High Luminosity LHC

Lessons learnt from LHC Operation for the Upgrade of the Injection and Beam Dumping Systems

Beam Transfer Systems
WP 14
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On behalf of WP 14 and all collaborators

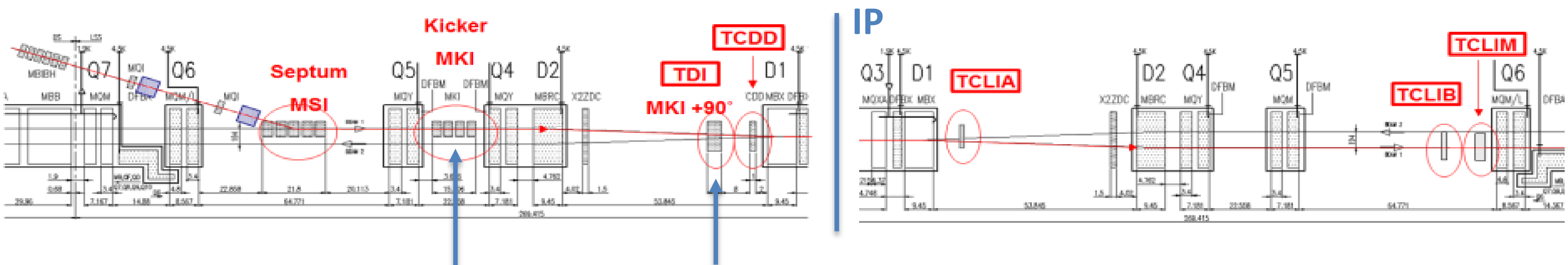
The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Lessons learnt from LHC Operation for the Upgrade of the Injection and Beam Dumping Systems

- **Work Package 14: Beam Transfer & Kickers**
- Outline
  - **Injection System**
    - Injection Protection absorber TDI
    - Injection Kicker Magnets MKI
    - Injection absorber integrated in separation dipole D1
  - **Beam Dumping System**
    - Generators of the extraction kickers MKD
    - Absorbers for protection in case of asynchronous dumps (TCDS, TCDQ)

Part I: Limitations during LHC operation related to the Injection System

- Injection absorber TDI, 2 stages:
  - Coming Christmas Shutdown: Replacement with consolidated spare TDI
  - In Long Shutdown 2 (2019 – 2020): Replacement with NEW design TDI Segmented (TDIS)
- Injection kicker MKI:
  - Only proto-type part of HL baseline
- WP14 also contains work on other absorbers which to date have not been limiting LHC operation

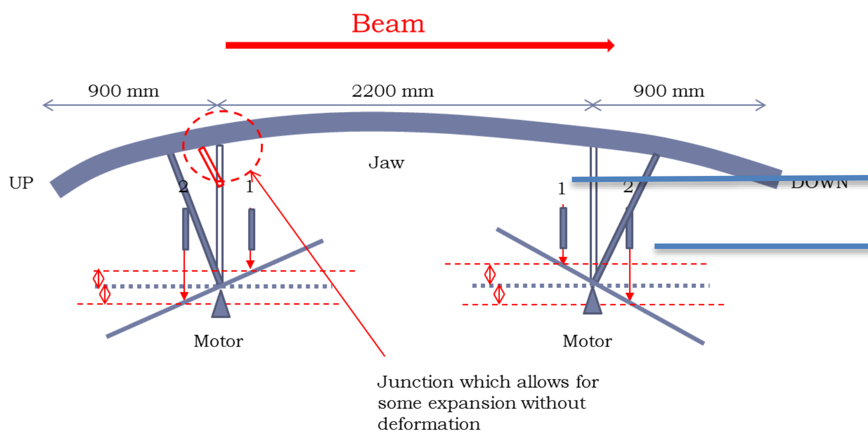


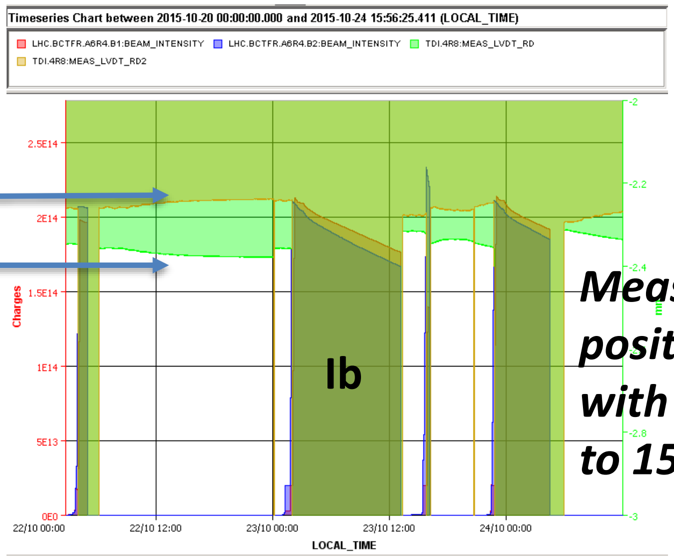
HV, ferrite based injection kicker, 4 per beam

Movable jaws at +/- 5 mm from beam
Upper and lower jaw, each 4.2 m long

Injection absorber TDI: Deformation of jaws

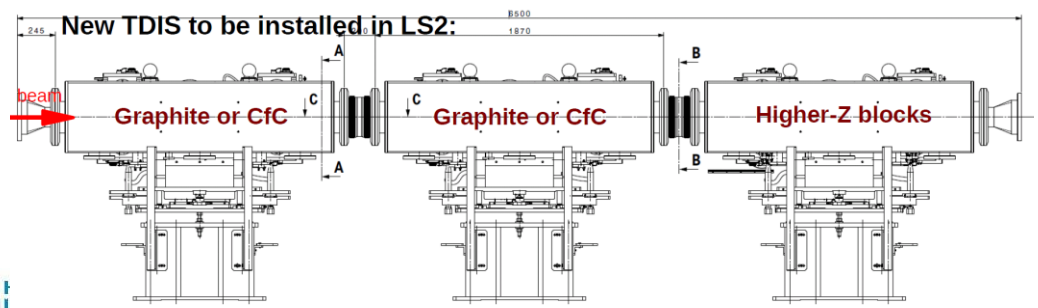
- Problems encountered during Run 1 and Run 2
  - Beam induced heating causing elastic deformation of the ***4.2 m long jaws***





Measured position drift with beam up to 150 µm

Measure: new design TDIS will consist of 3 separate jaws with an optimized impedance:

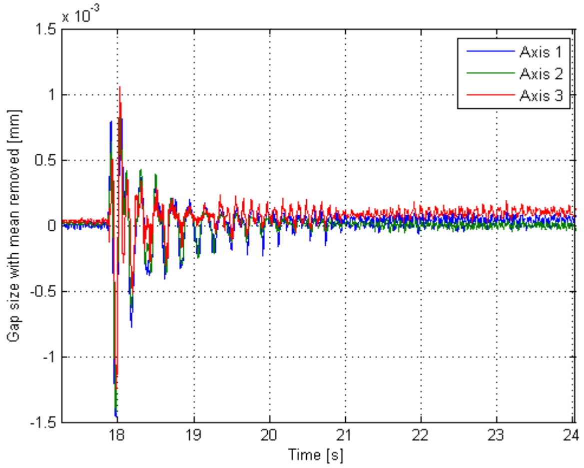


TDIS:
Active length of each jaw 1.5 m
To be installed Long Shutdown 2

Interferometry measurement of distance between jaws

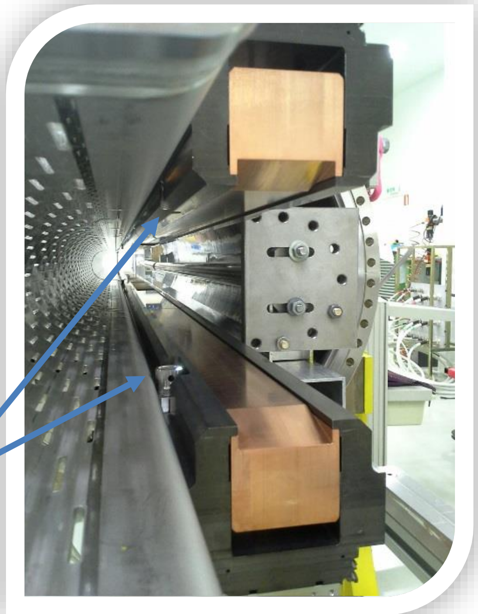
- Will be installed on replacement TDI system Christmas 2015 as test for new TDIS to be installed in LS2, to obtain operational experience
- Additional to 'standard' LVDT position measurement
- Interlocking via redundant system (based on beam dump Beam Energy Tracking System BETS)

Measured vibrations after light tank knock



Typical uncertainty	
Jaw Position	**Standard deviation [nm]**
On outer switches	37
Parking	27

Interferometer heads installed in jaw opposite retroreflectors



Absorber block material

- Spare ‘old type’ TDI absorbers were prepared for exchange during Christmas 2015 to obtain operational experience with the interferometric position measurements & copper coating to reduce the impedance
- Non-conformity of present hBN blocks, 20 % of blocks cracked during bake-out at 800 °C (previously 400 °C)
- For 2015 number of bunches per injection is limited to 50 % of nominal to keep hBN below 400 °C in case of an MKI erratic

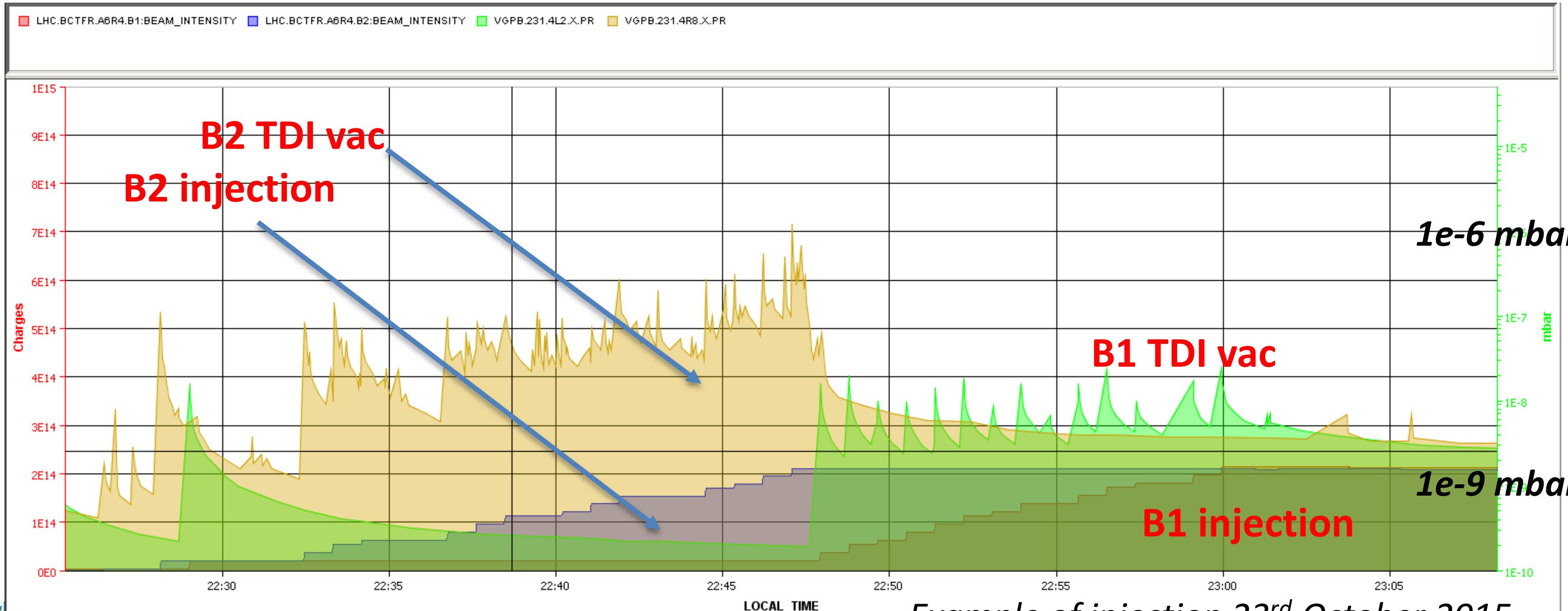
Measure:

Christmas 2015 exchange TDI will have blocks of graphite

TDIS LS2 exchange will consist of graphite (Gr4550) or CfC (carbon fiber reinforced carbon) as low Z absorber material

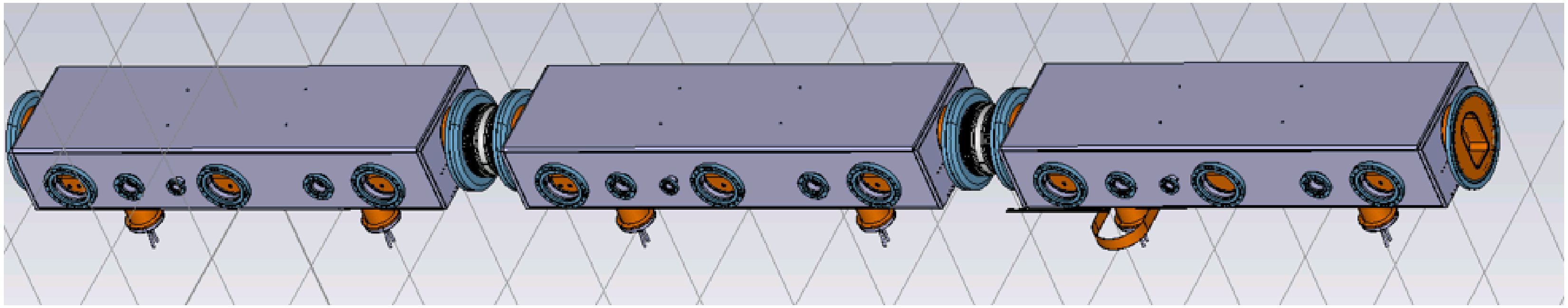
Vacuum behaviour present TDI for B2 injection

- Problems during Run 2, limit during scrubbing 25 ns
  - Vacuum behaviour of the TDI in point 8 due to non-conformity
    - Measured increased beam impedance TDI B2 rel. TDI B1. Contribution to total tune shift 40 % and 15 % respectively
  - Exact source unknown: inspection 2016 after replacement



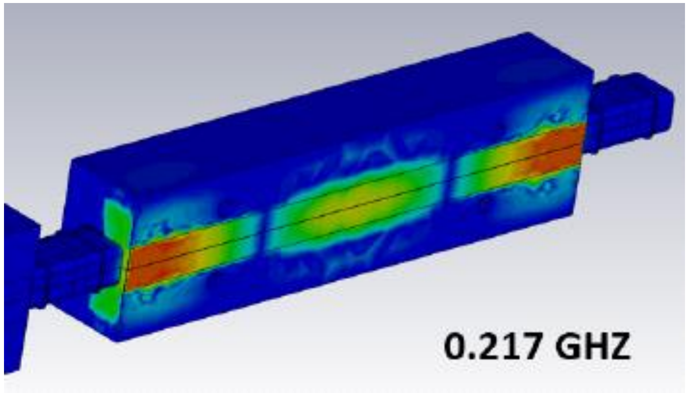
Example of injection 23rd October 2015

New Segmented TDIS design for Long Shutdown 2

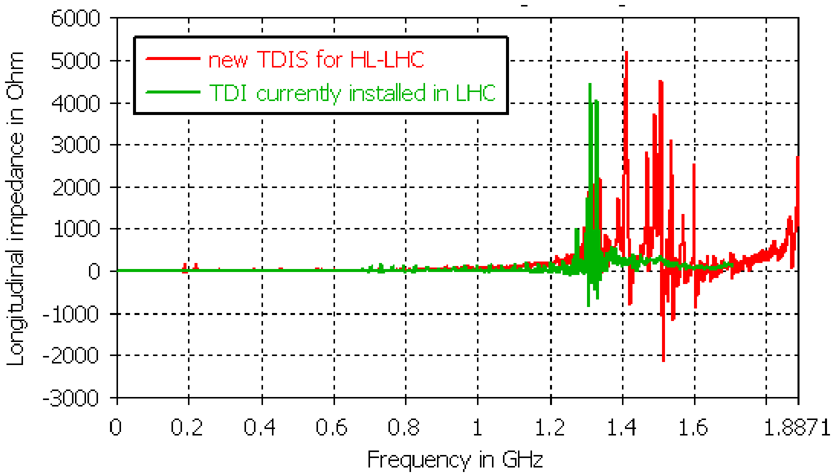


- Optimisation of impedances, presently ongoing
  - Of each absorber block through coating
  - Geometry within each tank
  - Transition between the tanks

See talk N. Biancacci parallel session Wed AM

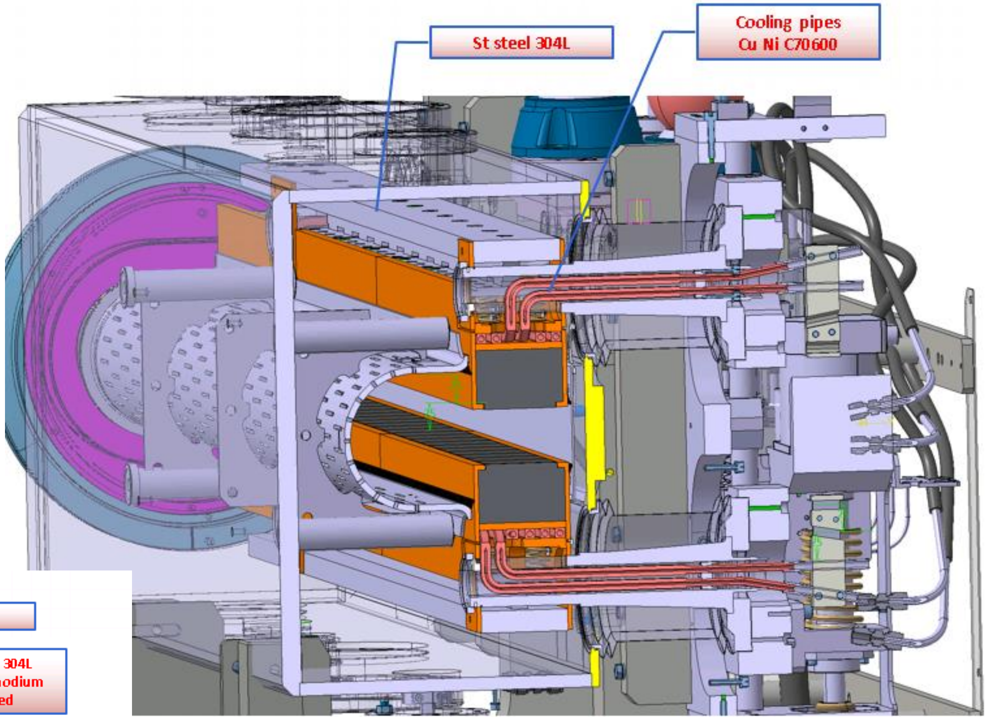


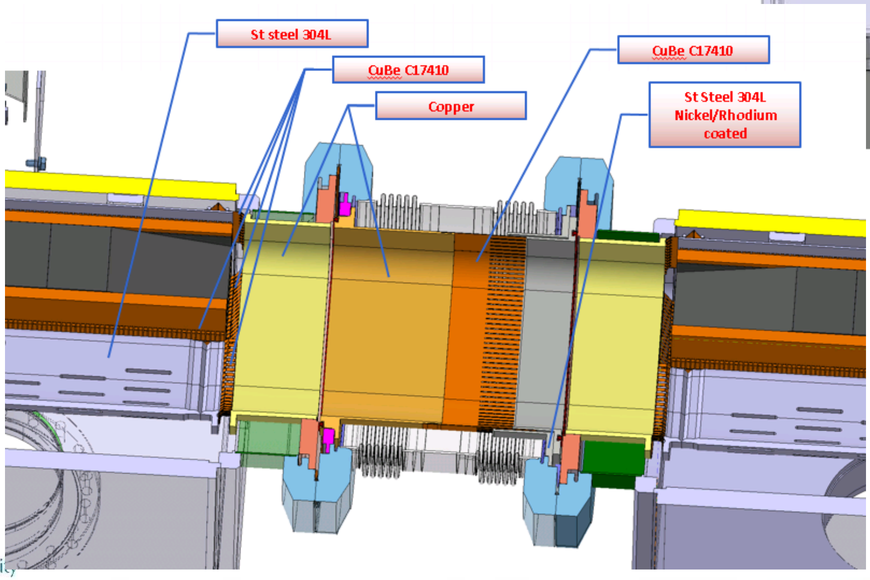
Example of impedance calculations (real part, longitudinal)



New Segmented TDIS design for Long Shutdown 2

The new jaw is completely interchangeable between the different tanks.
The jaws are 'efficiently' water cooled.
Detailed material studies to make sure that the complete system withstands the beam impact



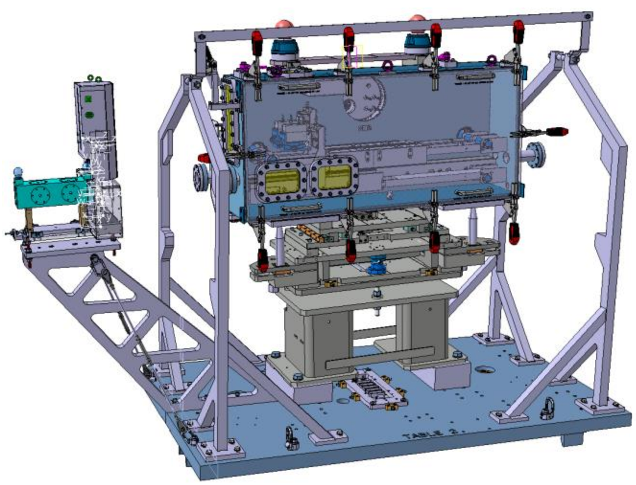


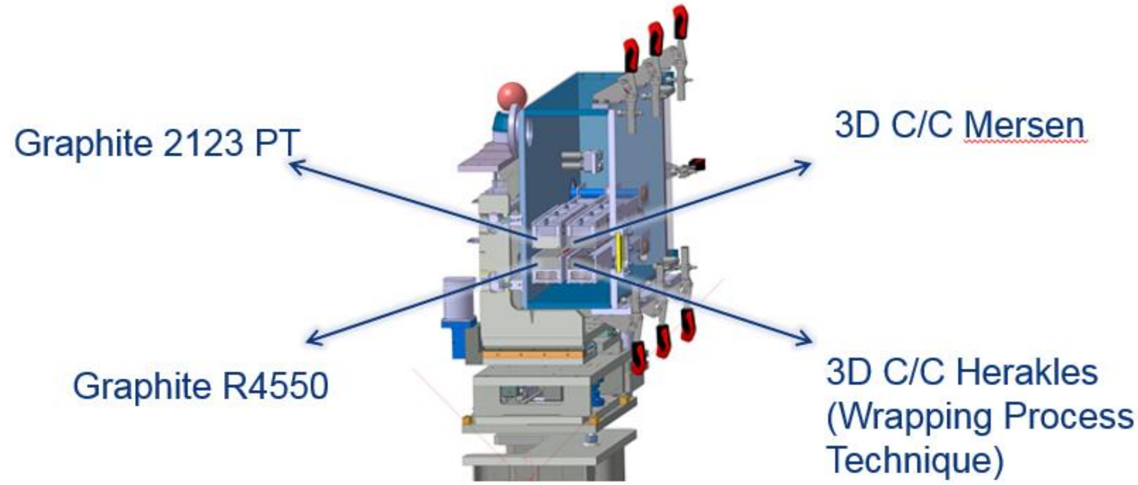
Interconnects between tanks

Test of new absorber materials with beam: HRMT-28

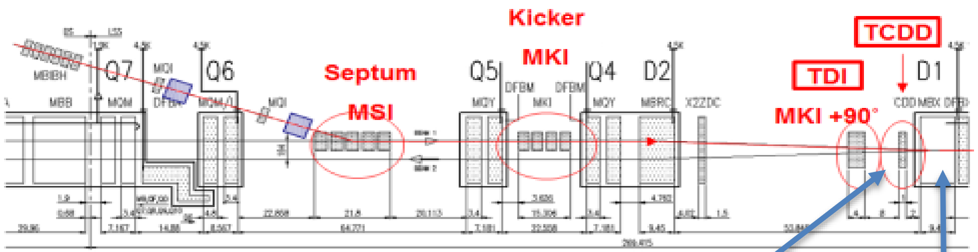
- SPS beam test facility, test scheduled for April 2016
- Jointly planned by LIU and HL-LHC WP14
- The goal is to probe the robustness of different grades of Graphite and 3D C/C from different producers
- Aims to reproduce the worst impact scenarios = **small impact beam parameters**
- The test will influence the **absorber material selection** for the new TL collimators (TCDIL) and HL-LHC injection absorbers (TDIS)
  - *Will also confirm if it will be possible to safely inject 288 BCMS bunches in one injection*

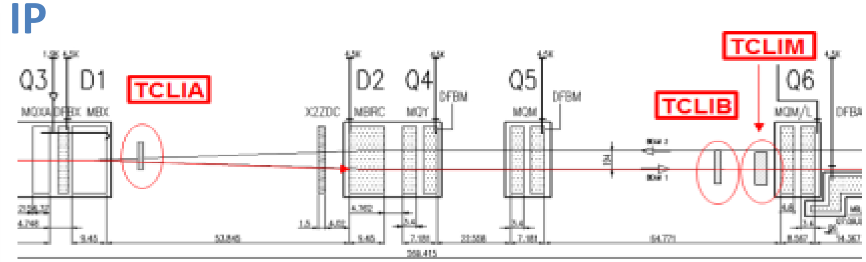
See talk F-X Nuiry parallel session Wed PM





Absorber in D1 instead of TCDD aperture change (Also foreseen for Long Shutdown 2)

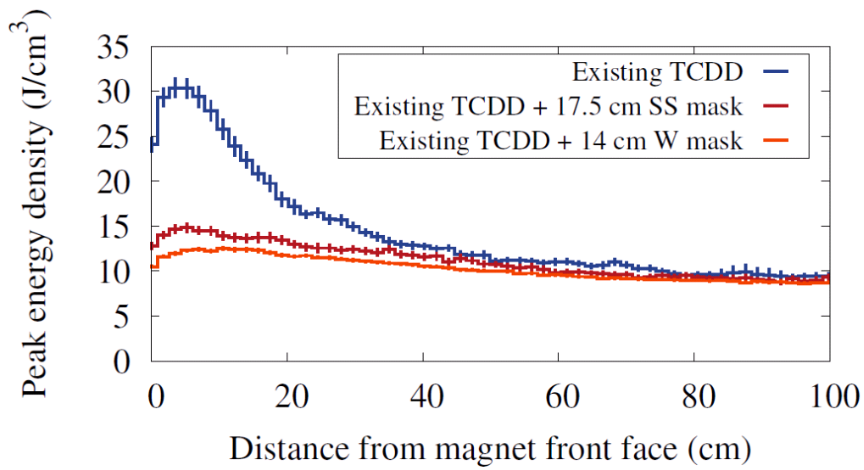


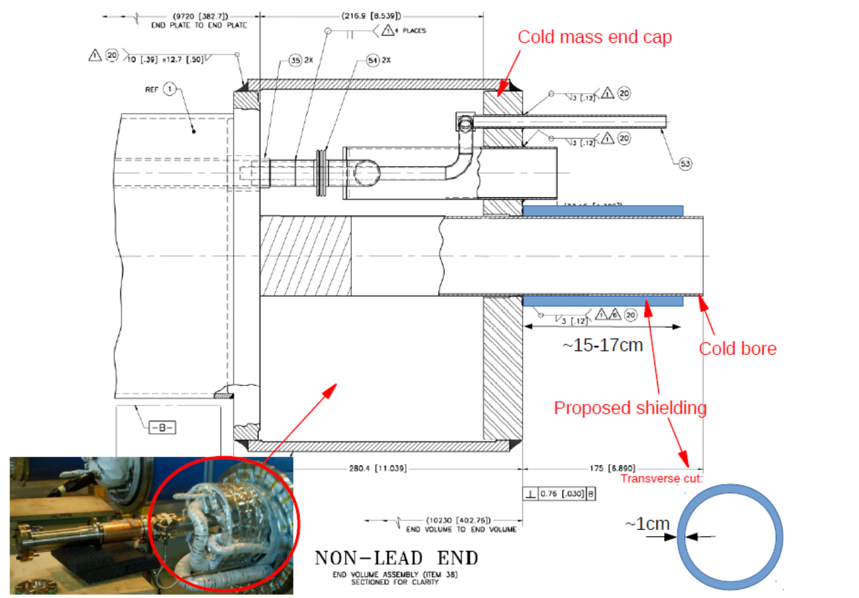


See talk V. Raginel on D1 damage limit, parallel session Wed PM

Mask to absorb the showers from the TDI(S),
TCDD aperture cannot be further reduced to increase efficiency

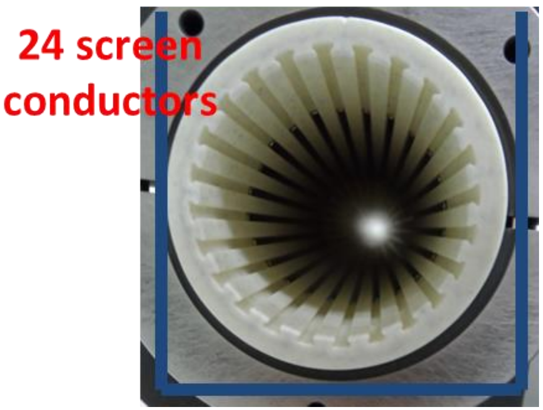
D1 sc separation dipole, most critical element to protect



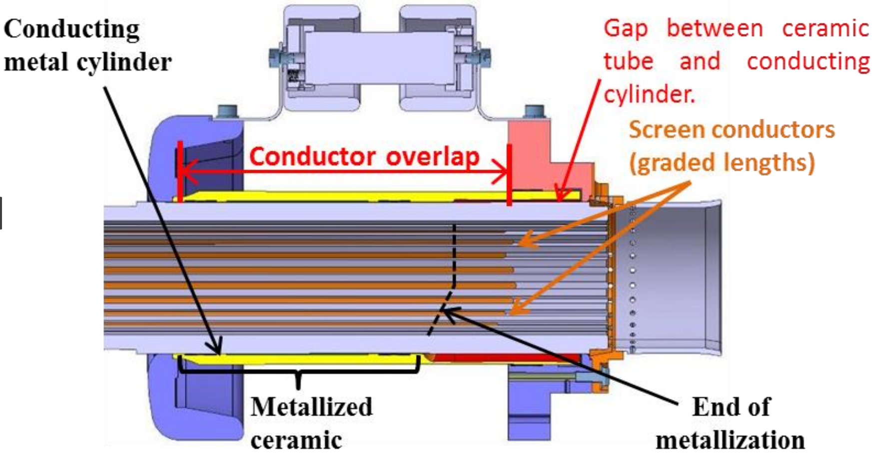


High Luminosity LHC

Injection kicker MKI: beam induced heating

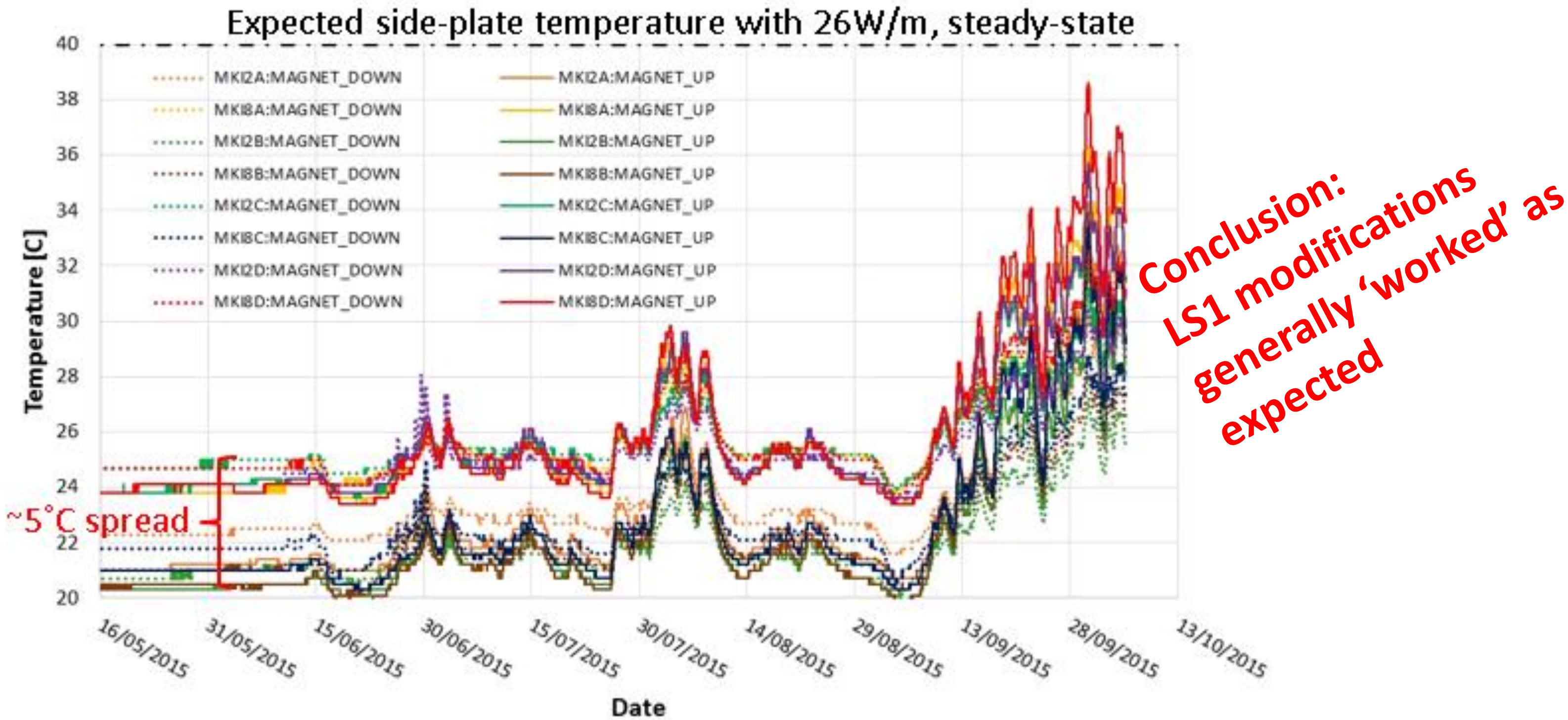


- LHC Run 1: heating on one non-conforming kicker limited Run1 performance (+1-2h turnaround, on a few occasions)
  - Ferrites reaching Curie temperature of 120 °C due to beam induced heating
  - Kicker MKI8D, with twisted beam screen and 161 W/m with Run1 beam
- Long Shutdown 1:
  - Increase number of screen conductors from 15 to 24
  - Change of geometry at capacitively coupled end of the ceramic chamber to reduce electric field



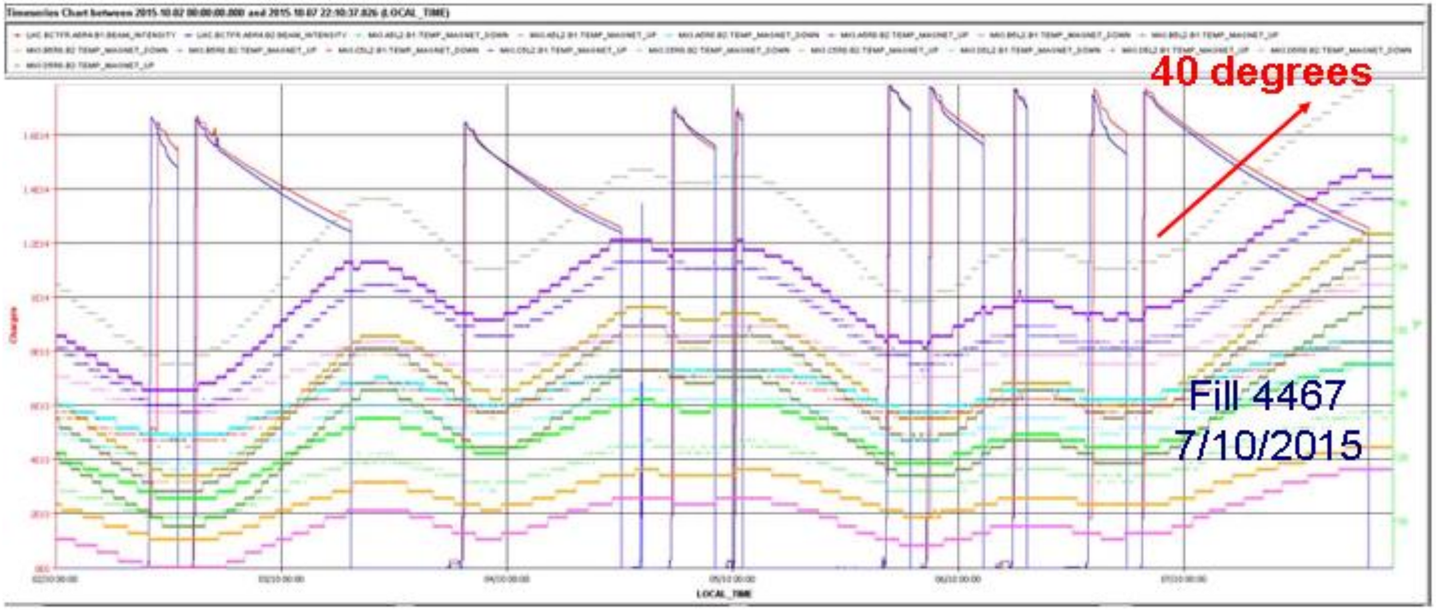
Injection kicker MKI: beam induced heating

- 2015 (post LS1):
  - Highest temperature measured 40 °C, corresponds to 56 °C at the ferrite and 26 W/m Power deposition (1033 bunches, 17/9/2015)

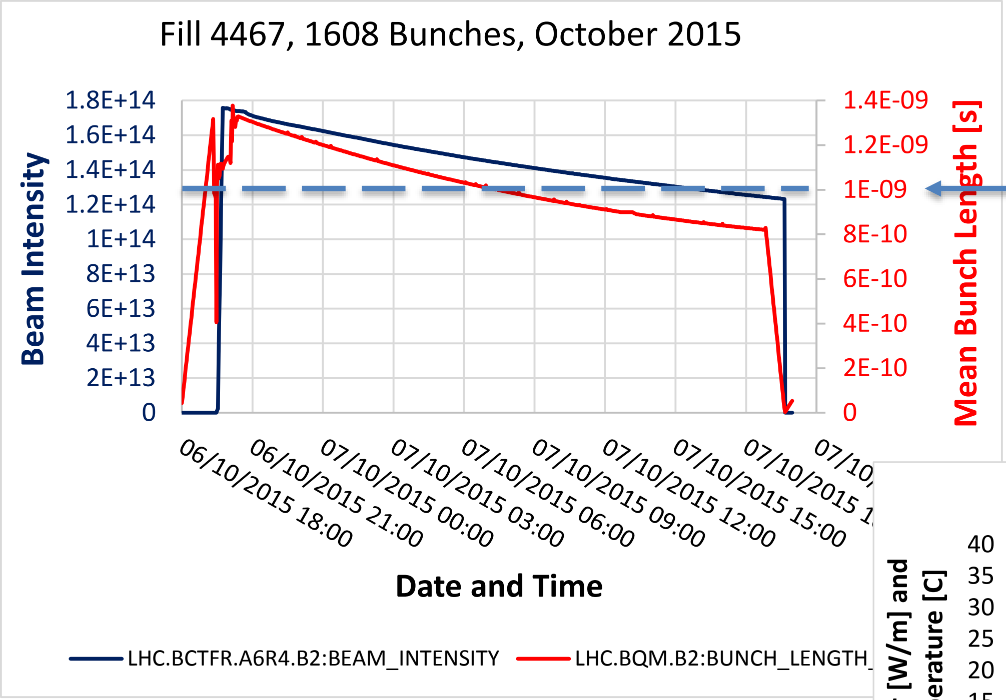


Injection kicker MKI: beam induced heating

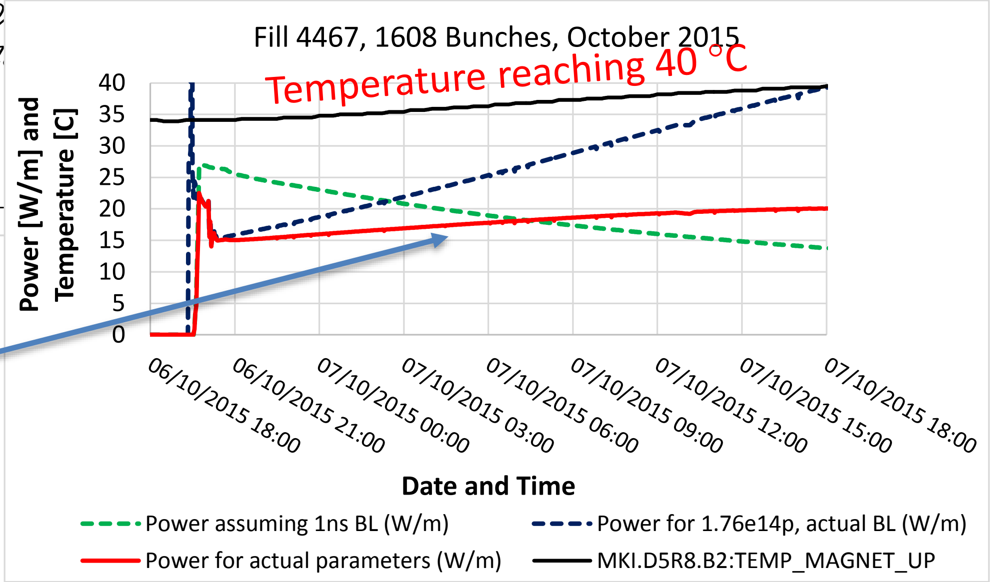
- For Run 2 expect ***average*** power deposition of 42 W/m (worst 52 W/m)
  - Ferrite temperature 74 °C: OK
- For HL-LHC expect ***average*** power deposition of 155 W/m (peak 191 W/m)
  - Close to 161 W/m during run 1; reaching Curie temperature
  - Strong dependence on bunch length
    - **Assumed 1.0 ns but see what can happen with 0.85 ns bunch length**



MKI Temperature: Zoom on fill 7 October 2015

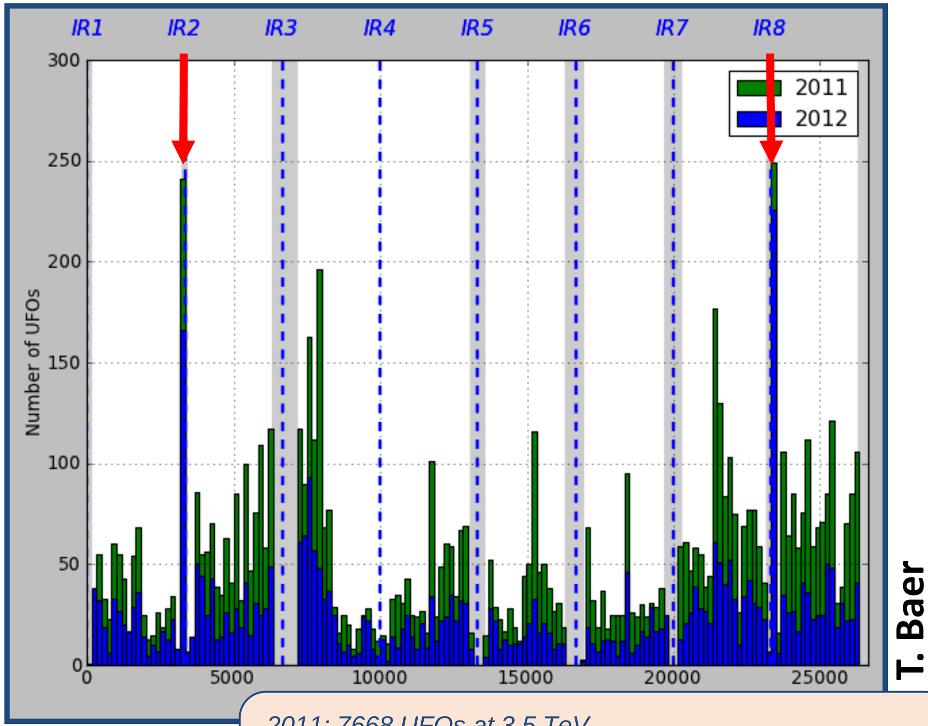


Bunch length assumed for MKI power deposition calculations

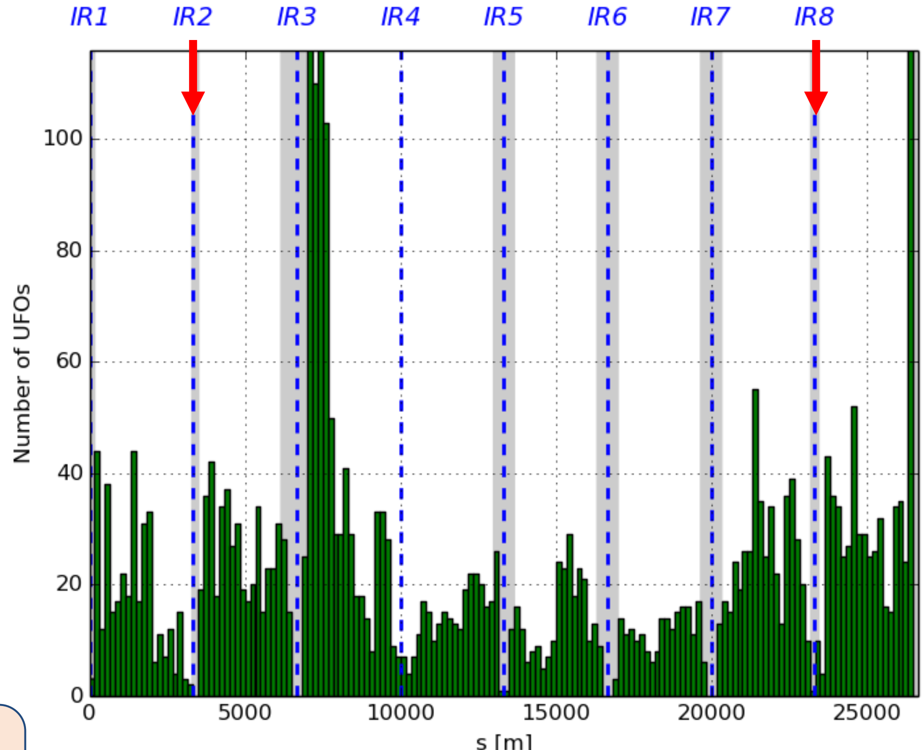


Power deposition for decreasing bunch length and intensity

Injection kicker MKI: UFOs



2011: 7668 UFOs at 3.5 TeV.
2012: 3719 UFOs at 4 TeV.
Signal RS04 > $2 \cdot 10^{-4}$ Gy/s.
Grey areas around IRs are excluded from the analysis.



2015: 3621 UFOs at 6.5 TeV.
Signal RS04 > $2 \cdot 10^{-4}$ Gy/s.

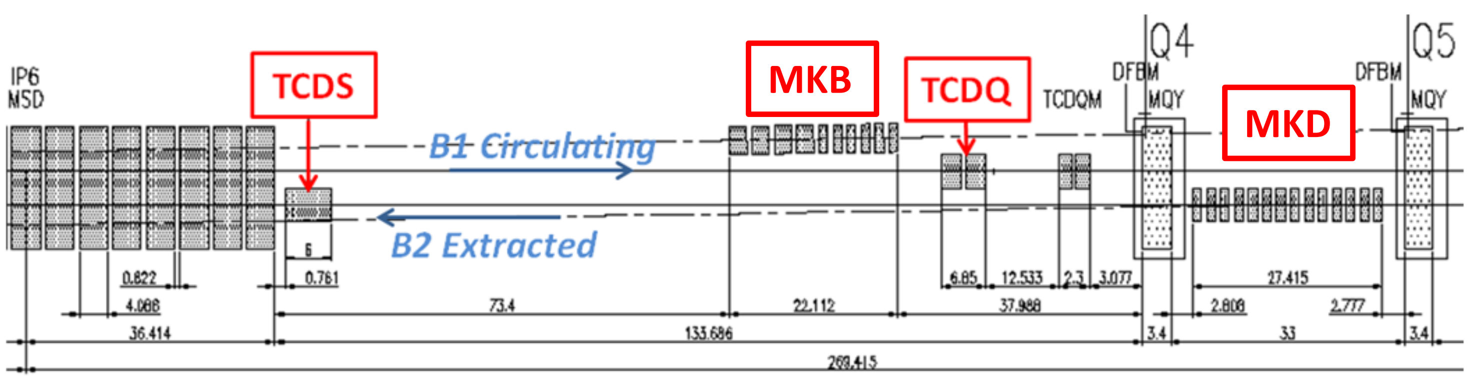
Improved cleaning procedure for ceramic tubes implemented during LS1: MKIs have now virtually vanished from the UFO statistics at 6.5 TeV.

MKI Conclusions and additional info

- Beam induced heating of the ferrites significantly improved after LS1 modifications and is in line with expectations
  - Little margin left for HL-LHC parameters, *strong dependence on bunch length*. Needs further operational experience Run 2 and studies to determine ***if series modification is required***
    - ***Series presently not part of HL baseline***
  - Proto-type with further measures to be installed before LS2
    - Further impedance reduction by reducing overlap at capacitively coupled end of ceramic tube
    - Improved cooling of the ferrites, e.g. Laser Engineered Surface Structures (LESS) of MKI stainless steel vacuum tank
    - Ferrites with higher Curie temperature
- Reduction of SEY of ceramic tube under study to reduce ecloud effect, also using LESS on tube. If possible to be tested with proto-type
- UFO under control with improved cleaning procedures
- No electrical breakdown during injection, four electrical breakdowns during automatic conditioning (Soft Starts)

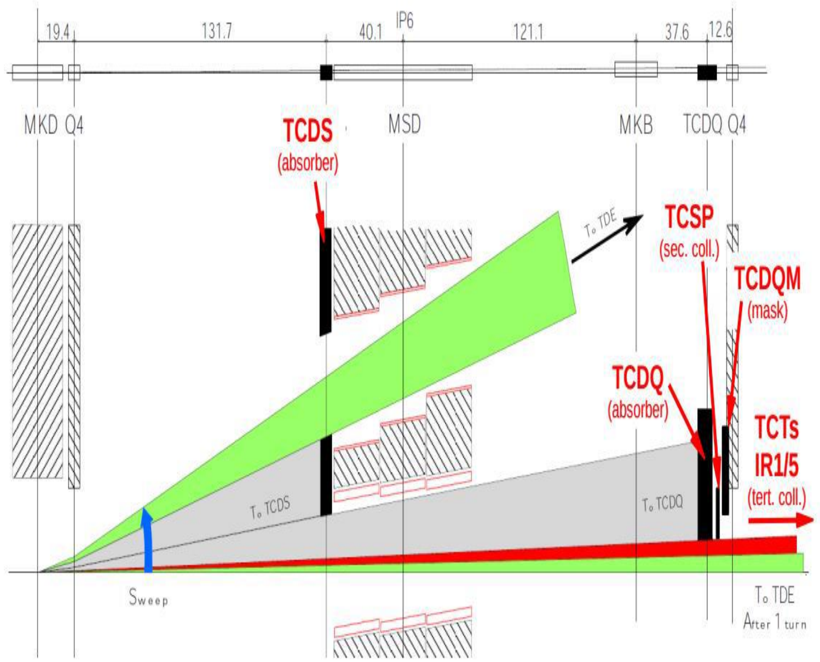
Part II: Limitations during LHC operation related to the LHC Beam Dumping System

- During Run 1 and Run 2 the LBDS has not been a direct operational limit of the LHC. However, from the reliability run at the end of LS1 we know we have little ‘HV margin’ on the extraction kickers MKD generators
- Keeping in mind that we presently run at 6.5 TeV instead of 7.0 TeV



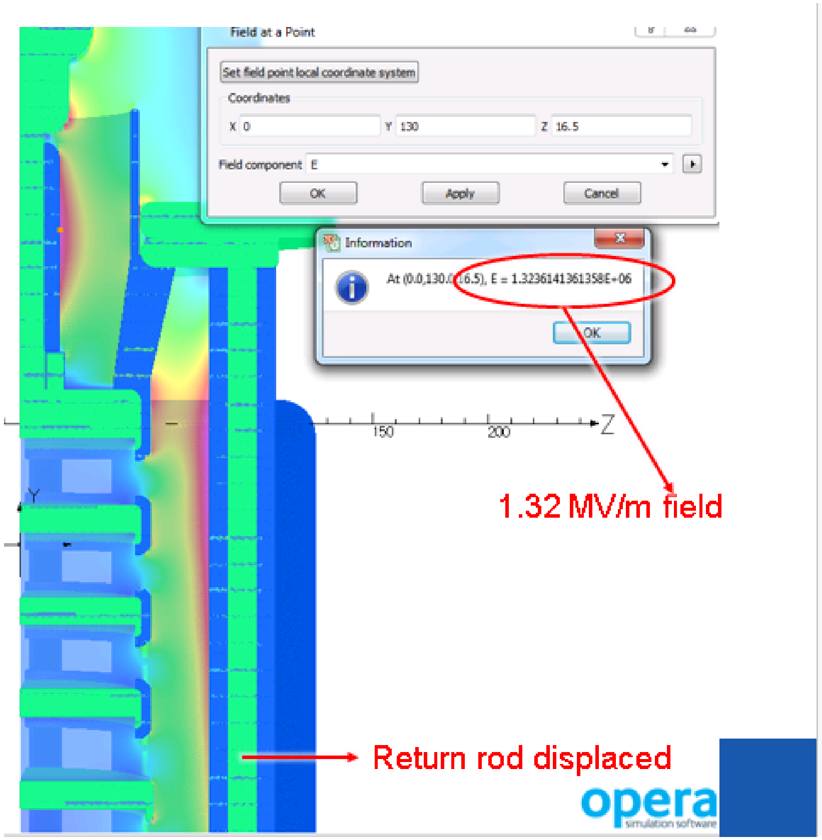
Extraction kicker MKD erratic switch

- HV break-down in an MKD generator leads to a so-called ‘asynchronous beam dump’
- During LS1 **reliability running there were too many HV break-downs**, mitigated by some insulator replacement and generator exchanges
  - Final statistics would still give 3 asynchronous beam dumps per beam, at 6.5 TeV
  - Luckily, so far only one occurred for both beams during operation with beam



Modification foreseen in LS2 to further reduce erratic switching

- Modify GTO stack and supports to reduce max E-field inside generator to **1.5 MV/m** (50% of dielectric strength of air), to avoid air ionisation, charging and surface breakdown. Before fields were as high as 8.0 MV/m, design weakness



Other MKD generator modifications

- Modify support for main capacitors
- Upgrade trigger transformer
  - Higher triggering current and commutation speed, to reduce coupling between GTOs and reduce stray inductance
- Add current transformer into GTO snubber circuit to survey sparking activity within stack
- Install non-perforated side panels on the top part of generator (main capacitor compartment) to reduce dust ingress
- Add damping ferrite on top of GTO stack to damp resonant ringing between parallel GTO stacks and reduce rise time

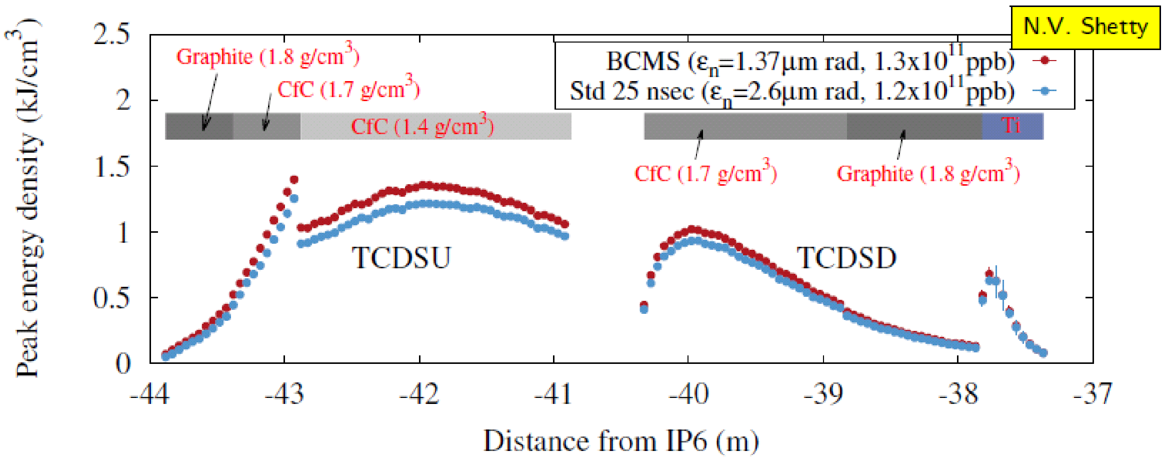
MKD controls modification objectives

- Implement real time monitoring in order to generate a synchrounous dump request in case of sparking activity increase
- Reduce re-trigger delay between detection of one generator going into conduction to the re-triggering of the 14 remaining generators. (Actual delay is in the range of ~900ns) → **reduce load on TCT collimators**
- Increase power trigger output current and dI/dt for better triggering performance (new transformer). Remove monitoring weak point in power triggering chain (possible loss of shielding efficiency). Increase internal diagnostic (monitoring of full output current… principal + compensation)
- Upgrade slow control for implementation of additional diagnostic functionalities (fast low level IPOC) and improve performance (feedback system for power supplies stability improvement…)

LHC Beam Dumping System Absorbers

- Energy deposition calculations (FLUKA) and material studies (ANSYS) for the LHC beam dumping system elements are ongoing for the HL-LHC parameters
- Presently it is assumed that the TCDS absorber will need a similar upgrade as which took place for the TCDQ in LS1
- Verification of all elements to be finished in 6 months

These results for LHC Run 2 parameters !!



Summary

See also parallel session on (WP2) – WP5 – WP7 – WP8 – WP14 on Wednesday PM Rooms 30-7-10 and 30-7-18

- Injection absorber TDI
  - 2015 – 2016: Replacement of absorber and added interferometry
  - 2019 - 2020 (LS2): TDIS, ready for HL-LHC
- D1 absorber instead of TCDD modifications
- Injection kicker MKI
  - 2017 – 2018: Proto-type to be installed
  - Series not part of baseline, strong dependence on bunch length !
- Beam Dumping System
  - 2019 – 2020 (LS2): Extraction kicker generators switch replacement to improve voltage holding
  - LS2: Control system upgrade MKD generators
  - LS3: Absorbers TCDS, tbc