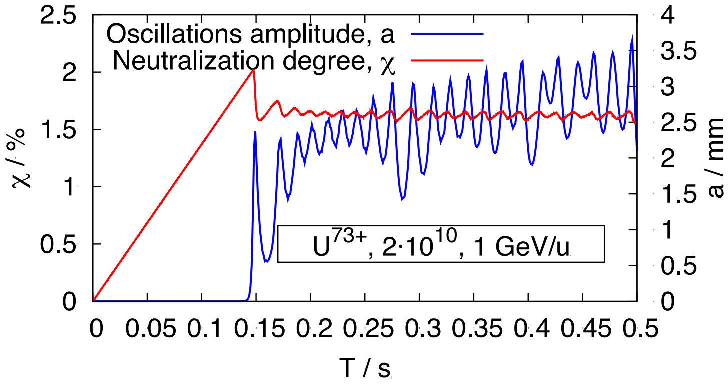
'PFN part'

eclouds@FAIR

BMBF project, TU Darmstadt, funding period 2009-2012: Fedor Petrov (PhD student), Fatih Yaman (postdoc)

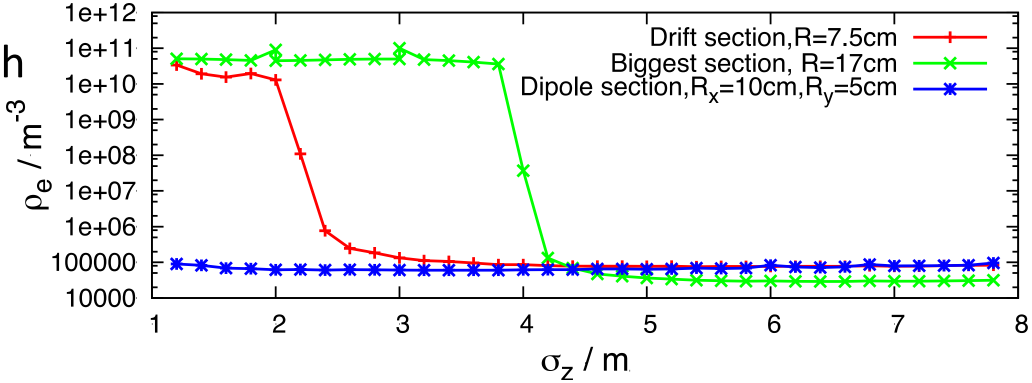
Intense **coasting heavy-ion beams** during slow extraction

- production of electrons from residual gas ionization
- accumulation in the space charge potential of the beam
- neutralization degree limited by the two stream instability



Bunch trains (bunch length > 5 m) in SIS-18/100

- production due to secondary emission
- electron accumulation from bunch to bunch
- beam instabilities and e-impedances



Single, 'short' (< 50 ns) bunch at extraction

- production due to secondary emission
- accumulation ?

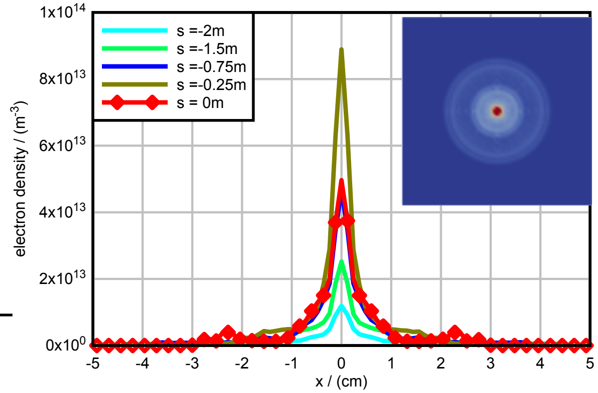
-Full 3D EM simulation of e-wakefields (-> F.Yaman)

Measurements in SIS-18:

- Indirect: Coherent beam signal from coasting beams

-Direct: Button-pickups installed in SIS-18

-> scheduled for April



Some conclusions on collective effects at FAIR

Space charge:
- determines the incoherent ‘space charge limit’ (due to resonance crossing).
- changes coherent stability limits: ‘intrinsic’ Landau damping of head-tail modes.

Thin vacuum chamber impedance:
- drives head-tail instabilities at SIS-100 injection.
- at low frequencies structures behind the wall might contribute !

Kicker impedance:
- potentially drives fast break-up instabilities at extraction (short proton bunch).
- Next steps: Network impedance, 3D impedance simulation, beam simulations.

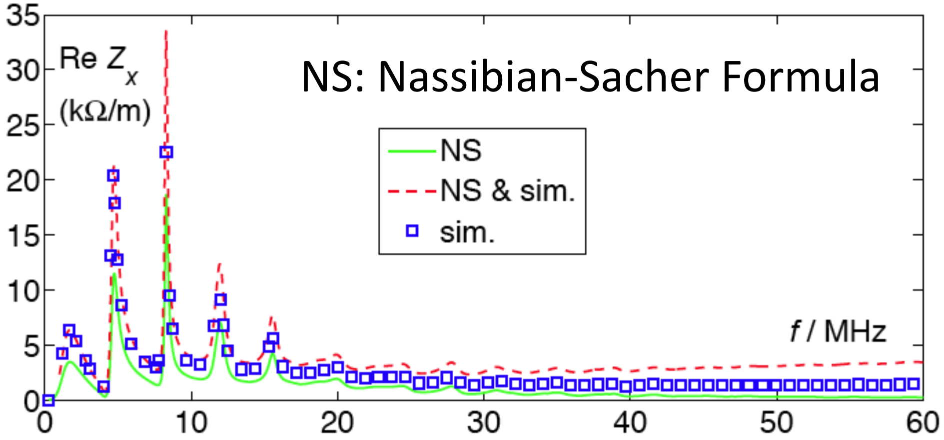
Electron clouds (talks by F. Petrov and F. Yaman):
- cause two stream instabilities in coasting heavy-ion beams during slow extraction
- buildup predicted for bunch trains

Full 3D EM simulation of the SIS-18/100 kicker impedances

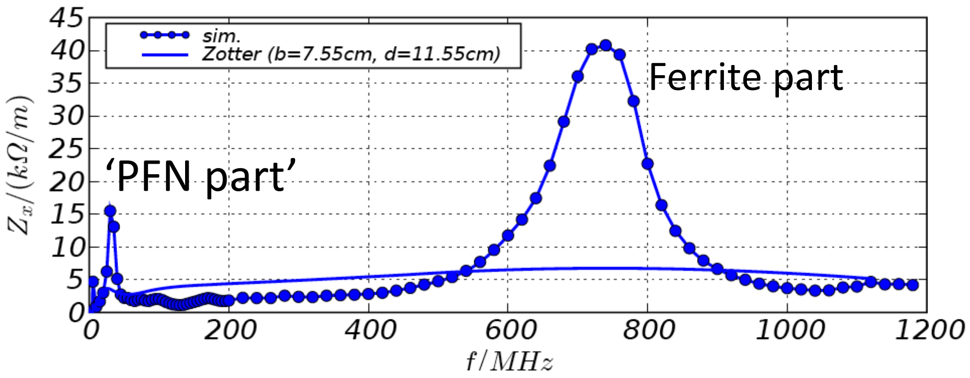
$$Z_x(\omega) = \frac{-i}{\beta_0 \bar{x}} \left(E_x + \left[\vec{v}_0 \times \vec{B} \right]_x \right)$$

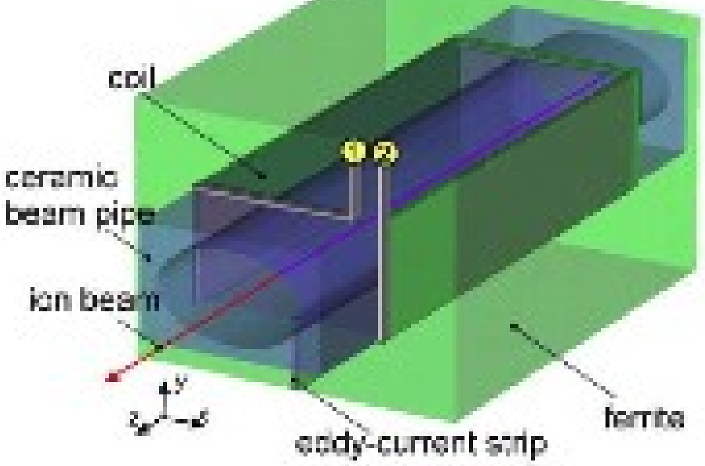
B. Doliwa, Th. Weiland, Proc. PAC 2005 + EPAC 2006, Phys. Rev. ST-AB (2007)

Contribution of the PFN (for SIS 18):



Contribution of the Ferrite (for SIS 100):





The kicker impedance can be divided in two parts:

1. PFN dominated
   low frequency (< 100 MHz)

2. Ferrite dominated
   high frequency (0.2-1 GHz)