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Beam screening and coating experience at CERN for fast pulsed magnets

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Acknowledgements to all the kicker team

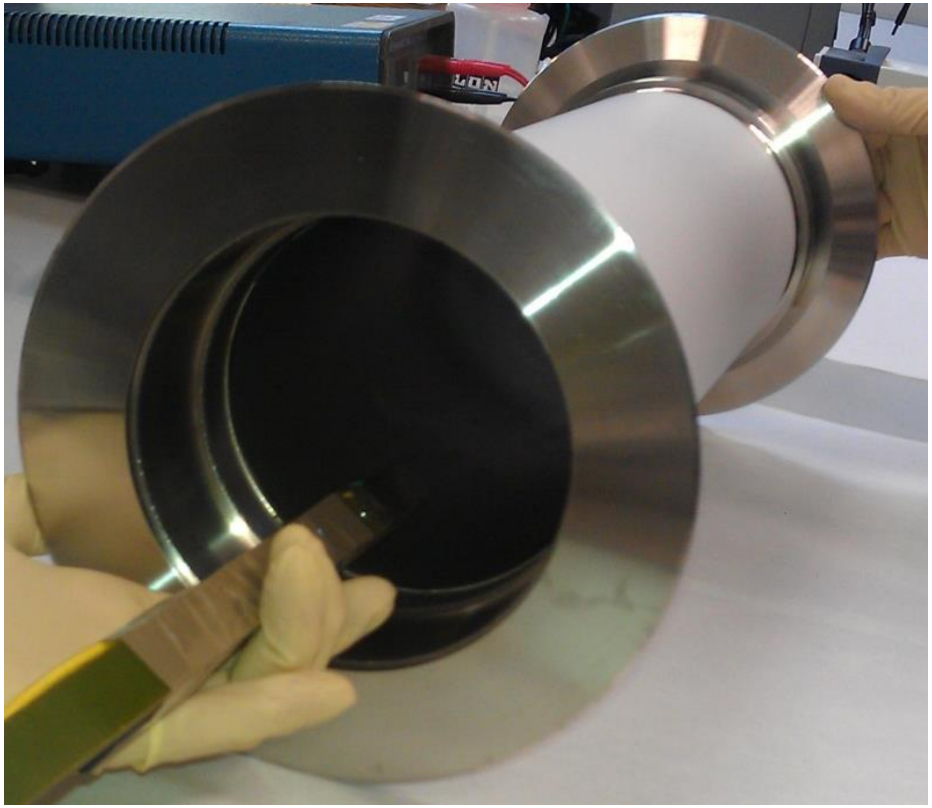
OUTLINE

- Beam heating effect

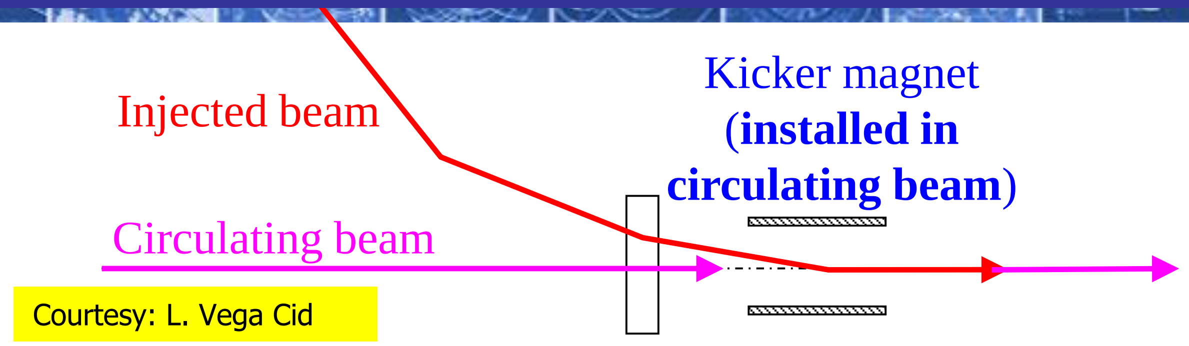
- Beam screening
  - Uniform resistive coating
  - Screen conductors
  - Serigraphy on ferrite
  - Serigraphy on ceramic

- Electron cloud
  - Reduction of SEY

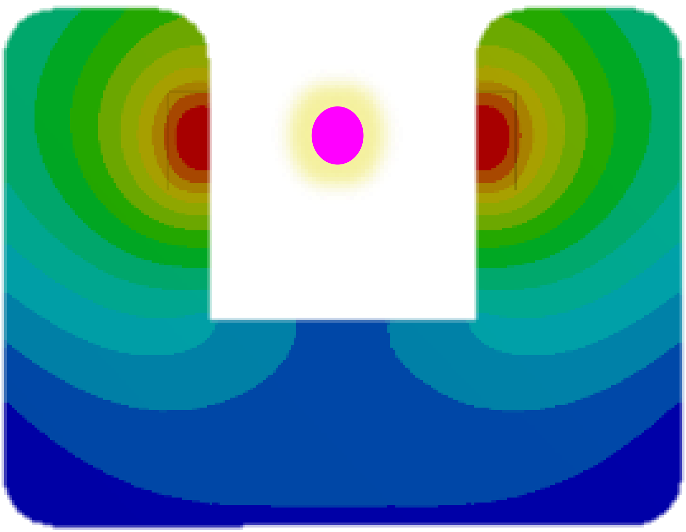
- Conclusion and outlook



BEAM HEATING EFFECT

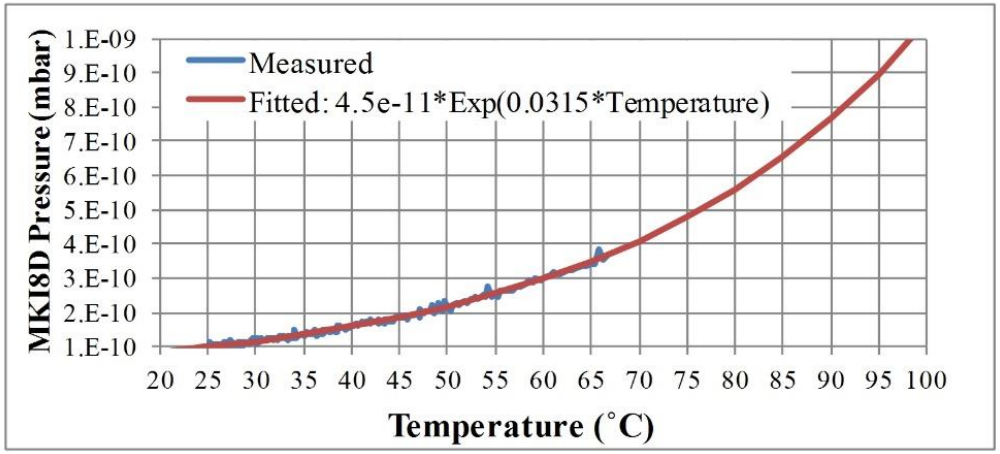


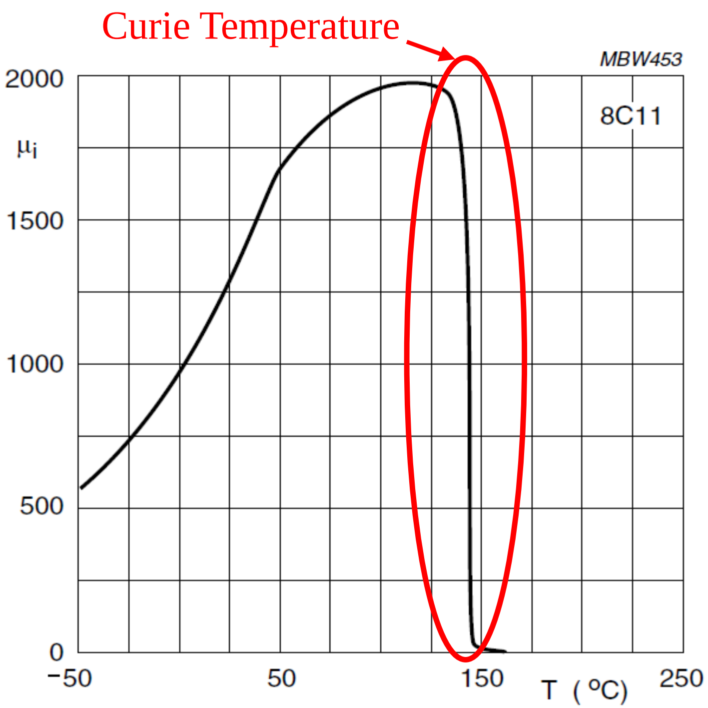
- Fast pulsed magnets, so called kicker magnets, are widely used at CERN for fast, single-turn, injection and extraction
- Typical field rise/fall-times range from tens to hundreds of nanoseconds
- During operation with high intensity beams, the real longitudinal beam-coupling impedance of kicker magnets can provoke significant heating of the ferrite yoke
- The induced heat is a function of :
  - magnet aperture geometry
  - beam intensity
  - beam structure
  - ferrite losses at beam frequencies
  - resonances caused by geometrical features



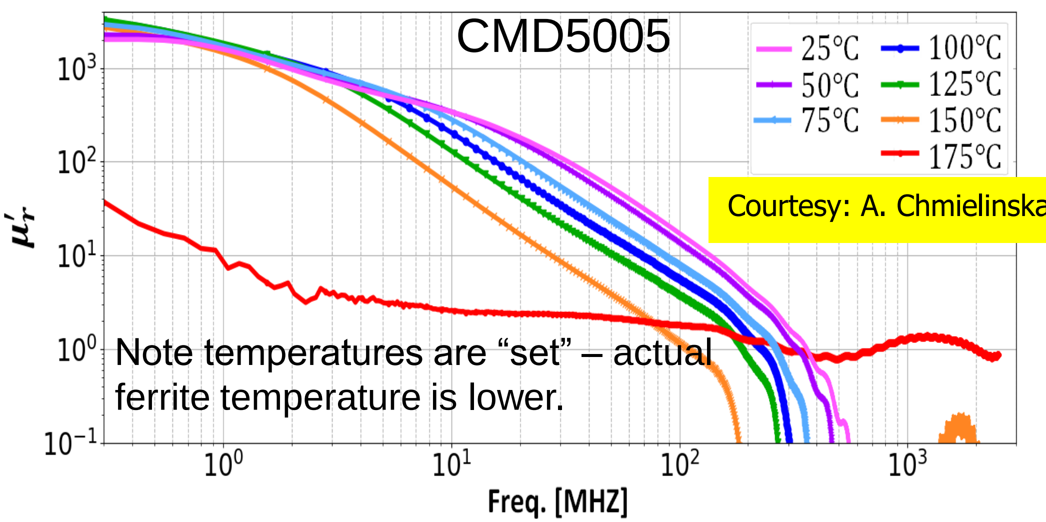
BEAM HEATING EFFECT

- The heating of the ferrite can result in :
  - local degradation of the vacuum
  - loss of the magnetic properties (Curie point exceeded)



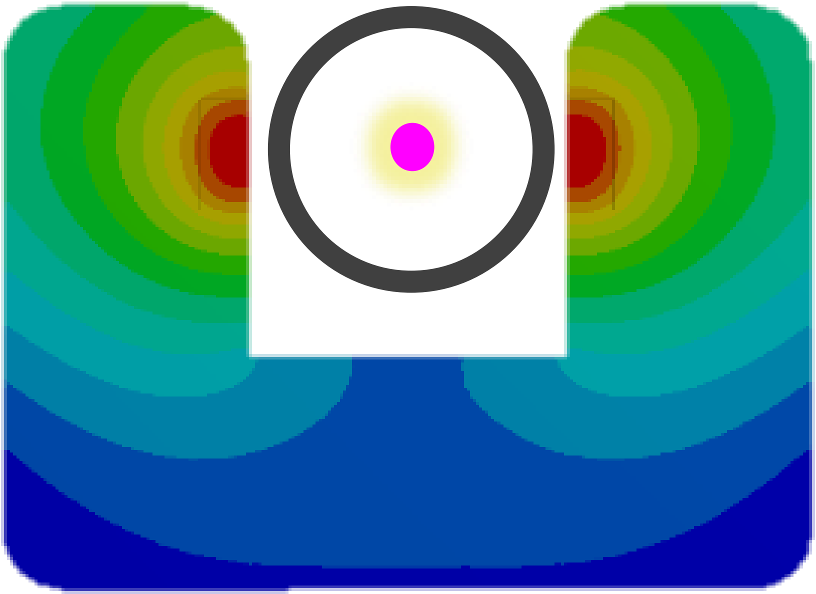


Above the Curie Temperature the ferrite temporarily looses its permeability.



BEAM SCREENING

- The beam coupling is reduced by providing a path for the beam image current, which screens the ferrite yoke from the wakefields
- Such a screen should be installed between the beam and the ferrite yoke

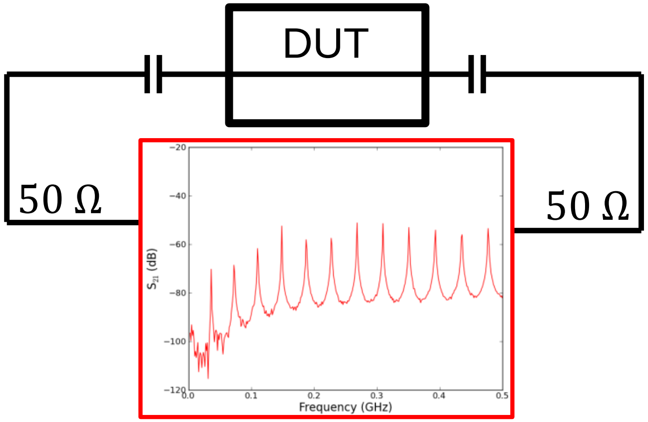


Courtesy: L. Vega Cid

- The transverse and imaginary longitudinal beam-coupling impedance of kicker magnets can provoke beam instabilities
- In addition to the beam impedance, high-impedance resonances usually occur when the image path of the beam is not continuous, for example, a gap between the end of the kicker magnet and the vacuum tank

Beam Impedance Measurements

- Method: resonant coaxial wire measurement → high sensitivity to low impedances
  direct coaxial wire measurement → continuous data, but less sensitive
- The device under test is turned into a coaxial resonator --> Q-factors can be accurately measured

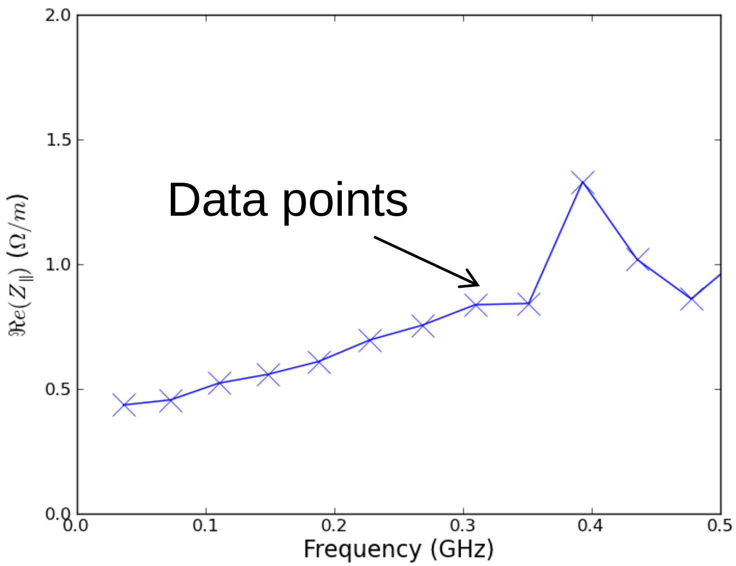


Vector Network Analyser

$\Delta f = nc/2L_{DUT}$

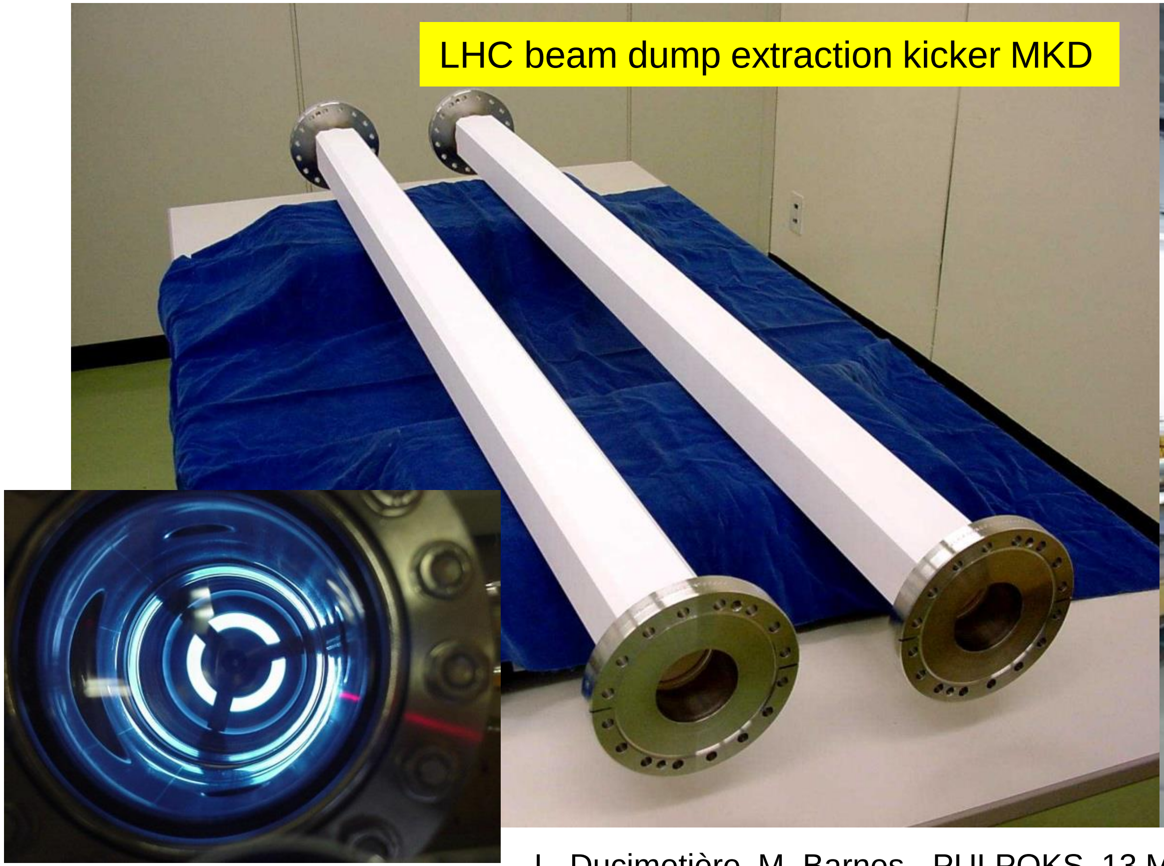
Example L_{MKI} = 3m : Δf = 41MHz
Can be improved by artificially lengthening the device

- Each resonance gives a data point : resonant frequency and the Q-factor (loaded, modify to find unloaded)
- Q-factor gives losses which gives the real longitudinal impedance



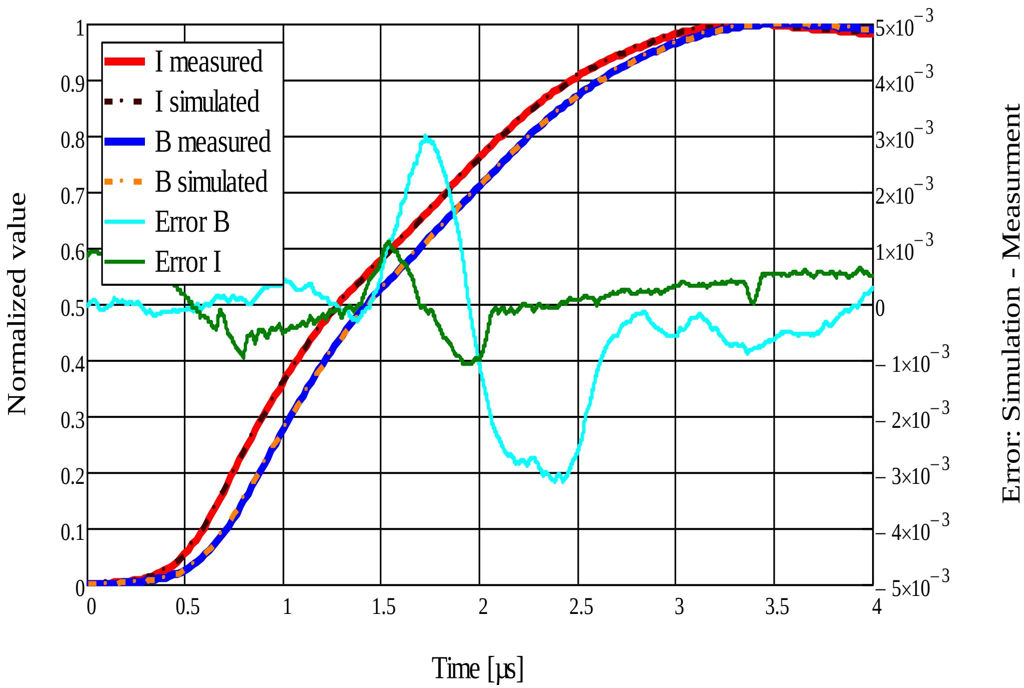
RESISTIVE COATING

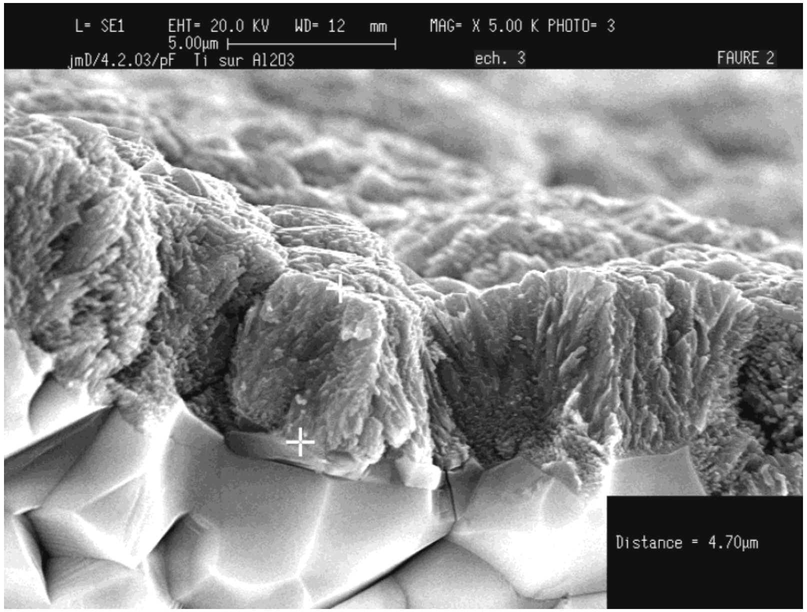
• An uniform resistive layer is the easiest way to provide beam screening when the field rise time is in the microsecond range
• However a ceramic chamber or plates are required on which to apply the layer, which requires an increase in the aperture of the magnet



RESISTIVE COATING

- The LHC beam dump extraction kicker MKD is equipped with a 1.5 m long ceramic vacuum chamber, which has been metallized with Titanium at 0.15 Ω/□.
- The field rise time is 3 μs.
- The time shift introduced by the metallization is about 100 ns





RESISTIVE COATING

- An analytic model has been proposed by S.H. KIM, APS, USA and was refined by Mike BARNES and Tobias STADLBAUER, who introduced a correction factor Δ_{corr}
- The formula gives the time constants τ of magnetic field decays for different chamber geometries, assuming a half-sine field pulse and spatially uniform coating over the chamber

$$\tau = \mu_0 \, \sigma \, d \, \Delta_{corr}$$

$$\Delta_{corr} = k_1 \, w^{1.995} + k_2 \, h^{1.646} - k_3$$

k_1, k_2 and k_3 are constant:

$k_1 = 3.498$ [$m^{-0.995}$]
$k_2 = 1.3$ [$m^{-0.646}$]
$k_3 = 2.97 \cdot 10^{-3}$ [m]

τ = magnetic field decay [s]

μ_0 = permeability of free space [H/m]

σ = coating conductivity [S/m]

d = equivalent coating thickness [m]

w = width of ceramic chamber [m] (width is defined to be orthogonal to the direction of the magnetic field)

h = height of ceramic chamber [m] (height is defined to be in the direction of the magnetic field)

- For round chambers the width and the height are both set equal to the diameter

RESISTIVE COATING

- The calculated time constant τ can be use for analytical calculations:
- Analytical equations for trapezoidal field

$$B_1(t) = B_0 \frac{\tau}{t_{rise}} \left(e^{-\frac{t}{\tau}} + \frac{t}{\tau} - 1\right) \quad \text{for} \quad t \le t_{rise}$$

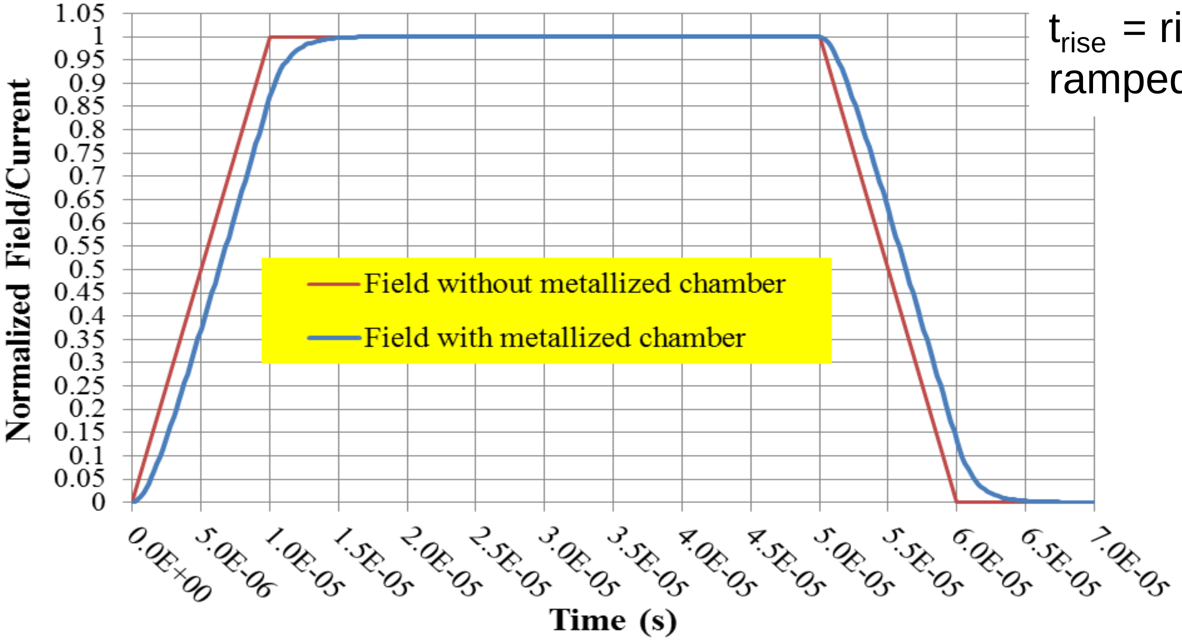
$$B_2(t) = B_1(t_{rise}) - B_1(t - t_{rise}) \quad \text{for} \quad t > t_{rise}$$

τ = time constant, including correction factor [s]

B_0 = maximum applied field [T]

B_1, B_2 = magnetic field at centre of vacuum chamber [T]

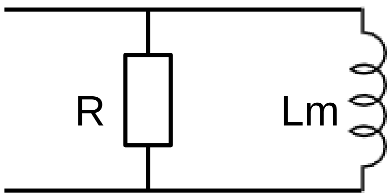
t_{rise} = rise time, 0% to 100%, of the ramped current [s]



RESISTIVE COATING

• The calculated time constant τ can also be use for analogue simulation for any pulse shape :

•The effect of the metallization is then modelled by a resistor R in parallel with the magnet inductance

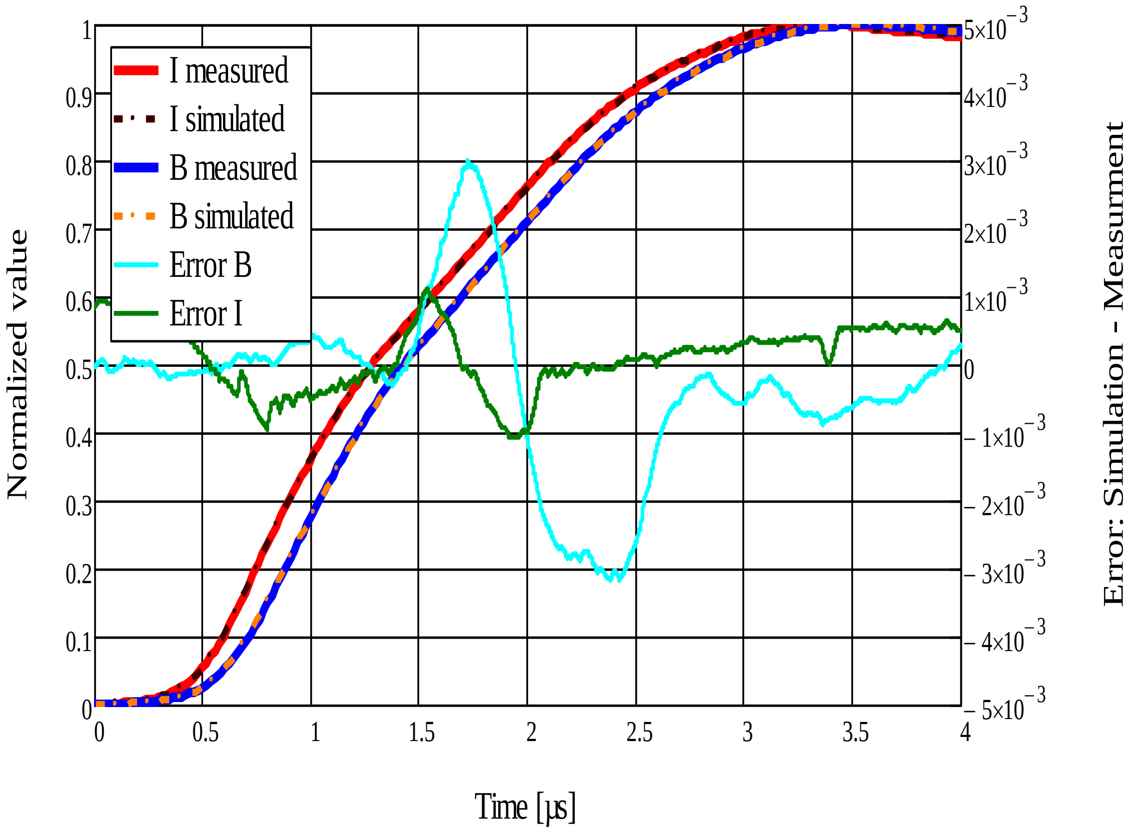


R = Equivalent resistance [Ω]

$$R = \frac{Lm}{\tau}$$

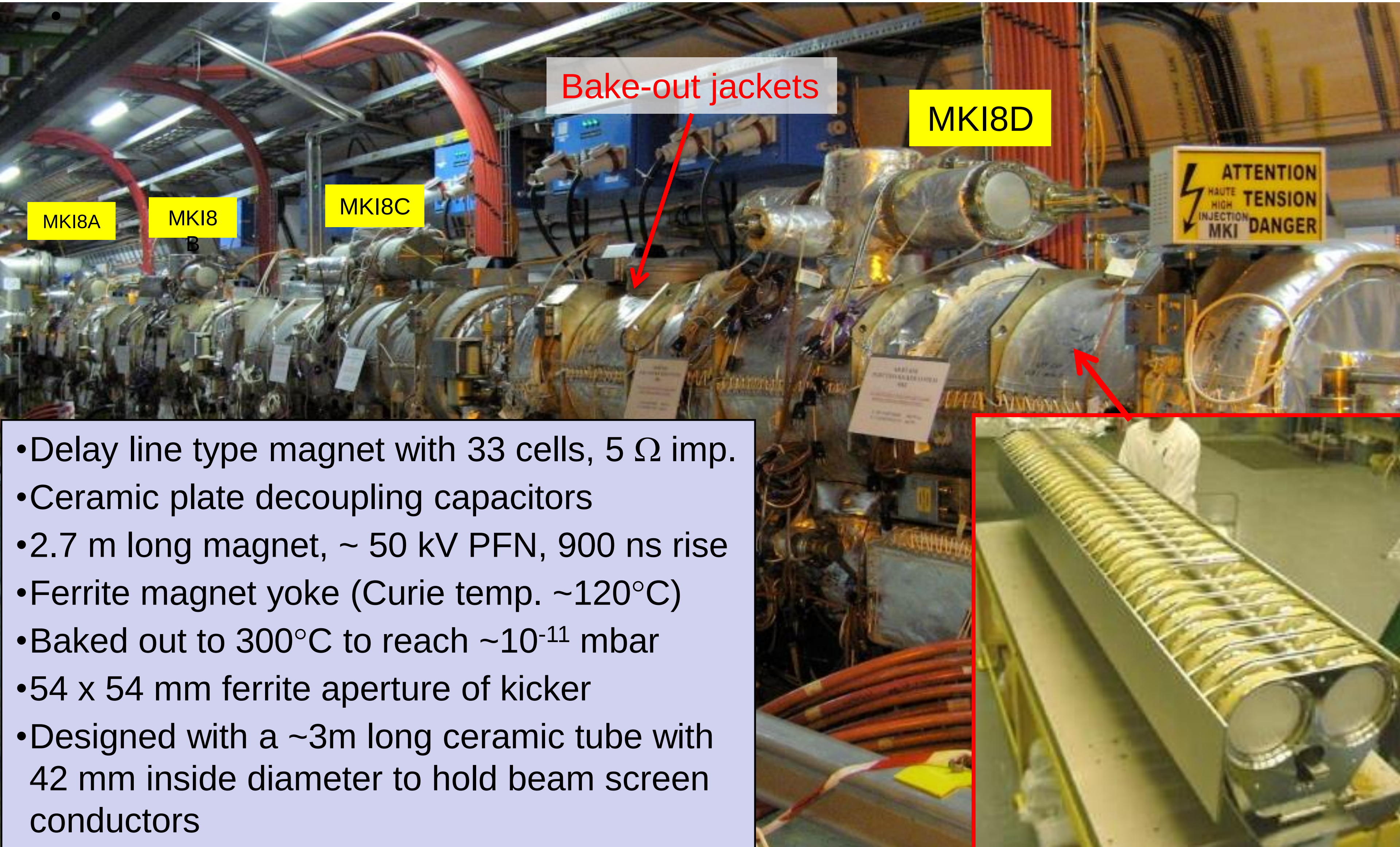
τ = time constant, including correction factor [s]

Lm = magnet inductance [H]



Screen conductors

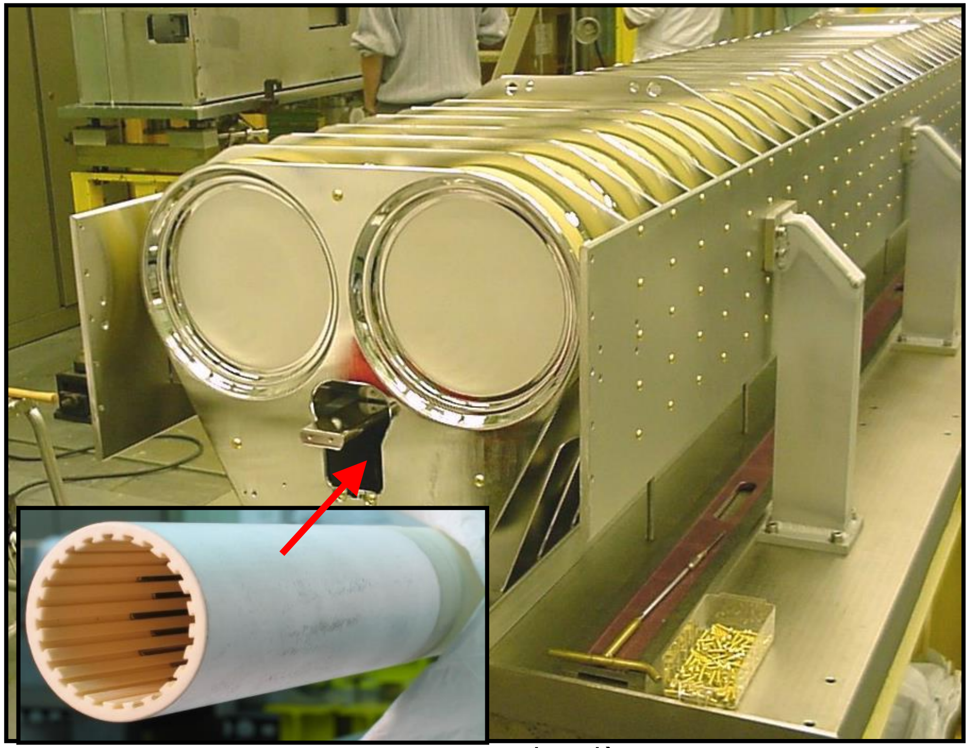
- LHC injection kicker magnets MKI - 4 MKIs per injection point

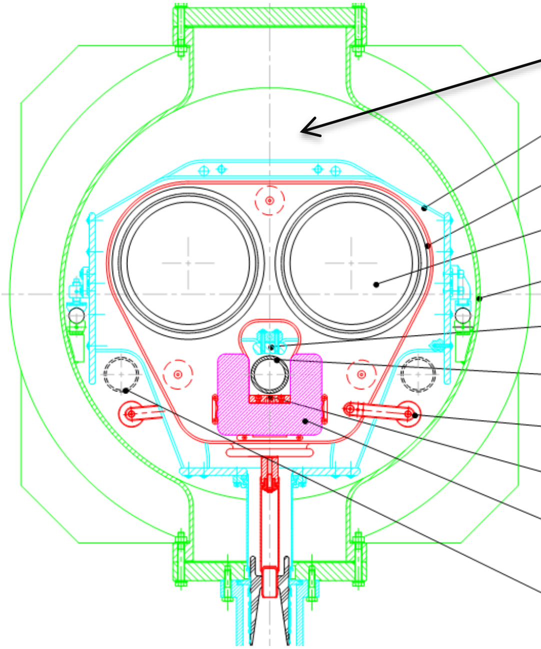


- Delay line type magnet with 33 cells, 5 Ω imp.
- Ceramic plate decoupling capacitors
- 2.7 m long magnet, ~ 50 kV PFN, 900 ns rise
- Ferrite magnet yoke (Curie temp. ~120°C)
- Baked out to 300°C to reach ~10^{-11} mbar
- 54 x 54 mm ferrite aperture of kicker
- Designed with a ~3m long ceramic tube with 42 mm inside diameter to hold beam screen conductors

Screen conductors

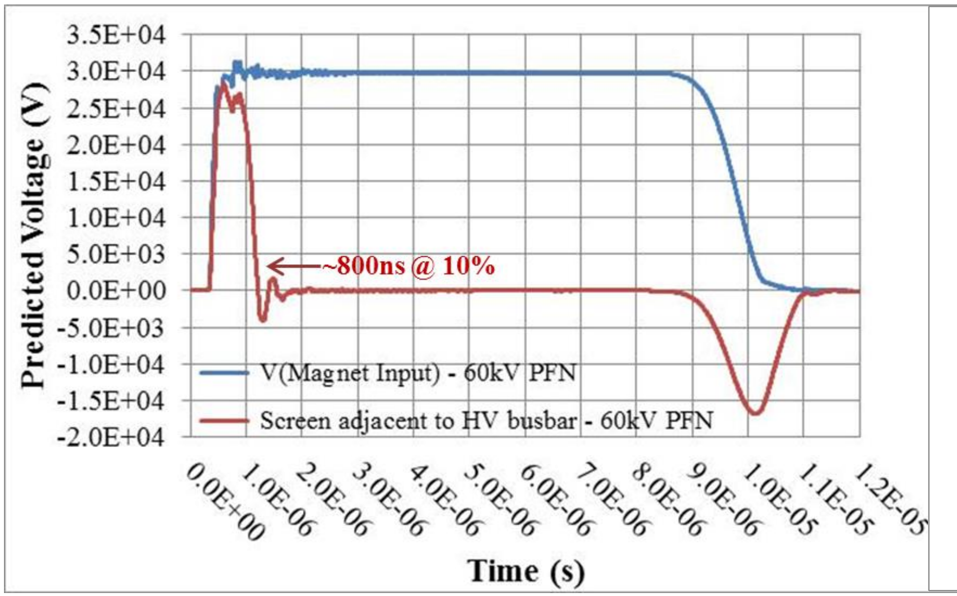
- The screening is provided by conductors lodged in the inner wall of a ceramic support tube.
- The conductors are made of nickel-chrome (80/20) stripes 0.7 mm x 2.7 mm with rounded corners
- On one end, all conductors are connected together to the grounded beam pipe
- On the other end, all conductor are open, but capacitively coupled to the beam pipe through the ceramic tube that is metalized on its outside over 200 mm

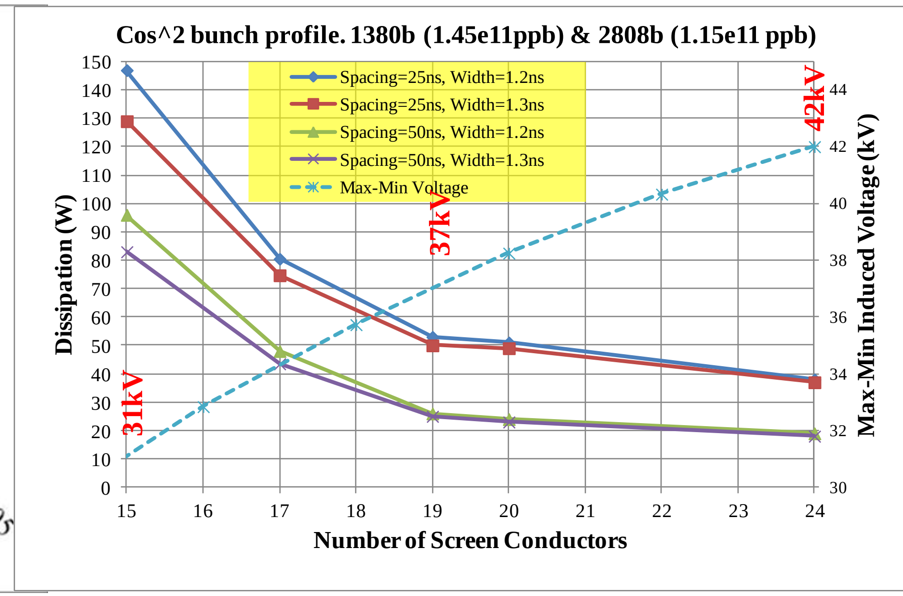




SCREEN CONDUCTORS

• Voltage is induced on a screen conductor mainly by mutual coupling with the cell inductance. The voltages at the open end of the screen conductors show a positive peak (max.) during field rise and a negative peak during field fall.
• The conductors closest to the HV busbar were initially removed to avoid flashovers: from the 24 stripes foreseen, only 15 stripes were installed up to 2012.

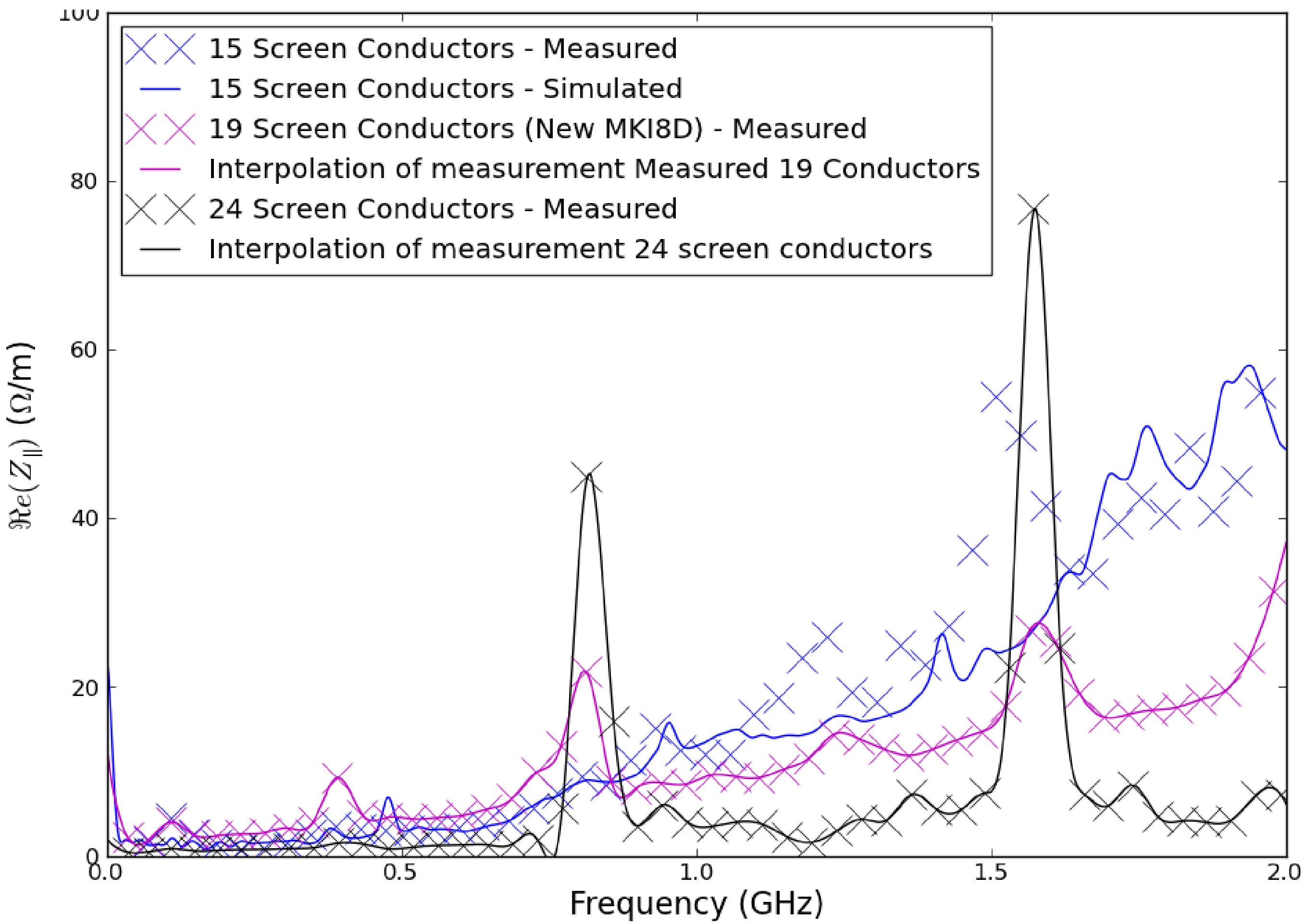




• Extensive studies have been carried out to successfully reduce the flashovers.
• The geometry of the tube end has been modified so that the predicted electric field was reduced by a factor 3
• Subsequently all 24 screen conductors were reintroduced.

SCREEN CONDUCTORS

- Beam impedance and expected losses deposition in ferrite yoke



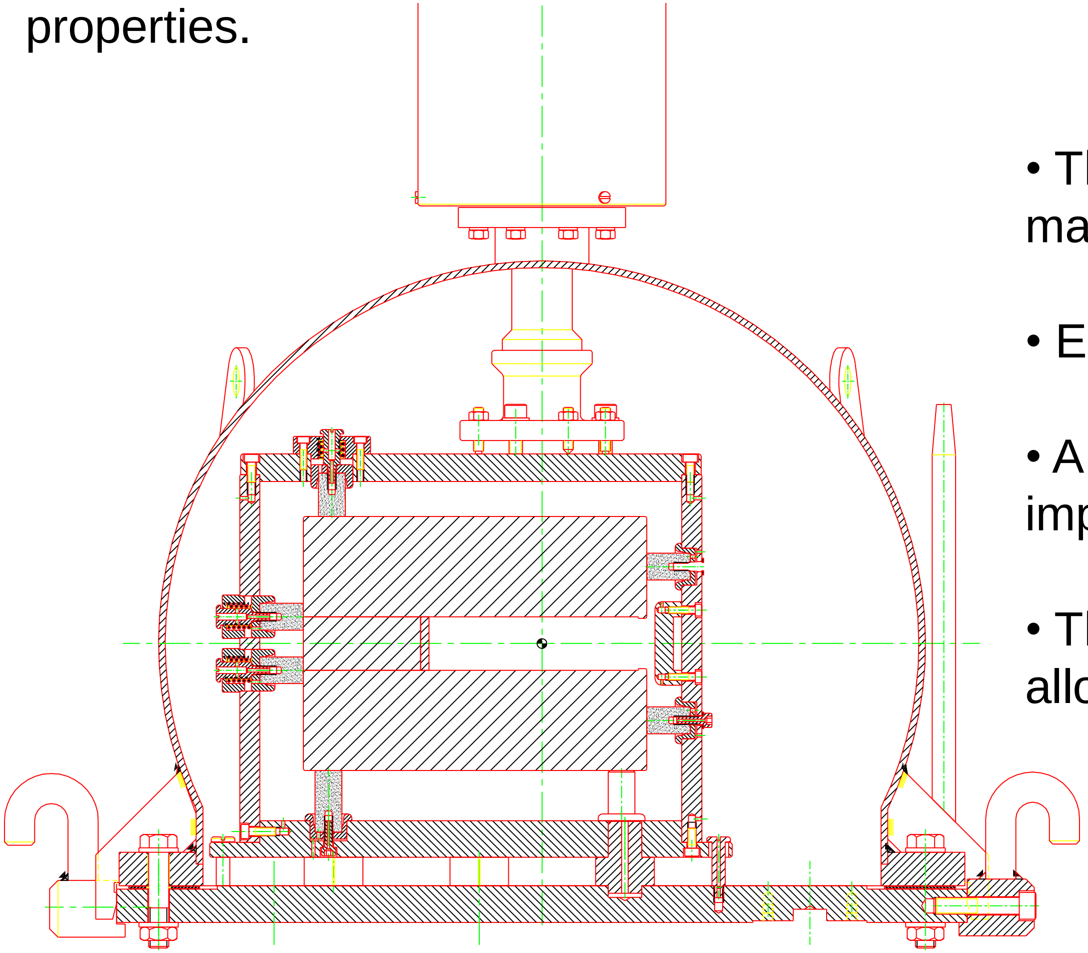
- In 2012 with nominal power and 15 conductors: ~70 W/m;

Improved screening (15 ➪ 24 conductors) reduces power deposition by a factor of 2 to 3;

- For the future high-luminosity LHC version : ~200 W/m with 24 conductors.

SERIGRAPHY ON FERRITE

• During scrubbing runs, the SPS extraction kicker magnet MKE went above about the Curie temperature of 120˚C. The 8C11 ferrite yoke temporarily lost its magnetic properties.



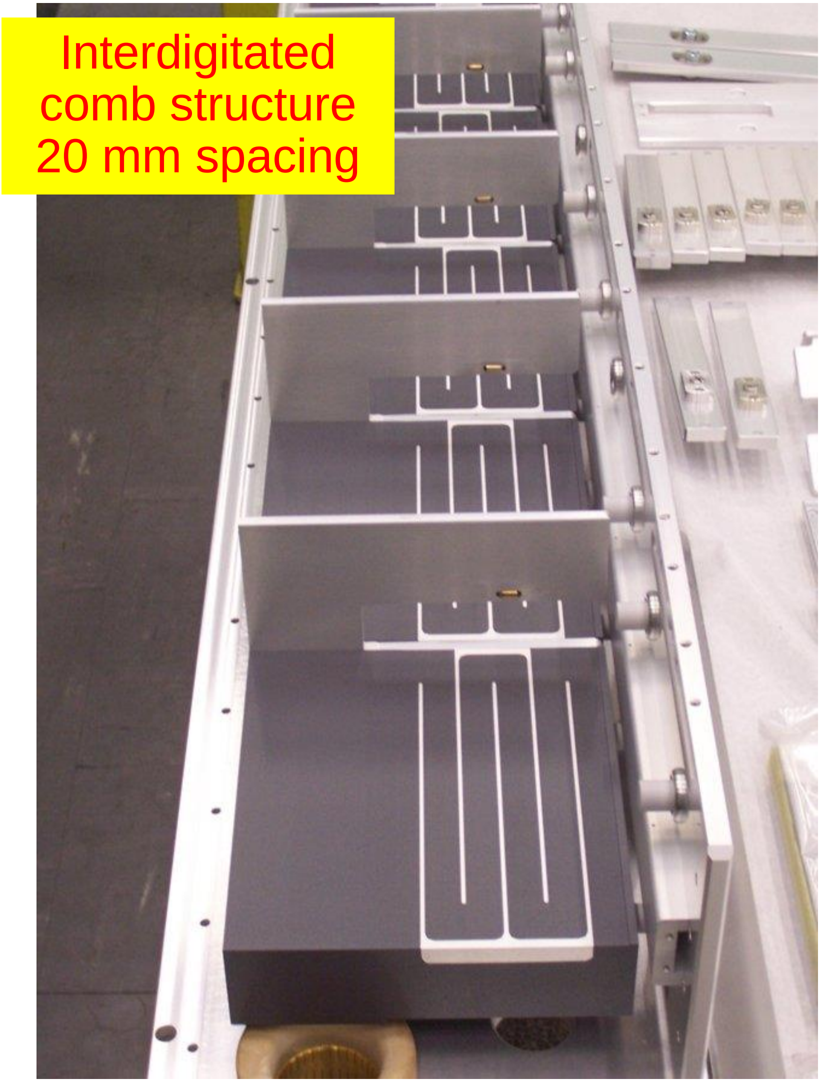
• The MKE is a delay line type kicker magnet made of 7 cells

• Each cell has a length of 230 mm

• A beam screen had to be implemented as retrofit

• The aperture is limited and does not allow for any insert

SERIGRAPHY ON FERRITE



- Beam coupling impedance has been reduced using conductive stripes (serigraphy), i.e. interleaved comb structure, directly printed onto the ferrite blocks, with a reliable contact to the metallic HV plates at either side

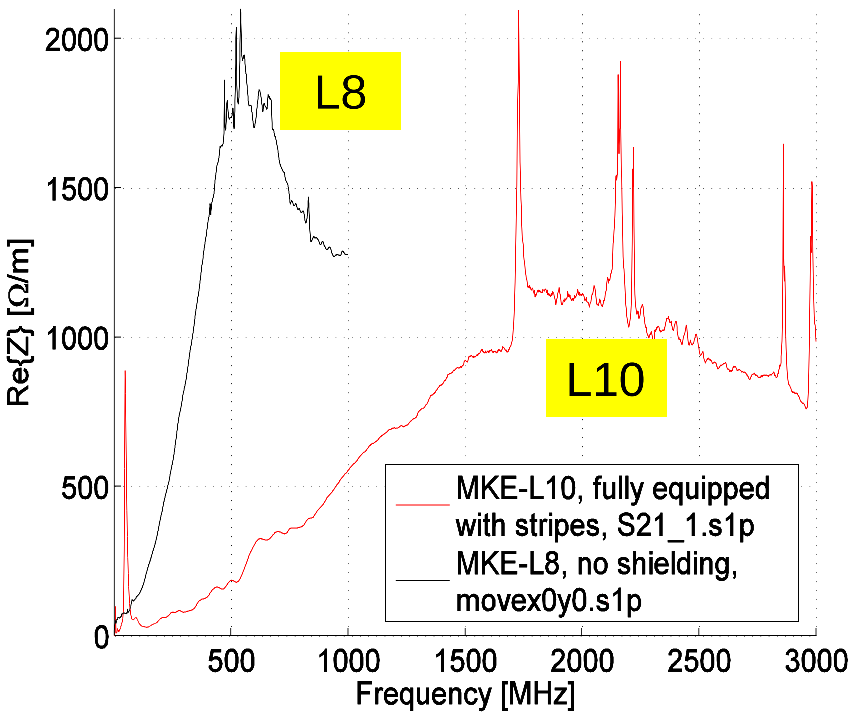
- The capacitive coupling between stripes carries the beam image current

- No impact on the beam aperture

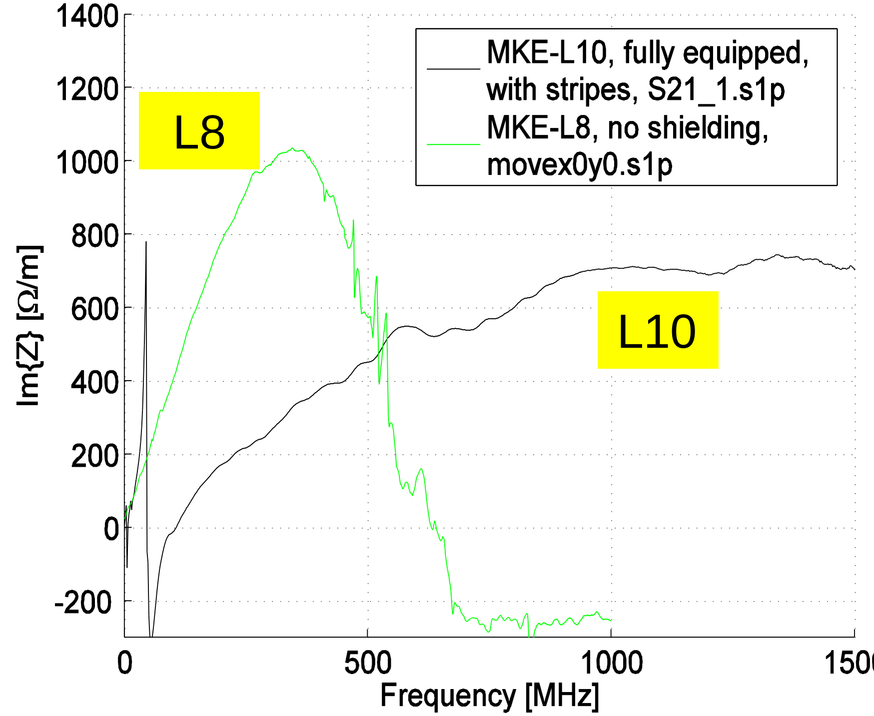
SERIGRAPHY ON FERRITE

- 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

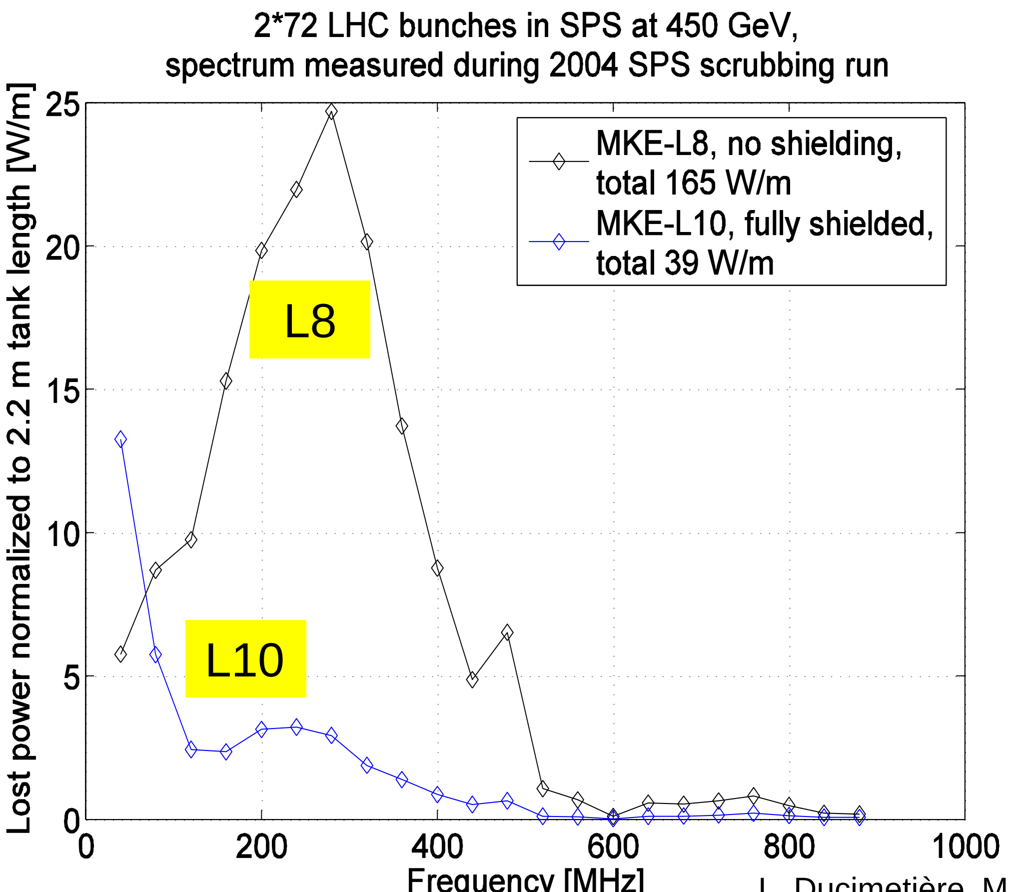


Imaginary part of Z



SERIGRAPHY ON FERRITE

• Power Deposition in Ferrite Yoke : comparison between fully shielded (L10 magnet) and unshielded (L8 magnet)



• Calculated using beam spectrum measured during 2004 SPS scrubbing run
  • 2*72 LHC bunches in SPS at 450 GeV;

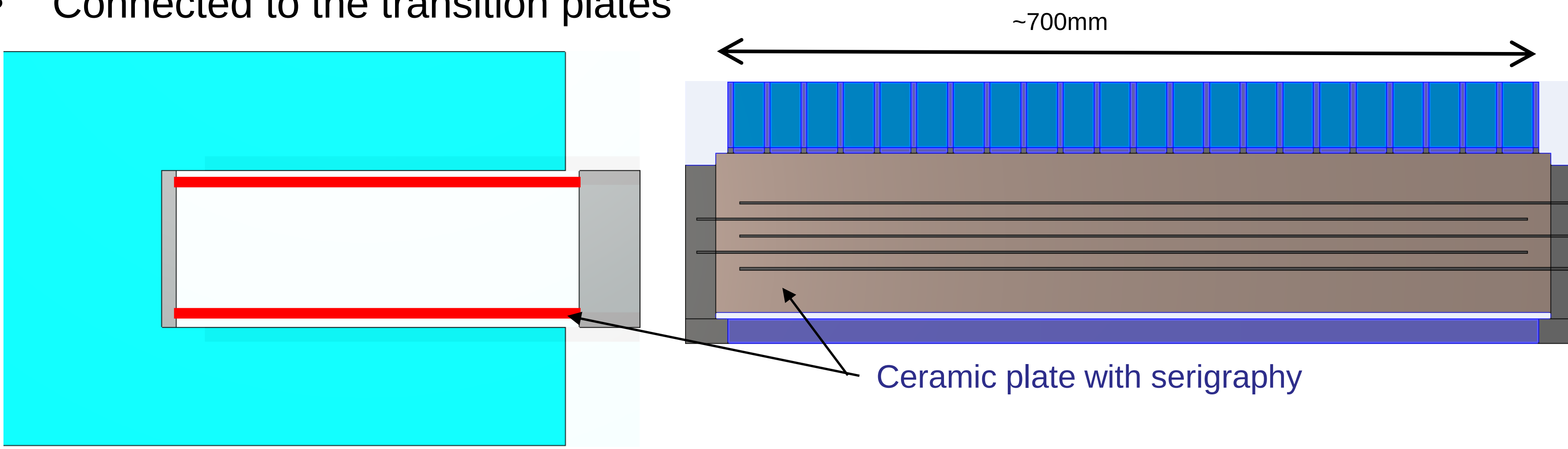
• Serigraphy (painted stripes) reduces calculated power deposition by a factor of >4, for LHC beam

SERIGRAPHY ON CERAMIC PLATE

Alternative for delay line type kicker magnet with short cells :

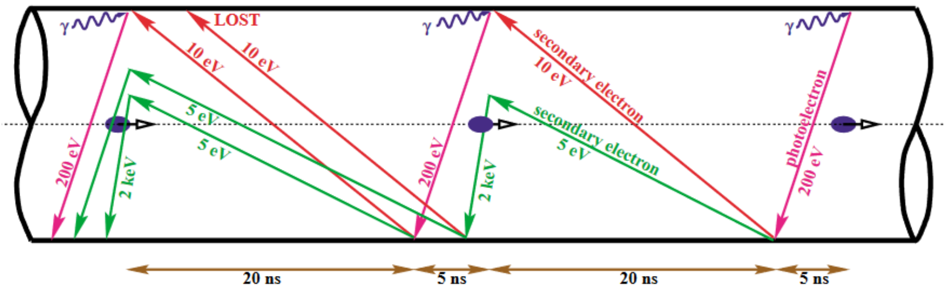
Injection kicker magnet for SPS : MKPL 22 cells, 700 mm total lenght

- Serigraphy over full length of module, applied onto a ceramic thin plate
- Connected to the transition plates



Currently under development …

Electron Cloud



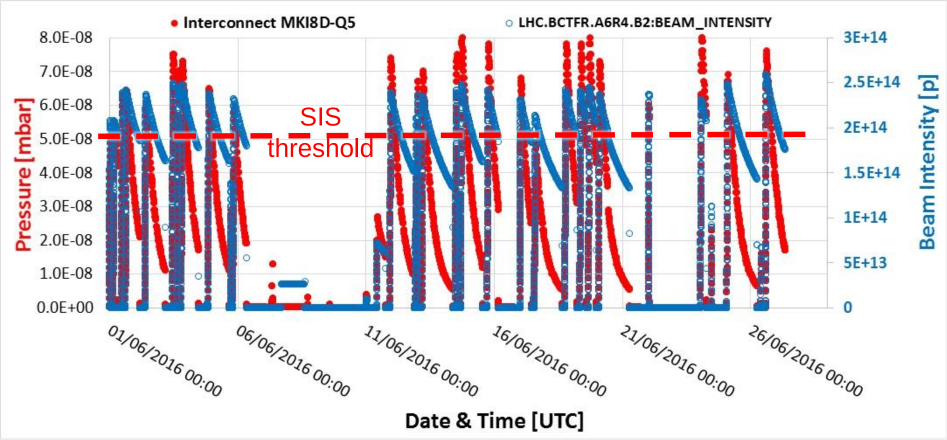
Schematic of electron cloud build-up mechanism in LHC (courtesy of F. Ruggiero)

- Due to the close bunch spacing of 25 ns, in the LHC, a significant number of electrons can accumulate in the LHC beam pipe.
- Seed electrons are accelerated by the beam electric field and can impact on the side of the vacuum chamber → if the Secondary Emission Yield (SEY) is greater than **1**, it can create a large number of secondaries.

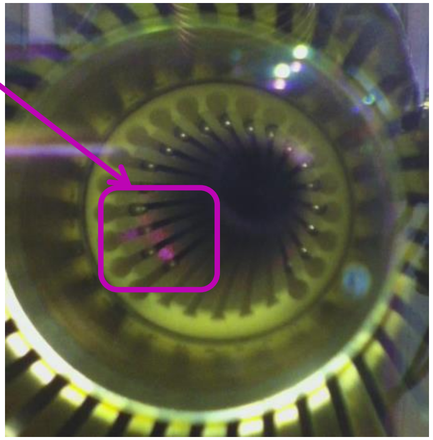
- SEY of alumina is in the range **5 to 10** !

Electron Cloud

In 2016 dynamic pressure rise attributed to high Secondary Electron Yield (SEY) of alumina tube, by a factor of ~20 to 1000 in MKI interconnects
→ it limited injection of high-intensity bunches into the LHC.



Electrical discharge could occasionally be observed (in lab) on "naked" alumina, at end of screen conductors, due to high induced voltage.

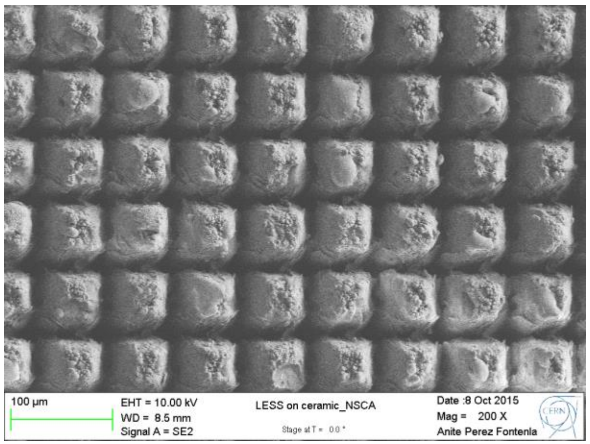


The SEY of the ceramic is also responsible for the surface flashover of the MKI beam screen conductors

→ **Highly desirable to reduce SEY**

Reduction of SEY

Laser Engineered Surface Structures (University of Dundee, UK): Trap electrons in "wells"

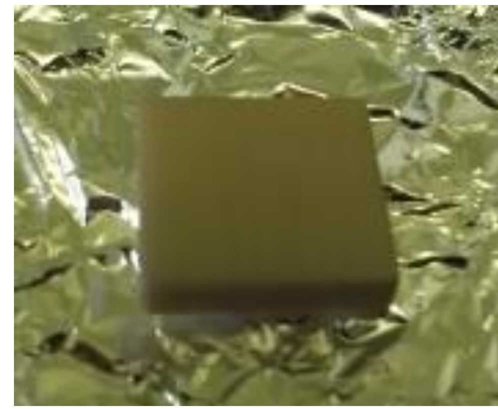


- Measured maximum SEY reduced to ~1.6
- Due to high resistivity, alumina charges up.

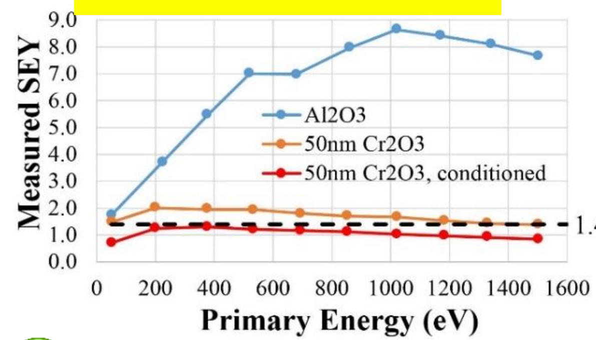
Cr_2O_3 coating applied by painting or spraying (Friatec, Germany):

- Measured maximum SEY reduced to ~1.7;
- Further conditions in lab to less than 1.4;
- Very dusty finish: surface can be sealed with Silicone ⇨ SEY increases to ~3.

Cr_2O_3 coating applied by magnetron sputtering (Polyteknik, Denmark):

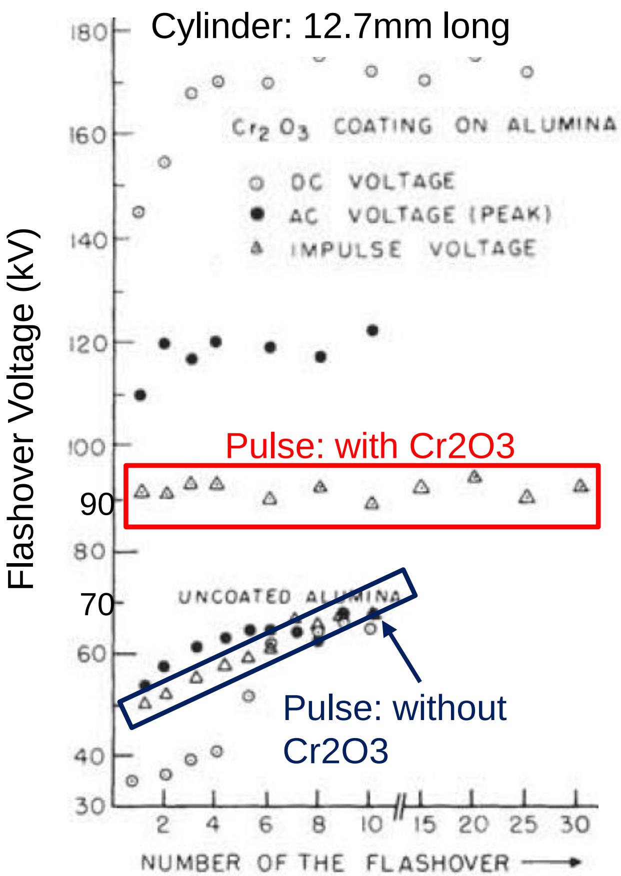


Measurements courtesy of:
E. Valdivieso & H. Neupert



- No dust.

Surface flashover



- Cr_2O_3 was originally studied for coating of MKI alumina tube in order to increase the voltage of flashover in vacuum by ~30% (based on papers by Sudarshan and Cross (1976), and by T. Shioiri (2006)) :
  - reducing secondary electron avalanche;
  - reducing surface charging due to decreased surface resistance ($10^{10} – 10^{11}$ Ω·cm).

One MKI magnet was equipped with a Cr2O3 coated alumina tube.
→ went successfully through two extended high voltage conditioning processes, with voltages up to 10% above operational voltage,
→ Installed in LHC.

CONCLUSION AND OUTLOOK

- Beam screens with uniform resistive coating are easy to implement, especially for lumped kicker magnets with rise/fall time in the microsecond range:
  - The field attenuation can be analytically predicted;
  - Requires a larger aperture, but also allows to build the magnet outside vacuum.

- Screen conductors are necessary for faster kicker magnets
  - Induced voltages are to be carefully taken into account

- Serigraphy combs on ferrite could be considered for retrofit solution when the cell length is large enough;
  - The aperture is preserved; geometrical resonances need to be considered.

- Retrofit solution with serigraphy on ceramic plate is under development

- CERN has pursued development of Cr_2O_3, applied by magnetron sputtering, to:
  - Reduce the SEY of the alumina surface facing the beam to limit electron cloud;
  - Improve the surface flashover capability of the ceramic under vacuum.

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Thank You !