First Year of Operation of the MKI-Cool

M.J. Barnes

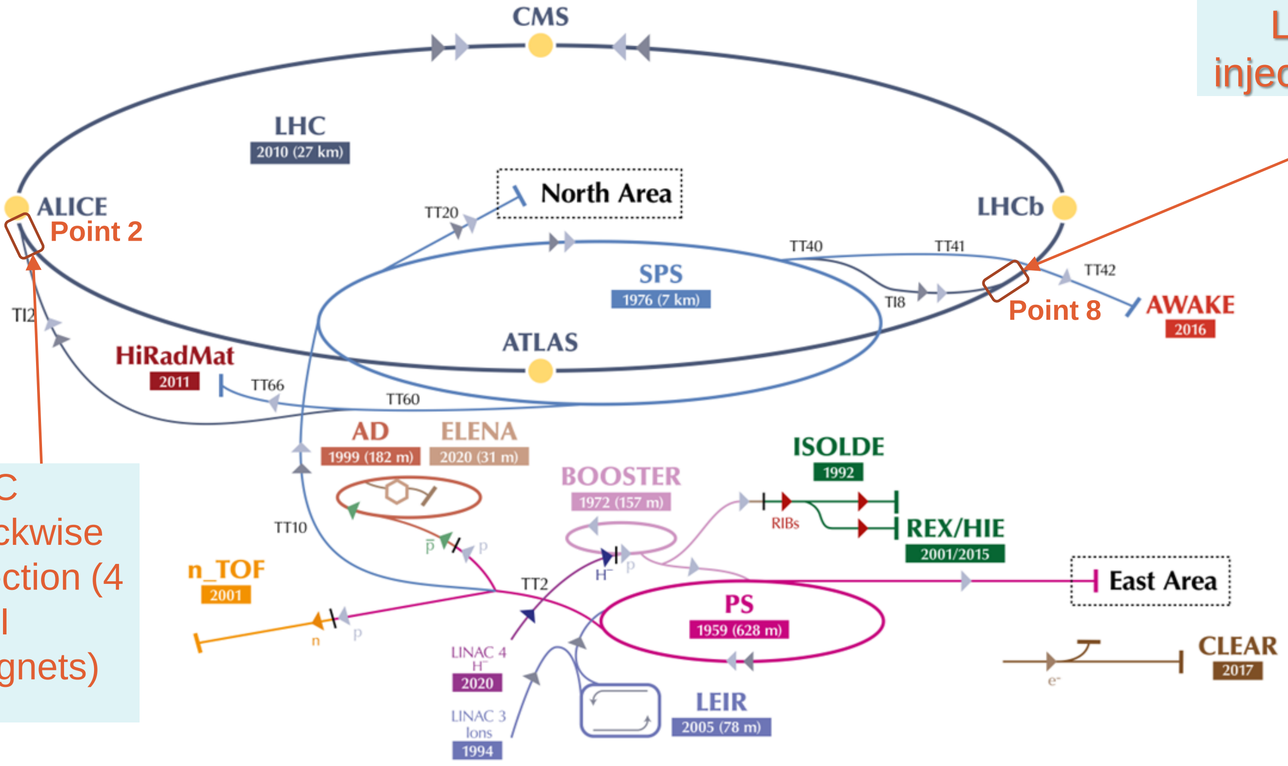
Acknowledgements:

C. Bracco, W. Bartmann, O. Bjorkqvist, M. Diaz, L. Ducimetière, Y. Dutheil, G. Favia, B. Goddard, T. Kramer, T. Maurin, V. Namora, A. Porret, D. Standen, T. Stadlbauer, P. Trubacova, L. Vega Cid, V. Vlachodimitropoulos, W. Weterings

Outline

1. **Context**
   - MKI purpose and design
   - Cr_2O_3 coating
   - Damping element and MKI cool
2. **First year of operation**
   - Vacuum
   - Temperature
3. **Looking forward**
   - RF damper
   - Alumina tubes
4. **Provisional planning for future MKI Cool installations in the LHC**
5. **Conclusions**

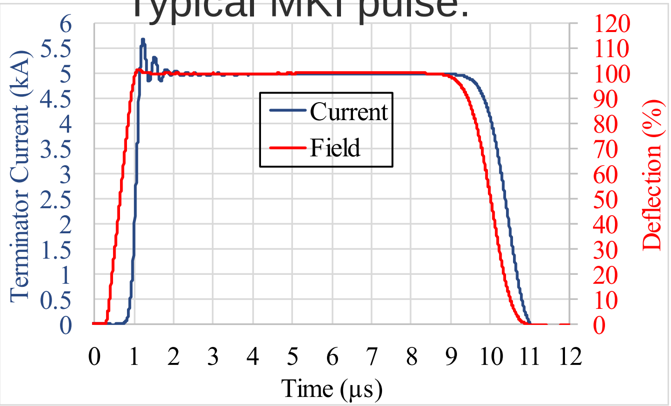
Context
MKI: Injector kicker magnets for the LHC



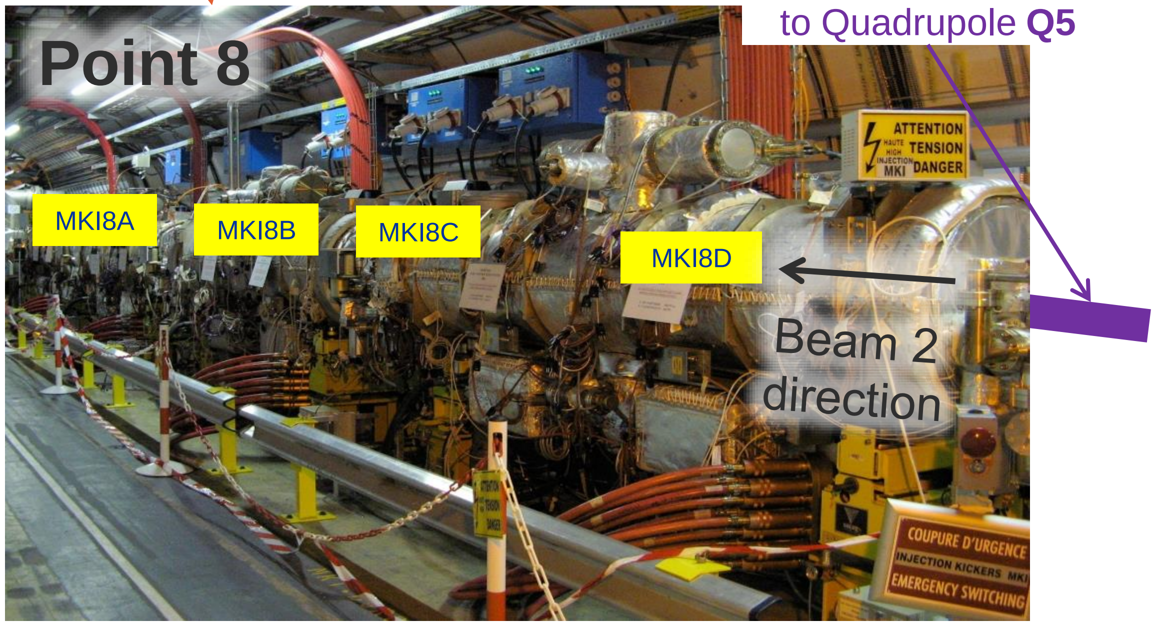
LHC clockwise injection (4 MKI magnets)

LHC anti-clockwise injection (4 MKI magnets)

Typical MKI pulse:



Vacuum **Interconnect** to Quadrupole **Q5**

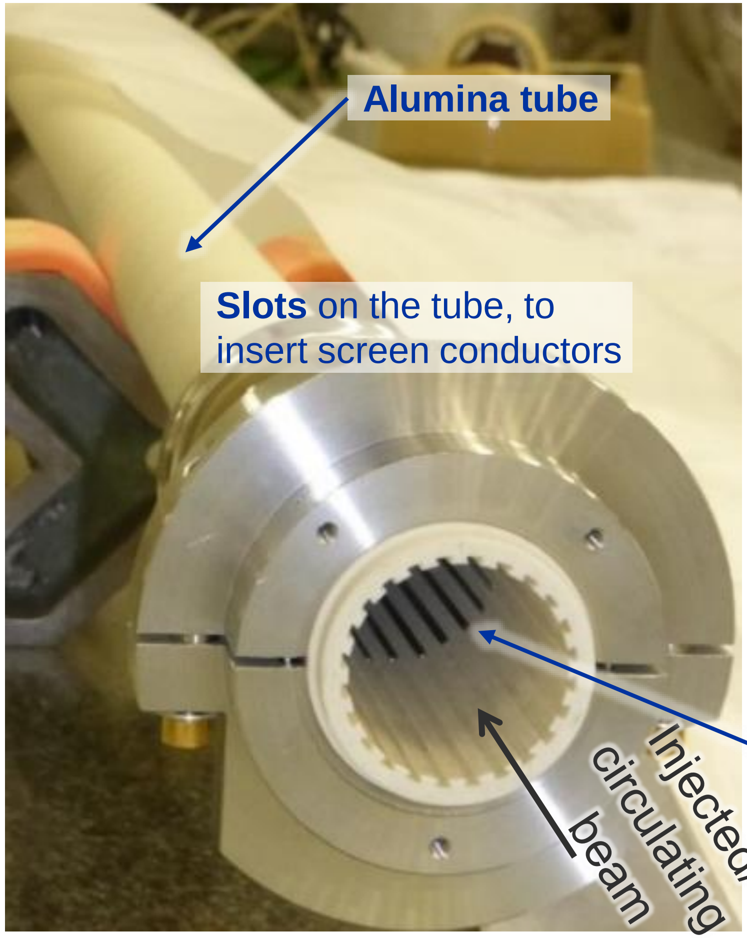


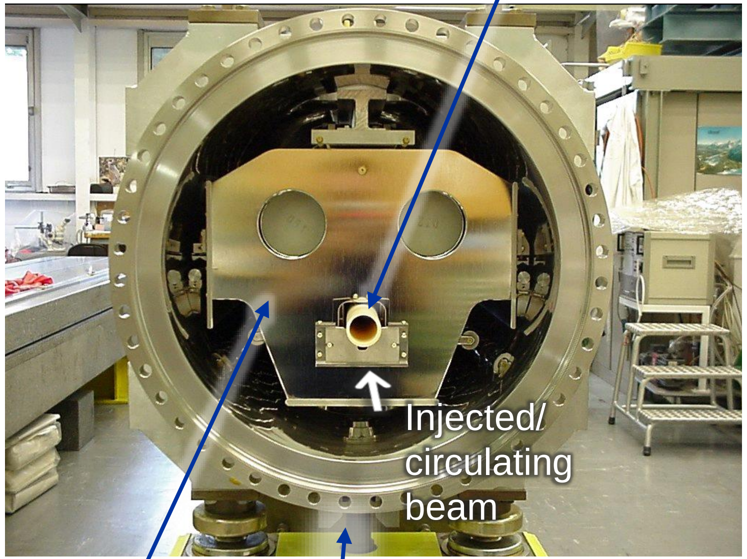
Context
Screen conductors inside MKI

- Screen conductors **carry image current of** circulating **beam**

⇓

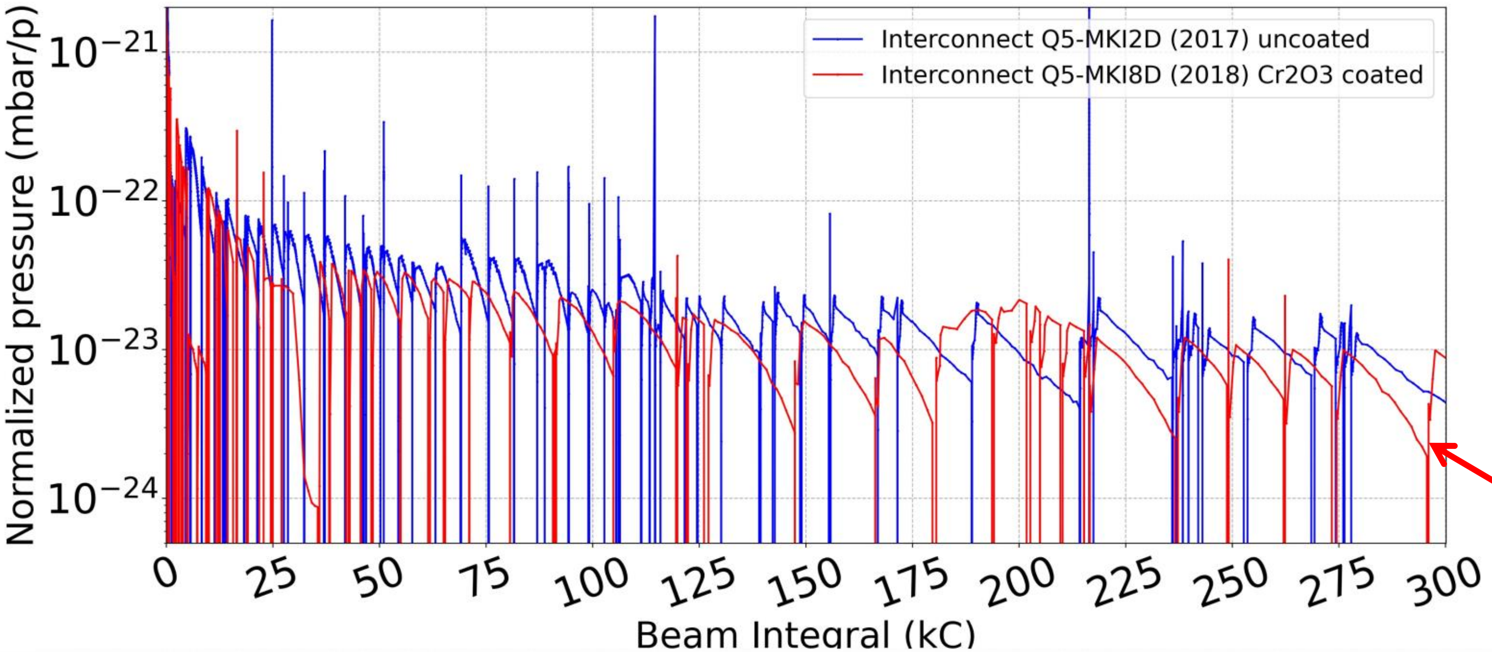
- **Reduce** beam induced **heating**
- Conductors are **supported** and electrically insulated **by alumina tube** (high SEY)
- 2017-18 YETS upgrade of MKI8D: alumina **tube coated on the inside with Cr_2O_3**:
  - has a low Secondary Electron Yield (SEY)
  - does not produce dust in the vacuum system
  - is beneficial for high voltage issues





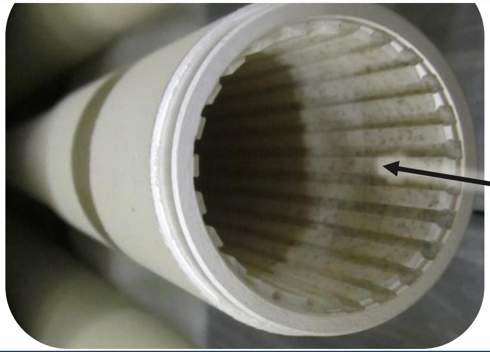
Context

Cr_2O_3 coating of MKI8D alumina tube, installed during YETS 2017/18



- **Before installation**:
  Pressure in **Q5-MKI8D** vacuum interconnect was a factor of ~**3** (2012, 2015 and 2017) to ~**12** (2016) **higher than** that of **Q5-MKI2D** [first MKI2 to see beam]

- **After installation**:
  The **factor** of 3-12 is **not observed** anymore in **Q5-MKI8D**. No other vacuum modifications were done: **pressure reduction** is attributed to **Cr_2O_3 coating** 👍

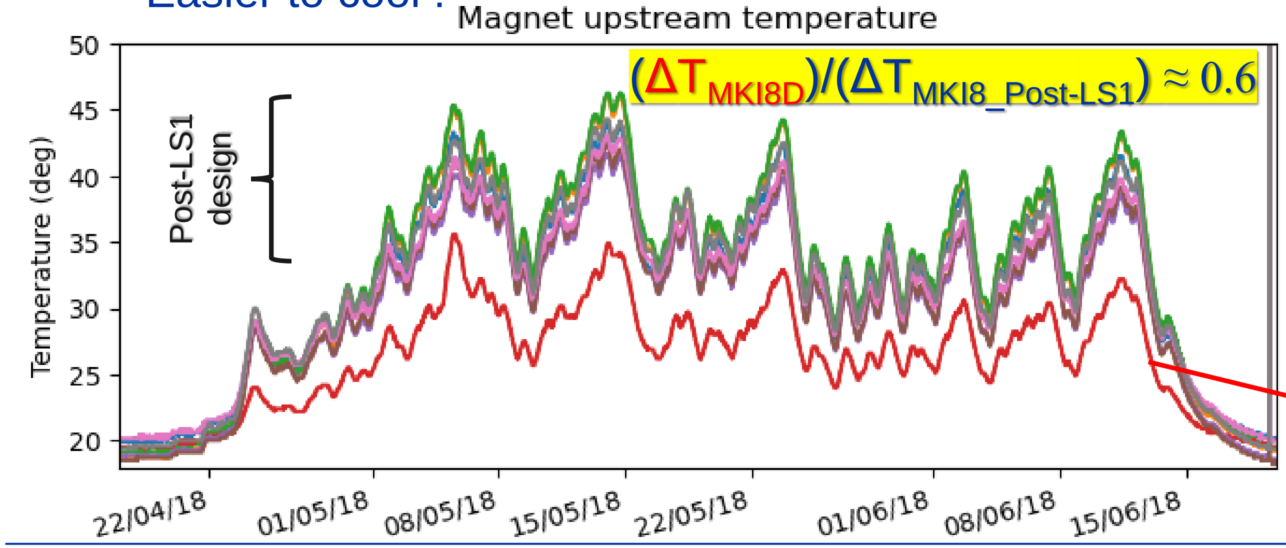


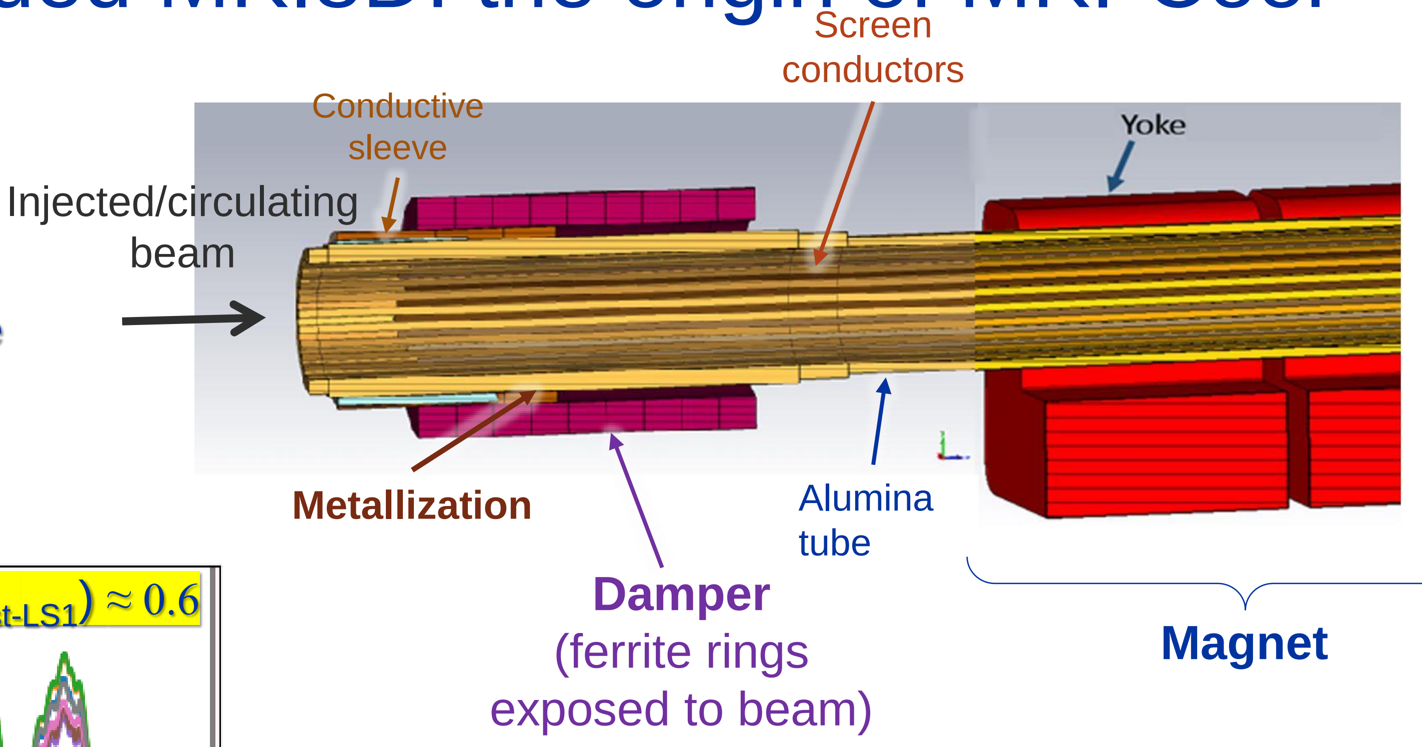
Alumina tube with **Cr_2O_3 coating** on the inside

Context

Damping element of upgraded MKI8D: the origin of MKI-Cool

- Redesigned **metallization** and ferrite rings (damper), on the alumina tube outside of the magnet aperture
  - Reduces beam induced power deposition and re-locates it from the ferrite yoke to the damper
- Damper is not at pulsed high voltage
  - Easier to cool !



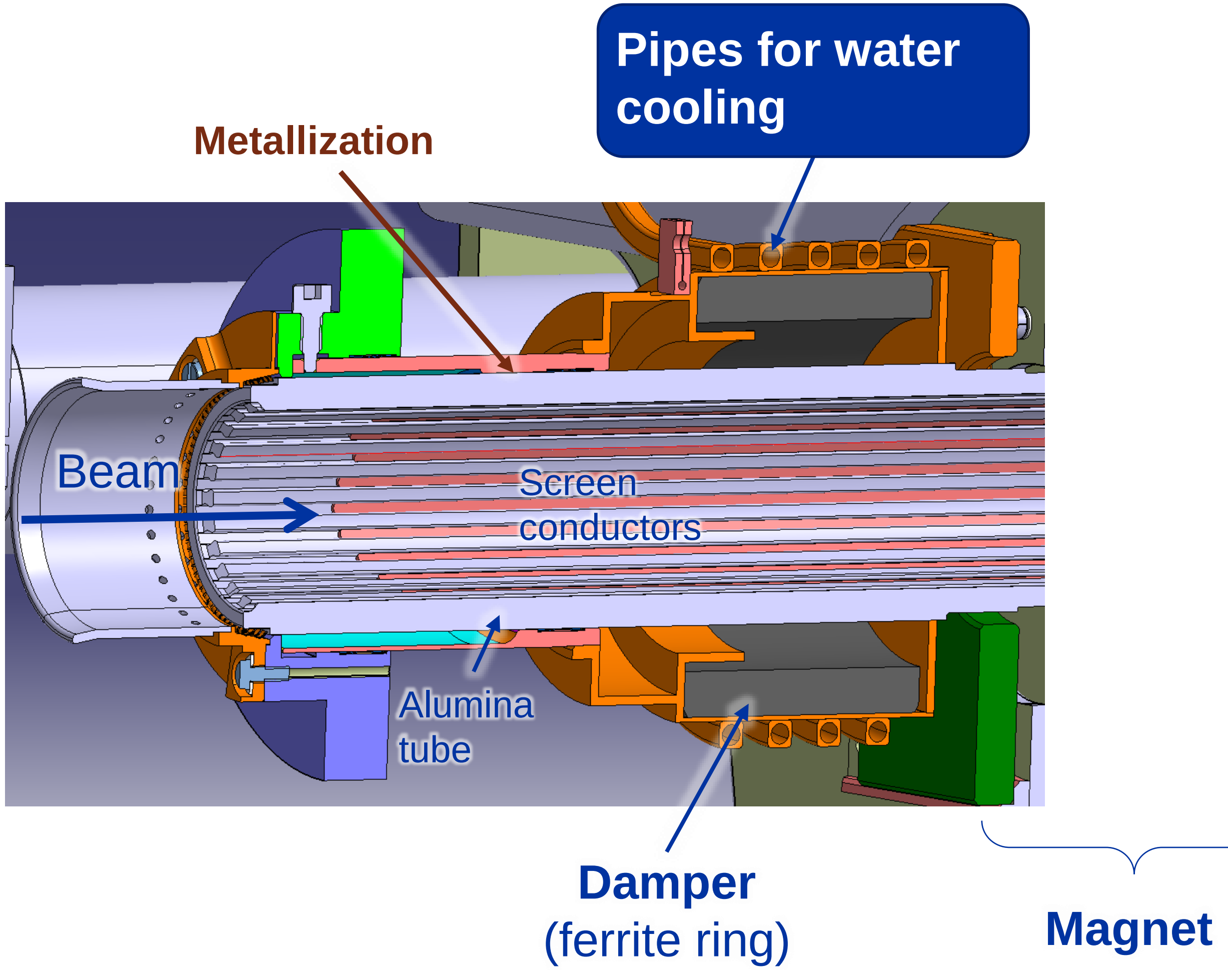


Context
MKI-Cool = damping element + water cooling

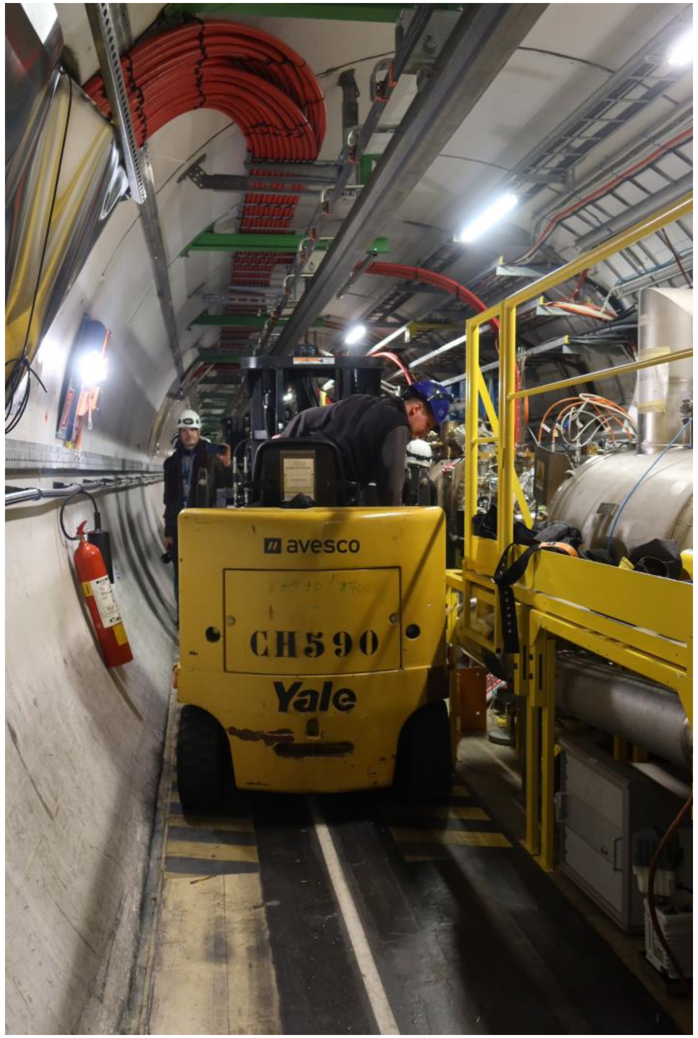
- Redesigned **metallization** and ferrite rings (damper) **reduces** beam induced **power** and **re-locates** it **from ferrite yoke to damper**

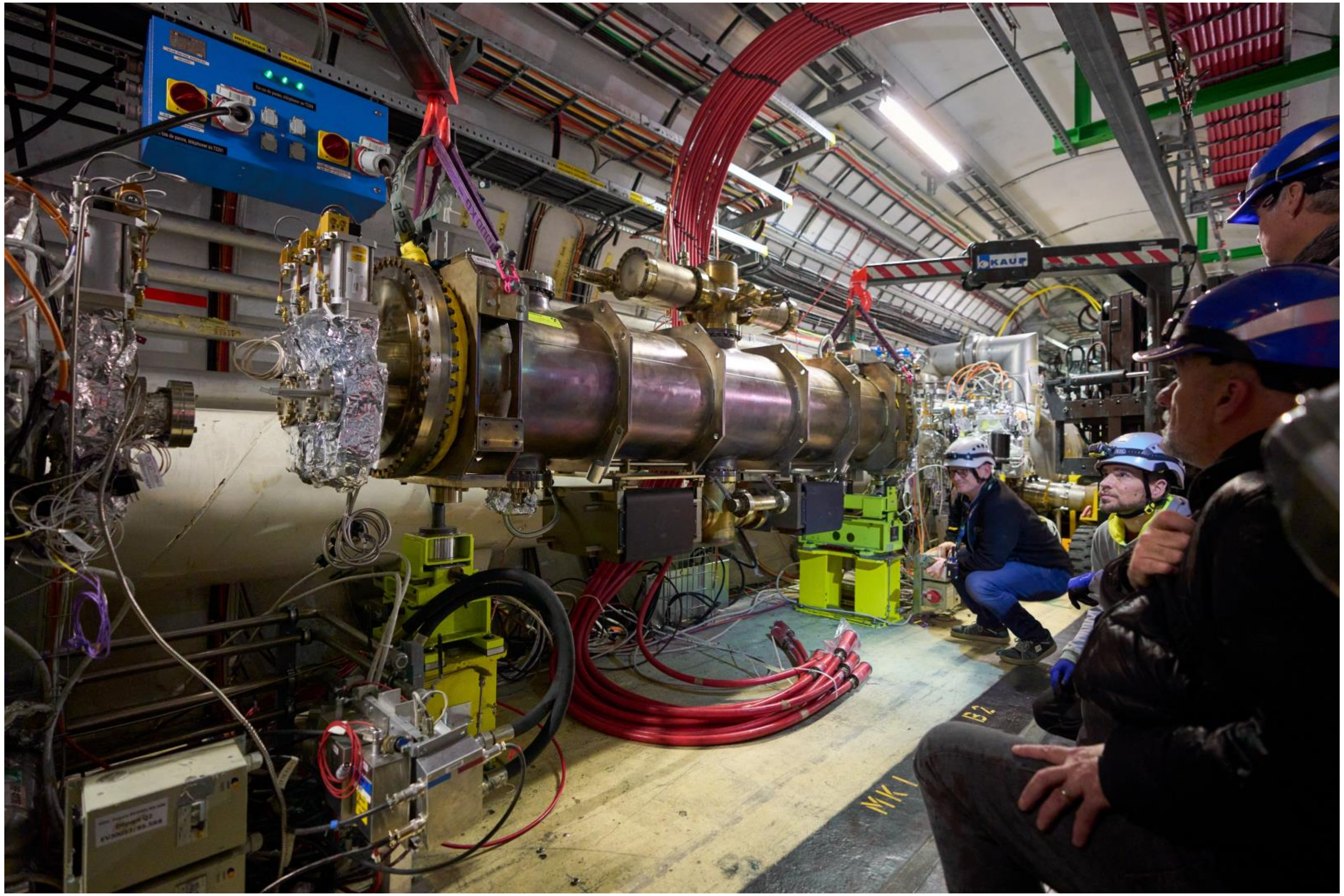
- BUT, with **HL-LHC beam,** an **uncooled RF damper would reach its Curie temperature**, and thus would no longer re-locate losses from the ferrite yoke → yoke temperature would increase

- **MKI-Cool:** water cooling of the RF damper to remove heat



First MKI-Cool: installed in LHC during YETS 2022/23



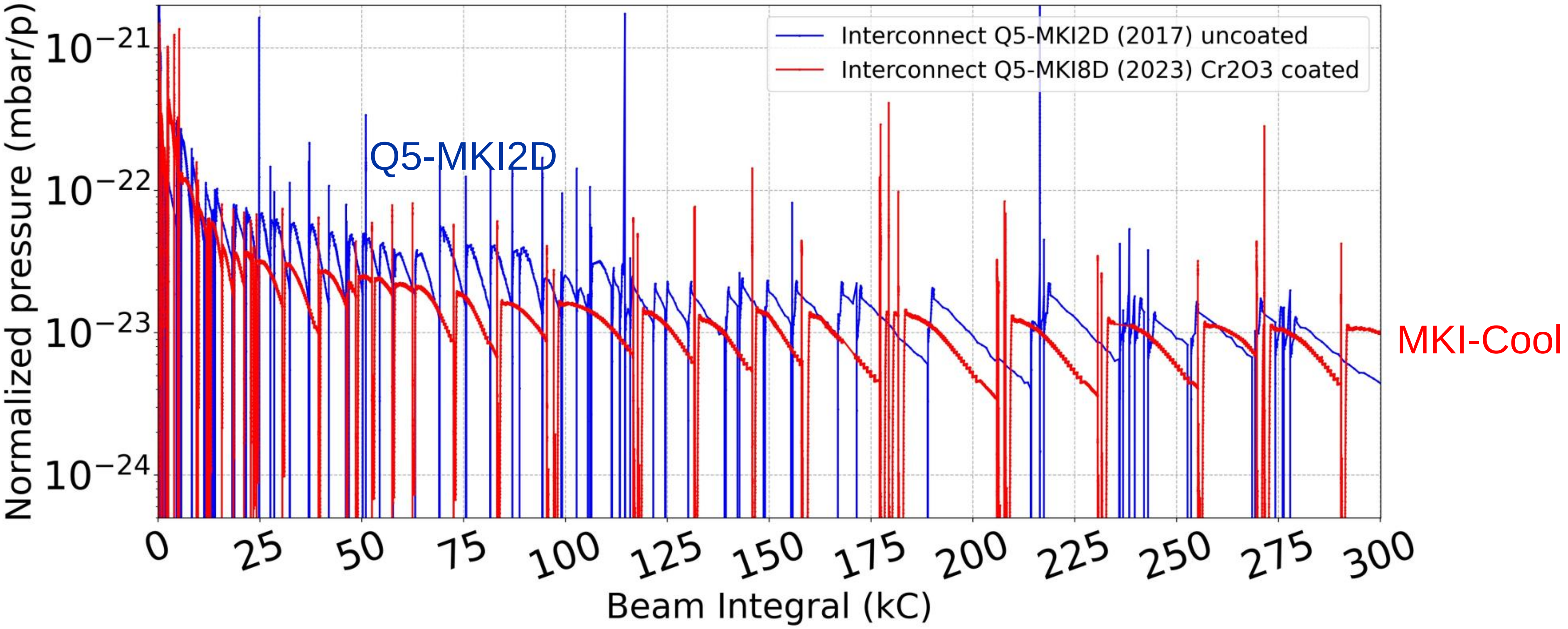


MKI-Cool installed at location MKI8D (exchanged for, prototype, upgraded MKI8D)

MKI-Cool operation in LHC during 2023 - Vacuum

Dynamic pressure:

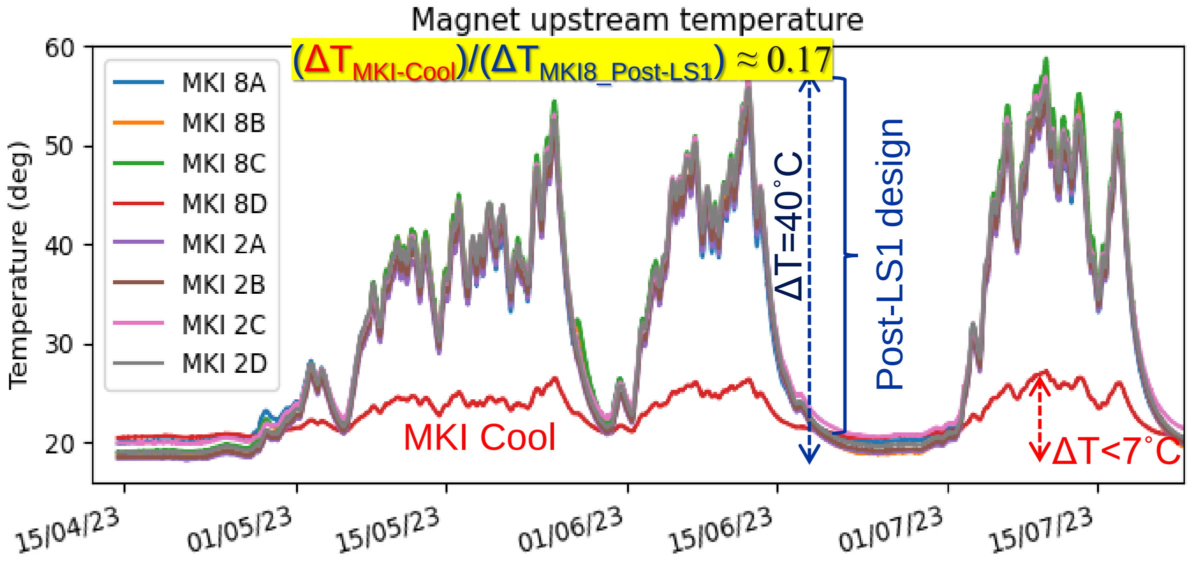
- Cr_2O_3 coated tube of MKI-Cool exhibited rapid conditioning with beam 👍

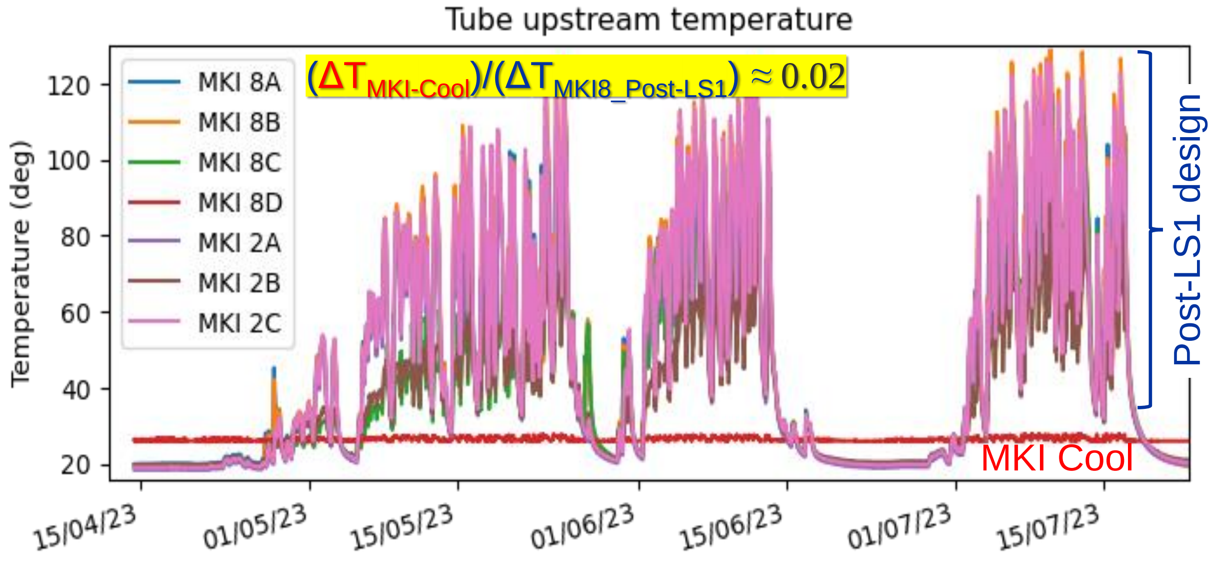


As per upgraded MKI8D installed during YETS 2017/18:

- pressure reduction attributed to Cr_2O_3 coating, of alumina tube, also seen for MKI-Cool 👍

MKI-Cool operation in LHC during 2023 - Temperature



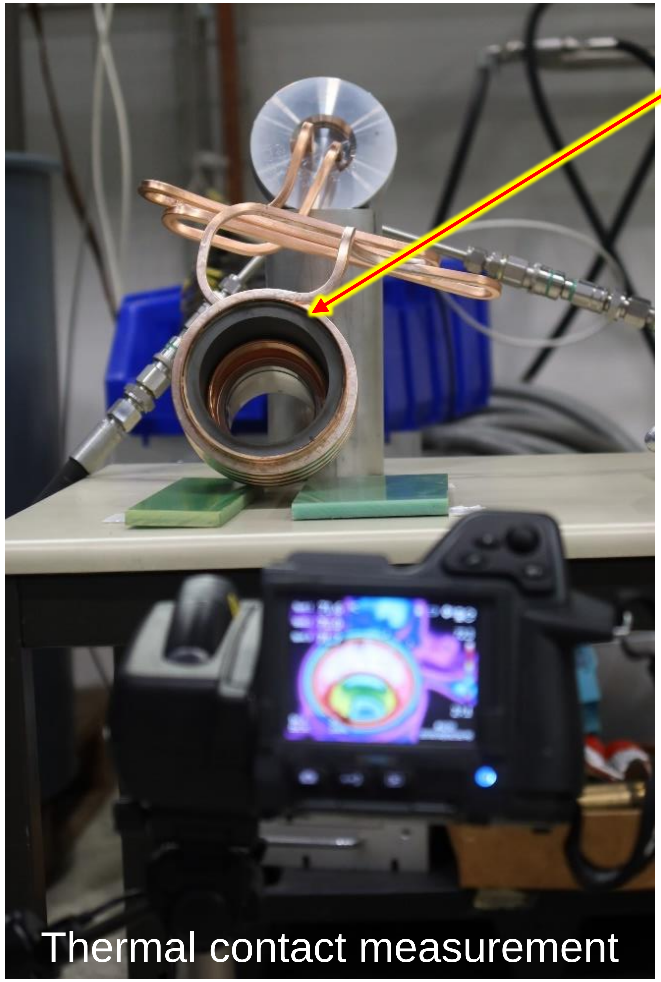


MKI-Cool shows significant reduction in measured temperatures

- Magnet upstream measured temperature rise of MKI-Cool < 20% of post-LS1 designs
- Tube upstream measured temperature rise of MKI-Cool < 2% of post-LS1 designs

For HL-LHC ultimate beam parameters, expected beam induced power will be a factor of <5 greater than for above: **no heating issues expected for the MKI-Cool.**

MKI-Cool RF Damper

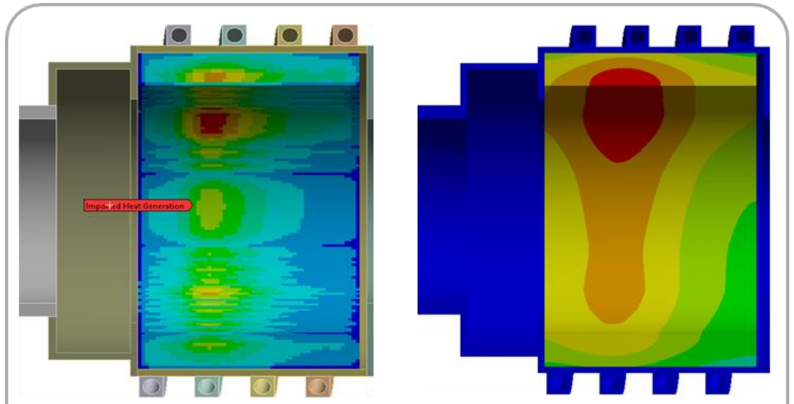


Good **thermal contact** of interface between ferrite and copper cylinder & cooling circuits is **essential** to:

- Limit maximum temperature of ferrite
- Limit mechanical stress in ferrite

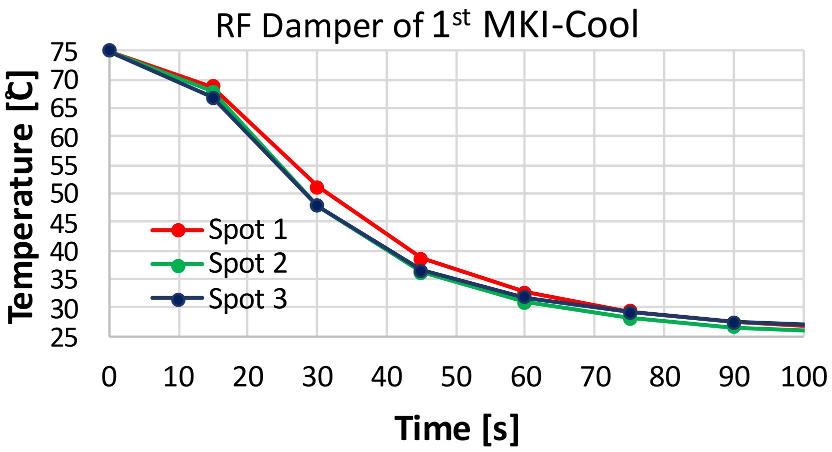
Hence, ferrite and copper cylinder are vacuum brazed.

Transient thermal measurements carried out to determine Thermal Contact Conductance (TCC) of brazing [**TCC** required: **≥ 1000** W/(m^2·K)]:



ANSYS: imported head load

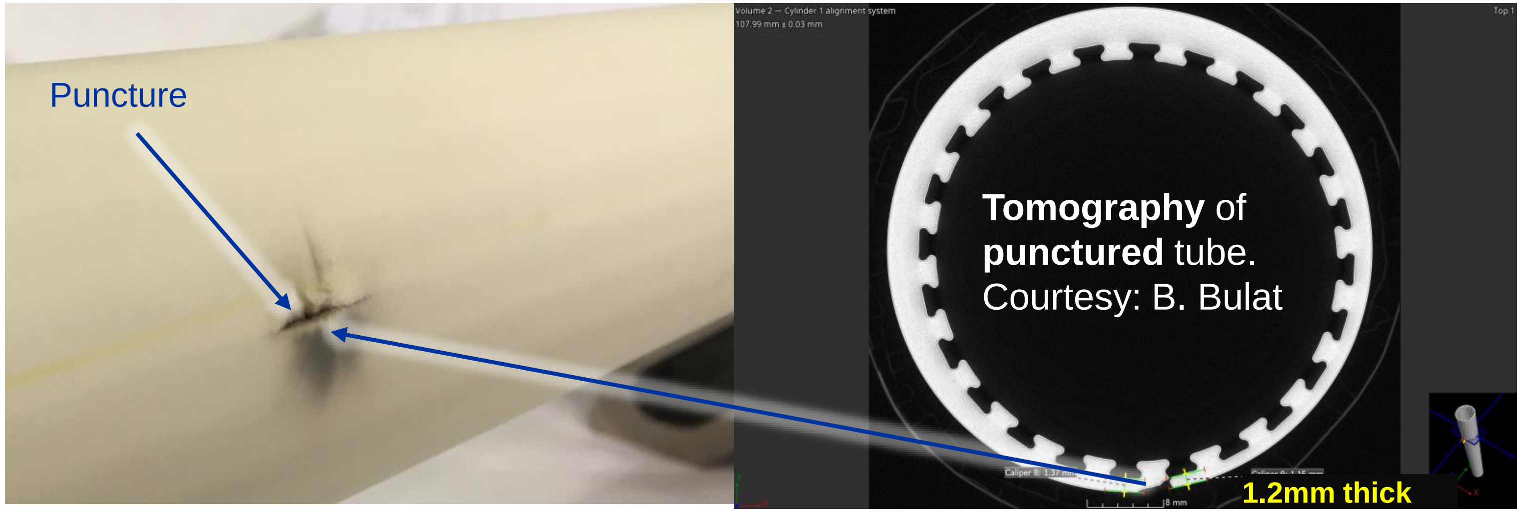
ANSYS: predicted temperature



- 1^{st} MKI-Cool RF damper: Tcc ~3000 👍
- Original prototype RF damper: Tcc ~1100 (to be used in 2^{nd} MKI-Cool) 👍
- Recent production of RF dampers: Tcc ~400 👎
- Studies ongoing to rectify brazing issues @ CERN. Also, discussions with industry

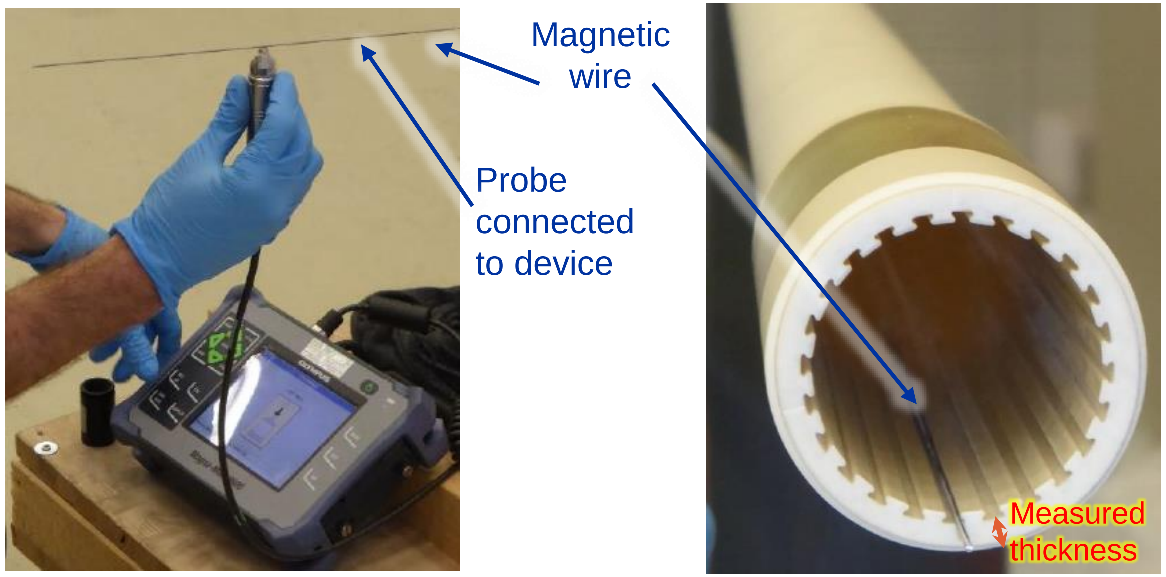
MKI-Cool Alumina Tubes

One of the batch of **alumina tubes**, ordered during **2017, punctured** during HV pulse condition of MKI, **due to a thin wall** 👎.
Also, an issue with **slots** being **too wide** 👎.



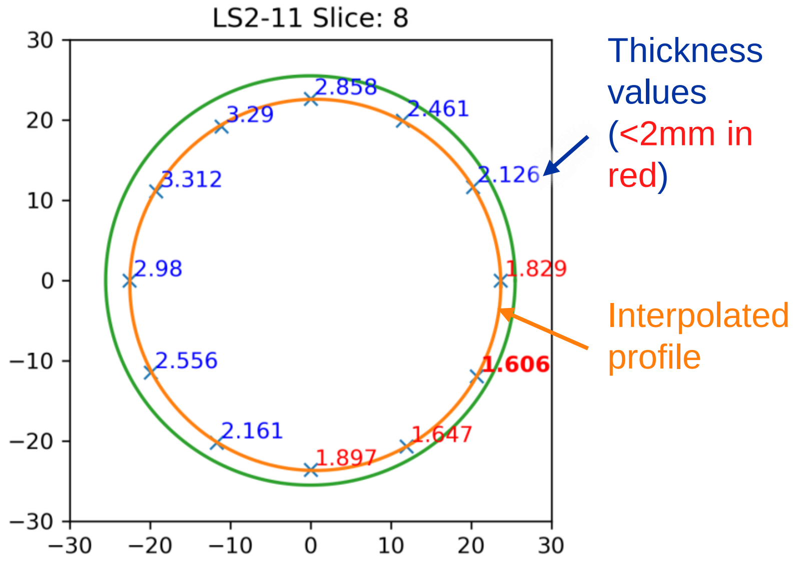
Technique developed to **measure the wall thickness of alumina tubes**

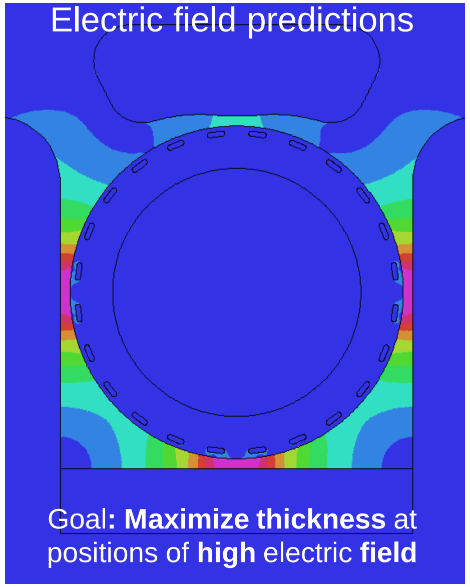
- Complete batch of 2017 tubes measured, using a magnetic gauge:
  - **Discussions with tube manufacturer** re increasing minimum wall thickness, while staying within specified geometric envelope (i.e. ensuring better concentricity of tubes)



MKI-Cool Alumina Tubes

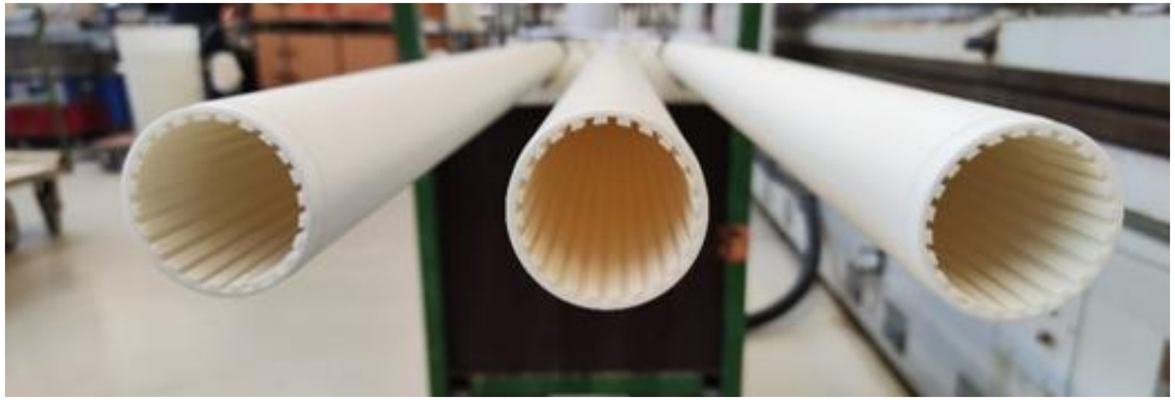
Python programme developed, to display the **wall thickness** of the alumina tubes **and optimize the angular orientation** of the tube in the MKI Cool (to minimize electric stress):





R&D has been carried out, by the manufacturer of the alumina tubes, to understand and overcome the previous production issues:

- Three tubes successfully manufactured 👍 are being shipped to CERN
- Detailed QA, including wall thickness measurements, to be performed at CERN prior to acceptance of tubes
- If R&D tubes are of good quality, order for series of tubes to be placed



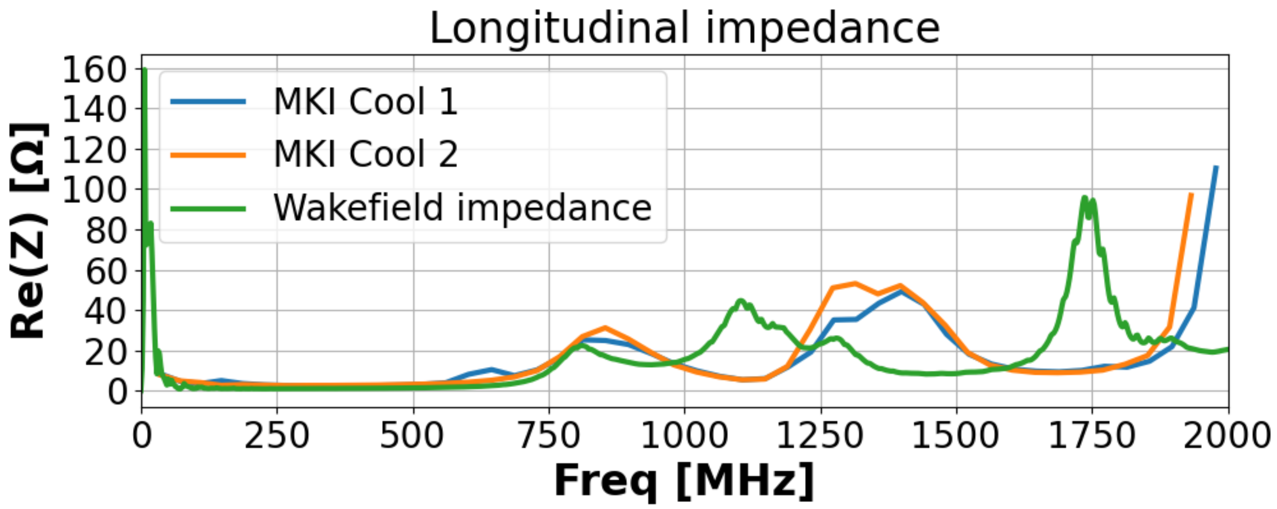
MKI-Cool Provisional Planning

1 MKI cool (#1) ✓	1 MKI cool (#2)	2 MKI cools	2 MKI cools	2 MKI Cools	4 Spare MKI Cools
YETS 22/23	YETS 23/24	YETS 24/25	Start of LS3	During LS3	During LS3
Point 8	Point 8	Point 8	Point 2	Point 2	

Note: planning could be constrained by available resources (HR and cleanroom).

MKI Cool #2:

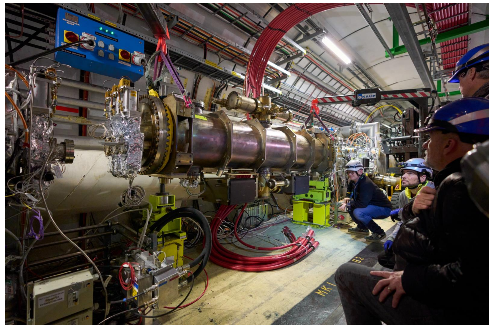
- Prototype MKI Cool RF damper used
- Cr_2O_3 coated tube recovered from upgraded MKI8D (removed from LHC during YETS 22/23)
- Longitudinal impedance measurements carried out:
  - Very similar impedance to MKI-Cool #1 👍

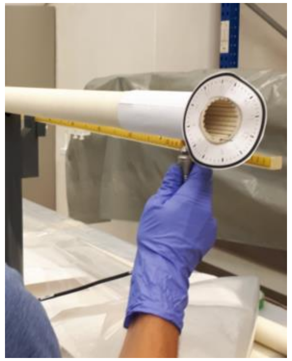


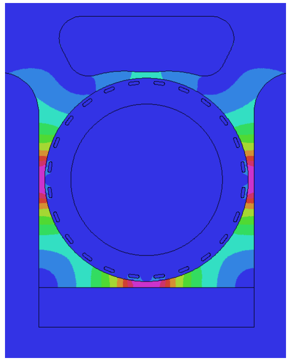
- MKI-Cool #2 presently undergoing oven bakeout
- Installation of MKI Cool, at position MKI8C, scheduled from 24/1/2024

Conclusions

- First **MKI-Cool**, with water cooled RF damper, **installed** during YETS 2022/23:
  - Cr2O3 coating of alumina tube conditioned rapidly with beam 👍
  - Temperature rise, due to beam induced heating of yoke, is < 20% of other MKIs 👍
  - For HL-LHC ultimate beam parameters, no heating issues expected for the MKI-Cool 👍
- **Issues with brazing ferrite to copper** cylinder (bad thermal contact), for series of RF dampers:
  - Under investigation with CERN MME
  - Possibilities under discussion with industry
- **R&D carried out, by the manufacturer of the alumina tubes, to understand and overcome the production issues:**
  - Three tubes successfully manufactured and are being shipped to CERN 👍
  - Detailed QA, including wall thickness measurements, to be performed at CERN prior to acceptance of tubes
- Based on **excellent results of MKI-Cool operation** 👍**, MKIs to be upgraded to MKI-Cools** – provisional planning shown





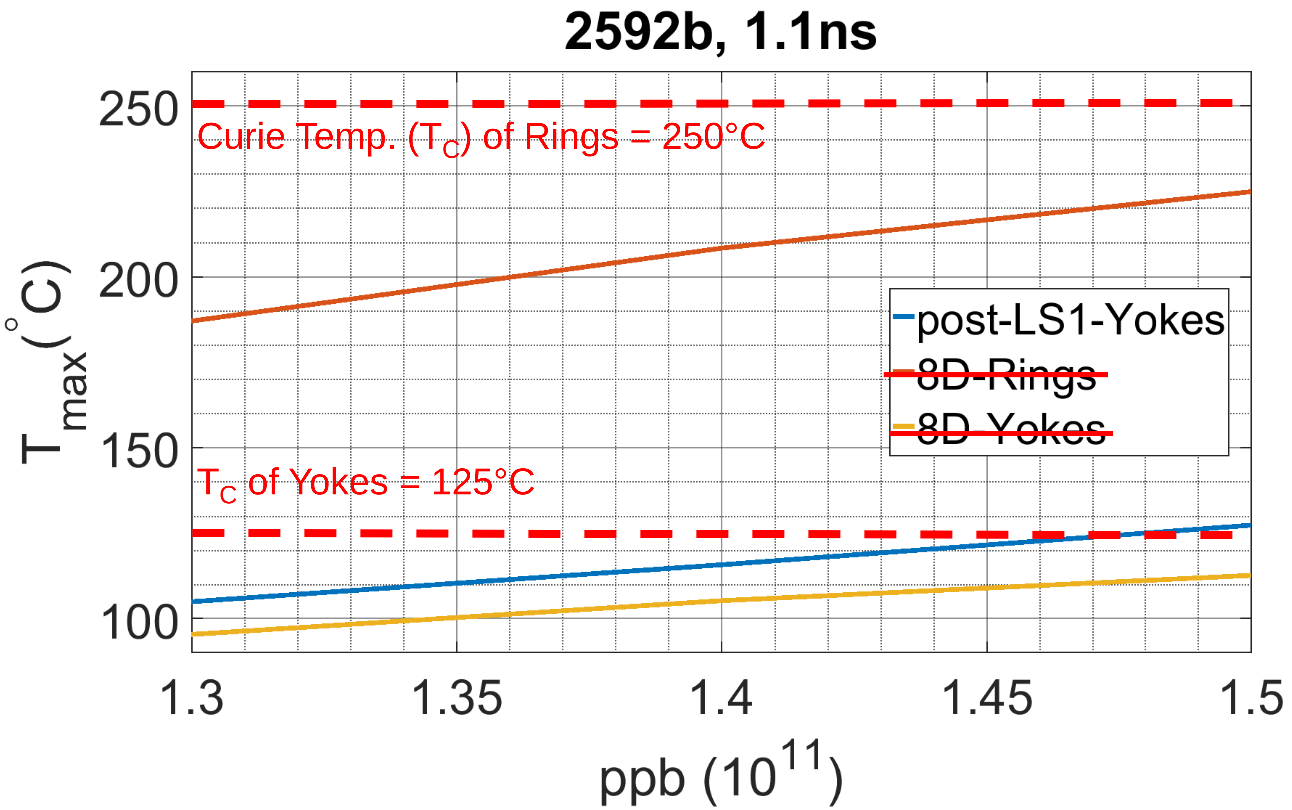


Questions ?

Spare slides

Beam Induced Heating Limitations (1)

- MKI limits for max number of circulating bunches are given by post-LS1 magnets installed
  - Details in: V. Vlachodimitropoulos, "Hardware limitations at injection" (https://indico.cern.ch/event/663598/) and "Update on MKI impedance studies" (https://indico.cern.ch/event/734086/)
- Can consider these as 'soft' limits: exceeding them by a small amount will not damage the MKIs nor cause a beam dump. However, cooling with existing MKIs is very poor (predicted **thermal time constant for cool-down of yoke is several hours**): hence, these operational limits will avoid heavy efficiency penalties.

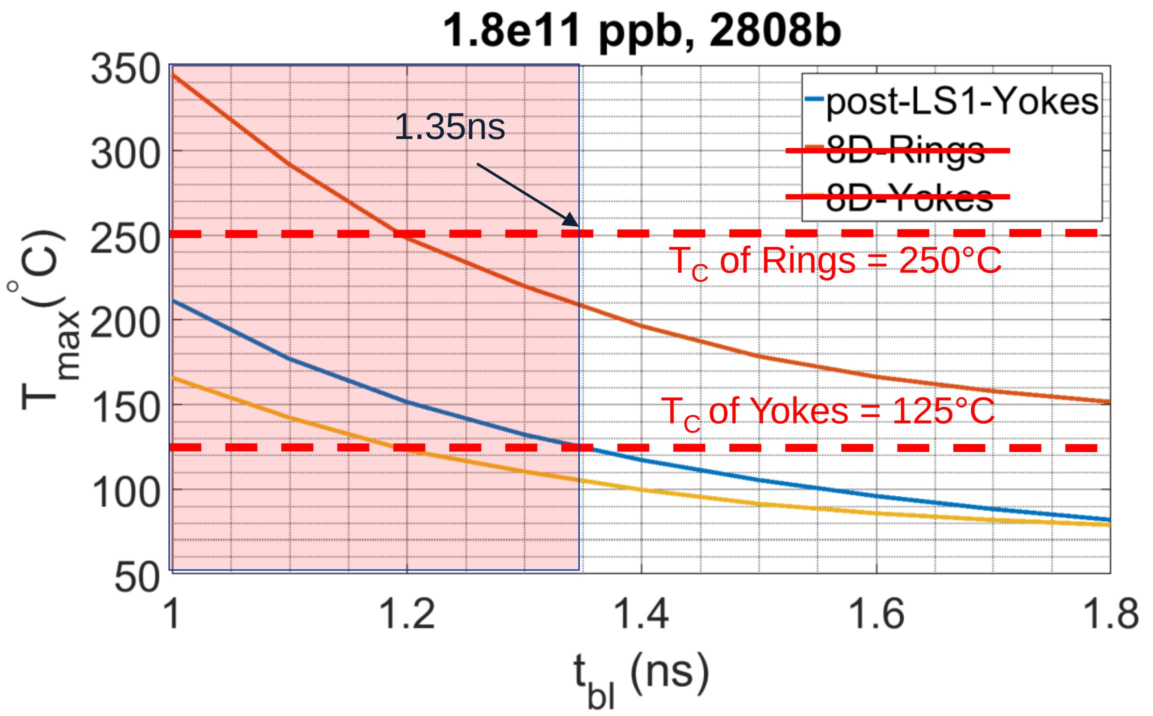


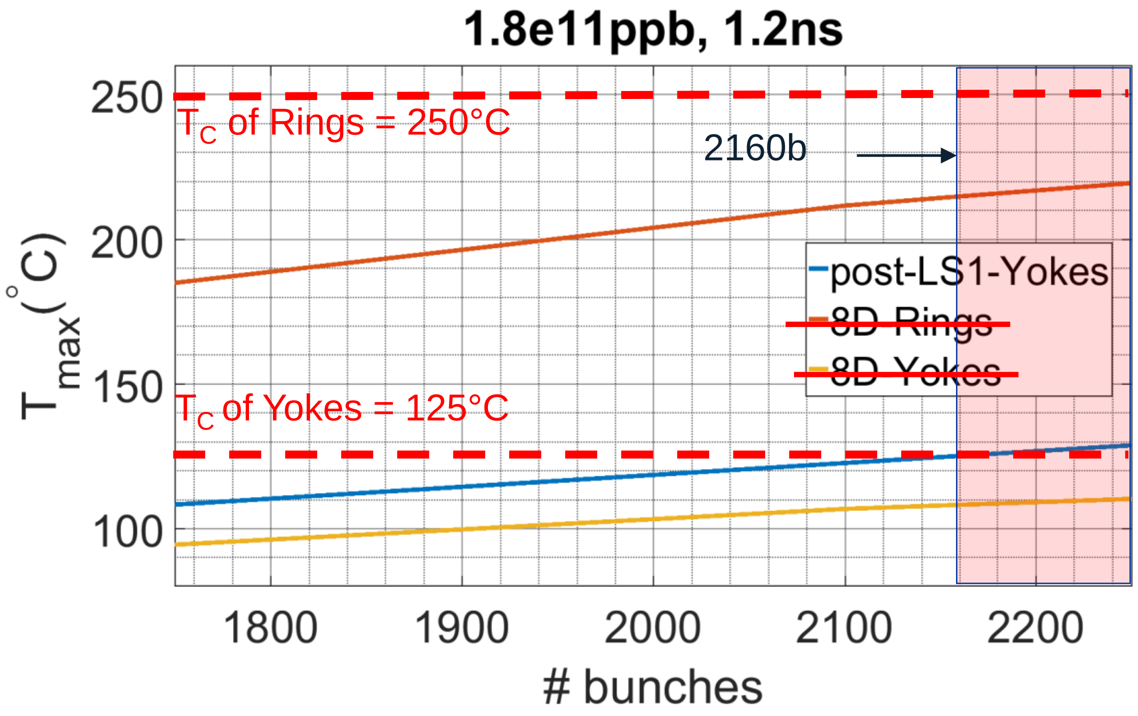
Beam Induced Heating Limitations (2)

- Steady state approach used for thermal simulations for post-LS1 MKIs and upgraded MKI8D (YETS 2017/18)
- Gaussian longitudinal profile with equi-populated bunches for beam

The following limits are intended for normal operation

- In case of usage for specific tests, depending on the operational conditions foreseen (previous cool down, time at flat top, etc.), allowed parameters (number of bunches and bunch length) to be evaluated





Expected heating for post-LS1 design

Approach to modify the scaling factor for the other magnets (see Lorena's presentation for a more detailed analysis)

- Get maximum reached temperatures (of MagnetUp sensors during 2017 operation)
- Correct for differences in initial temperatures between the different sensors (data from March 2017) and equalize with ambient temperatures (i.e. no beam/dissipated power) used in thermal simulations (22°C)
- Use P_loss-T graph to estimate the differences in total dissipated power within each magnet
- Modify the scaling factor accordingly

Example below to make things more clear (hopefully!)

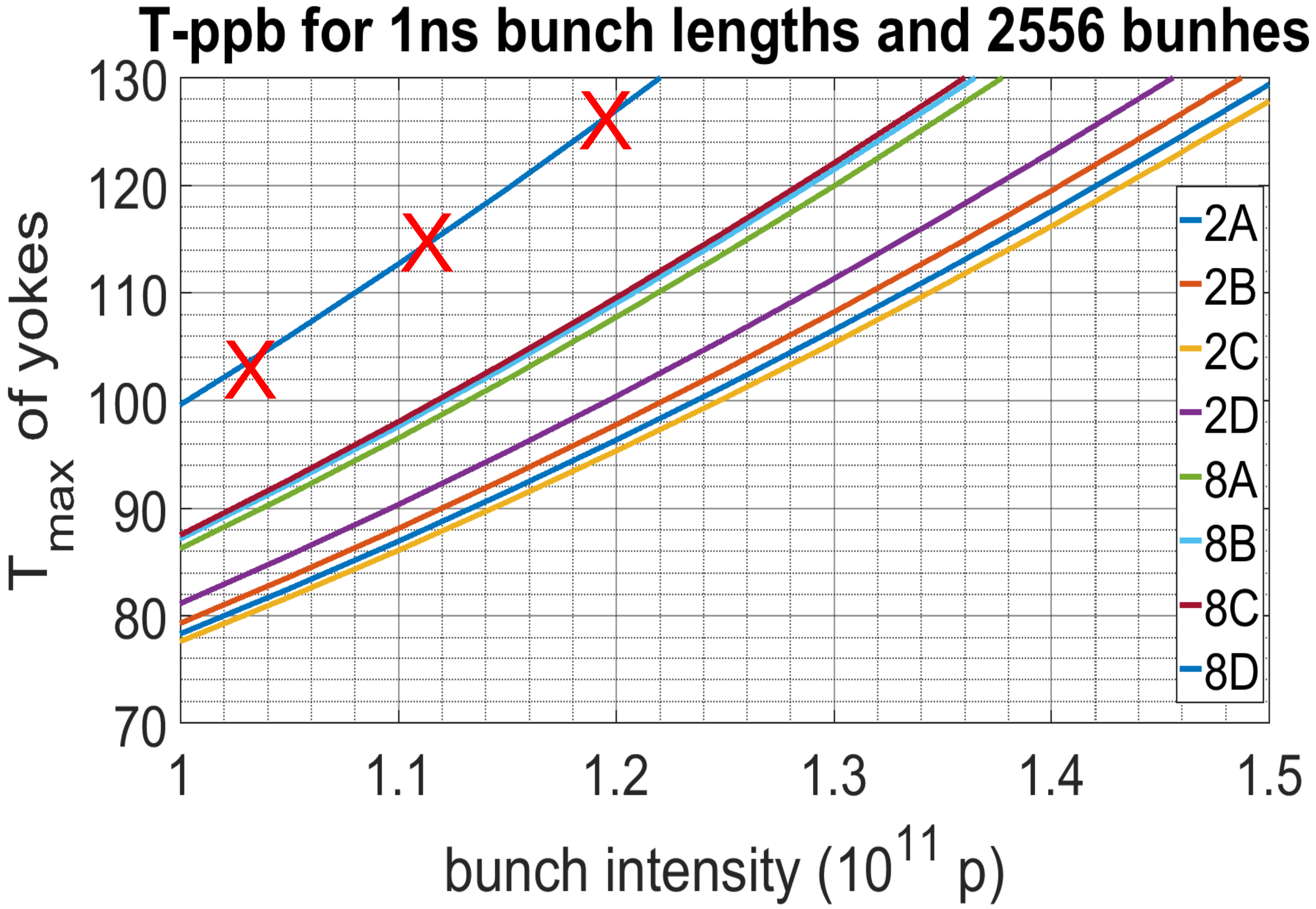
Current limitation (after MKI8D upgrade) is MKI8C: ~1.32e1

MKI8A-C have very close intensity margins

	MKI 8C	MKI 8D*
Measured max T (°C)	55.5	62.6
Initial T (°C)	20	23
"Corrected" max T (°C)	57.5	61.6
Estimated dissipated power (W)	57	71
Power ratio	0.8	1

*Before it was upgraded in YETS 17/18

Margins shown for MKI8D, are the ones before the replacement with the upgraded MKI during YETS 2017/18

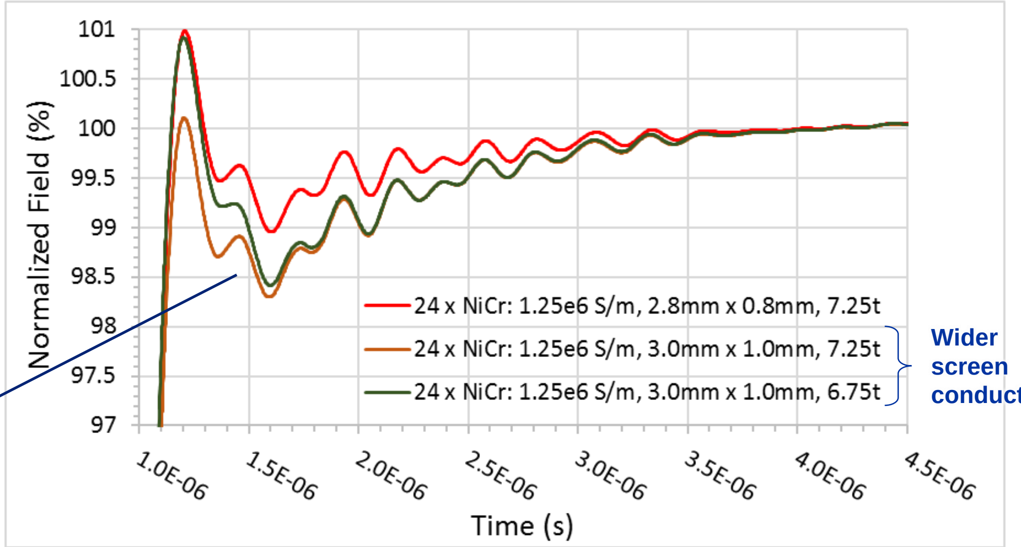


Historical issues – now solved
During 2019

Non-conformity of **slots** in alumina **tubes purchased during 2017**: slots were too wide. Thus, it was necessary to use **screen conductors** with a small **zig-zag**

[HL-NCR: https://edms.cern.ch/document/2440015/1.0]

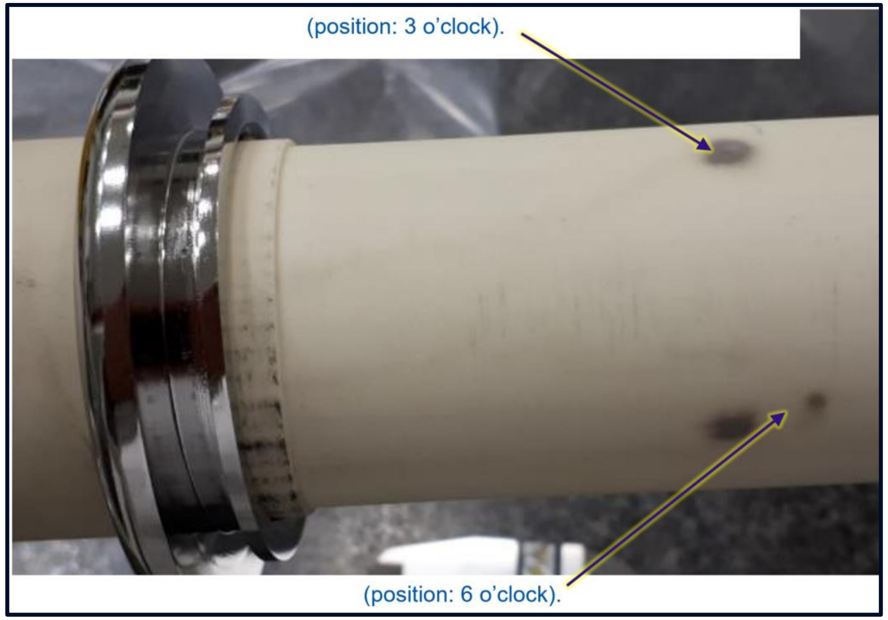
Using **wider screen conductors** was **discarded** due to **influence** on **magnetic field** (eddy currents)



HV pre-conditioning of MKI cool **failed**:

[HL-NCR: https://edms.cern.ch/document/2440015/1.0]

- 18 **strong sparks** occurred over two weeks
  Conditioning plateaued at ~**45kV** (**goal=56.1kV**)
- Three **black marks** from HV **breakdowns to** alumina **tube**



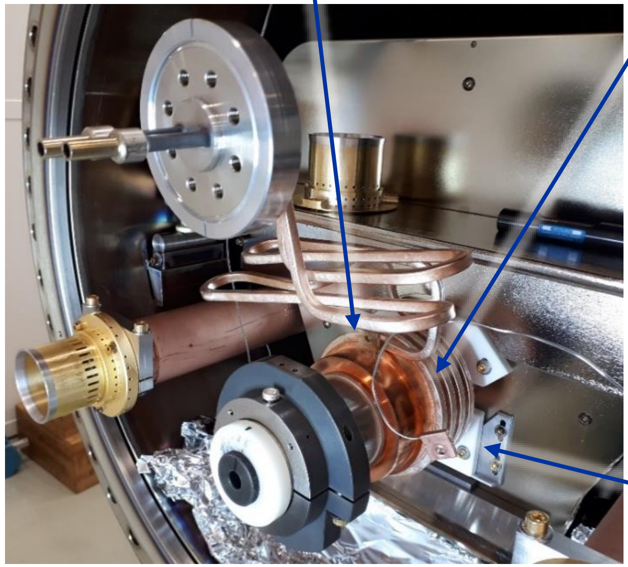
2. Issues – now solved
During 2019. Actions carried out

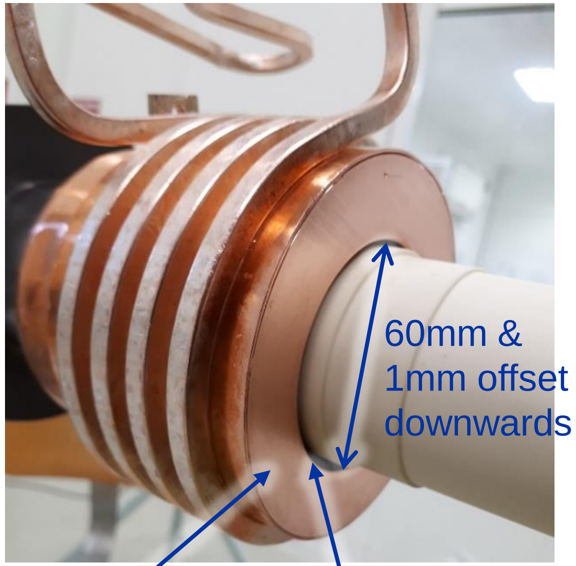
RF damper structure was modified to mitigate HV breakdowns:

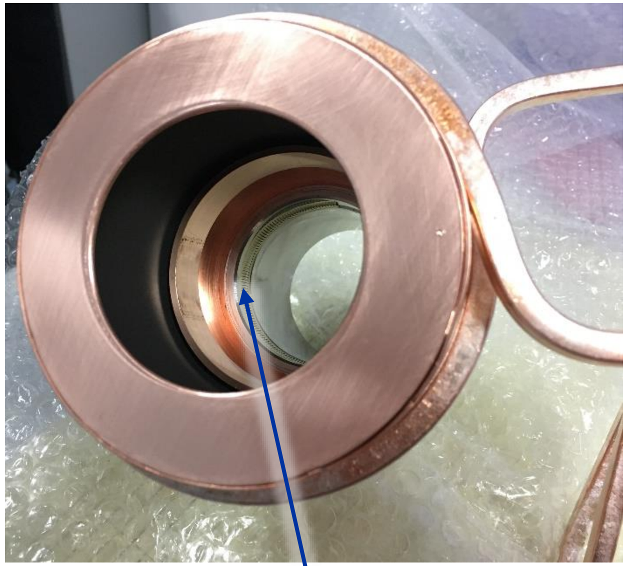
1. Metal **supports for tube** replaced by **macor**

2. RF damper end **cap inside diameter enlarged** (from 56mm to 60mm), to **increase distance to** alumina **tube**

3. **Sharp edge** on stainless steel short eccentric tube removed (manufacturing error)



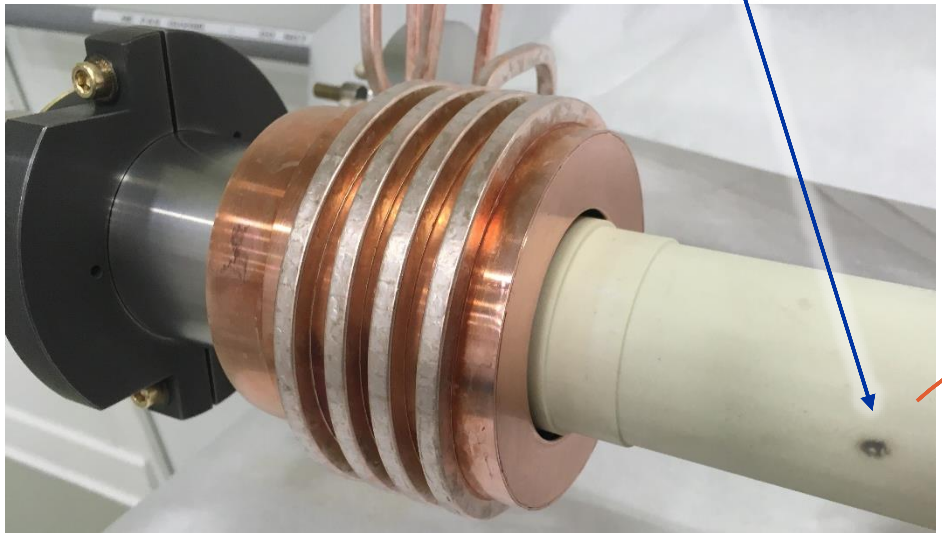




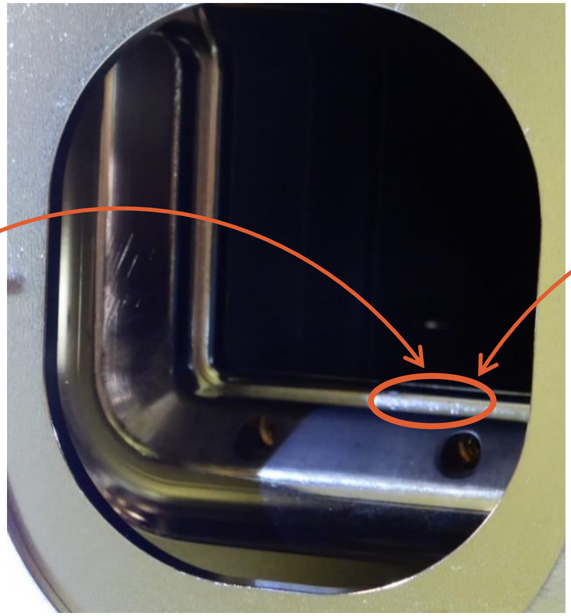
2. Issue – now solved
Inspection after conditioning (November 2020)

First observation: Still one **black mark** seen **on** the **tube**, at the end (3 marks in 2019)

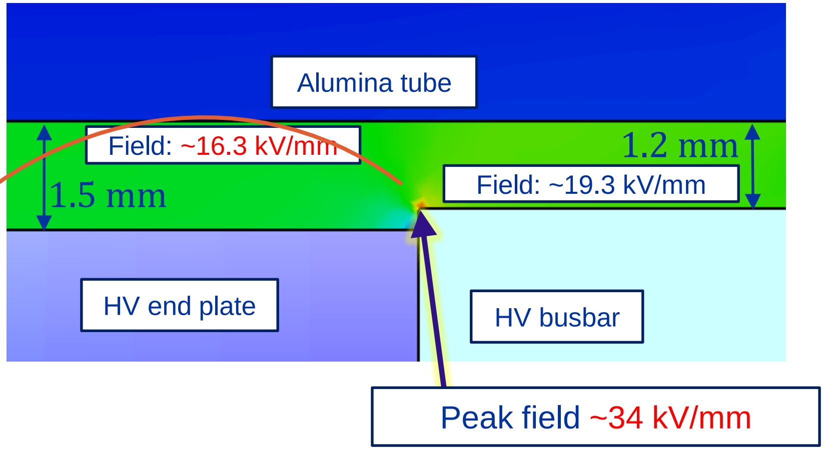
The **reason** was a **sharp edge** due to **mis-alignment of HV busbar** of the magnet ➡ **Solved** with correct alignment



Alumina tube **outside of magnet**



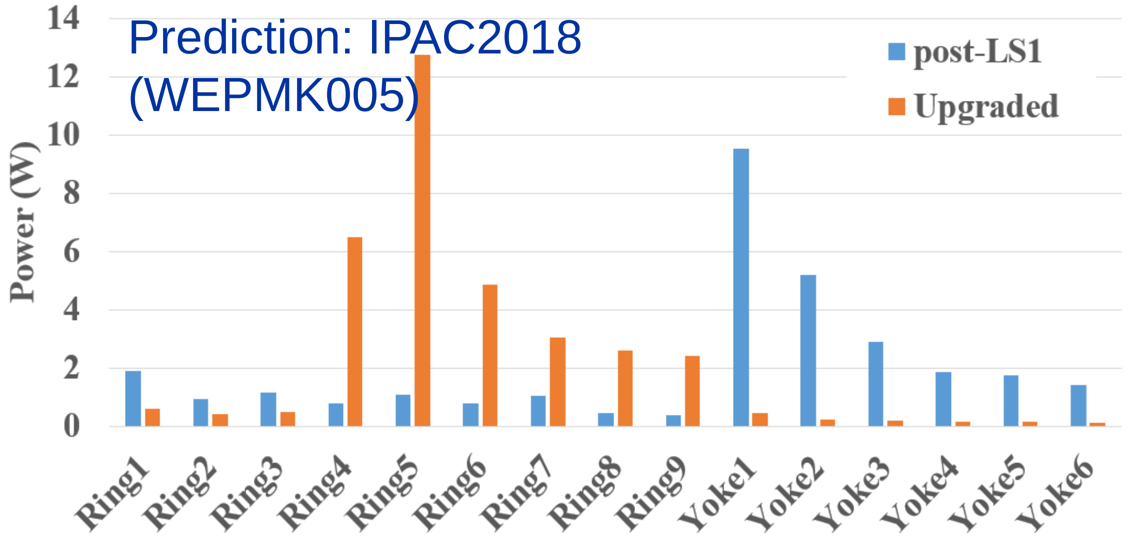
End of magnet, without tube



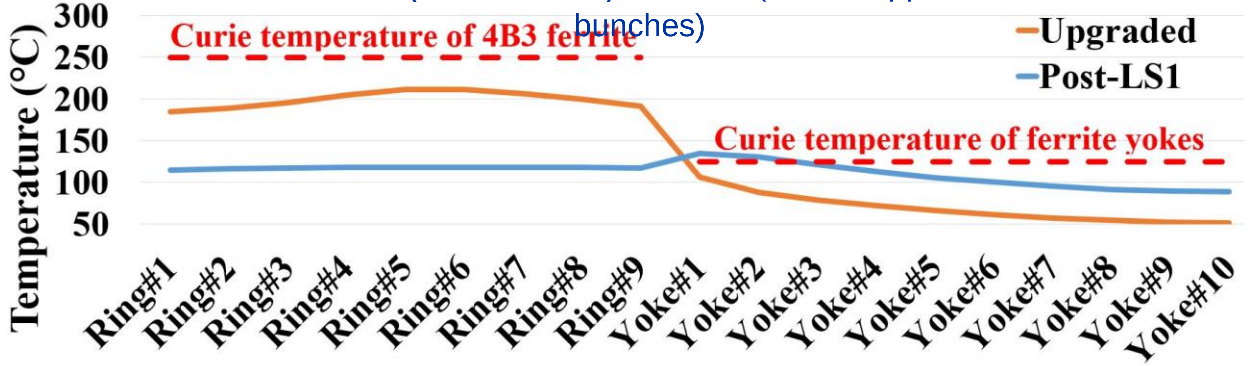
Enhanced electric **field** (~doubled) **due to dealignment** of HV busbar

MKI Beam Screens – Predictions & Measurements

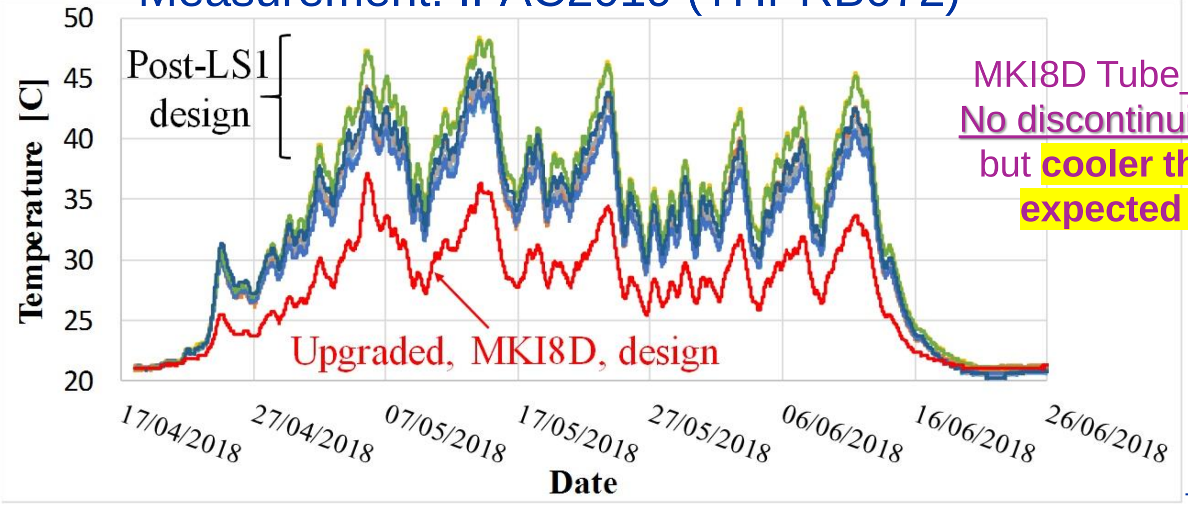
Prediction: IPAC2018 (WEPMK005)



Prediction: IPAC2018 (WEPMK001) – Run 2 (1.15e11 ppb, 2808b, 1ns Gaussian bunches)

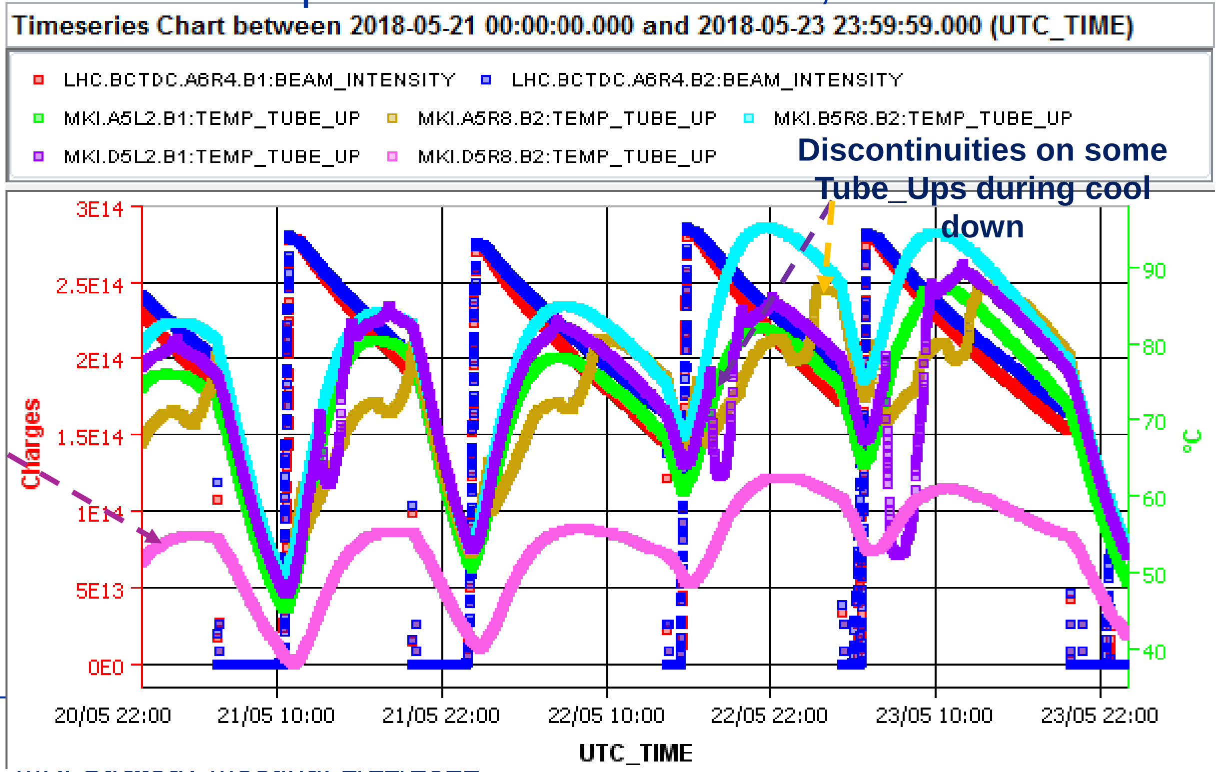


Measurement: IPAC2019 (THPRB072)



MKI8D Tube_Up
No discontinuities,
but **cooler than expected**!

Vasilis: presentation to 21st IWG, 26/6/2018



Discontinuities on some Tube_Ups during cool down