Impedance Mitigation Techniques for Kicker Magnets

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Acknowledgements: M. Barnes, A. Chmielinska, H. Day, L. Ducimetier, L. Vega Cid, W. Weterings

Outline

- What is beam coupling impedance?
- How to estimate and how to measure it?
- How to mitigate it?
  - Serigraphy – the SPS extraction kicker (MKE)
  - Conducting wires – the LHC injection kicker (MKI)
- Discussion

Beam impedance:
What it is and why we (should) care!

- Mathematical concept that quantifies the interaction of the beam with its surroundings

- Ratio of the developed voltage in a structure to the current that created it

Disclaimer

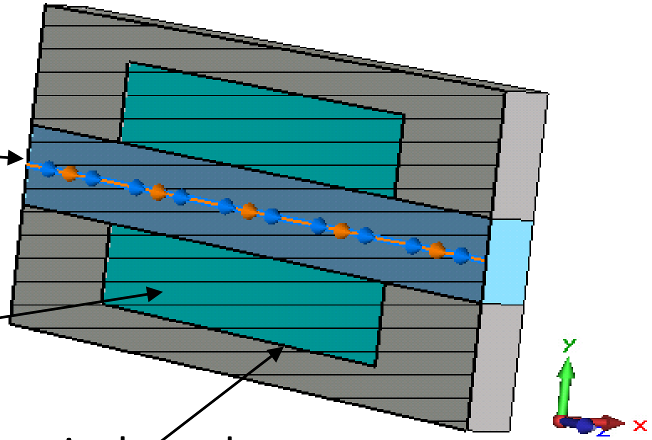
For the rest: impedance = real longitudinal impedance

contributors to instability thresholds

- Quantifies e/m power loss → RF heating = main concern for kicker magnets

Simple examples

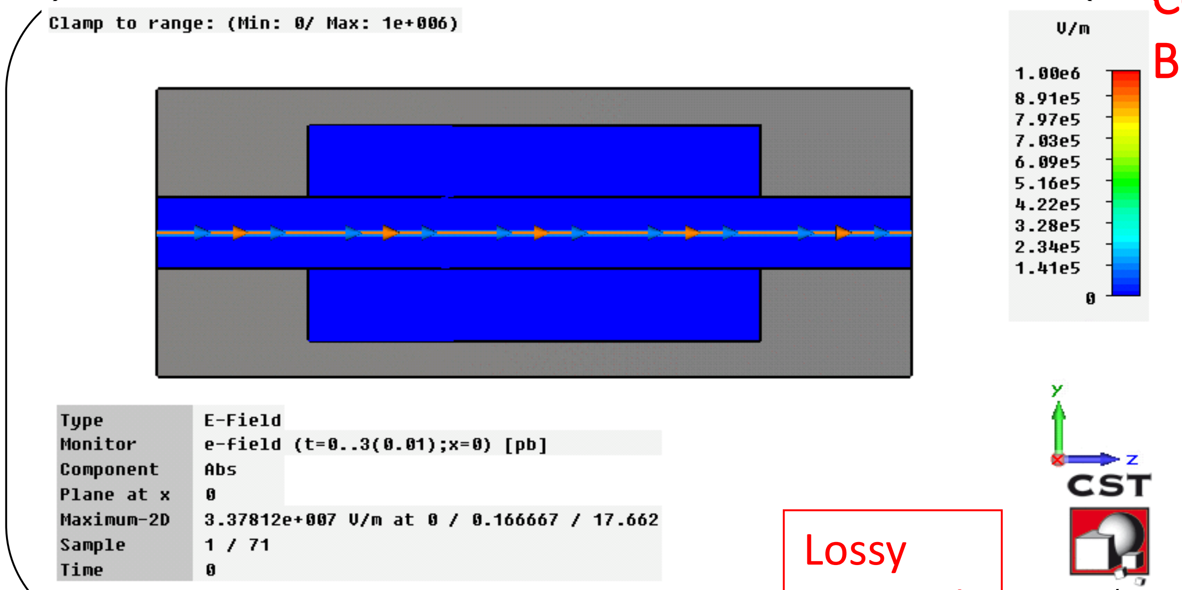
Courtesy: B. Salvant



Particle Beam

Variable material

Perfect electrical conductor

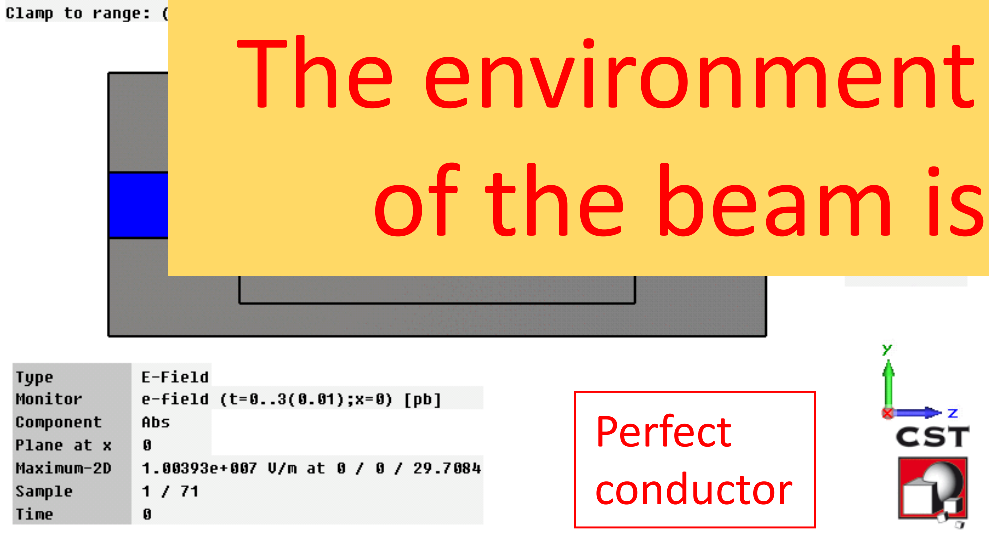


```
Clamp to range: (Min: 0/ Max: 1e+006)

Type          E-Field
Monitor       e-field (t=0..3(0.01);x=0) [pb]
Component     Abs
Plane at x    0
Maximum-2D    3.37812e+007 V/m at 0 / 0.166667 / 17.662
Sample        1 / 71
Time          0
```

Lossy material

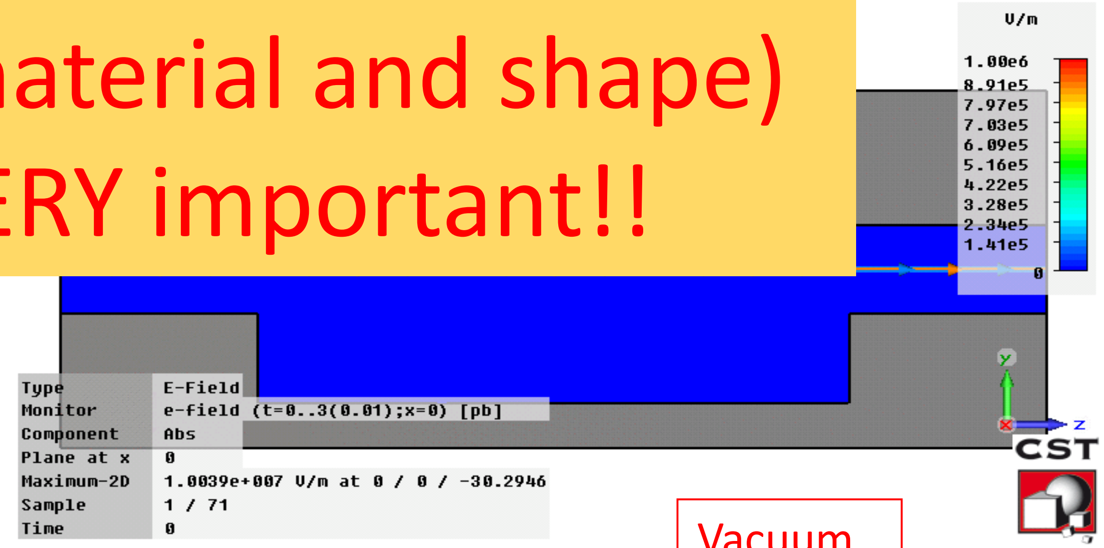
The environment (material and shape) of the beam is VERY important!!



```
Clamp to range: (

Type          E-Field
Monitor       e-field (t=0..3(0.01);x=0) [pb]
Component     Abs
Plane at x    0
Maximum-2D    1.00393e+007 V/m at 0 / 0 / 29.7084
Sample        1 / 71
Time          0
```

Perfect conductor



```
Type          E-Field
Monitor       e-field (t=0..3(0.01);x=0) [pb]
Component     Abs
Plane at x    0
Maximum-2D    1.0039e+007 V/m at 0 / 0 / -30.2946
Sample        1 / 71
Time          0
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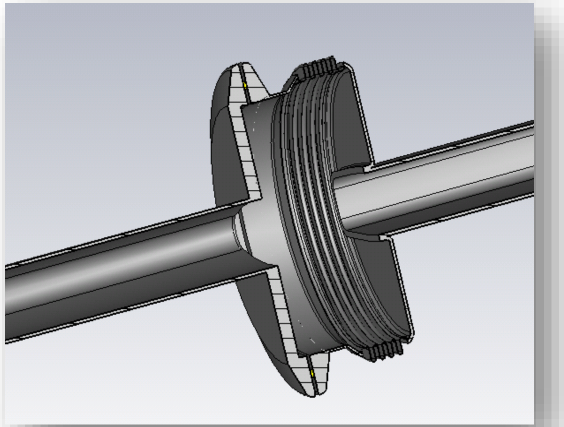
Vacuum (cavity)

Impedances are everywhere!

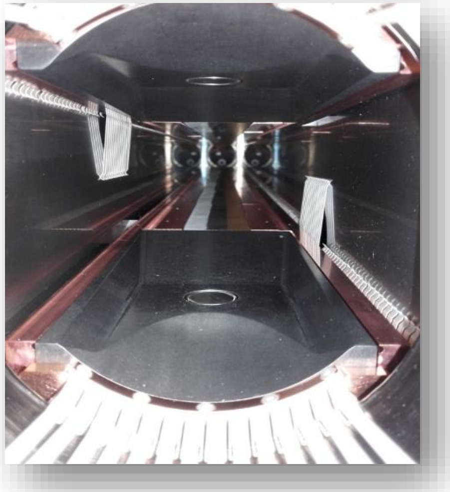
Vacuum Flanges

Bellows

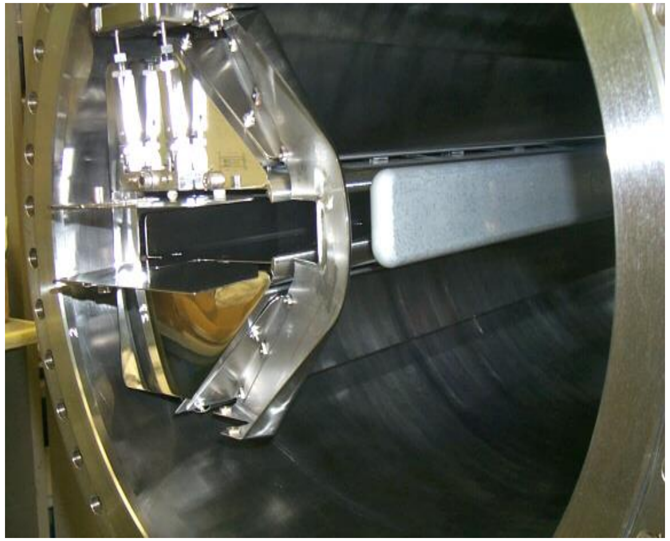
RF Cavities

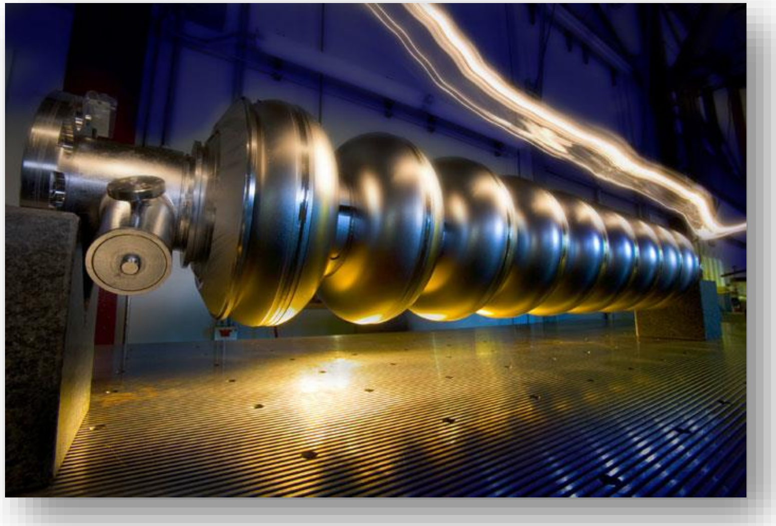


Collimators

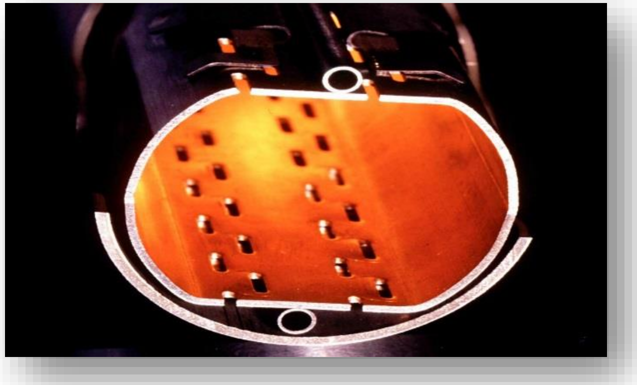


Septa





Impedance Sources

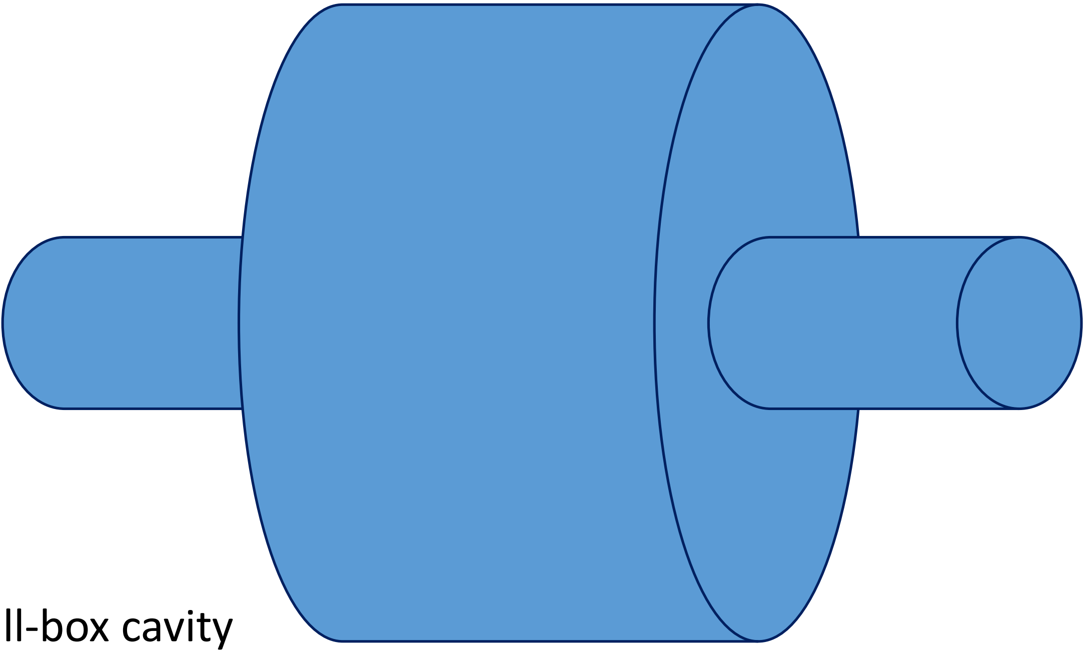


Beam Pipe

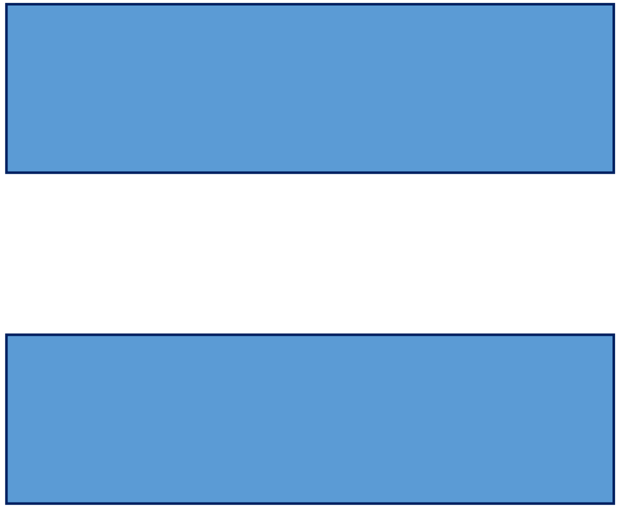
Kickers

How to estimate impedances? (1/2)

- Analytical formulas
  - Applicable for very few simplified geometries → not very useful when real, complex, structures are considered and quantitative answers are needed
  - Useful to validate numerical tools and obtain physical intuition



Pill-box cavity

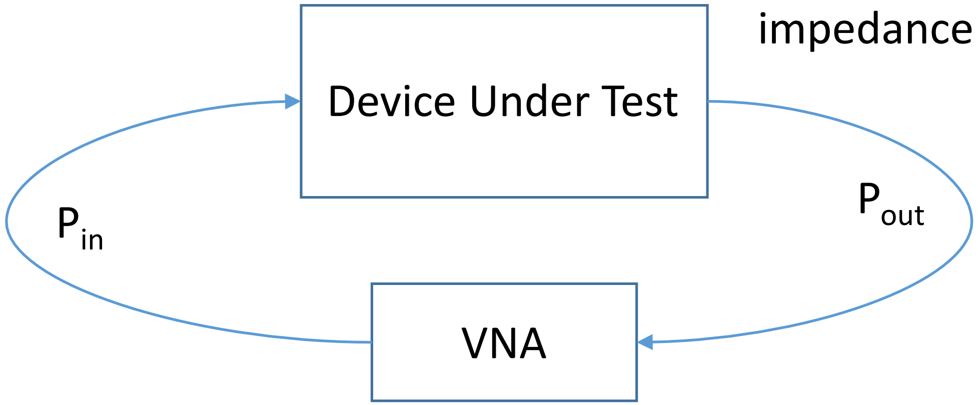


Tsutsui model

How to estimate impedances? (2/2)

- Numerical tools
  - Can model complex geometries, many types of materials
  - Physically reasonable approximations/simplifications are needed when creating the model
  - Don’t trust them blindly!
  - Results need to be validated whenever possible – e.g. back of the envelope calculations with simple analytical models, bench measurements

How to measure impedances?



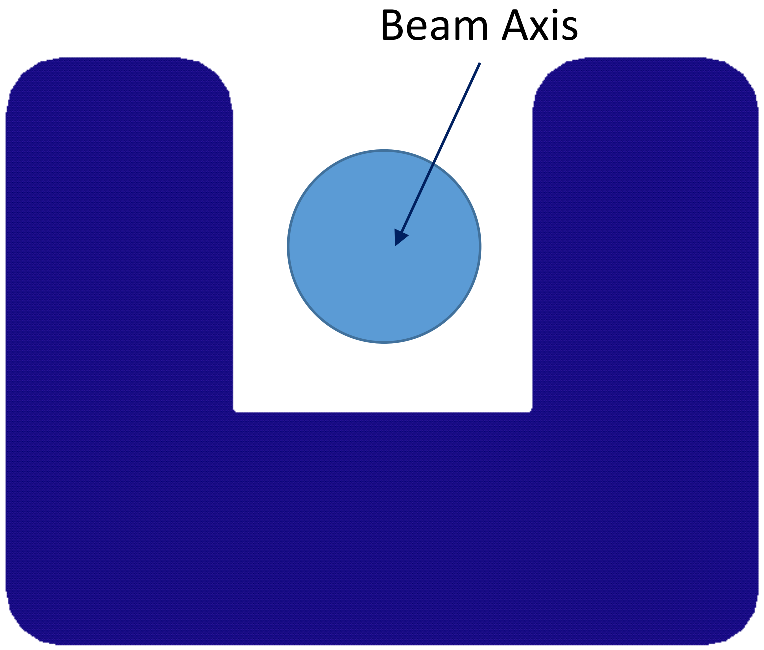
Losses in the system give information about its impedance

- Bench measurements
  - Several available methods
    - Classical Wire
    - Resonant
    - Probe
    - Bead pull
  - Interpretation formulas to convert measurement data to impedance values
  - Used in combination with simulation data to accurately characterise the component under consideration
- Beam based measurements: performed in dedicated runs to validate the total impedance model of an accelerator.

Mitigation Techniques

The unshielded kicker

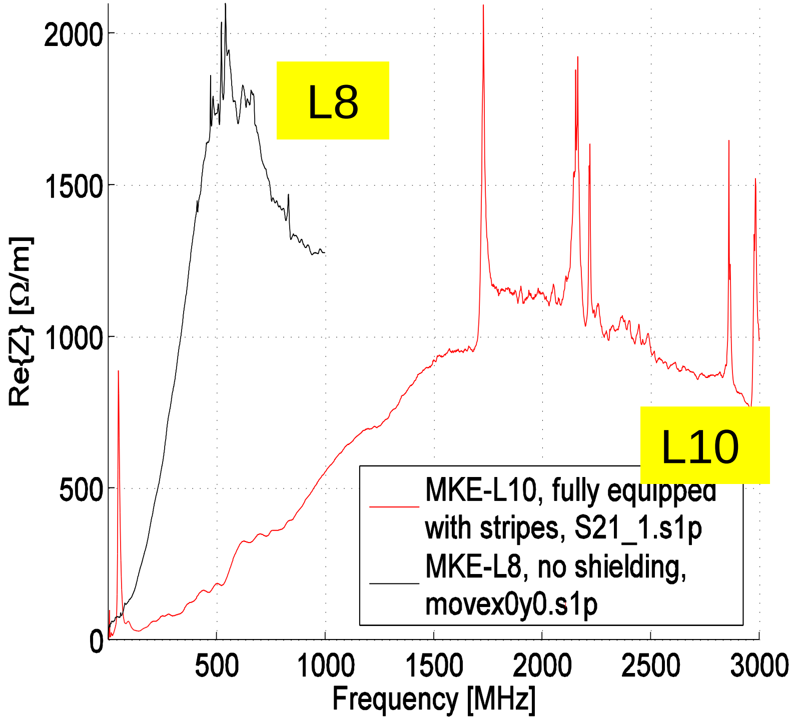
- The ferrite is directly exposed to the e/m field of the beam
- High RF losses → High temperatures in the yokes
- If ferrite is above its Curie temperature → possible long turn-around times -> reduces machine’s availability!
- We need to take measures!

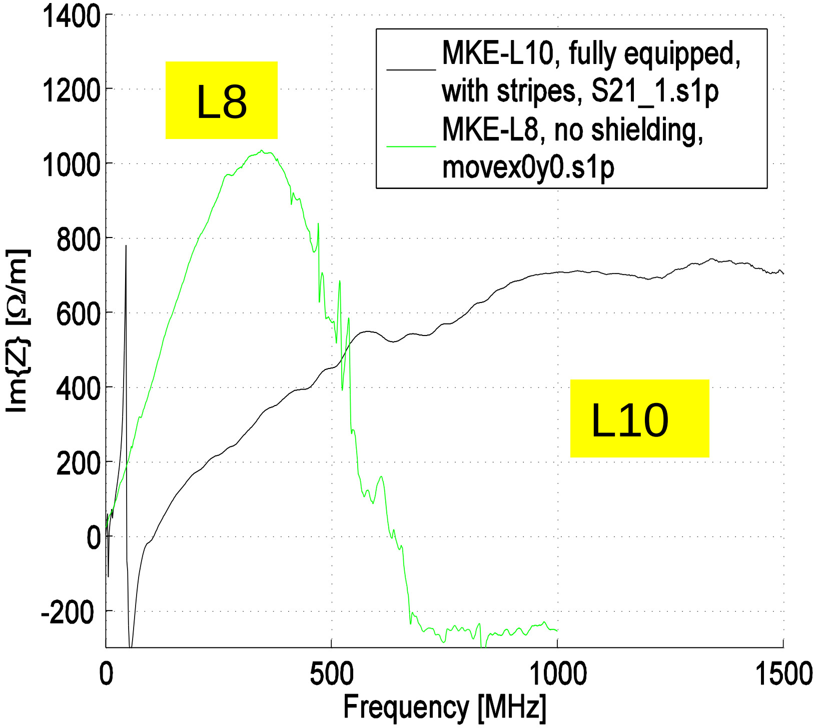


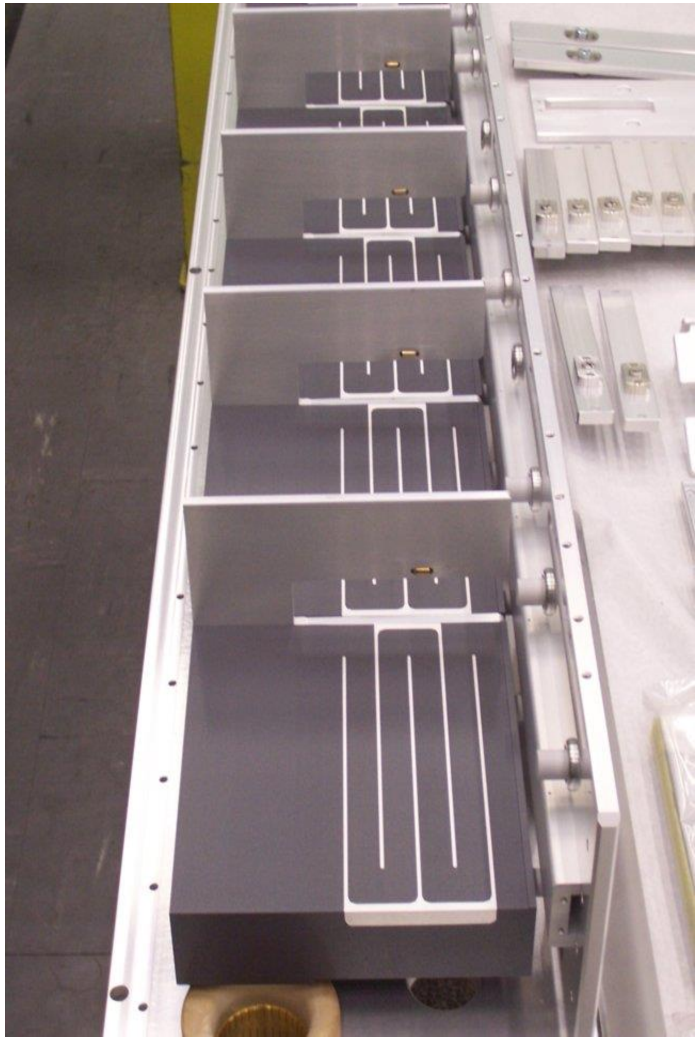
$$P_{Loss} = 2 * \overbrace{I_b^2}^{\text{Beam Parameters}} * \sum_{n=1}^{\infty} \left| \overbrace{\lambda_{beam}(n\omega_0)}^{\text{Beam Spectrum}} \right|^2 * \overbrace{Re\{Z_L(n\omega_0)\}}^{\text{(Real) Beam Coupling Impedance}}$$

Serigraphy – SPS Extraction Kicker (MKE)

- Comparison between the two extreme cases:
  - MKE-L8, without any serigraphy on ferrites;
  - MKE-L10, serigraphy on all seven ferrite cells.
- Significant reduction of real longitudinal beam-coupling impedance from serigraphy.
- Low frequency resonance directly linked to geometry of serigraphy (length of stripes).

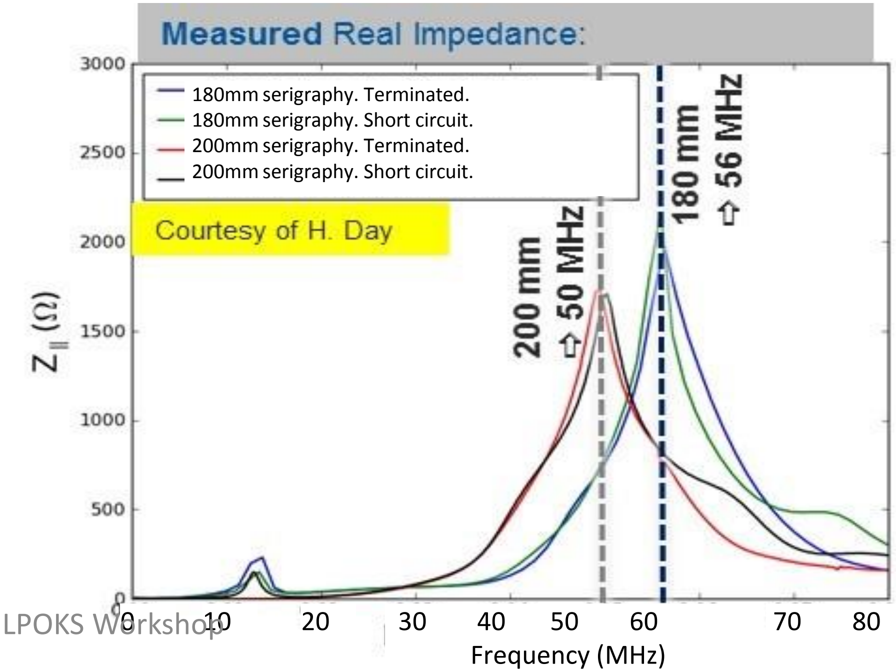

Real part of Z


Imaginary part of Z



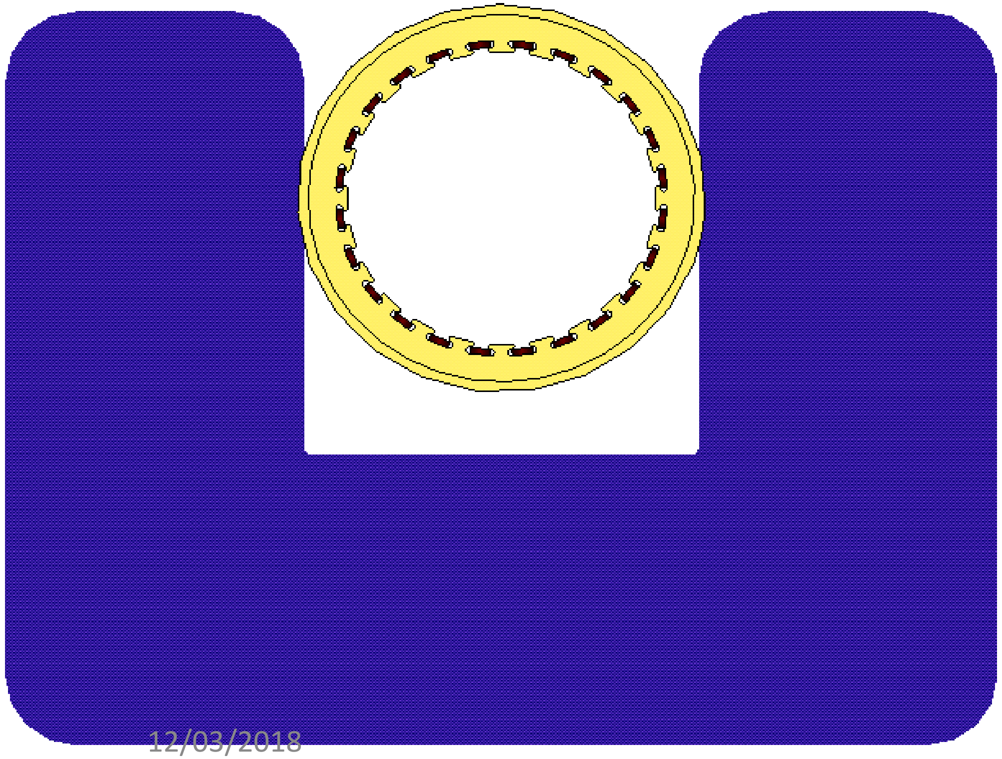
Serigraphy – Length optimization

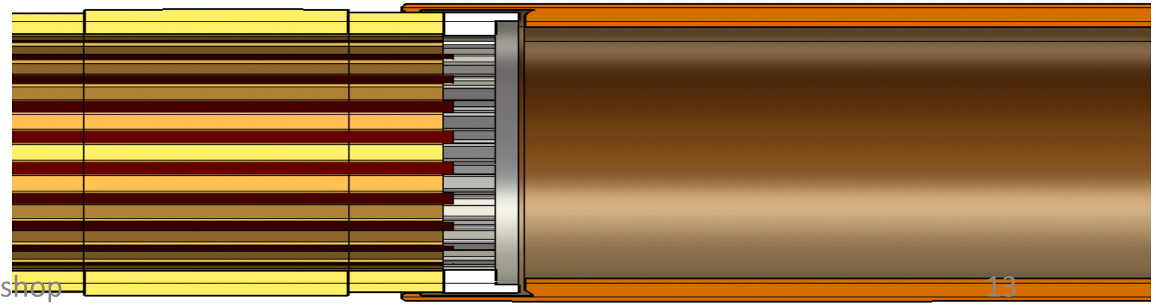
- Serigraphy increases the surface conductivity of the surroundings → reduced broadband impedance
- The conducting “fingers” act as λ/4 resonators
- High shunt impedance resonances can lead to high losses and beam instabilities
- Optimize length to shift resonance away from main beam harmonics (40MHz lines for 25ns bunch spacing)



The MKI beam screen

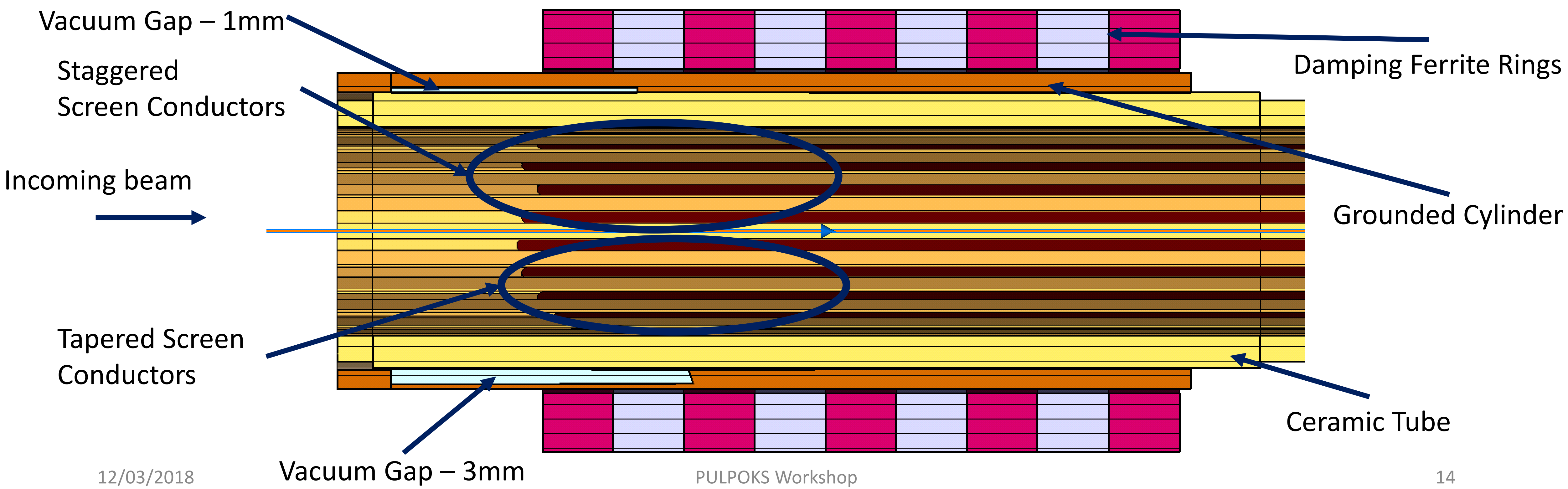
- Conducting wires, in the magnet aperture, along the length of the magnet
- Ceramic tube (Al_2O_3) for support
- Wires cannot be grounded at both ends → eddy currents would greatly increase the rise time
- Capacitive coupling to the ground at one end





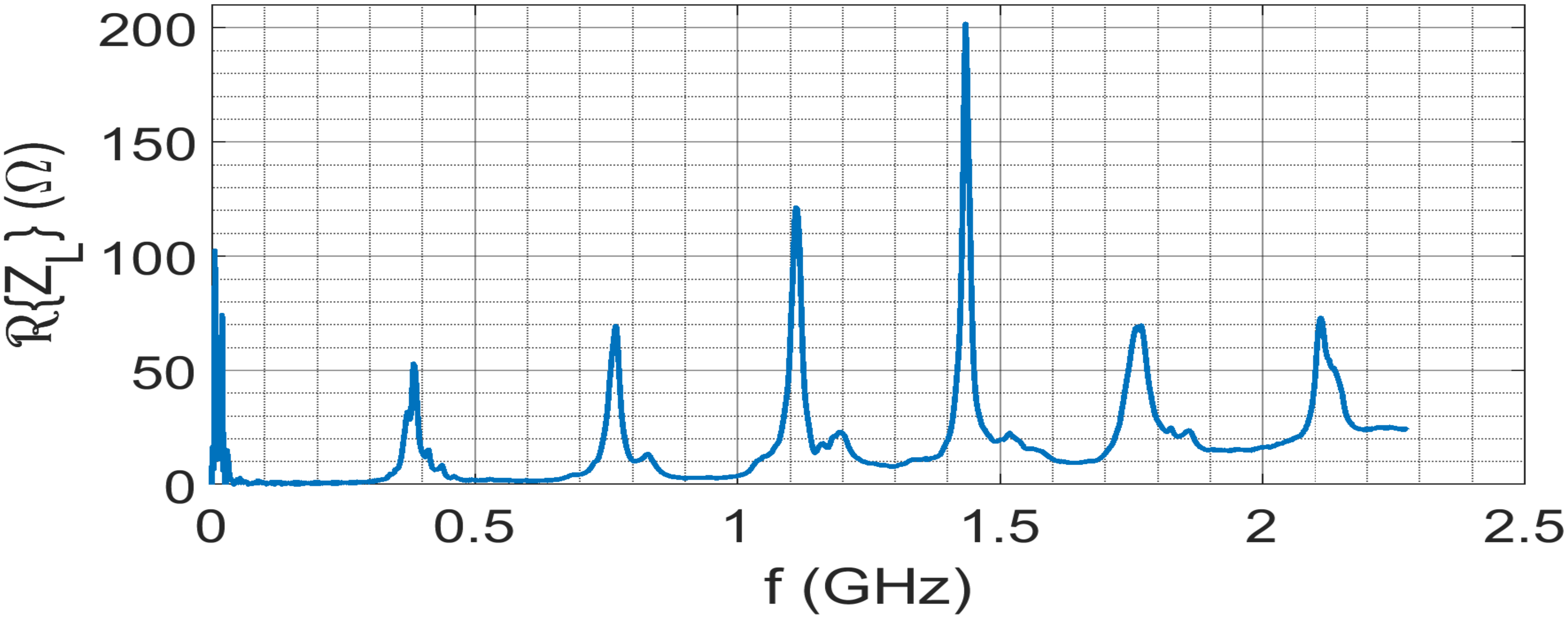
Close-up to the capacitive coupled end

- Design optimization: trade off between impedance and HV requirements
- Distance between end of screen conductors: upper half staggered, lower half tapered
- Vacuum gap between the screen conductors and the grounded cylinder: reduces electric field and thus the probability for a surface flashover
- Vacuum gap close to the HV plate (lower part) bigger (3mm vs 1mm) than the gap in the upper part – cannot be made too big because it degrades impedance
- Ferrite rings to damp low frequency modes: screen conductors act like λ/4 resonators



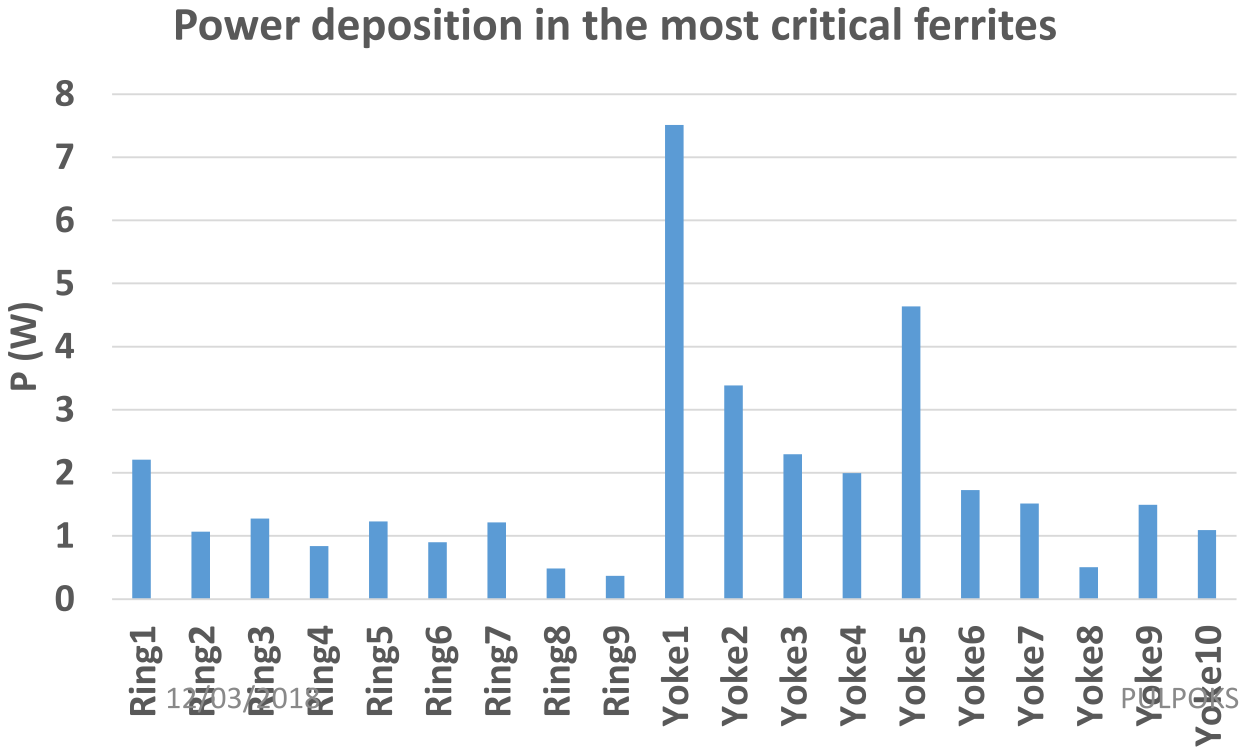
The MKI impedance

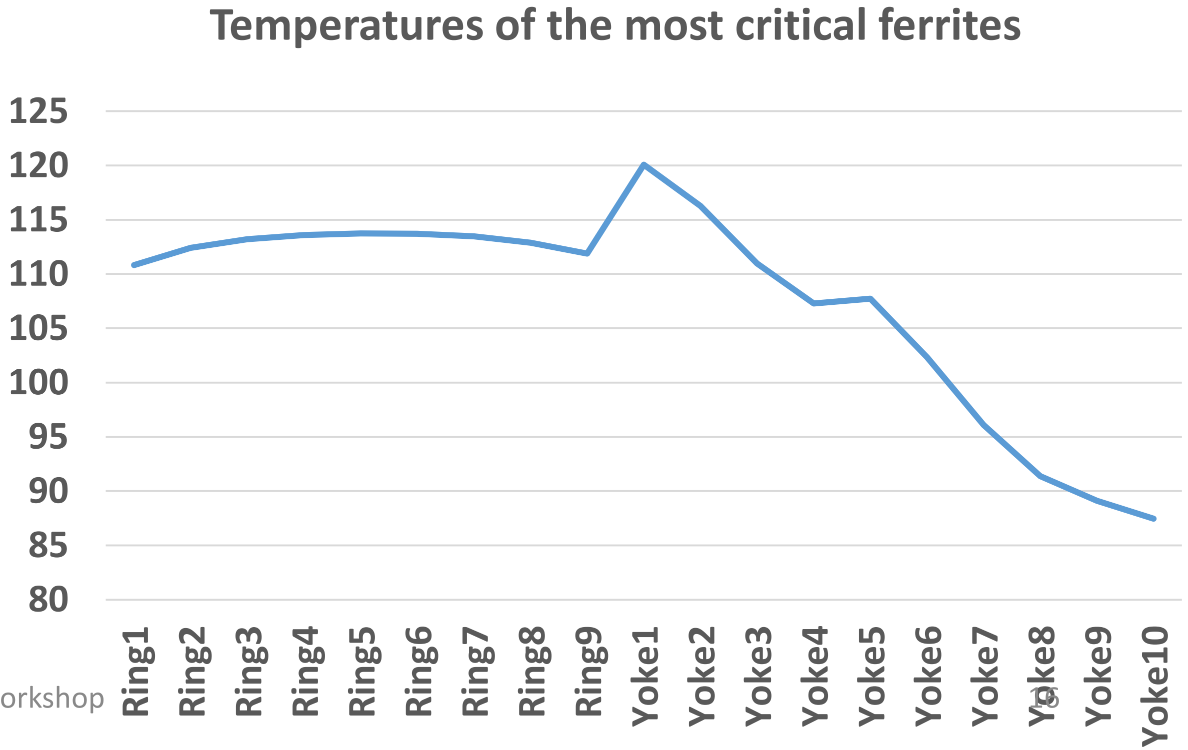
- The proposed shielding significantly reduce the MKI impedance
- Turned it from broadband to resonant
- This behaviour is attributed to the coaxial resonator that is formed at the upstream end



Temperatures in MKI

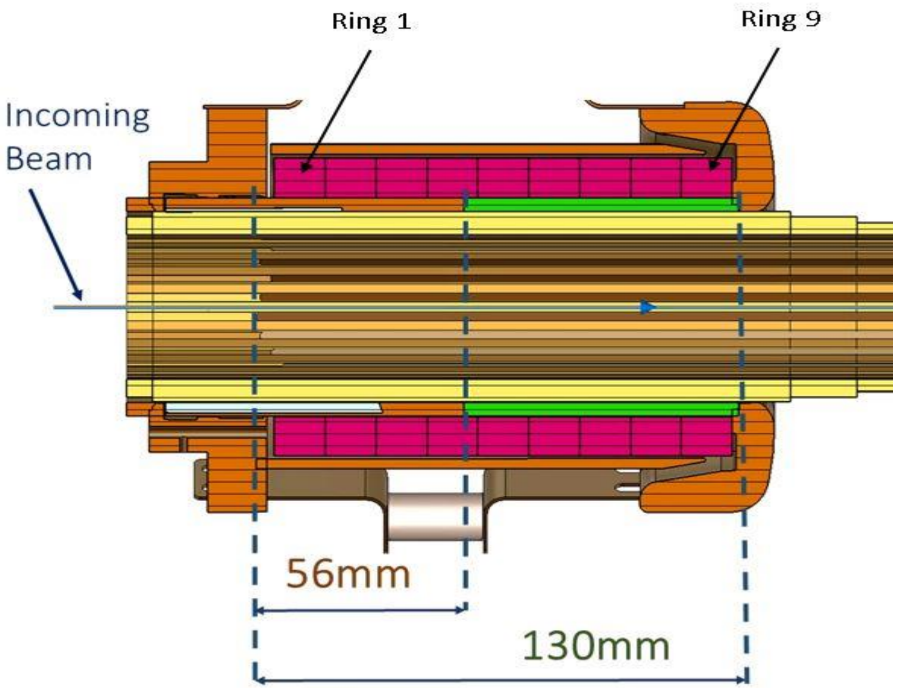
- Eventually temperatures are what matter for proper kick operation!
- Depends upon total power loss and its distribution along the magnet
- Our approach
  - Impedance (e/m) simulations + post processing → power loss deposition
  - Power loss deposition + thermal simulations → temperature distribution along the magnet
  - Steady state estimations (i.e. long physics fills)

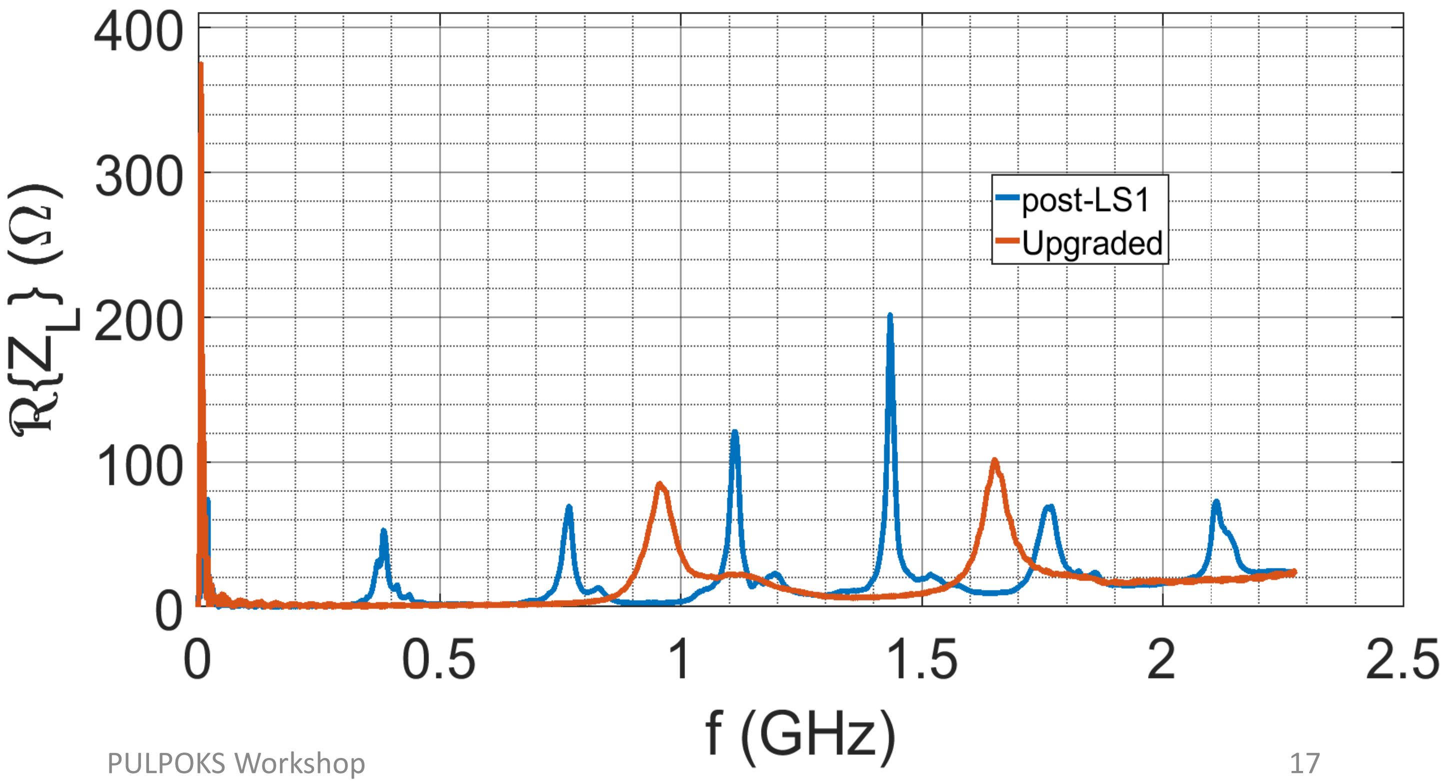




Further impedance mitigation - Approach

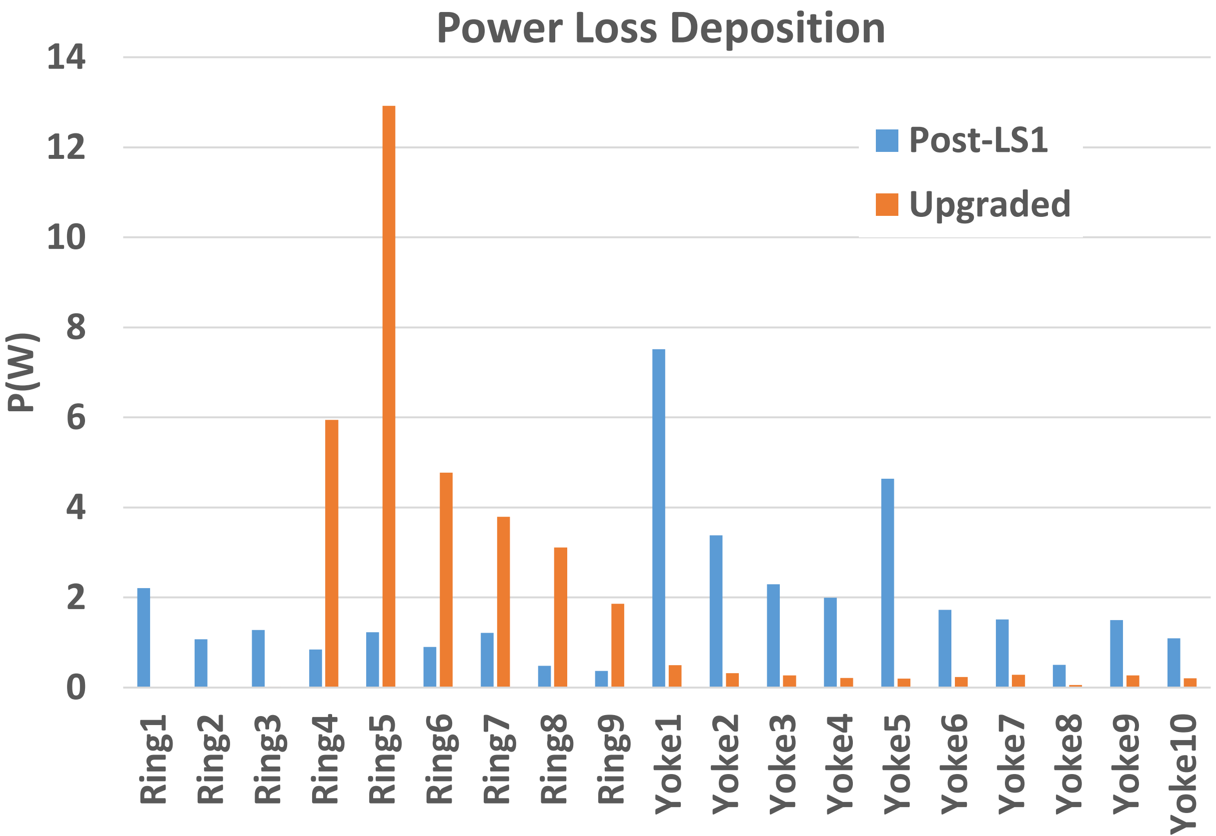
- Key point: beam power spectrum decreases with infrequency frequency
- Resonator length ↓ → Impedance peaks ↑ in frequency → lower losses
- Changes at capacitively coupled end led to relocation of power loss deposition to more easily cooled parts

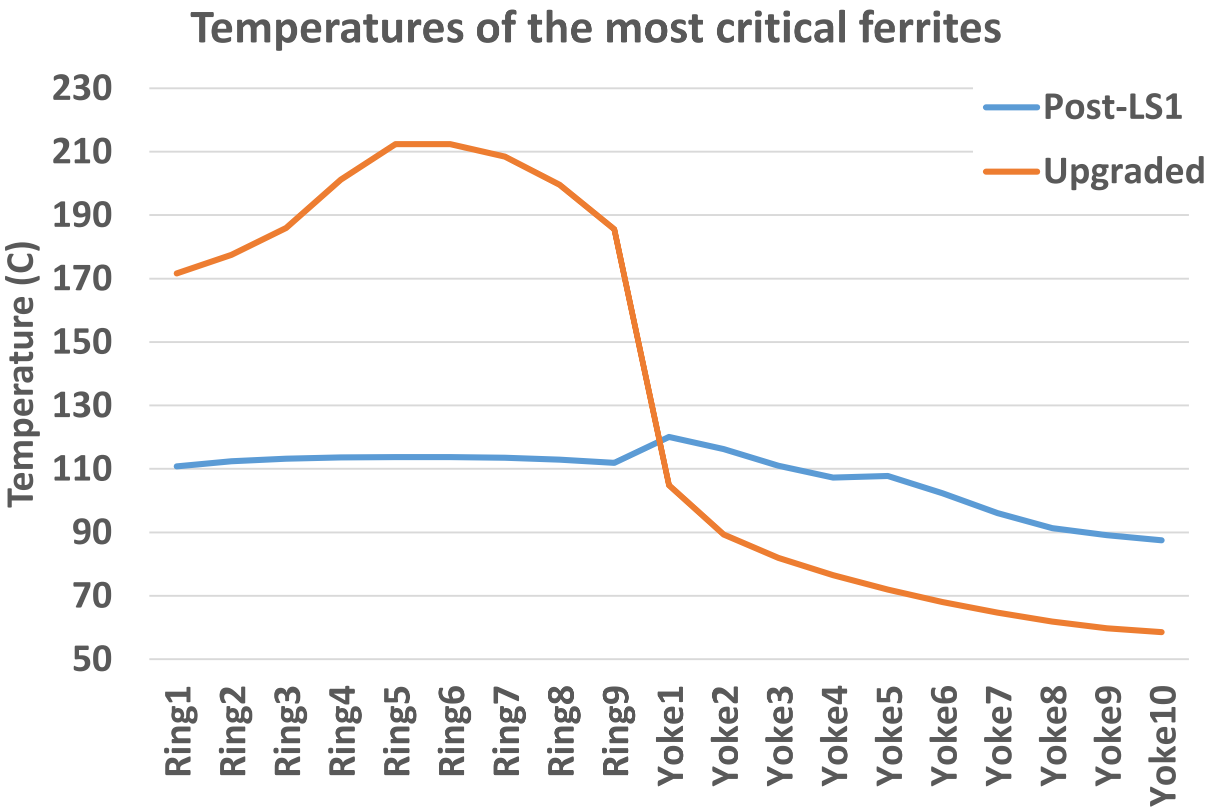




Power loss relocation

- With the modified design, losses are primarily concentrated in the ferrite rings
- “Direct” heat deposition in the yokes is reduced, but yokes are now heated more by the heat conduction from the rings
- Rings are not at HV and a cooling system can be installed more easily, if necessary (HL-LHC)





Conclusions

- Impedance is an important parameter of every component of a synchrotron close to the beam
- It can affect the equipment (heating), the beam quality and eventually the overall accelerator performance (emittance growth, intensity limitations, machine availability etc.)
- Powerful simulation tools and measurement techniques are available
- Many clever ways to improve existing components if necessary, but…
- It is important that impedance is taken into account early in the design process!

Thank you for your attention!