

Sensitivity of CLIC and the ILC to Stray Magnetic Fields and Mitigation with Passive Shielding

C. Gohil

CERN, Geneva, Switzerland

Acknowledgements:

N. Blaskovic Kraljevic, B. Heilig, D. Schulte, P. N. Burrows

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Contents

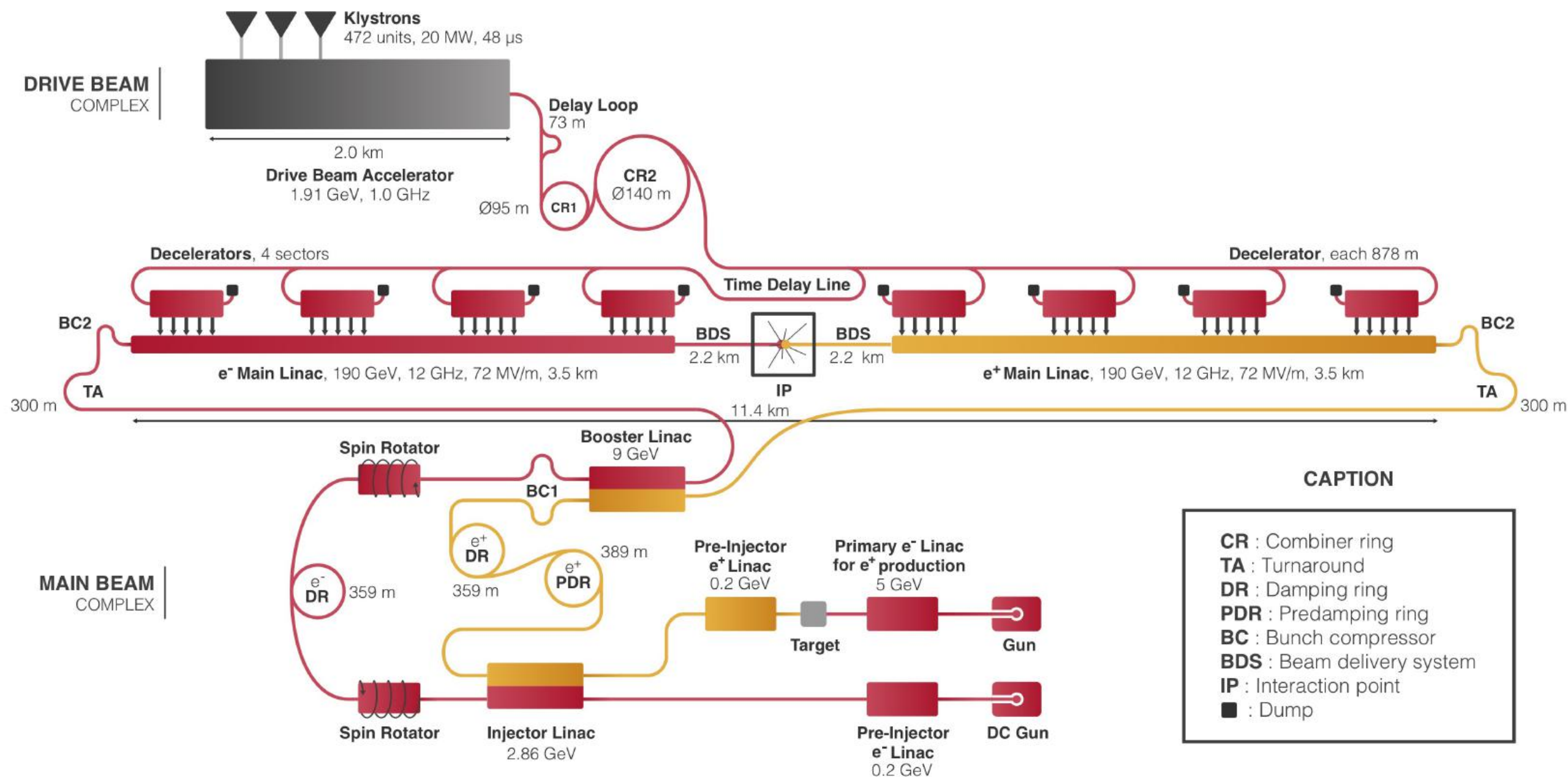
- Stray Magnetic Field Tolerances:
 - CLIC
 - ILC
- Passive Shielding
 - Shielding Mechanisms
 - Low Amplitude Magnetic Fields
 - Measurements
 - Iron
 - Mu-Metal
- Conclusions

Stray Magnetic Field Tolerances

Stray Field Tolerances

- Simulations were performed with PLACET.
- A grid of dipoles was inserted in to the lattice.
 - Dipole spacing was 1 m.
- Dipoles exerted the integrated kick over the 1 m spacing from the stray field.
- The dipoles kick the beam vertically.
- Tolerances calculated as the the amplitude that results in 4% emittance growth of the end of the section.
 - This is equivalent to 2% luminosity loss.
- 1.2 nm emittance growth budget in CLIC, 1.4 nm emittance growth budget in the ILC.

CLIC at 380 GeV



CLIC Stray Field Tolerances

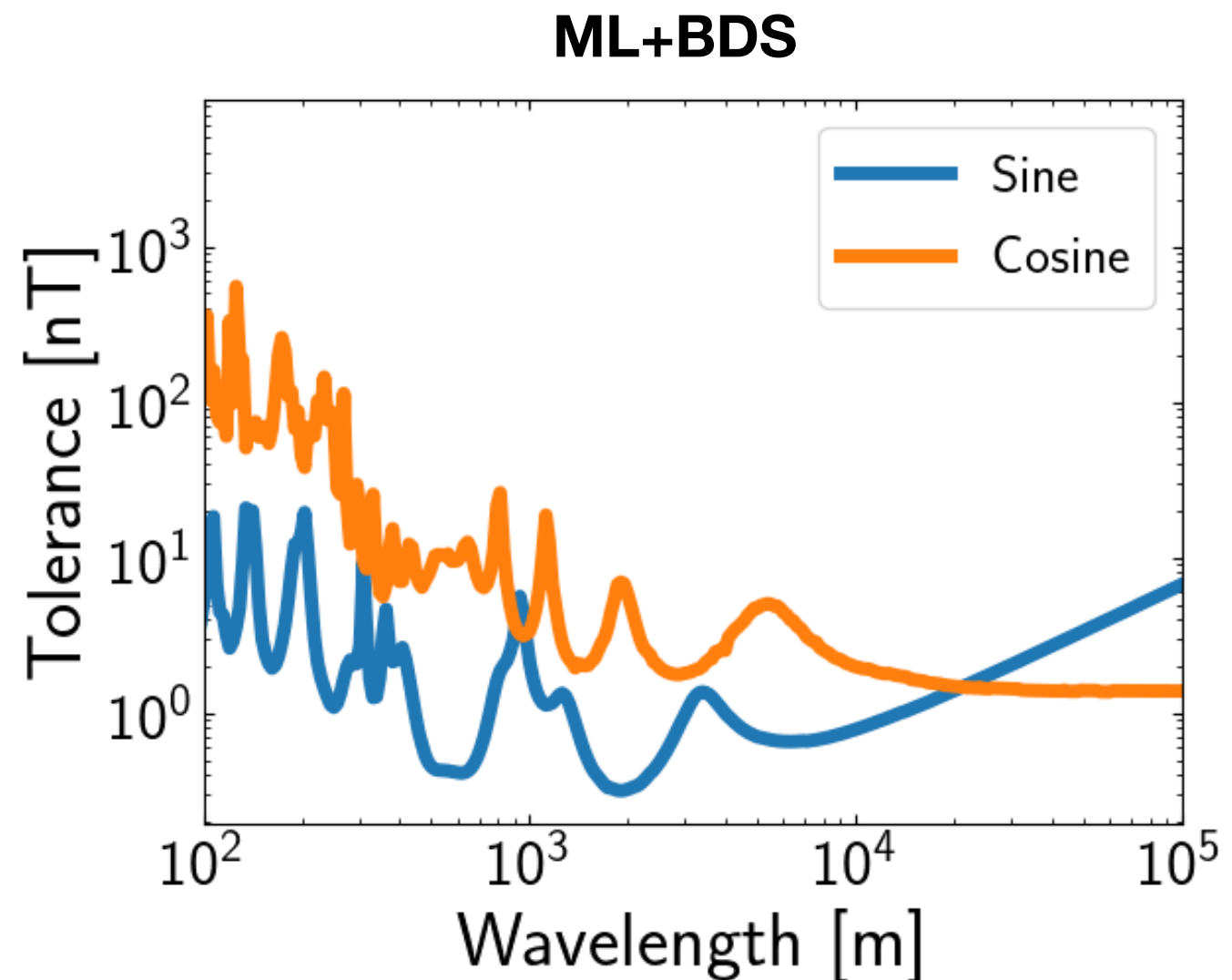
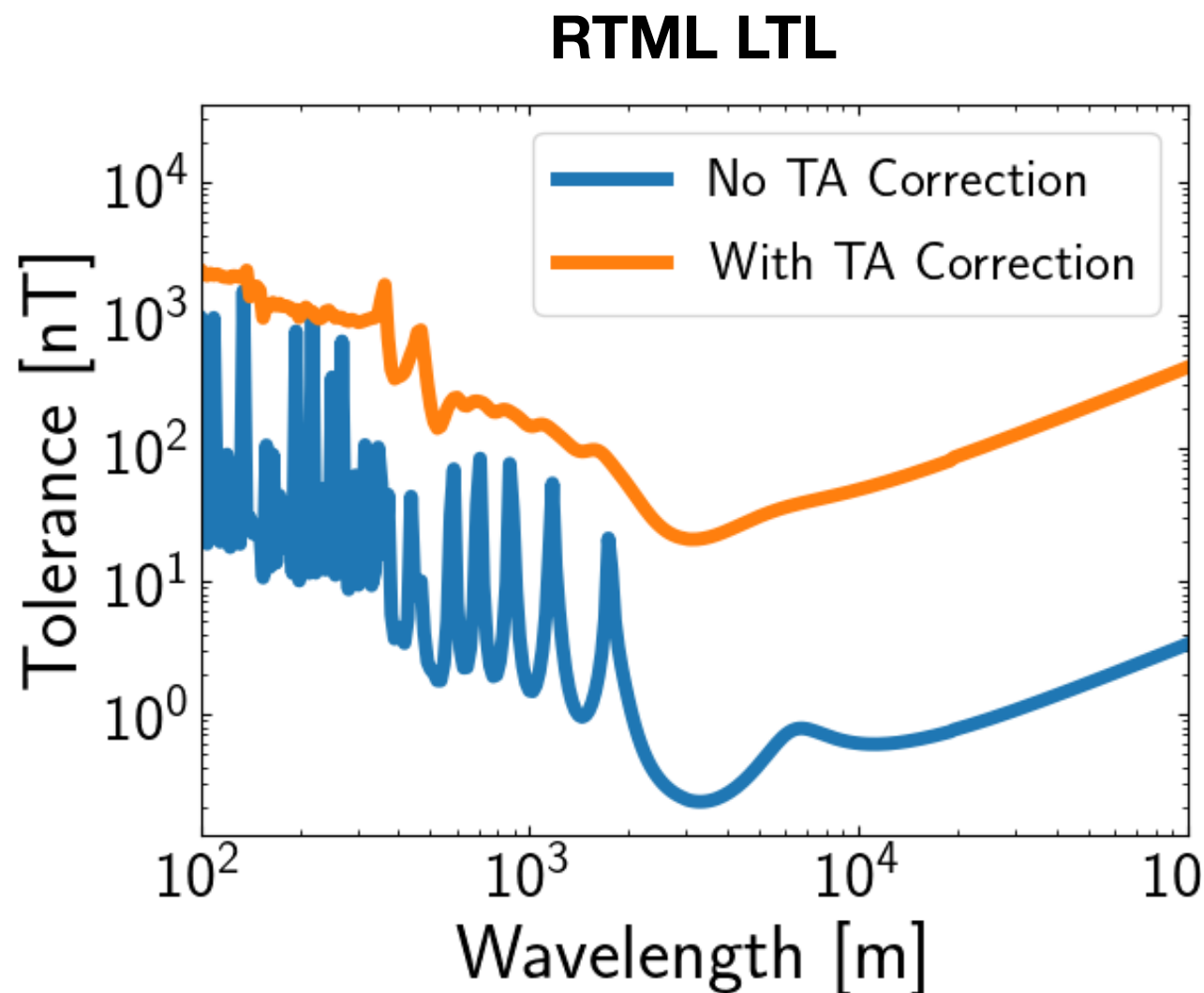
- Homogeneous spatial distribution:

	Tolerance [nT]
Long Transfer Line	27
Main Linac	540
Beam Delivery System	1.3

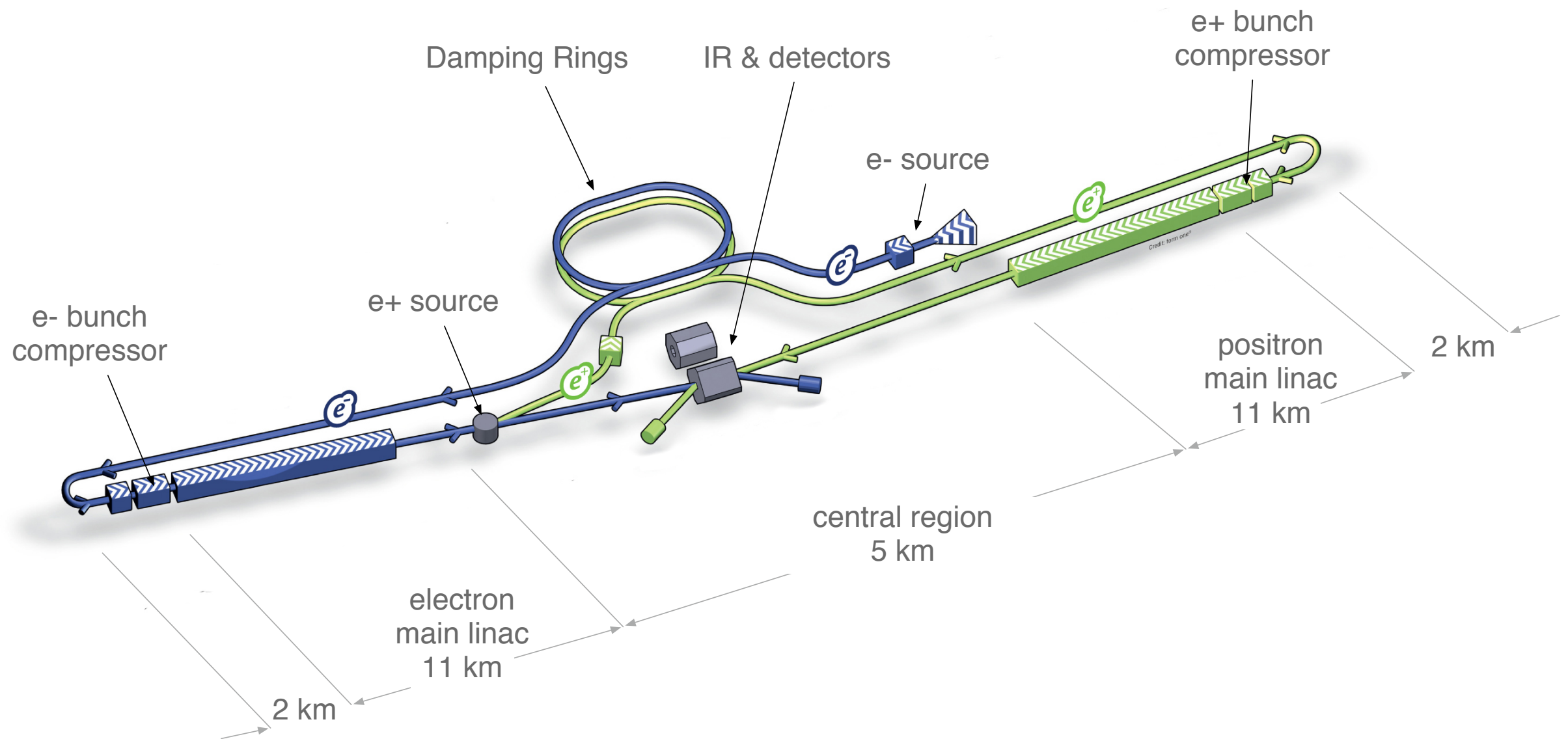
- Tightest tolerance **O(1 nT)** in the BDS.
- ML is the least sensitive.

CLIC Stray Field Tolerances

- Sinusoidal spatial distribution:



ILC



- Superconducting cavities in the ML shield the beam from stray fields.

ILC Stray Field Tolerances

- Technical Design Report:

7.4.2 Stray Fields

Studies have found that fields at the level of 2.0 nT can lead to beam jitter at the level of $0.2\sigma_y$ [142]. This is considered acceptable since the orbit feed-forward corrects most of this beam motion. Measurements [143] indicate that 2 nT is a reasonable estimate for the stray-field magnitude in the ILC. Emittance-growth considerations also place limits on the acceptable stray fields, but these are significantly higher.

ILC Stray Field Tolerances

- K. Kubo, “Rough Estimation of Effects of Fast-Changing Stray Field in Long Transport of RTML”, ILC-NOTE-2007-008, ILC-Asia-2006-06A:
 - White noise stray field in the RTML.
 - Tolerance for $0.2\sigma_y$ beam jitter (2% luminosity loss):
 - $B_{RMS} = \mathbf{2\ nT}$ without feed-forward correction.
 - $B_{RMS} = \mathbf{7.5\ nT}$ with feed-foward correction.

ILC Stray Field Tolerances

- J. Frisch, et al., “Sensitivity to Nano-Tesla scale stray magnetic fields”, SLAC-TN-04-041 (2004):
- NLC BDS:
 - Homogeneous stray field tolerance for $0.5\sigma_y^*$ beam jitter:
 - **$B = 8.7$ nT.**
 - Sinusoidal stray field at worst wavelength (790 m) tolerance for $0.5\sigma_y^*$ beam jitter:
 - **$B = 0.5$ nT.**

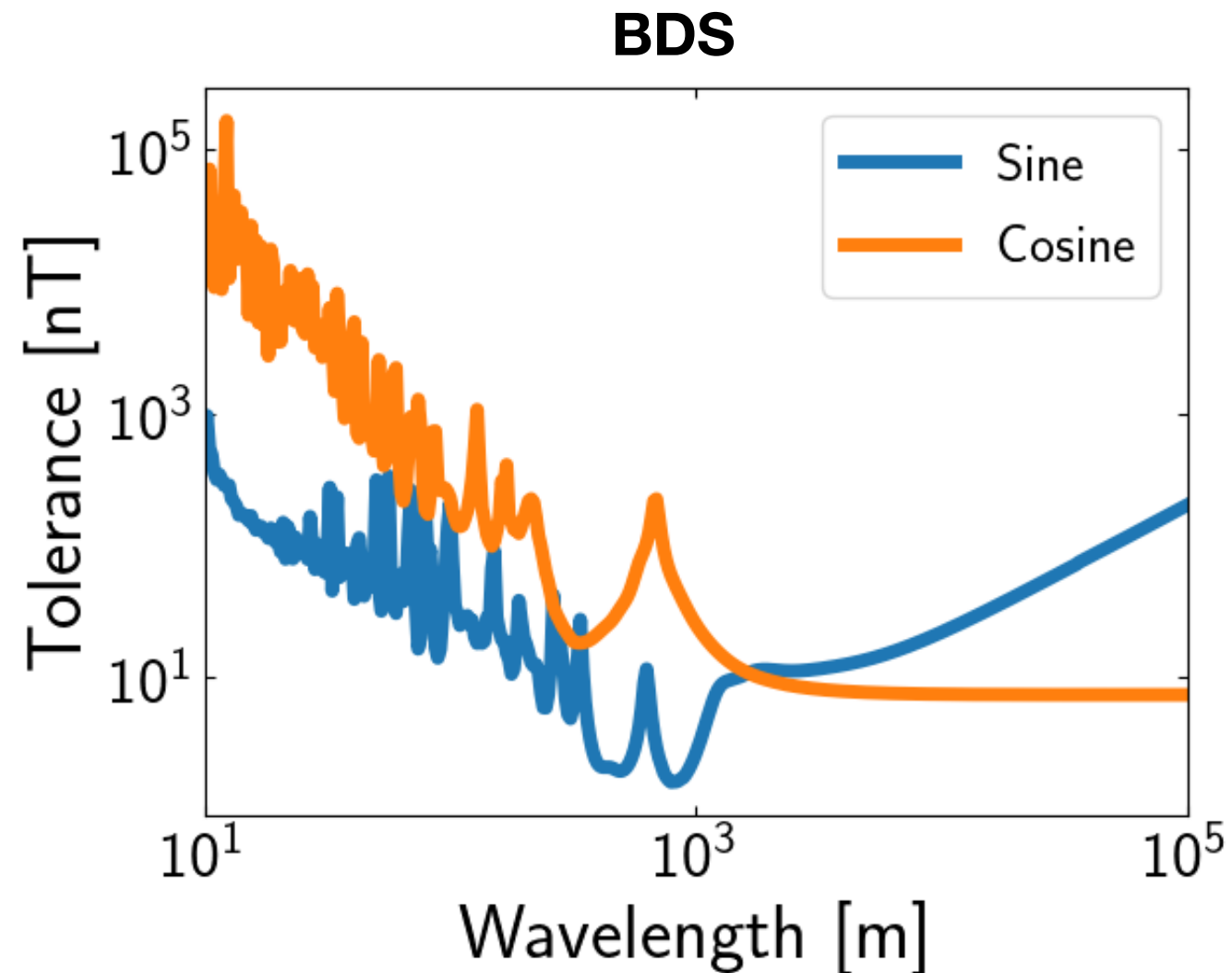
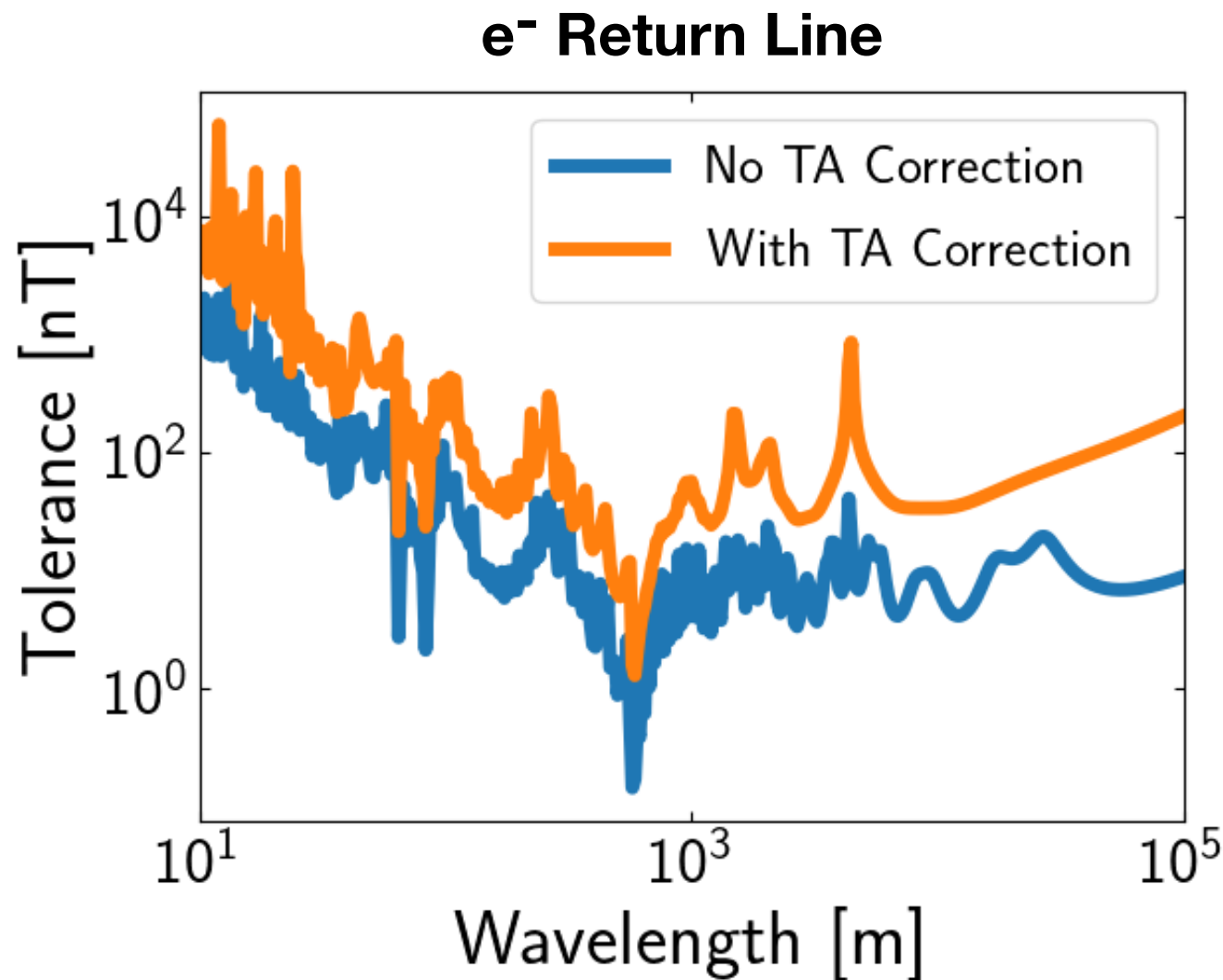
ILC Stray Field Tolerances

- Previous tolerances were calculated analytically.
- Using an ILC (500 GeV) simulation in PLACET:
 - Homogeneous spatial distribution:

	Tolerance [nT]
e⁻ Return Line	31
Beam Delivery System	7.3

ILC Stray Field Tolerances

- Sinusoidal spatial distribution:

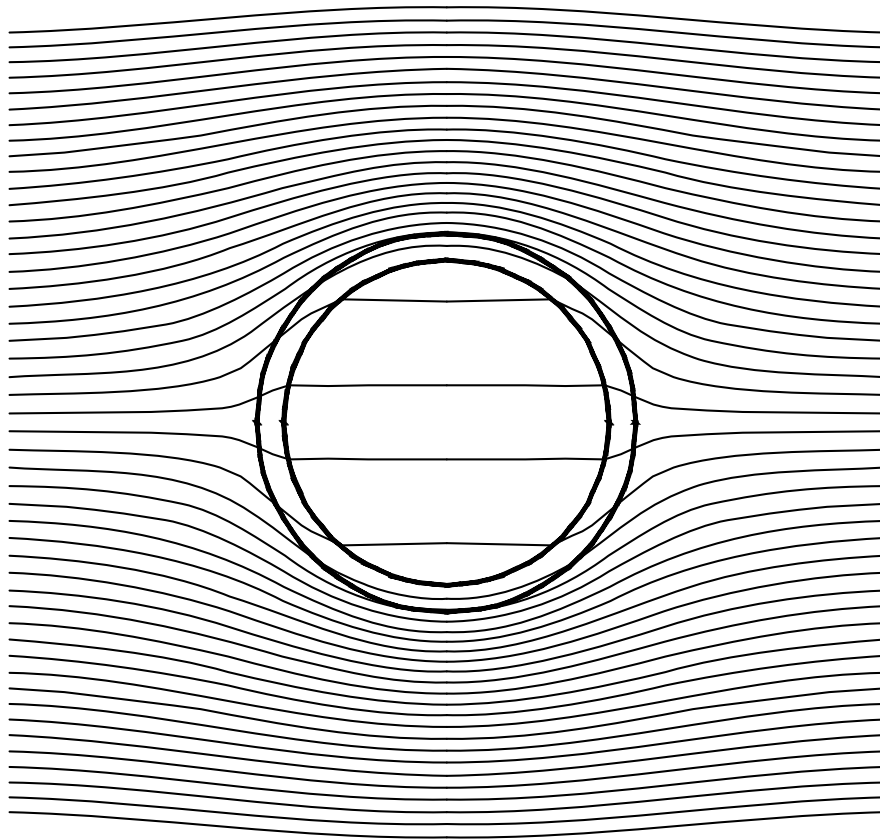


Stray Field Measurements

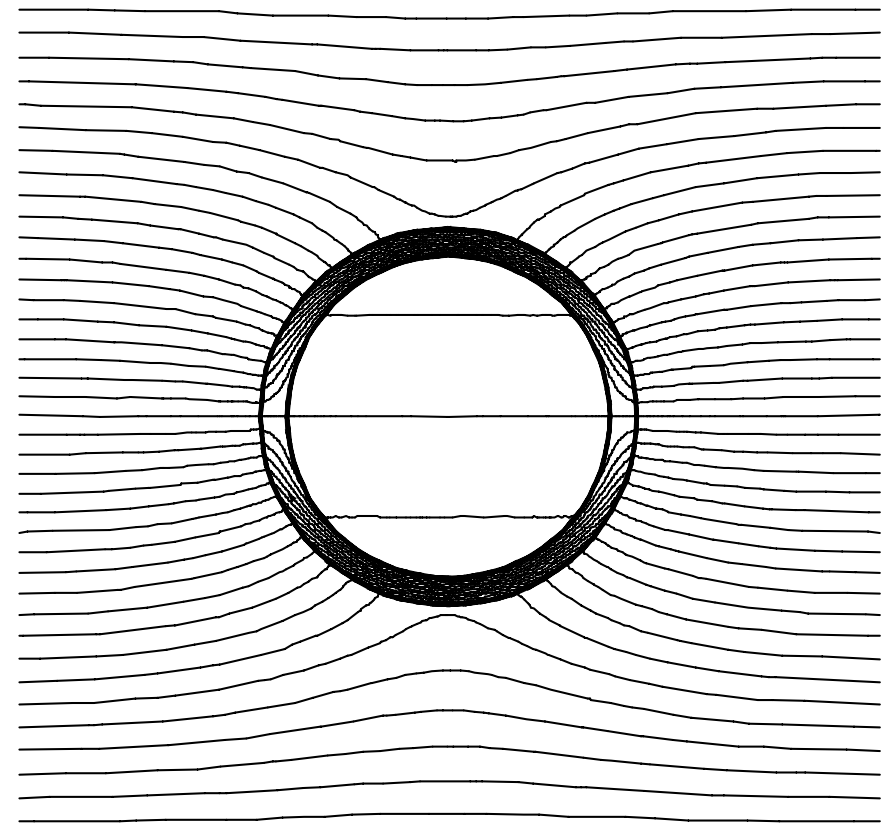
- Both CLIC and the ILC have nT sensitivities:
 - CLIC: $O(0.1 \text{ nT})$
 - ILC: $O(1 \text{ nT})$
- What is the expected level of stray fields to be experienced by the beam?
 - Need to know both the temporal and spatial variation.
 - **Another talk: “Measurements to Characterise Stray Magnetic Fields for CLIC”.**
 - Typical ambient magnetic fields measured in accelerator environments is $O(100 \text{ nT})$.
 - Mitigation will be needed!
- Assuming the worst, is it possible to shield stray fields to a 0.1 nT level?

Passive Shielding

Magnetic Shielding Mechanisms



Flux-Shunting

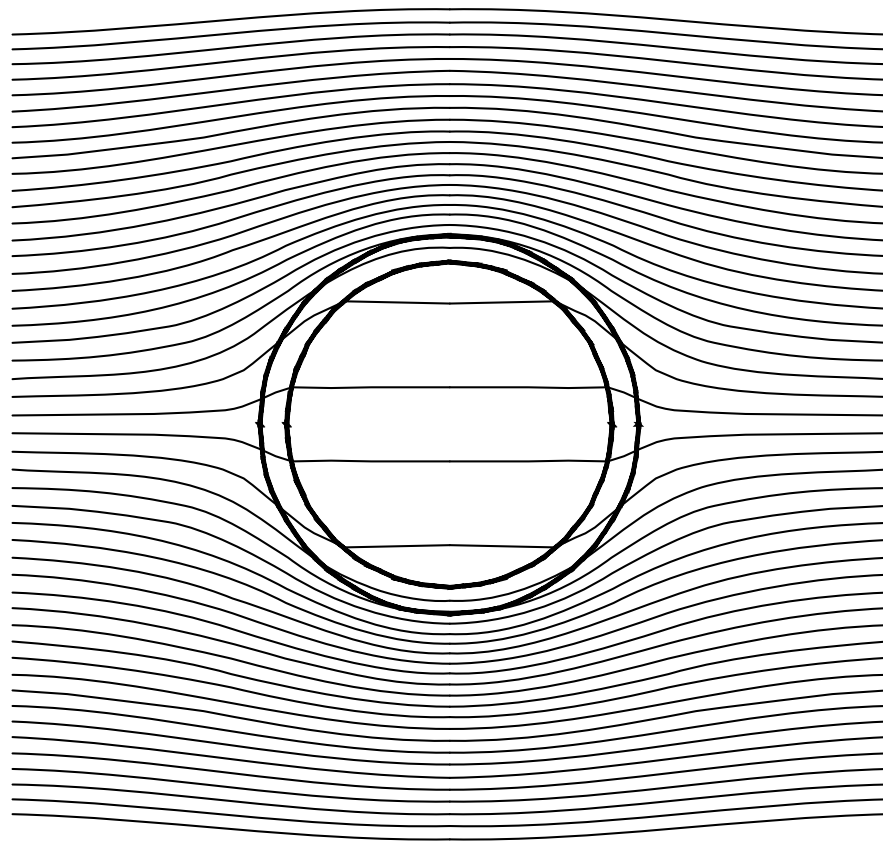


Eddy-Current Cancellation

Magnetic Shielding Mechanisms

- Which of the mechanisms is dominant depends on:
 - Material properties:
 - Electrical conductivity
 - Magnetic permeability
 - Properties of the external magnetic field:
 - Frequency
 - Amplitude - implicitly through the permeability
- Shielding factor also depends on the shield geometry: radius and thickness.

Shielding Low Amplitude Magnetic Fields



Flux-Shunting

- Low frequency shielding can only occur via flux-shunting.
- Relies on reorienting magnetic dipoles in the material:
 - Is there a minimum amplitude threshold?
- Low amplitude behaviour implicit through the permeability, μ .

Shielding Low Amplitude Magnetic Fields

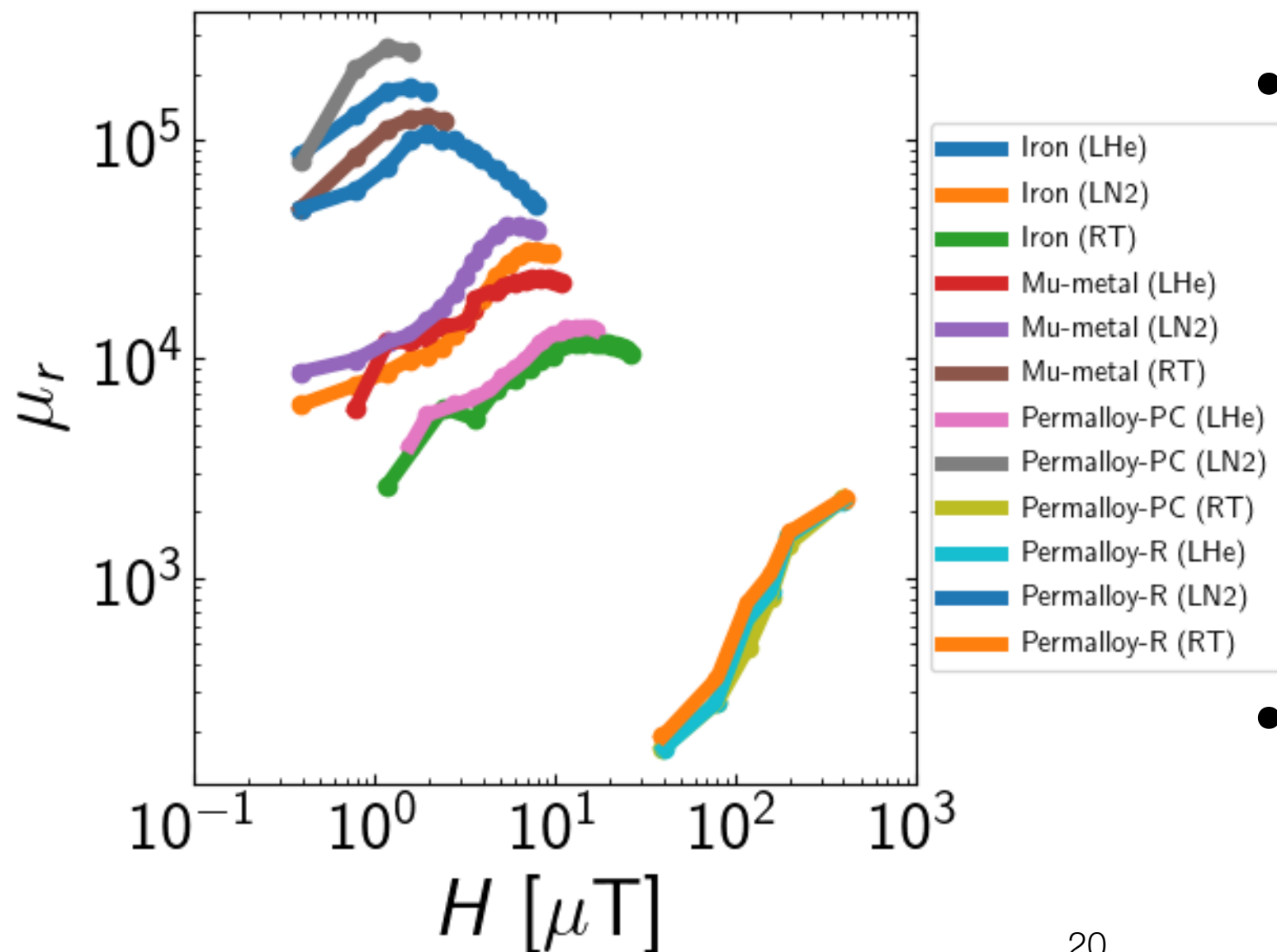
- The behaviour of μ for low amplitude magnetic fields is governed by Rayleigh's law:

$$\mu(H) = \mu_i + \nu H$$

- The permeability tends to the initial permeability, μ_i , for low amplitude fields.
- c.f. B. D. Cullity, C. D. Graham, "Introduction to Magnetic Materials", John Wiley & Sons, 2011.

Shielding Low Amplitude Magnetic Fields

- Decreasing permeability observed by others working on magnetic shielding for accelerator applications:



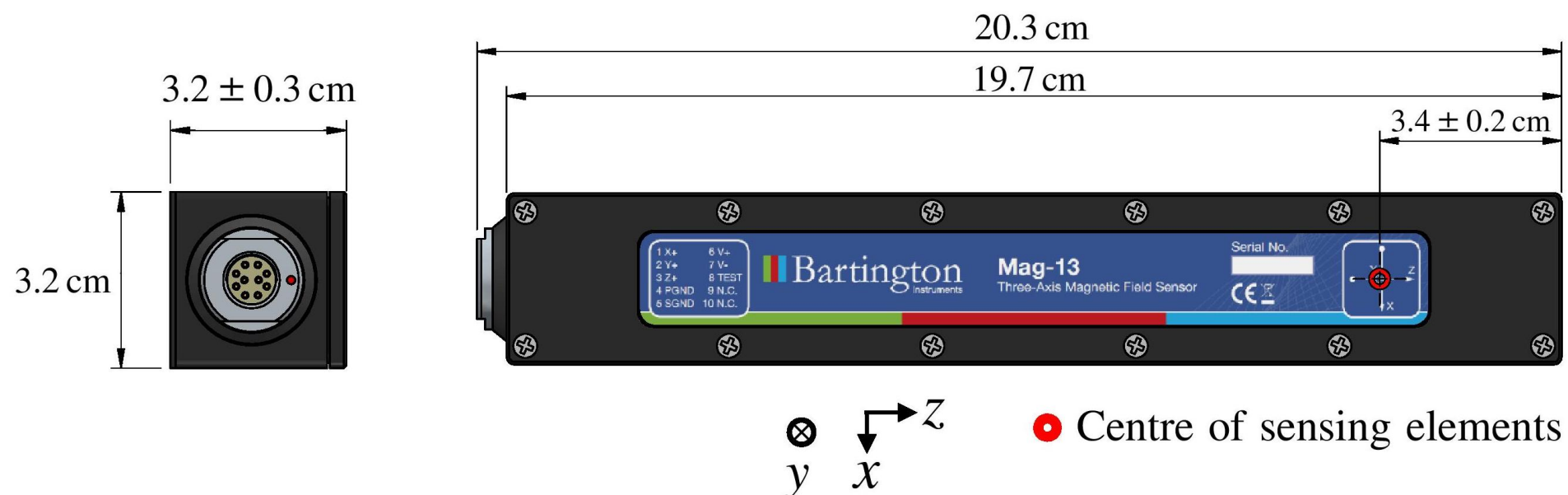
- K. Tsuchiya, et al., “Cryomodule Development For Superconducting RF Test Facility at KEK”, Proc. EPAC’2006.
- Need measurements at lower fields.

Shielding Measurements

- Two cylinders made of different materials were tested:
 - Soft iron.
 - Mu-metal.
- Cylinder geometry:
 - Inner diameter = 5 cm
 - Thickness = 1 mm
 - Length = 0.5 m

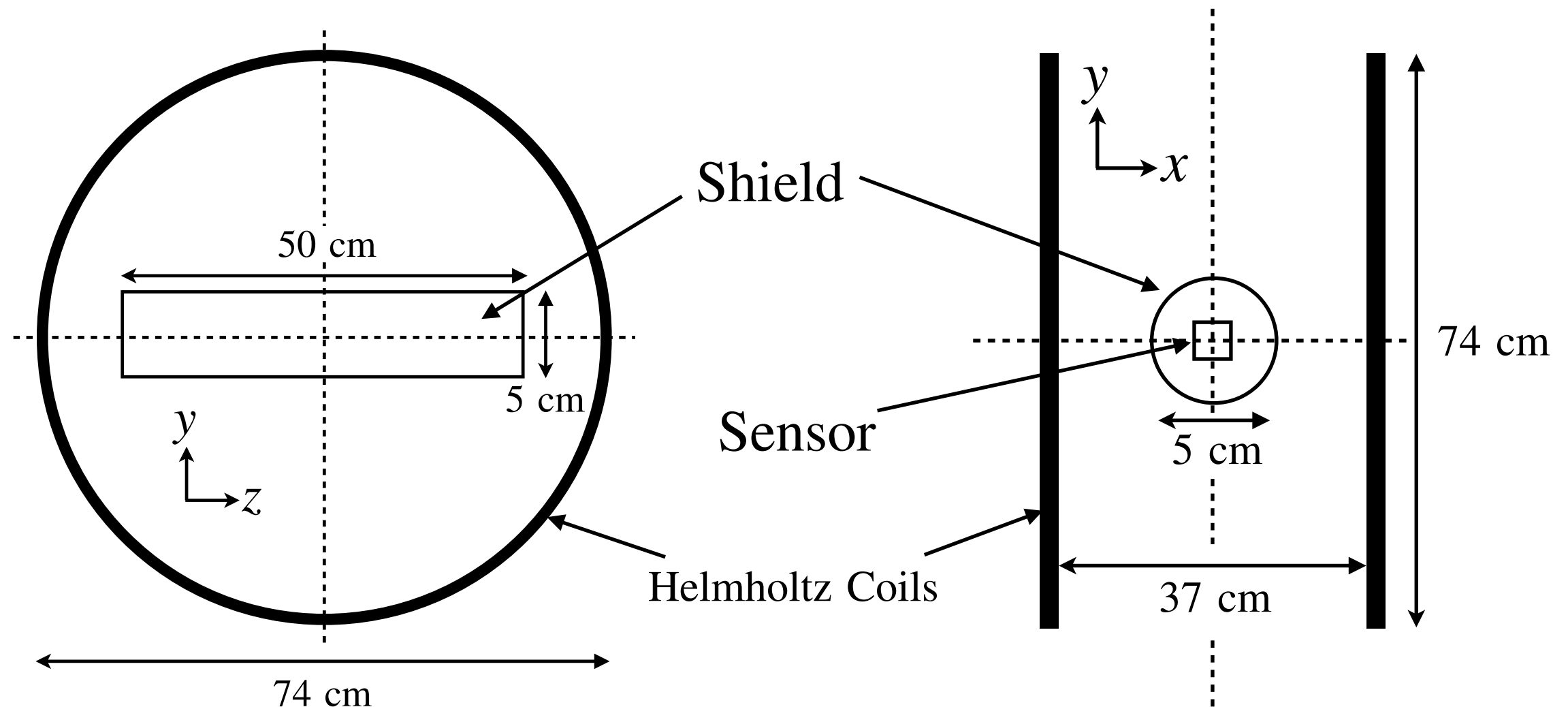
Magnetic Field Sensor

- Mag-13 sensor produced by Bartington Instruments, UK:
 - Frequency range: DC-3 kHz
 - Noise at 1 Hz: 7 pT/ $\sqrt{\text{Hz}}$
- ± 0.5 V 24-bit National Instruments DAQ (NI 9238).



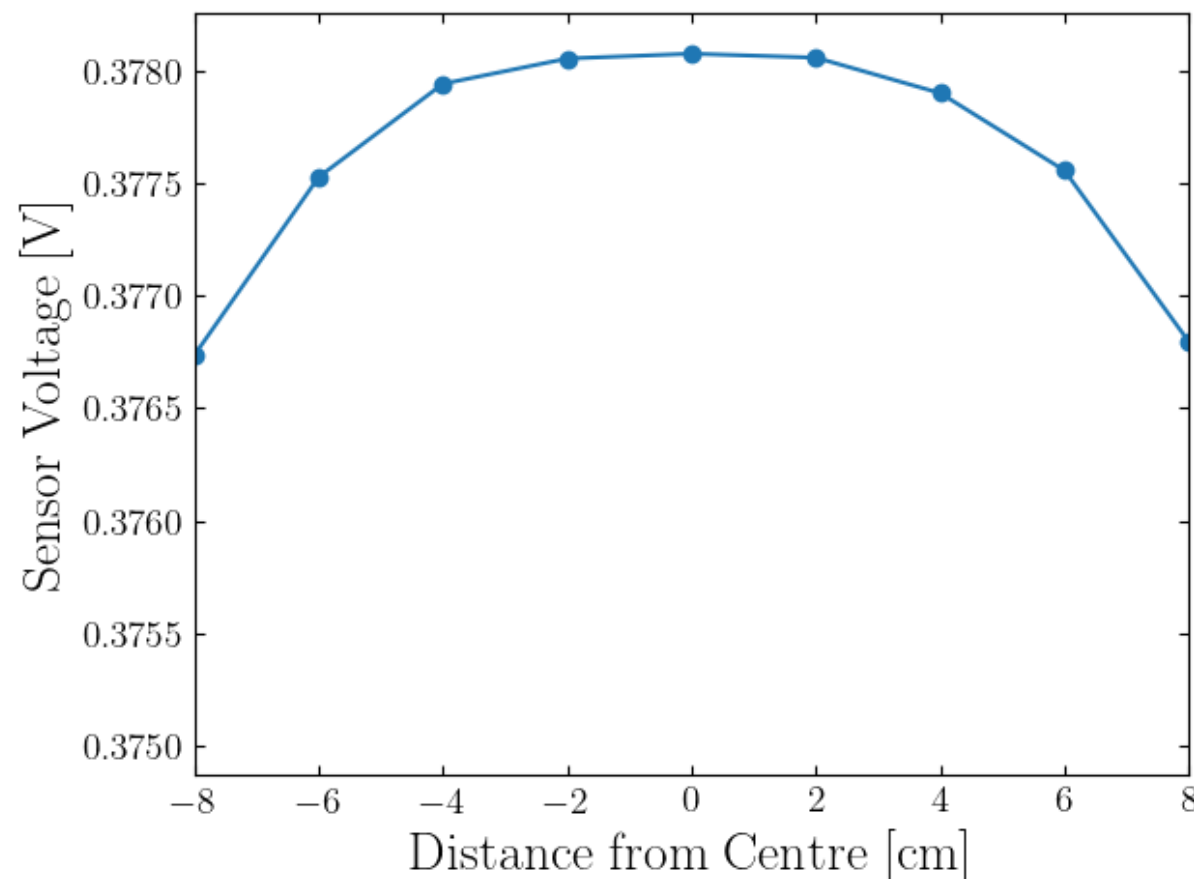
Measurement Setup

- Measurements were performed with a set of Helmholtz coils:



Measurement Setup

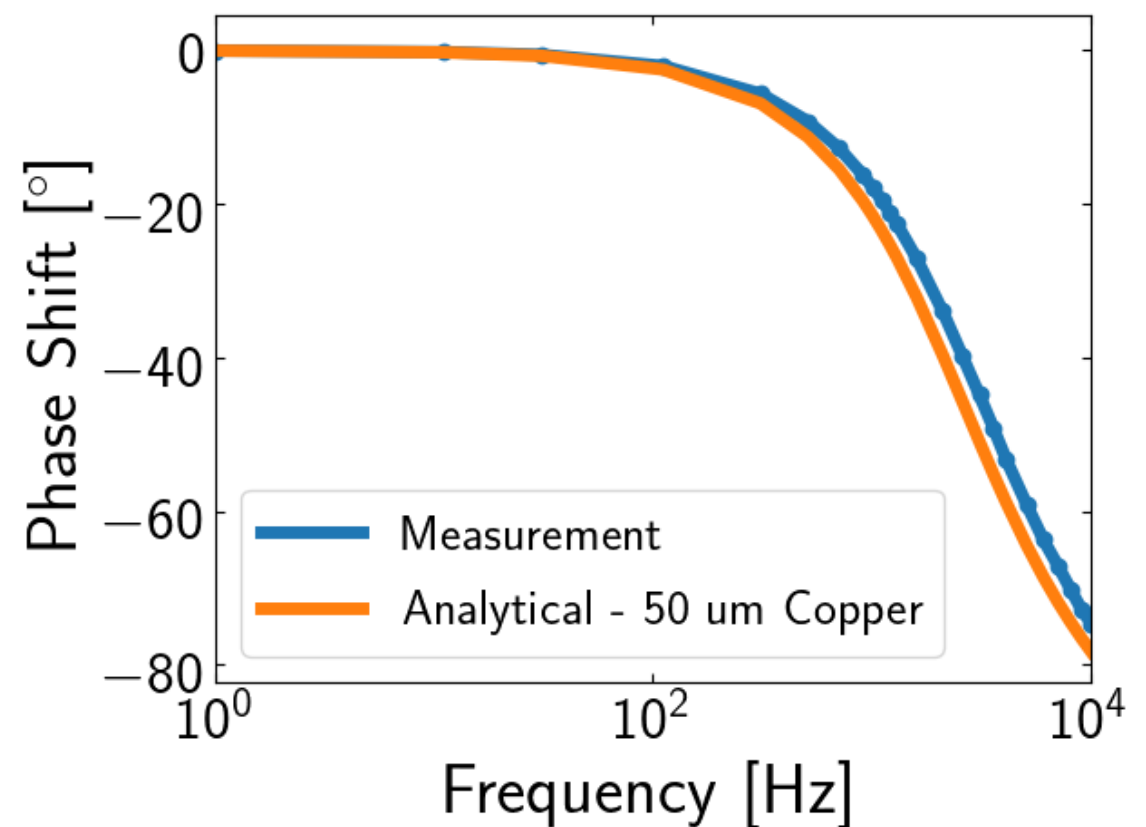
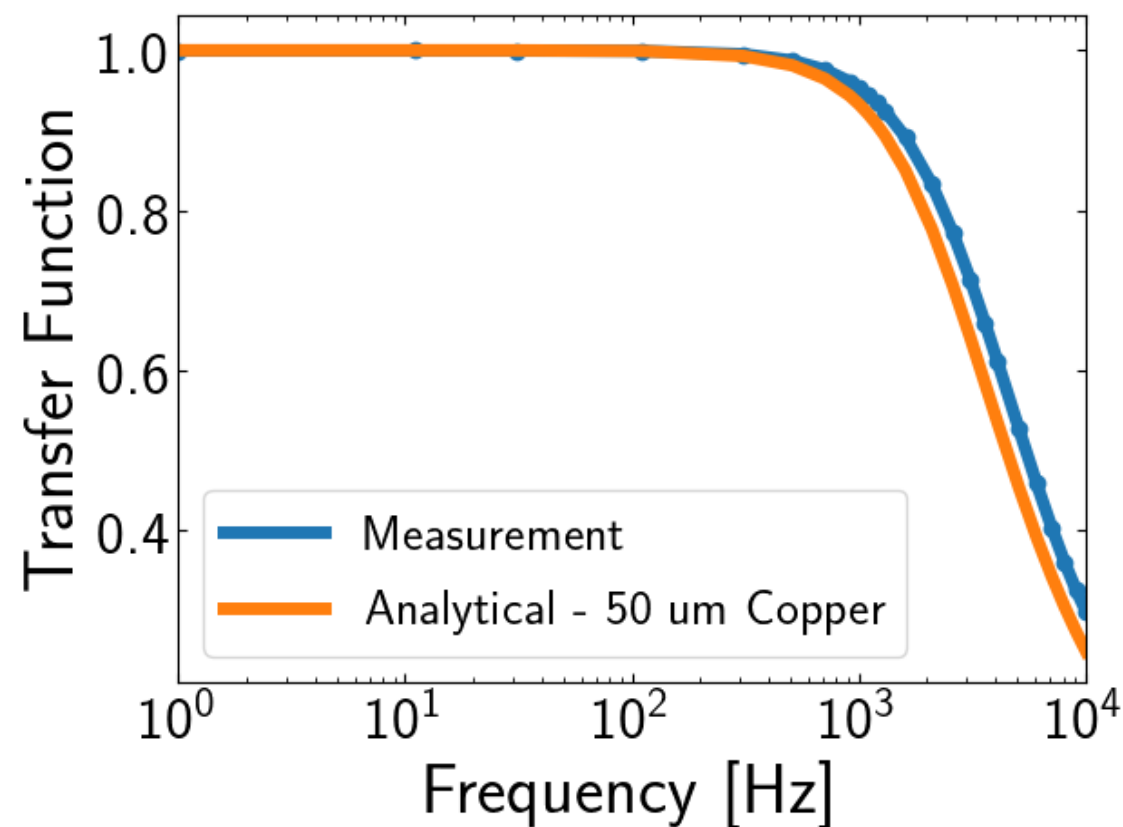
- Measurements were performed with a set of Helmholtz coils:
 - AC magnetic field was excited in the x-direction (transverse to shield).
 - Coils provided a very uniform field:



Sensor was moved in the x-direction.

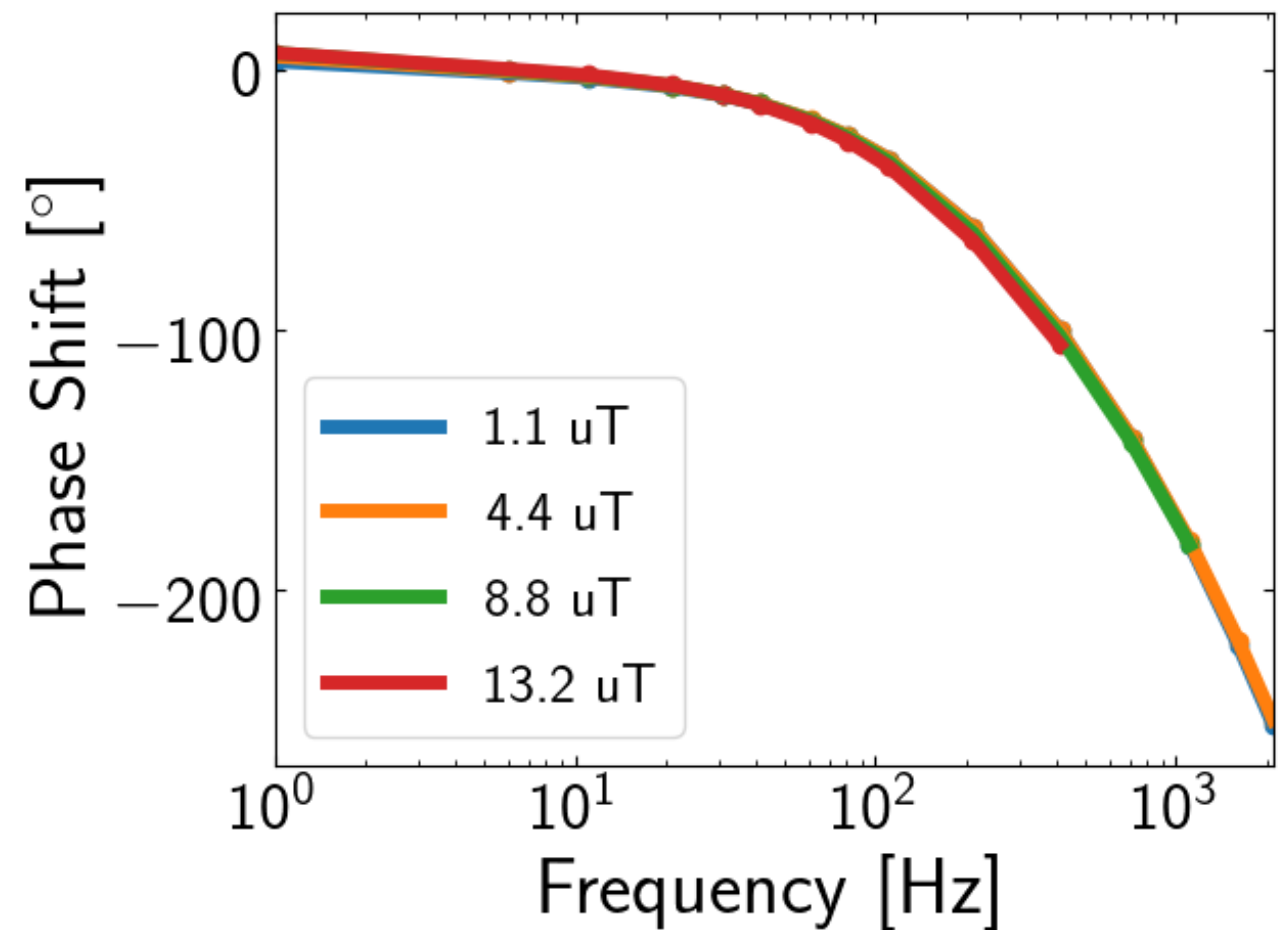
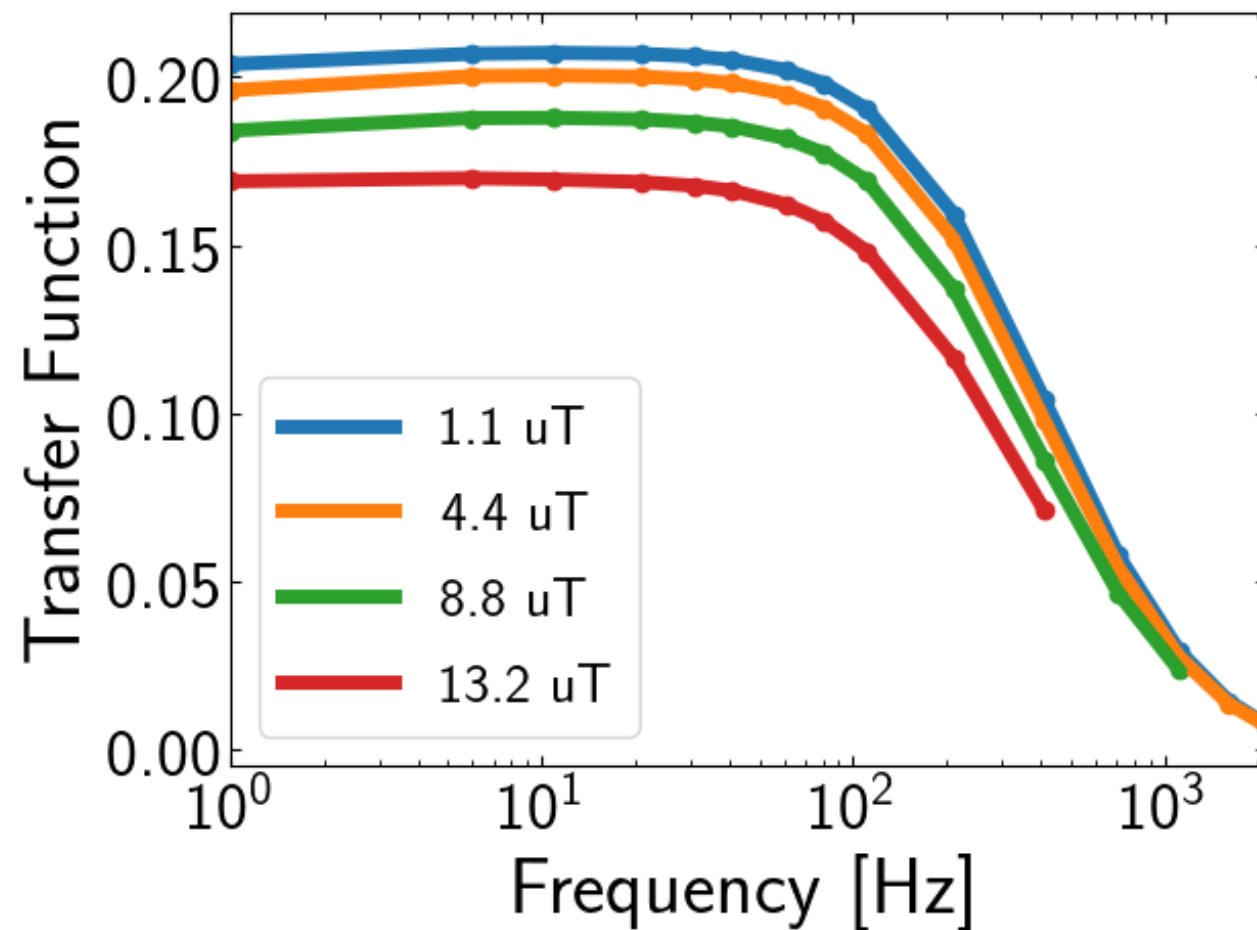
LHC Beam Screen

- Typical accelerator beam pipe:
 - Consists of 1 mm steel and 50-100 μm inner copper coating.



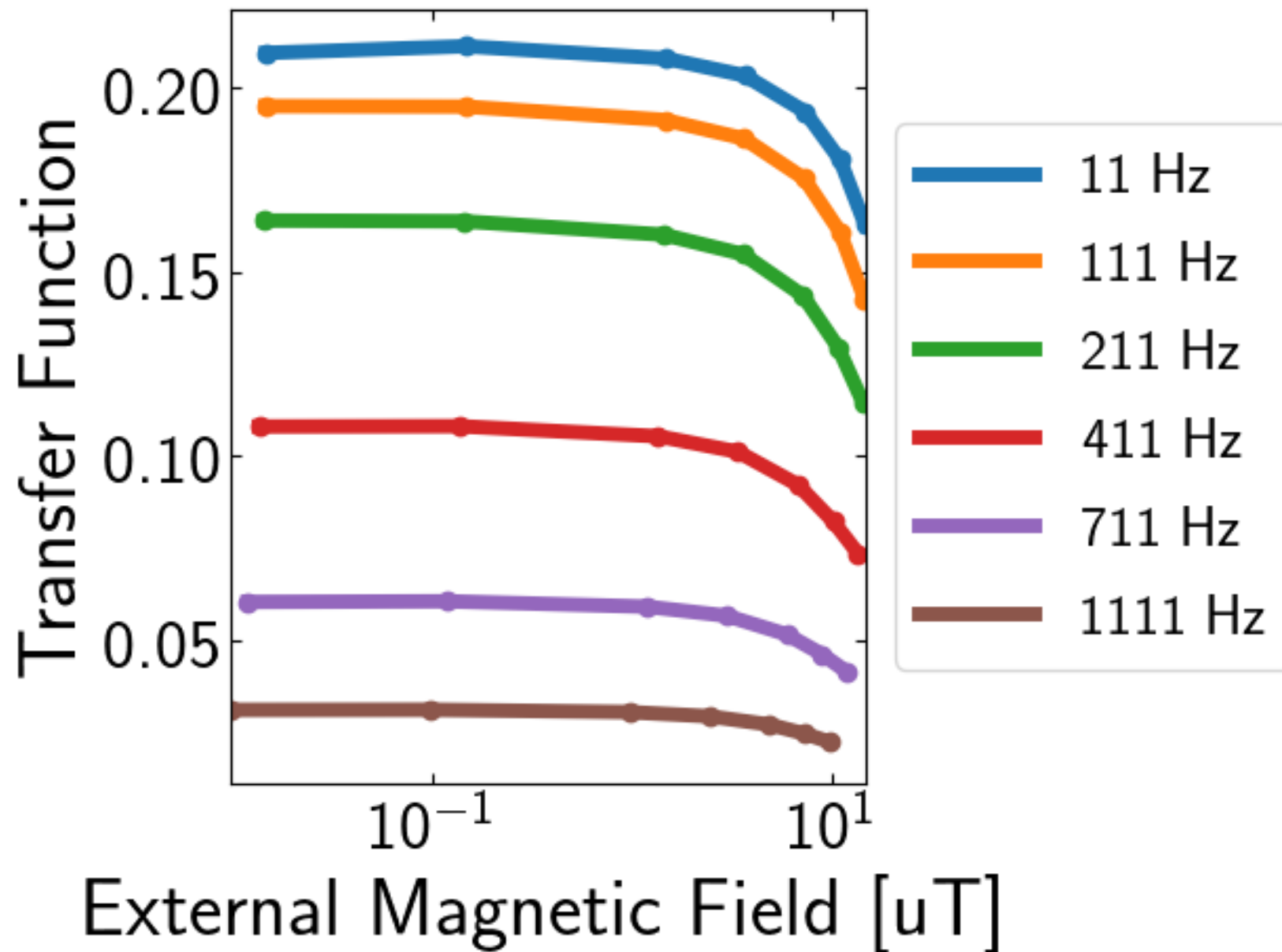
- No effect below a 1 kHz.

Soft Iron



- Transfer function improves with external field amplitude!

Soft Iron



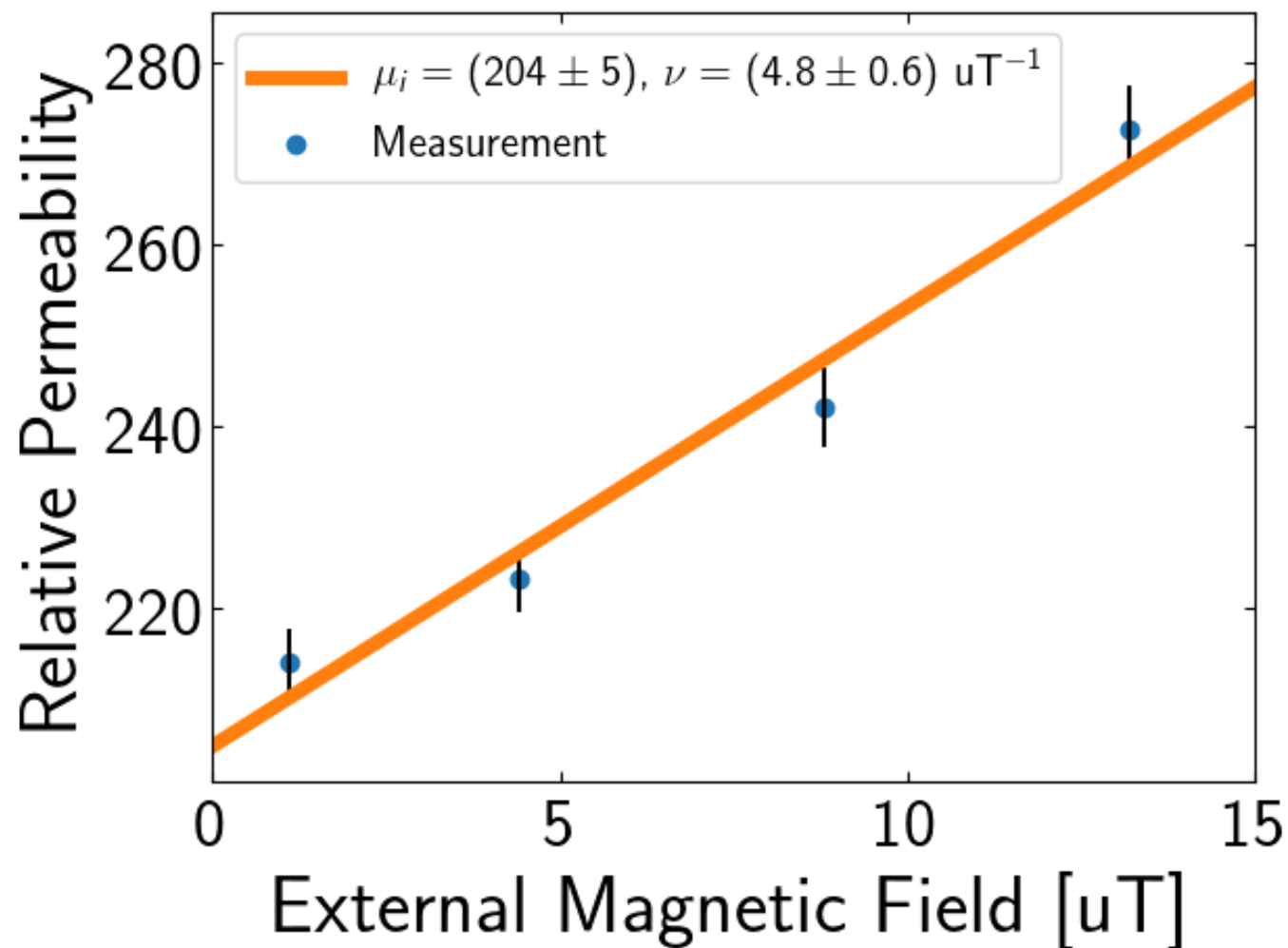
- Transfer function tends to a 'low-field' value.
 - I.e. shielding does not go to zero as the external field is reduced.

Transfer Function

- For cylindrical shields the transfer function can be calculated analytically:
 - J. F. Hoburg, “A Computational Methodology and Results for Quasistatic Multilayered Magnetic Shielding”, IEEE Transactions on Electromagnetic Compatibility, vol 38, 1996.

Soft Iron

- Using this model a permeability can be fitted to each transfer function:



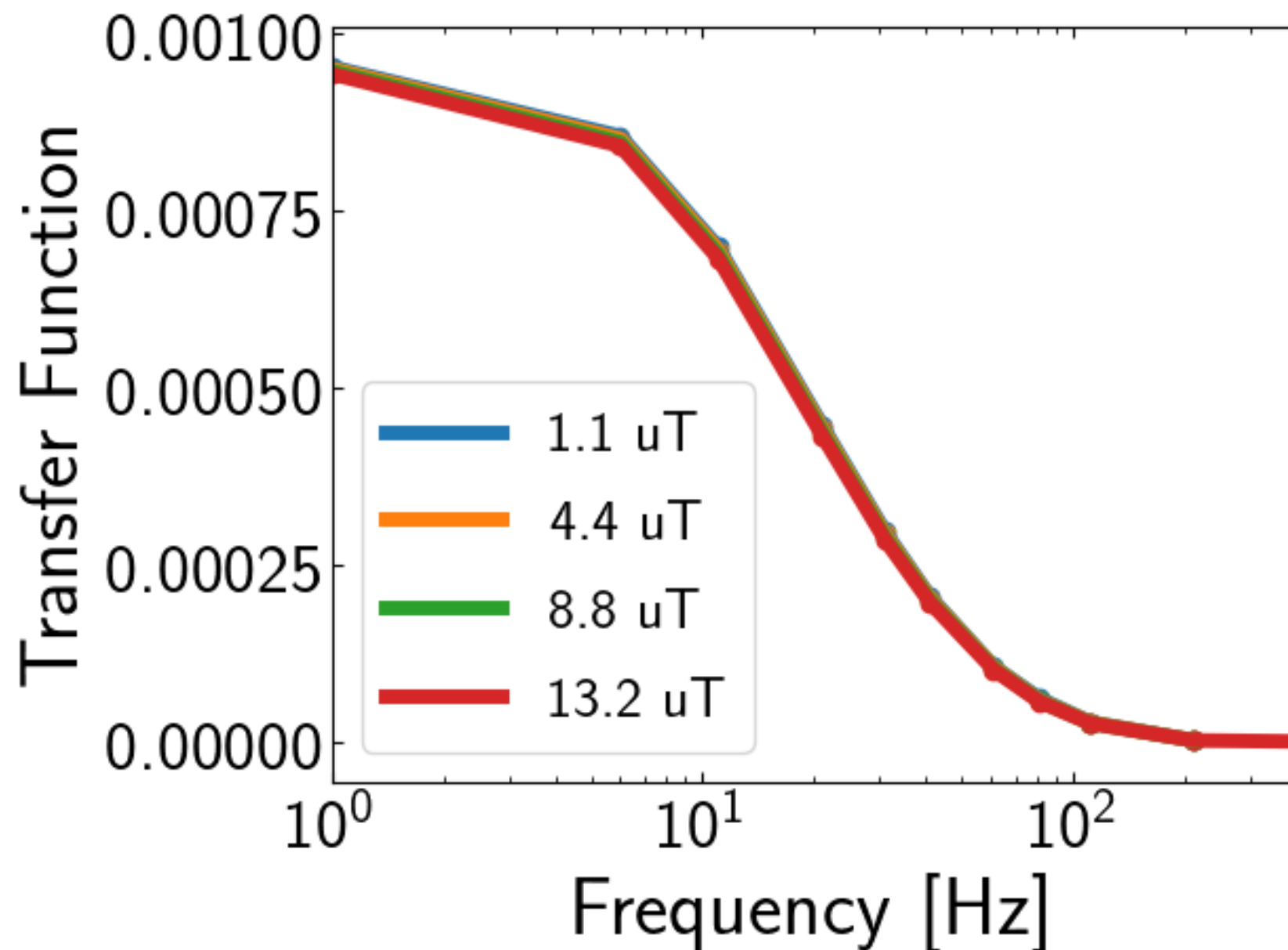
- The advertised initial permeability is 300-500.
- Much lower than the 'catalogue' permeability usually quoted.

Soft Iron

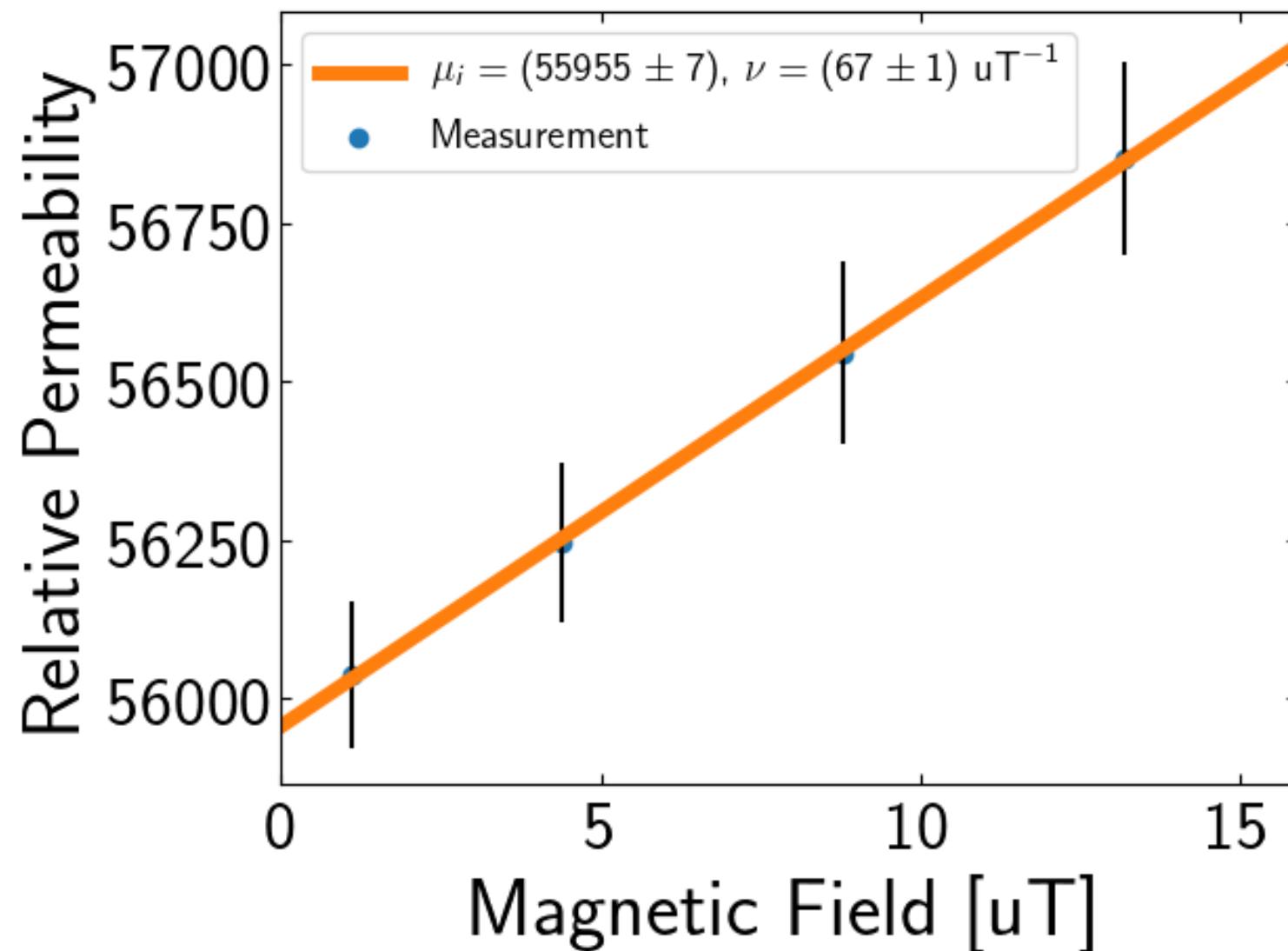
- How much iron would be needed?
 - Shielding roughly scales linearly with thickness.
 - 1 mm: $TF = 0.2$ at low frequencies.
 - Assuming 10 nT outside the shield, 2 cm needed to have 0.1 nT inside!
- Need a material with a better permeability.

Mu-Metal

- This is an iron-nickel alloy often used for magnetic shielding.



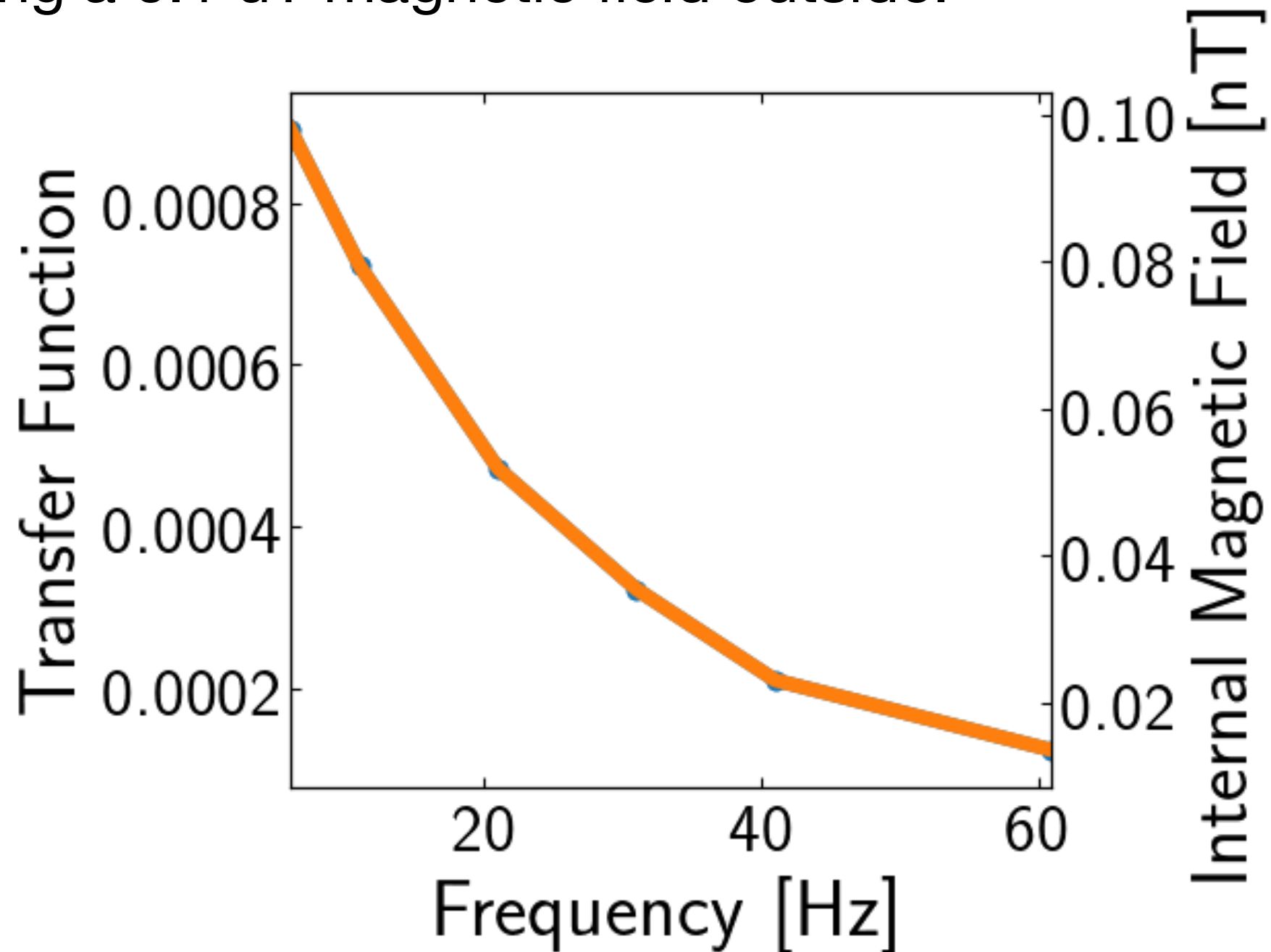
Mu-Metal



- Initial permeability of ~50,000.
- Could make a very effective shield.

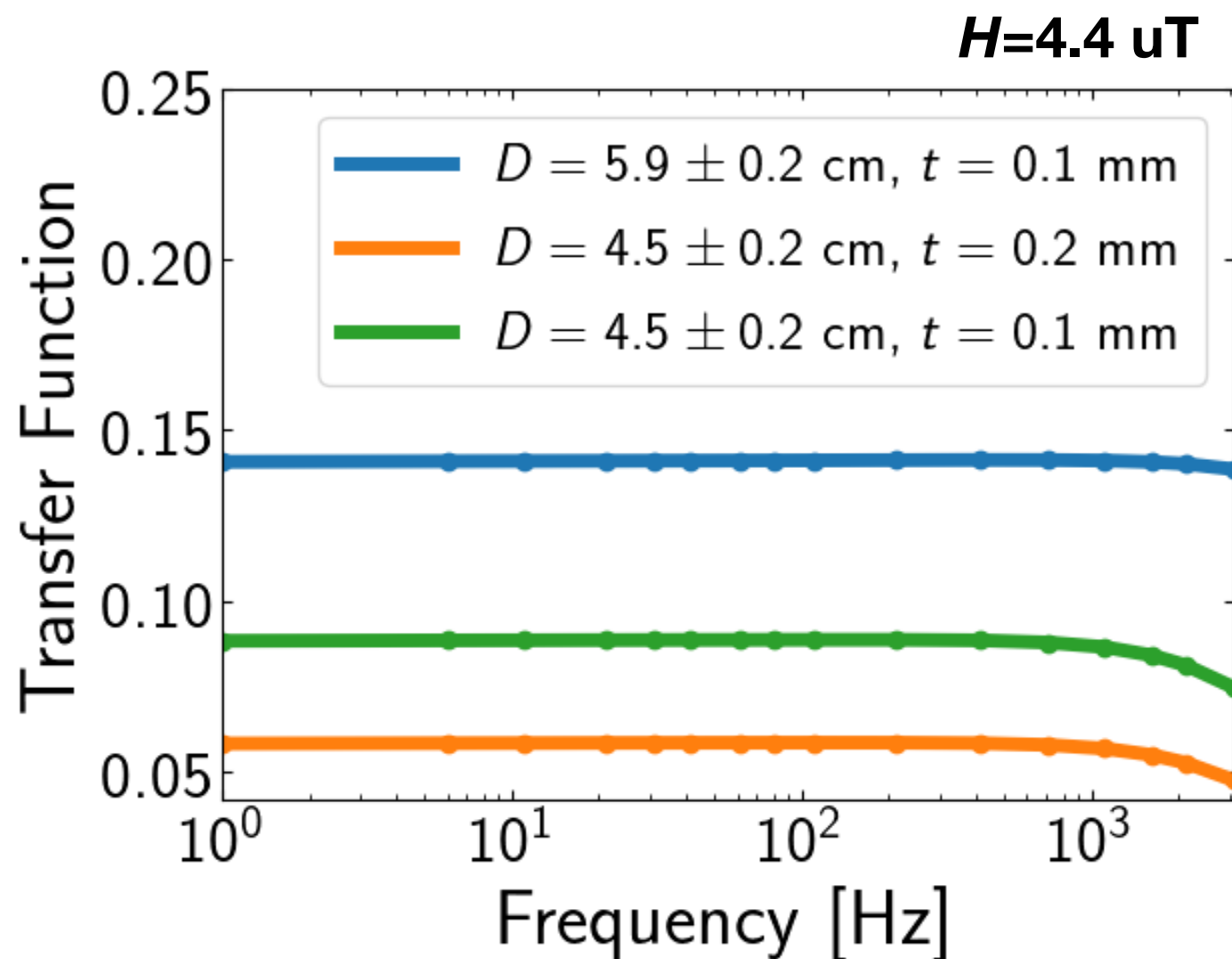
Mu-Metal

- Exciting a 0.1 uT magnetic field outside:



Mu-Metal Foils

- Annealed mu-metal foils:



- Scaling roughly agrees with $\text{TF} \propto \frac{D}{t}$.
- TFs consistent with permeability $O(5,000)$.
- Permeability likely to have been damaged from deformation.
- This is reversed by re-annealing.

Conclusions

- CLIC and the ILC have nT level tolerances.
- Accelerator environments typically have O(100 nT) stray fields.
 - Need shielding!
- Mu-metal can be used to shield to 0.1 nT levels.
- Scaling of TF $\propto \frac{D}{t}$ for mu-metal has been verified.
- Deformation can damage the permeability.