Highlights and New Challenges for WP14

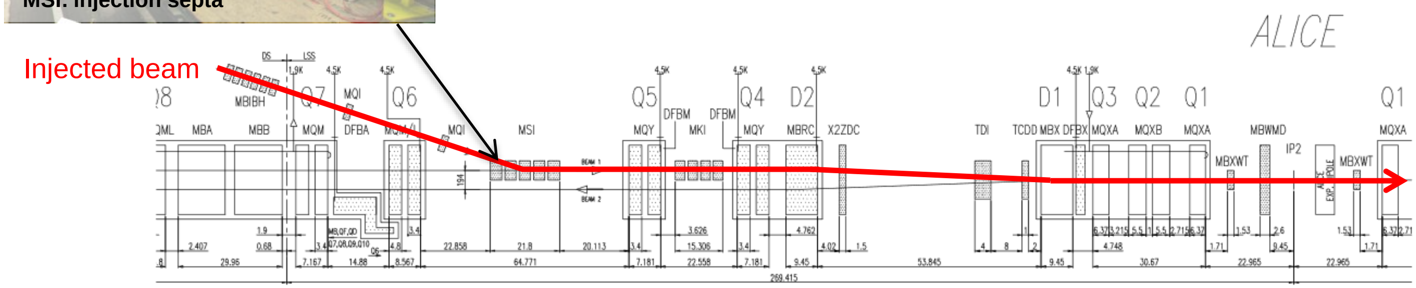
C. Bracco on behalf of WP14

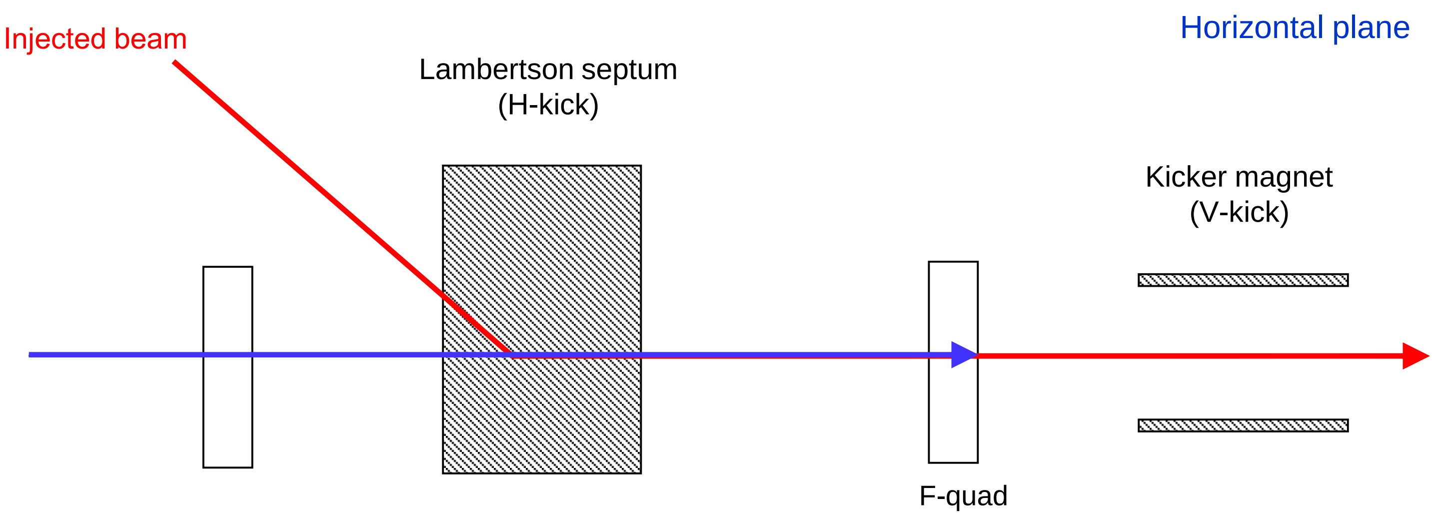
Special acknowledgments: M. Calviani, D. Carbajo Perez, M.I. Frankl, L. Gentini, I. Lamas Garcia, A. Lechner, A. Perillo Marcone, T. Polzin.
M. Barnes, L.O. Bjorkqvist, L. Vega, V. Vlachodimitropoulos, C. Wiesner.

Outlines

- Highlights:
  - Injection system
    - MKI
      - Run I-II history
      - Operational performance with first prototype
      - MKI-Cool
    - TDI
      - Run I-II history
      - New design
      - Status
- New Challenges:
  - Beam dump

The LHC Injection System





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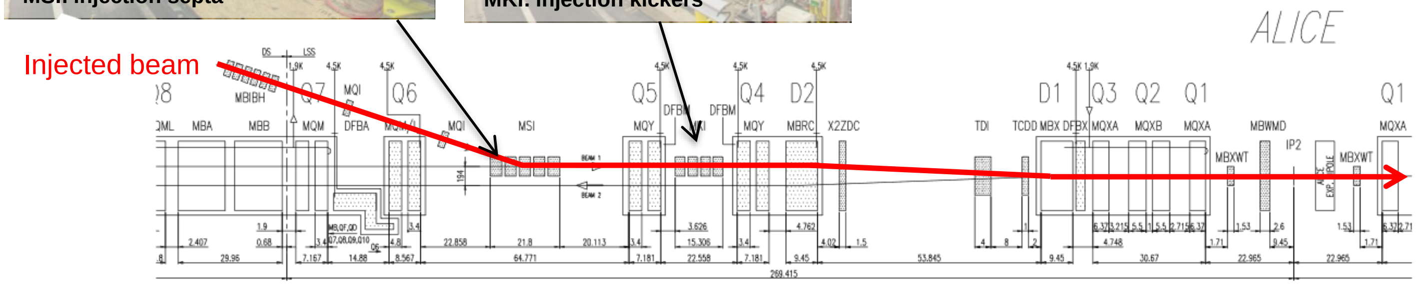

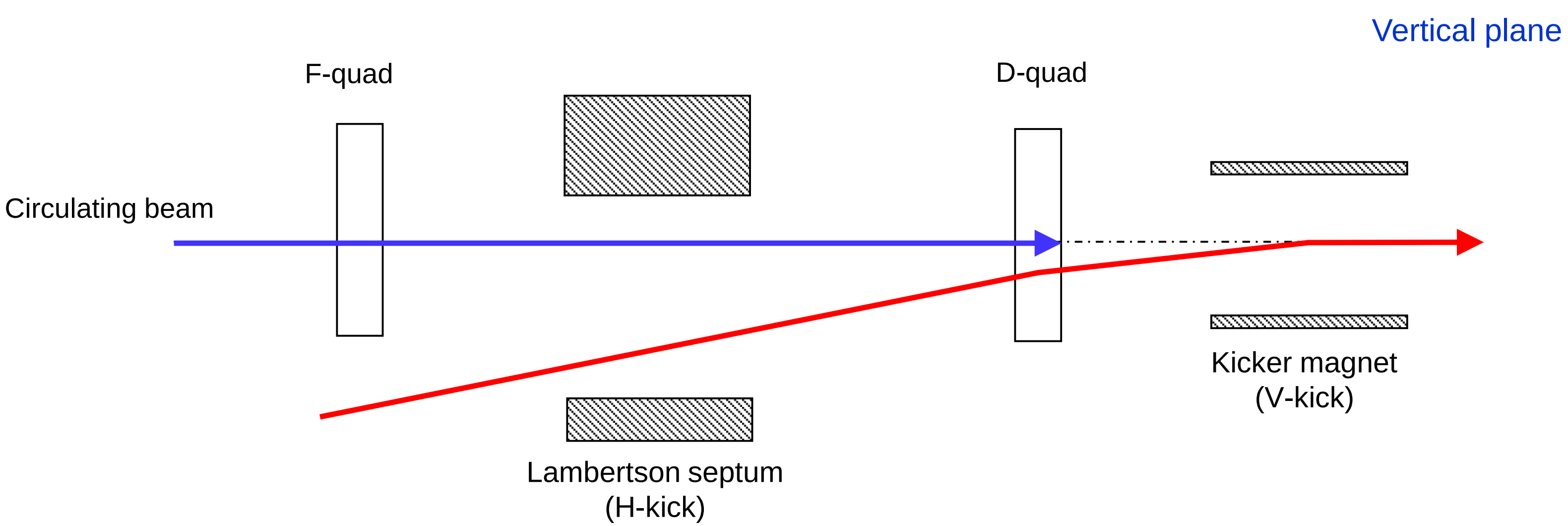

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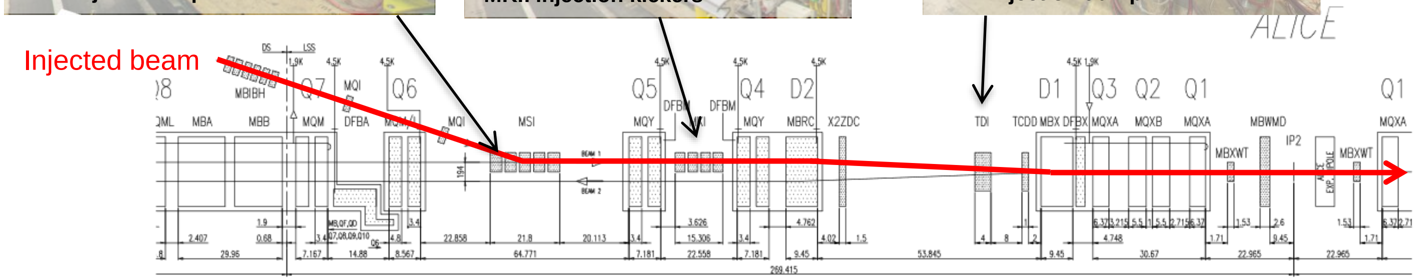

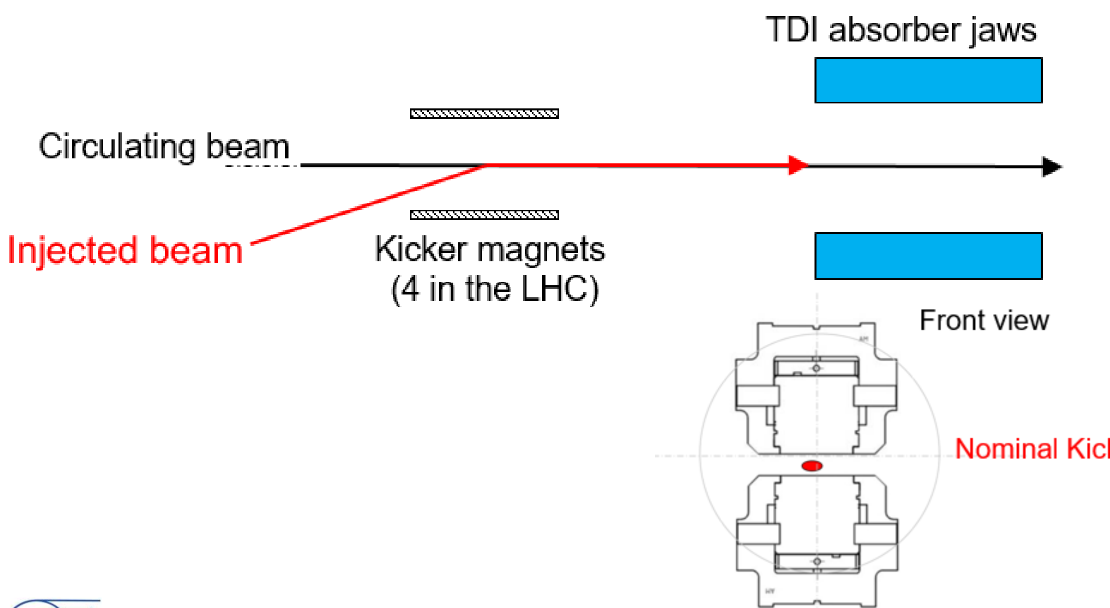

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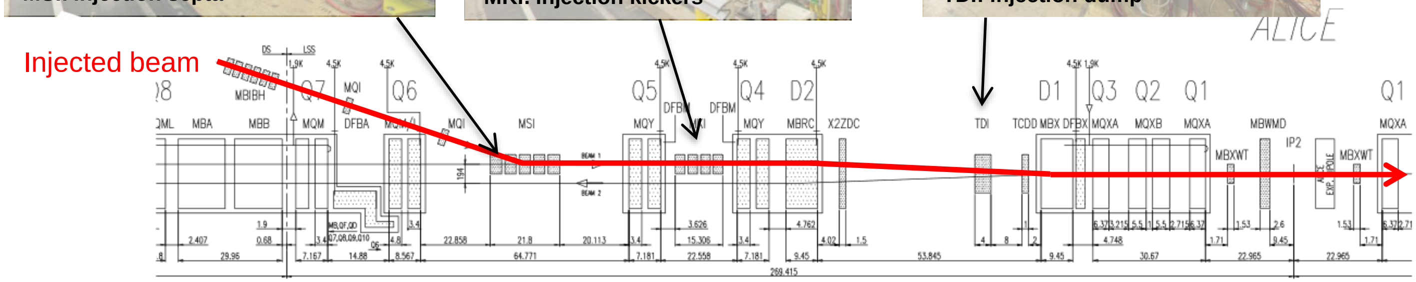
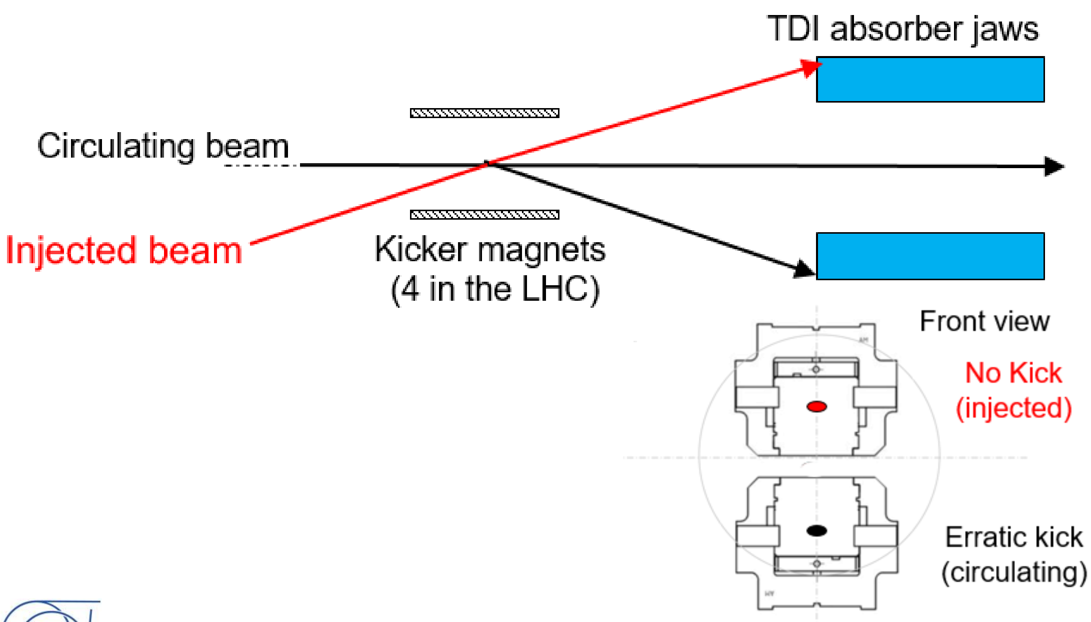


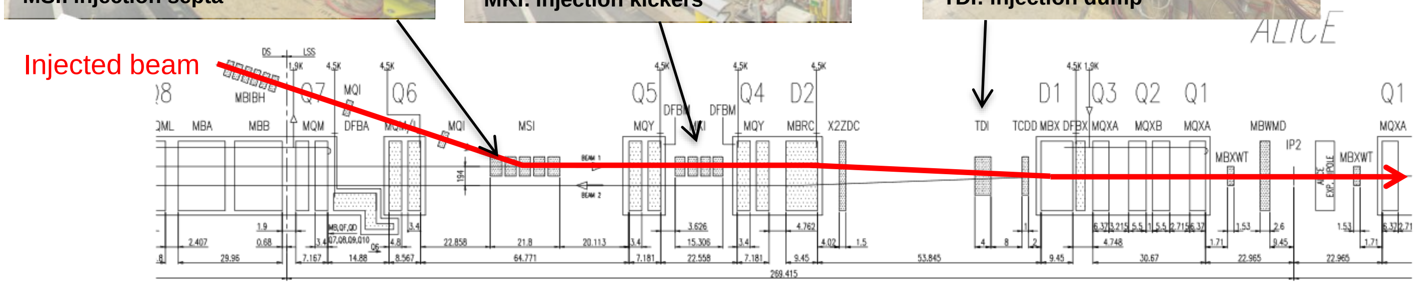


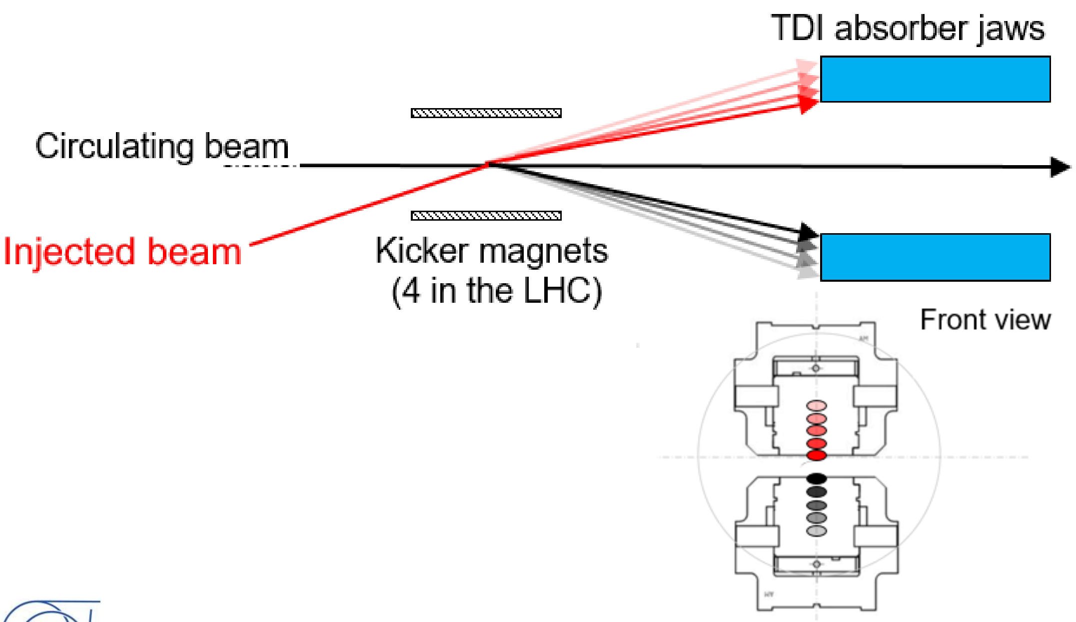
The LHC Injection System

MSI: injection septa

MKI: injection kickers

TDI: injection dump





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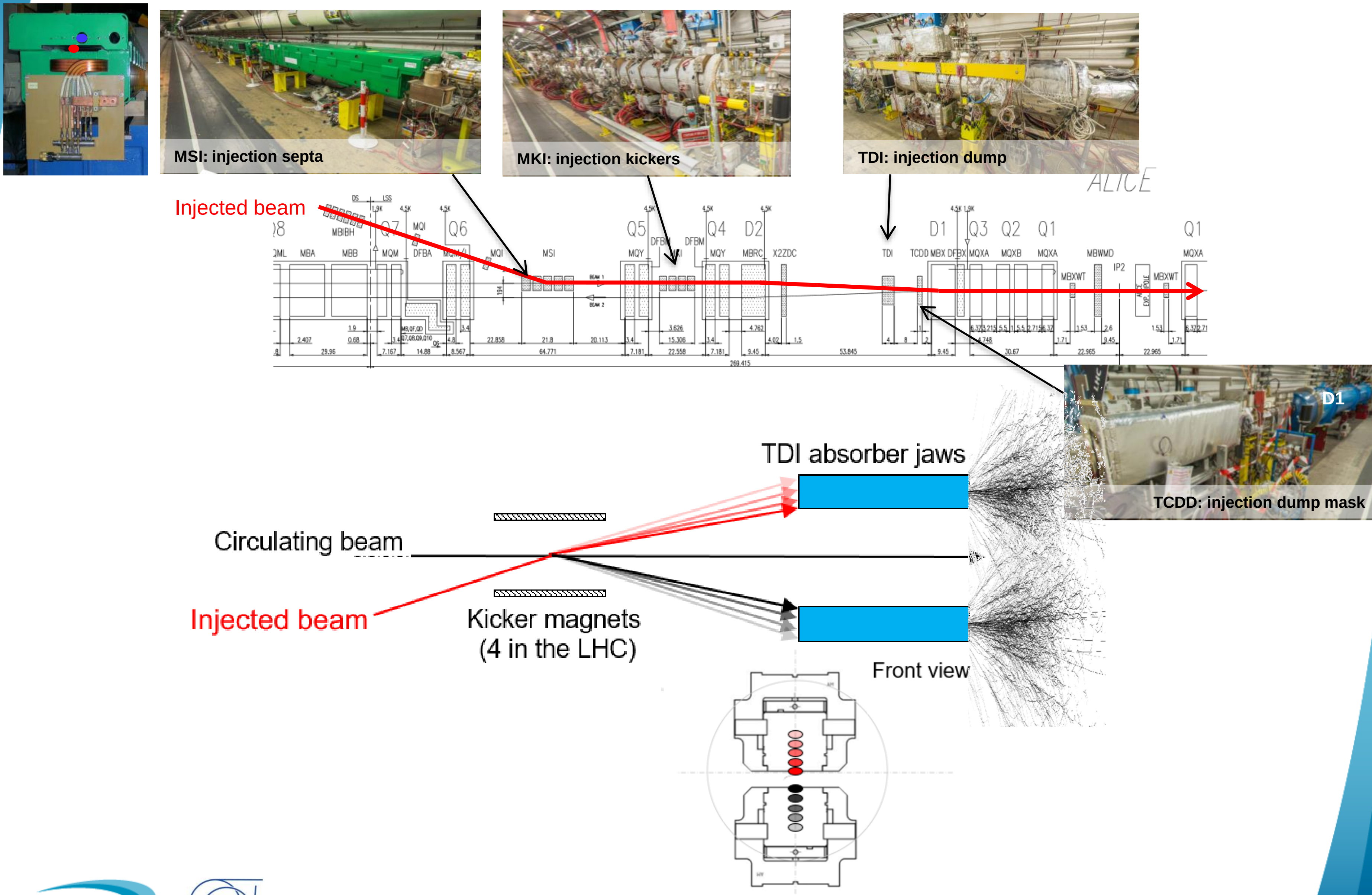
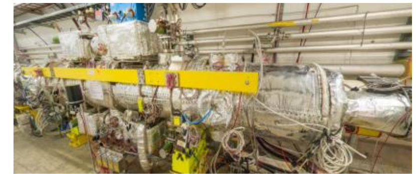


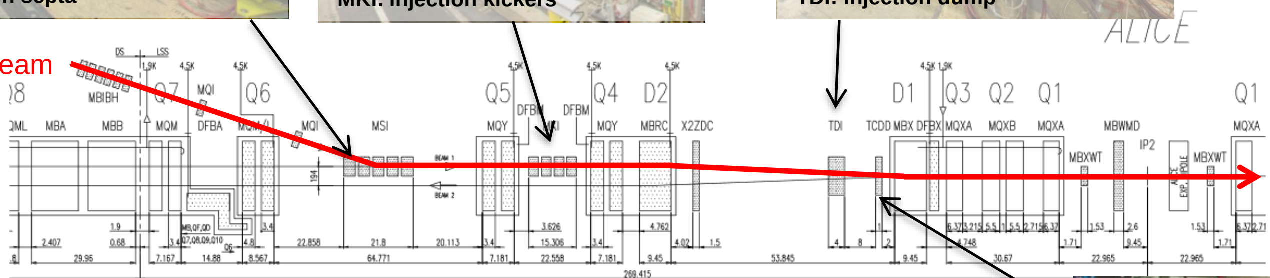
The LHC Injection System

MSI: injection septa

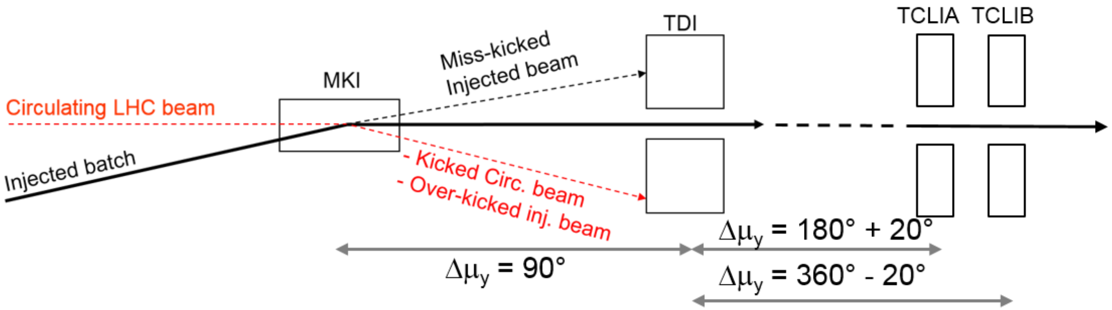
MKI: injection kickers



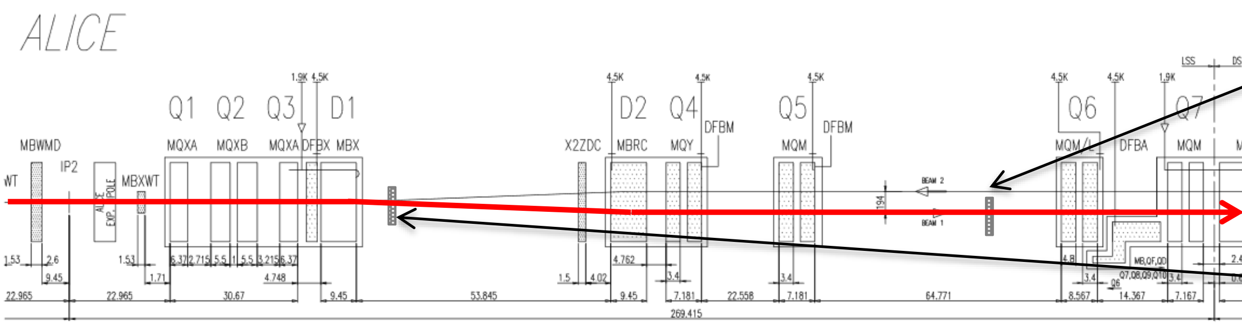
TDI: injection dump



TCDD: injection dump mask

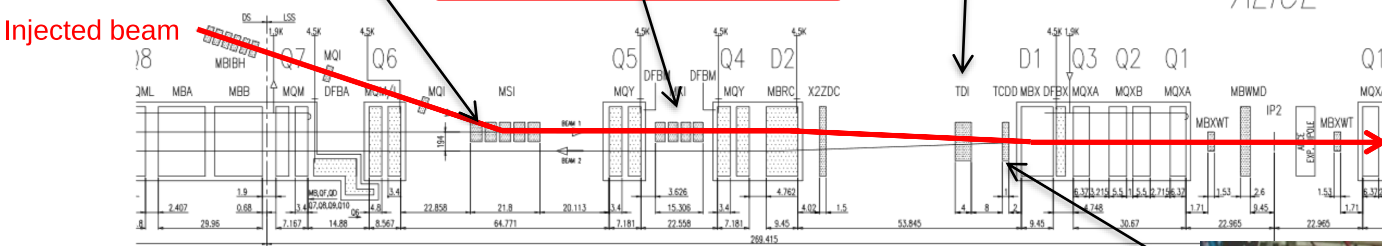


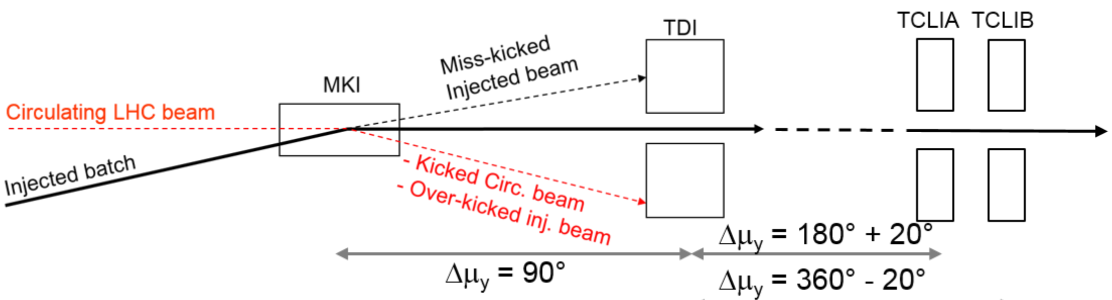
TCLIB: auxiliary protection collimator

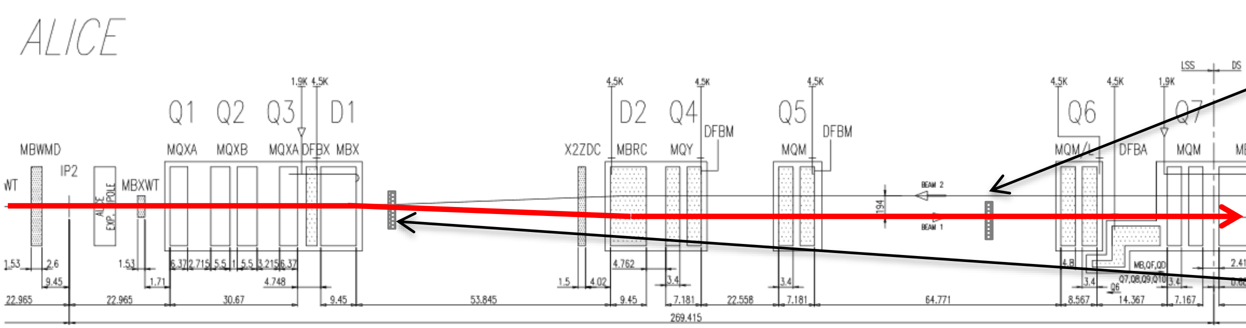


TCLIA: auxiliary protection collimator

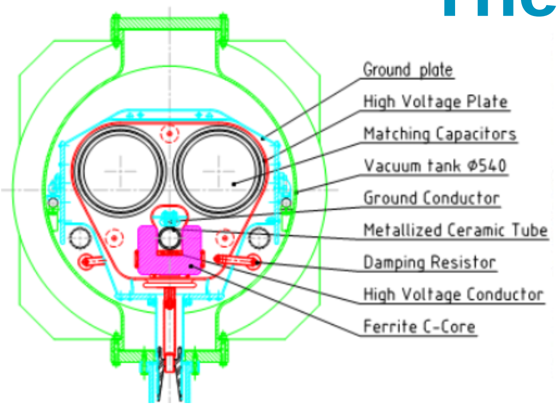
The LHC Injection System

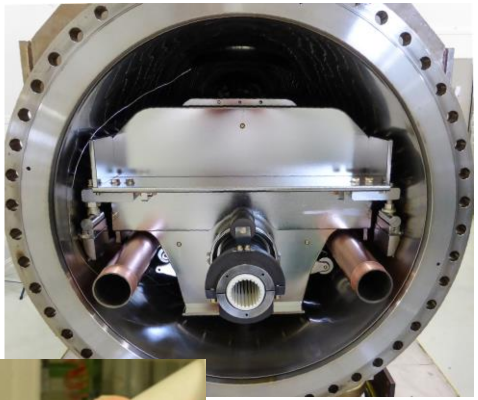






The MKIs



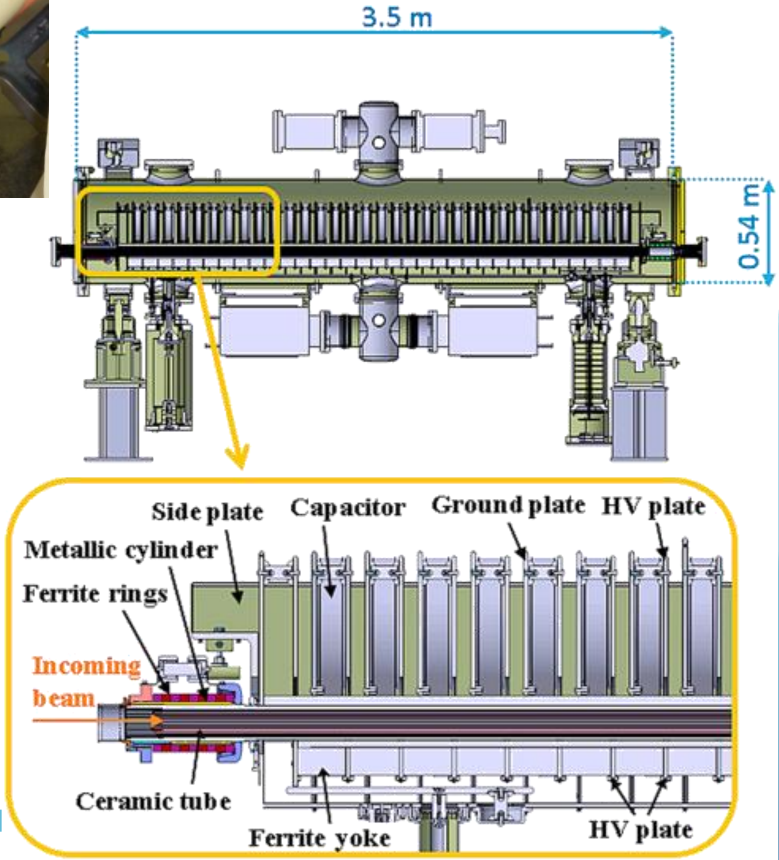


Four kickers pulsed at 25 kV, ~ 5 kA Magnet operated at **~10^{-11} mbar to limit risk of flashover**

33 cells each consisting of **U-core ferrite yoke** between two high voltage plates and two ceramic capacitors between a HV and a grounded plate.

A 3 m long **alumina tube with screen conductors** is placed within the aperture of the magnet:

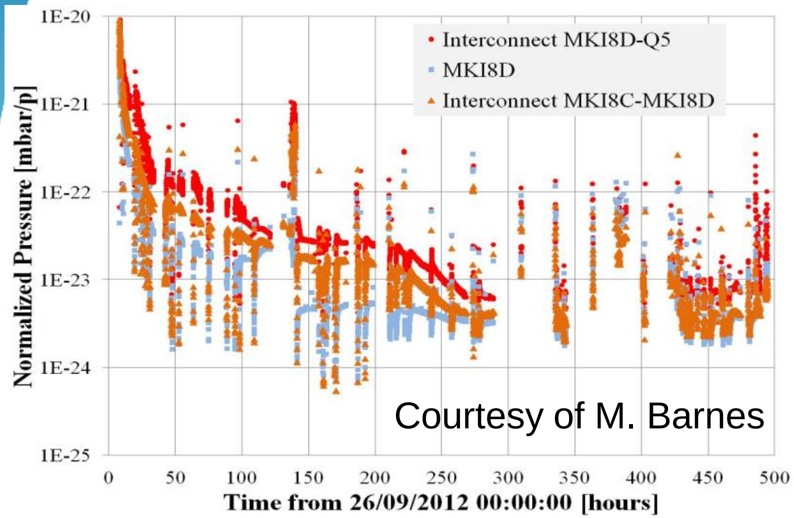
- Allow a **fast magnetic field rise-time** (low eddy currents)
- Limit longitudinal beam coupling impedance (**limit beam induced heating ➔** ferrite permeability reduction)



The screen conductors are directly connected to the beam pipe at the downstream end whilst the upstream end is capacitively coupled.
At both ends 9 ferrite rings are installed to damp low-frequency resonances.

The MKI History

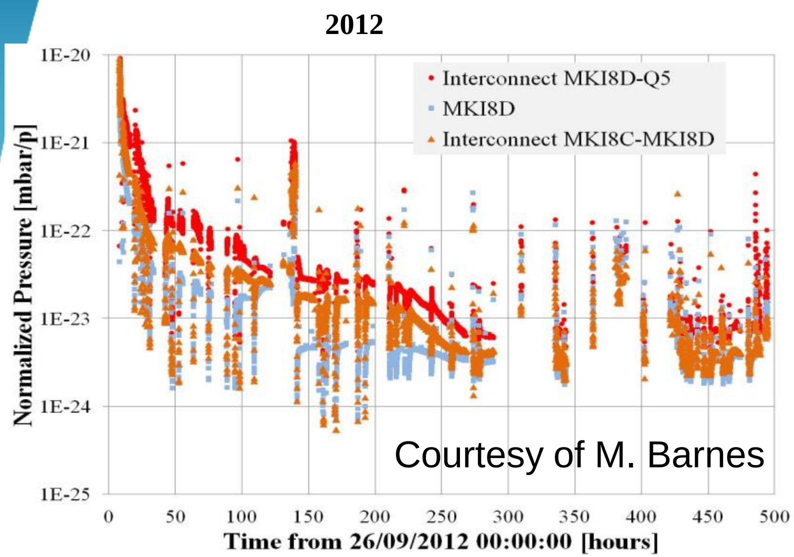
2012



Run I:

- Long conditioning time to reach target normalised pressure <E-23 mbar/p (~280 hours with 50 ns beam for magnet replaced during TS in 2012)
- Beam induced heating physics fills ➔ In a few occasion > 1 hour waiting time before next fill to allow for kicker cooling down.

The MKI History



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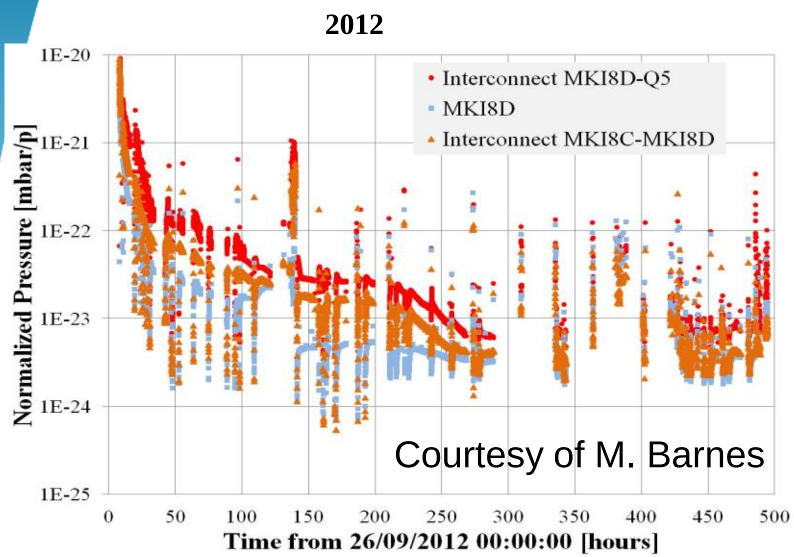
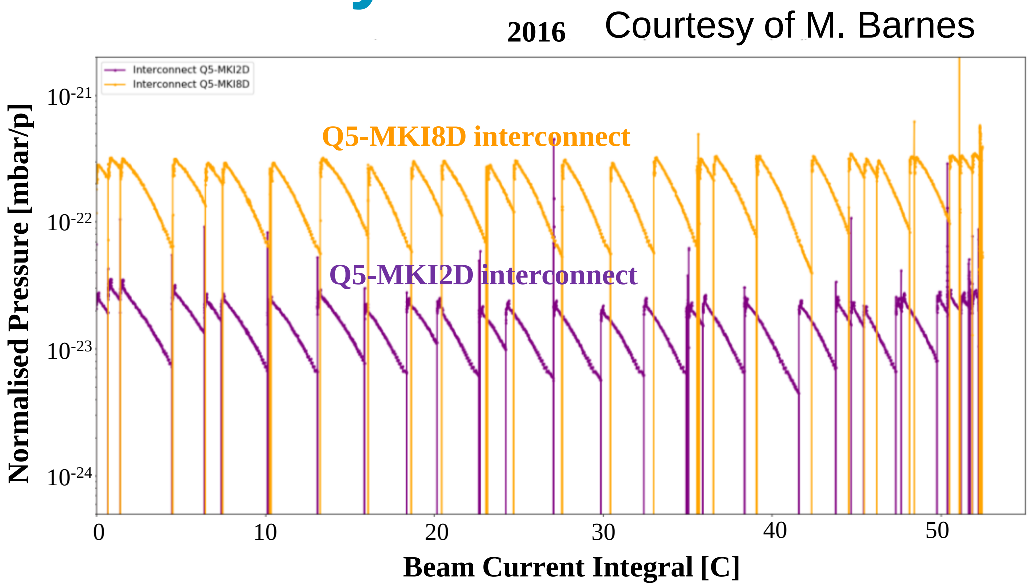
LS1 actions:

- NEG coating and NEG cartridges at interconnects
- New chambers 15 ➔ 24 screen conductors, ion bombardment of vacuum tank (not very effective)

The MKI History





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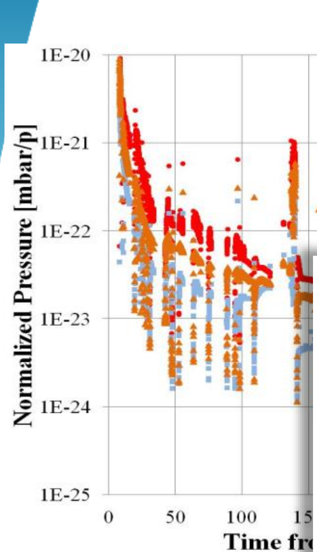
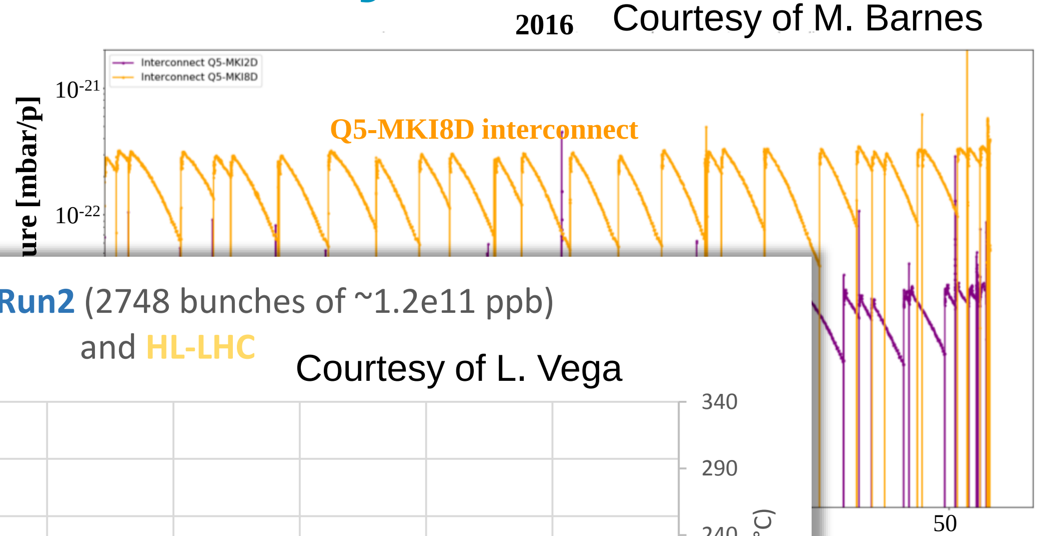
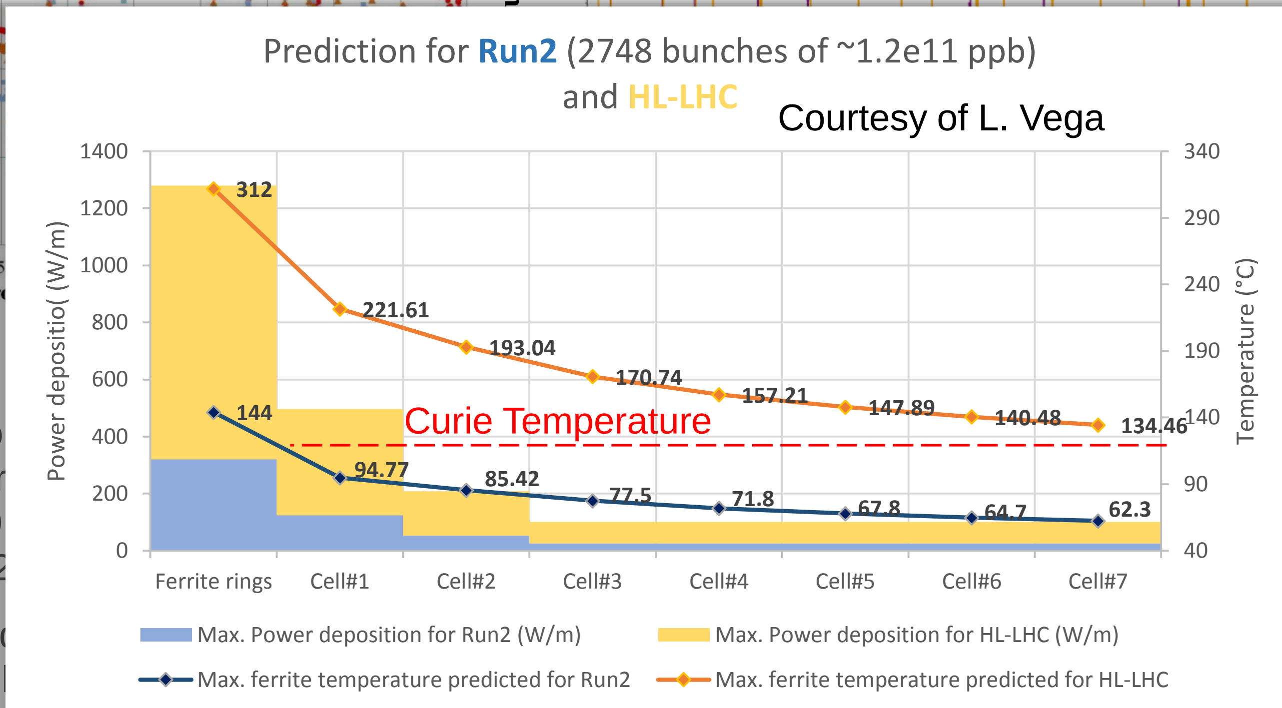
Run II:

- Long conditioning time for new alumina chambers (~400 hours with 25 ns beam).
- MKI8D normalized pressure systematically higher than MKI2D
- Factor 3 reduction in beam induced heating ➔ no more stops in Run II
- Further improvement needed for operations with HL-LHC beams

The MKI History







Run I:

- Long conditio ... na
  normalised pr ... am).
  hours with 50 ... tically
  during TS in 2
- Beam induced ... eating ➔
  occasion > 1
  to allow for kicker cooling down.

LS1 actions:
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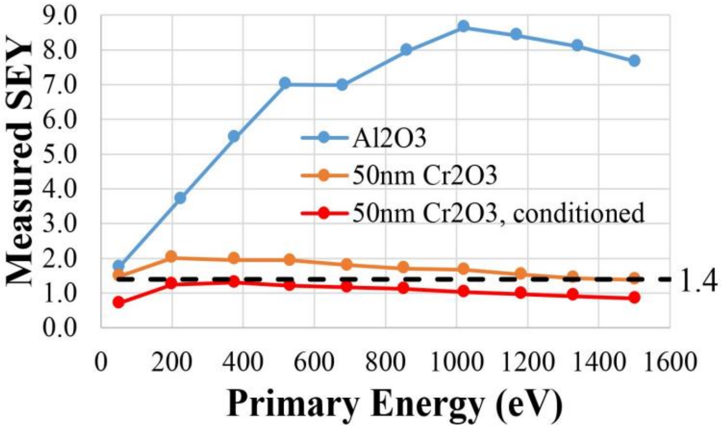
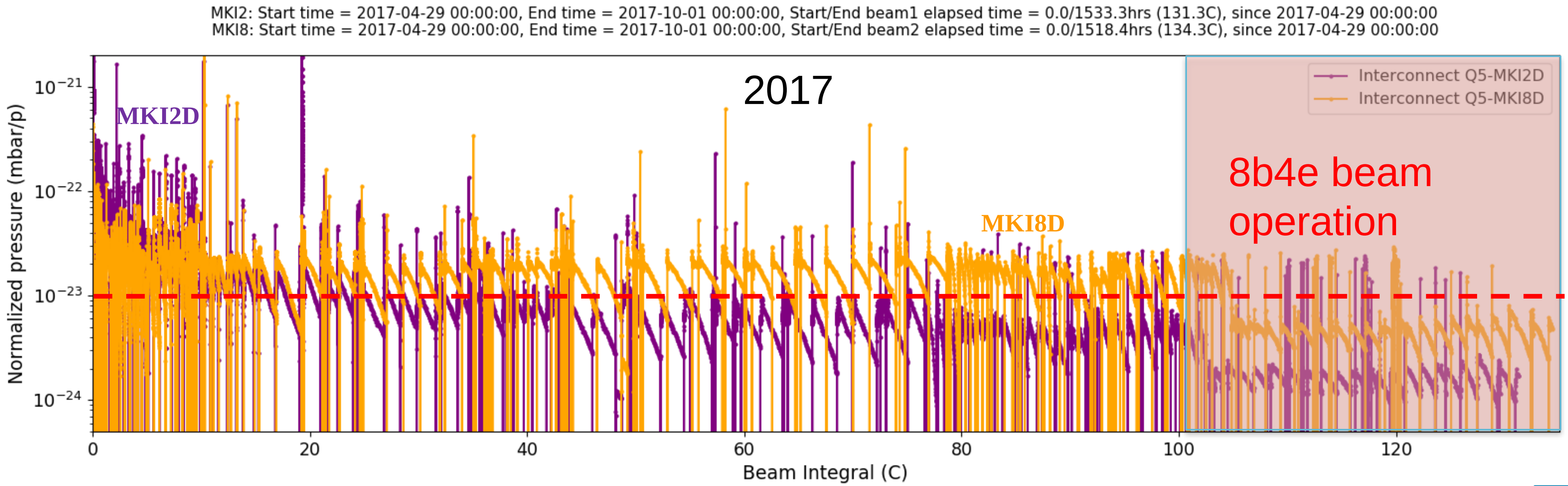
- Further improvement needed for operations with HL-LHC beams

Upgraded MKI Operational Performance

- MKI8D prototype with Cr2O3 coated alumina tube installed in YETS 2017-2018
- MKI2D exchanged in EYETS 2016-2017 conditioned in >40 C to a factor 3 better than MKI8D

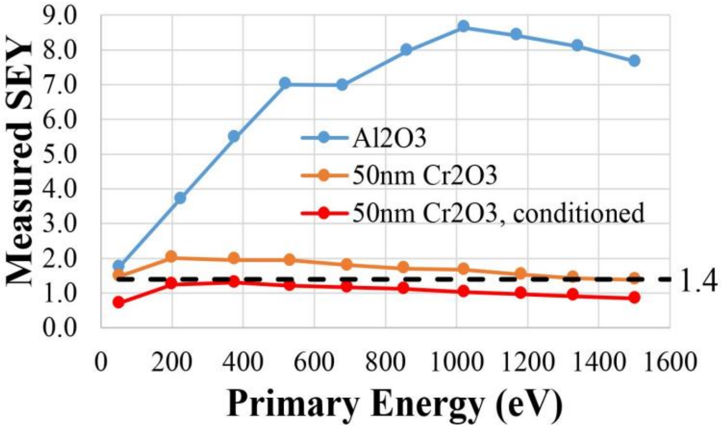


Courtesy of M. Barnes



Upgraded MKI Operational Performance

- MKI8D prototype with Cr2O3 coated alumina tube installed in YETS 2017-2018
- MKI2D exchanged in EYETS 2016-2017 conditioned in >40 C to a factor 3 better than MKI8D
- Faster initial beam conditioning of Q5-MKI8D in 2018 (~20 C) than Q5-MKI2D in 2017 (uncoated tubes);
- In addition, with 25ns beam: "historical" higher normalized pressure at Q5-MKI8D than at Q5-MKI2D has "disappeared"



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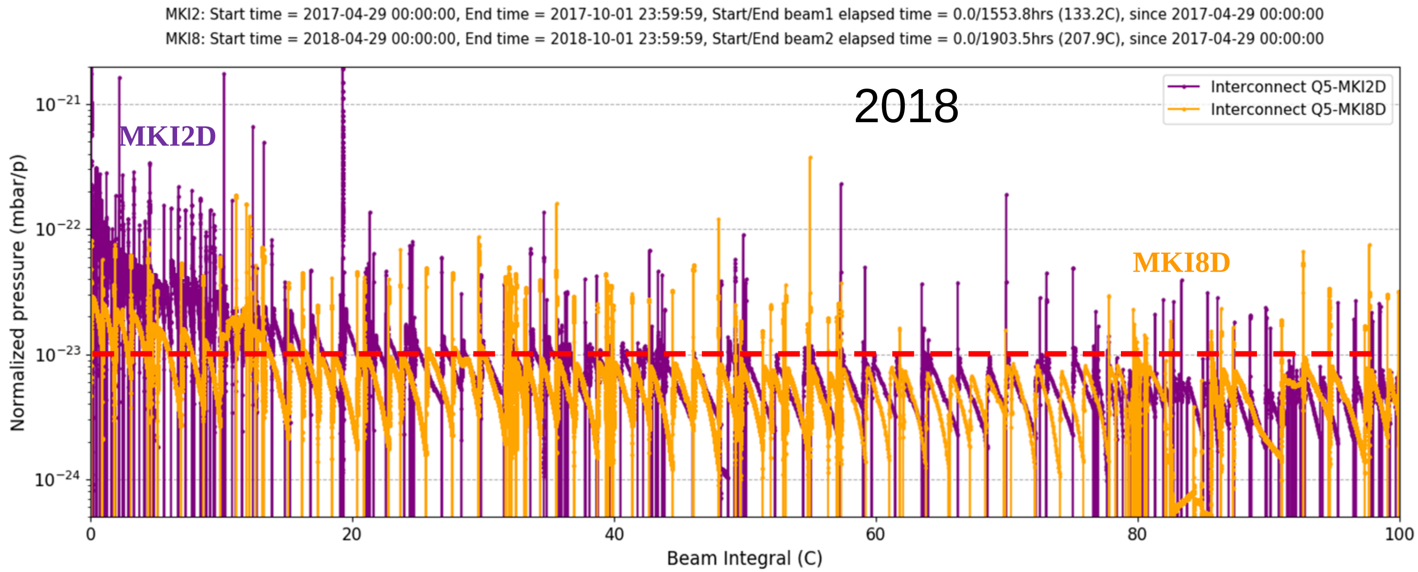

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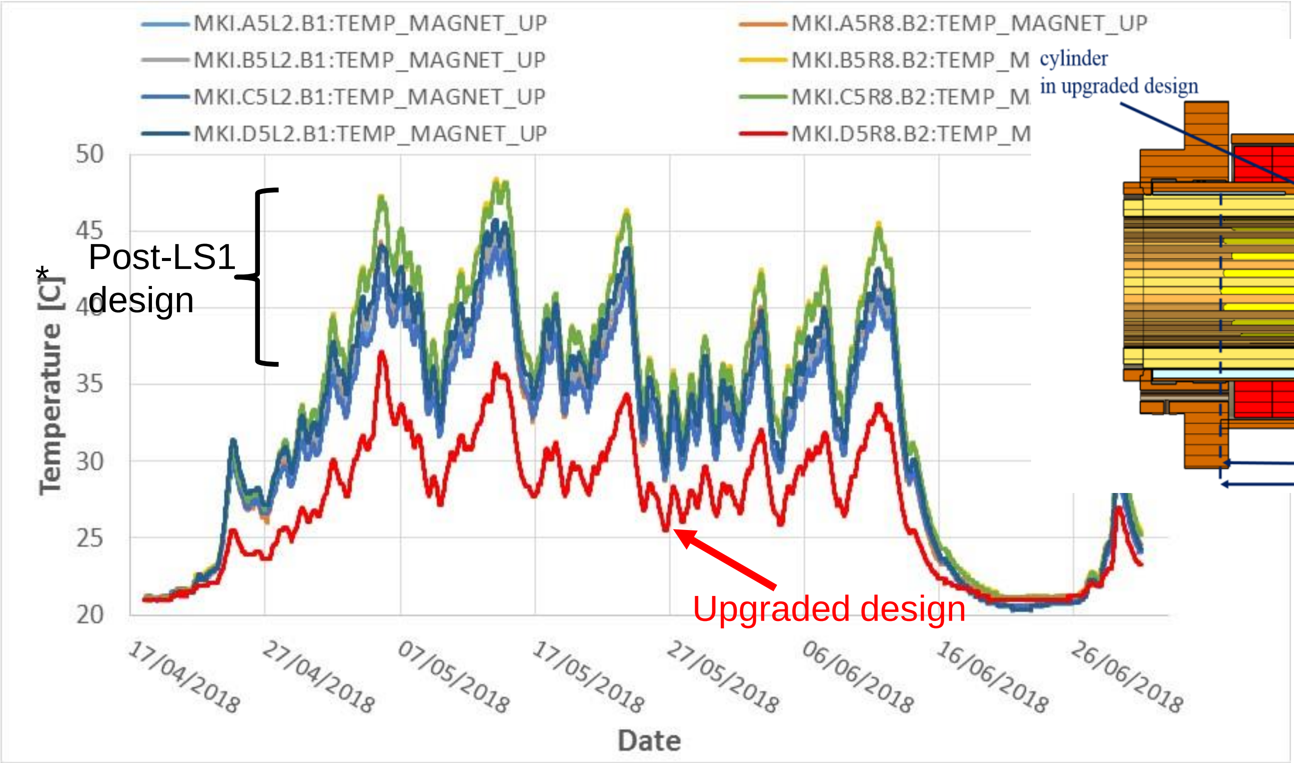
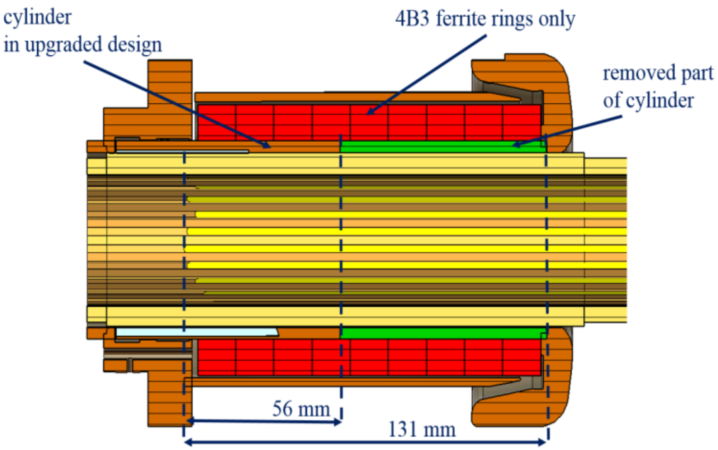


Upgraded MKI beam screen design (only MKI8D)



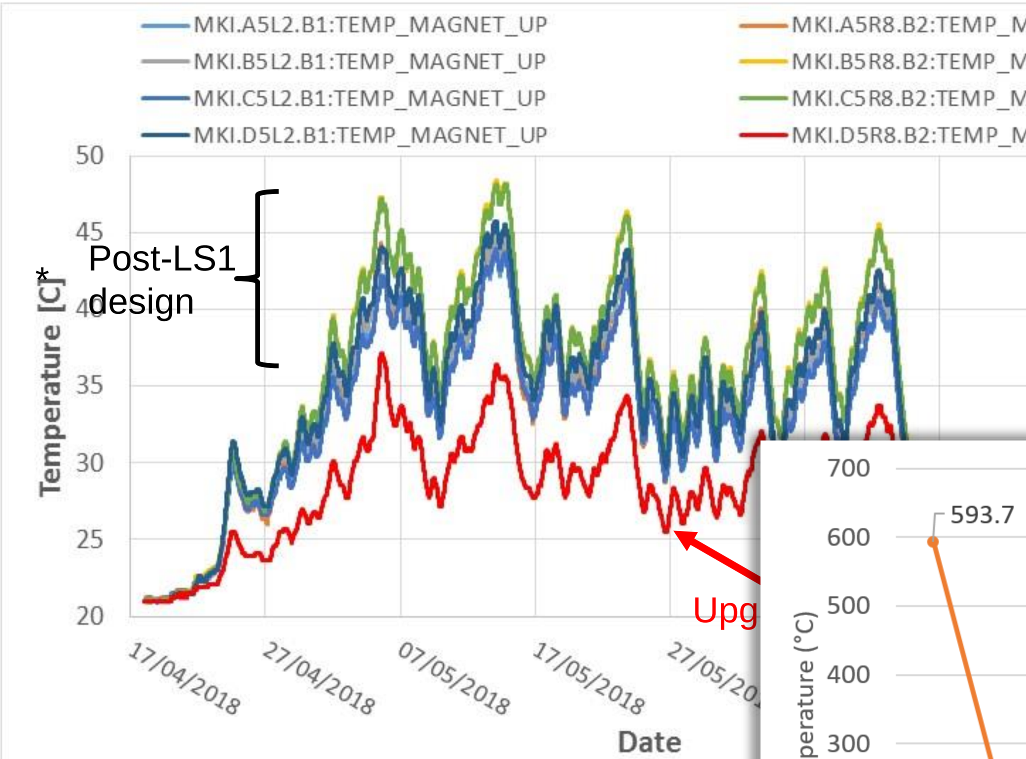
*Note: PT100 offset, at ambient temperature, corrected.

Upgraded MKI8D beam screen magnet shows a significantly lower temperature than those of the Post-LS1 MKIs.

Still not enough for operation with HL-LHC beams

Upgraded MKI Operational Performance

Courtesy of M. Barnes



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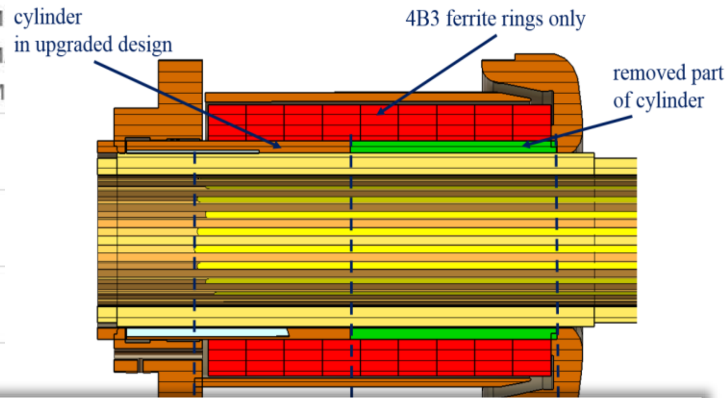
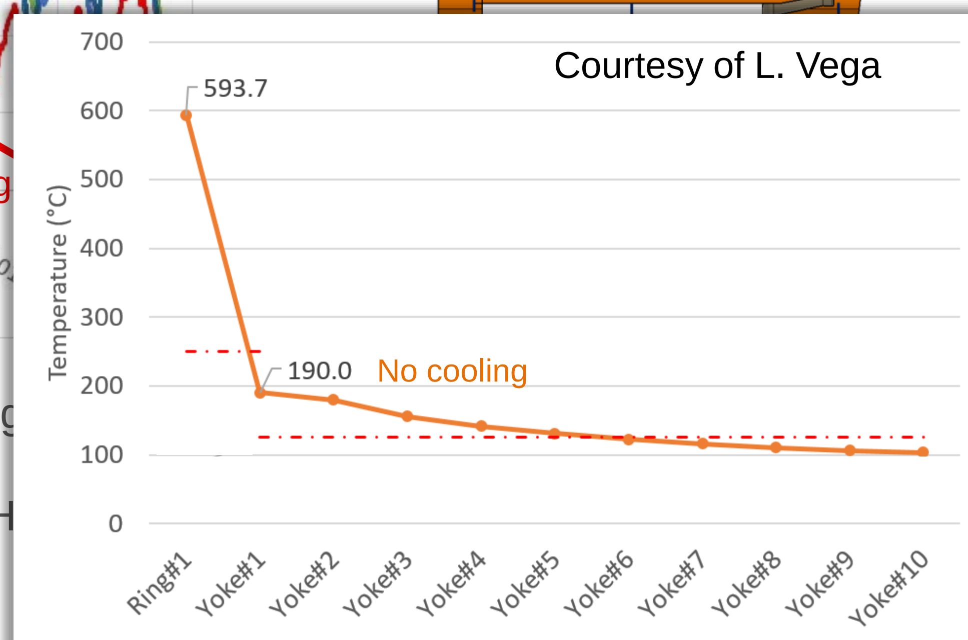


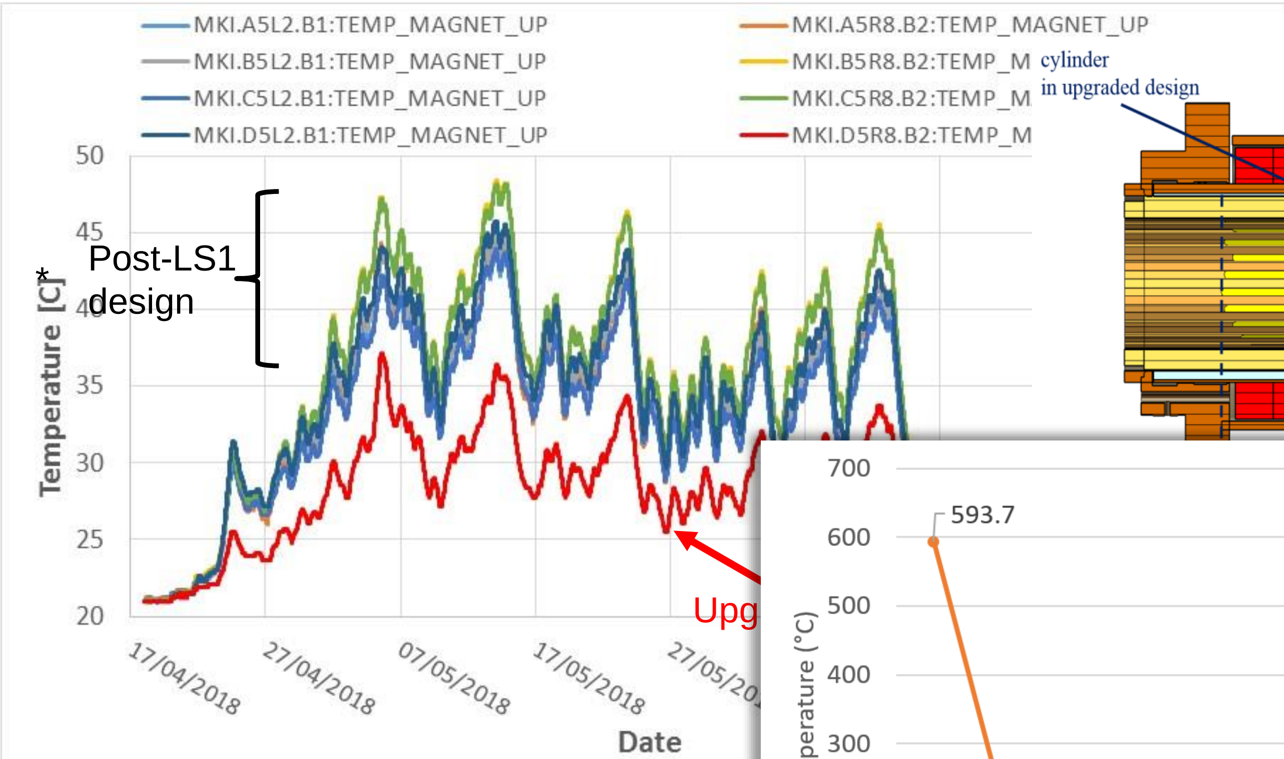


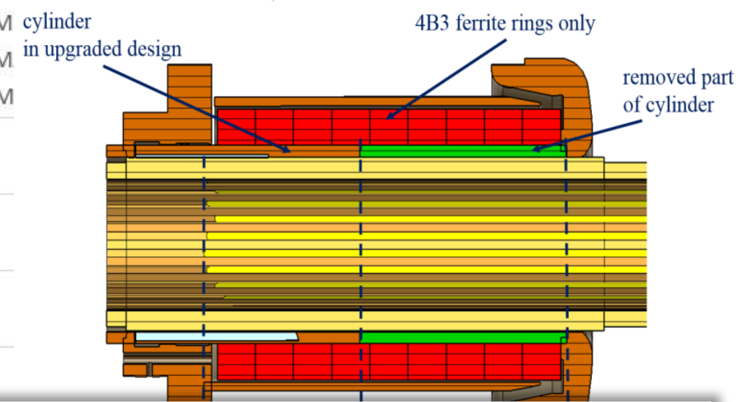
Upgraded MKI8D beam screen mag
those of the Post-LS1 MKIs.
Still not enough for operation with H

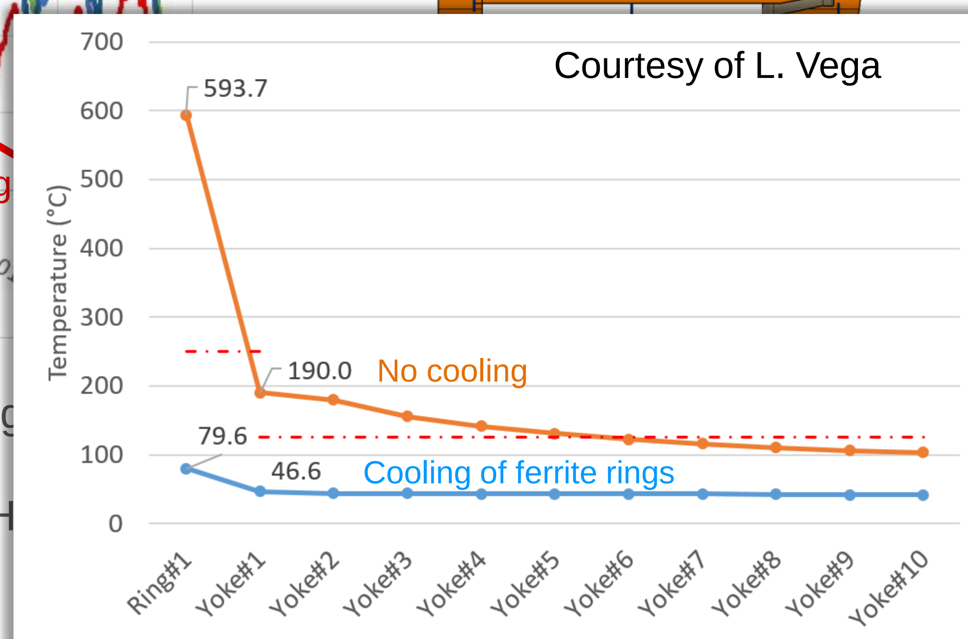
Upgraded MKI Operational Performance

Courtesy of M. Barnes

Upgraded MKI beam screen design (only MKI8D)







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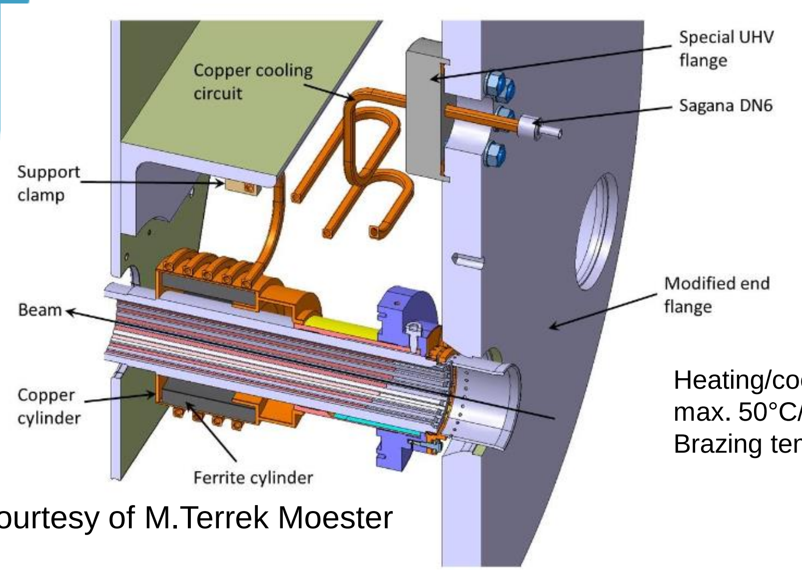
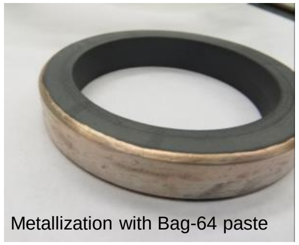
Still not enough for operation with H

MKI-Cool Prototype

Ferrite-Cu vacuum brazing

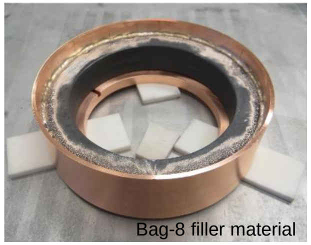


Courtesy of M.Terrek Moester



Metallization with Bag-64 paste

Silver plating

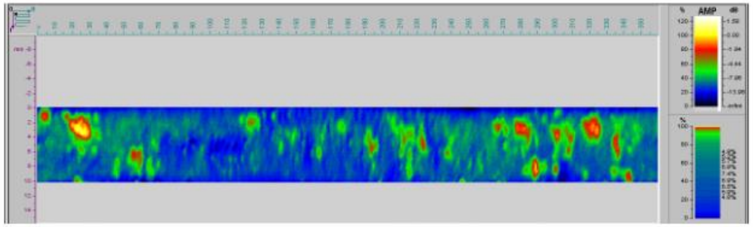


Bag-8 filler material

Courtesy of F. Motschmann

Heating/cooling rate <760°C max. 50°C/h
Brazing temperature: 790°C

US C-scan of brazing joint wit Ag-plating

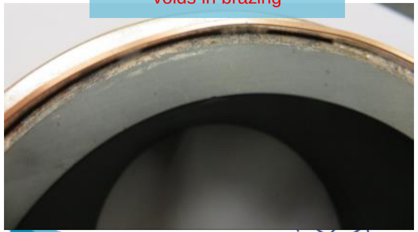


Observations:
Brazed area >90%. Some local reflections, but in general homogenous.

Some issues during brazing tests:

- 1st assembly – significant voids in brazing;
- 2nd assembly – good brazing, but longitudinal cracks in ferrite.
- Final assembly showed good brazing and no cracks

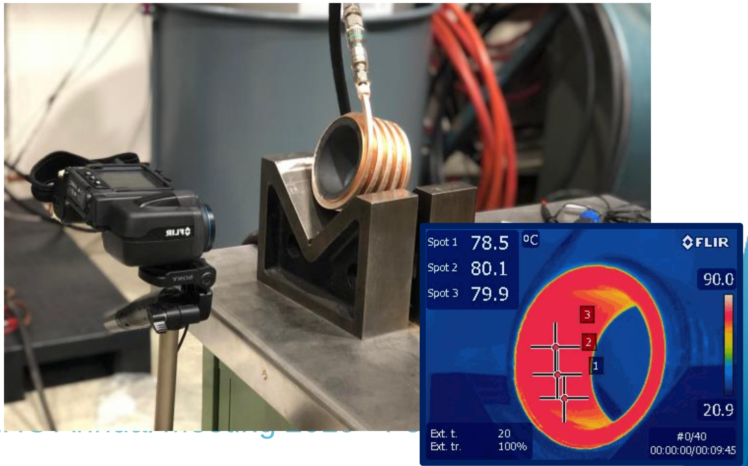
1st prototype: significant voids in brazing



2nd prototype: good brazing, longitudinal cracks

Courtesy of L.O. Bjorkqvist

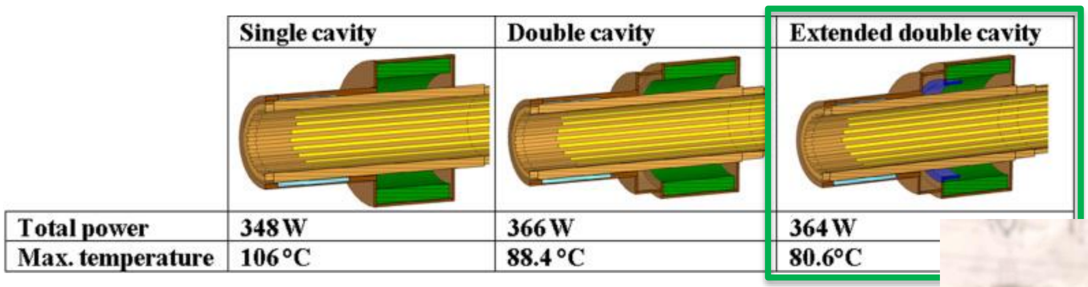
- Thermal measurements to assess Thermal Conductance between ferrite and cooling pipes



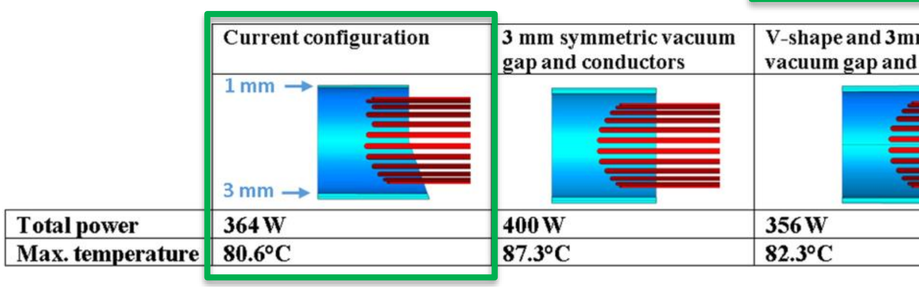
MKI-Cool Prototype

Optimised design of capacitively coupled end of beam screen:

- Length of ferrite cylinder: 60 mm, trade-off between total power reduction and mechanical properties
- Inner radius 38 mm and 10 mm thickness for uniform heat distribution and efficient heat extraction through cooling system
- Extended double cavity to smooth out the longitudinal heat distribution ➔ lowest temperature despite higher power
- Length and disposal of screen conductors (with constraints imposed by HV behavior)

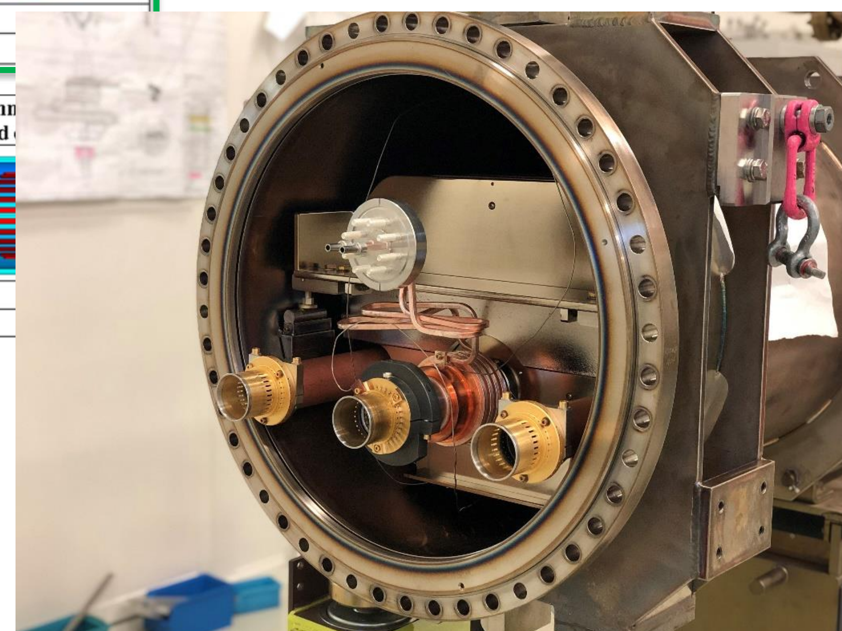


	Single cavity	Double cavity	Extended double cavity
Total power	348 W	366 W	364 W
Max. temperature	106 °C	88.4 °C	80.6°C



	Current configuration	3 mm symmetric vacuum gap and conductors	V-shape and 3mm vacuum gap and
Total power	364 W	400 W	356 W
Max. temperature	80.6°C	87.3°C	82.3°C

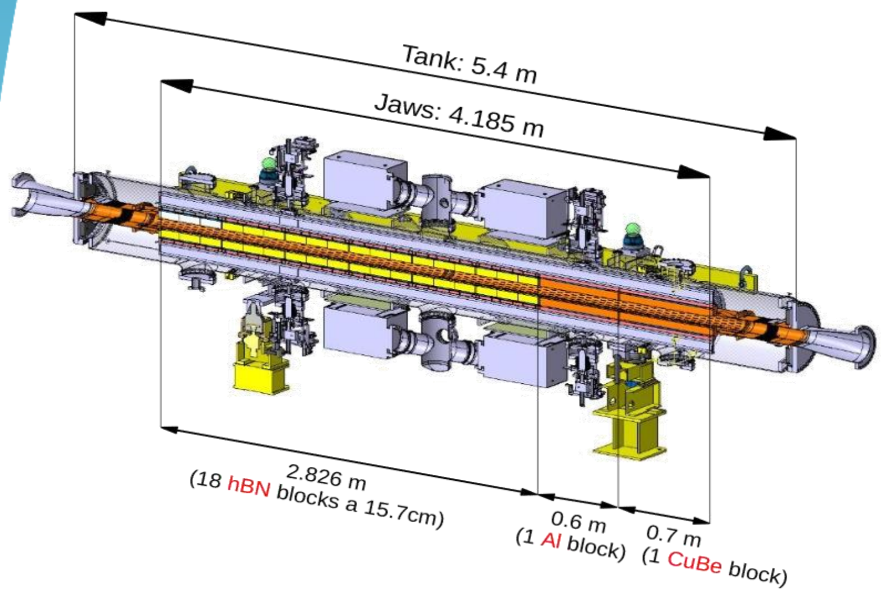
Prototype ready for vacuum and HV conditioning and installation in IR2 in March 2020



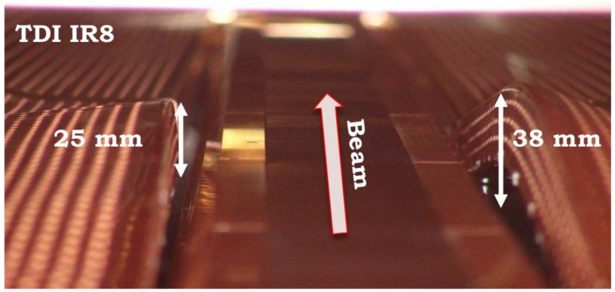
Courtesy of L. Vega and V. Vlachodimitropoulos

The TDI History

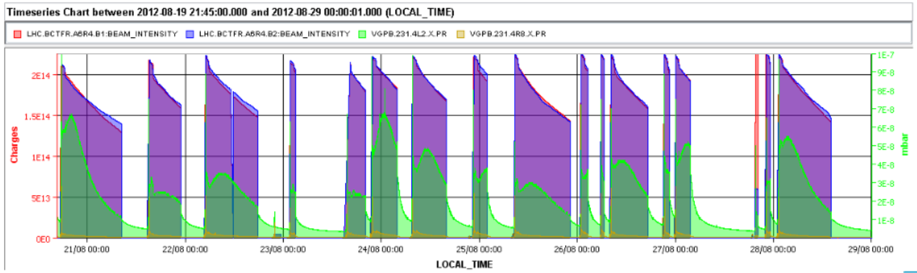
- Original design (Run I)



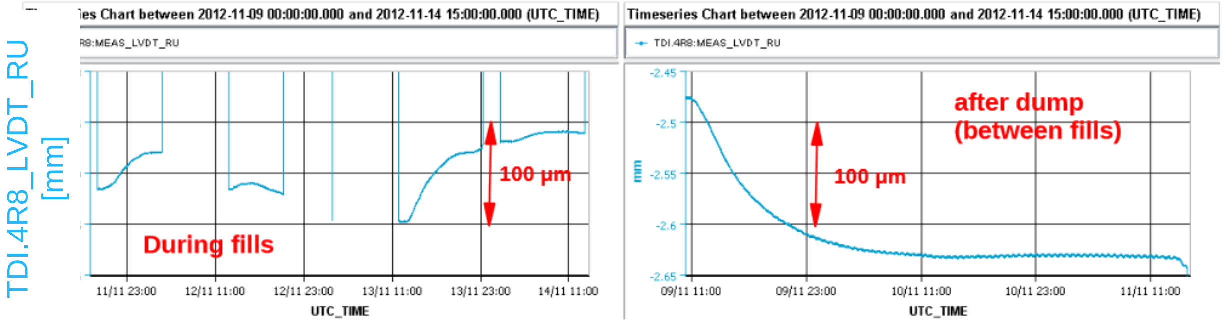
1. Cu beam screens deformed and sliding contacts blocked (TDI.4L2 and TDI.4R8)



2. Increased outgassing during fills (mainly at TDI.4L2 ➔ background in ALICE)



3. Thermal drift of jaw positions measure by LVDTs (TDI.4L2 and TDI.4R8), no straightforward correlation LVDT <-> actual jaw deformation. Interlock limits adjusted several times.



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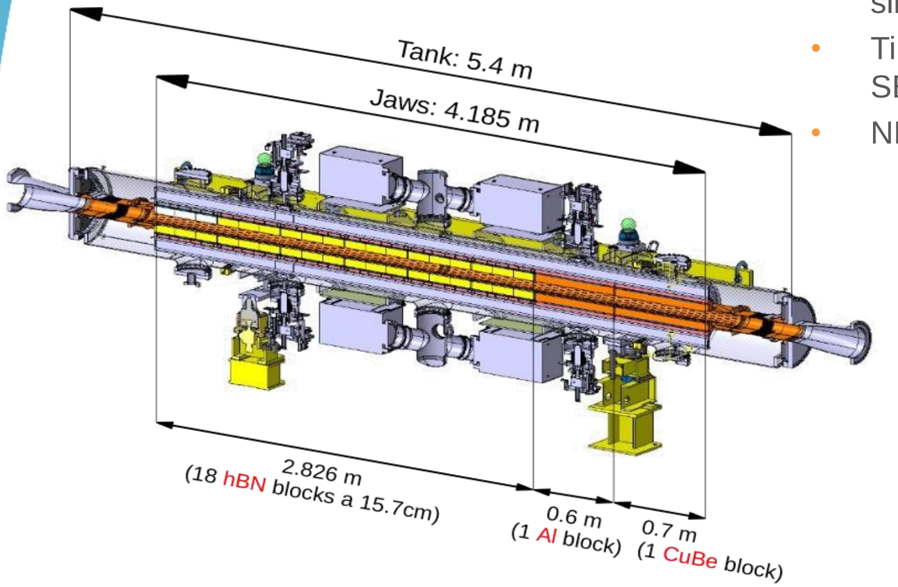
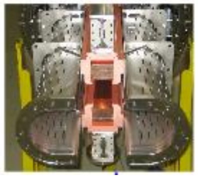
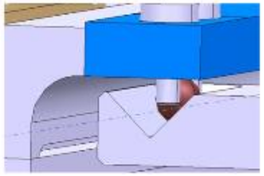


LS1:

- Reinforced beam screen made of stainless steel and improved sliding contacts (ceramic spheres)
- Ti coating on Al blocks to reduce SEY
- NEG cartridges installation





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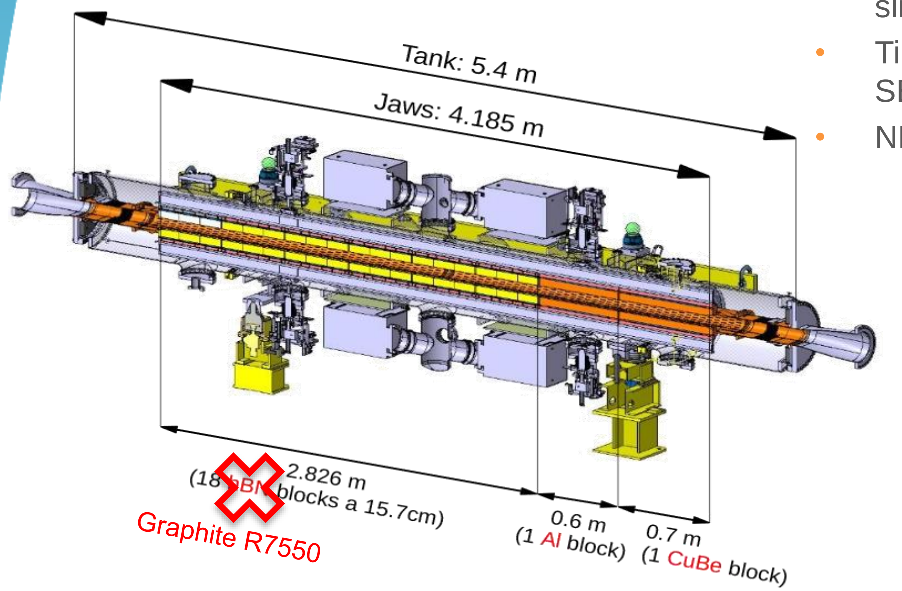

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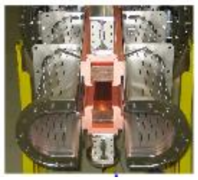
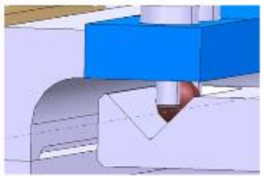
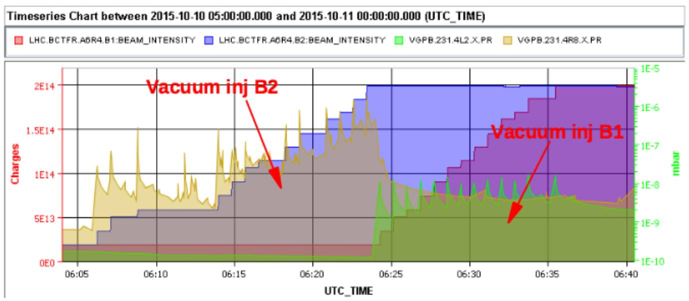




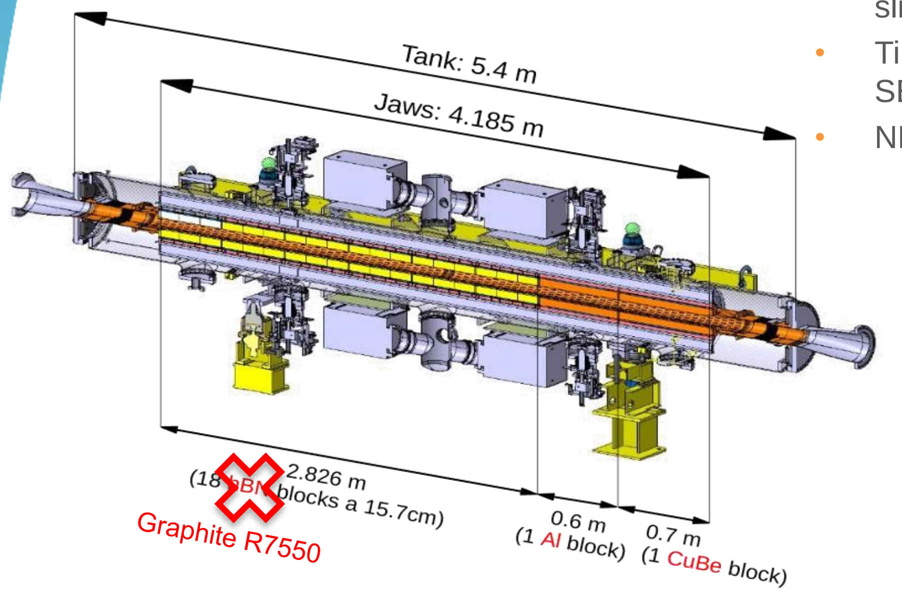
Run II – 2015:

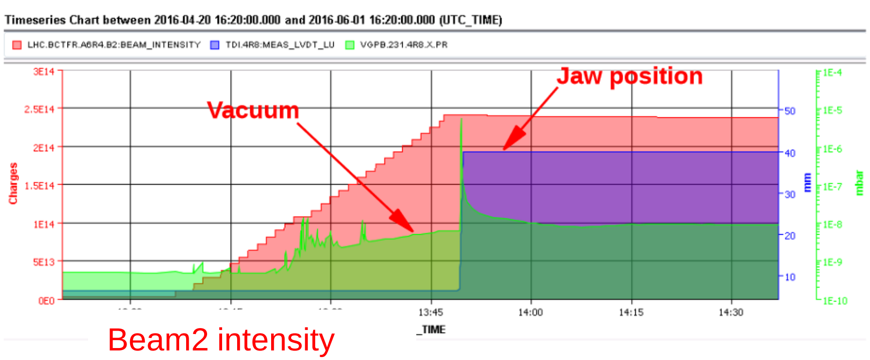
- Quality issues with hBN blocks after treatment in vacuum at high temperature ➔ replaced with graphite with Cu coating in YETS
- Vacuum spikes at TDI.4R8 during injections (build up pressure) and spurious spikes during physics ➔ limit on maximum number of injected bunches (96 BCMS).
- Ti coating found degraded over large surface areas and blisters found on Cu coating of Al frame.



The TDI History

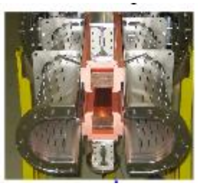
- Original design (Run I)

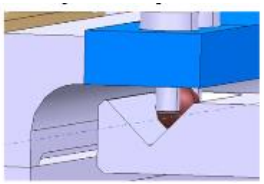




LS1:

- Reinforced beam screen made of stainless steel and improved sliding contacts (ceramic spheres)
- Ti coating on Al blocks to reduce SEY
- NEG cartridges installation





Run II – 2015:

- Quality issues with hBN blocks after treatment in vacuum at high temperature → replaced with graphite with Cu coating in YETS
- Vacuum spikes at TDI.4R8 during injections (build up pressure) and spurious spikes during physics → limit on maximum number of injected bunches (96 BCMS).
- Ti coating found degraded over large surface areas and blisters found on Cu coating of Al frame.

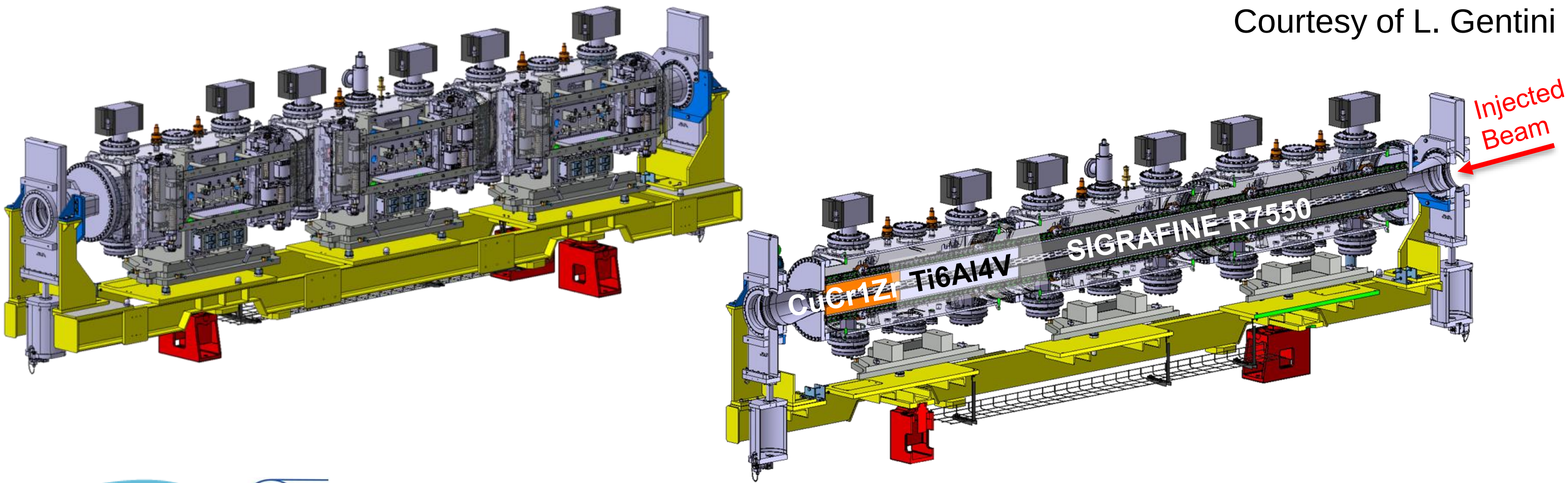
Run II – 2016 →2018:

- Strong pressure increase at TDI.4R8 while moving the jaws to parking, the problem was solved by retracting the jaws to 40 mm instead of 55 mm (e-cloud as possible explanation)
- No more intensity limitations during Run II

New Design TDI → TDIS

- Three independent shorter modules (1.6 m each) → improve alignment accuracy and reduce beam induced deformation.
- The modules are installed on a common girder, aligned on surface and transported as a single device in the tunnel (spares under vacuum and ready for installation with reduced bake out in the tunnel).
- Minimise impedance (beam induced heating): materials, coating, longitudinal and lateral RF fingers, tapering, tank and transition geometry, cooling, etc.
- Improve vacuum performance: materials, coating, operational gaps.
- Improve mechanics and diagnostics
- Improve spare policy: full assembly vacuum conditioned (additional sector valves) for installation in tunnel without bake-out

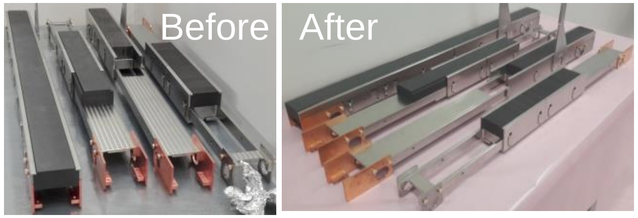
Courtesy of L. Gentini



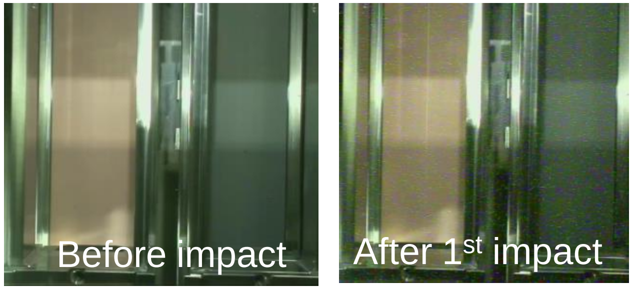
HiRadMat Tests

- HRMT-28 (June 2017): graphite and 3D CC ➔ both survived and flatness within specs (<100 μm) ➔ R7550 graphite chosen as low Z absorber material

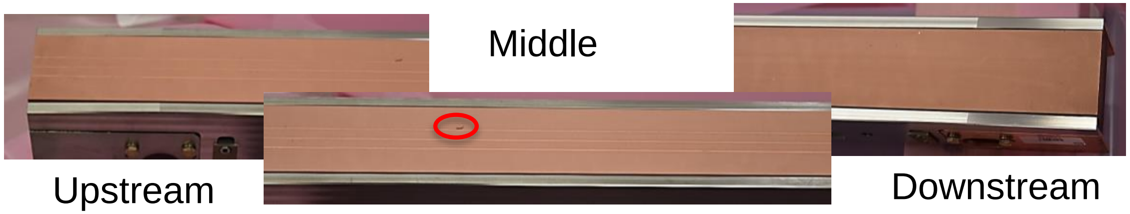
Jaw flatness	Graphite Sigrafine® R7550 (SGL)	Graphite 2123 PT (Mersen)	3D C/C A412 (Mersen)	Sepcarb® 3D C/C (Airbus Safran Launchers)
Before Impacts	80 μm	56 μm	128 μm*	44 μm
After Impacts	96 μm	58 μm	82 μm	44 μm



- HRMT-35 (August 2017): visible traces on Cu coating but no apparent surface rupture ➔ baseline: not to apply any Cu coating since cooling capacity enough against resistive wall beam induced heating



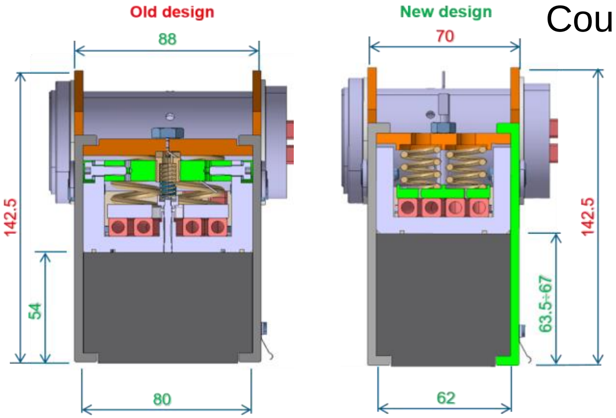
Courtesy of I. Lamas Garcia



- HRMT-45 (August 2018): validation of new jaw design and back-stiffener material (Molybdenum Zirconium TZM) in case of deep beam impact

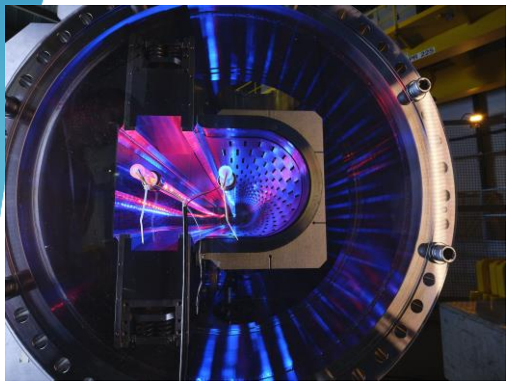
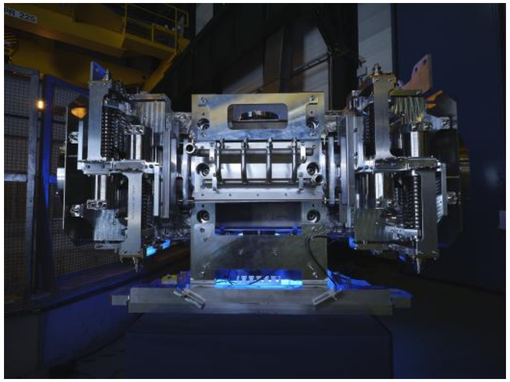
Design Fully Validated

Courtesy of L. Gentini



* Possible block movement during handling

TDIS Status

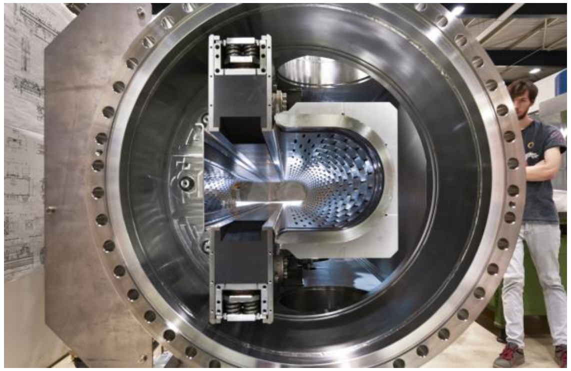
One TDIS module at:

CERN OPENDAYS
Explore the future with us
Explorez le futur avec nous

First TDIS being assembled, it will be completed by end October 2019 ➔ ready for installation in IR2 in Q2 2020

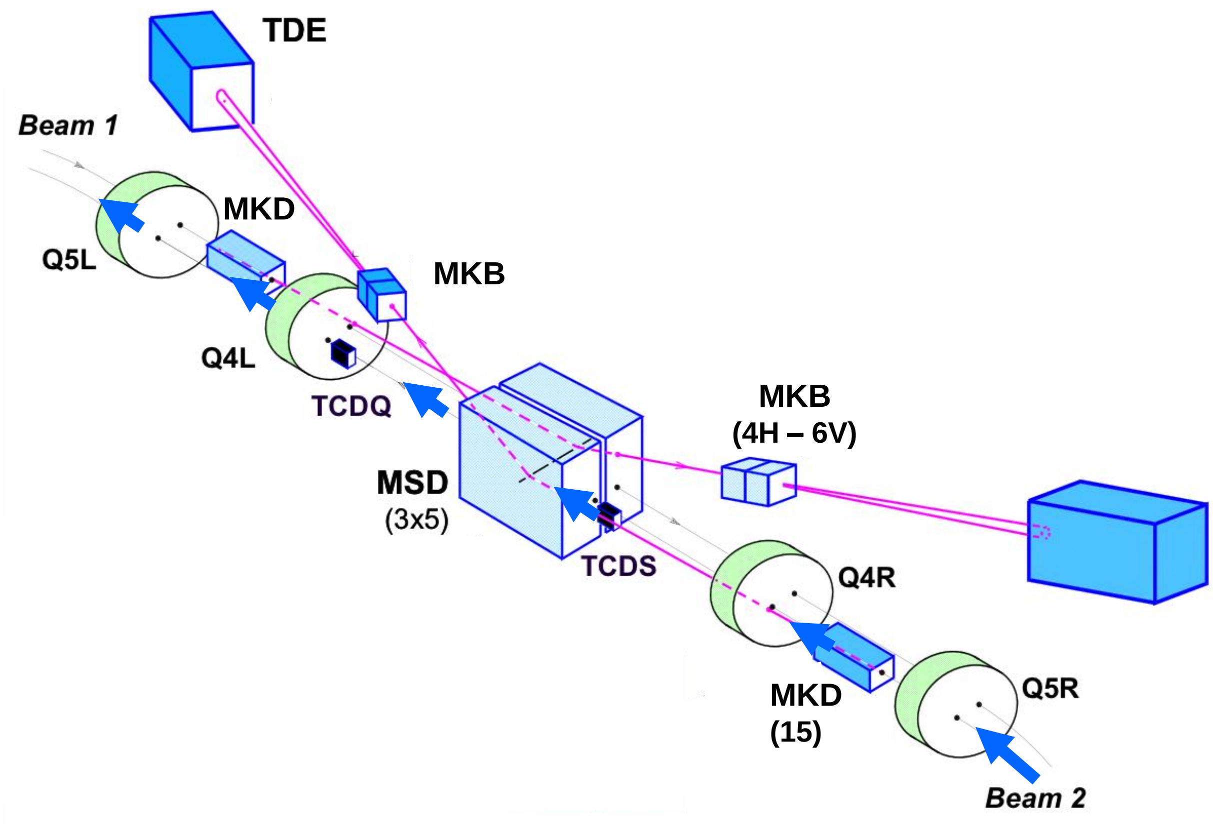
Next steps:

- Cabling, impedance measurements and vacuum tests
- 2nd TDIS ready by end of March 2020 ➔ installation in IR8 in Q3 2020
- 3rd and 4th TDIS (spares) ready by July 2020

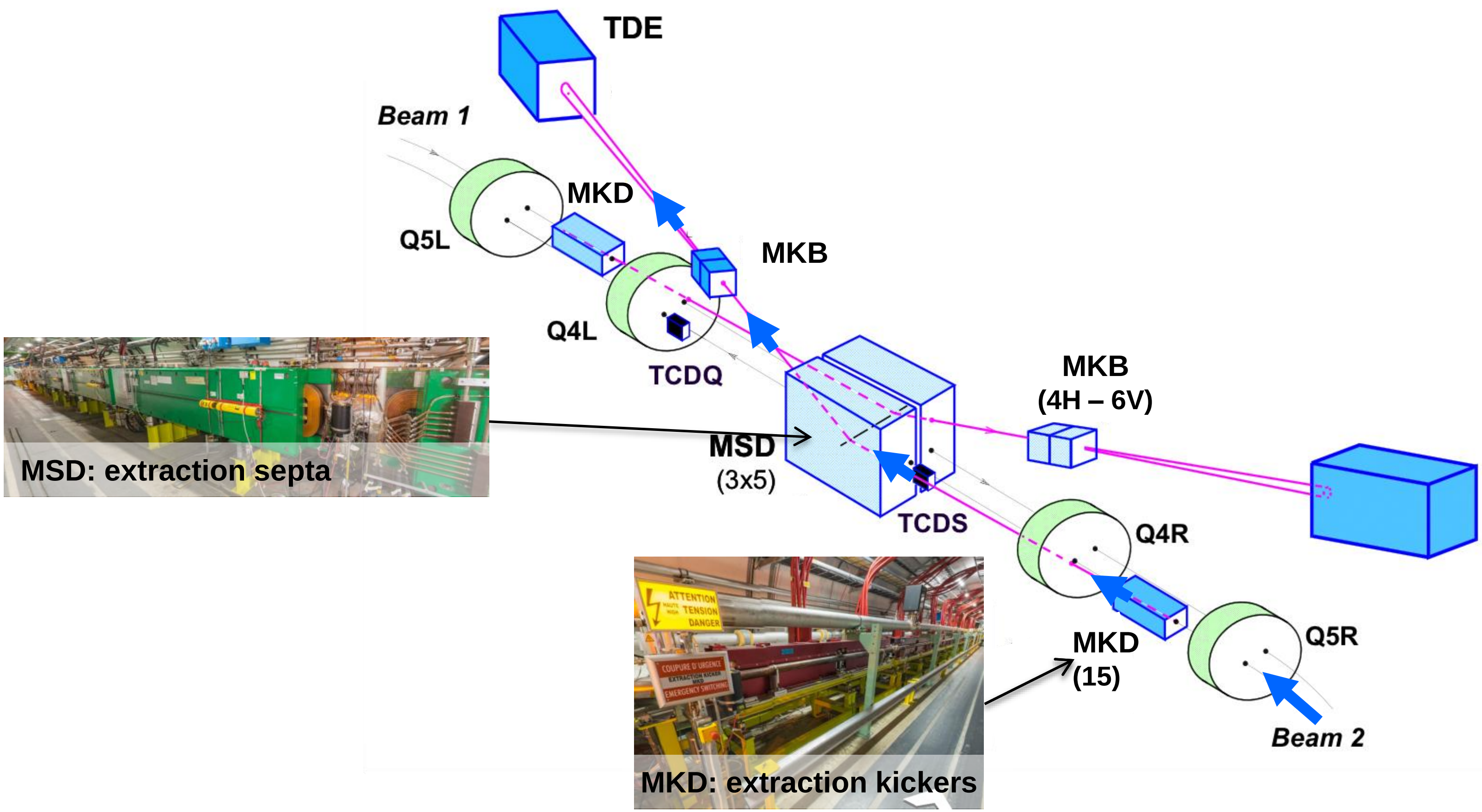



Courtesy of M. Calviani and D. Carbajo Perez

The LHC Beam Extraction and Dump System



The LHC Beam Extraction and Dump System



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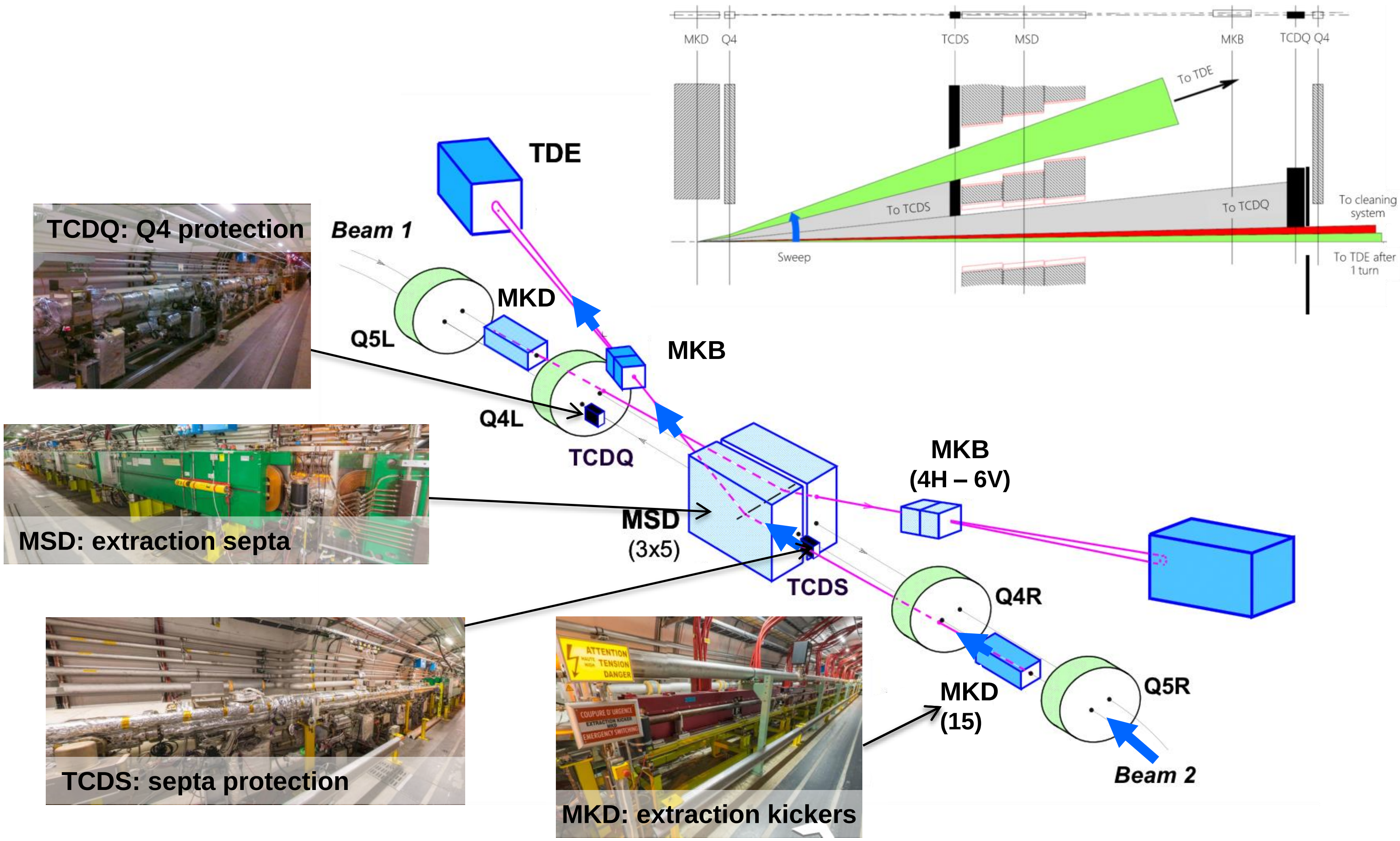

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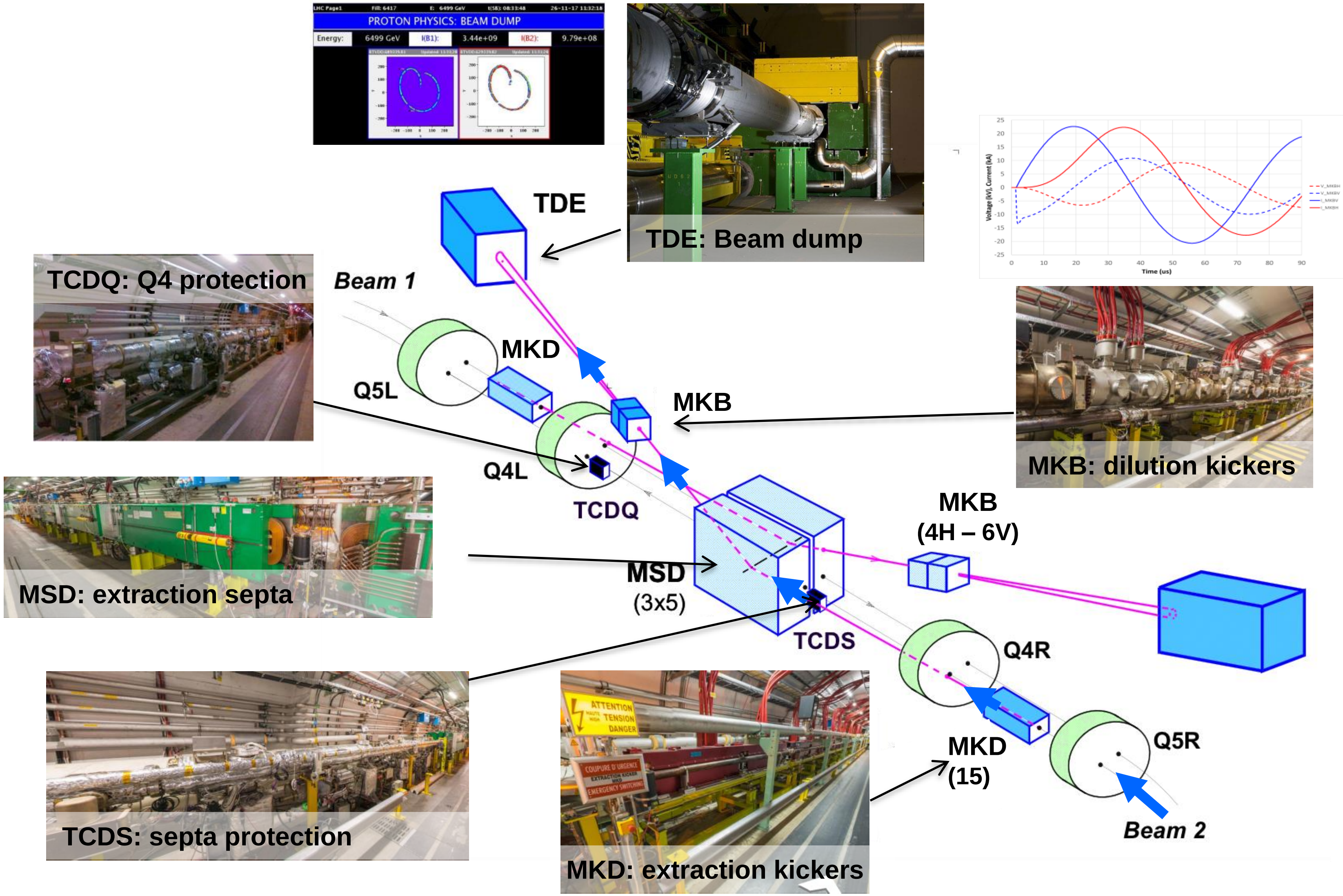

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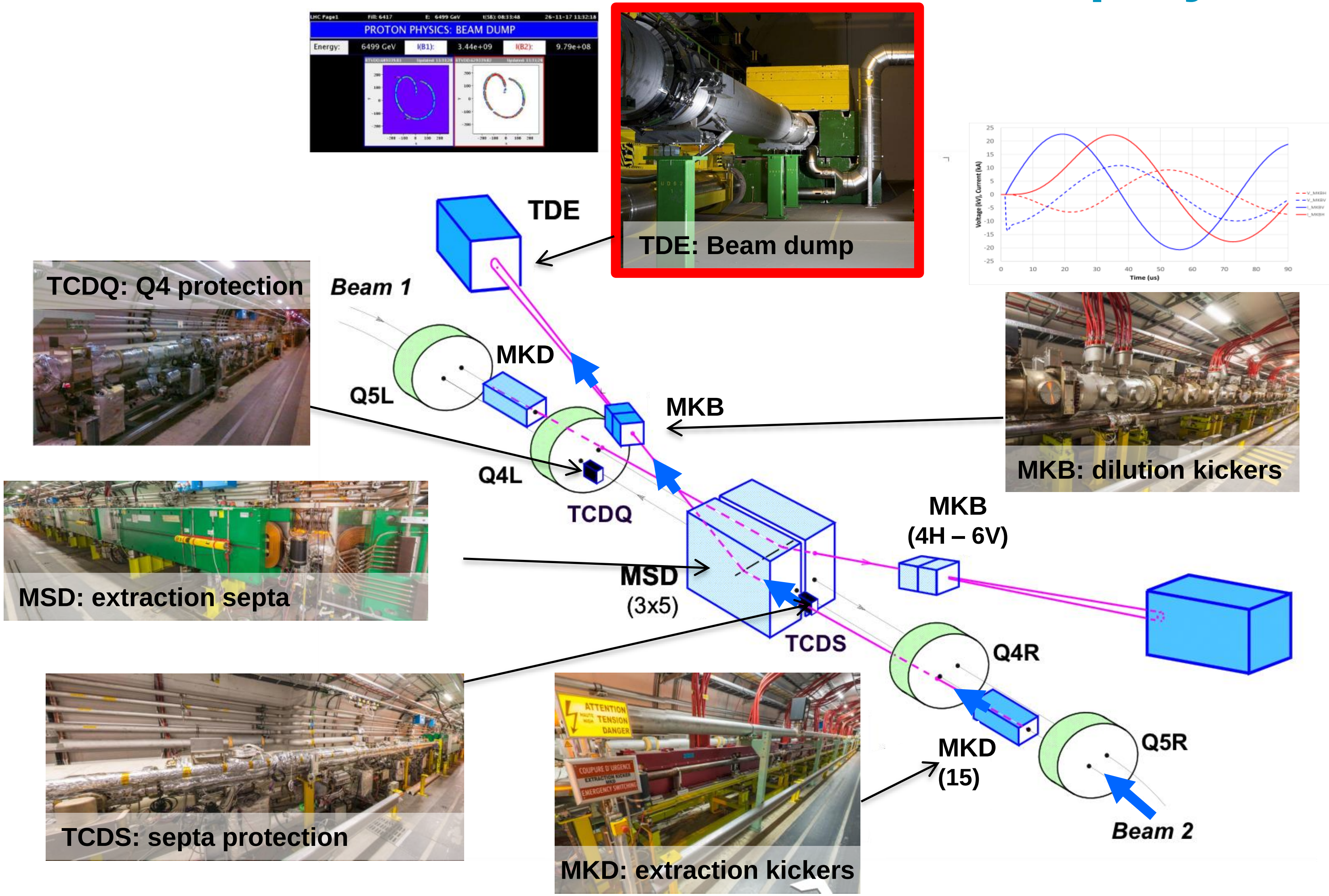
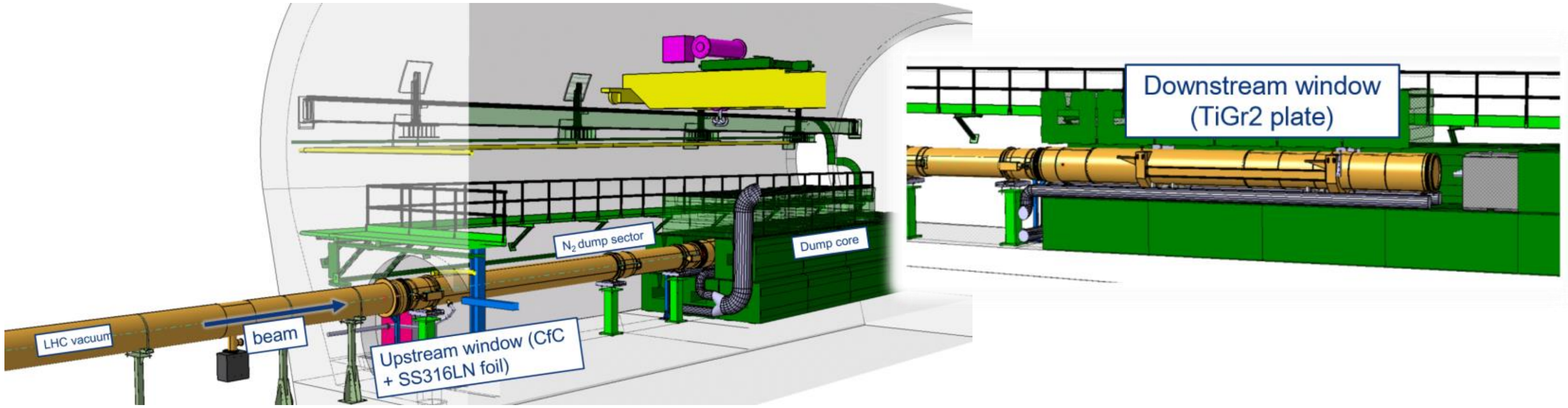
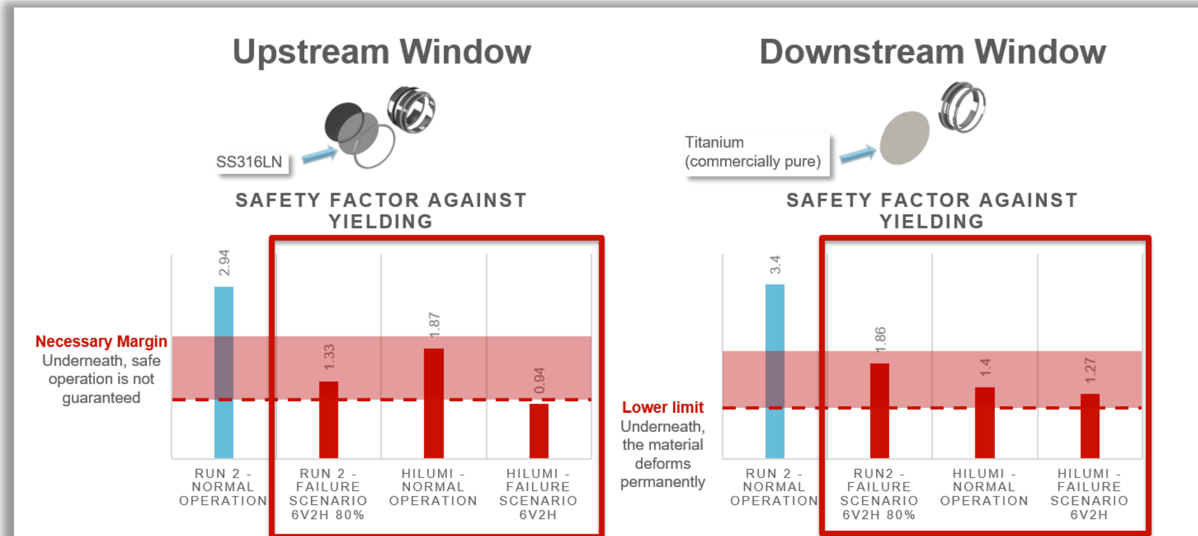


Beam Dump TDE: Known Issues



- Robustness of upstream and downstream windows in case of dilution failure

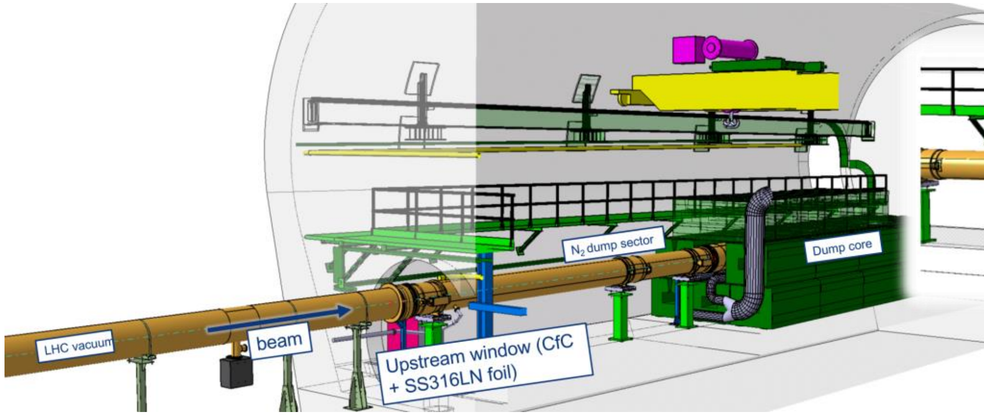


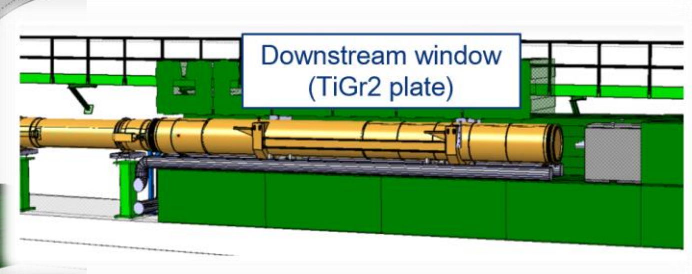
$$S_y = \frac{R_y}{\sigma_{eq}}$$

S_y = safety factor against yielding (permanent deformation) around reached temperature; always conservative
R_y = yield strength of the material
σ_{eq}= equivalent v. Mises stress

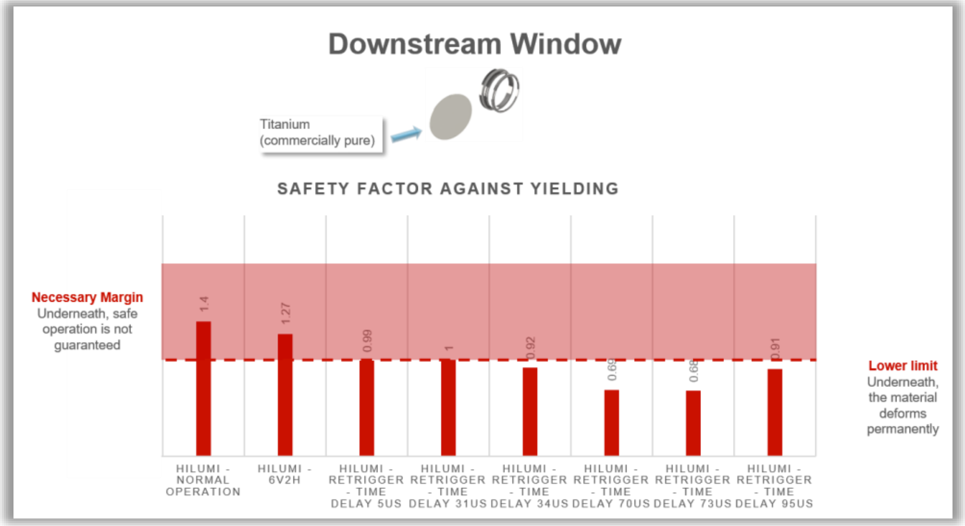
Courtesy of T. Polzin

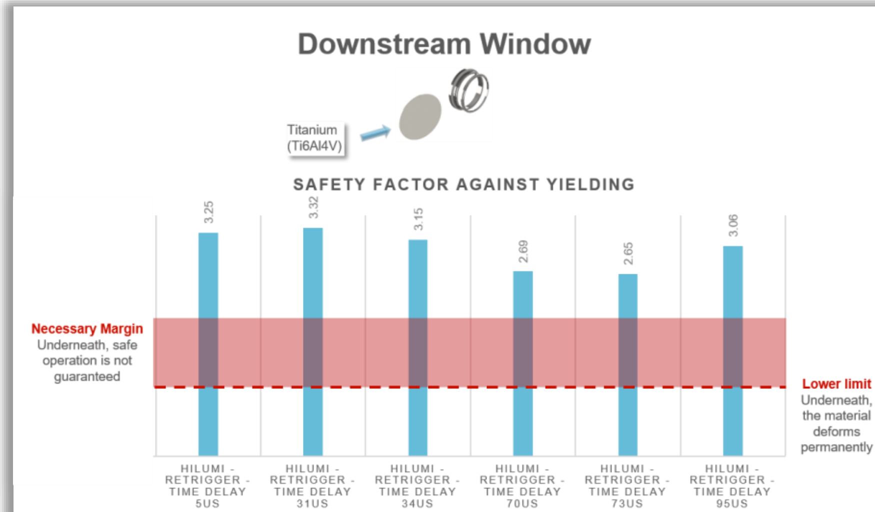
Beam Dump TDE: Known Issues





- Robustness of upstream and downstream windows in case of dilution failure
- New downstream window (pure Ti ➔ Ti-Gr5) will be replaced in LS2, design compatible with HL-LHC operation and MKB erratic failures over all range of delays (new MKB retriggering system)





Courtesy of T. Polzin

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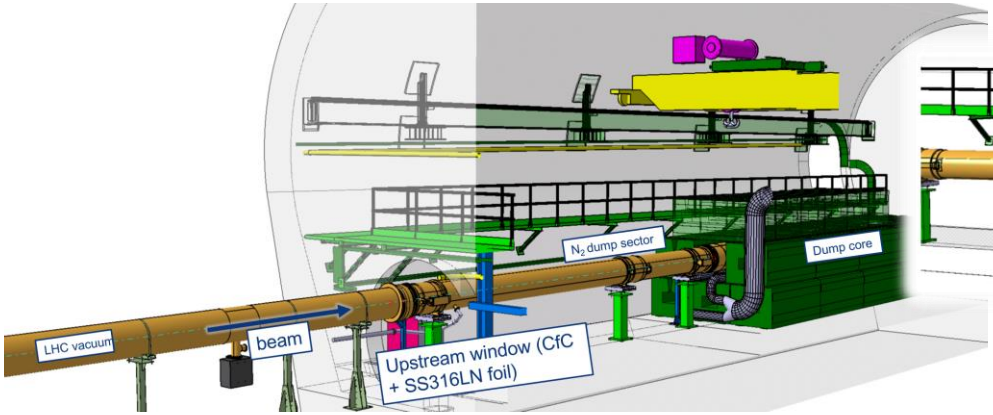

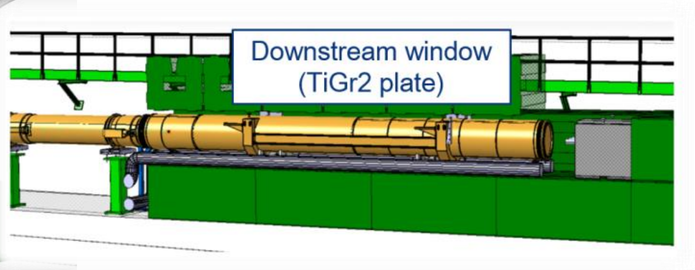

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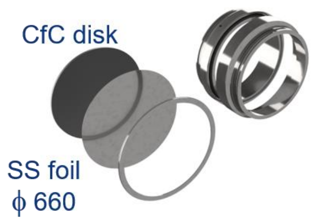
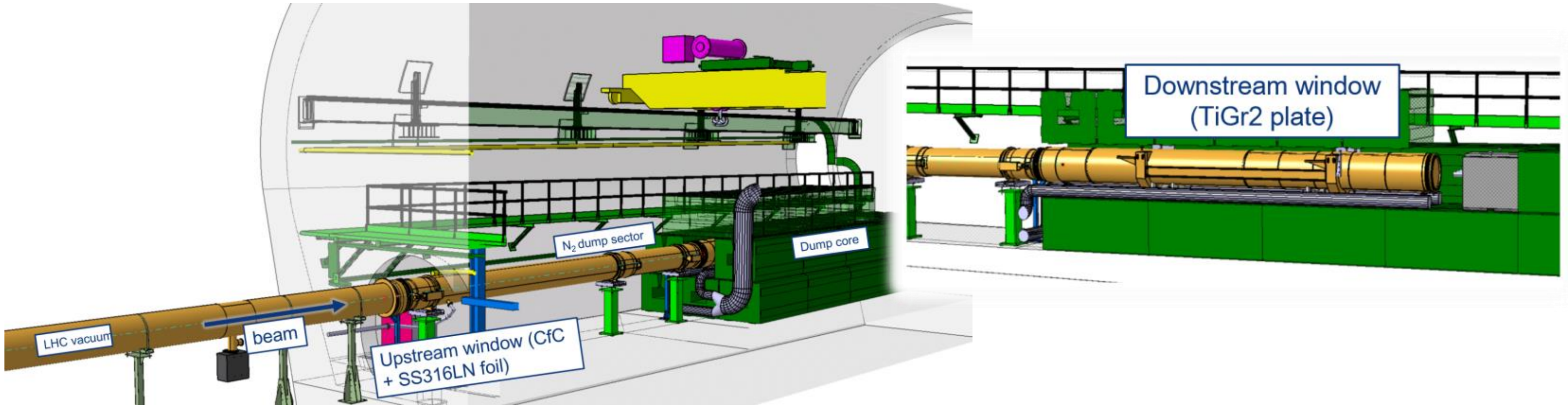
Upstream Window



Beam Dump TDE: Known Issues



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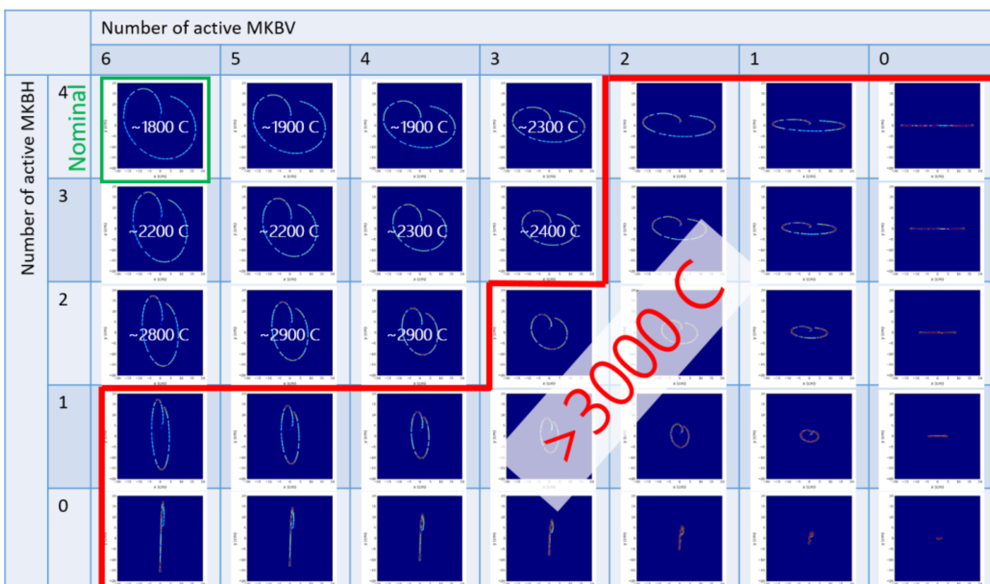

Courtesy of C. Wiesner and M.I. Frankl

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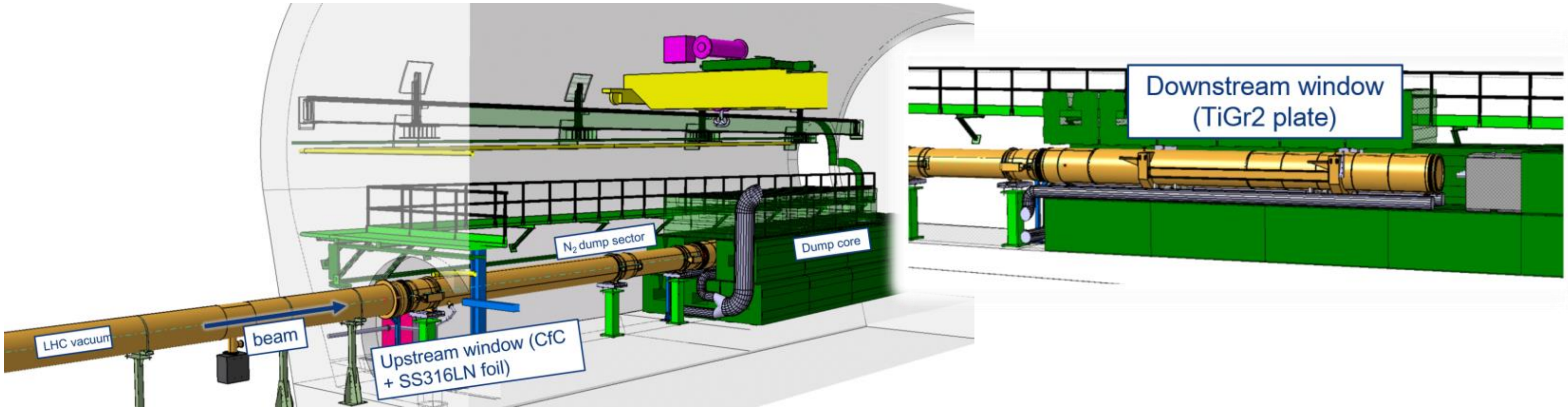

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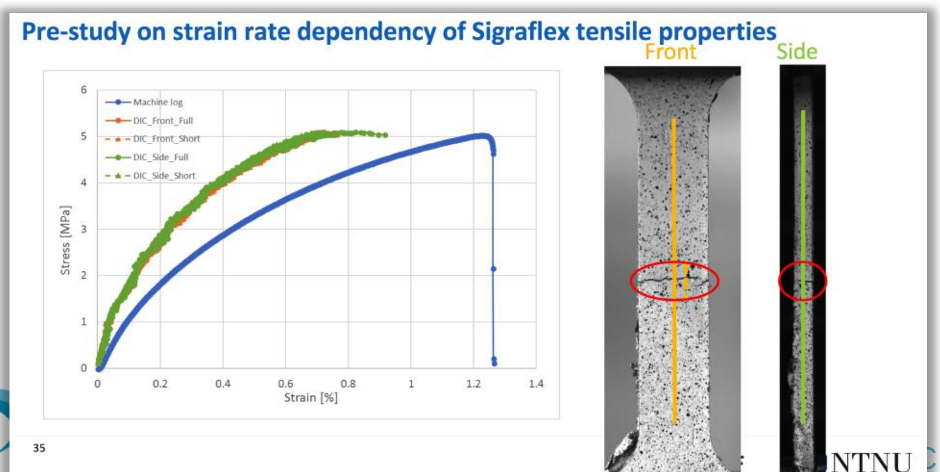
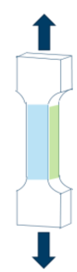
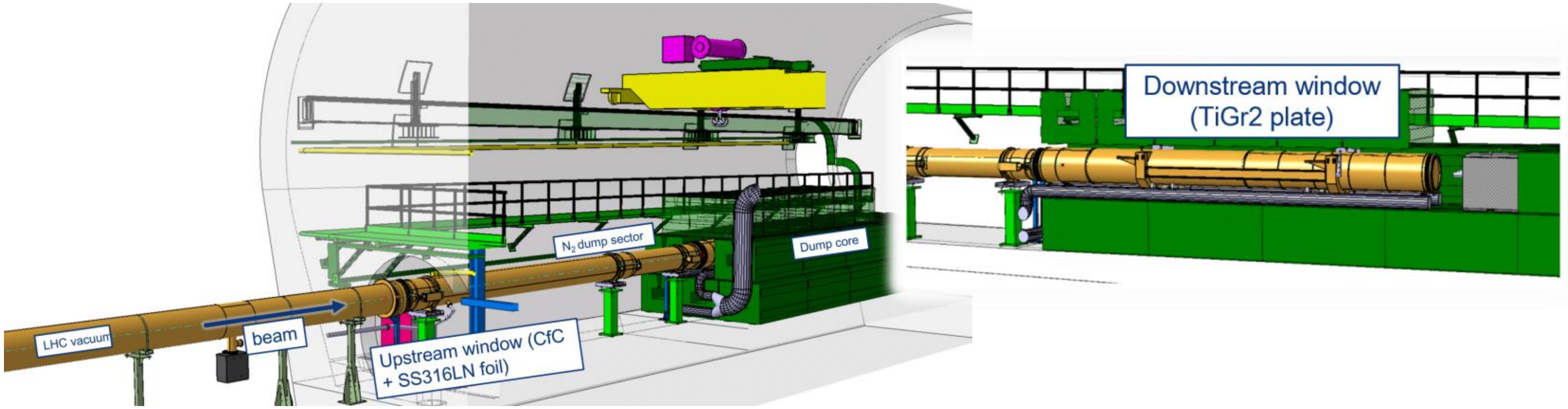




Beam Dump TDE: Known Issues



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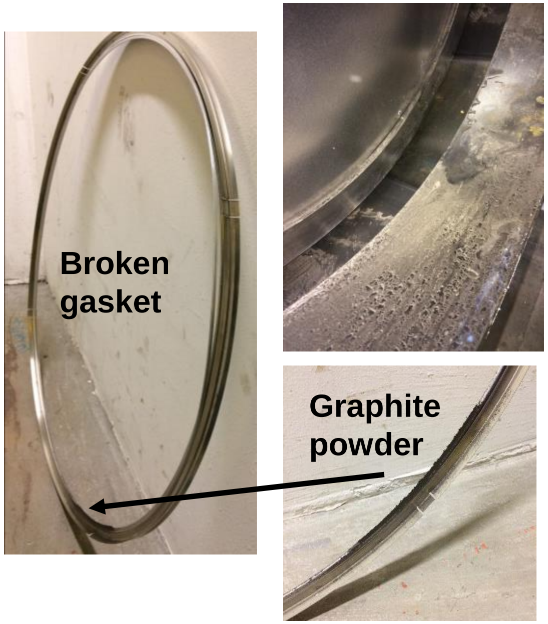
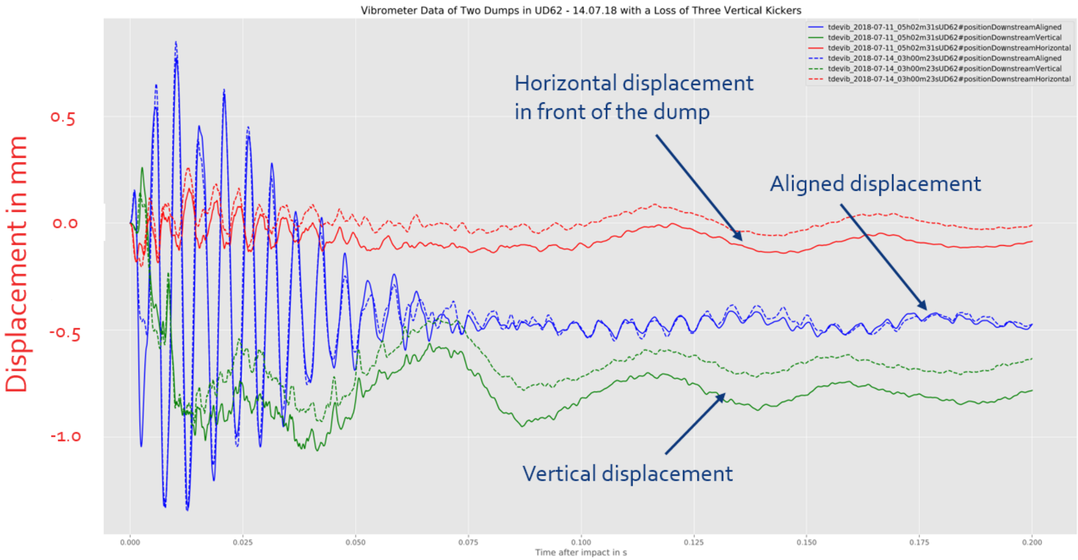
- Proposed to install two additional horizontal MKBs (more sensitive in H plane since only 4 magnets operated at with higher voltage) to sensibly reduce the risk and the sensitivity to any possible failure (erratic and flashover)

New Challenges: TDE vibrations

- **High intensity dumps** (16L2 issue) leading to major **nitrogen leaks** at UD62 (Beam 2) dump (>>10 mbar*l/s). A small leak appeared also at UD68. Main mitigations:
  - Flanges periodically tightened plus replacement of gaskets
  - Nitrogen line and surface supply (YETS 2017/2018)
  - Installation of interferometer to measure dump movements
- Measured **vibrations** during high intensity **normal** dumps and a permanent displacement towards the downstream shielding wall **➔ suspected cause of leak. Larger vibrations and displacements when moving to higher intensities.**





Investigating a new design which addresses all known issues (robustness, vibration and drifts) to insure no impact on HL-LHC availability and minimize interventions to reduce radiation exposure to personnel

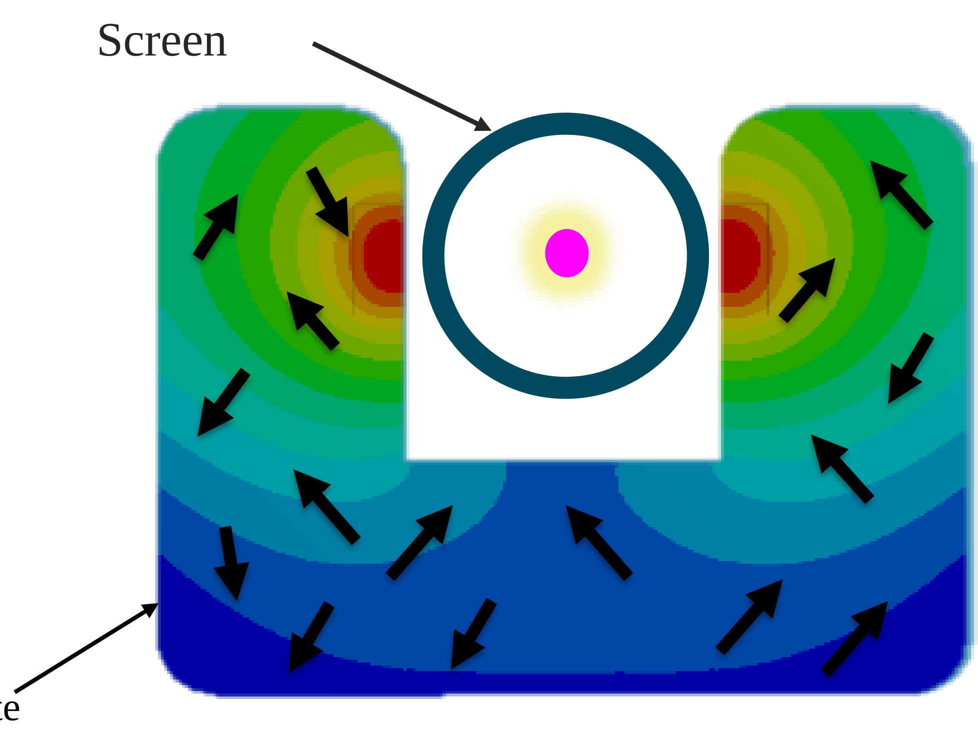
Courtesy of T. Polzin

Conclusions

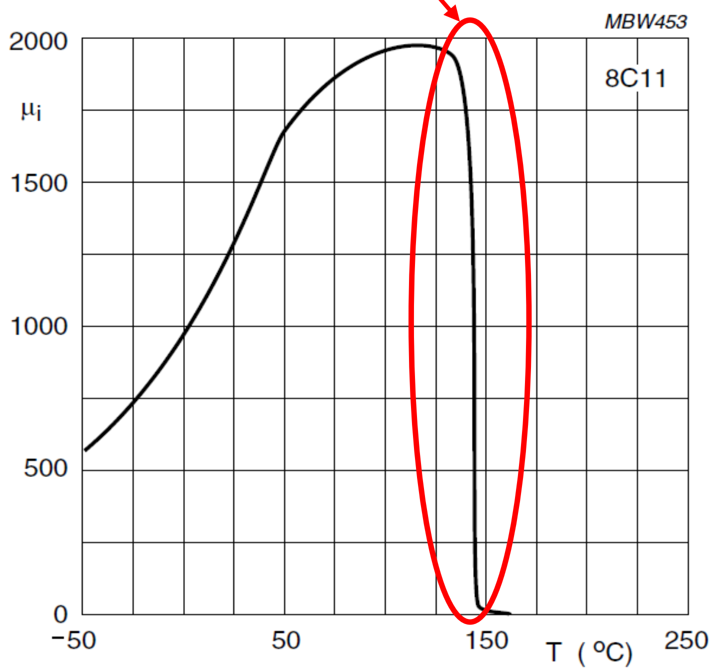
- Operational experience during first LHC run allowed to identify the week points of the injection and the extraction systems
- Some mitigations were put in place during LS and YETS for TDI and MKI but not good enough for operation with HL-LHC beams ➔ upgraded designs proposed
  - MKI-cool prototype almost ready for installation in IR2 in Q1 2020 to be tested with beam in Run III ➔ series production
  - First TDIS being assembled and ready for installation in Q2 2020, second one will be installed in Q3 2020 and two spares will be also ready in 2020
- Main new challenge: design of a beam dump addressing all known issues (robustness, vibrations and displacements) and allowing a safe operation both in nominal conditions and in case of dilution failures (proposal to add 2 MKBH to reduce risk and sensitivity to failures)

Thank you for your attention!

Beam Induced Heating



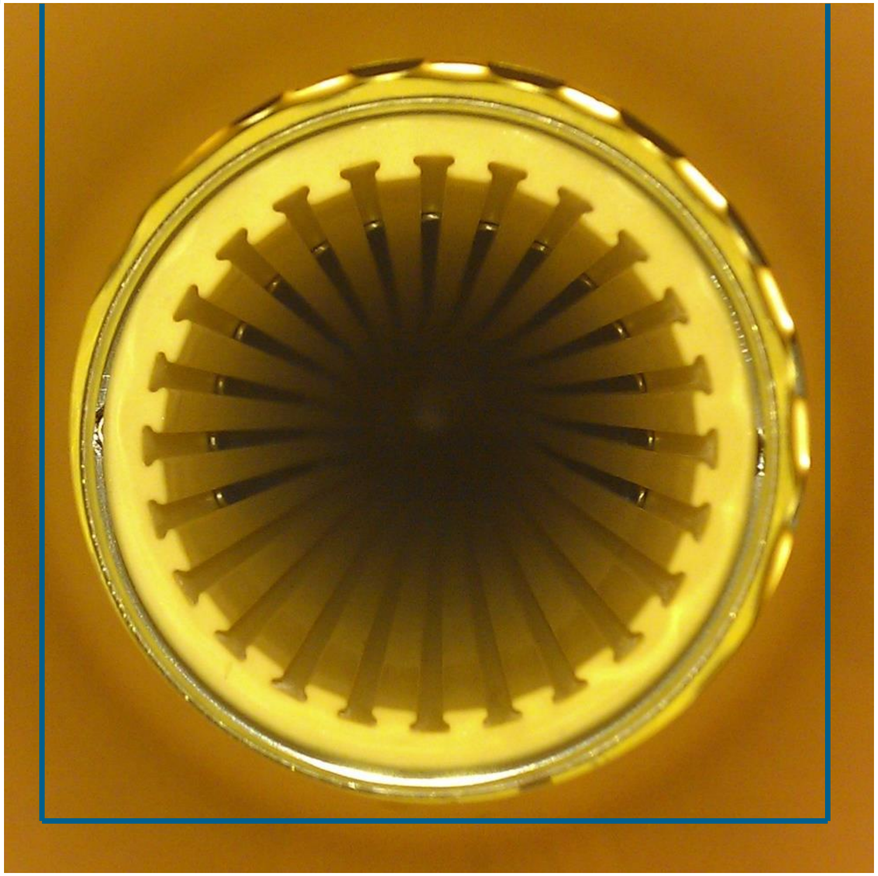
Curie Temperature



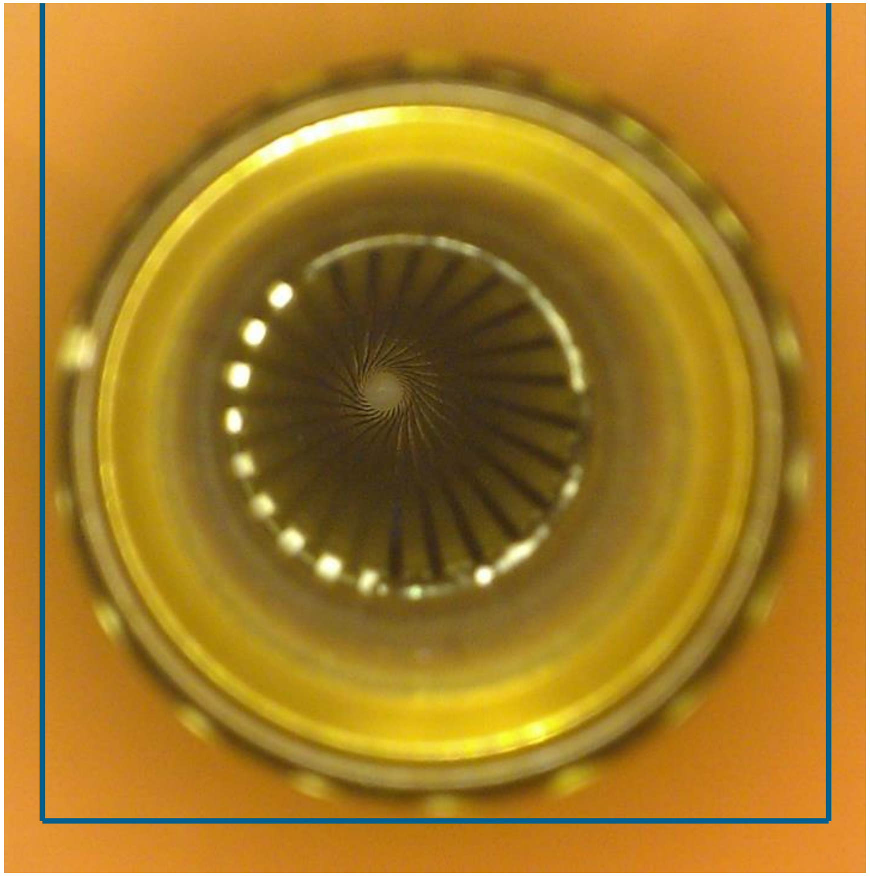
Above the Curie Temperature the ferrite temporarily looses its permeability.

If the temperature goes above the Curie temperature and the permeability decreases ➔magnet inductance is reduced ➔ reduced rise-time and magnet strength

MKI8D Removed from LHC during TS3, 2012



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.