Impedance Simualtions and Bench Measurements for SIS100

Uwe Niedermayer and Oliver Boine-Frankenheim

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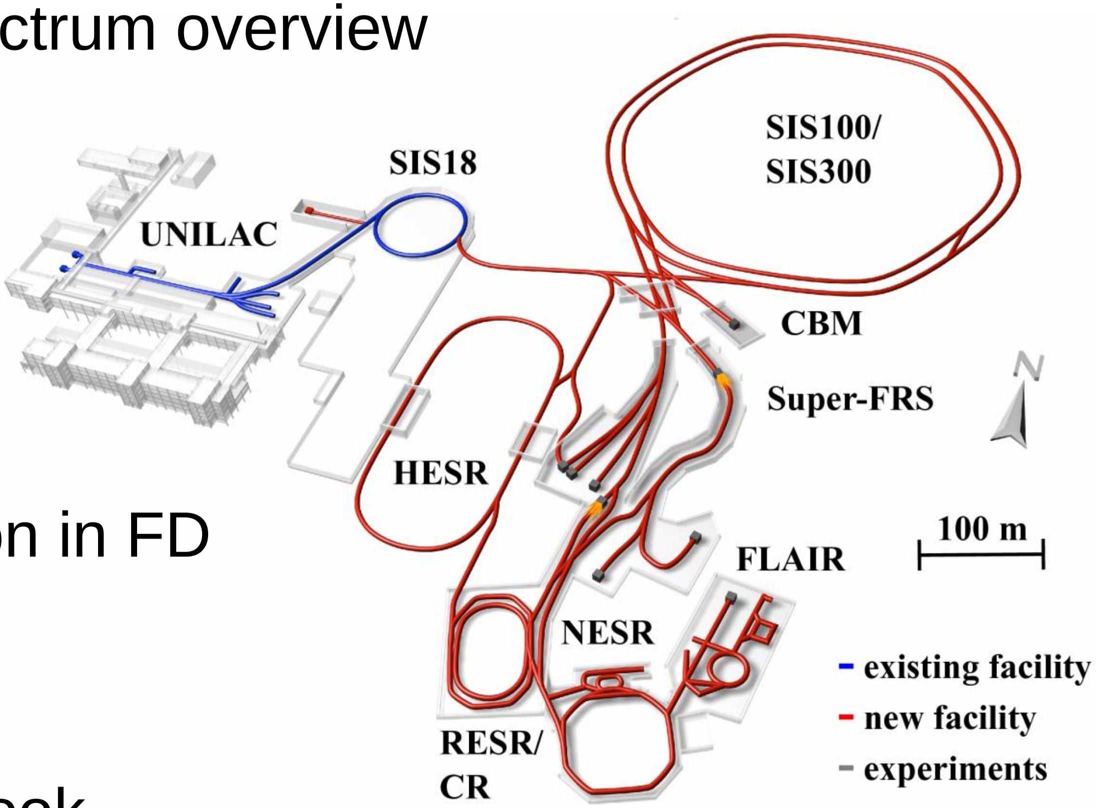
- Motivation
- Definitions
- SIS100 impedance spectrum overview
- Numerical calculation
  →TD vs. FD
- Simplified numerical calculation
  - Method & results
- Full numerical simulation in FD
- Preliminary TD results
- Bench measurements
- Current status and outlook



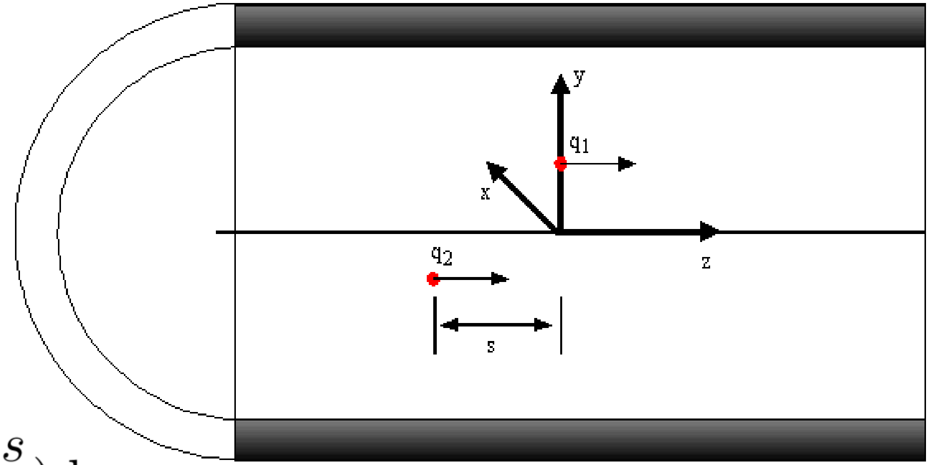
Motivation

- As discussed in Oliver Boine-Frankenheim‘s talk: Especially coasting beam and high intensity proton bunch are susceptible to impedance driven transverse instability

- The following components of SIS100 have been identified to cause large impedance contribution:
  → Beampipe (thin, flat dipole sections)
  → Ferrite-Kicker and its supply network
  → Proposed “Inductive Insert“ for long. SC-comp.
  → Collimators

Wake Fields and Impedance

- Rigid Beam
- Fields depend on structure
- Excited by leading charge
- Measured by trailing charge



$$\vec{W}(\vec{r}_2, s) := \frac{1}{q_1 q_2} \int_{-\infty}^{\infty} \vec{F}(\vec{r}_2, z_2, \frac{z_2 + s}{v}) \mathrm{d}z_2$$

$$= \frac{1}{q_1} \int_{-\infty}^{\infty} \left(\vec{E}(\vec{r}_2, z_2, \frac{z_2 + s}{v}) + \vec{v} \times \vec{B}(\vec{r}_2, z_2, \frac{z_2 + s}{v}) \right) \mathrm{d}z_2.$$

$$\Delta \vec{p}(\vec{r}_2, s) = \frac{q_1 q_2}{v} \vec{W}(\vec{r}_2, s).$$

Longitudinal Distribution

$$\vec{W}_{potential}(\vec{r}, s) = \int_{-\infty}^{\infty} \vec{W}(\vec{r}, s') \lambda_l(s - s') \mathrm{d}s'$$

Wake Fields and Impedance cont‘d

- Especially for many turn issues, a frequency domain description is prefered.
- This is called the beam coupling impedance

$$\underline{Z}_{||}(\vec{r},\omega) = \frac{1}{v}\int_{-\infty}^{\infty} W_{||}(\vec{r},s)e^{-i\omega s/v}ds$$

$$\underline{Z}_{\perp}(\vec{r},\omega) = \frac{-i}{v}\int_{-\infty}^{\infty} \vec{W}_{\perp}(\vec{r},s)e^{-i\omega s/v}ds$$

- Usually one performs a multipole expansion
  - Z long dominated by monopole
  - Z trans dominated by dipole

Details: See e.g. Palumbo et al. Wake Fields and Impedance, 1994

Definition of coupling impedances in FD

Uniform cylindrical beam:

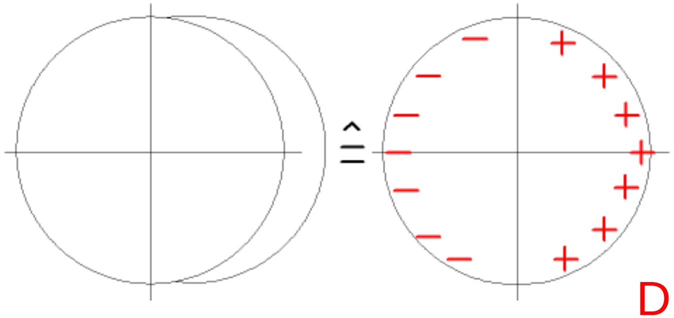
Radius of the beam

Displacement of the beam

$$\boxed{\sigma(\varrho,\varphi) \approx \frac{q}{\pi a^2}\left(\Theta(a-\varrho) + \delta(a-\varrho)d_x \cos\varphi\right)}$$

$$\underline{J}_{s,z}(\varrho,\varphi,z,\omega) = \sigma e^{-i\omega z/v}$$

$$\underline{\varrho}_s(\varrho,\varphi,z,\omega) = \frac{1}{v}\sigma e^{-i\omega z/v}$$



- Rigid beam
- Finite integration length due to infinite pipe length

Dipolar beam current

$$\boxed{\underline{Z}_{\parallel}(\omega) = -\frac{1}{q^2}\int_{beam} \underline{\vec{E}}\cdot\underline{\vec{J}}_{\parallel}^{*}\,\mathrm{d}V}$$

$$\boxed{\underline{Z}_{\perp,x}(\omega) = -\frac{v}{(qd_x)^2\omega}\int_{beam} \underline{\vec{E}}\cdot\underline{\vec{J}}_{\perp}^{*}\,\mathrm{d}V}$$

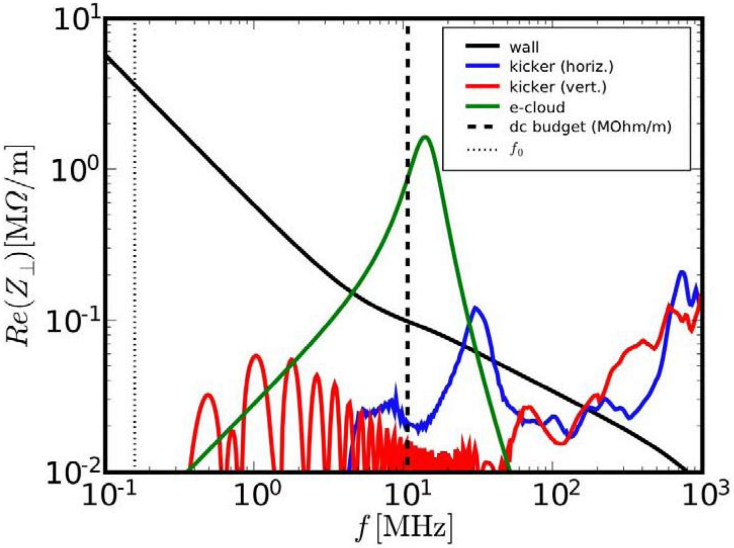
Details: See e.g. R. Gluckstern, *CAS*, 2000 or T. Weiland and R. Wanzenberg, CAS, 1992

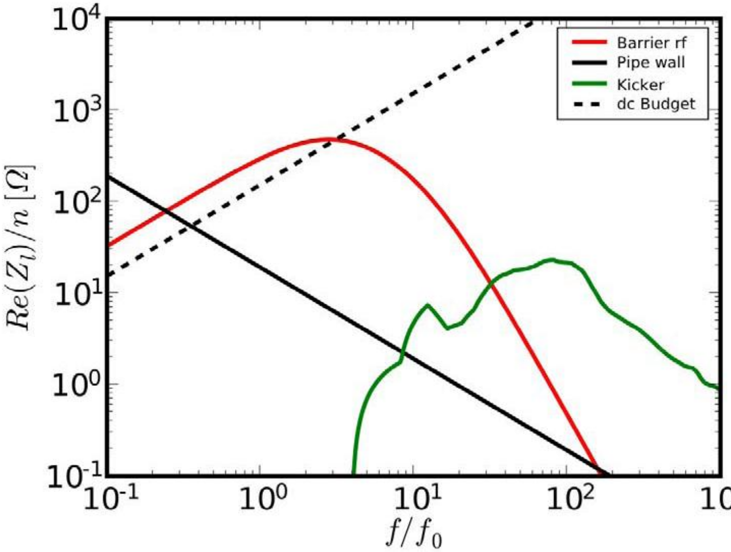
Imaginary part dominated by SPACE CHARGE!

The coupling impedance spectrum in SIS18 and SIS100

Dominating devices

$\mathrm{Re}\left\{\underline{Z}_\perp\right\}$	Beampipe (wall current)	Kicker, loading network (PFN)	Kicker, Ferrite yoke	Waveguide cutoff of beampipe (structural dependence)
$\mathrm{Re}\left\{\underline{Z}_\parallel\right\}$	MA Cavities (Broadband)	Ferrite Cavities (Narrowband)	Kicker	





Rough estimate!

$$f_0 = 156\mathrm{kHz}$$

Taken from SIS100 design spec.

Courtesy of O. Boine-Frankenheim

Time domain vs. Frequency domain

- Time Domain Calculations by commercial Software CST Particle Studio (Wake Potential)
- Impedances obtained by FFT
- Limitation by uncertainty relation

$$\boxed{\Delta t \Delta f \geq 1}$$

- Long wake length for low frequency $\Delta z \geq \frac{\beta c}{\Delta f} \approx 100 \text{ m @ } 1 \text{ MHz}$
- Large Gaussian bunchlength → impossibly long computation
- High computational effort for low velocity (large extension of source fields)

→FD approach pursued

for low and medium frequencies (<1GHz)

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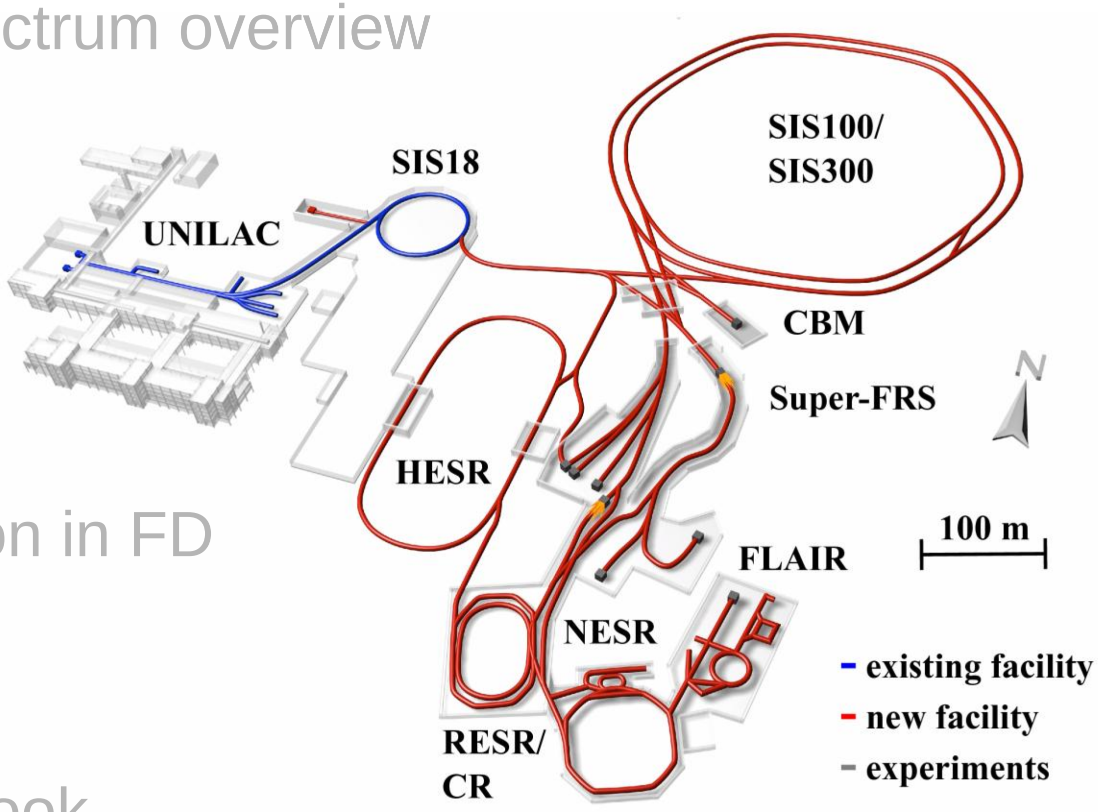


Analytical calculation

- "Axial model", beam with charge and current

$$\boxed{\partial_z \to -i\omega/v}$$

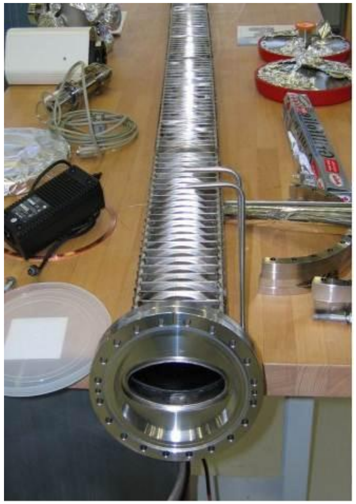
$$\boxed{\left(\triangle_\perp - i\omega\mu_0\kappa - \frac{\omega^2}{\beta^2\gamma^2c^2}\right)\underline{E}_z = -i\omega\mu_0\sigma(\vec{r})\frac{1}{\beta^2\gamma^2}e^{-i\omega z/v}}$$

- Simplified low frequency approach "Radial model"

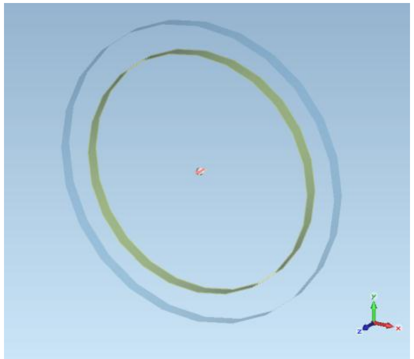
$$l << \lambda = c/f \qquad \boxed{\partial_z \to 0}$$

$$\boxed{\left(\triangle_\perp - i\omega\mu_0\kappa + \frac{\omega^2}{c^2}\right)\underline{E}_z = i\omega\mu_0\sigma(\vec{r})}$$

- Suitable for LF impedance of beampipe

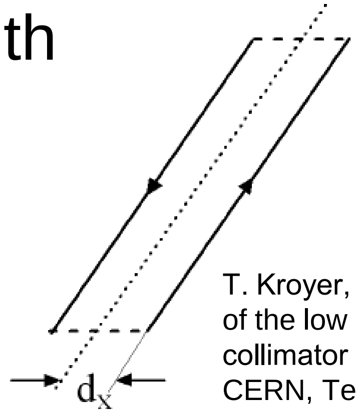


Simplified numerical method (according to “radial model“)



- Power loss calculation with CST EM STUDIO®
- MQS Frequency-Domain

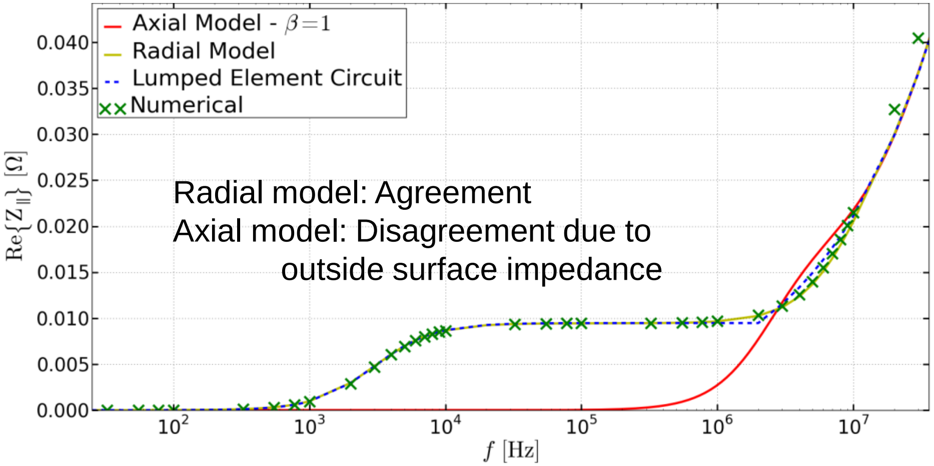
$$\delta P = \frac{1}{2} \int_{pipe} \underline{\vec{E}} \cdot \underline{\vec{J}}^{*} \, \mathrm{dV}$$



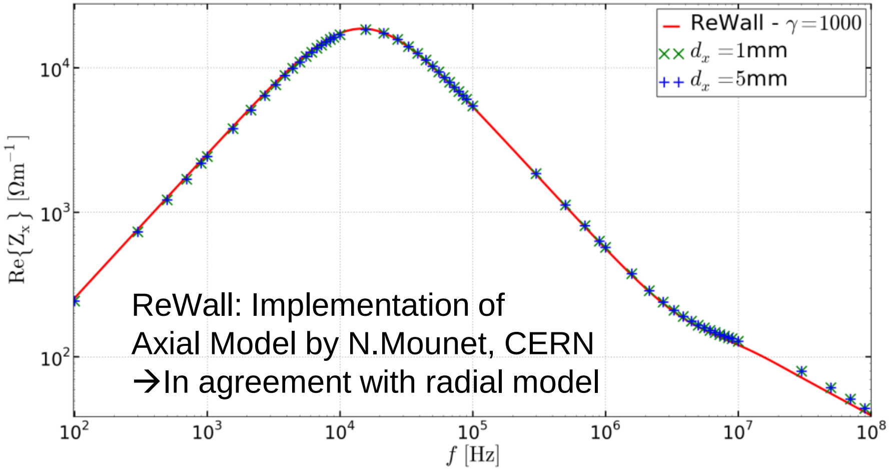
T. Kroyer, “Simulation of the low frequency collimator impedance” CERN, Tech.Rep., 2008

$$\boxed{\frac{\mathrm{Re}\{\underline{Z}_{\|}\}}{l} = \frac{1}{I^2}\frac{\delta P}{\delta z}}$$

$$\boxed{\frac{\mathrm{Re}\left\{\underline{Z}_{\perp,x}(\omega)\right\}}{l} = \frac{c}{\omega d_x^2}\frac{1}{I^2}\frac{\delta P}{\delta z}}$$

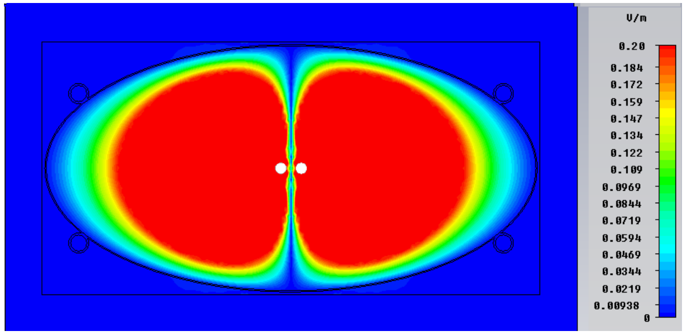


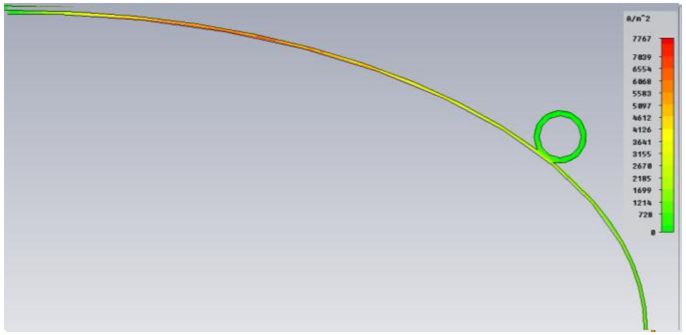
Radial model: Agreement
Axial model: Disagreement due to outside surface impedance



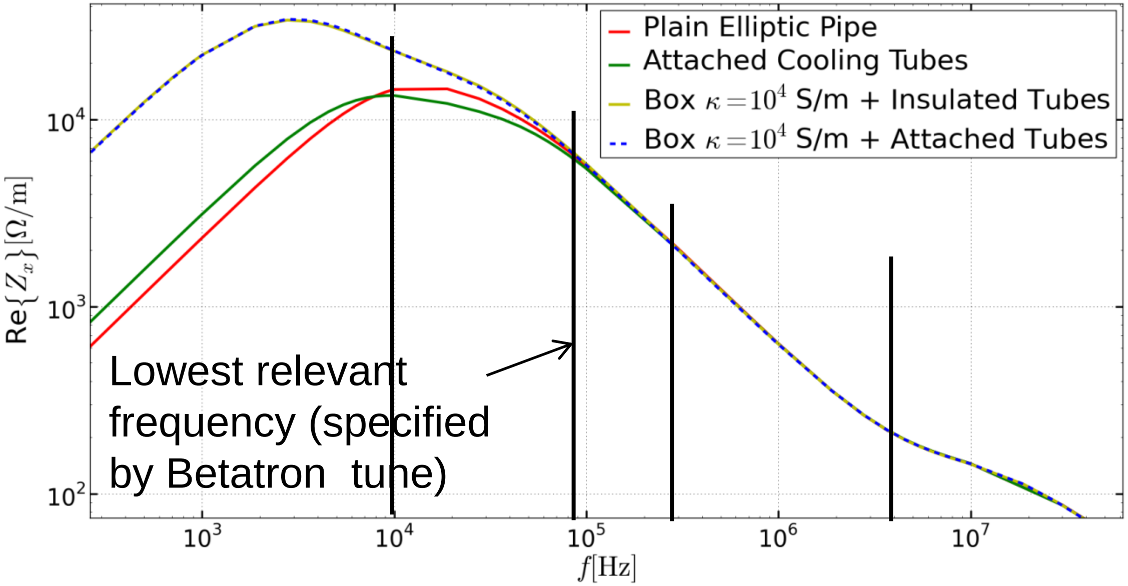
ReWall: Implementation of Axial Model by N.Mounet, CERN
→In agreement with radial model

Numerical calculation for SIS100 dipole chamber

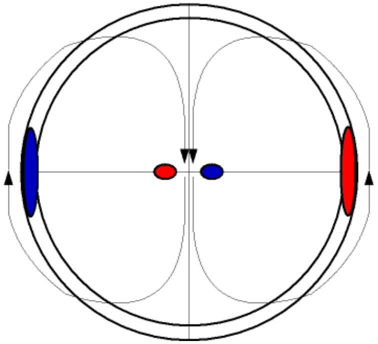


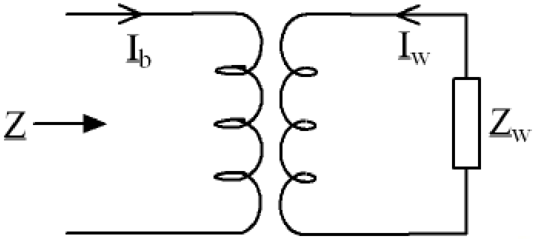


Longitudinal E-field and wall current for $f = 300\,\mathrm{kHz}$

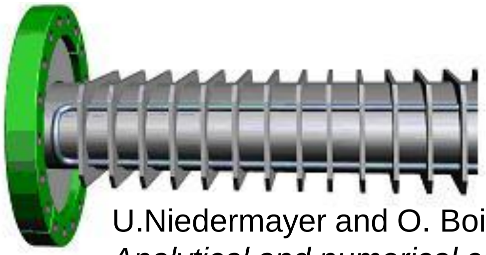


Lowest relevant frequency (specified by Betatron tune)





Transformer between dipolar beam-current and wall-current



U.Niedermayer and O. Boine-Frankenheim, *Analytical and numerical calculations of resistive wall impedances for thin beam pipe structures at low frequencies*, NIM A, 2012

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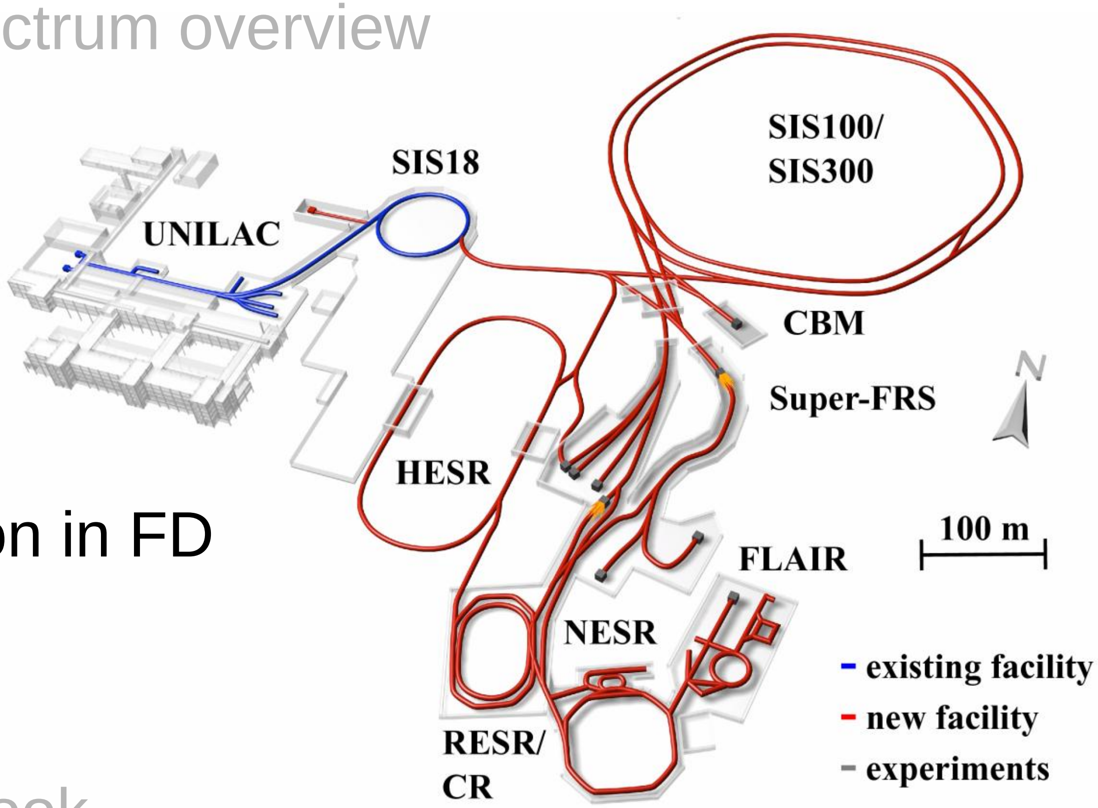


Full numerical simulation in FD

$$\nabla \times \frac{1}{\underline{\mu}} \nabla \times \underline{\vec{E}} + i\omega\kappa\underline{\vec{E}} - \omega^2 \varepsilon \underline{\vec{E}} = -i\omega \underline{\vec{J}}_{ext}$$

$$\oint_{\partial A} \vec{E} \cdot d\vec{s} = -\frac{d}{dt}\int_A \vec{B} \cdot d\vec{A}$$

$$\oint_{\partial A} \vec{H} \cdot d\vec{s} = \int_A \left(\frac{\partial \vec{D}}{\partial t} + \vec{J}\right) \cdot d\vec{A}$$

$$\oint_{\partial V} \vec{D} \cdot d\vec{A} = \int_V \rho \, dV$$

$$\oint_{\partial V} \vec{B} \cdot d\vec{A} = 0$$

$$\xrightarrow{\text{FIT}}$$

$$\mathbf{C}\widehat{\mathbf{e}} = -\frac{d}{dt}\widehat{\widehat{\mathbf{b}}}$$

$$\widetilde{\mathbf{C}}\widehat{\mathbf{h}} = \frac{d}{dt}\widehat{\widehat{\mathbf{d}}} + \widehat{\widehat{\mathbf{j}}}$$

$$\widetilde{\mathbf{S}}\widehat{\widehat{\mathbf{d}}} = \mathbf{q}$$

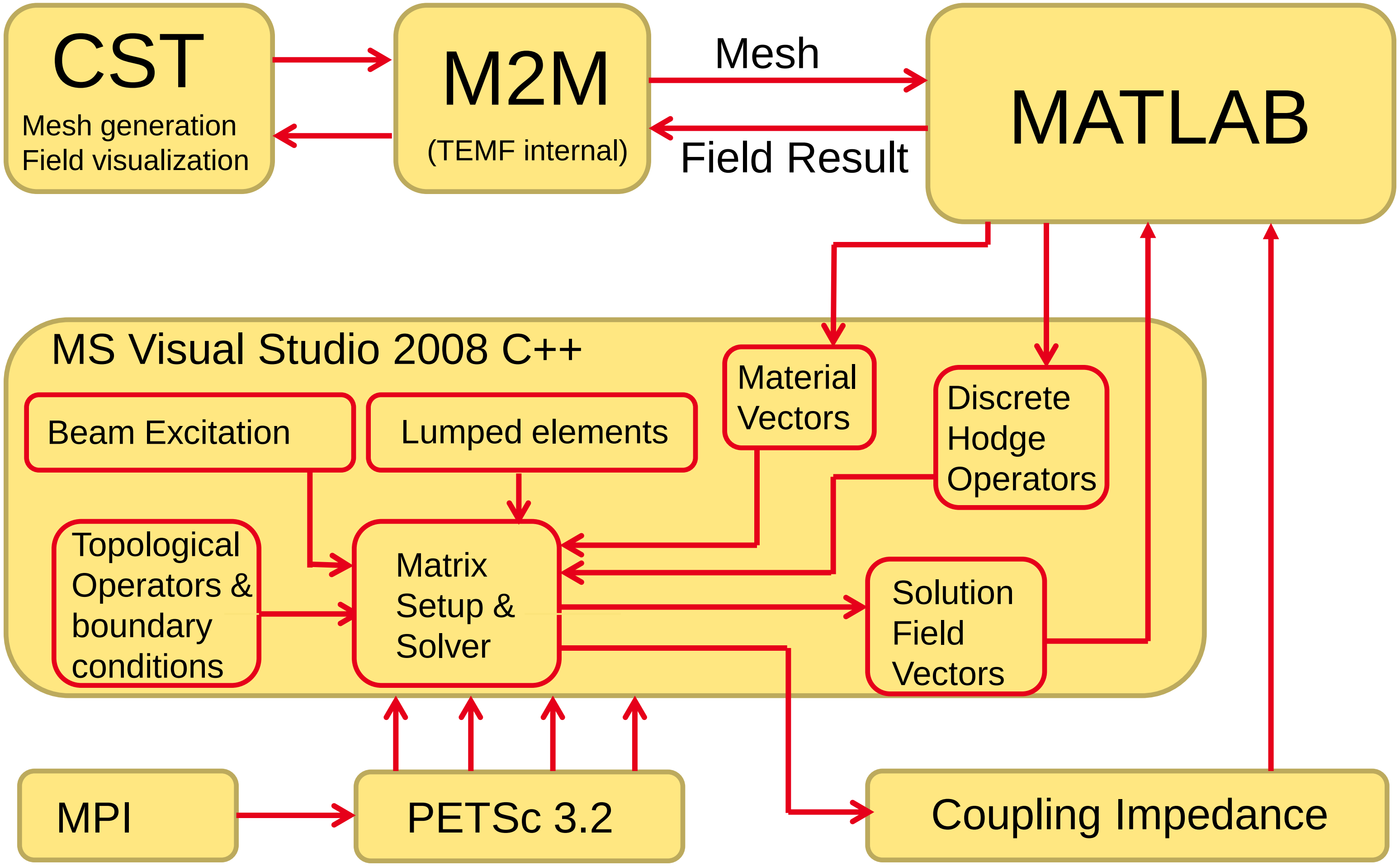
$$\mathbf{S}\widehat{\widehat{\mathbf{b}}} = \mathbf{0}$$

FIT is a mimetic discretization based on the INTEGRAL FORMULATION of Maxwell‘s equations (Weiland 1977)

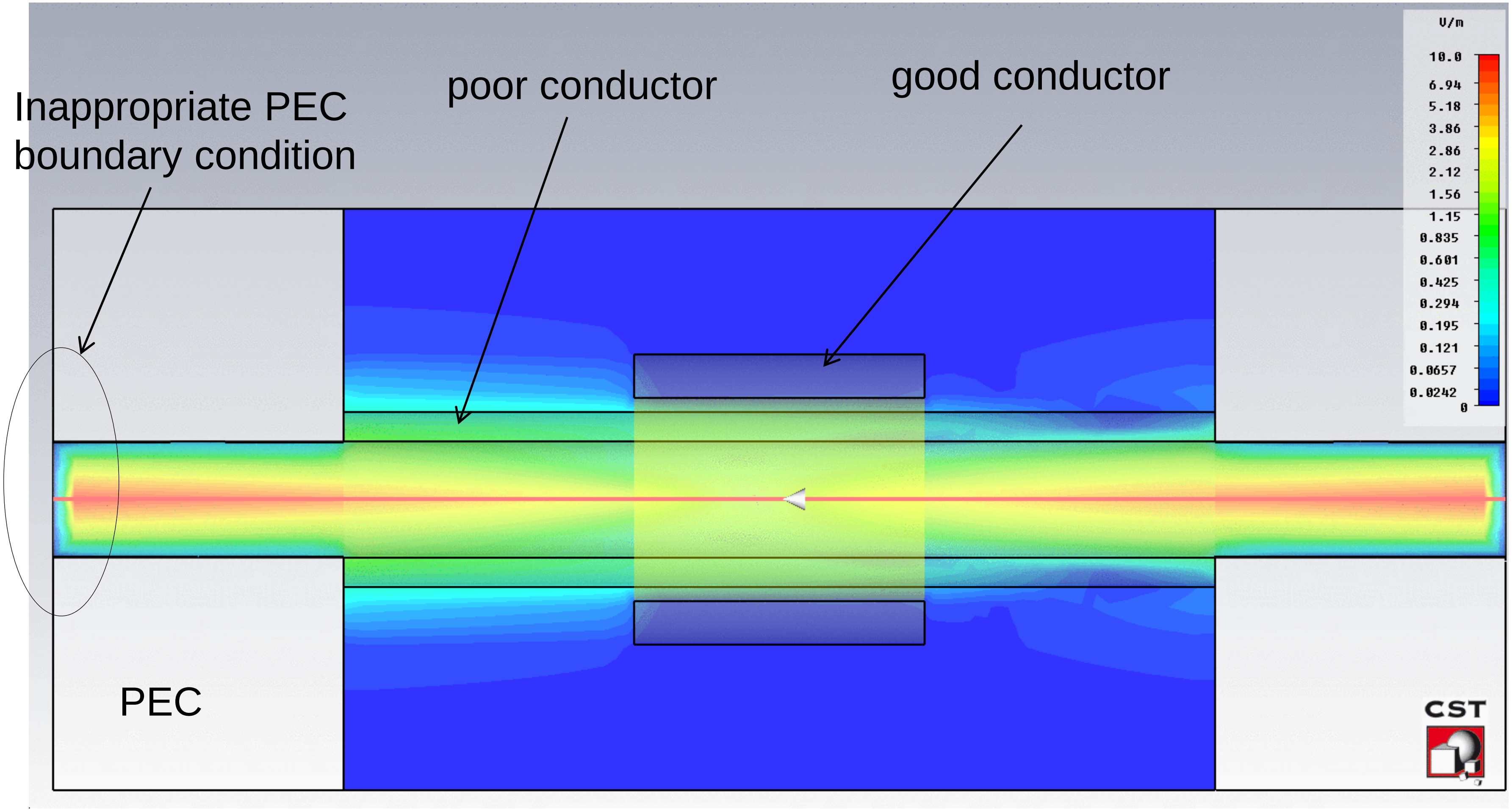
$$\widetilde{\mathbf{C}}\mathbf{M}_{\mu^{-1}}\mathbf{C}\underline{\widehat{\mathbf{e}}} + i\omega\mathbf{M}_{\kappa}\underline{\widehat{\mathbf{e}}} - \omega^2\mathbf{M}_{\epsilon}\underline{\widehat{\mathbf{e}}} = -i\omega\underline{\widehat{\widehat{\mathbf{j}}}}_{ext}$$

Complex linear system of size 3np, indefinite ill-conditioned matrix

Implementation



First Results for Arbitrary Test Structure



Beam adapted boundary conitions

- Assume infinitely long beam pipe stubs
- Analytical solution would violate discrete charge conservation
- Create 2D subgrid (also called 2.5D approach)

$$\partial_z \to -i\omega/v \qquad P_z \to diag(-1 + exp(-i\omega\triangle z/v))$$

- Include solution as Neumann BC to preserve symmetry of the system matrix
- Currently under test in the C++ code

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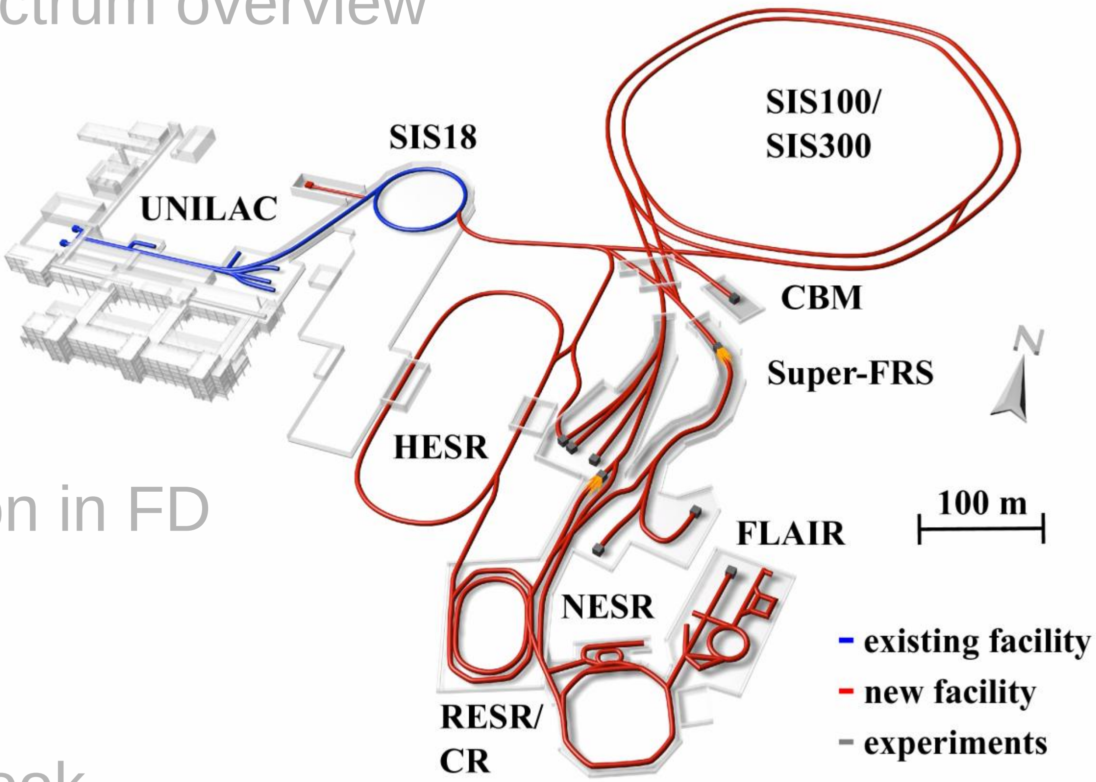
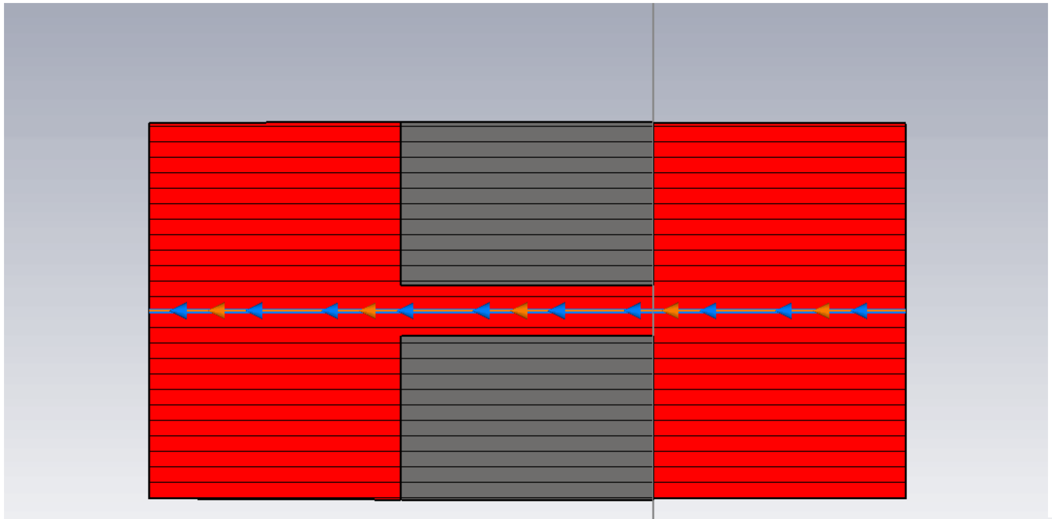
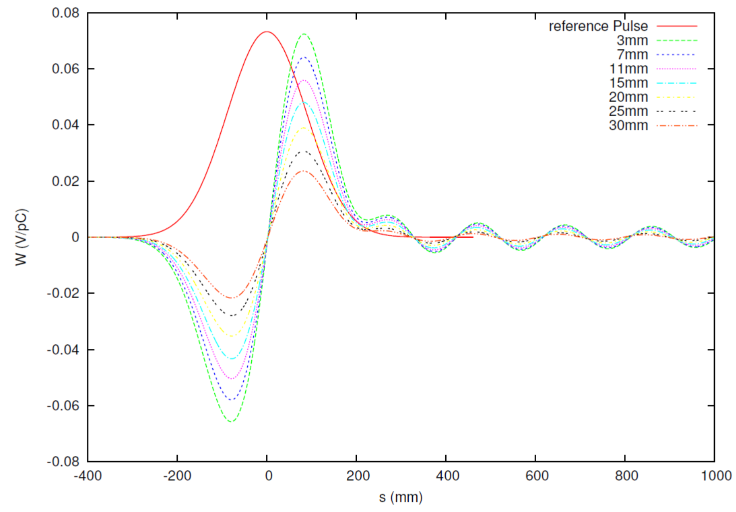
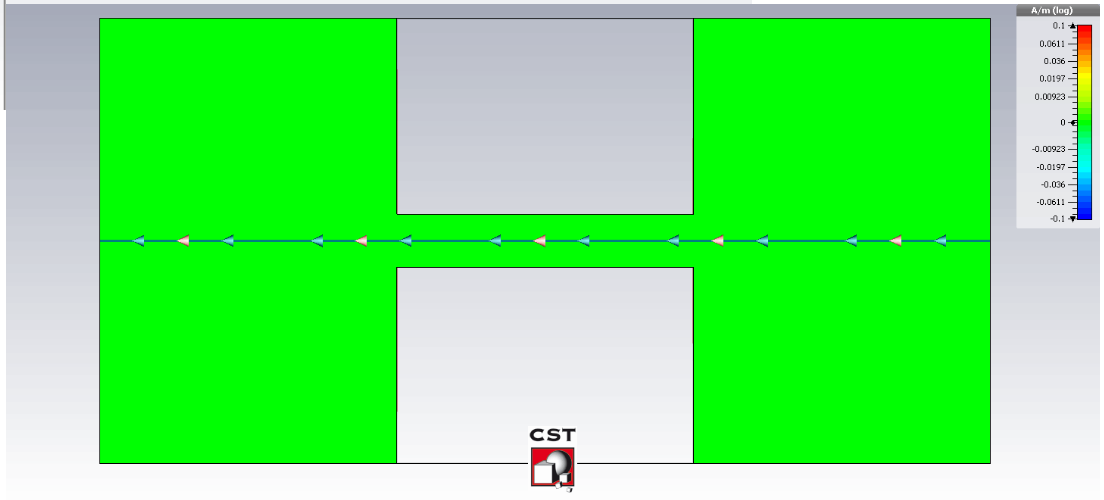


Time Domain Simulations (CST Particle Studio)



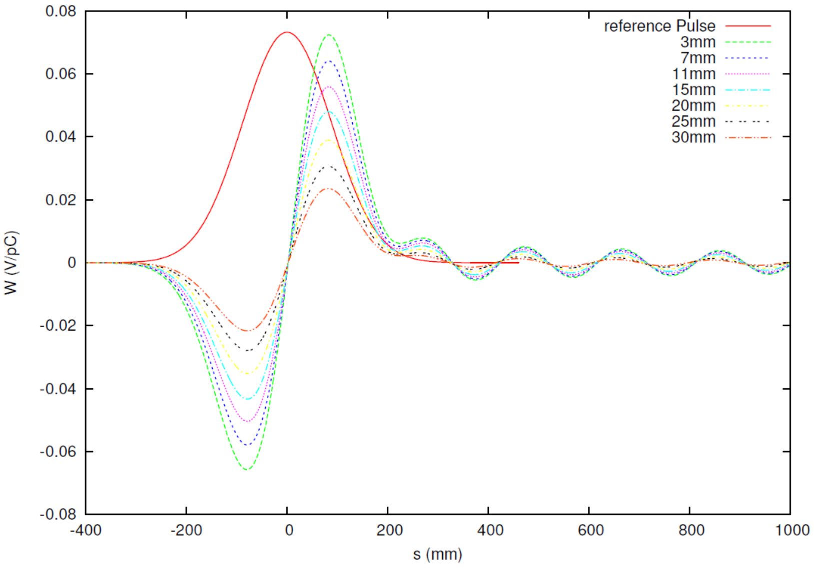


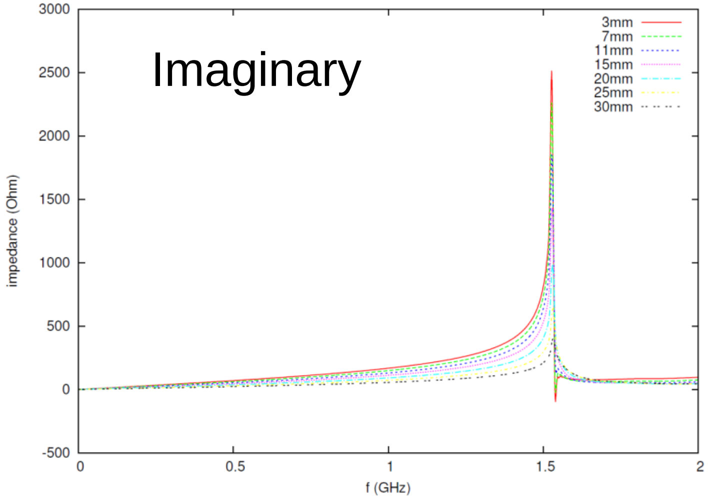
Magnetic Field Amplitude

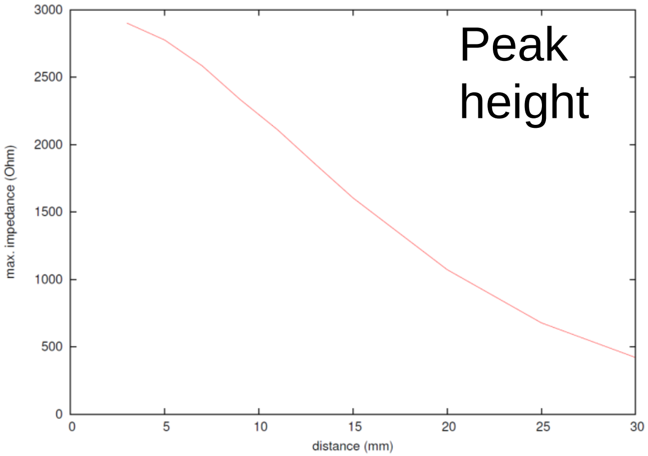


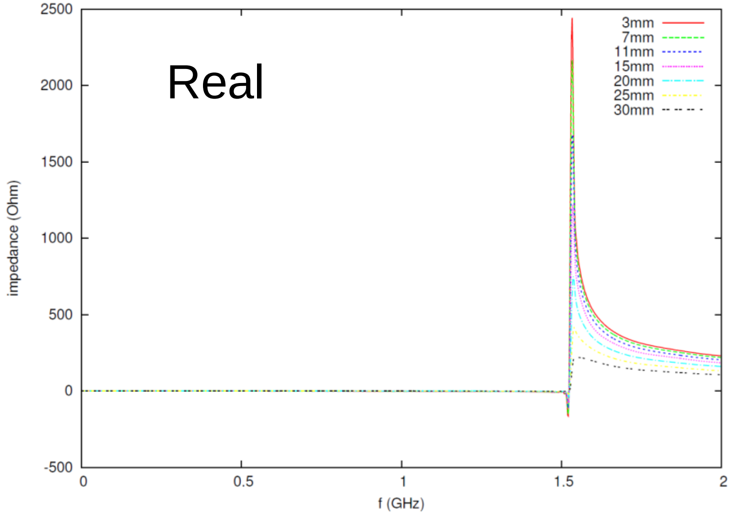
L. Eidam,
MSc Student
in our group

Time Domain Simulations cont‘d (Preliminary results)









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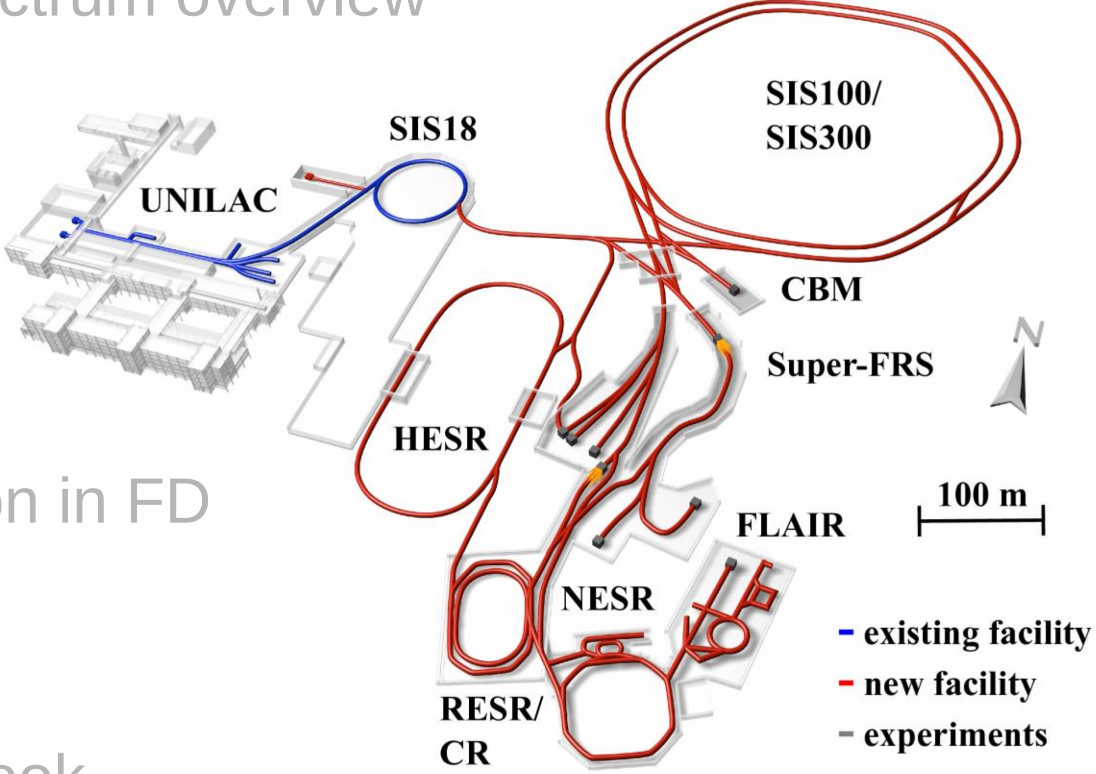
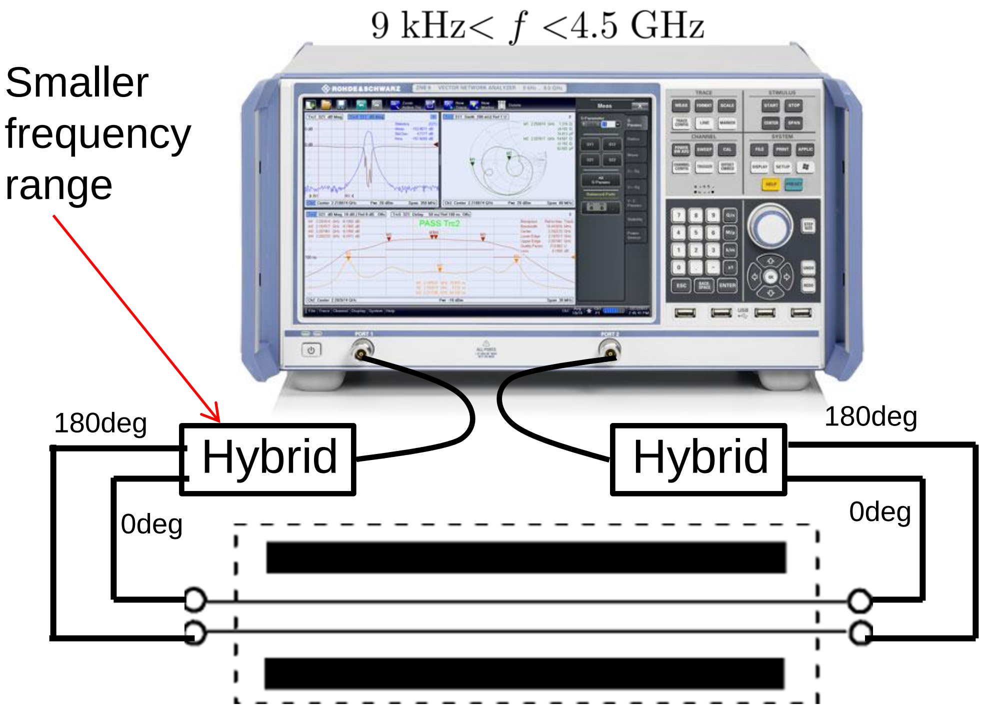


High Frequency Measurement setup



$9\ \mathrm{kHz} < f < 4.5\ \mathrm{GHz}$

Smaller frequency range

180deg

Hybrid

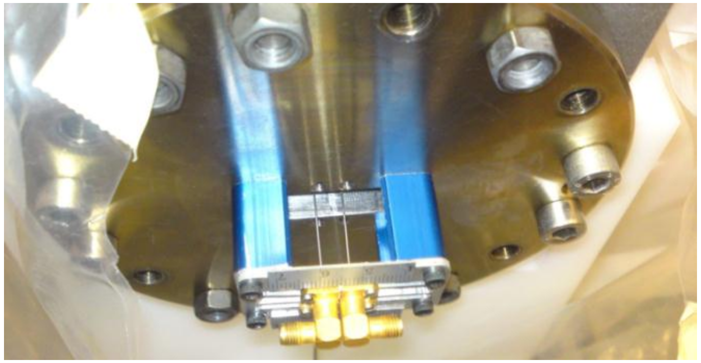
0deg

180deg

Hybrid

0deg

DUT



Setup @ CERN (MKE-Kicker)

$$\underline{Z}_\perp = \frac{cZ}{\omega\Delta^2}$$

$$\underline{Z}^{lumped} = 2Z_c \frac{1-S_{21}}{S_{21}}$$

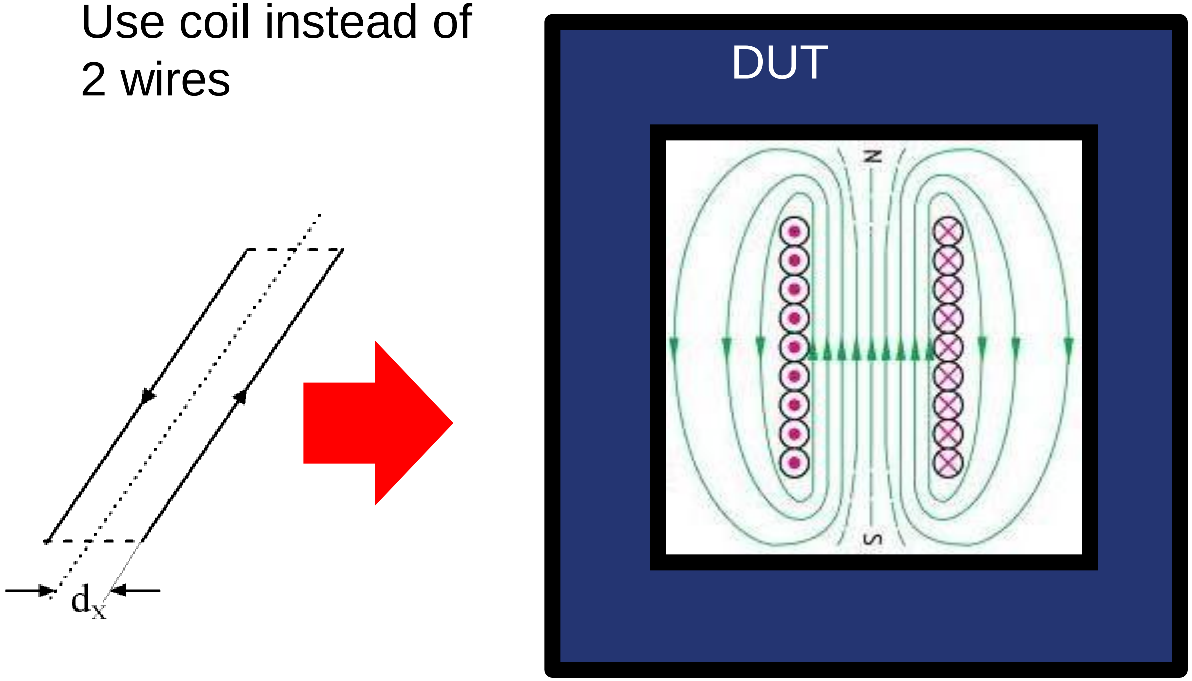
$$\underline{Z}^{dist} = 2Z_c \ln S_{21}$$

Normalized S-parameters (to REF)

Walling 1989, Caspers 1992

LF Transverse impedance

Coil Measurement:
Use coil instead of
2 wires



LCR Meter

20 Hz< f <2 MHz

$$\underline{Z}_\perp = \frac{c(\underline{Z}^{DUT} - \underline{Z}^{REF})}{\omega N^2 \Delta^2}$$

Drawback: Upper frequency limit due to coil resonance @ approx. 1MHz

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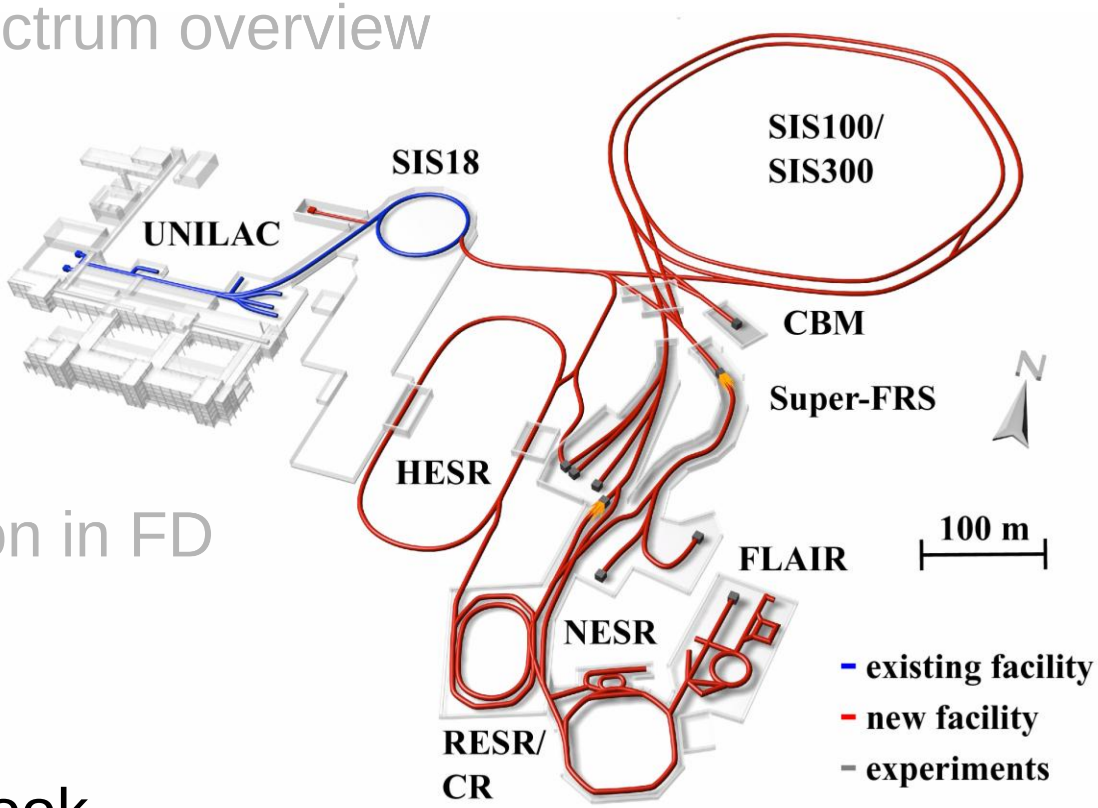
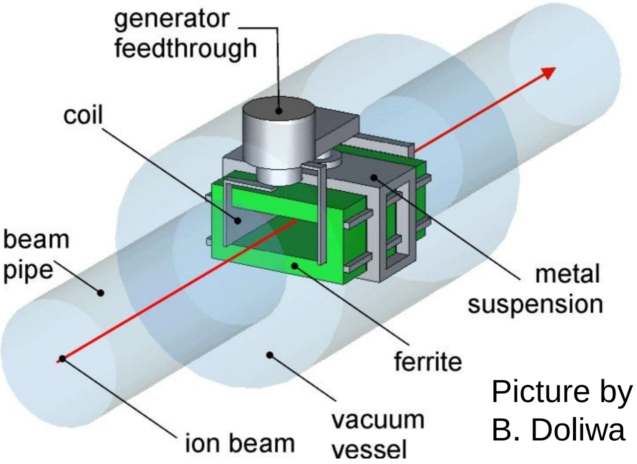


Treatment of SIS100 components

- Kickers
  - FD simulation (with network)
  - Simplified analytical models
    - Nassibian and Sacherer 1978
    - Tsutsui 2000
  - LF and HF measurements
- Collimators
  - TD simulation for good conducting materials
  - FD simulation / measurements for poor conductors
- Beampipe: Done.



Picture by B. Doliwa

Proposed SC compensation insert

- Longitudinal Space Charge is like a negative inductance

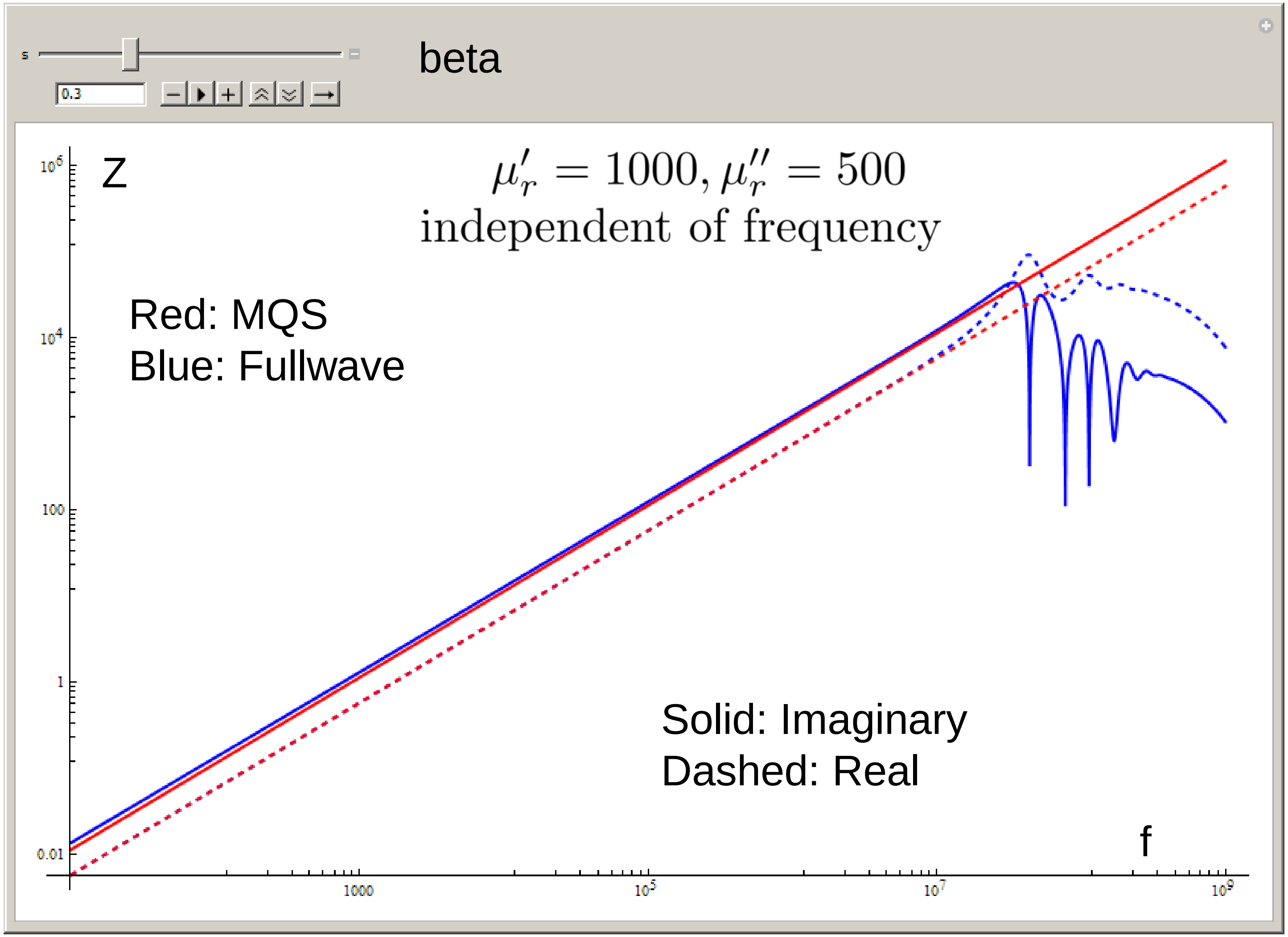
$$\underline{Z}_{\parallel}^{SC} = -i\omega\frac{\mu_0 g_0 l}{4\pi\beta^2\gamma^2}$$

- Causes potential well distortion / decrease of bucket-height
- Can be compensated by positive Inductance

$$\underline{Z}_{\parallel}^{INSERT} \approx i\omega\frac{\mu}{2\pi}l\ln\frac{h}{b}\ , \quad f < 10\ \mathrm{MHz}\ \ , \quad \beta > 0.3$$

- Implemented in PSR / Los Alamos using highly permeable material (Ferrite)
- Magnetization losses cause real part of impedance
  →Negative mass instability @ PSR (PhD Thesis C. Beltran, 2003)
- Impact on transverse impedance???

Analytical calculations for SC compensation insert



$\mu_r' = 1000, \mu_r'' = 500$

independent of frequency

Red: MQS

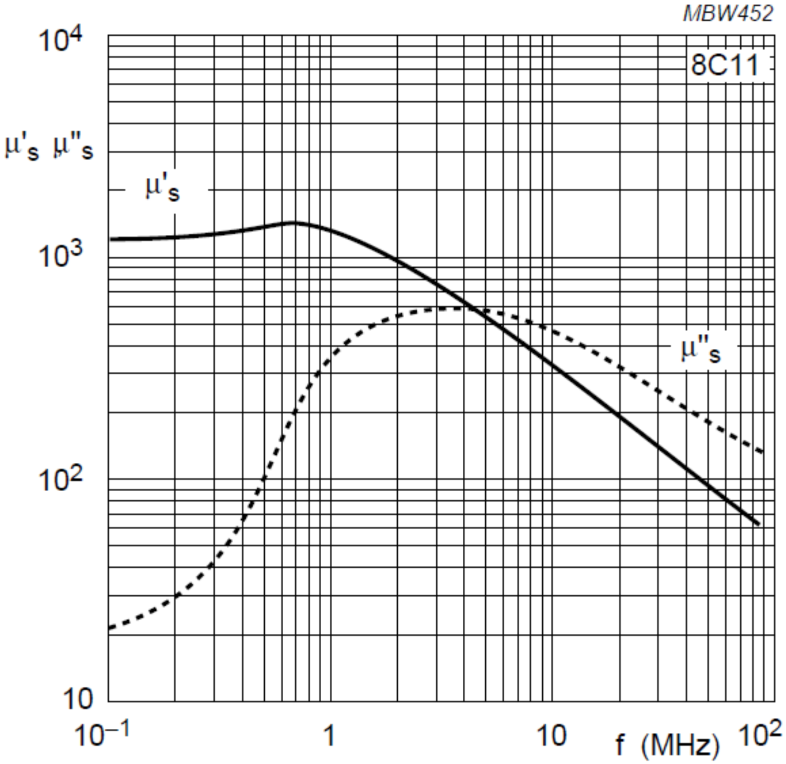
Blue: Fullwave

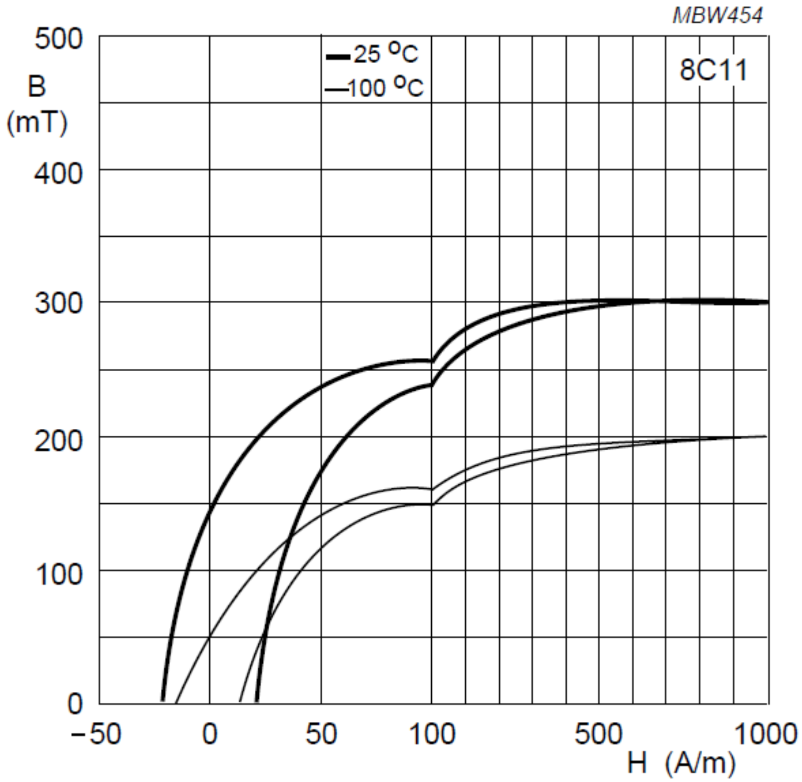
Solid: Imaginary

Dashed: Real

Sensitivity on material parameters

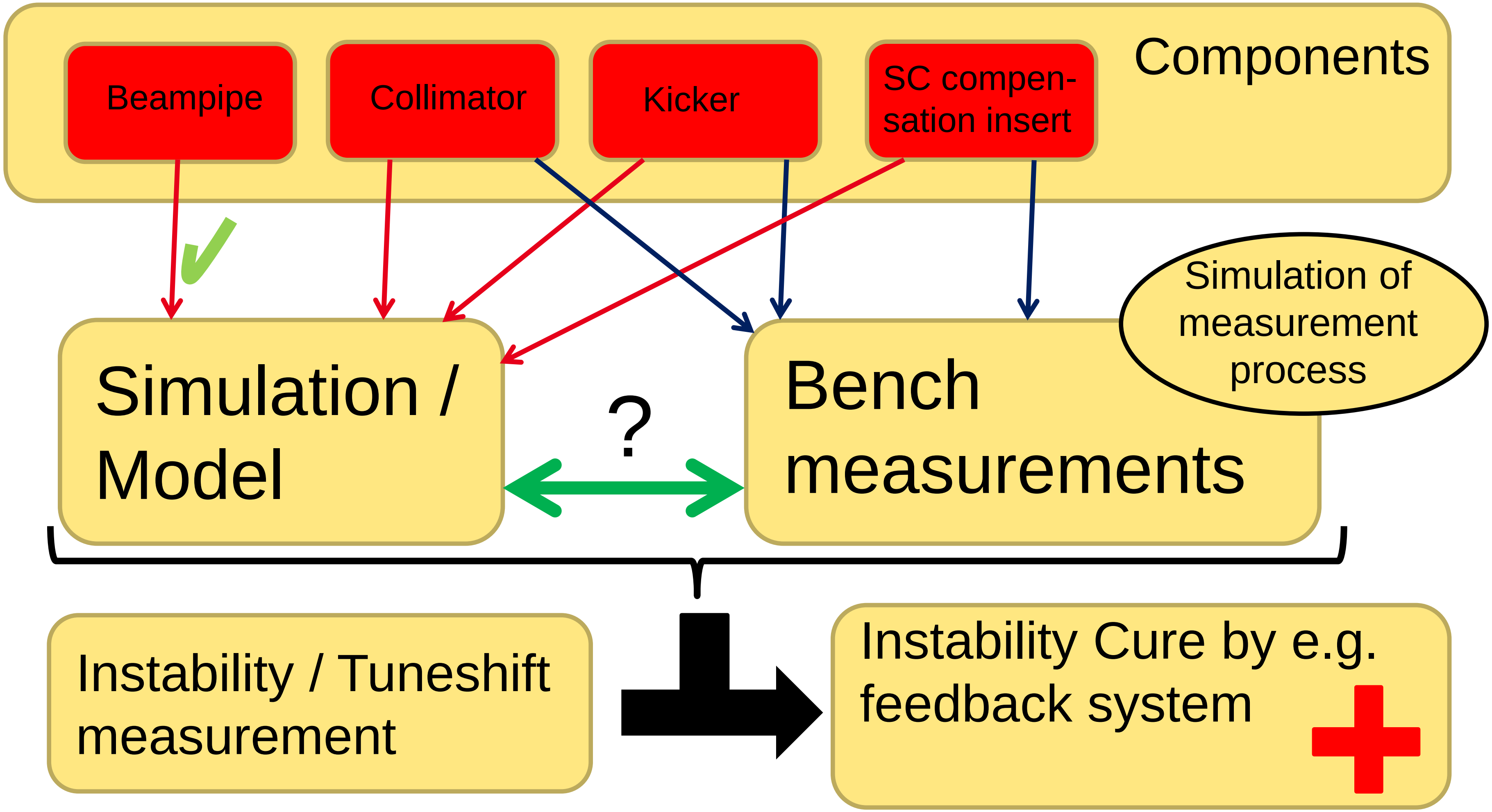
Ferroxcube 8C11





- Calculation of extremal cases
- Estimation of higher harmonics (nonlinear response)

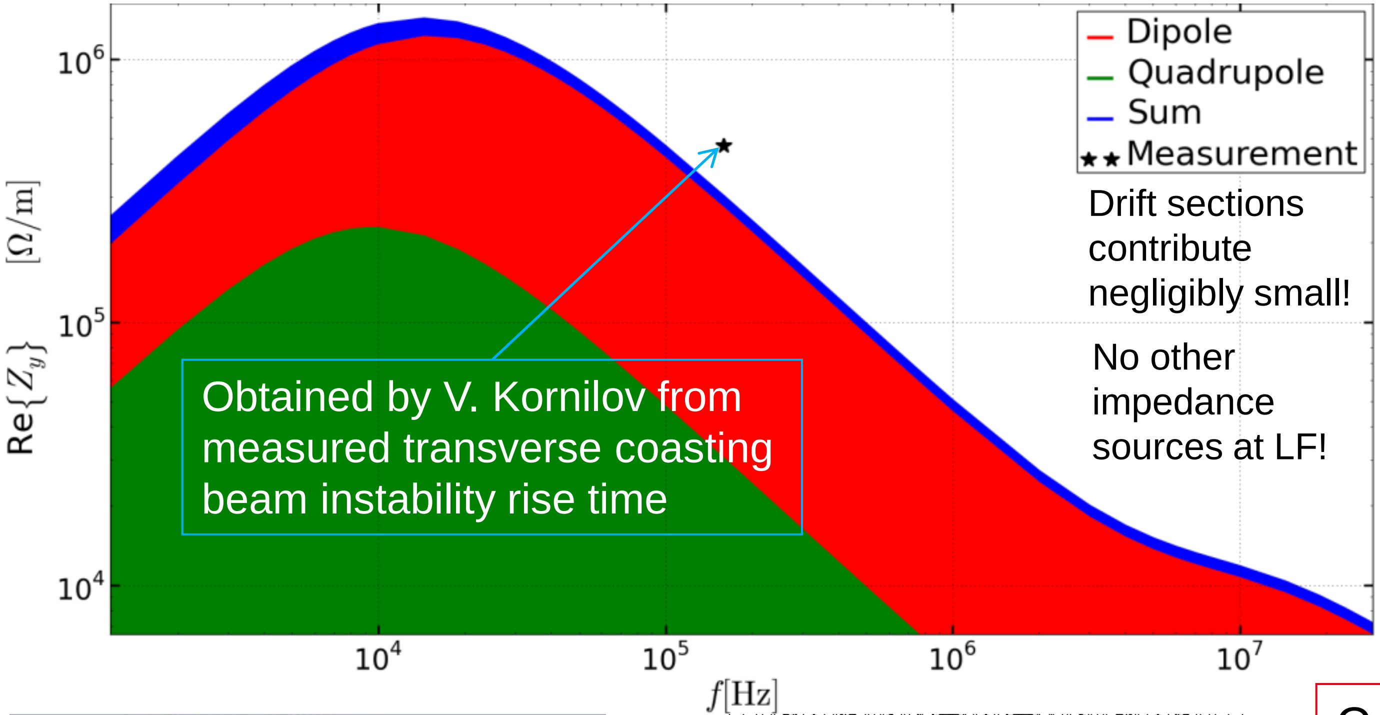
Conclusions
(current status and outlook)



THE END

- Thank you for your kind attention
- Thanks to all coworkers
- Any questions?

Numerical LF transverse impedance model for SIS18 and measurement

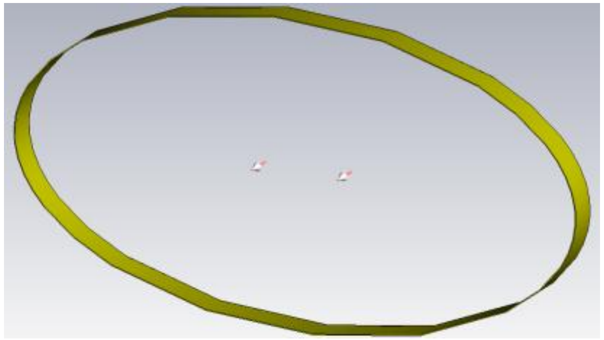


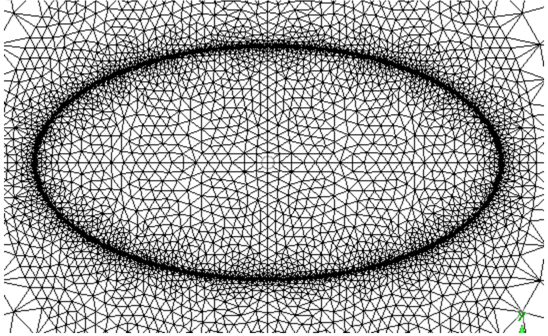
Obtained by V. Kornilov from measured transverse coasting beam instability rise time

Drift sections contribute negligibly small!

No other impedance sources at LF!

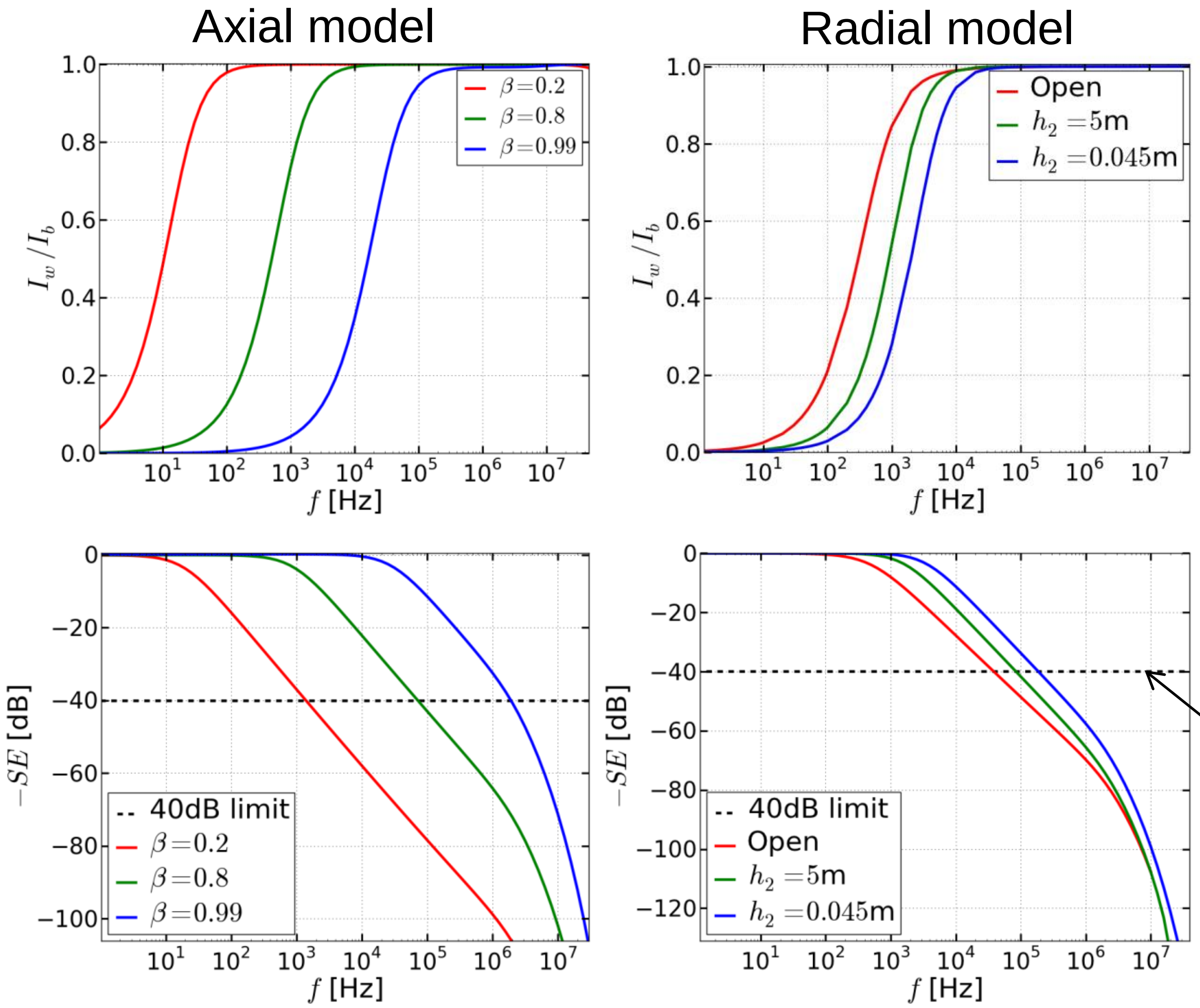
Reason for higher measured impedance: closed orbit deviation





Cannot be calculated by analytical model for circular pipe! (equivalent radius frequency dependent)

Wall current and shielding effectiveness



Axial model

Radial model

$$\underline{I}_w = 2\pi\kappa \int\limits_b^h \underline{E}_z(\varrho)\varrho\,\mathrm{d}\varrho$$

PEC pipe: $\underline{I}_w = \underline{I}_b$

(surface current)

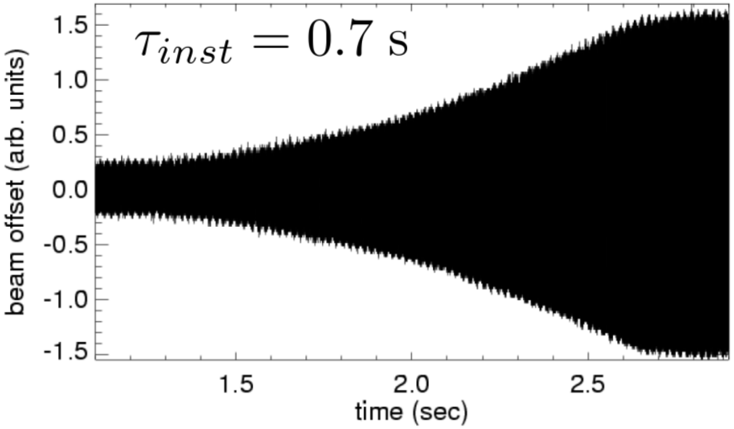
$$SE = -10\log\left|\frac{\underline{S}_\varrho|_h}{\underline{S}_\varrho|_b}\right|$$

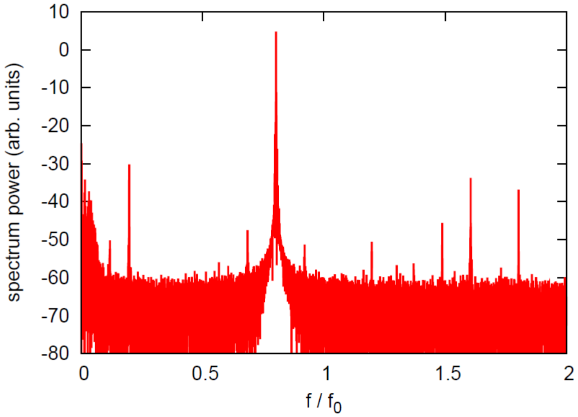
For comparison:
FCC Class B
shielding requirement

U. Niedermayer, Coupling impedance calculation for a thin layered beampipe, Diplomarbeit, 2011

Transverse coasting beam instability in SIS18

H





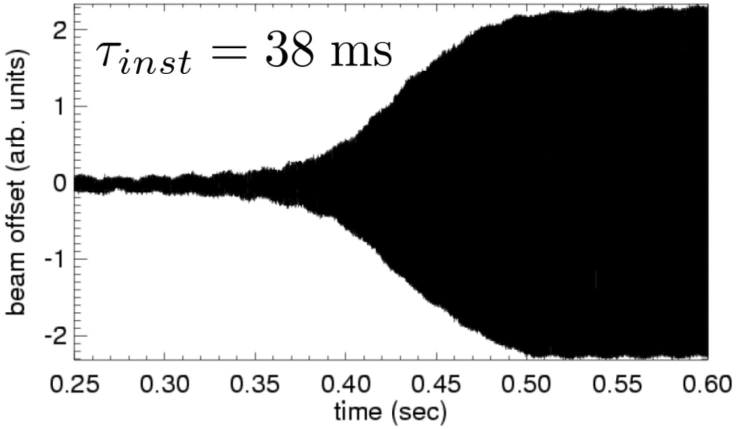
Courtesy of
V. Kornilov, GSI

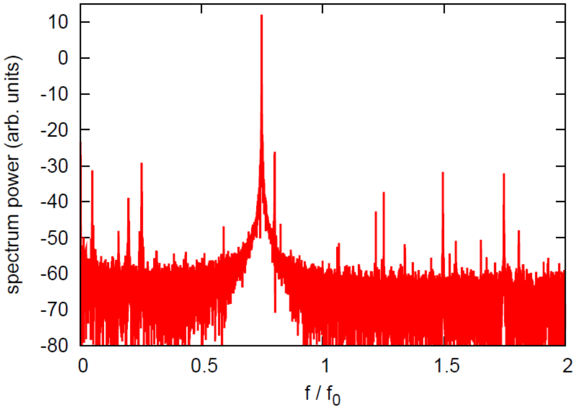
$$f/f_0 = 4/5$$

↑

Revolution frequency

V





$$f/f_0 = 3/4$$

$$n = \lceil Q_x \rceil$$

Betatron tune

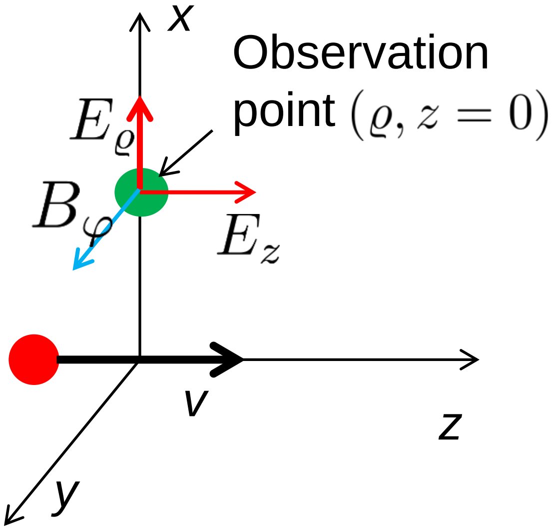
Transverse impedance provides coherent force
→ coherent instability

$$\boxed{\frac{1}{\tau_{inst}} = \frac{N_{ions} q_{ion}^2}{4\pi l Q_x m_{ion} \gamma} \mathrm{Re}\left\{\underline{Z}_{\perp,x}[(n - Q_x)\omega_0]\right\}}$$

Source Fields

- Coulomb field in moving frame

$$\vec{E}' = \frac{q}{4\pi\varepsilon}\left(\frac{\varrho'}{\sqrt{\varrho'^2+z'^2}^3}\vec{e}_\varrho + \frac{z'}{\sqrt{\varrho'^2+z'^2}^3}\vec{e}_z\right)$$



- Lorentz transformation to lab-frame

$$\vec{E} = \frac{q}{4\pi\varepsilon}\left(\frac{\gamma\varrho}{\sqrt{\varrho^2+(\beta\gamma ct)^2}^3}\vec{e}_\varrho + \frac{-\beta\gamma ct}{\sqrt{\varrho^2+(\beta\gamma ct)^2}^3}\vec{e}_z\right), \quad B_\varphi = \frac{v}{c^2}E_\varrho$$

$$\begin{cases} \underline{E}_z = iq\frac{\mu_0}{2\pi}\frac{\omega}{\beta^2\gamma^2}\mathrm{K}_0\left(\frac{|\omega|}{\beta\gamma c}\varrho\right) \xrightarrow{\gamma\to\infty} 0 \\ \underline{E}_\varrho = q\frac{\mu_0}{2\pi}\frac{|\omega|}{\beta^2\gamma}\mathrm{K}_1\left(\frac{|\omega|}{\beta\gamma c}\varrho\right) \xrightarrow{\gamma\to\infty} q\frac{Z_0}{2\pi\varrho} \end{cases}$$

“Source Fields“

TEM Mode!