Ferrite materials for in-vacuum instruments

Mike BARNES and Laurent DUCIMETIERE,
Systems Department: Accelerator Beam Transfer Group

Acknowledgements to all the kicker team and O. Bjorkqvist, F. Caspers, M. Beck, A. Chmielinska, H. Day, O. de Frutos, F. Motschmann, B. Salvant, L. Vega Cid, V. Vlachodimitropoulos, C. Zannini

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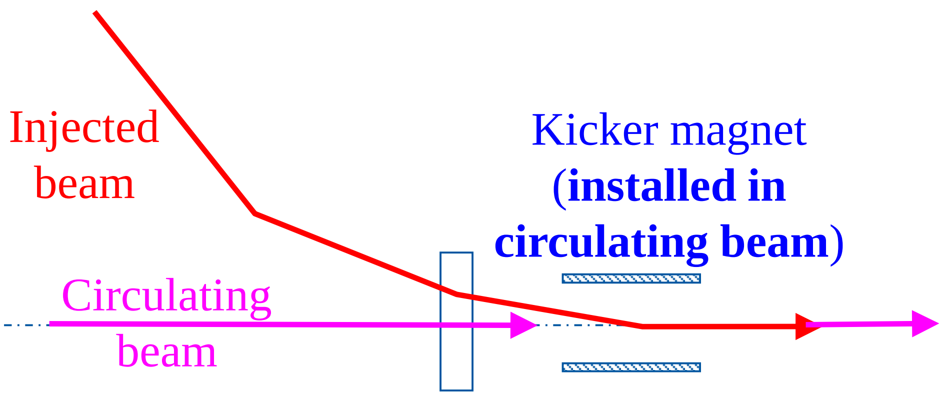
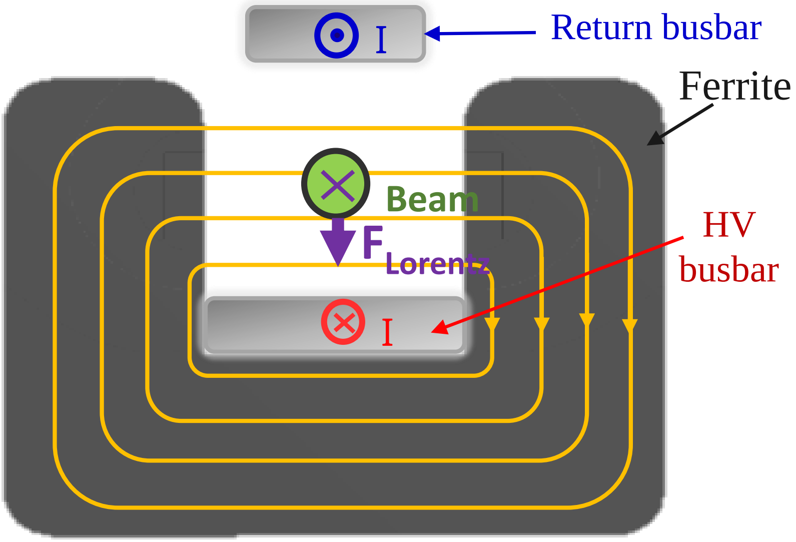
Kicker magnet - introduction

Fast pulsed magnets, so called **kicker magnets**, are widely used at CERN for fast, single-turn, injection and extraction.
At CERN kicker magnets are typically **installed in beam vacuum**.

- Typical field rise/fall-times range from tens to hundreds of nanoseconds
- Typical pulse current up to several kA
- Typical pulse voltage (on magnet) to 40 kV





Ni-Zn **ferrite yoke** is always used for fast pulse applications - e.g. 8C11, CMD5005

- Material with high relative permeability guides magnetic field
  - Reducing otherwise required pulse current
  - Ensures field homogeneity in aperture of kicker magnet

Ferrite

Isostatically pressed ferrite is preferred:

- High density → higher permeability and possibly (to be quantified) higher thermal conductivity
- Lower porosity → better vacuum properties

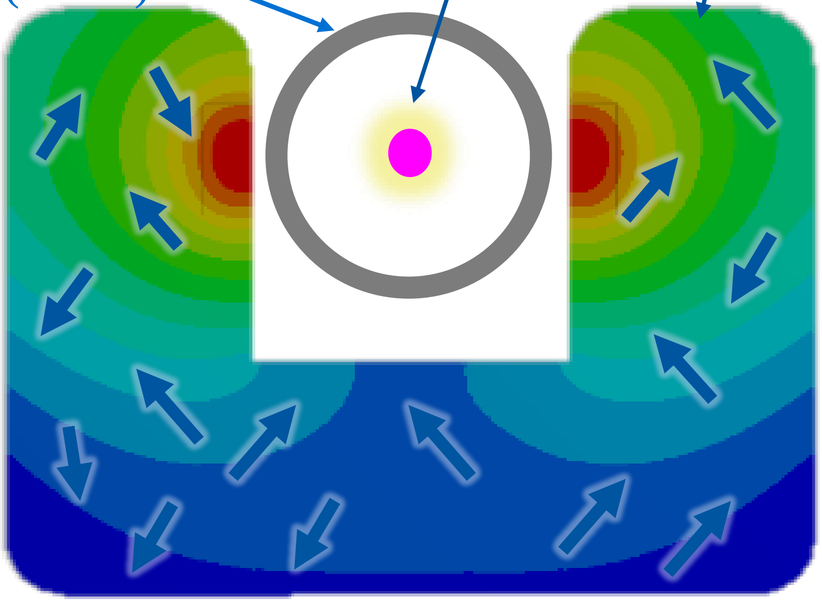
CERN treats ferrite for UHV application at **1000ºC in air and 1000ºC under vacuum** but this raises questions:

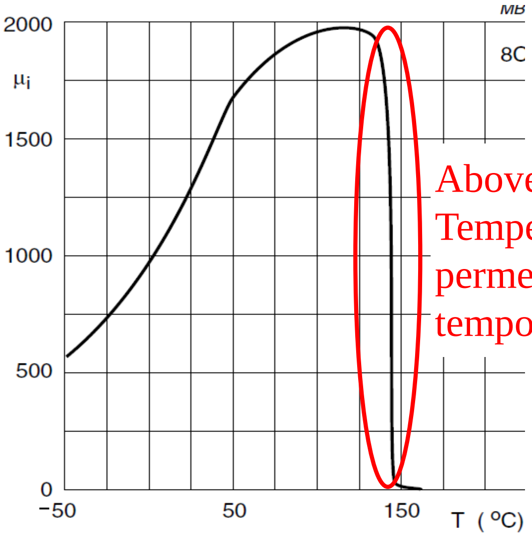
- Impact on magnetic properties ?
- Impact on surface conductivity ?
- Impact on mechanical properties ?

Some ferrite testing recently carried out by CERN Mechanical and Materials Engineering (MME) group – some results reported in this presentation.

In addition, for some kicker magnets, e.g. LHC injection, the complete kicker magnet is designed to be baked out to **300ºC under vacuum.**

Beam induced heating of ferrite





Heating of the ferrite can result in:

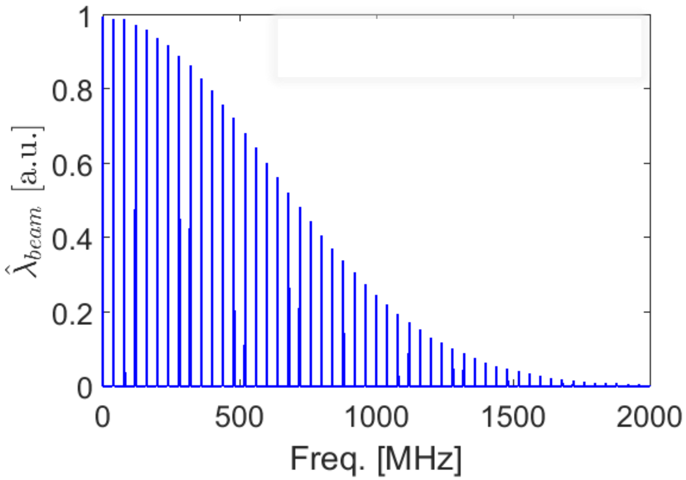
- **degradation of the vacuum**:
  - → beam loss
  - → increased probability of electrical breakdown (flashover) during pulsing
- **temporary loss of the magnetic properties** (Curie point exceeded):
  - → Cannot safely inject/extract beam

Beam coupling impedance

Example:

Frequency domain ⇨ Beam coupling impedance

(Time domain ⇨ Wakefields)



Total power loss (P_t) is given by:

$$\boldsymbol{P_t} = 2{I_b}^2 \sum_{n=0}^{\infty} |Y(\omega_n)|^2 \, Re\{Z_L(\omega_n)\}$$

Where:

I_b Average beam current

$|Y(\omega_n)|$ Fourier transform of the normalised beam current

$Re\{Z_L(\omega_n)\}$ Real part of the longitudinal beam coupling impedance

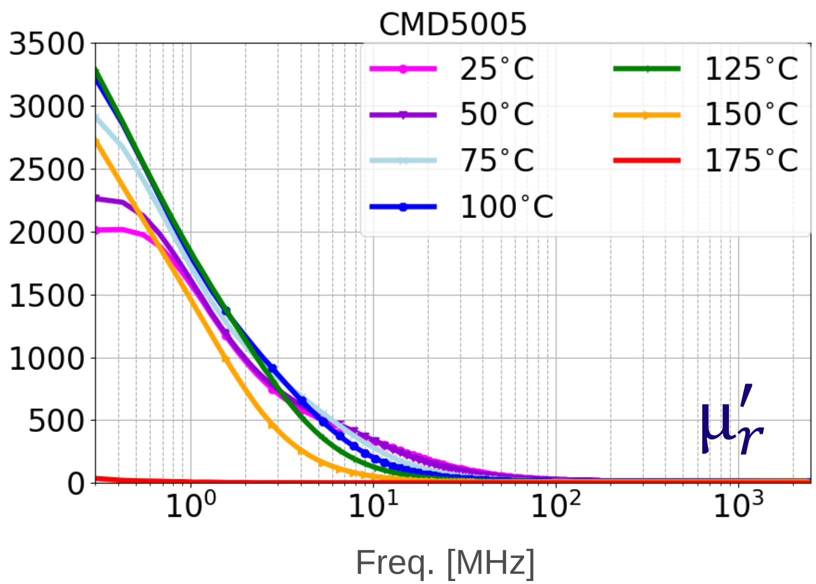
The power loss (due to beam induced heating in the ferrite) is a function of:

- beam intensity (see above)
- beam spectrum (see above)
- magnet aperture geometry (influences $Re\{Z_L(\omega_n)\}$)
- ferrite imaginary permeability at beam frequencies (influences $Re\{Z_L(\omega_n)\}$) – see next slide
- resonances caused by geometrical features

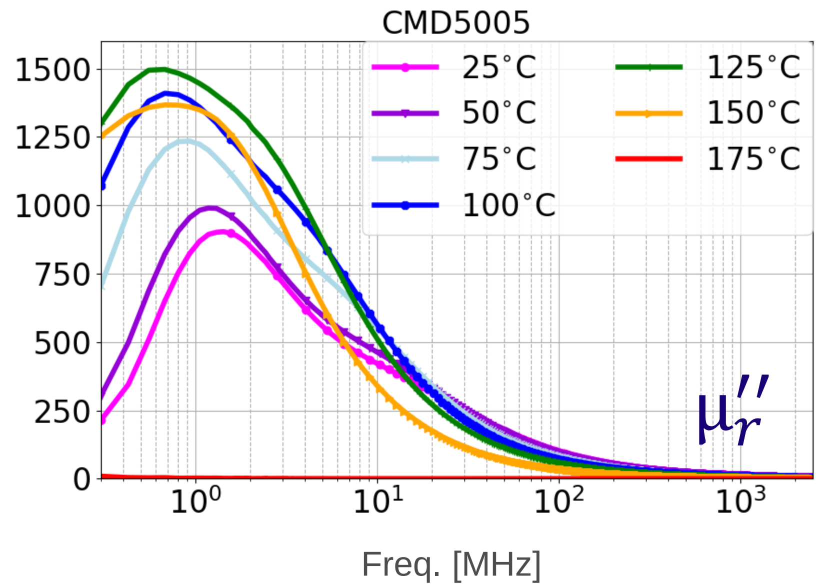
Simulations (optimisation) of impedance and power loss with computer code CST.
Impedance verified by measurements in the lab.

Ferrite: permeability & temperature

Real relative permeability (CMD5005):



Imaginary relative permeability (CMD5005):

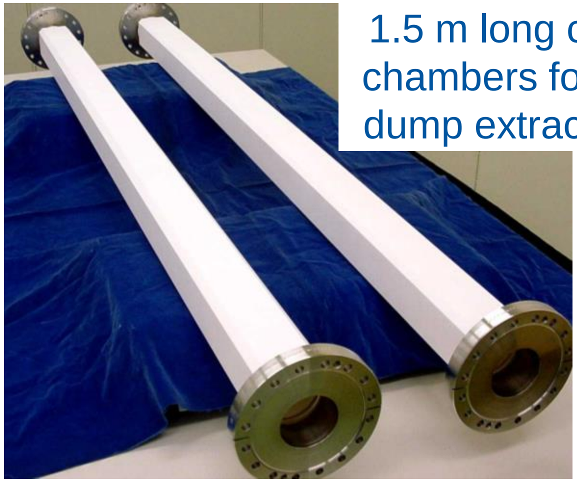


- Strong temperature dependance of ferrite's permeability
- Above the Curie temperature, both real and imaginary permeability's significantly drop:
  → necessity to maintain the temperature of the ferrite below the Curie temperature.

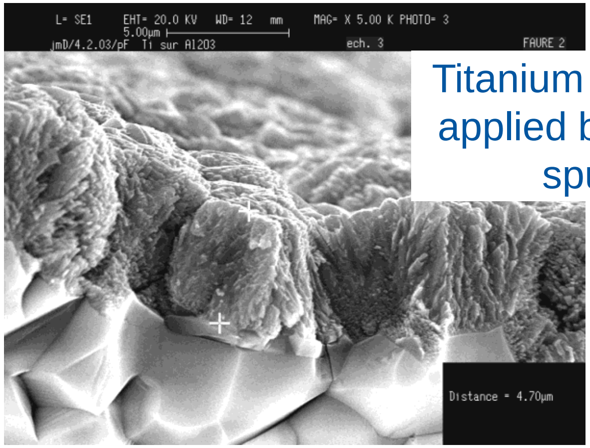
A. Chmielińska *et al.* "Measurements of electromagnetic properties of ferrites as a function of frequency and temperature", In *Journal of Physics: Conference Series,* vol. 1067. No. 8, p. 082018. IOP Publishing.

Shielding: resistive coating

A uniform resistive layer is the easiest way to provide beam screening when the field rise time is in the microsecond range

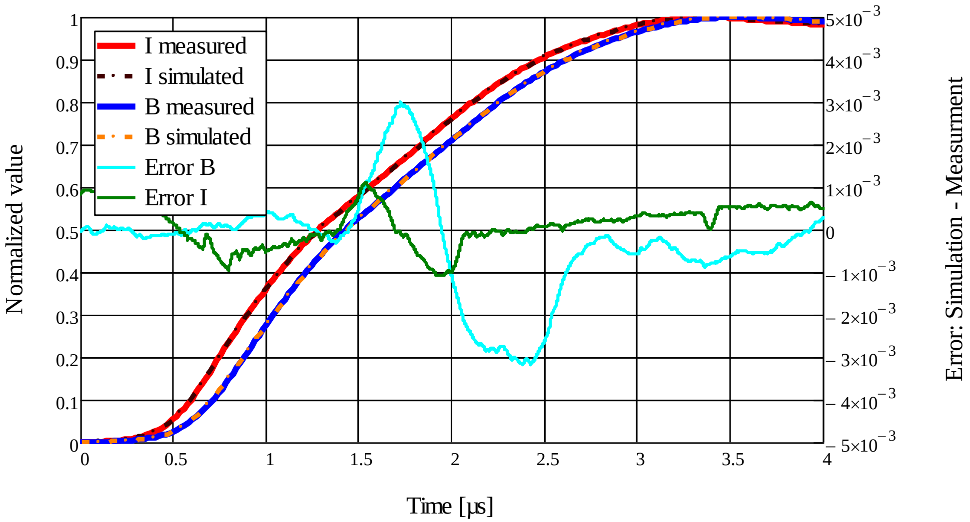


1.5 m long ceramic vacuum chambers for the LHC beam dump extraction kicker MKD



Titanium metallization: applied by magnetron sputtering

The time shift introduced by the metallization is about 100 ns for a field rise time of 3 µs:



Shielding: serigraphy on ferrite

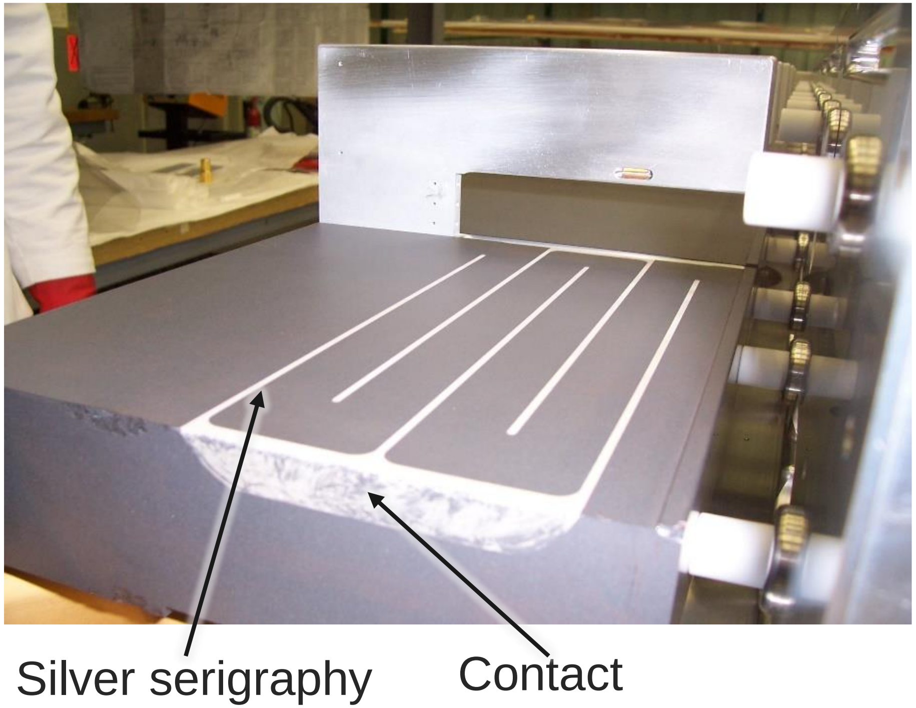
When magnet cells are made of 'long' ferrite, it is possible to apply a beam screen directly on ferrite by serigraphy

SPS extraction kicker magnet MKE:

- Ferrite has a length of 230 mm for each cell
- The beam aperture is limited and does not allow for any insert

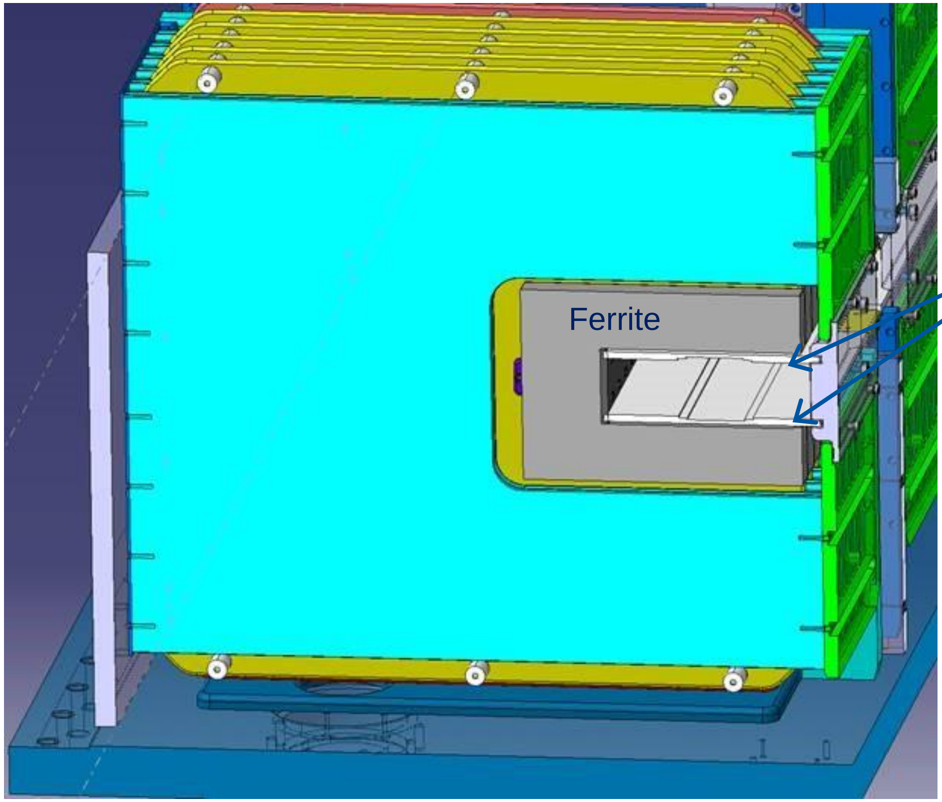
Beam coupling impedance can be reduced using conductive stripes as a retrofit:

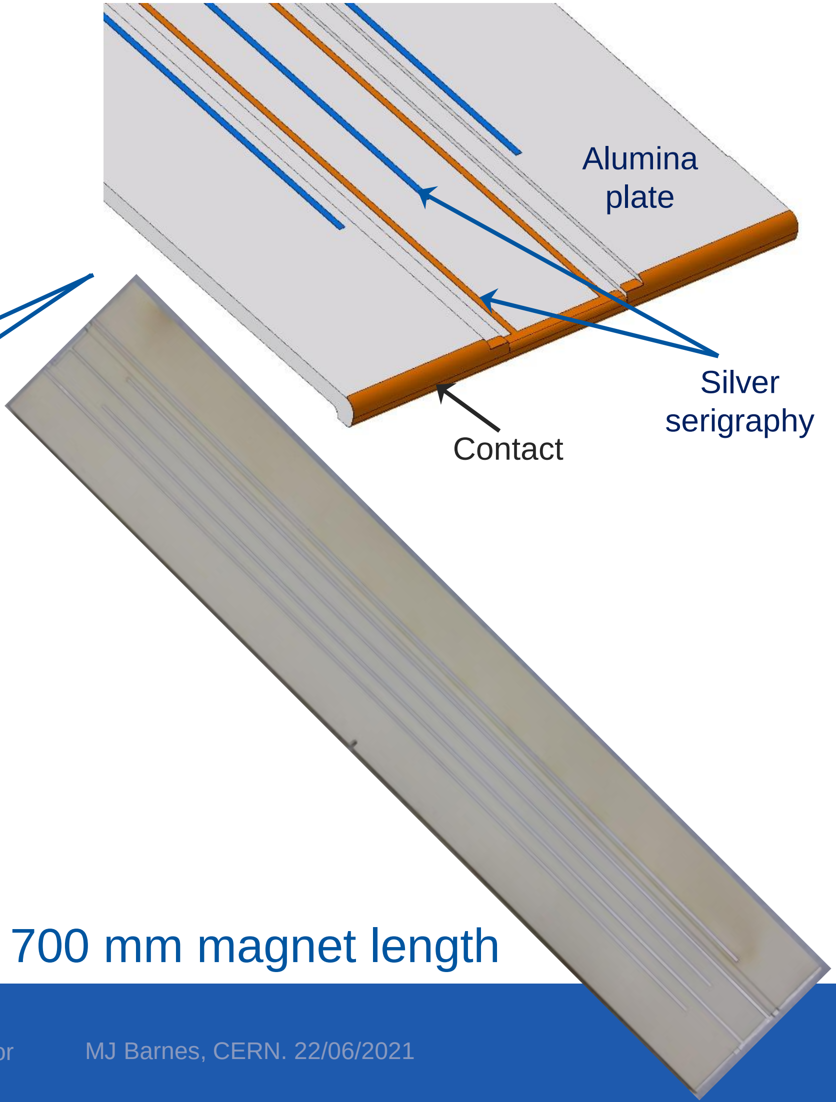
- An interleaved comb structure is directly printed onto the ferrite blocks, with a contact at either side
- Capacitive coupling between stripes carries the beam image current
- No impact on the beam aperture
- Important to optimize length of 'fingers' to avoid resonances at beam harmonics



Shielding: serigraphy on alumina

For a transmission line type kicker magnet with ‘short’ cells, e.g. SPS injection, serigraphy can be applied onto a thin alumina support over the full length of the ferrite yoke:

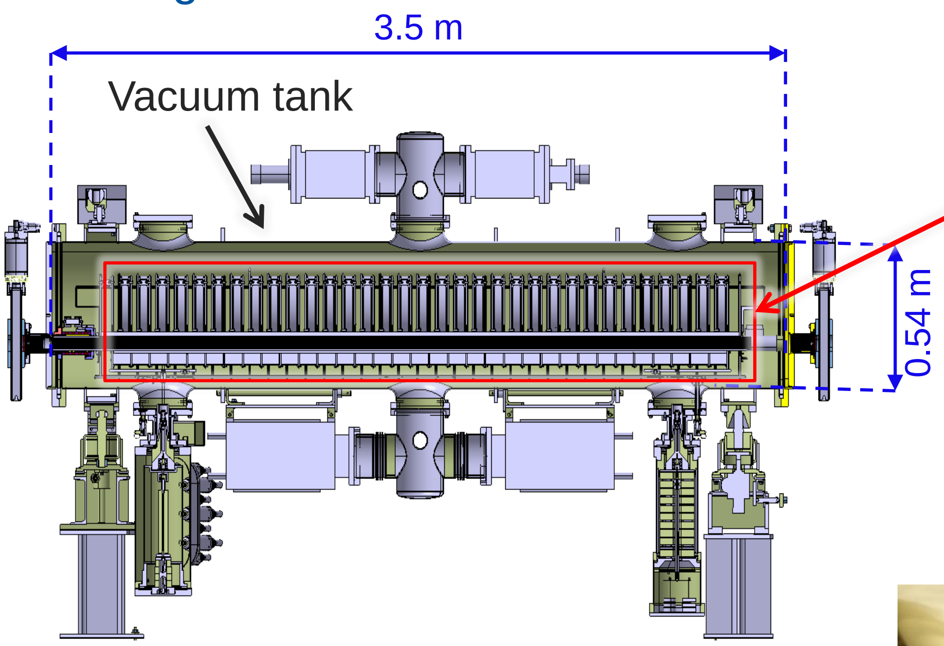


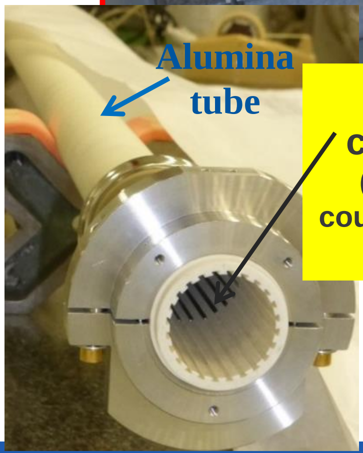


SPS injection kicker magnet (MKP-L)
22 cells (ferrite of each cell: ~26mm length). 700 mm magnet length

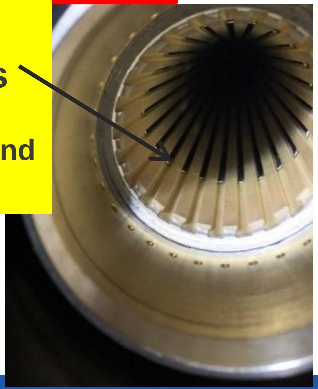
Shielding: Screen conductors

For injection into the LHC (MKI), screen conductors are used, supported inside a ~3m long alumina tube to achieve a low beam coupling impedance:



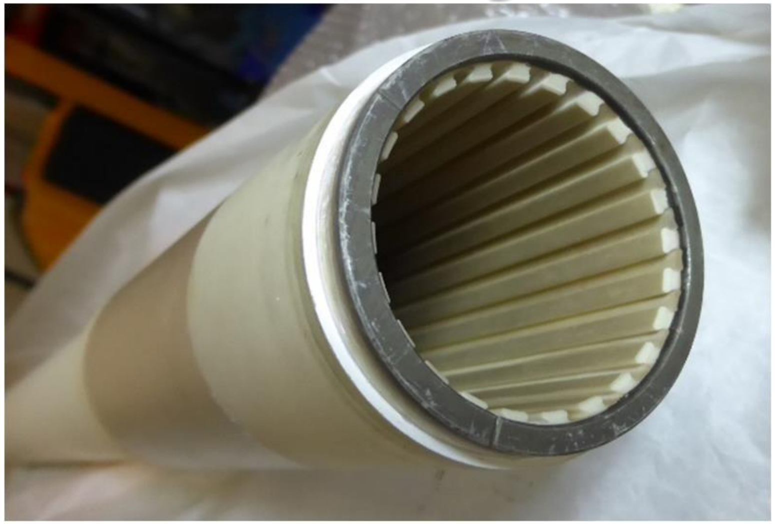


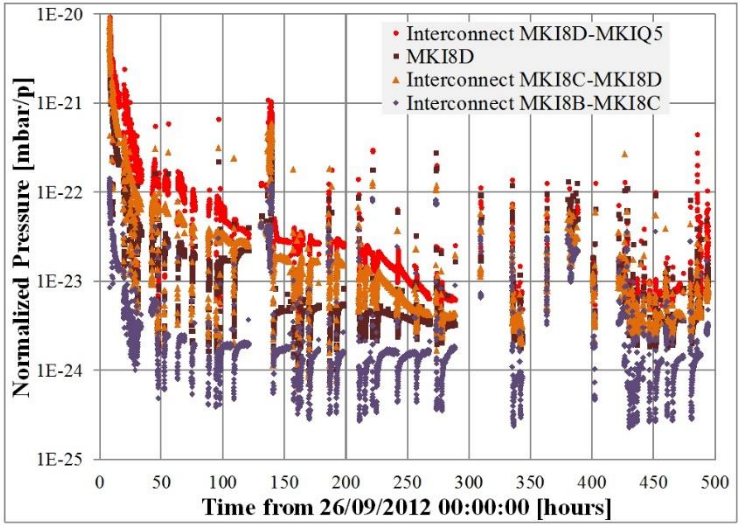
Screen conductors (capacitively coupled to ground at one end)

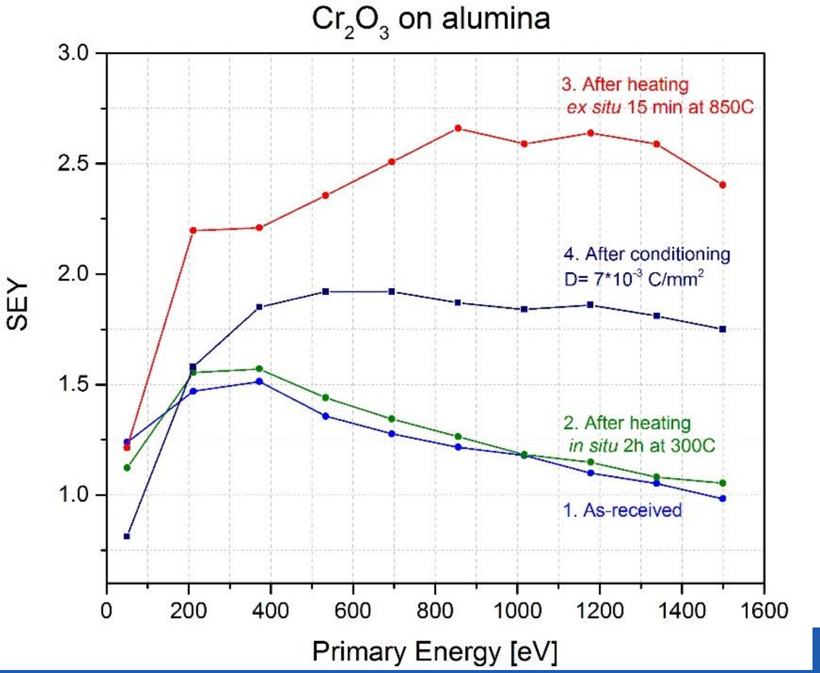


- Low beam coupling impedance achieved – significantly reduces beam induced heating;
- Nevertheless, for HL-LHC type beams, temperature of some ferrite yokes could exceed their Curie temperature….

Secondary Electron Yield (SEY)





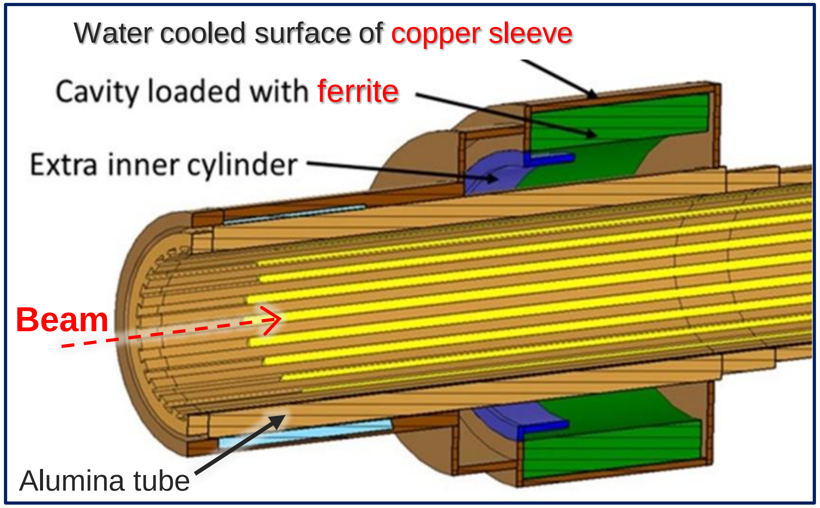


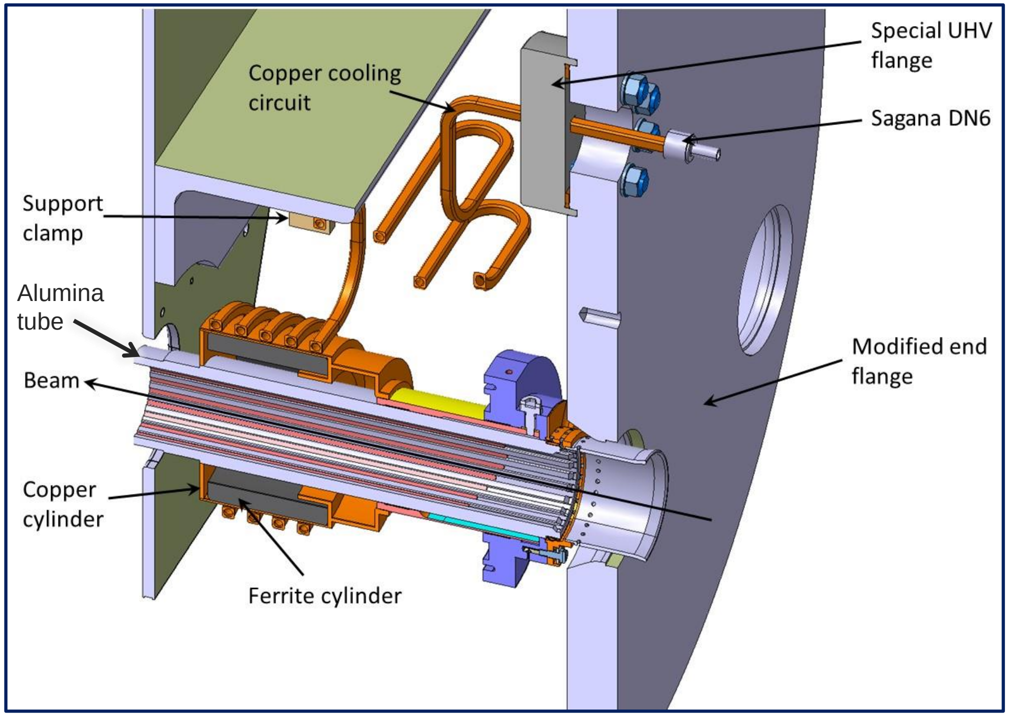
- Alumina has a high SEY – typically ~10
  - This can result in electron-cloud and thus high pressure;
  - The alumina can take a considerable time to condition to a lower SEY;
  - A coating, e.g. Cr_2O_3, can be used to significantly reduce the SEY.

RF Damper

- It is not feasible to cool the ferrite yoke of the MKIs since they are at pulsed HV.
- To limit the **beam induced power deposition** in the ferrite yokes, an **RF damper** has been developed: it is designed to reduce total beam induced power dissipation and **move dissipation away from the yoke** and, instead, into the damper itself.

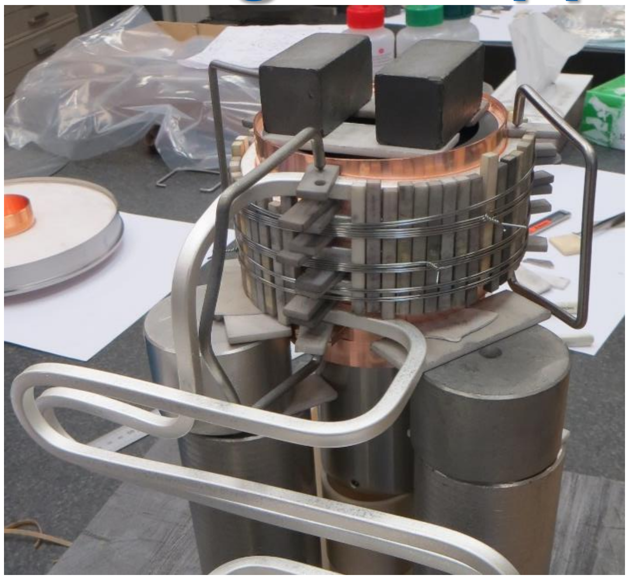
RF Damper on one end of alumina tube:

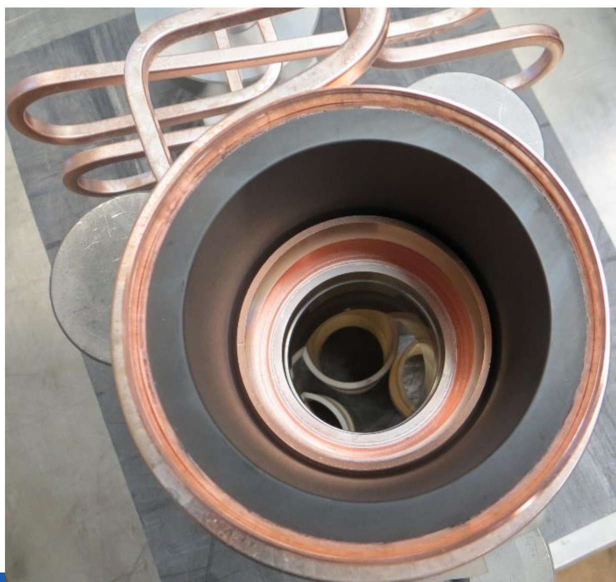


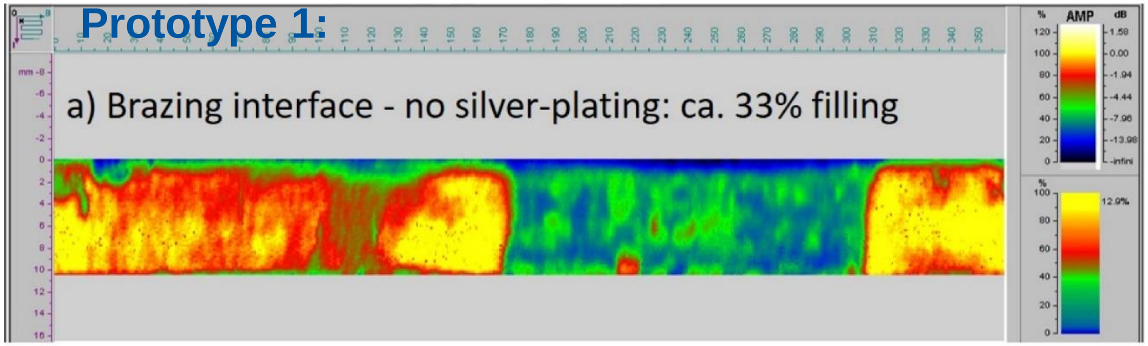


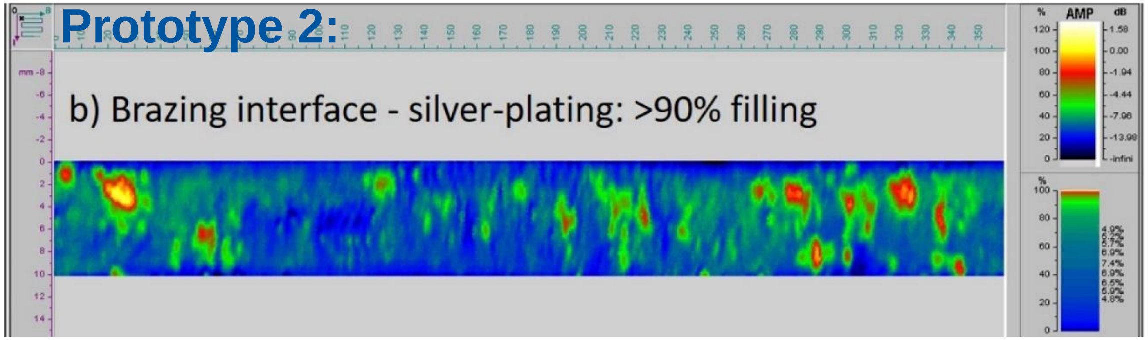
- The ferrite in the RF damper is subject to significant heating, especially on its inner surface: it is cooled externally;
- It is crucial that there is a **good thermal bond** between the ferrite cylinder and copper sleeve;
- **Temperature gradient** in ferrite → **mechanical stress** and **risk of cracking**

Brazing of copper sleeve and ferrite cylinder





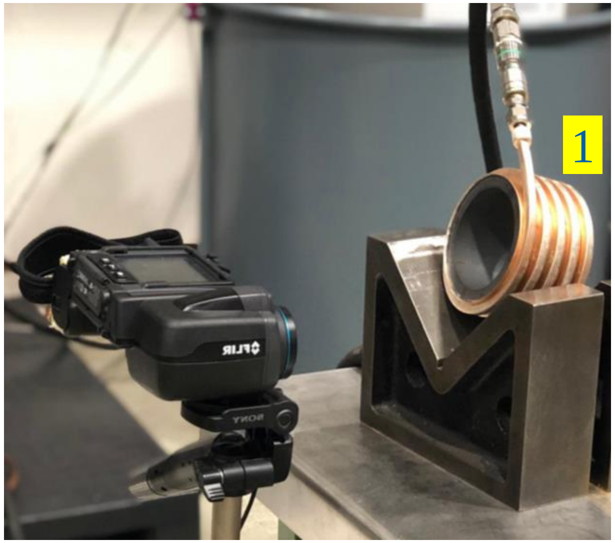


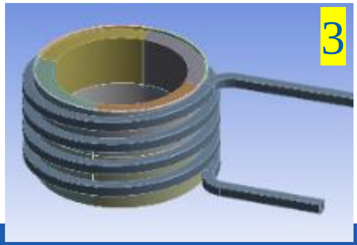


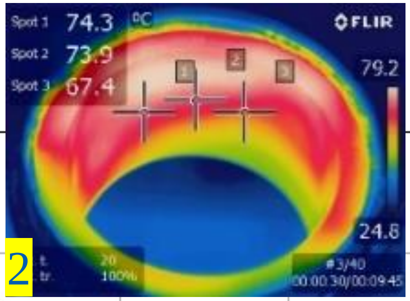
Ultrasound echo from the brazing joint of two prototype RF dampers. A high amplitude (yellow, red) indicates a lack of filler metal and a low amplitude (blue, green) a filled interface.

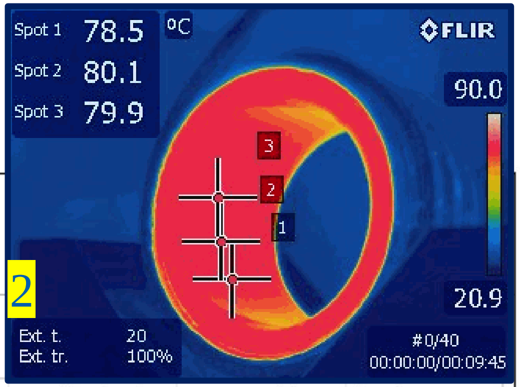
Thermal contact between ferrite and Cu

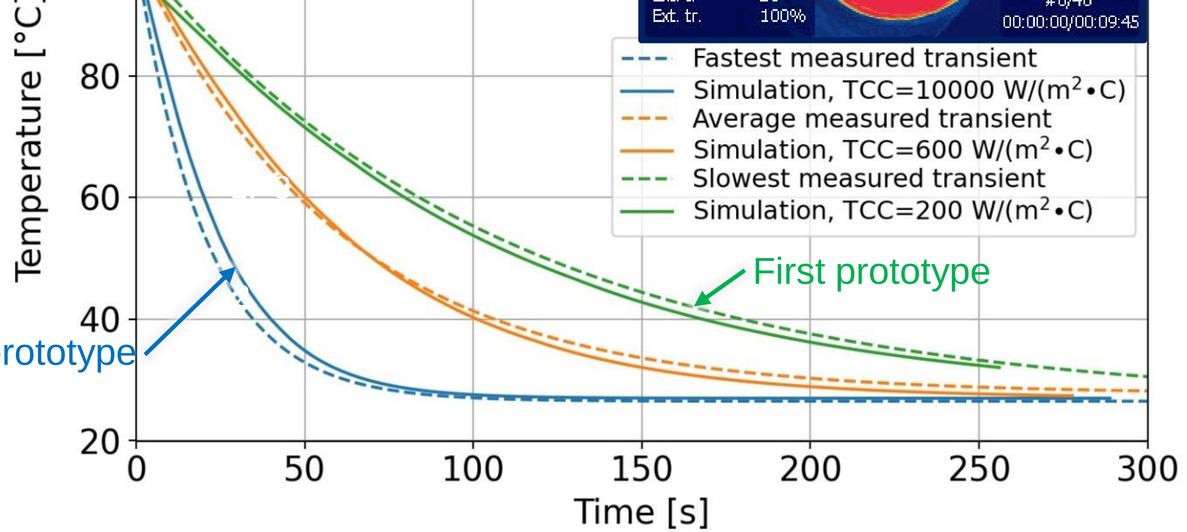
To estimate the Thermal Contact Conductance (TCC) value between the critical contact surfaces of the copper sleeve and the ferrite cylinder, the assembled RF damper is heated to a homogeneous temperature. Cold water is then run through the cooling pipes (1) and the cool-down transient on the inside of the ferrite ring is recorded using a thermal camera (2). The cooling transient is compared with an ANSYS thermal model (3).







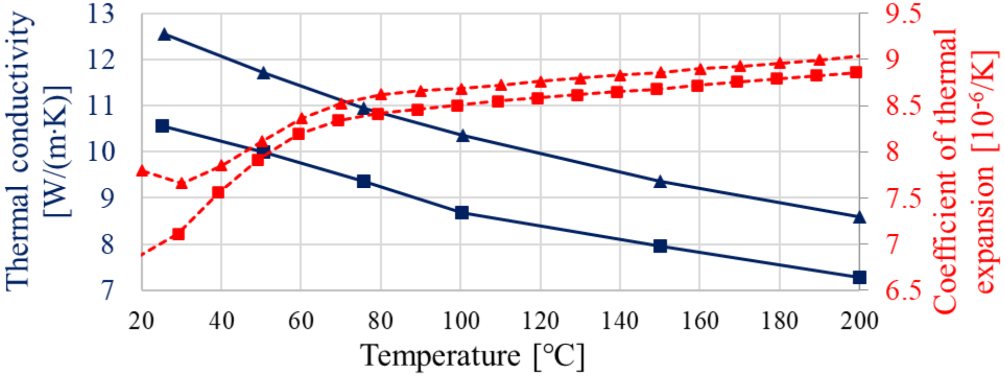




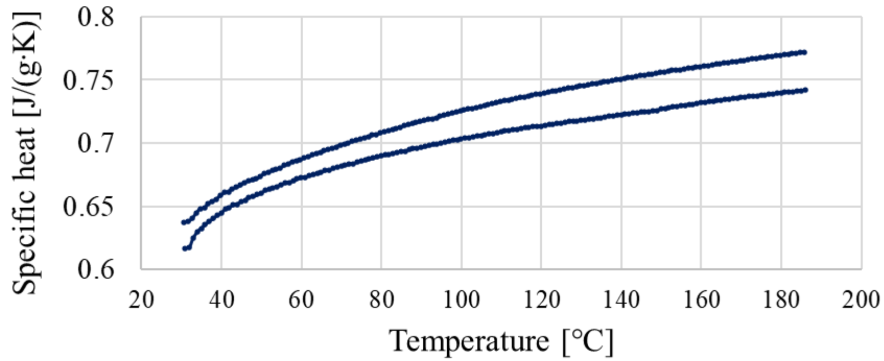
Ferrite thermomechanical properties

Min. and max. range of measured thermomechanical material properties of isostatically pressed CMD10 ferrite (Curie temperature ≈ 250°C):

Data measured by CERN MME:



Note: thermal expansion is measured for heating of samples



☺ The thermal conductivity is ~two times higher than the manufacturers datasheet value.

✓ Other thermomechanical properties shown above are similar to datasheet values.

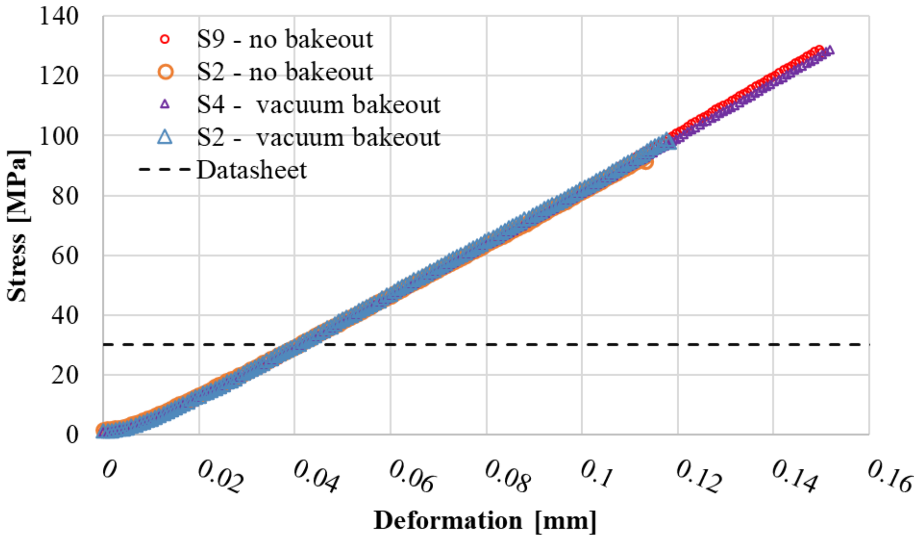
Ferrite mechanical properties

Ten samples of CMD10 ferrite used for each of several mechanical tests.

Data measured by CERN MME:

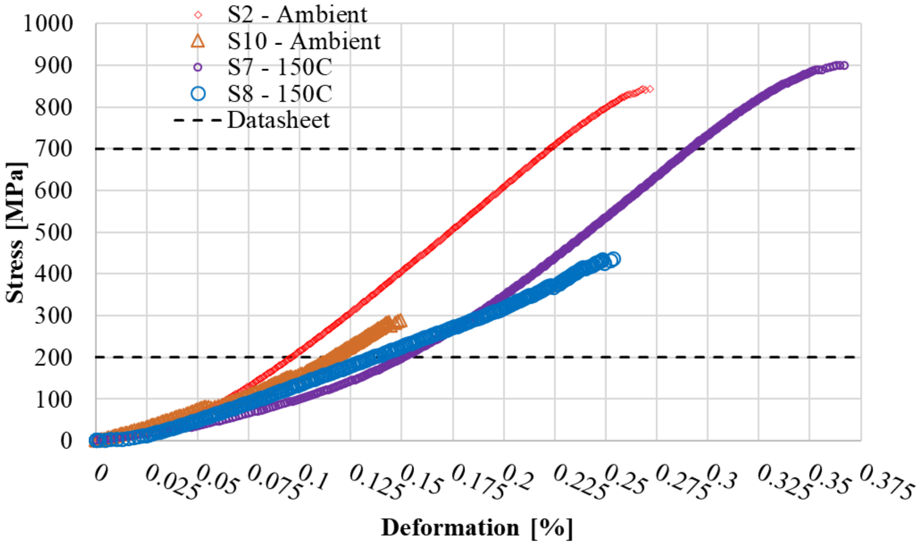
Tensile Stress (MPa):

No bakeout or baked in air and vacuum to 1000°C.



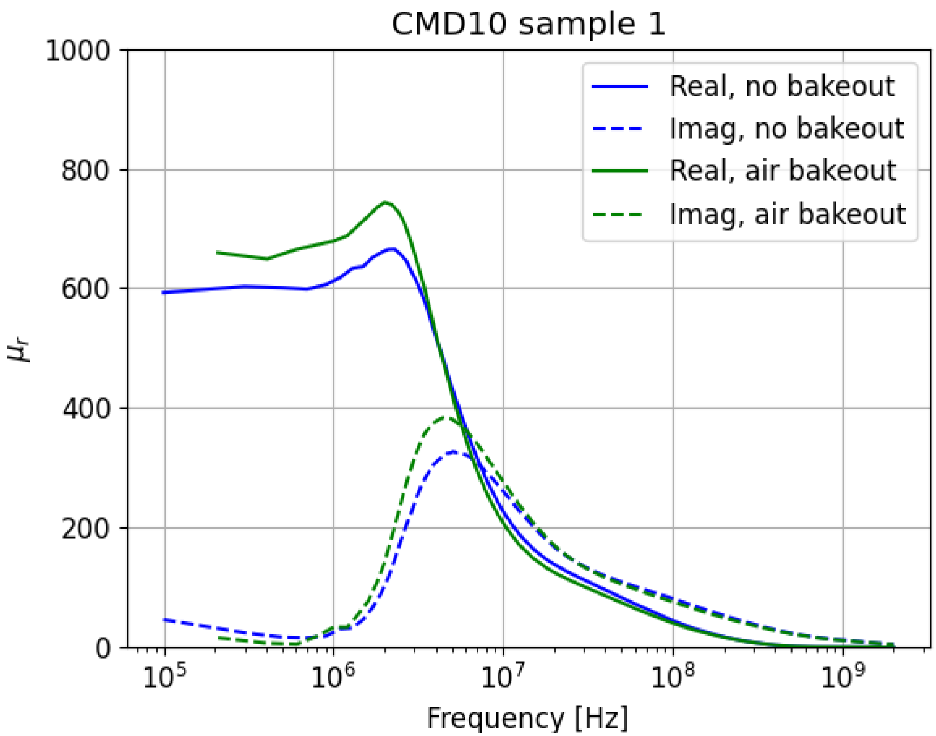
Compressive Stress (MPa):

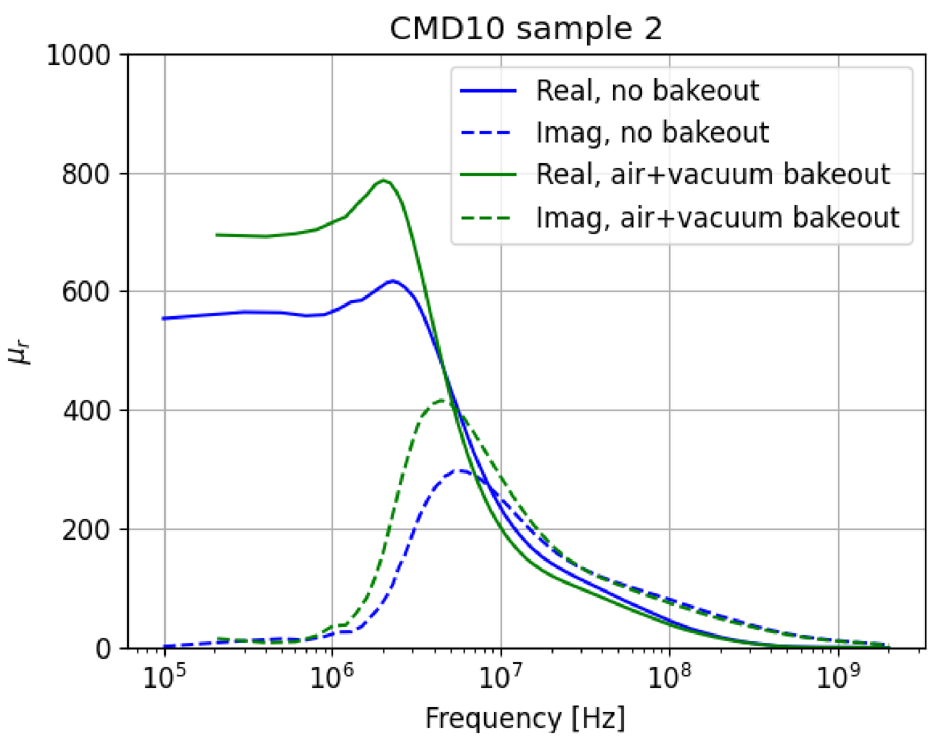
No samples tested which were unbaked or just baked in air.



Measured ultimate tensile and compressive strengths, for each sample, are all above the minimum datasheet value.

Ferrite: permeability & thermal treatment





Measurement of electromagnetic properties in lab, for several samples of ferrite, show that:

- ✓ Air bakeout increases real permeability below ~6MHz. No significant change in real or imaginary permeability above 10MHz.
- ✓ A further vacuum bakeout increases real permeability below ~6MHz. No significant change in real or imaginary permeability above 20MHz.

Conclusion and outlook

- Ni-Zn ferrite is mainly used as yoke in kicker magnets for its high frequency response and vacuum compatibility
- Beam heating effect is an issue with high intensity beams and requires impedance shielding (screening):
  - Beam screens with uniform resistive coating are easy to implement, especially for lumped kicker magnets with rise/fall time in the microsecond range
  - Serigraphy combs on ferrite can be considered as a retrofit solution when the cell length is large enough
    - The aperture is preserved
  - For short cell length, a retrofit solution with serigraphy on alumina support is being prototyped at CERN

- Screen conductors are necessary for very low beam coupling impedance
- An RF damper has been developed to move the heat load outside the magnet yoke, where heat can be extracted by water cooling
  - Good thermal contact is essential between ferrite and water cooled surface of damper
  - Thermomechanical, mechanical and electromagnetic properties of ferrite must be known!

Thank you for your attention

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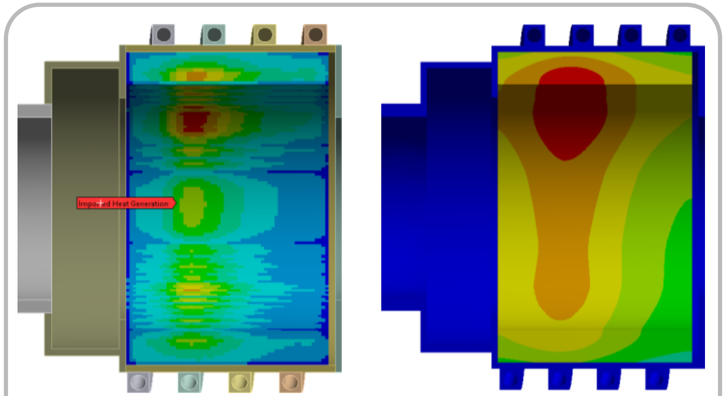
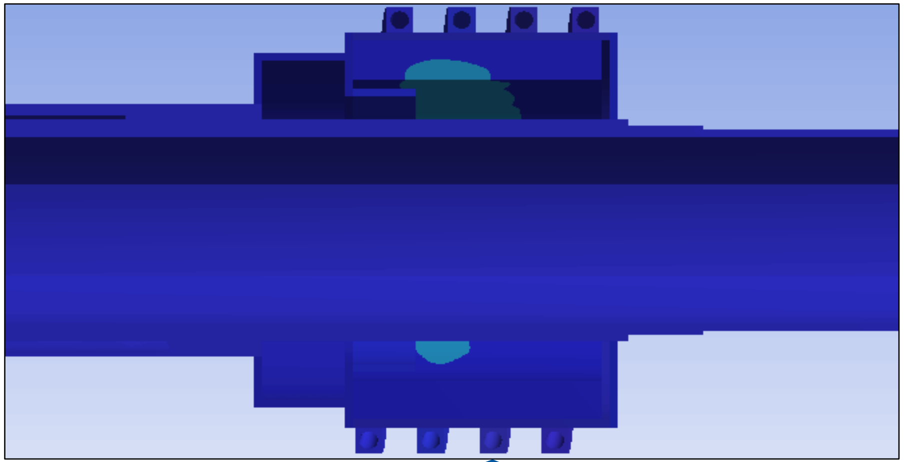
Spare slides

Beam induced heating simulations

- Measurements of TCC are used in the ANSYS model.
- Combined electromagnetic and transient thermal simulations for complete beam induced heating model.
- Total power dissipation based on measured impedance model and the following beam parameters: 2.2e11 ppb, 1 ns bunch length, 2748 bunches.
- Historically, a safety factor of 2.5 has been used for beam induced power deposition (this is equivalent to ~450 W being dissipated inside the damper!) – recent simulations and comparison with measurements indicate that this safety factor is not required for the MKI Cool.



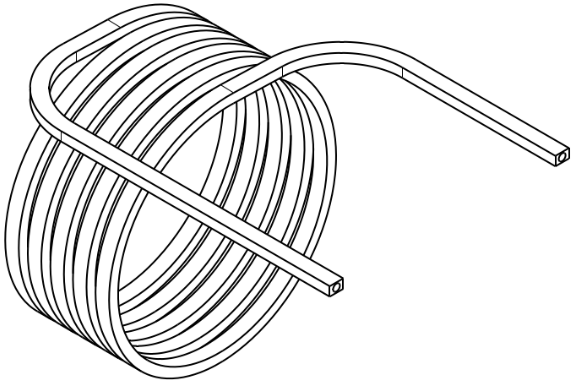
Imported heat load   Simulated temperature



Water temp = 30 °C

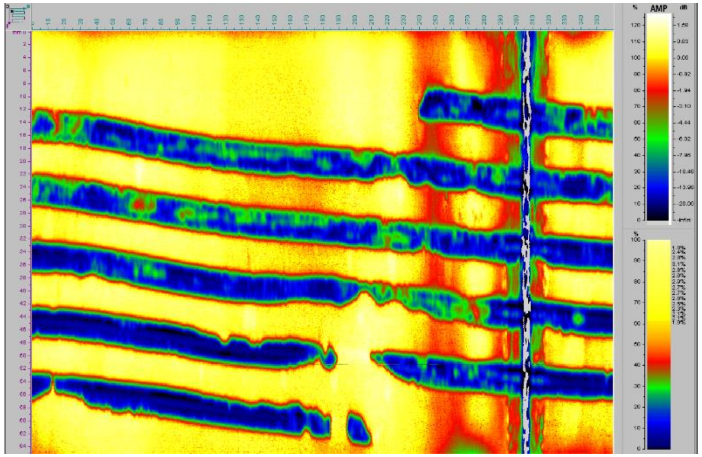
Vacuum Brazing Copper/Ferrite

Brazing of cooling-coil on copper cylinder



Test-Coil LHCMKIMA0356

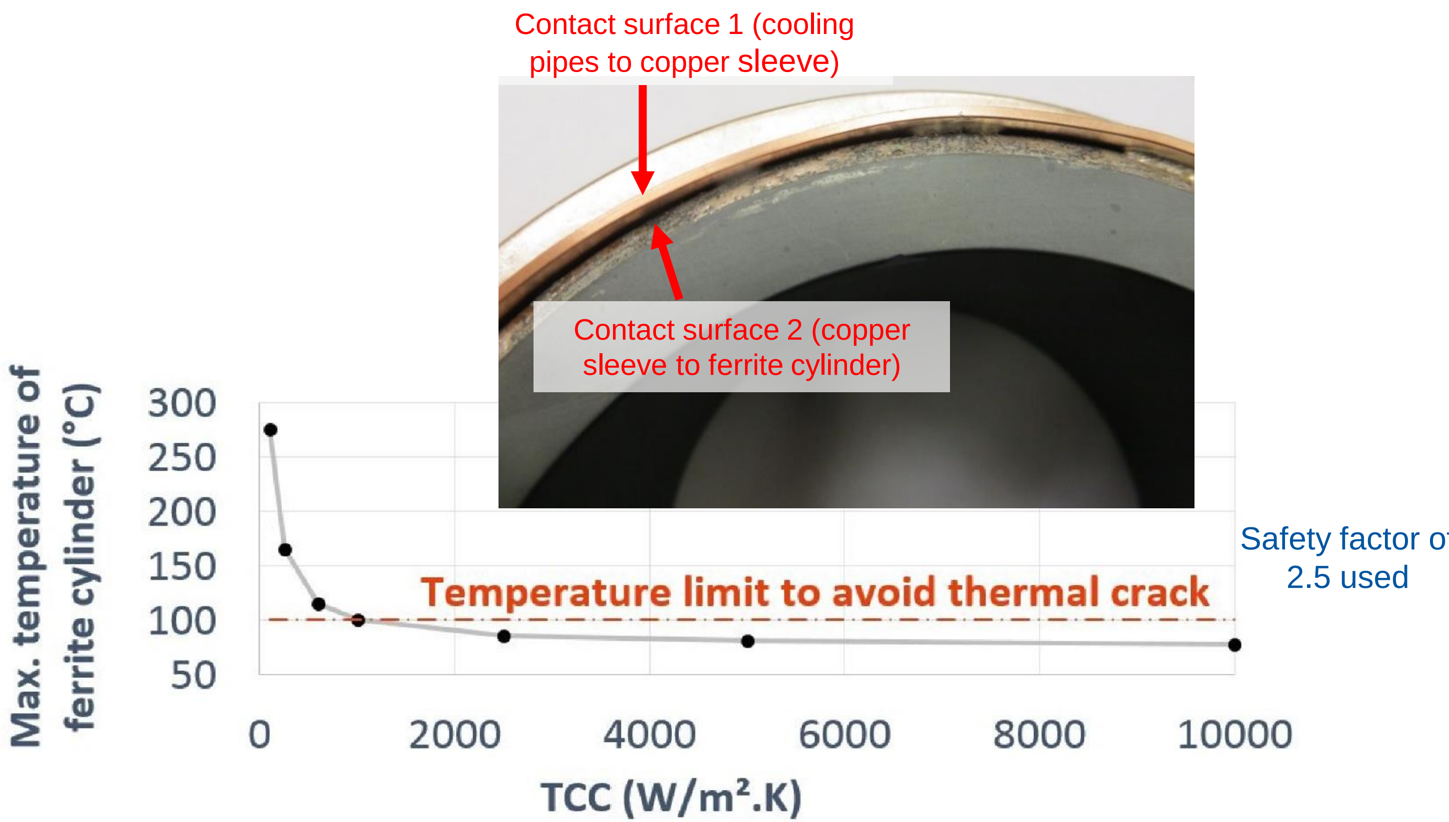
Brazing assembly – Ag-plated coil on Cu-tube



Brazed coil and UT-image of contact surface between coil and tube

Importance of TCC

- Previous thermal simulations, based on generic ferrite thermomechanical properties, set a maximum temperature of 100°C, to limit mechanical stress and avoid cracking of the ferrite of the RF damper.
- This gives a lower limit of 1000 $W/(m^2 \cdot K)$ for the Thermal Contact Conductance (TCC) between ferrite cylinder and copper sleeve.



Helical beam screen

Beam coupling impedance