Optimization of Beam Impedance Mitigation Measures for HV Reliability in an SPS Injection Kicker Magnet

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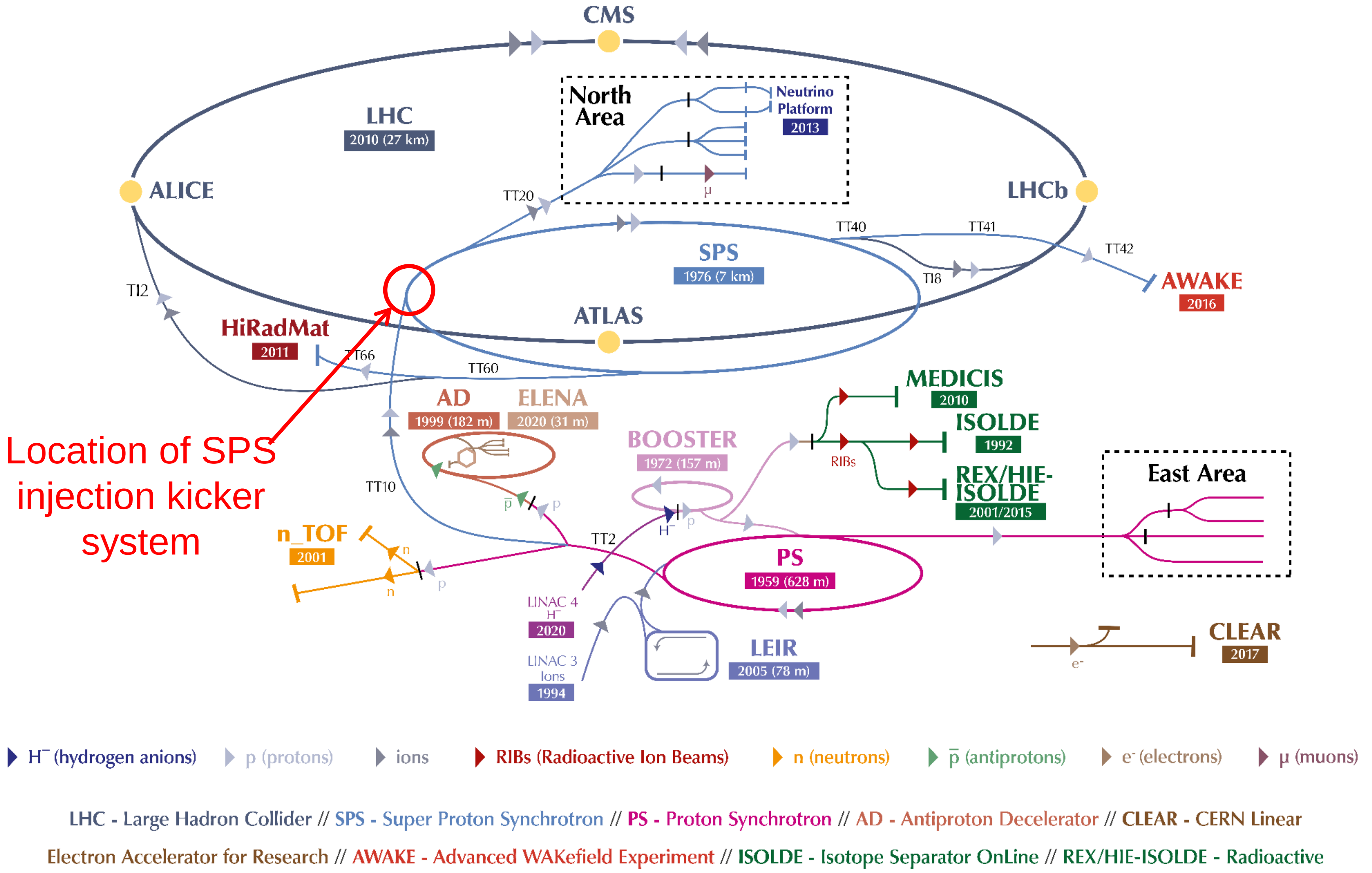
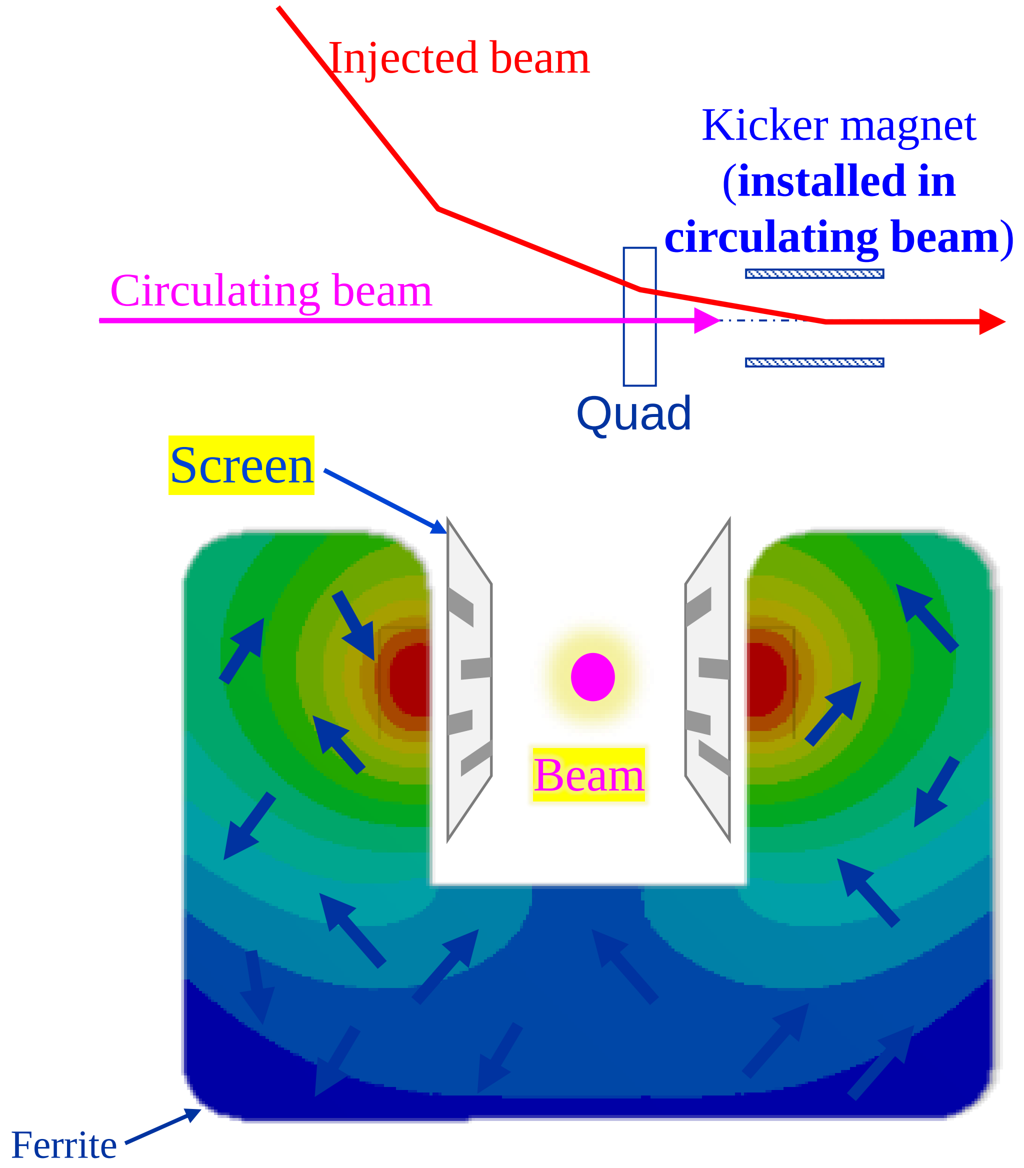
OUTLINE

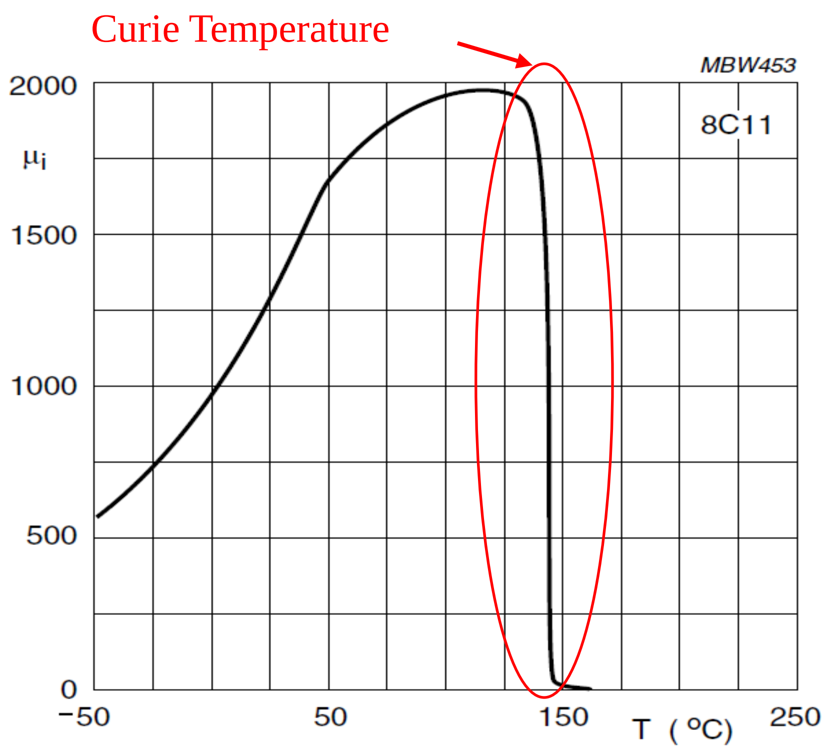
- Introduction to SPS injection kicker system
- Problem
- Solution – silver fingers
- HV issues during pulse testing
- Final design
- Beam coupling impedance
- Results from SPS operation
- Conclusion

CERN Accelerator Complex



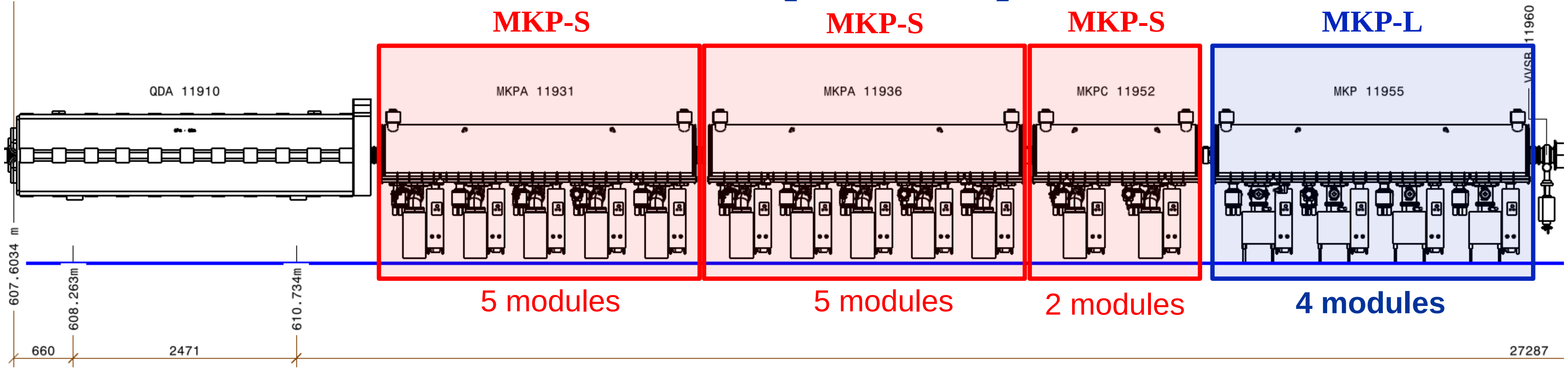
BEAM INDUCED HEATING - INTRODUCTION





Above its Curie Temperature the ferrite temporarily looses its permeability.

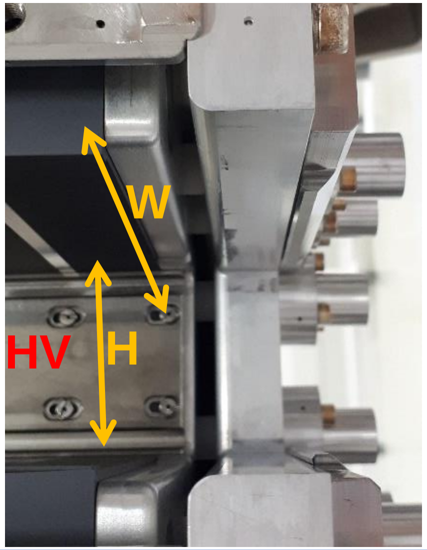
SPS Injection System (MKP)

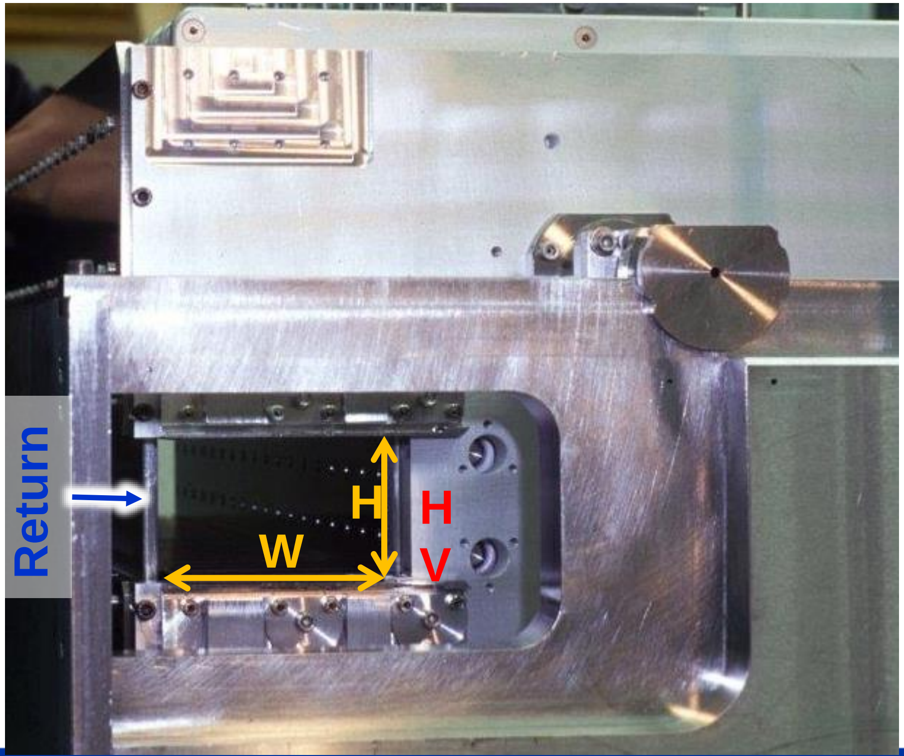


- MKP consists of 16 modules
  - 12 x MKP-S (W=100mm, H=61mm)
  - **4 x MKP -L (W=141.5mm, H=54mm)**

MKP-L:

- Transmission line magnet: 200ns electrical delay
- Operated up to 50kV PFN (25kV on modules)
- >2.1µs pulse width (fixed)

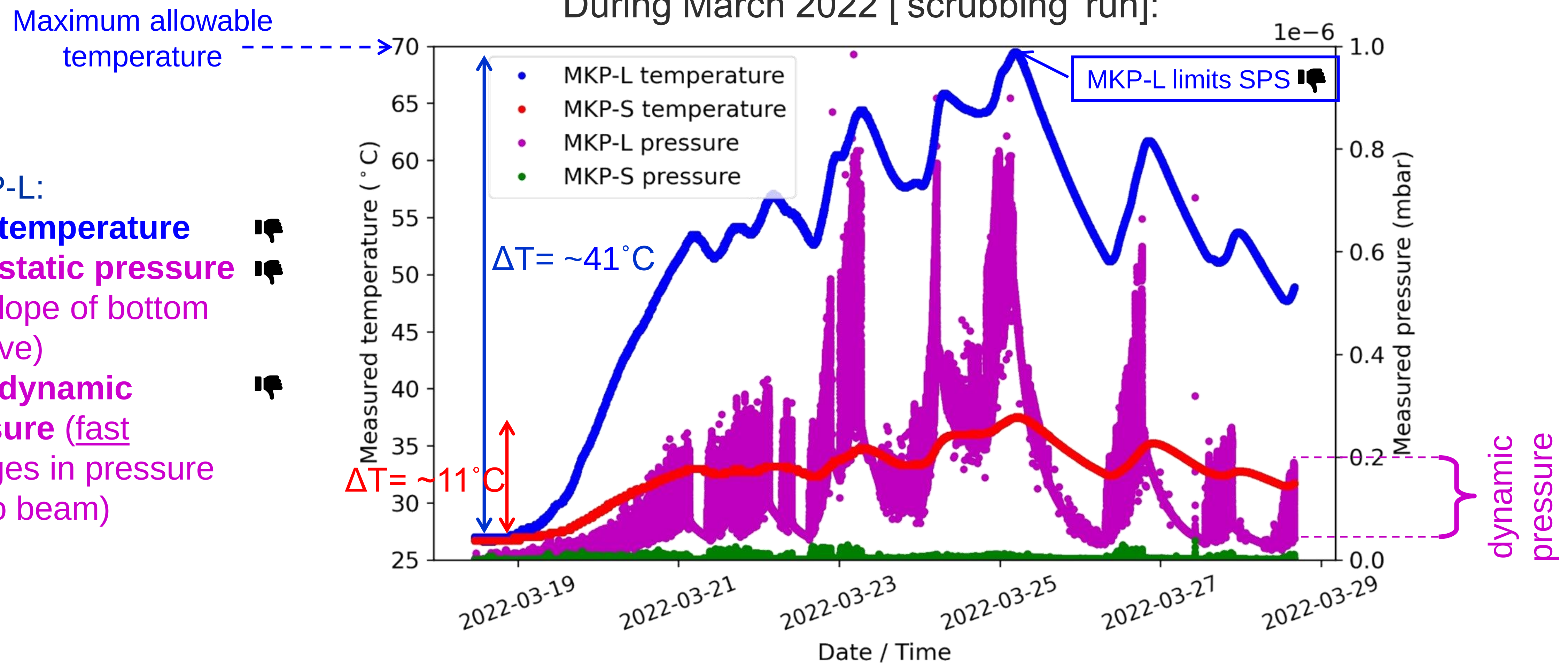




MKP: Beam Induced Heating

- MKP-L aperture dimensions -> susceptible to beam induced heating (the MKP-L has a high broadband beam coupling impedance – see next slide).

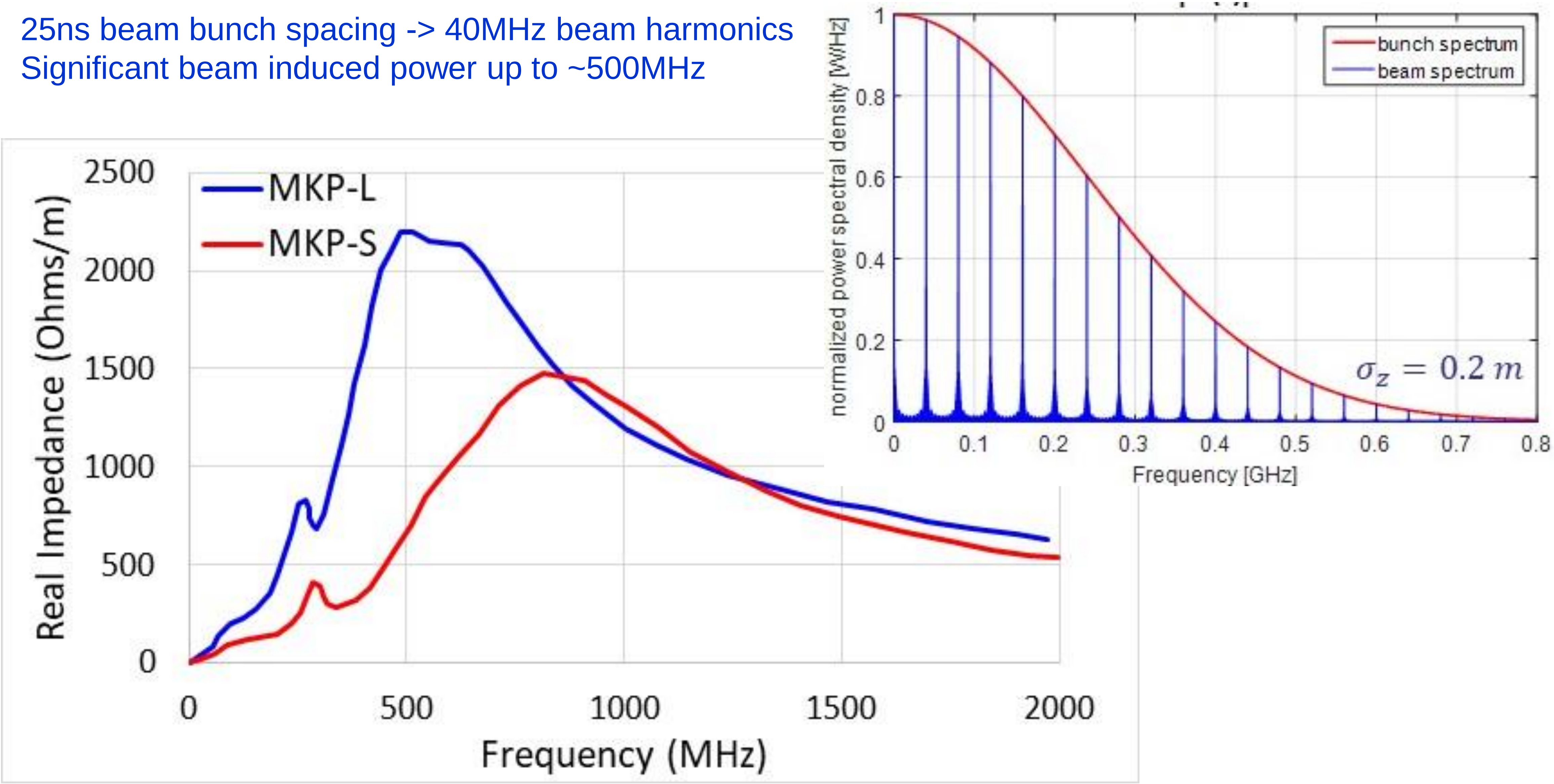
During March 2022 [‘scrubbing’ run]:



Old MKP-L:
- **High temperature**
- **High static pressure** (envelope of bottom of curve)
- **High dynamic pressure** (<u>fast</u> changes in pressure due to beam)

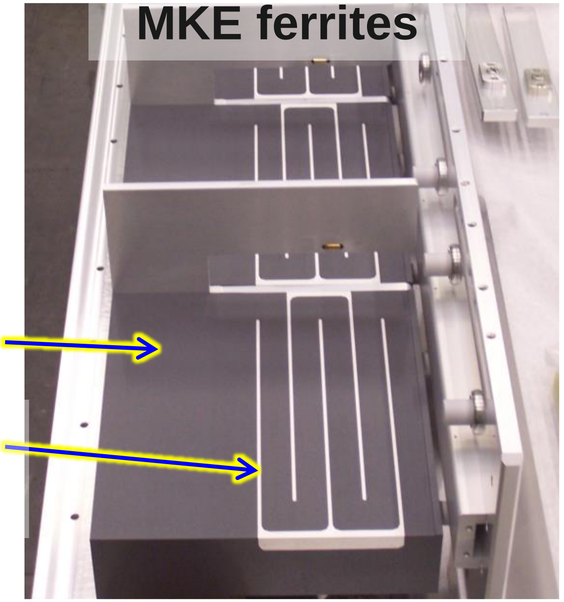
MKP: Beam Coupling Impedance

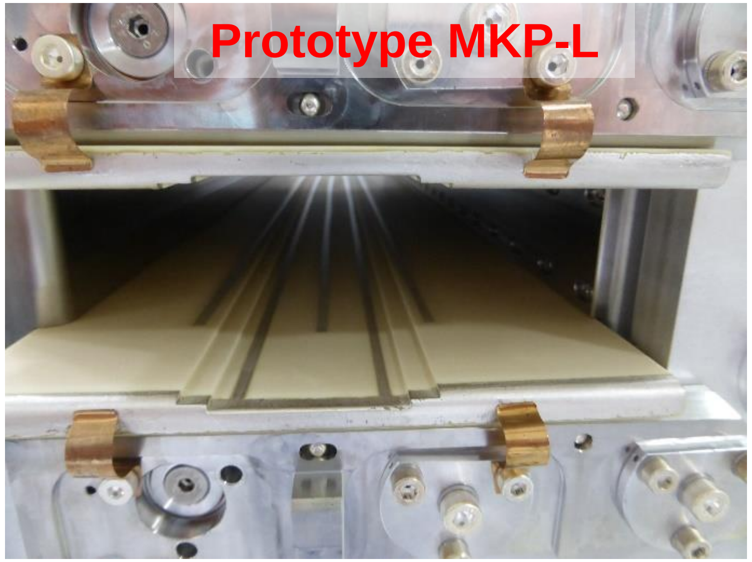
- 25ns beam bunch spacing -> 40MHz beam harmonics
- Significant beam induced power up to ~500MHz

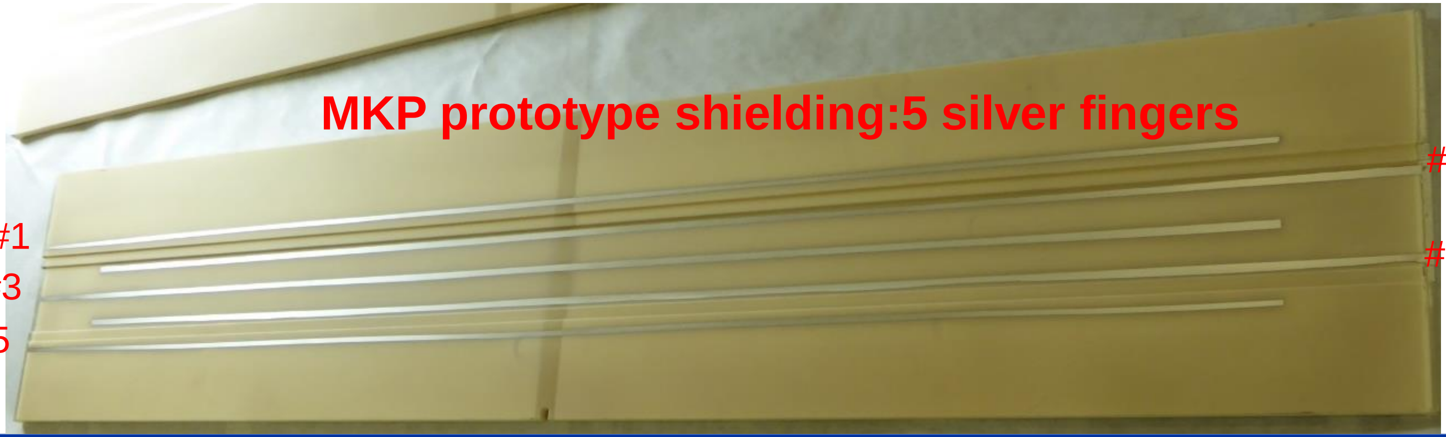


PROPOSED SOLUTION TO REDUCE IMPEDANCE

- Insufficient time and budget to redesign and build new MKP-L magnets
- Instead adopt, as a baseline, a previously used solution – the SPS extraction kicker (MKE) had silver painted fingers on ferrite (MKE ferrite cell length = 235 mm)
  - ✓ Capacitive connection between the two sets of silver fingers
  - ✓ Allows circulation of image current of the beam (high frequency components)
  - ✓ Does not interfere with magnetic field rise time
- However, MKP-L ferrites are too short (26mm), hence:
  - Not effective for shielding ferrites from beam
  - Would introduce severe HV issues

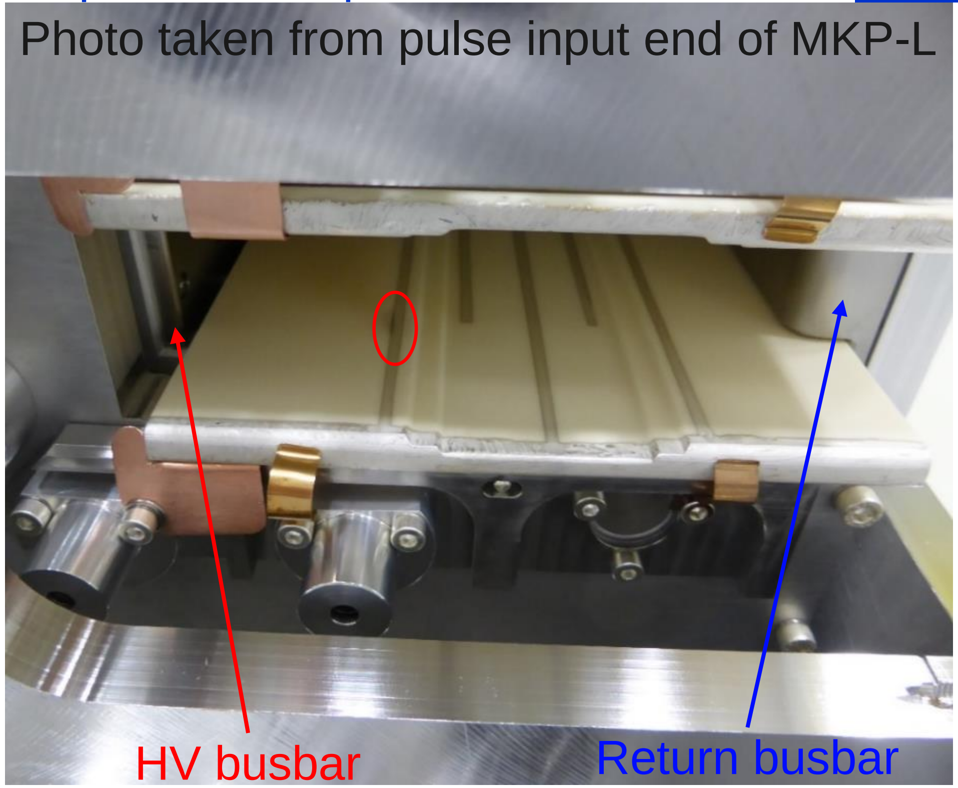




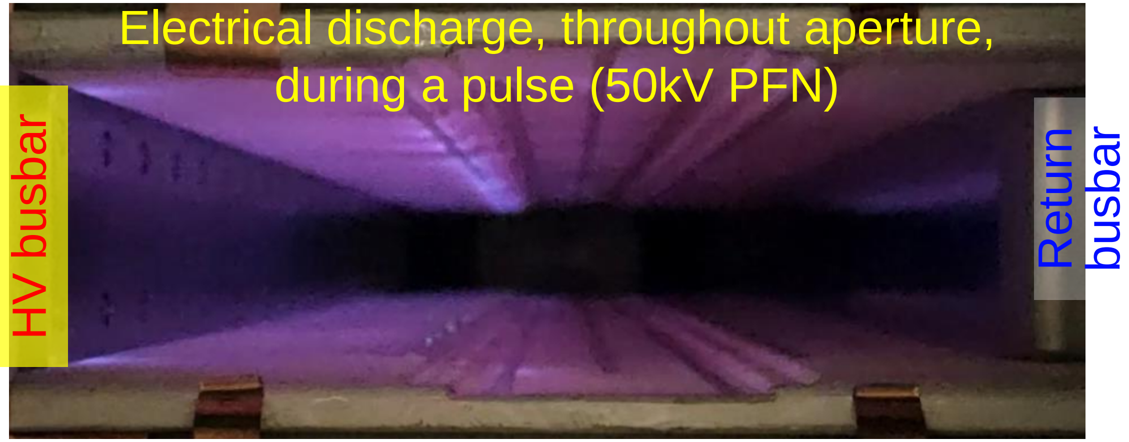


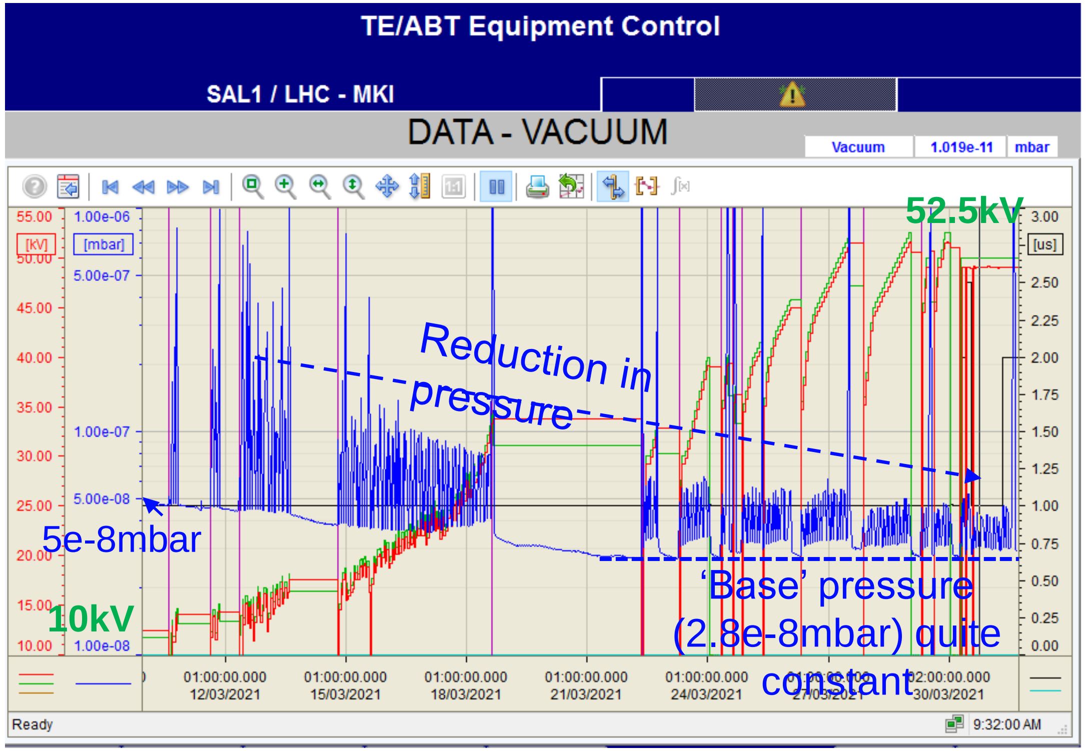
PROTOTYPE MKP-L #1: HV PULSE TESTING

5 fingers per alumina plate, connected to end **ground plates**:



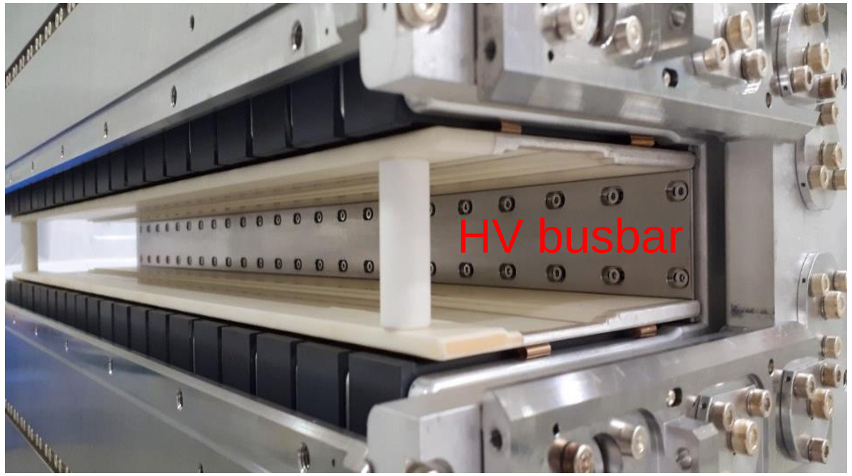
- **Corona & breakdowns** between fingers and HV busbar, when pulsing magnet
- Pressure rise dependent on pulse length:
  1×10^{-8} mbar (@50 kV PFN and 1 μs)
  2×10^{-8} mbar (@50 kV PFN and 2 μs)

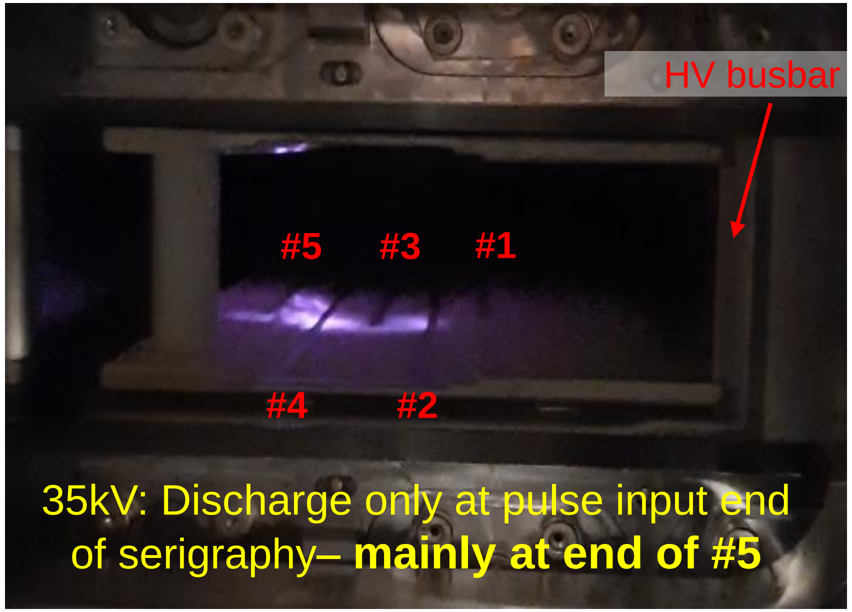


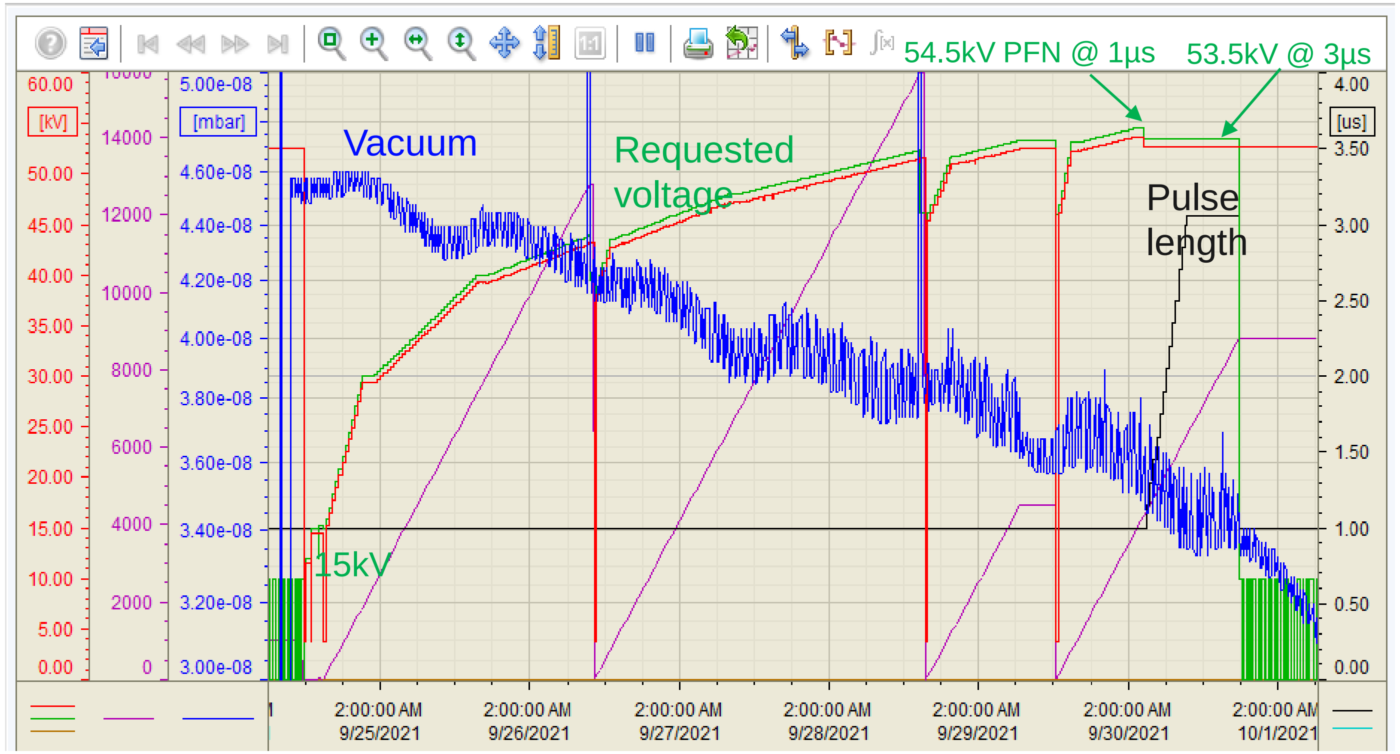


PROTOTYPE MKP-L #2: HV PULSE TESTING

Fingers connected to **HV end plates:**







🙂 With serigraphy connected to HV end plates, much reduced corona and breakdown :

- ΔP = ~0.2 x10^{-8} mbar at 50 kV PFN
- No dependence of vacuum on pulse length
- Not yet ideal**: need to reduce max. electric field by at least 50%…..**

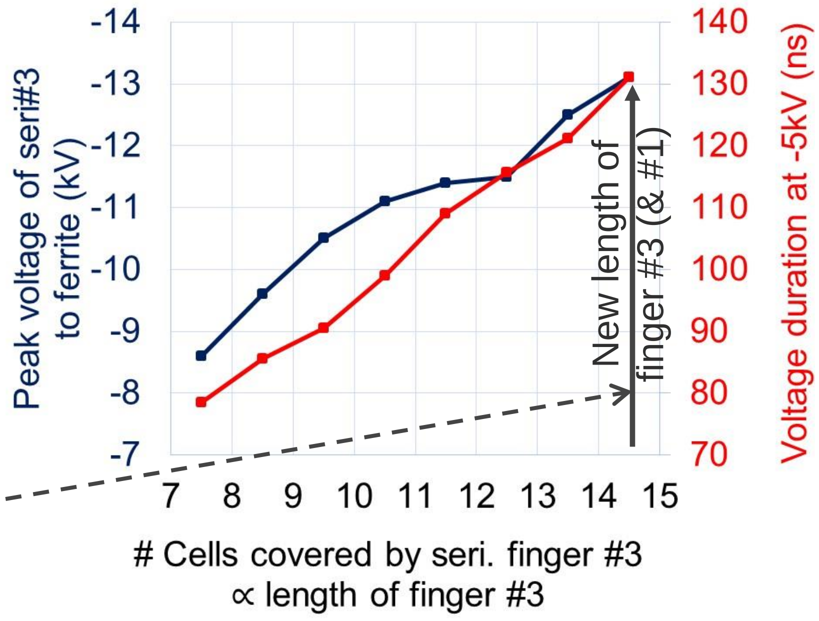
REDUCTION OF MAX. ELECTRIC FIELD

PSpice and electrostatic simulations of V#2 show that:

- Highest voltage difference, between fingers and ferrite, is associated with tip of finger #5
    - Fingers connected to the output end (#1, #3 & #5) are at negative potential w.r.t. the ferrite

Hence, to reduce electric field, at end of worst-case fingers, by at least 50%:

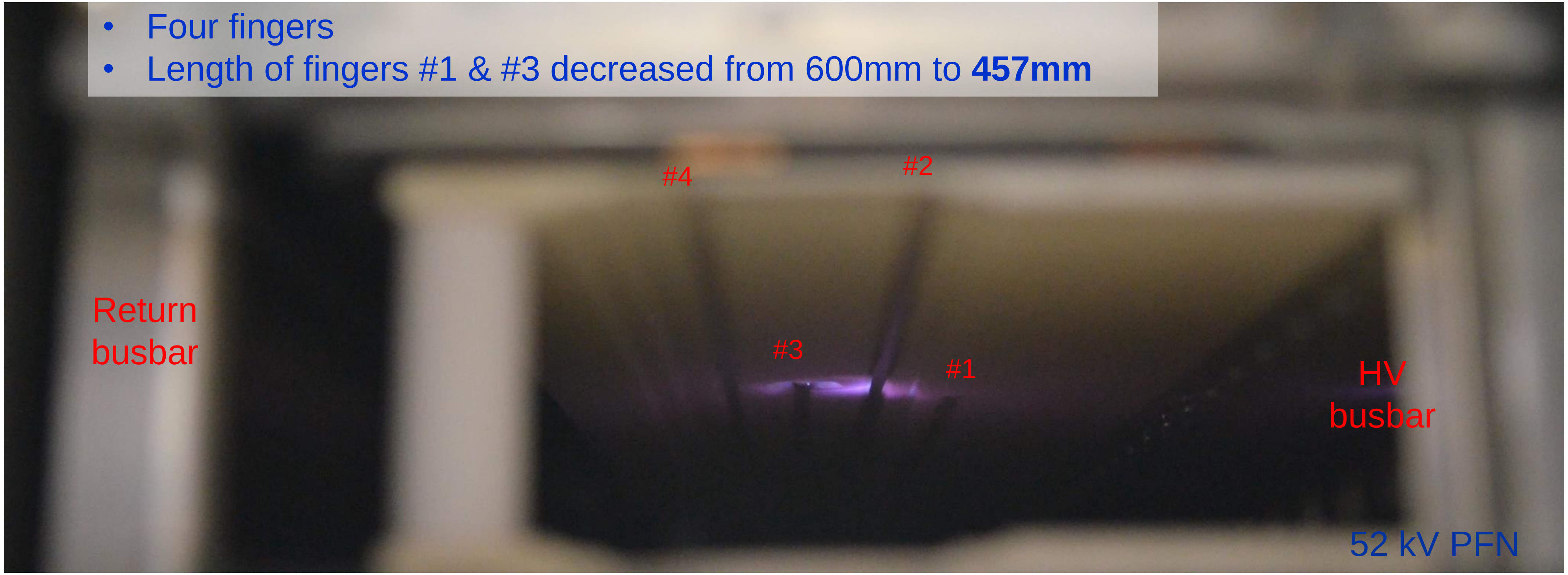
- Eliminate fifth silver finger (-> four instead of five fingers)
- Introduce a ‘slot’ or ‘groove’ at end of the third finger
- Offset fingers towards HV busbar
- Length of fingers #1 & #3 decreased from 600mm to **457mm**
- Length of fingers #2 & #4, decreased from 600mm to **581mm**



PROTOTYPE MKP-L #3: HV PULSE TESTING

Fingers connected to **HV end plates:**

- Four fingers
- Length of fingers #1 & #3 decreased from 600mm to **457mm**



With only four fingers connected to HV end plates:

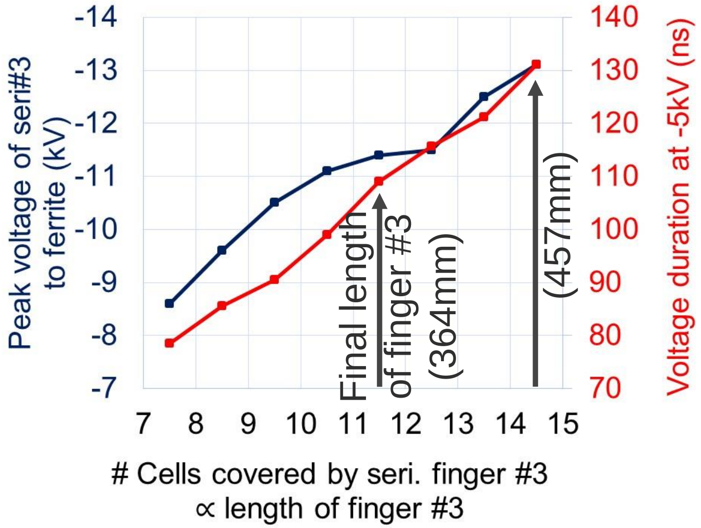
- **Less corona and lower pressure**
- **No dependence of vacuum on pulse length.**

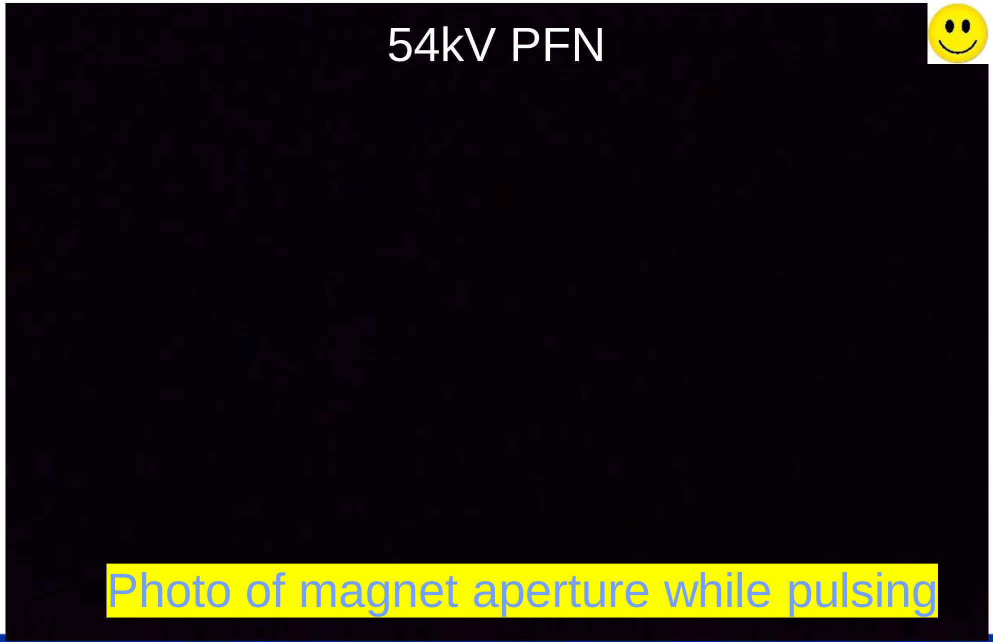
~180k pulses at 52kV PFN (for reference, ~400K on MKP-L in SPS during 2021)

- Beam coupling impedance remeasured after HV pulse testing ⇒ no significant change (i.e. no degradation)

MKP-L Final Version: HV Pulse Testing

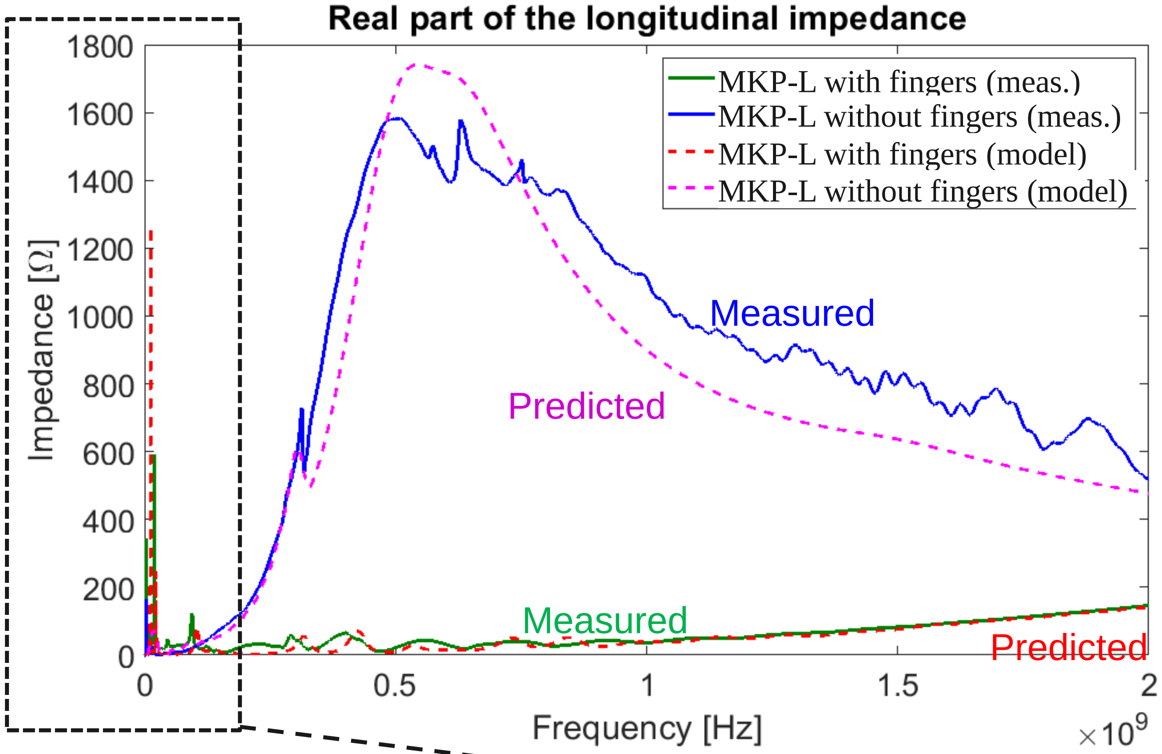
- Two alumina U-chambers, rather than plates
- Four serigraphy fingers applied on each U-chamber
  - Fingers #1 & #3 length further decreased from 457mm to 364mm
  - Fingers #2, #4 remain at 581mm
- Each chamber to be Cr_2O_3 coated on the inside





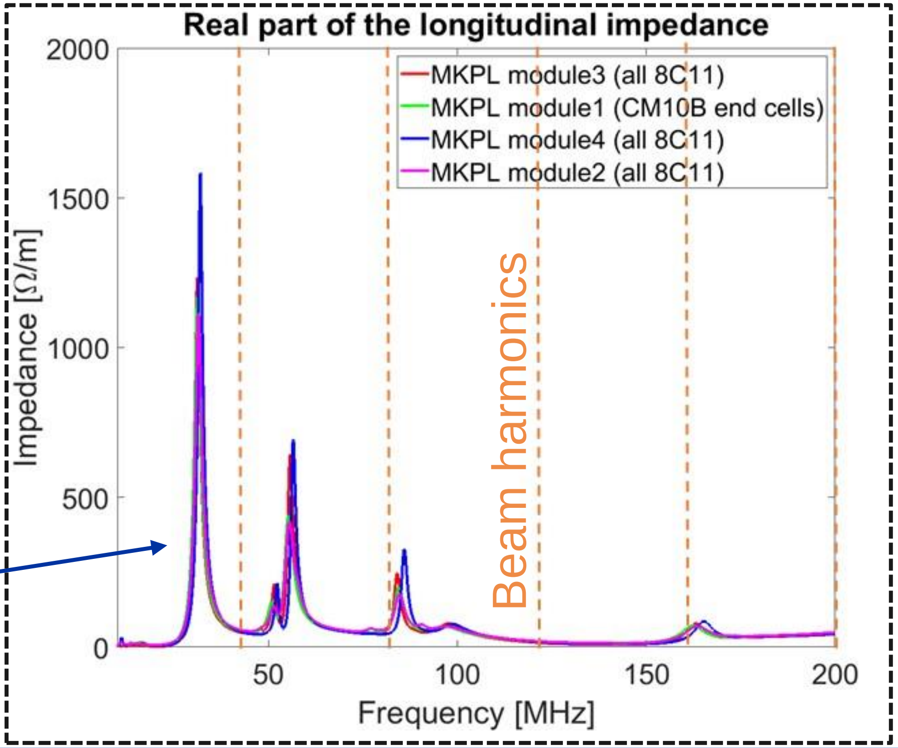
- Negligeable pressure rise (~0.02 x10^{-8} mbar at 50 kV PFN and 2 μs)
- No dependence of vacuum on pulse length
- 80k pulses at 52kV PFN

MKP-L: Beam Coupling Impedance



- Good agreement between predictions (CST) and measurements
- Real impedances is sufficiently low

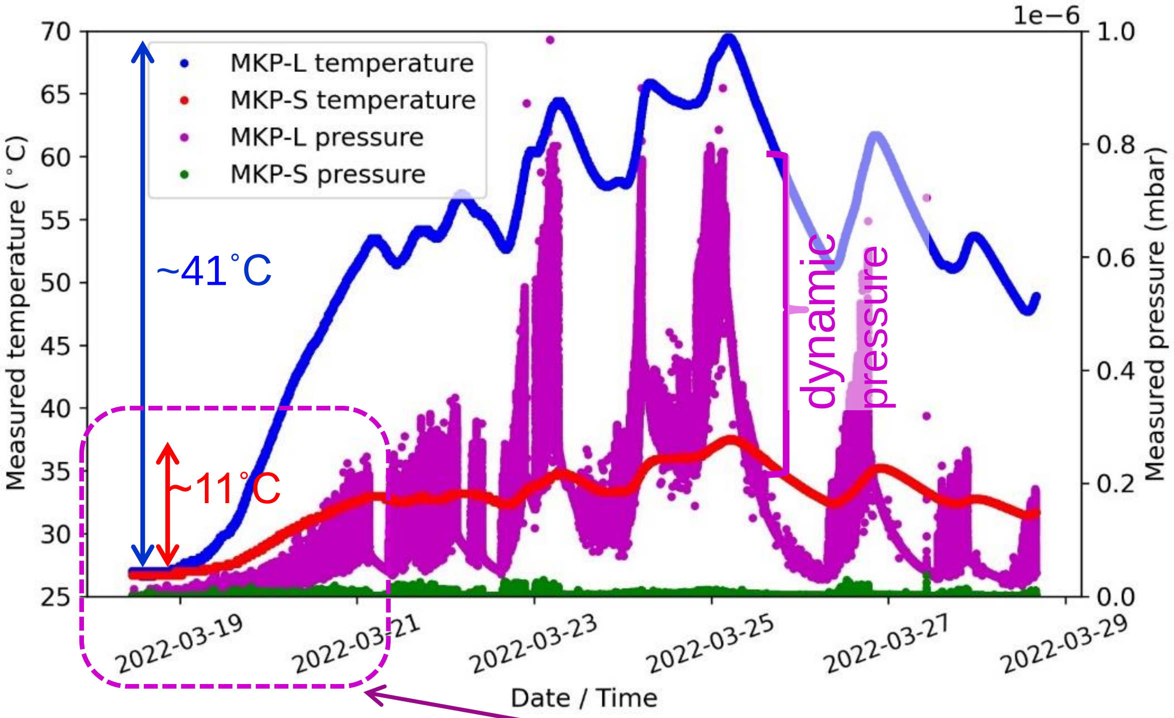
Measurements for four final MKP-L modules:



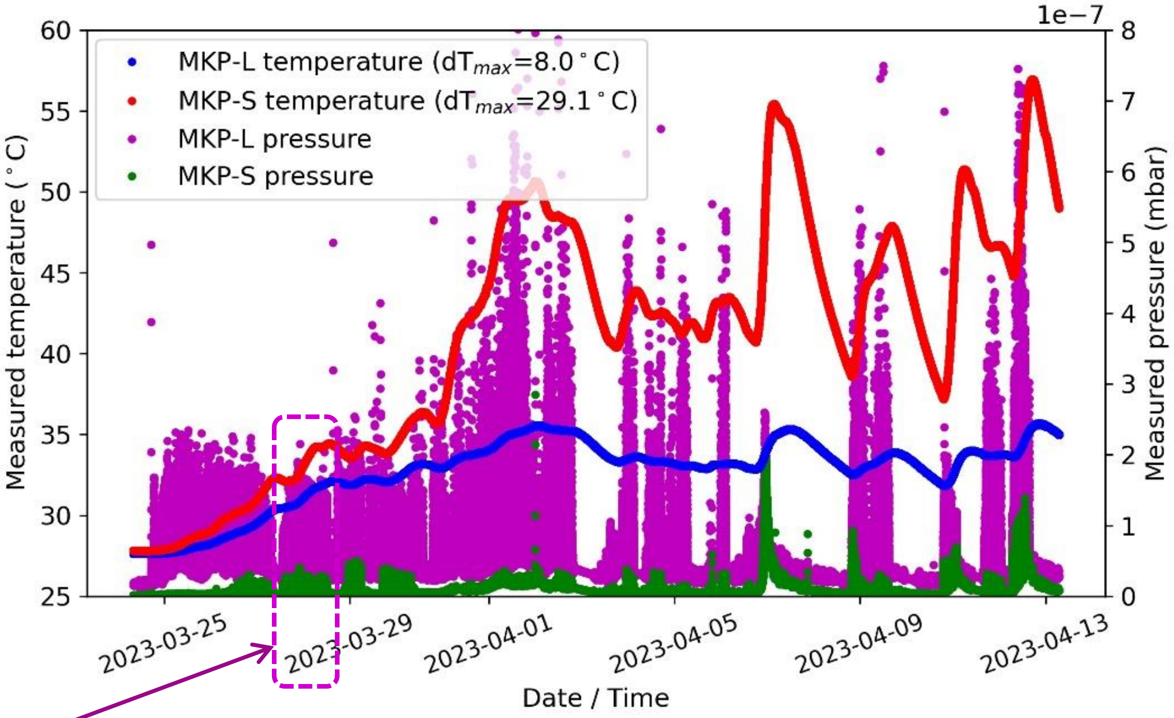
⚠ A resonance occurs at low frequency: but finger length is chosen so resonance is **far enough from beam harmonics**

Beam Induced Heating: Experience

March 2022 (unshielded MKP's)



March/April 2023 (low impedance MKP-L)

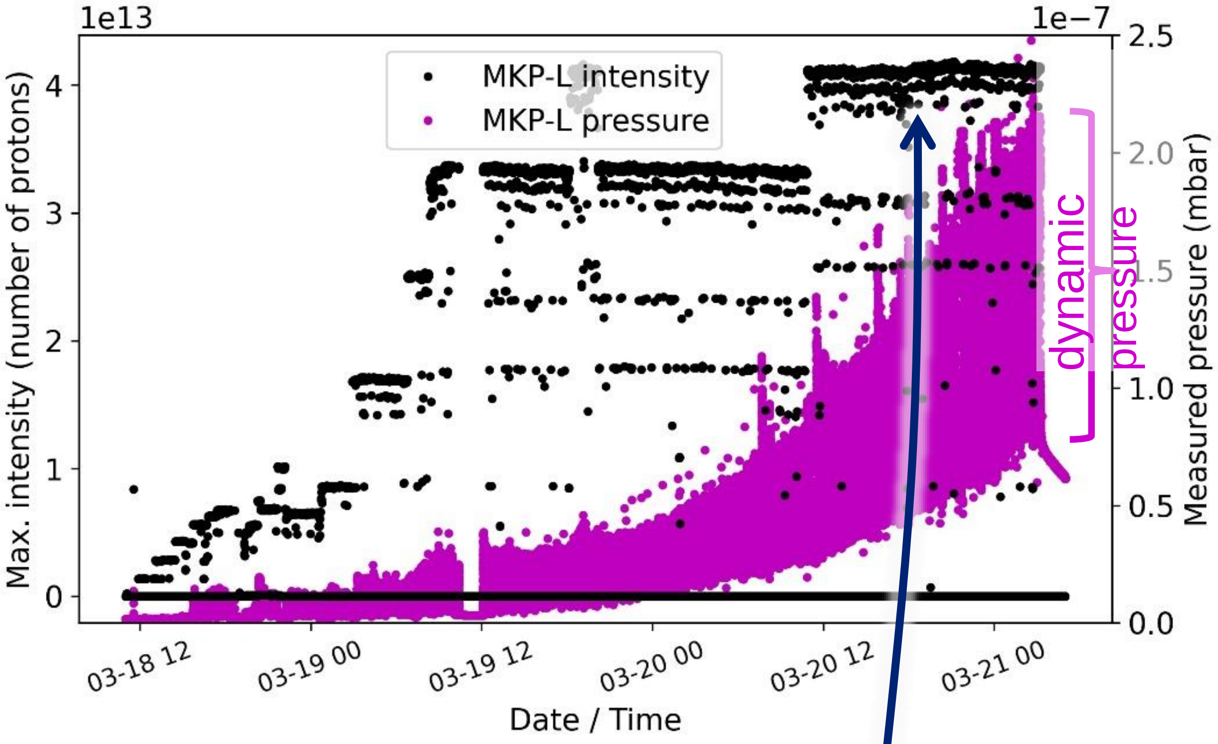


See next slide

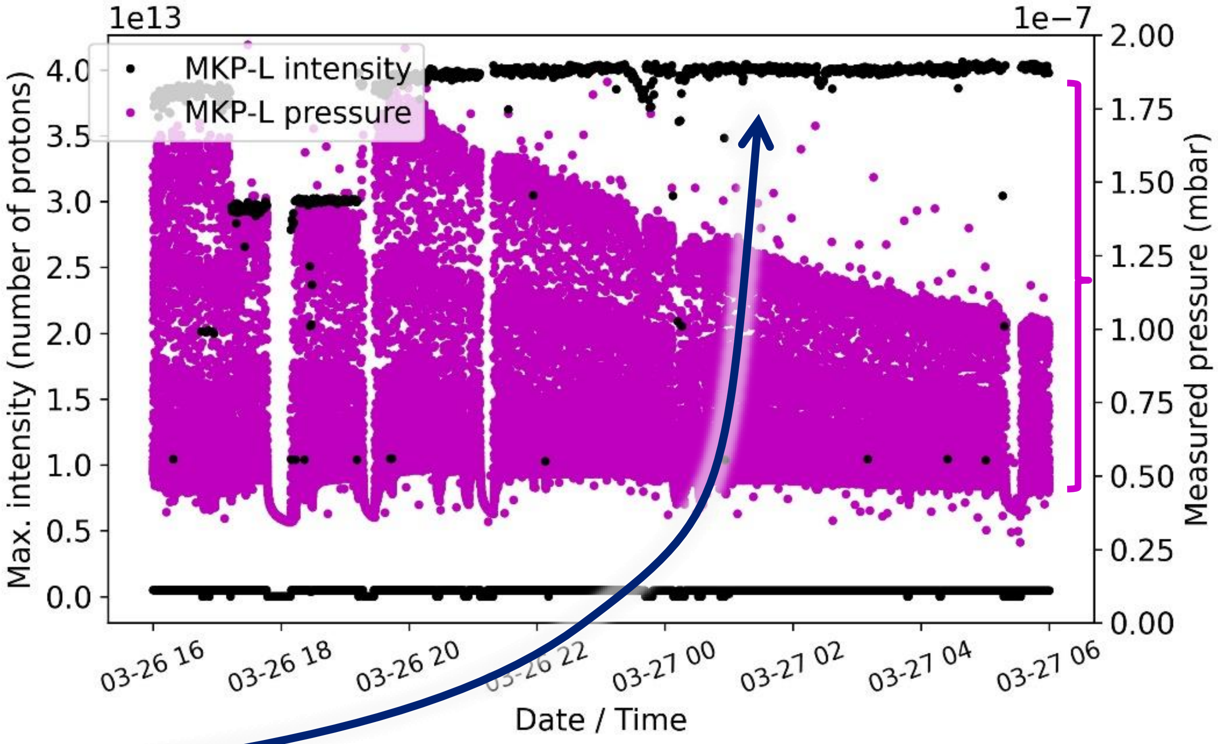
- Maximum temperature of **<u>unshielded</u>** MKP-L ~4 times higher than MKP-S
  - SPS beam limited by MKP-L temperature during 2022
- Maximum temperature of **<u>shielded</u>** MKP-L ~one-third of MKP-S
  - SPS beam no longer limited by MKP-L temperature

DYNAMIC PRESSURE: EXPERIENCE

March 2022 (**unshielded MKP-L's**)



March/April 2023 (**low impedance MKP-L's**)



With a same intensity of beam (~4 x 10^{13} protons):

New MKP-L shows lower dynamic pressure (even if old MKP-L is expected to be conditioned, following installation for ~7years)

➕

New MKP-L is still conditioning (dynamic pressure is decreasing)

CONCLUSION AND OUTLOOK

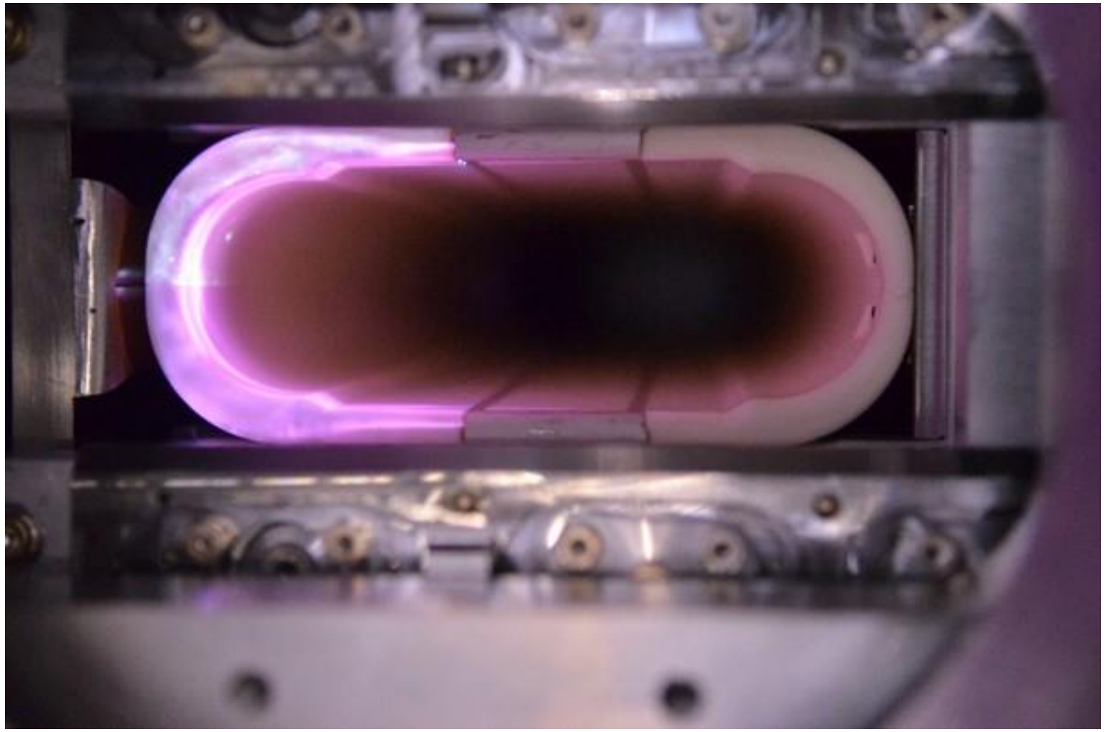
- Several prototype MKP-L's constructed and tested in a relatively short-time…..
- However, operation with high intensity beam shows that the final low-impedance design, with Cr_2O_3 coating on the alumina chamber, has:
  - Significantly reduced beam induced heating (factor of ~12) compared with the original MKP-L
  - Demonstrates relatively rapid conditioning of the dynamic pressure
- These observations validate the low-impedance design of the MKP-L
- The low-impedance design improves machine availability and allows for the full HL-LHC potential for the SPS injection system
- A spare. low-impedance MKP-L, will be constructed

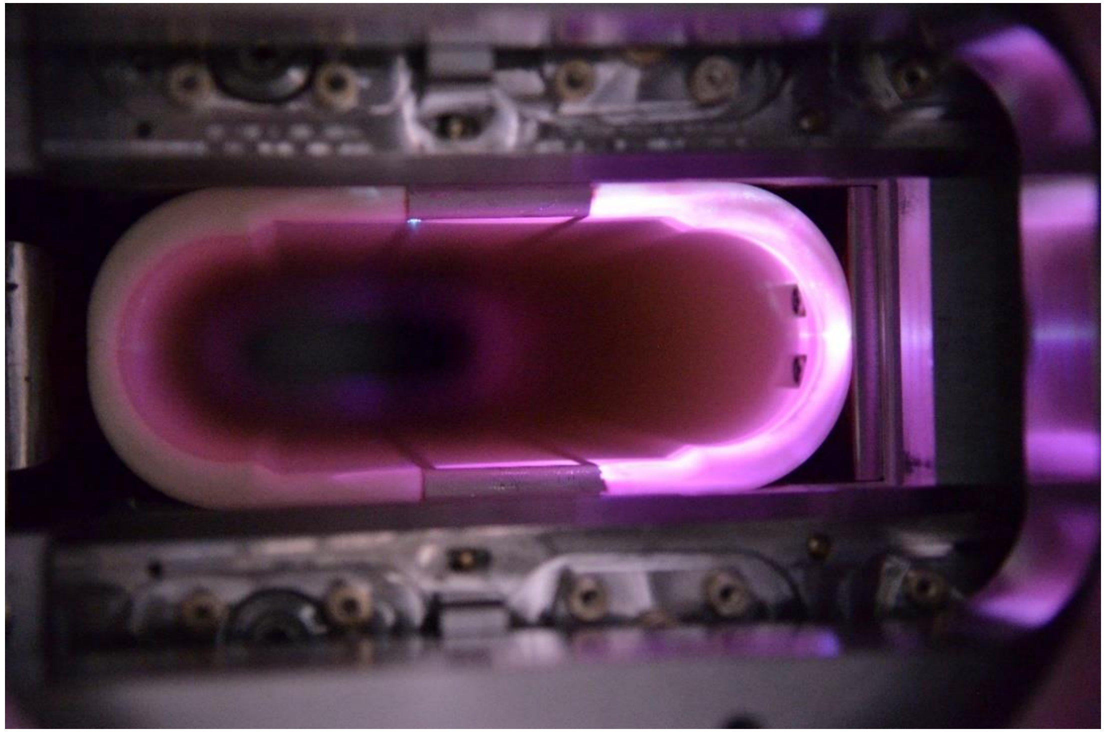
Questions ?

Spare Slides

Input End Of Chamber

Significant and unexpected **glow** on the input end of the alumina chamber:





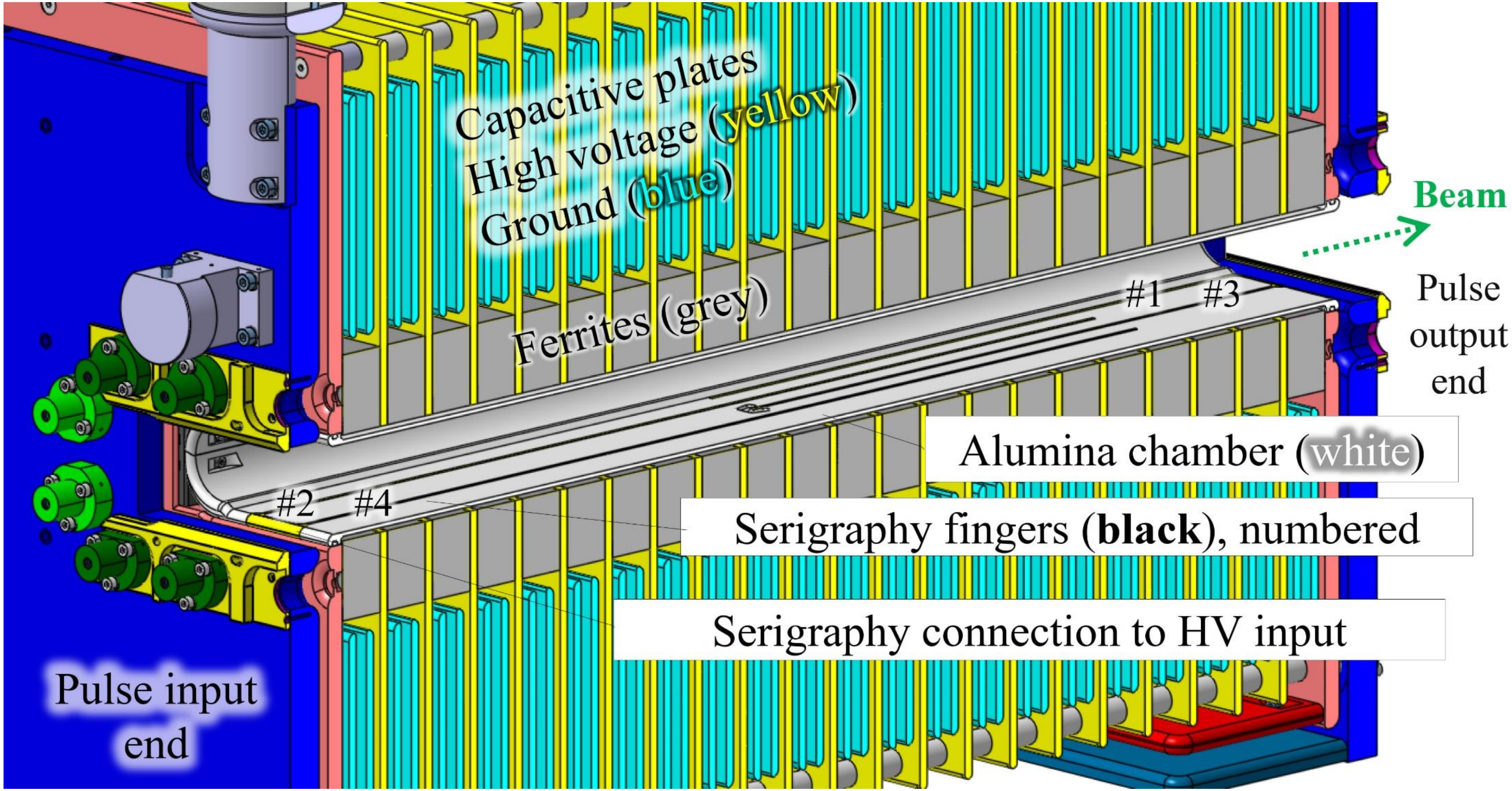
- Pulsed from input end (40kV PFN)
- ΔP = 1.8x10^{-8} mbar (@46kV PFN and 1μs)

- Pulsed from input end (40kV PFN)
- ΔP = 2.5x10^{-8} mbar (@39kV PFN and 2μs)

In the final version:

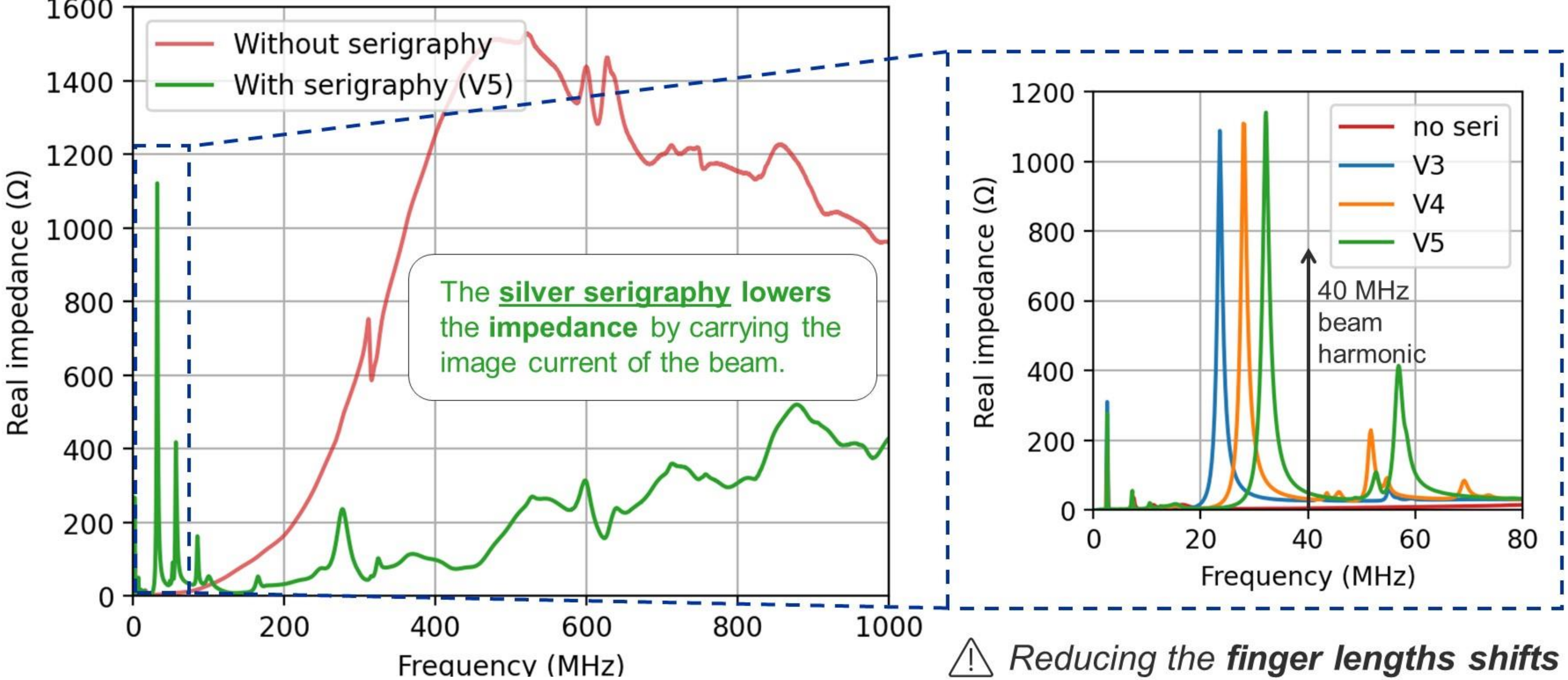
- High **SEY** of **alumina** was probably **contributing** to electron avalanche. The **two ends** of the chamber were **coated** with **amorphous carbon** (low SEY)
- The ends of the fingers were reinforced (wider)

CROSS-SECTION OF FINAL MKP-L



BEAM IMPEDANCE & RESONANCES

Fingers all referenced to HV end plates

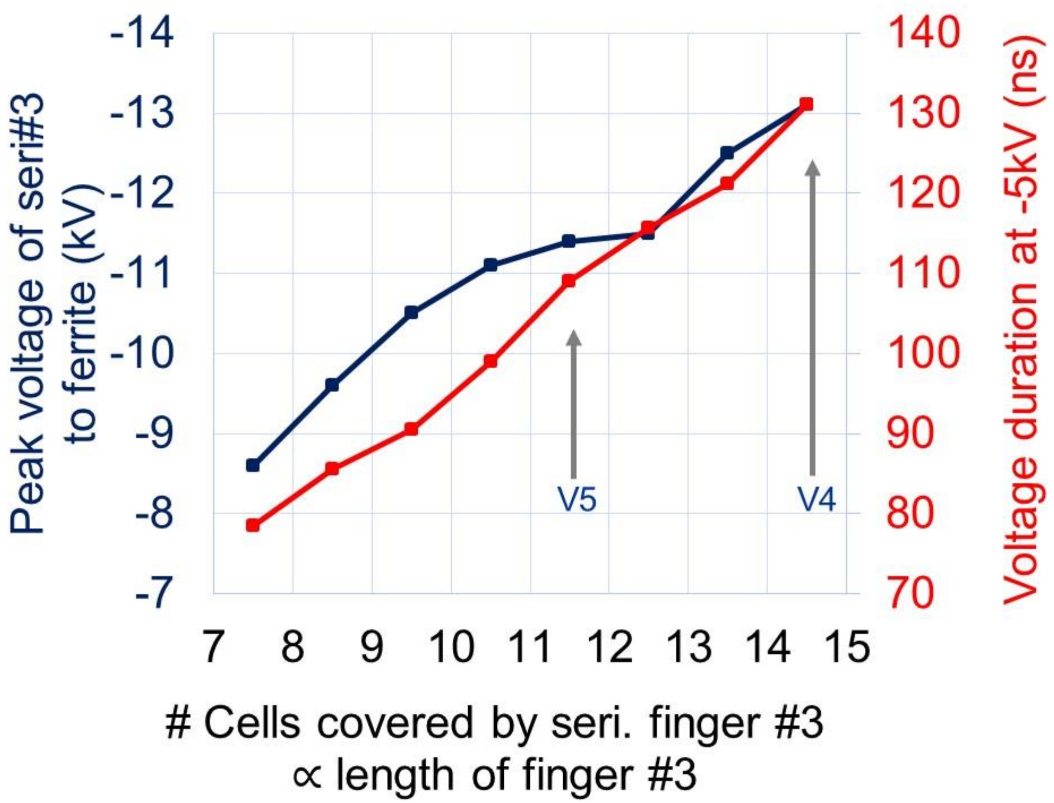


⚠ *Reducing the* ***finger lengths shifts*** *the main resonance* ***towards*** *the* ***40MHz*** *beam harmonic, which must not coincide*

- V3 = 5 fingers per alumina plate, 600mm long each
- V4 = 4 fingers per alumina plate:
    - 457mm long: fingers #1, #3
    - 581mm long: fingers #2, #4
- 4 fingers per alumina chamber:
    - 364mm long: fingers #1, #3
    - 581mm long: fingers #2, #4

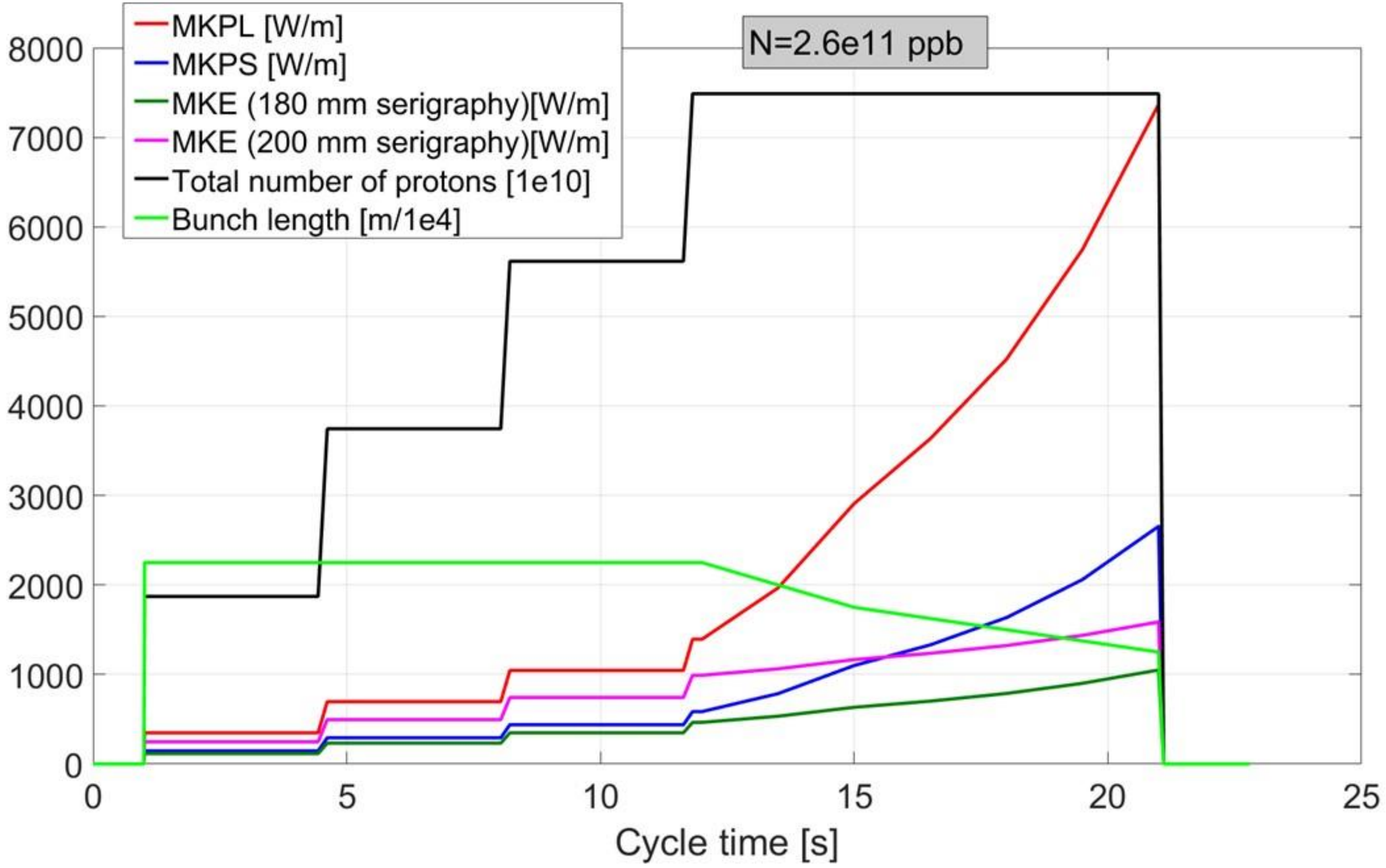
Corona & Finger Length

- **Light inside the magnet** (early versions) is due to high **electric fields** on the tip of the serigraphy **fingers connected to output** end (#1 and #3)
- **The tip** of fingers #1 & #3 are **transiently** at **negative potential** in comparison to the ferrite, during pulse propagation, due to:
  - **Induced voltage** from magnetic field
  - **Electrical delay of magnet** (as the fingers are connected to the output end)
- **Decreasing the length of fingers** #1 and #3 reduces both the duration and the magnitude of the voltage difference to the ferrite

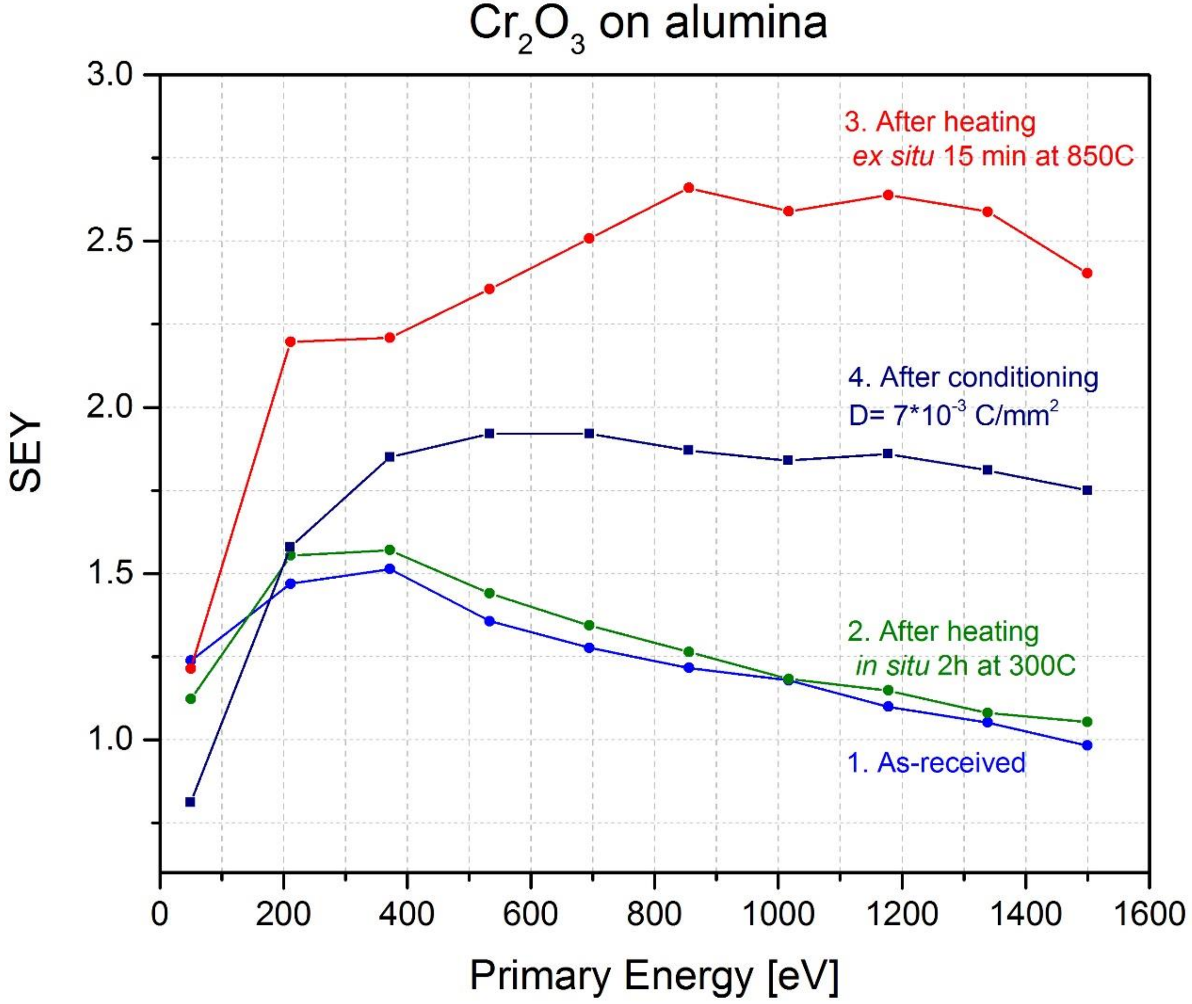


***Magnitude** and **duration** of induced **voltage** difference at **critical fingers** (#3). Both are **worse as length increases**.*

POWER-LOSS DURING AN SPS CYCLE

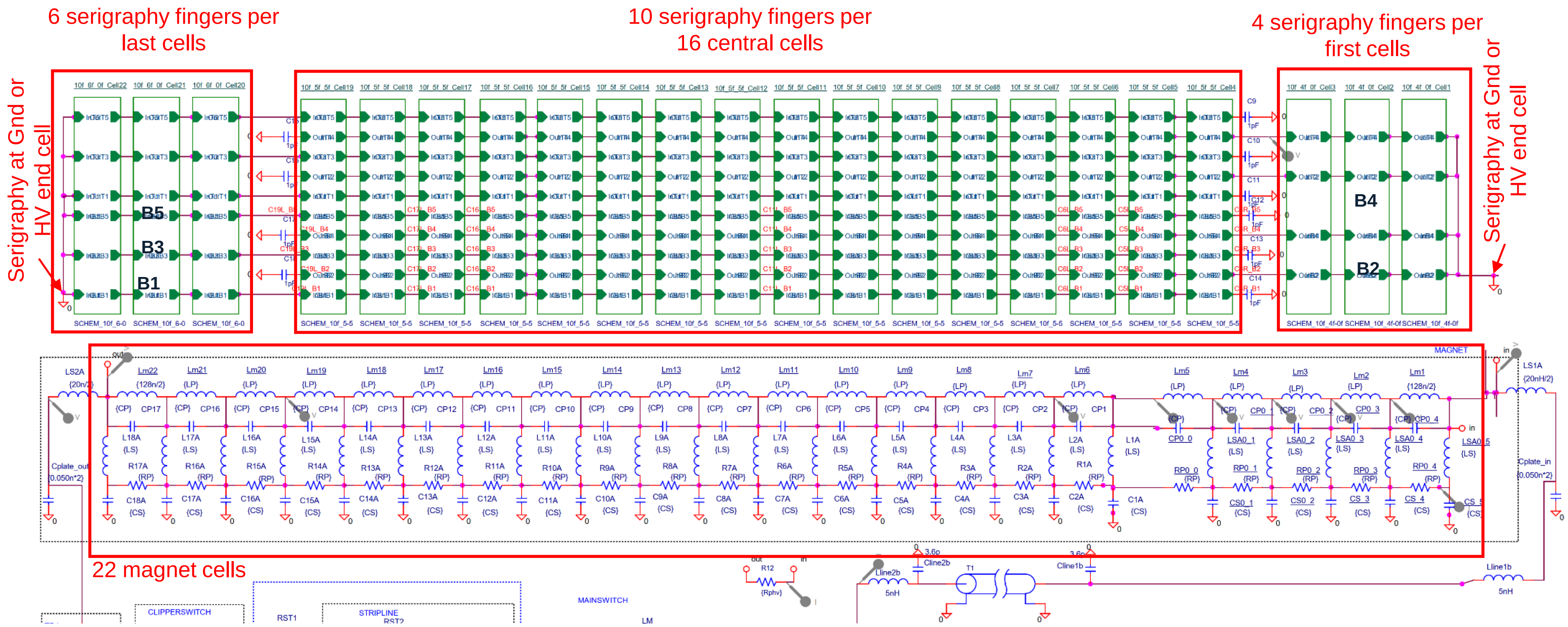


Measured SEY of C_r2O_3 Coating on Alumina



Measurement of SEY of 50 nm coating of Cr_2O_3 on alumina: (1) as received; (2) after heating in vacuum for 2 hrs at 300◦C; (3) after heating in air for 15 mins at 850◦C; (4) as per (3) but following bombardment (conditioning) with an electron dose of 7 mC/mm^2

PSpice Module & Serigraphy Model



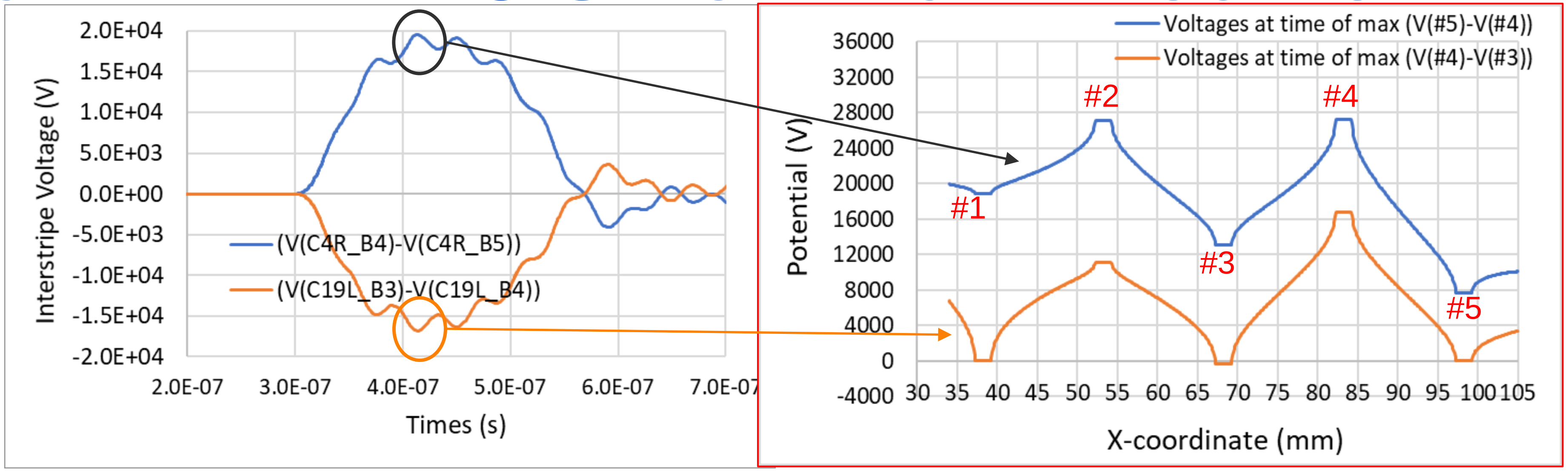
11x11 inductance matrix derived as per:

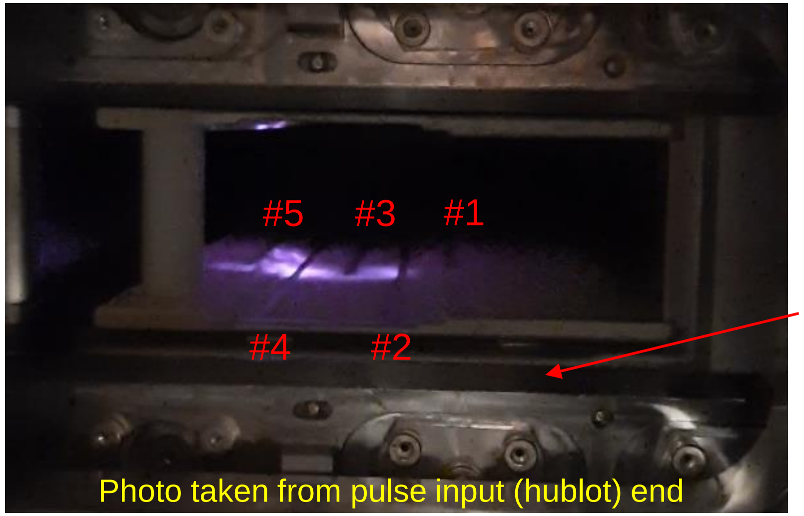
- L. Jensen and M.J. Barnes, “Report on simulations of beam induced circuit resonances for KFA14 kicker system”, Geneva, Switzerland, Sept. 2020, https://edms.cern.ch/document/2416466/1
- O. Nielsen and M.J. Barnes, “Application note: calculation of self and mutual partial inductances using flux linkage methods in Opera-2d”, Geneva, Switzerland, Apr. 2020, https://edms.cern.ch/document/2364744/1

Serigraphy labelling:

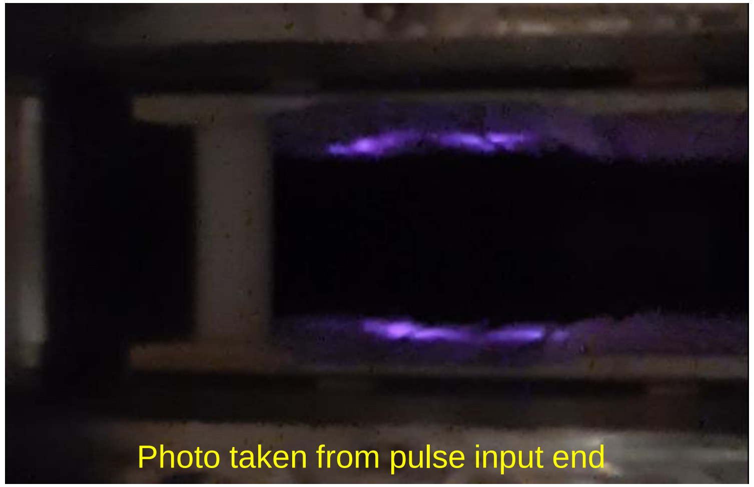
- B1 (HV busbar side) to B5 (GND busbar)
- T1 (HV busbar side) to T5 (GND busbar

PSpice MKP-L V3 Simulation Results



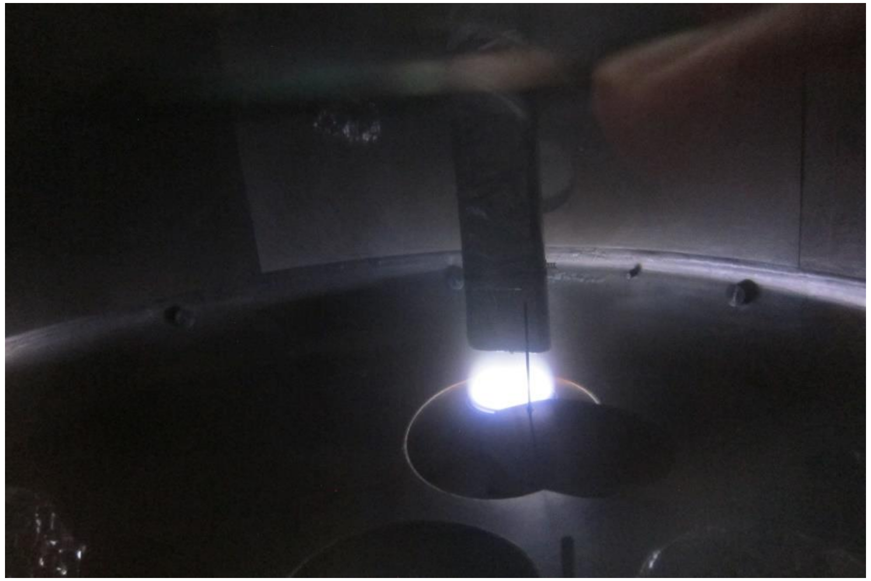


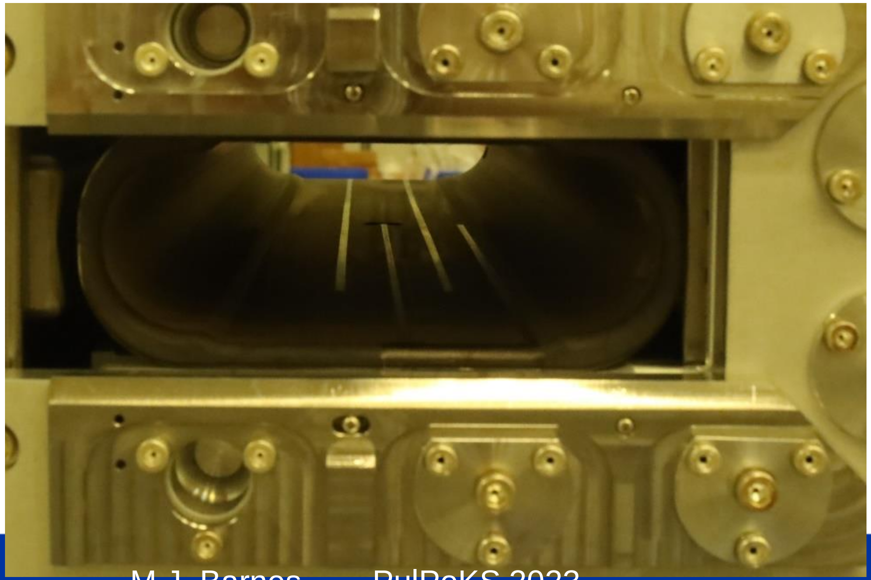
HV end plate



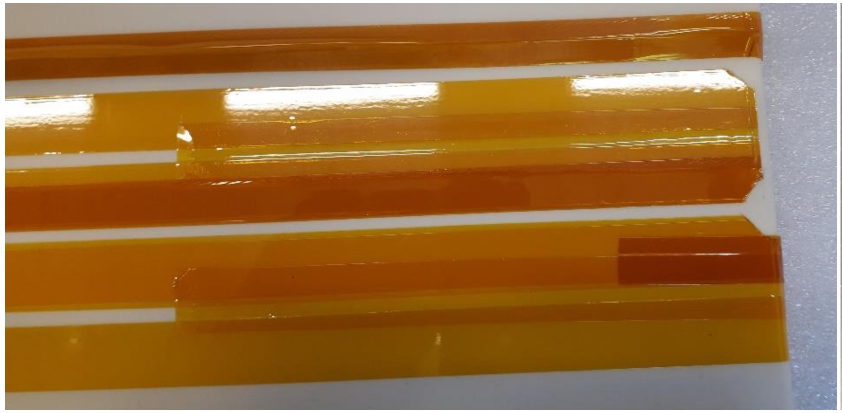
- Brightest light on edges of #4 & #2 next to ends of #5 & #3
- No light towards TMR end of aperture

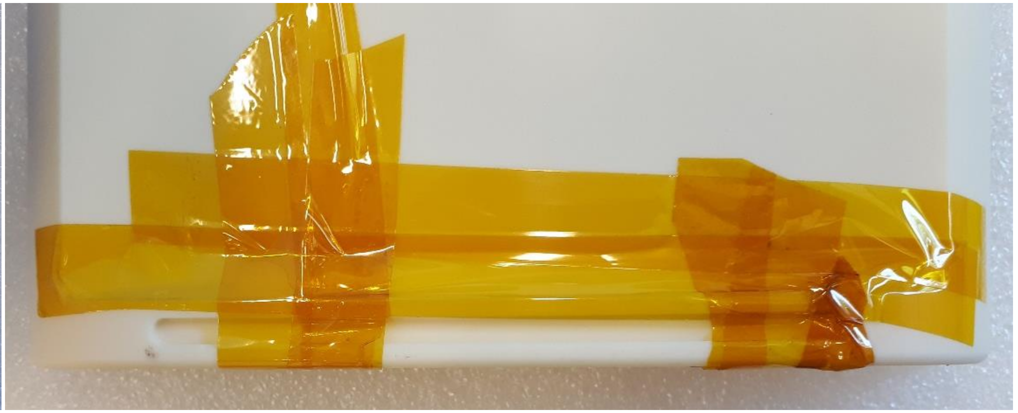
Amorphous Carbon Coating of Ends of Chambers

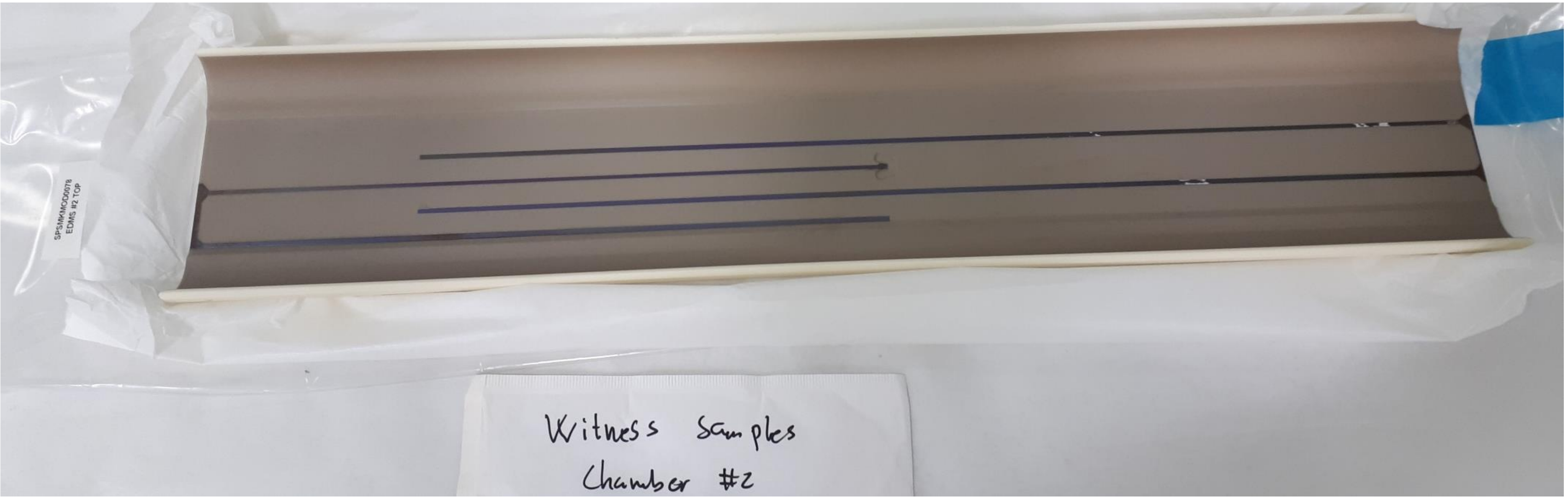




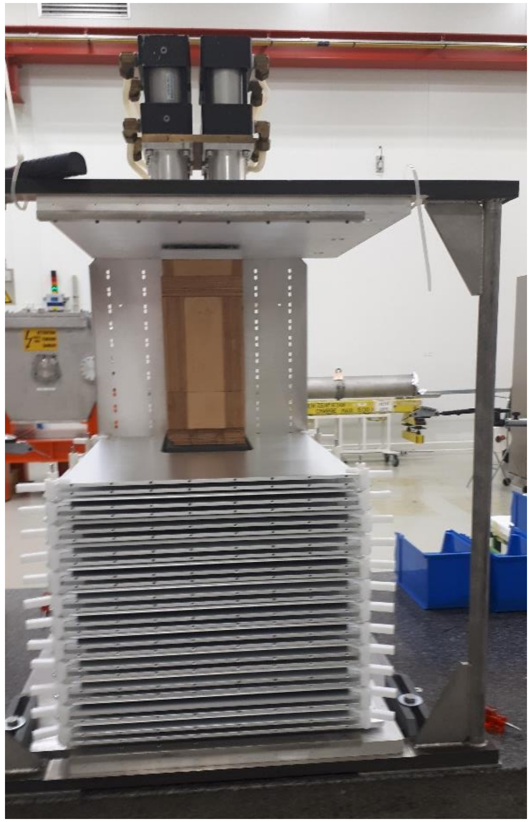
SILVER FINGERS ON FINAL U-CHAMBERS







CONSTRUCTION OF AN MKP-L MODULE



ELECTRON CLOUD

- Circularly accelerating charged particles emit photons as synchrotron radiation. These photons impact release low energy electrons from the accelerator walls through the photoelectric effect.
- These can then be accelerated by the passing particle beam, re-impacting the surface of the accelerator and release, on average, more than one secondary electron through electron multipacting.
- This becomes a positive feedback loop and builds up a large number of electrons in the beam chamber that can cause bunch instability, coherent tune shift, vacuum pressure rises and additional heat loads.

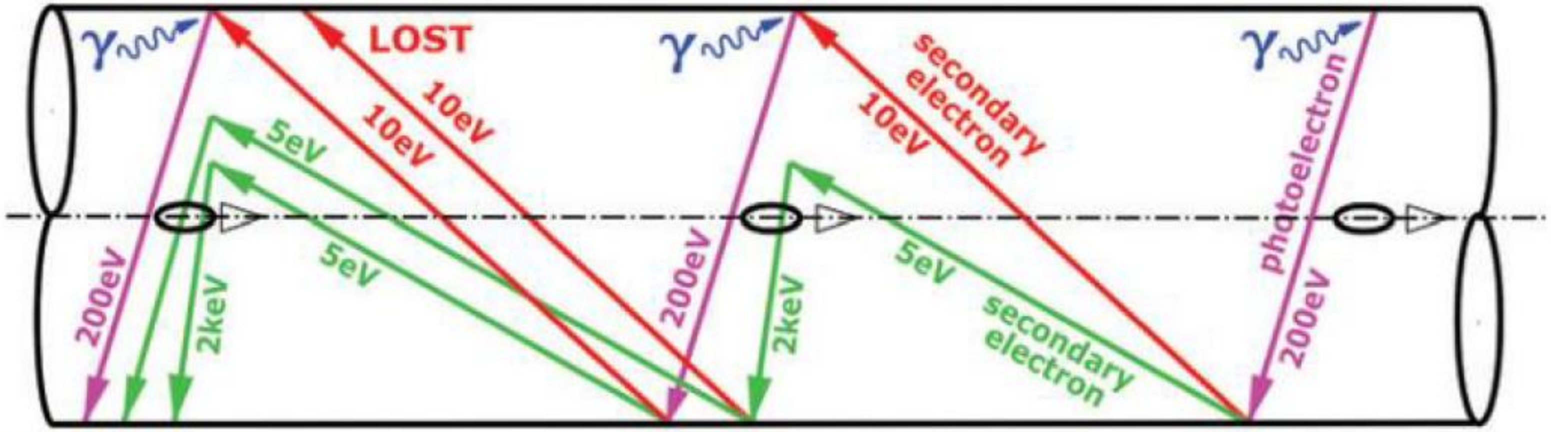


Fig. 1. Artistic view of the e− cloud process at LHC (adapted from the original representation by F. Ruggero and in his memory). From Ref. 1, thanks to R. Cimino

R. Cimino and T. Demma, "Electron cloud in accelerators," https://doi.org/10.1142/S0217751X14300233 29 (2014)

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