Kicker Magnets and Vacuum

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Acknowledgements:

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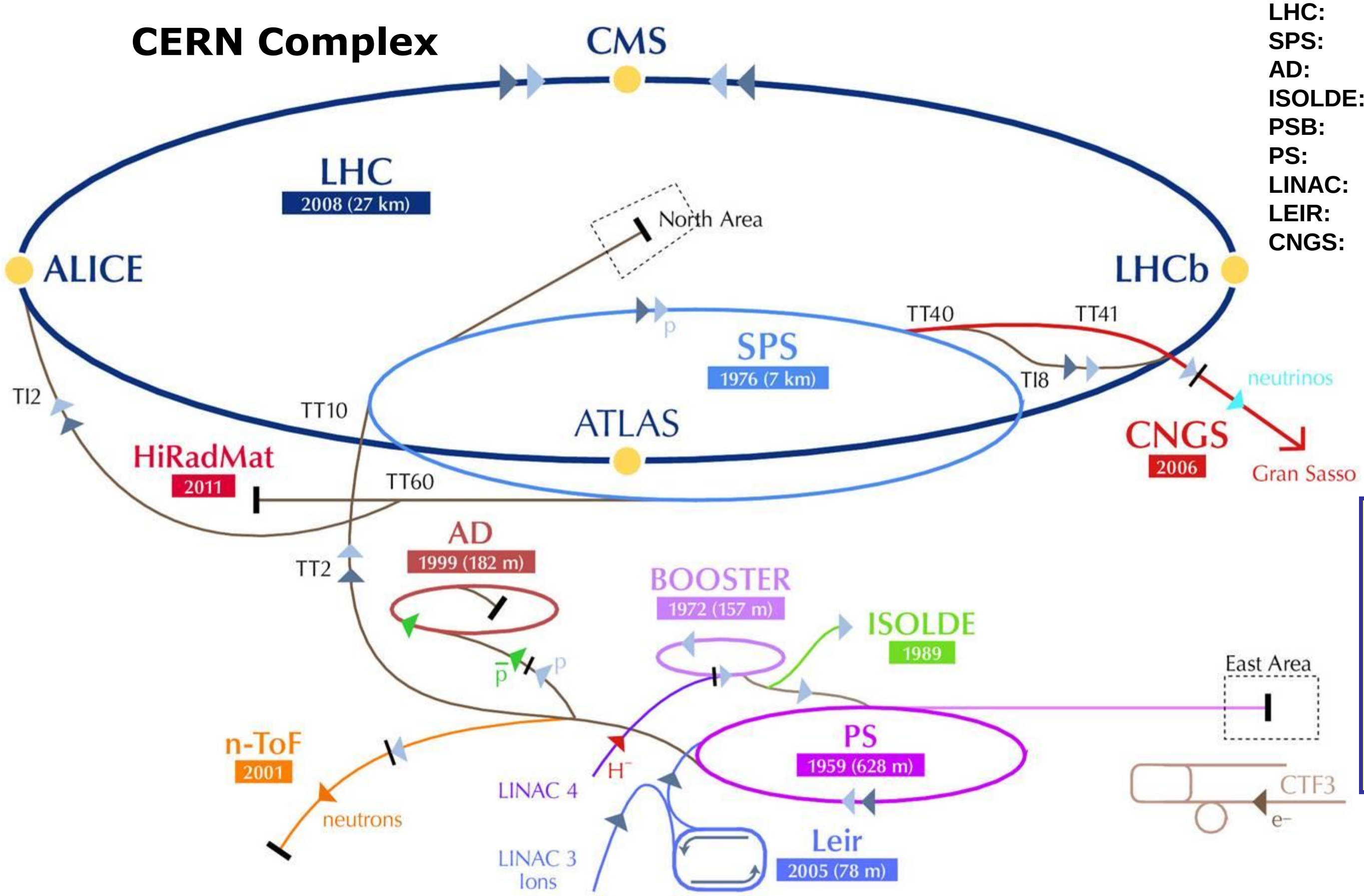
Overview

- Why are kicker magnets required?;
- What is a kicker magnet?;
- Overview of a kicker magnet system;
- Why do we typically install kicker magnets in machine vacuum?
- Influence of beam upon a kicker magnet, and (some possible) remedies:
  - Heating;
  - Vacuum pressure;
  - Electrical breakdown;
- Conclusions

Injection, Extraction and Transfer

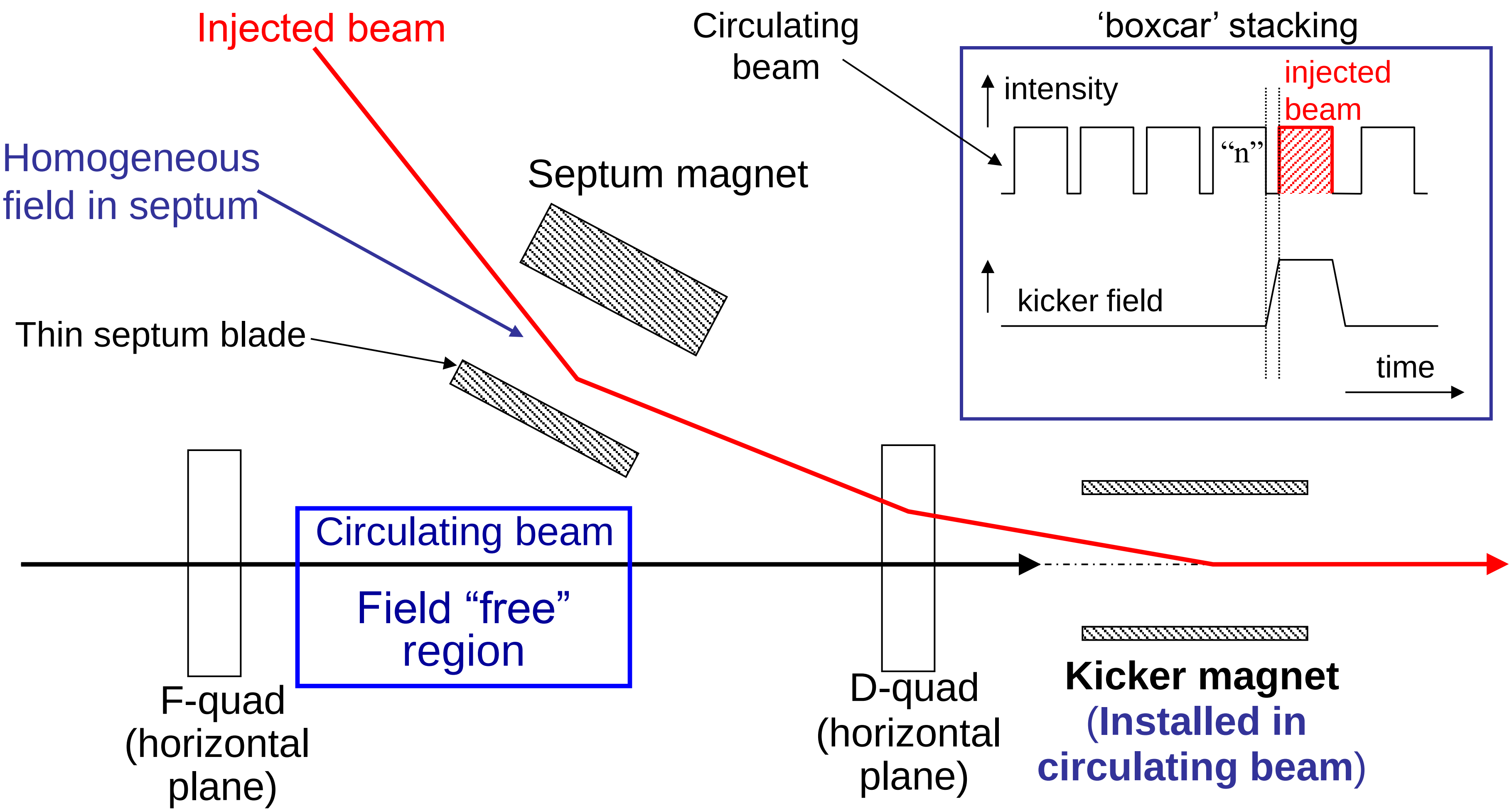


LHC:	Large Hadron Collider
SPS:	Super Proton Synchrotron
AD:	Antiproton Decelerator
ISOLDE:	Isotope Separator Online Device
PSB:	Proton Synchrotron Booster
PS:	Proton Synchrotron
LINAC:	LINear Accelerator
LEIR:	Low Energy Ring
CNGS:	CERN Neutrino to Gran Sasso

Beam transfer (into, out of, and between machines) is necessary: hence septa and kicker magnets are required.

- An accelerator stage has limited dynamic range;
- A chain of stages is needed to reach high energy;
- Periodic re-filling of storage (collider) rings, such as LHC, is required.

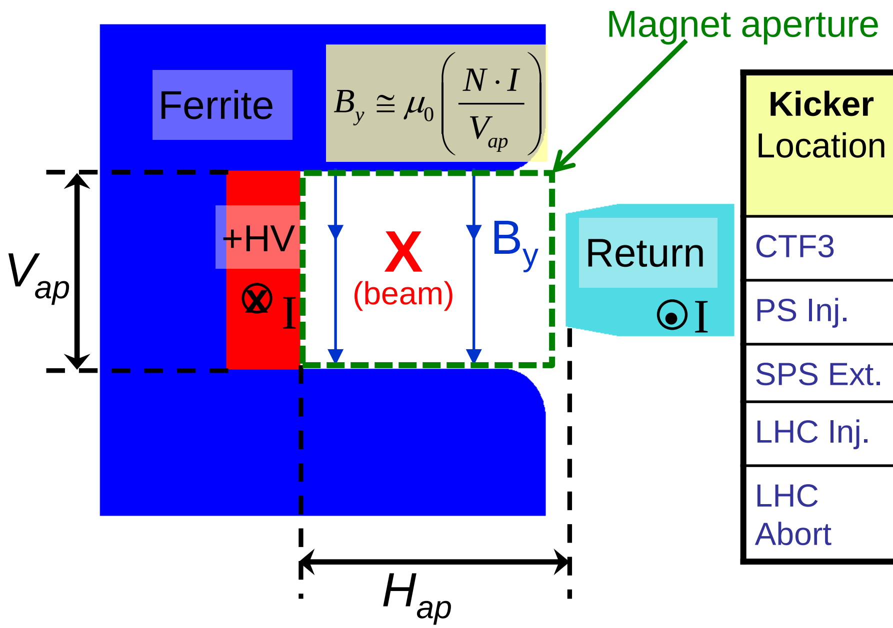
Injection – Horizontal Plane



- Septum deflects the beam onto the closed orbit at the centre of the kicker;
- Kicker (installed in circulating beam) compensates for the remaining angle;
- **The rise and fall time of the field of the kicker magnet must be FAST.**

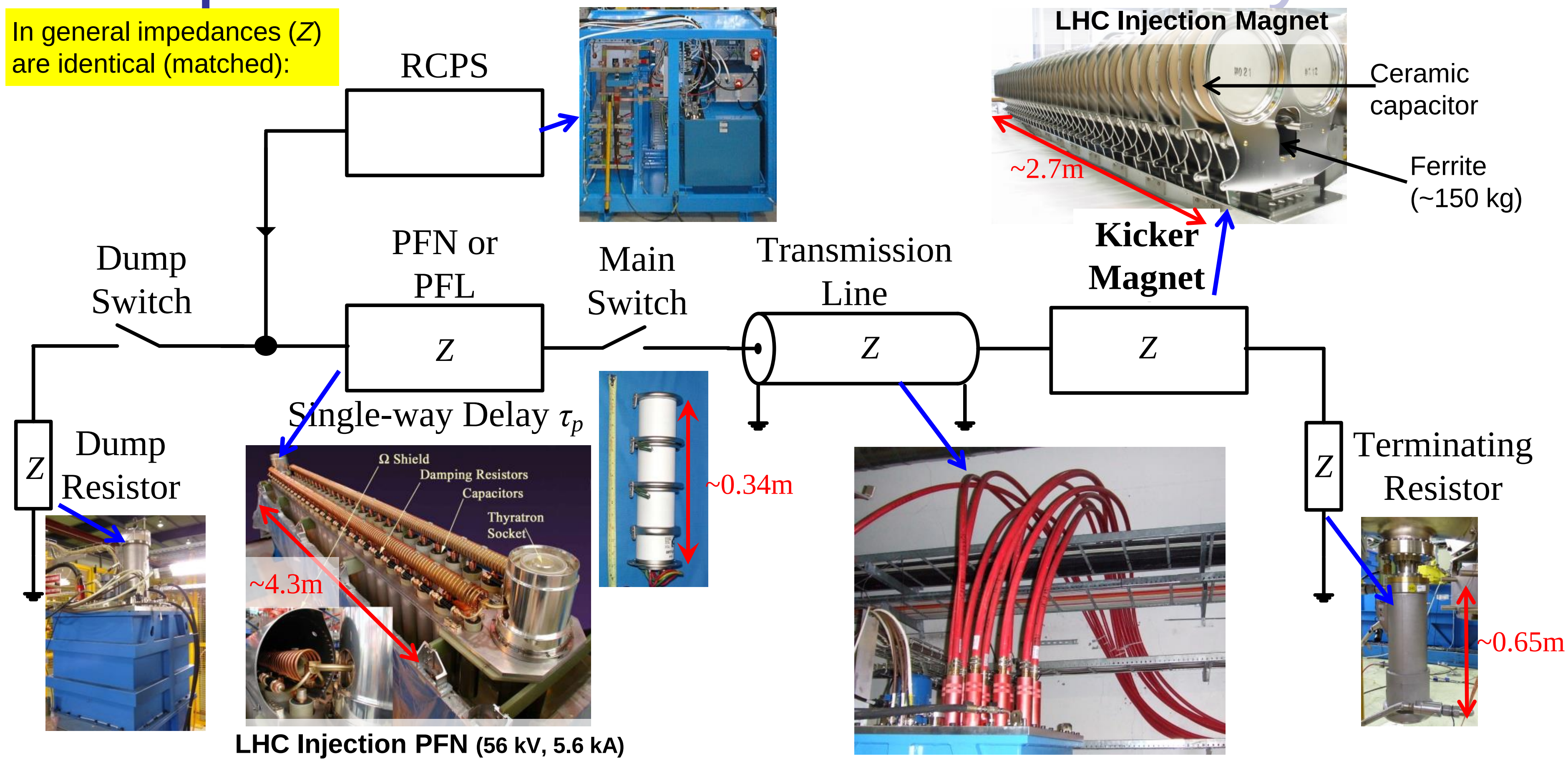
What is a kicker magnet?

- A kicker magnet typically uses a, fast, pulsed magnetic field to deflect beam, and normally uses ferrite to guide the field lines;
- The electrical circuit, of the complete system, is carefully designed to allow fast pulses to propagate with minimal distortion;
- High current (I) and voltage may be required: minimizing the aperture dimension V_{ap} will minimize the current required:



Kicker Location	Beam momentum (GeV/c)	Gap Height [V_{ap}] (mm)	**Current (A)**	**Field Rise Time (ns)**	Deflection (mrad)
CTF3	0.2	40	**56**	**~4**	1.2
PS Inj.	2.14	53	**1’520**	**42**	4.2
SPS Ext.	450	32 to 35	**2’560**	**1’100**	0.48
LHC Inj.	450	54	**5’120**	**900**	0.82
LHC Abort	450 to 7’000	73	**1’300 to 18’500**	**2’700**	0.275

Simplified Schematic of Kicker System

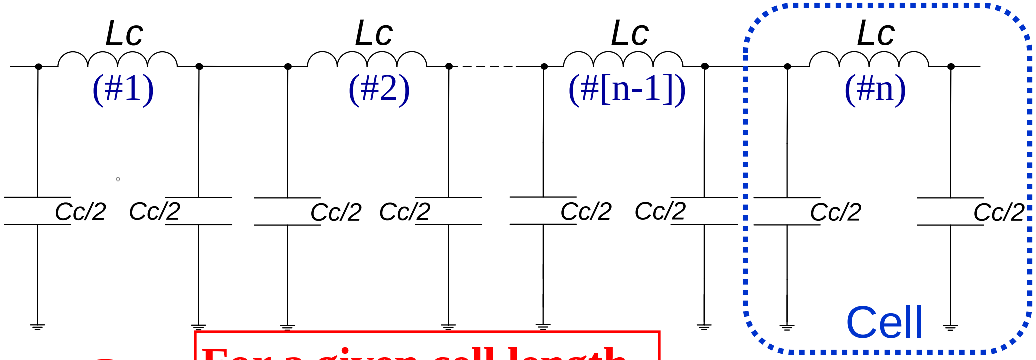


Typical circuit operation:

- PFN/PFL (Pulse Forming Network/Line) is charged to a high-voltage by the RCPS (Power Supply);
- Main Switch is turned-on and a pulse is launched, through the transmission line, towards the kicker magnet.
- Once the current pulse has travelled through the magnet and reaches the (matched) terminating resistor full-field has been established in the kicker magnet.

Transmission Line Kicker Magnet

- Developed at CERN in early 1960's;
- Consists of few to many "cells" to approximate a coaxial cable;

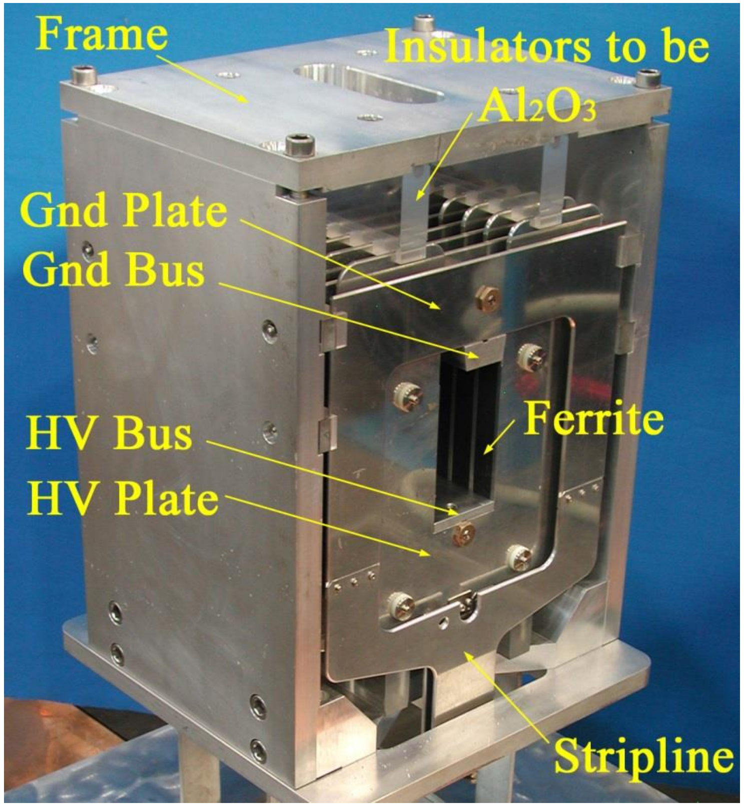


$$Z = \sqrt{\frac{Lc}{Cc}}$$

For a given cell length, *Lc* is fixed by aperture dimensions.

$$\tau_m = n \cdot \sqrt{Lc \cdot Cc} = n \cdot \left({}^{Lc}\!/_{Z} \right) = {}^{Lm}\!/_{Z}$$

- Ferrite cores are sandwiched between **high voltage (HV)** capacitance plates;
- One U-core, together with its ground and HV capacitance plates, is termed a cell;
- The "filling time" (τ_m) is the delay required for the pulse to travel through the "n" magnet cells.

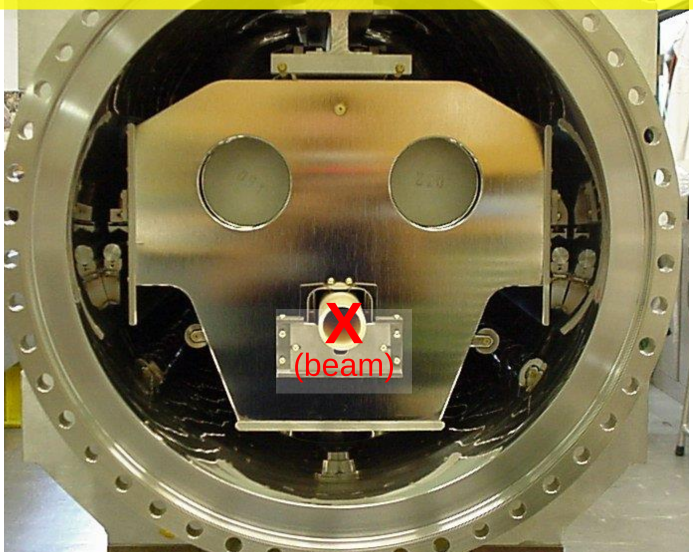


Installing Kicker Magnets in Machine Vacuum

<u>Disadvantages:</u>

- Costly to construct (use of UHV materials and cleaning, bake-out, vacuum tank, pumping);
- Coupling impedance to beam (a ceramic tube, suitably treated, may be required in any case);
- Heat removal from magnetic yoke.

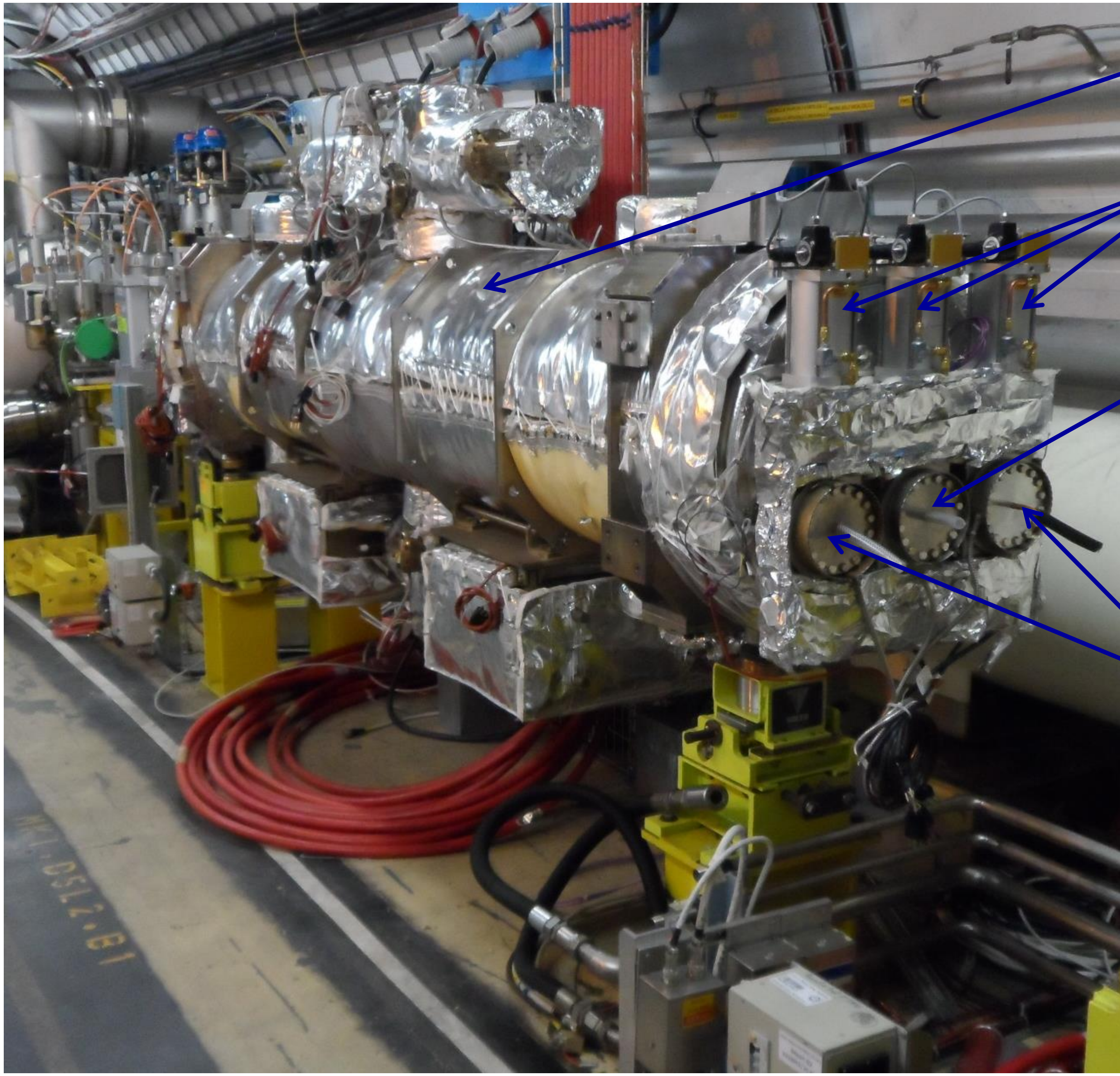
Kicker Magnet in a Vacuum Tank



<u>Advantages:</u>

- Aperture dimensions are minimized, therefore voltage and current are minimized for a given kick, rise-time and length;
- Machine vacuum is a reliable dielectric (7 kV/mm OK) – generally "recovers" after an electrical breakdown, whereas a solid dielectric, outside vacuum, may not recover.

An MKI Magnet in-situ in the LHC



Bake-out jackets

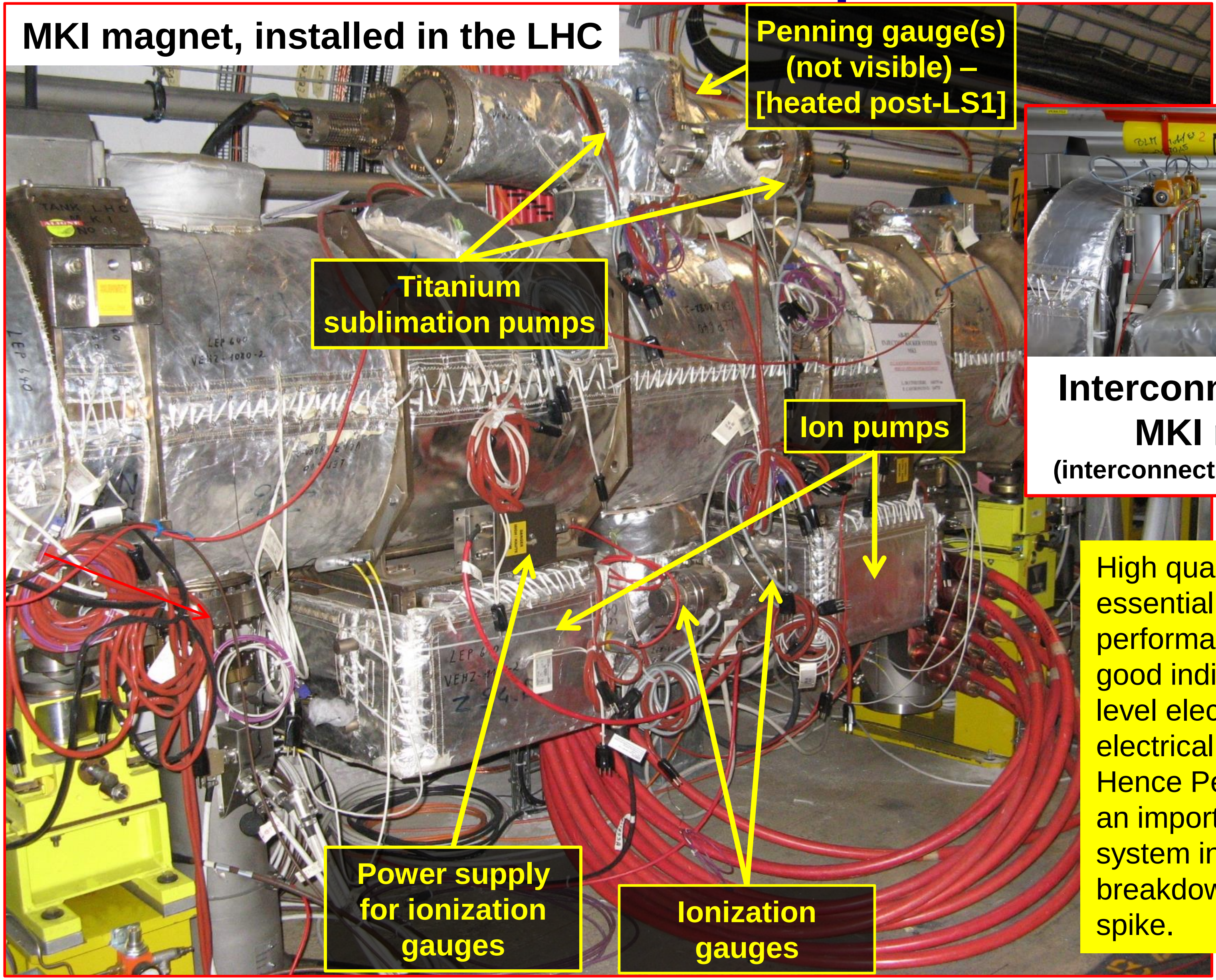
Vacuum valves (one per vacuum port)

Port for injected and circulating beam

One of these outer ports used for counter-rotating beam (copper tubes, within the MKI magnet, are called Bypass Tubes)

8 MKIs required in the LHC:
- 4 at Point 2,
- 4 at Point 8.

MKI: Vacuum Pumps & Gauges

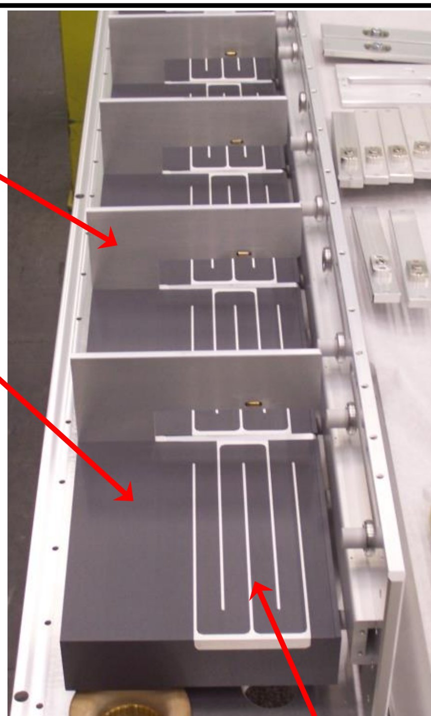


Interconnect between MKI magnets
(interconnects now NEG coated)

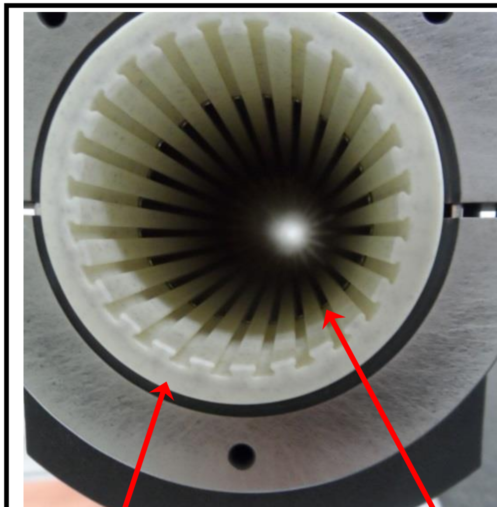
High quality vacuum is essential for a good HV performance. Vacuum is a good indicator of both low level electrical activity and electrical breakdown. Hence Penning gauges are an important part of kicker system interlocks: electrical breakdown ⇨ pressure spike.

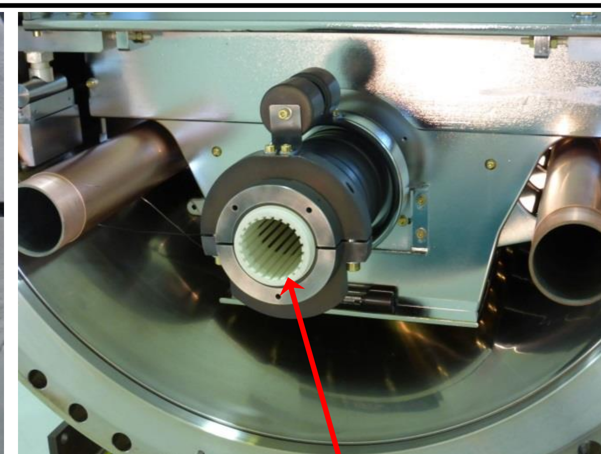
Beam Induced Power Deposition

In order to reduce beam coupling impedance (and hence power deposition, induced in the ferrite of the kicker magnet by the circulating beam) the ferrite must be shielded from the beam, by providing a path for beam image current. However the design must ensure that eddy-currents, induced in the screen conductors by the fast rising field, do not unduly increase field rise-time.



MKE (SPS) Kicker: serigraphy (silver paint) on ferrite





MKI (LHC Injection) Kicker: 24 (screen) conductors supported, and electrically insulated, by a (3m long) ceramic tube

Cooling of Ferrite

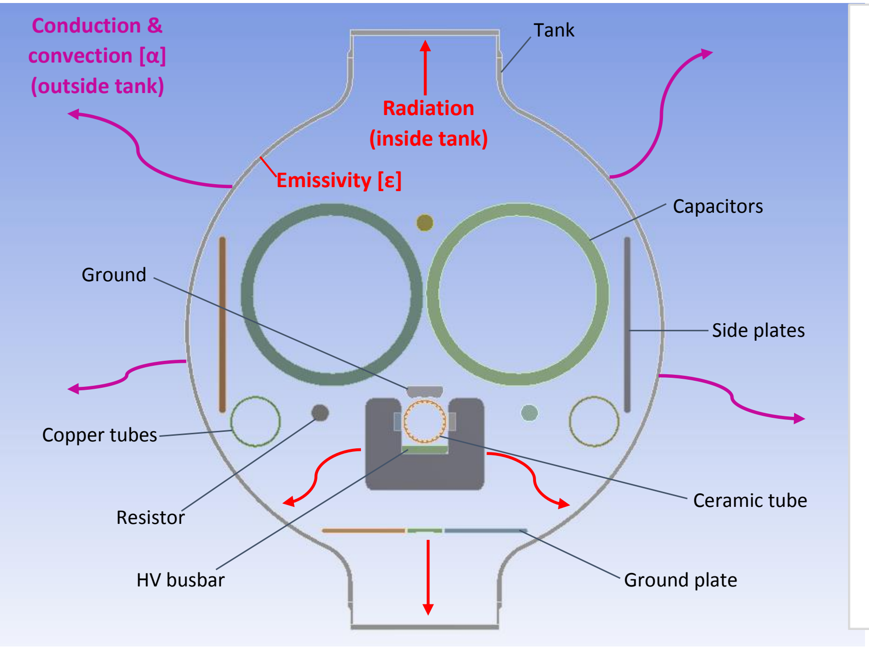
Cooling of the ferrite of the LHC injection kicker magnet :

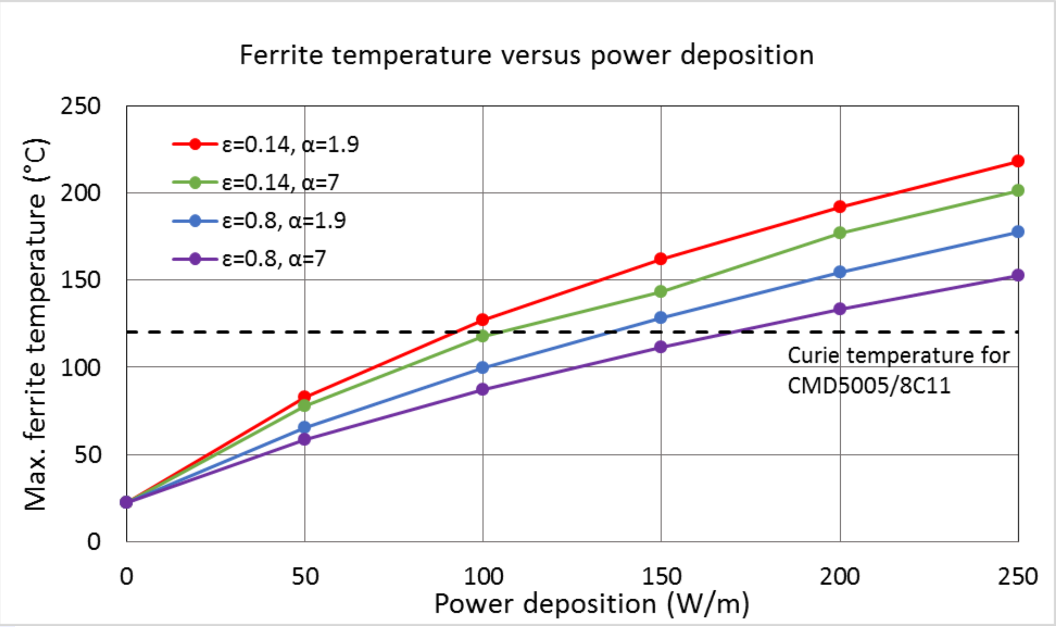
- convection is negligible as the tank is under vacuum conditions;
- is mainly by radiation;
- parts surrounding the ferrite act as radiation shields that reduce the amount of heat radiated to the tank.

➢ without any shielding of the MKI magnet, power deposition of ~1000 W/m would be expected post-LS1.

➢ with 24 screen conductors installed ➩ ~50 W/m post-LS1; HL-LHC ➩ ~200 W/m.

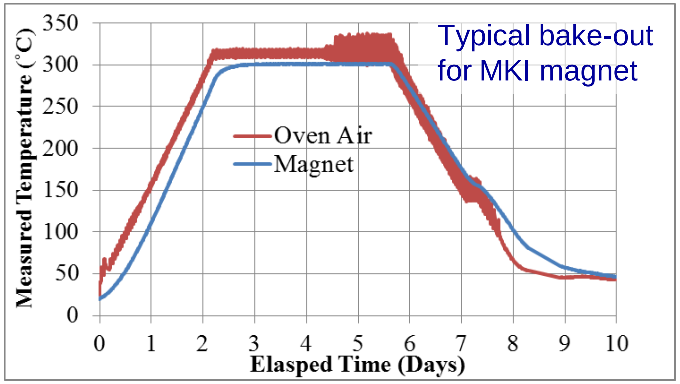
➢ to be compared with 70 W/m to 160 W/m pre-LS1, with 15 screen conductors installed.



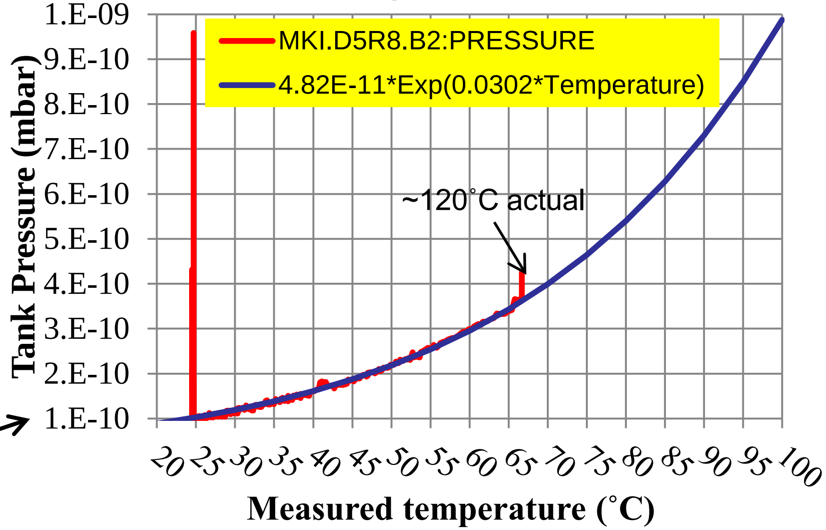


Ferrite Temperature

- Before magnet assembly, ferrite is baked at ~1000˚C, under vacuum, for 2 hours;
- Each MKI kicker magnet is baked twice, to ~300˚C, in its vacuum tank, for 3+ days;

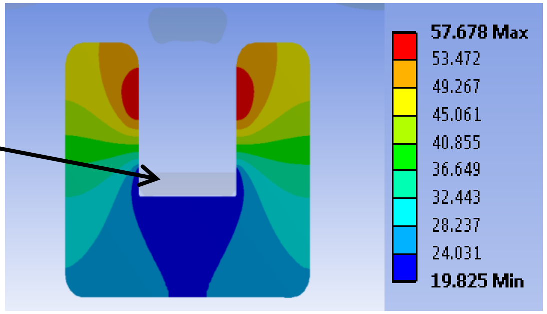


- Despite these bake-outs, increased ferrite temperature has a significant influence on ferrite out-gassing in the machine.

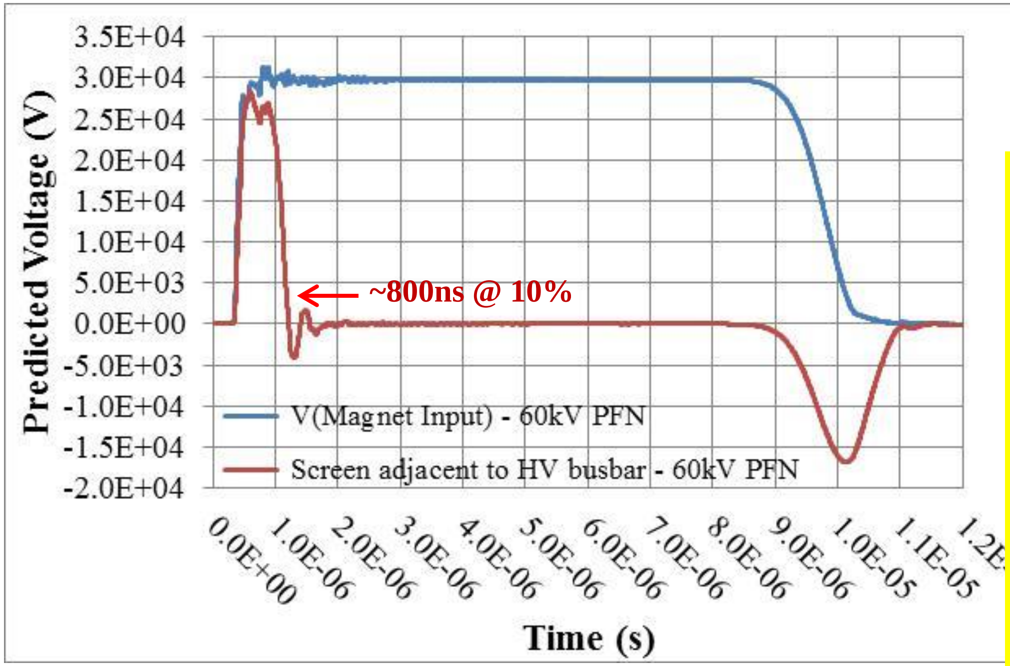


Options for reducing ferrite yoke temperature, in a machine, (in order of preference):

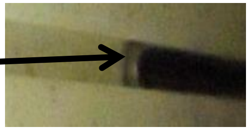
- ✓ Further decrease beam induced power deposition;
- ✓ Improve radiative cooling;
- ✓ Liquid cooling of parts of magnet (e.g. HV busbar);
- ✓ Utilize ferrite with a higher Curie Temperature.



Electrical Stress: Screen Conductors

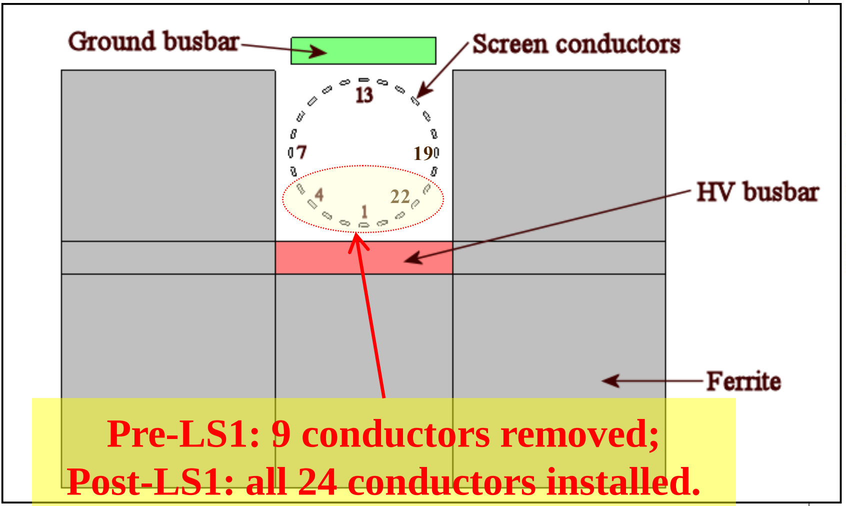


Interface between ceramic, conductor and vacuum (triple junction) is a point of high electric stress.

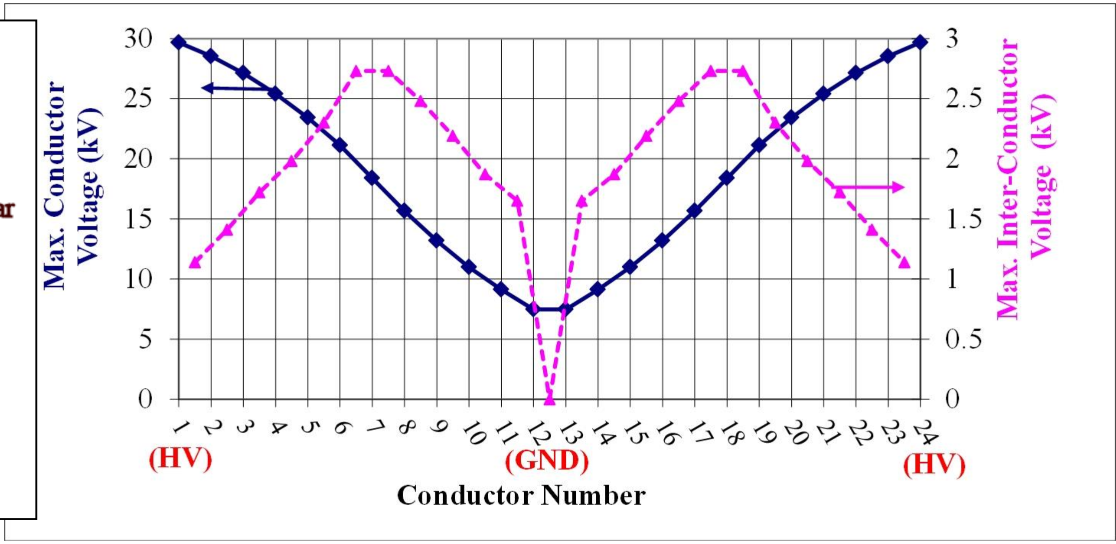


Changing magnetic field induces voltage on screen conductors:

1) Positive induced voltage is ~twice the magnitude of the negative induced voltage.
2) Negative induced voltage (for injection) occurs ~8 µs after end of positive voltage.
3) Pre-LS1, to permit operation at the required injection field (magnet voltage/current), most MKIs had only 15 screen conductors installed.
4) Part of MKI screen has been re-designed to reduce electrical stress at the triple junction.



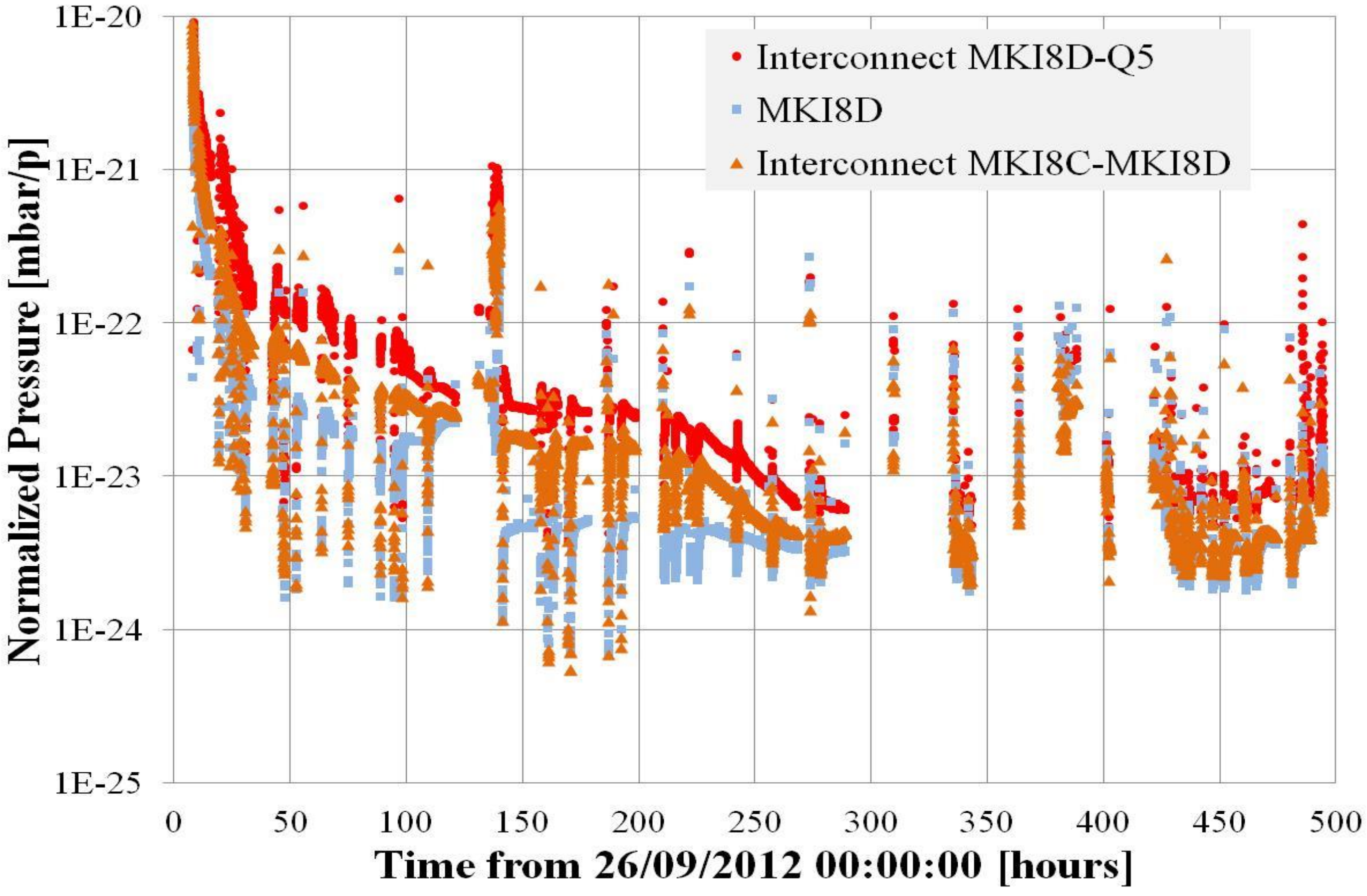
Pre-LS1: 9 conductors removed;
Post-LS1: all 24 conductors installed.



Multipacting in Ceramic Tube

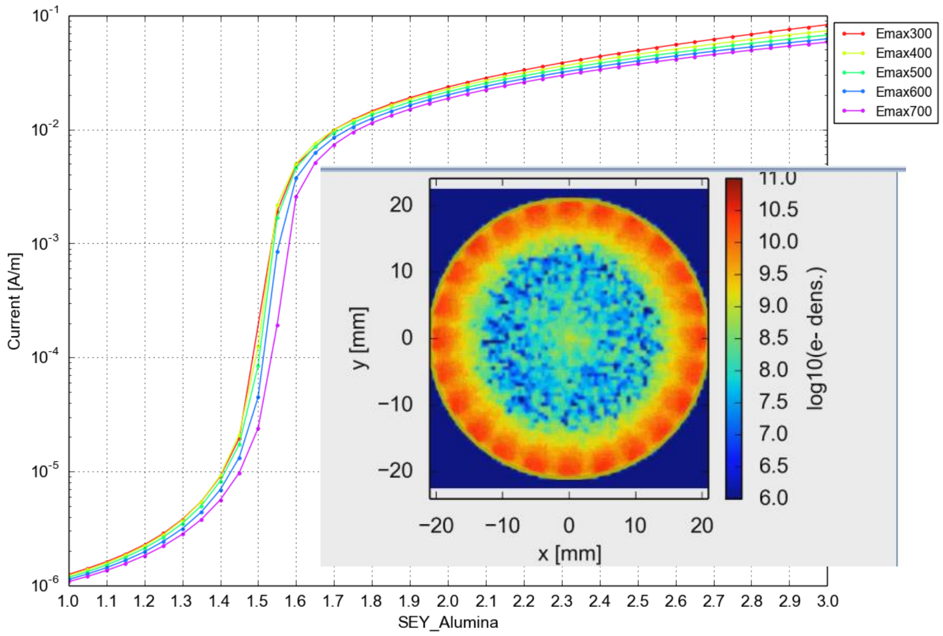
During Technical Stop 3, 2012, an MKI magnet was replaced in the LHC. Immediately following the restart of the LHC the vacuum pressure close to this MKI, with beam present, was relatively high.

The new ceramic tube required ~250 hours, with beam, to achieve a normalized pressure similar to the pre-replacement (~4E-24 mbar/p) level: this is thought to be due to the relatively high Secondary Electron Yield [SEY] (6 to 10) of the ceramic.



Coating of inside of the Ceramic Tube

Simulations by A. Romano, G. Iadarola & G. Rumolo show that the SEY of the inner surface of the ceramic tube should have an SEY of ≤1.4 to prevent mulitpacting.



Chromium based coating.

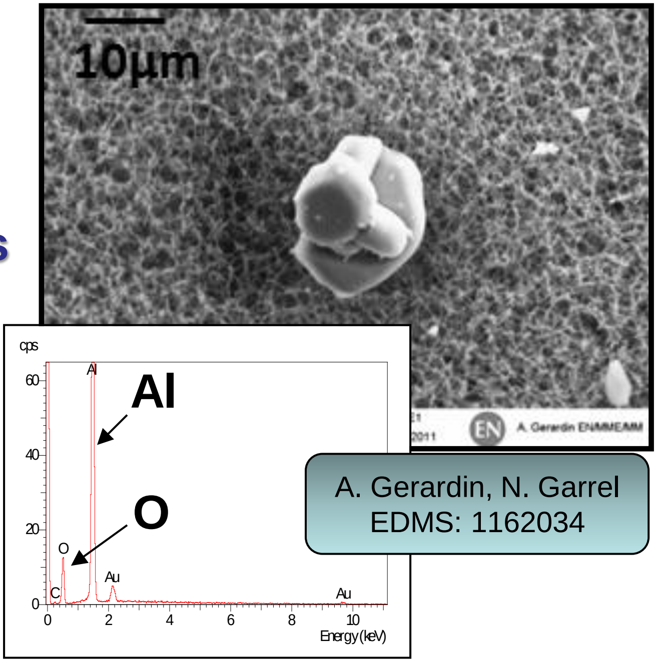
Amorphous carbon coating.

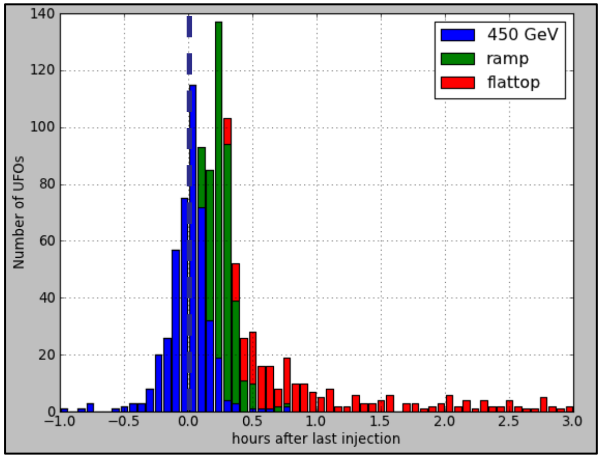
Chromium and amorphous carbon coatings show promise for both reducing SEY to ≤ 1.4 and increasing the breakdown voltage of the triple junction. These are thus being studied in conjunction with TE-VSC.

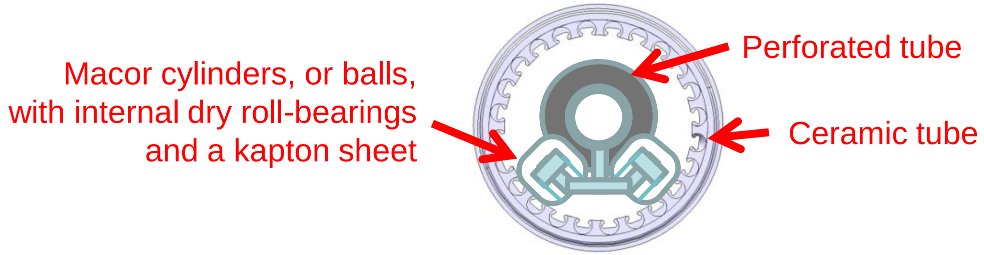
UFOs

Courtesy: T. Baer

- "UFOs" occur around the LHC, including at the MKIs.
  - In 2012*: 8 dumps by MKI UFOs.*
  - *2011: 11 dumps by MKI UFOs (2010: 2)*
  - *2012: 6 dumps from MKI.D5L2 (since 2010: 17).*
- During MKI inspection in 2011 many **macro particles** were found, which originate from the **Al_2O_3 ceramic tube** (e.g. from conductors been slid into slots).
  - *Typical macro particle diameter: **1-100 µm.***
  - *Temporal distribution:*
    - *Mainly within **30min after last injection**.*
    - *Many events within a **few hundred ms after MKI pulse**.*
- Positive correlation between **MKI UFO rate** and **pressure** in MKI tank at 450 GeV.
- Improved cleaning of MKI ceramic tube, with high pressure nitrogen, has reduced the number of macro particles by a factor of > 20.







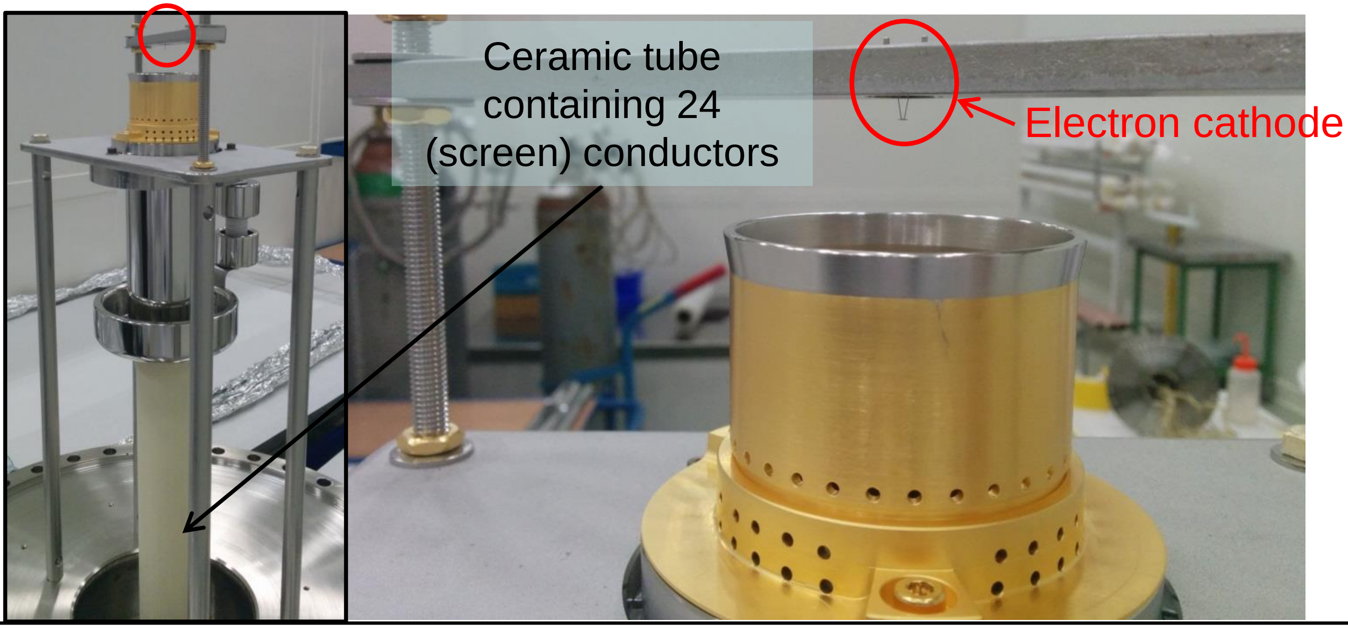
Electrical Breakdown

LHC

- During 2012 the average electrical breakdown rate of an MKI, with 15 screen conductors installed, was **1 breakdown per $2x10^5$ pulses**.
- However, during a machine development (MD) study in 2012, anti-ECloud solenoids on the MKI interconnects were turned off: pressure in one interconnect increased from $1x10^{-10}$ to $7x10^{-9}$ mbar:
  - After 10 pulses, an electrical breakdown occurred in one of these MKI magnets. **Hence it is thought that the breakdown rate is pressure dependent.**

Tests in the Lab

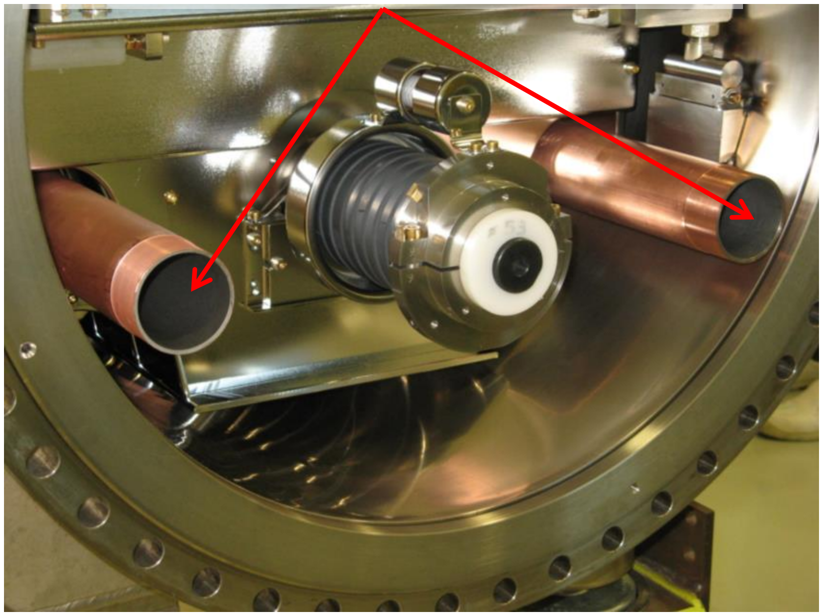
- Inject H_2 to increase the pressure in a test tank (no magnet, only screen conductors connected to pulsed HV) – no increase in electrical breakdown rate noted at pressures up to 10^{-7} mbar !;
  - But, maybe, the presence of ionized H_2, in the LHC, results in an increased rate of breakdown? Tests ongoing in the lab with an electron cathode…

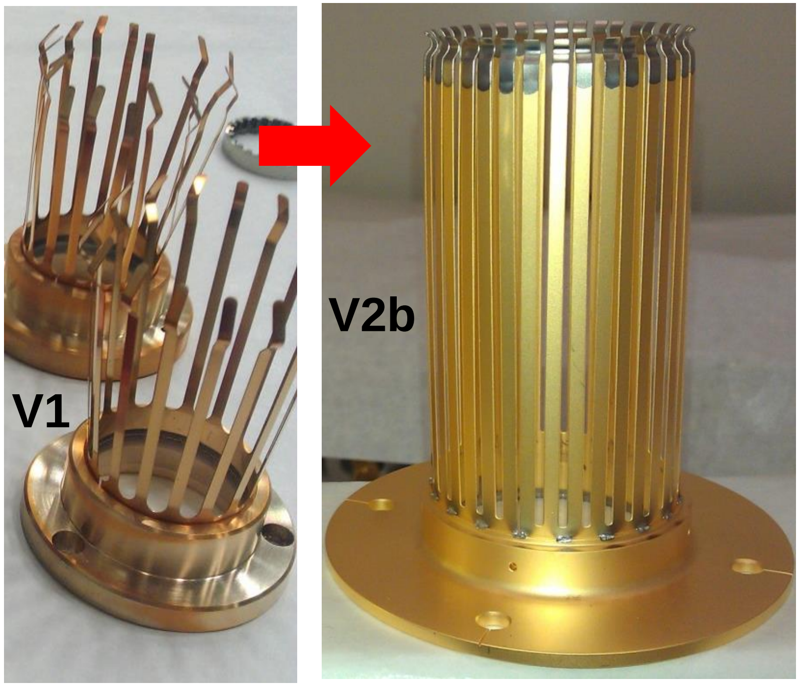


Vacuum Related Upgrades on MKIs

- NEG coating of the bypass tubes;
  - Vacuum in bypass tube previously limited scrubbing with beam;
- RF fingers are required to allow bake-out of MKI magnets to ~300˚C (different thermal expansion of tank and internal parts);
  - RF finger V2b (installed in MKI8D since TS3 2012; and V2a in MKI2B since October 2010) ⇨improved design for bake-out (to 300˚C+), c.f. V1, and smaller gaps between fingers
  - V2b approved by LHC RF Fingers Task Force.

New NEG coated bypass tubes





Conclusions

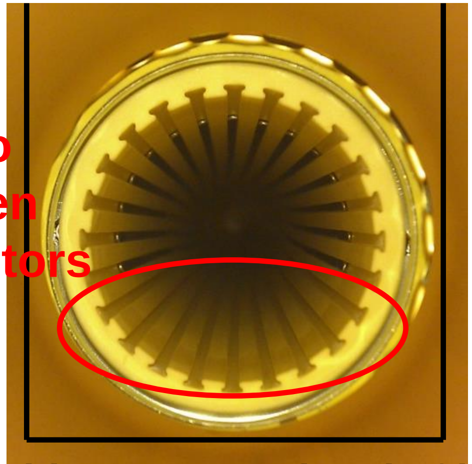
- Kicker magnets are required for fast injection and extraction;
- A kicker magnet is typically installed in vacuum to minimize aperture dimensions, and hence the magnitude of pulse current/voltage required, and makes use of the vacuum for insulation;
- A kicker magnet can have a significant amount of vacuum equipment installed on it;
- The quality of vacuum is essential to allow a good high voltage performance;
- The vacuum pressure is a good indicator of electrical activity in the magnet tank and is used as an interlock;
- Cooling of the ferrite yoke is challenging and, in vacuum, is typically by thermal radiation;
- It is challenging to shield the ferrite yoke from the beam, without unduly increasing the rise/fall time of the field;
- The ceramic tube, used to support the screen conductors in the MKI, has a relatively high SEY and thus, with beam, there can be electron cloud;
- The ceramic tube has historically been a source of UFOs, but improved cleaning has reduced the numbers of macro particles;
- Electrical breakdown, on the surface of the ceramic tube, is thought to be pressure dependent – this is under investigation in the kicker lab.

Thank you for your attention.

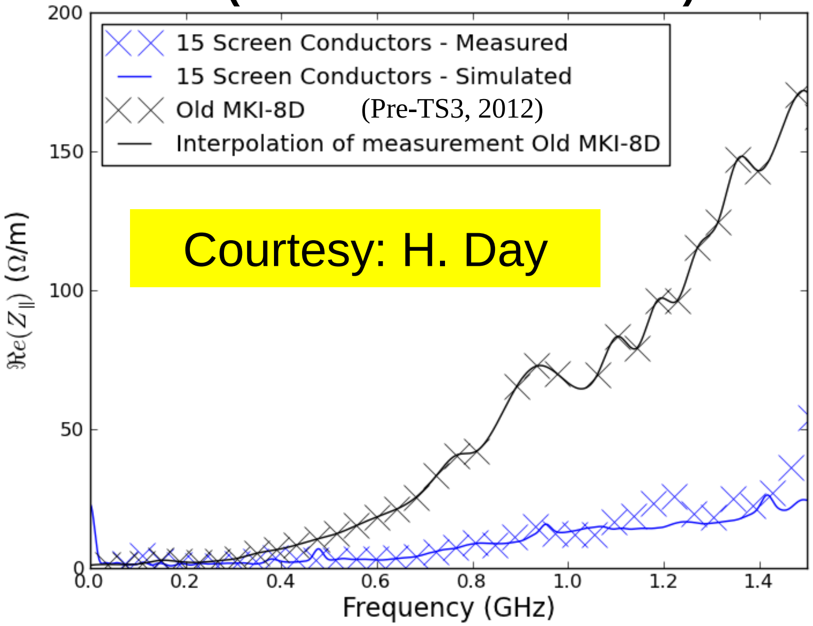
Questions ?

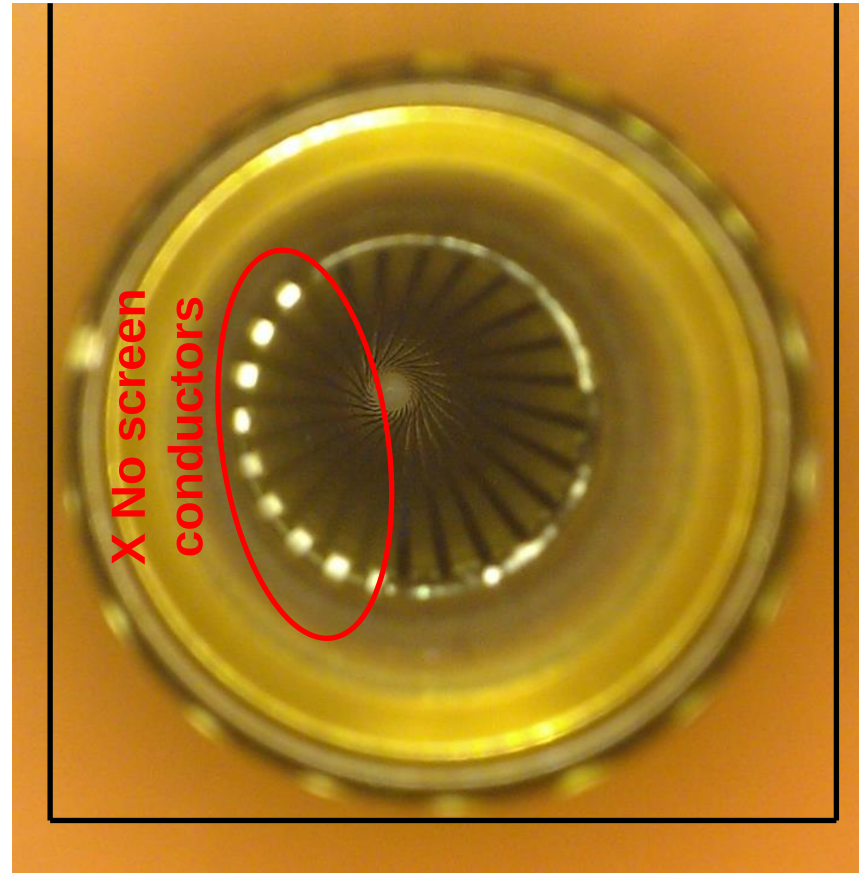
MKI8D Removed from LHC during TS3, 2012

✓No screen conductors



Capacitively coupled end of beam screen (and outline of U-ferrite)





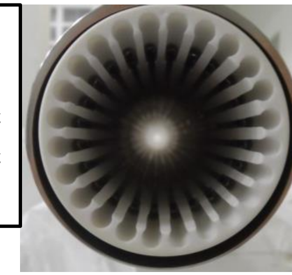
Directly connected end of beam screen (and outline of U-ferrite).

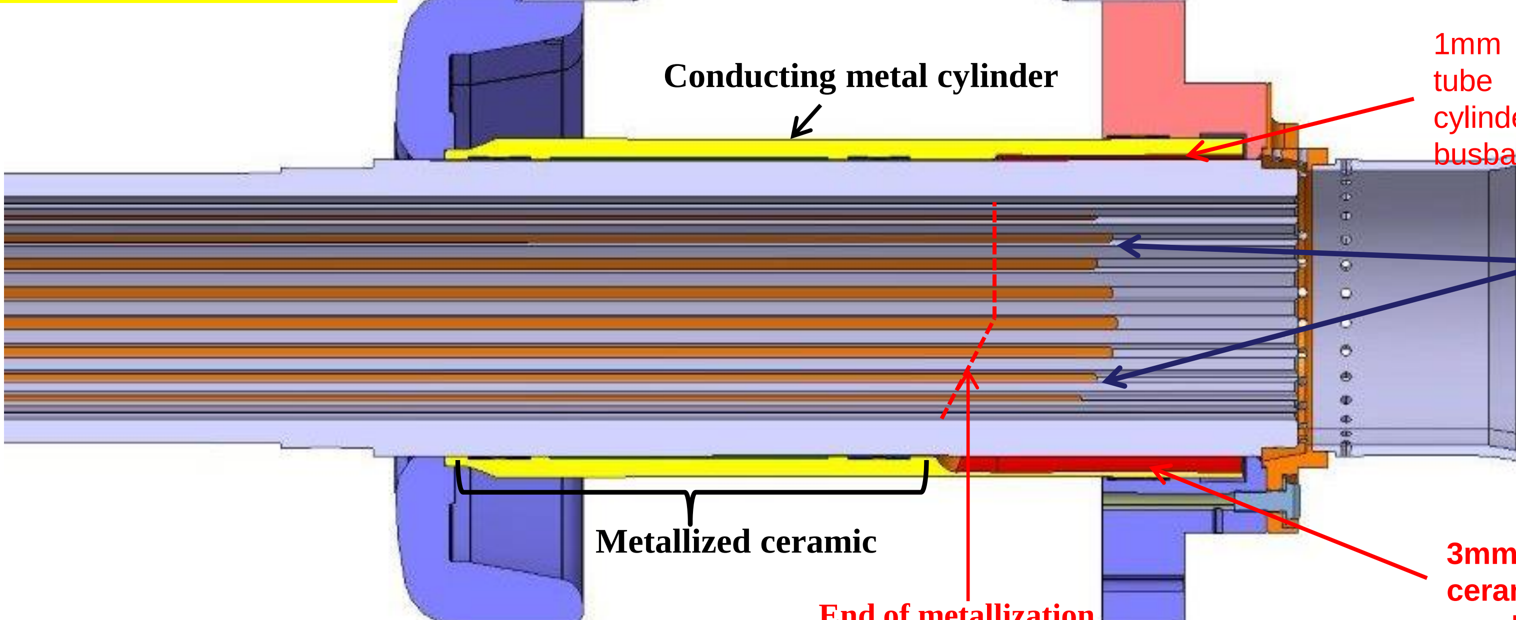
Highest heating at downstream end, where LHS ferrite leg is unshielded from circulating beam (because of 90˚ twist in stripes).

Good understanding of cause of heating of MKI8D, pre TS3 2012 ! – can't happen with 24 screen conductors.

Modified Beam Screen for MKI – implemented during LS1

Balls will not be installed on end of screen conductors as they increase radial electric field. Hence latest ceramic tubes are not “drilled”.



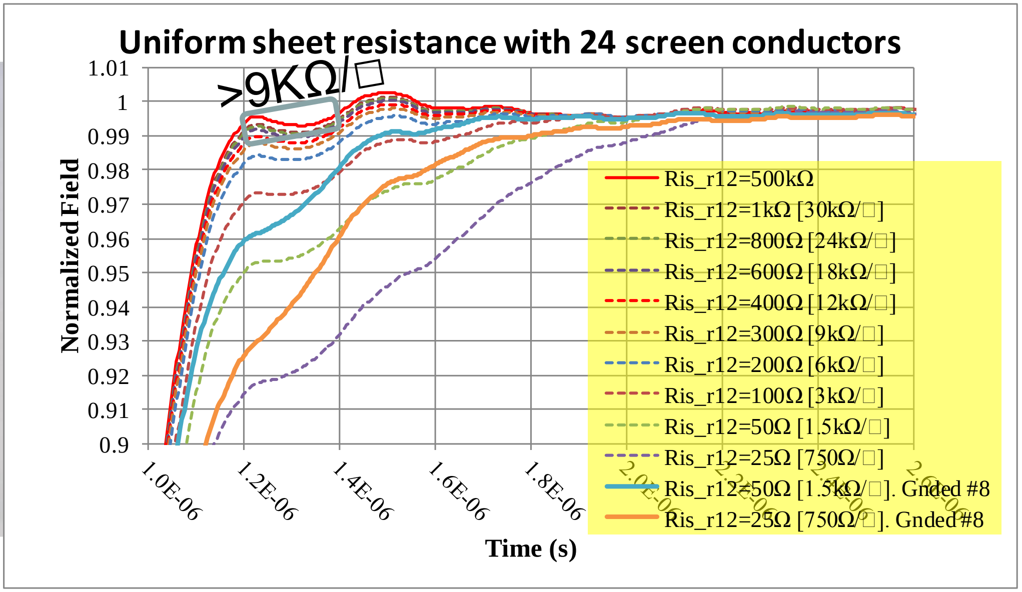


After LS1:

- **Metallization removed from ceramic tube ~20mm before end of screen conductor;**
- **Conducting metal cylinder with a (vacuum) gap of between 1mm and 3mm to ceramic tube;**
- **Modified beam screen reduces predicted electric-field by a factor of ~3 (max. field is factor of 2 less than for the 19 conductor version installed in TS3 2012);**
- **24 screen conductors installed.**

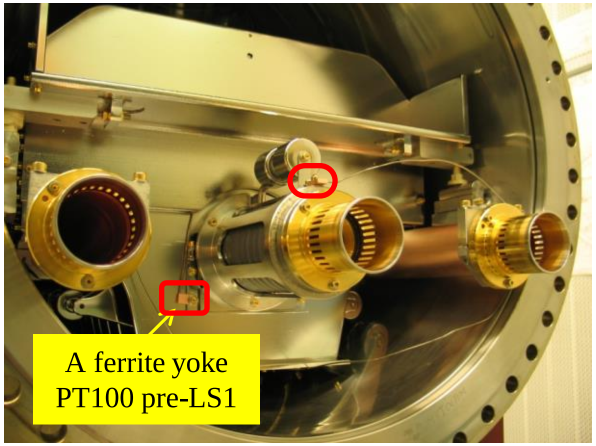
aC Coating

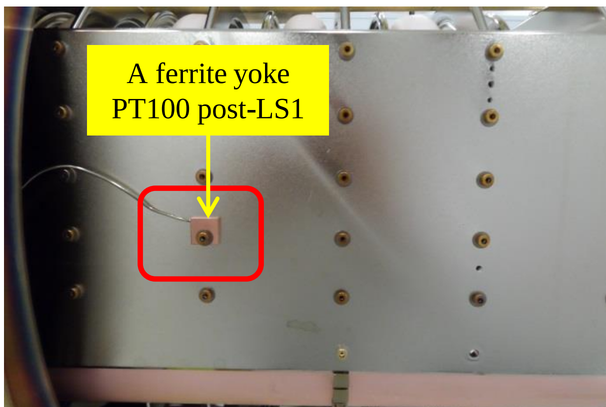
- Pedro Costa Pinto has coated a 25cm long ceramic tube with amorphous carbon:

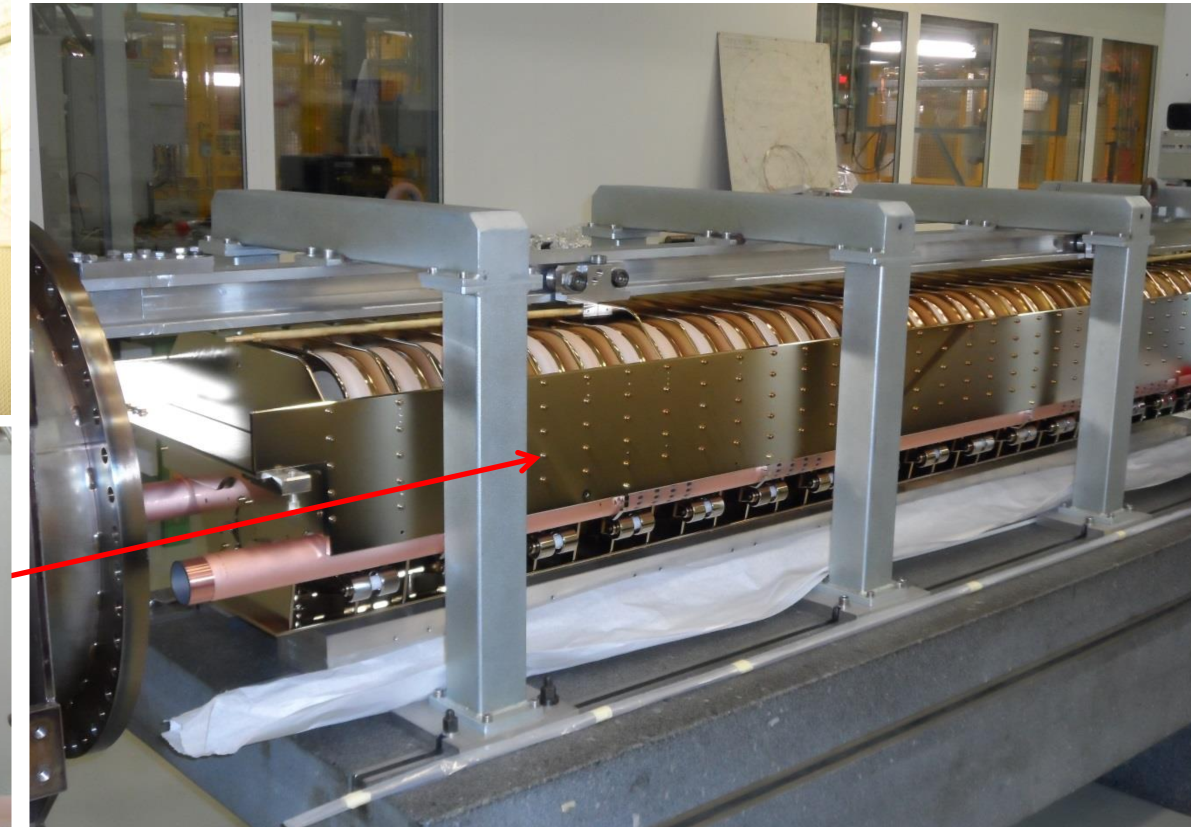


- A resistance of at least 10kR/□, and preferably > 20kR/□, is required in order that the field rise time is not increased.
- Measurements on the first (25 cm long) test ceramic show an average resistance, for the “teeth” of the ceramic, of ~145kR/□: however there is some doubt about the measurement technique employed and the measurements will be repeated with another technique.
- A 50 cm long tube will be internally coated with aC for high voltage tests in a Simi-tank.

PT100's new position, post-LS1





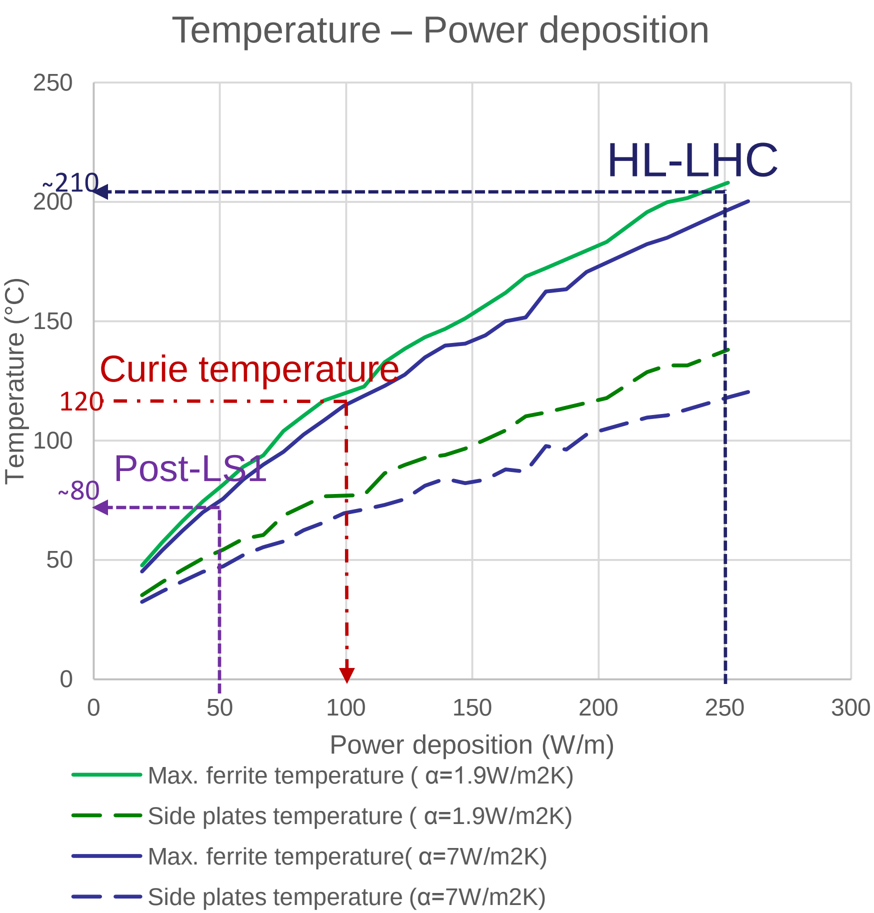


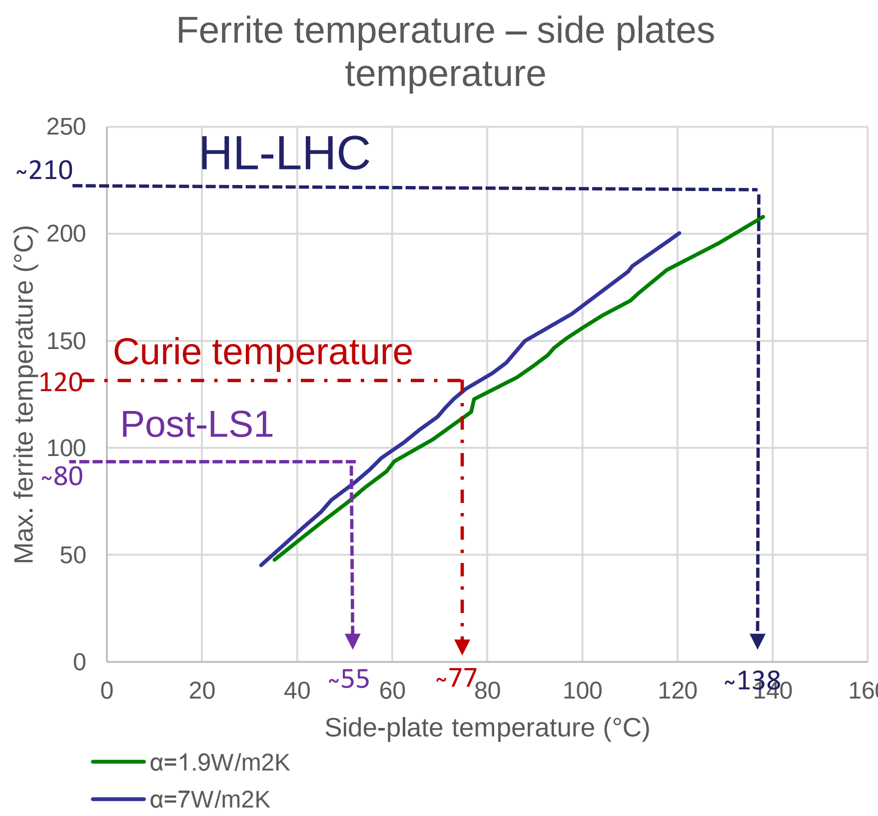
MKI8**C** upstream (capacitively coupled end) toroidal ferrites occasionally heated to>180˚C: thermal radiation onto ferrite yoke PT100 gave falsely high measurements for upstream yoke temperature.

The MKIs upgraded during LS1 have the "ferrite yoke PT100's" moved from the end ground plate to the side-plates. Advantages include:

- ✓ The PT100's on the side plate will give a measurement temperature more representative of the ferrite yoke temperature;
- ✓ Ferrite yoke PT100's will be distant from the ferrite toroids and should thus not be directly influenced by a high temperature of the toroids.

New location of the PT100 sensors (2)



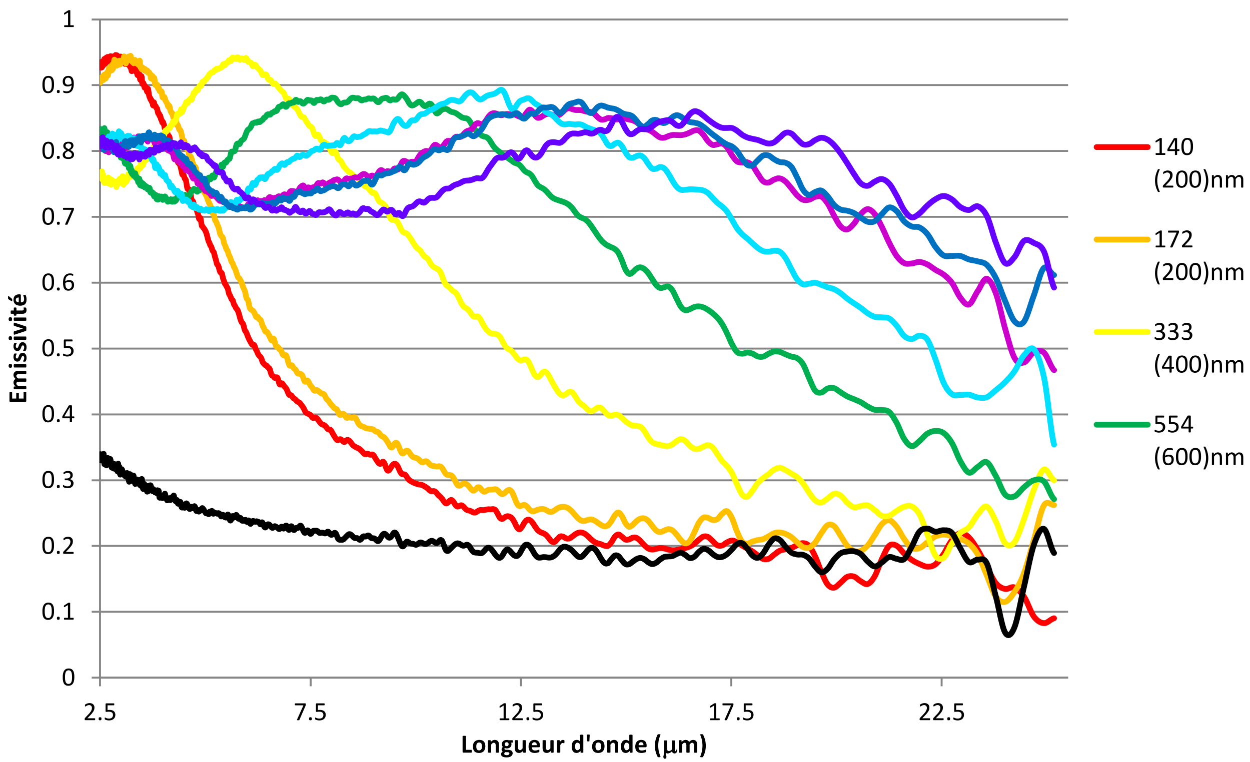


Double Magnetron Sputtering

Influence de l'épaisseur d'un dépôt carbone sur l'émissivité

Courtesy: M. Bardo

Emissivité hémisphérique absolue après différentes épaisseurs de dépôts C (centre échantillons)



- Remarque : Problème d'adhérence