LBDS and Injection System

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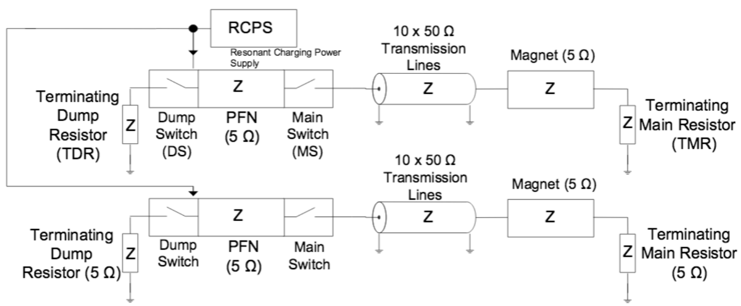
Acronyms

LBDS: LHC Beam Dump System
MSI: injection septum
MKI: injection kicker
TCDI, TDI, TCDD, TCLIM, TCLIA and TCLIB: injection protection (dumps, collimators and masks)
BTV, BPMX: diagnostics (screens and pickups)
RCPS: diagnostics on Resonant Power Supply for MKIs
TDR: Terminating Dump Resistor for MKI
SIS: software interlock
SS: Soft start (form MKI, also called MKISS)
AGK: Abort Gap Keeper
MKD: extraction kickers
MSD: extraction septa
MKB: dilution kickers
TCDQ and TCDS: dump protection
TDE: dump block
GTO/IGBT: MKD/MKB switches (IGBT for triggering and re-triggering system).
IQC: injection quality check (diagnostics)
XPOC/IPOC: external and internal diagnostics for LBDS
R2E: Radiation to Electronics
BETS: Beam Energy Tracking System
SEB: Single Event Burnout
HEH: High Energy Hadrons
PLC: Programmable Logic Control
BCMS: high brightness beams



Outline

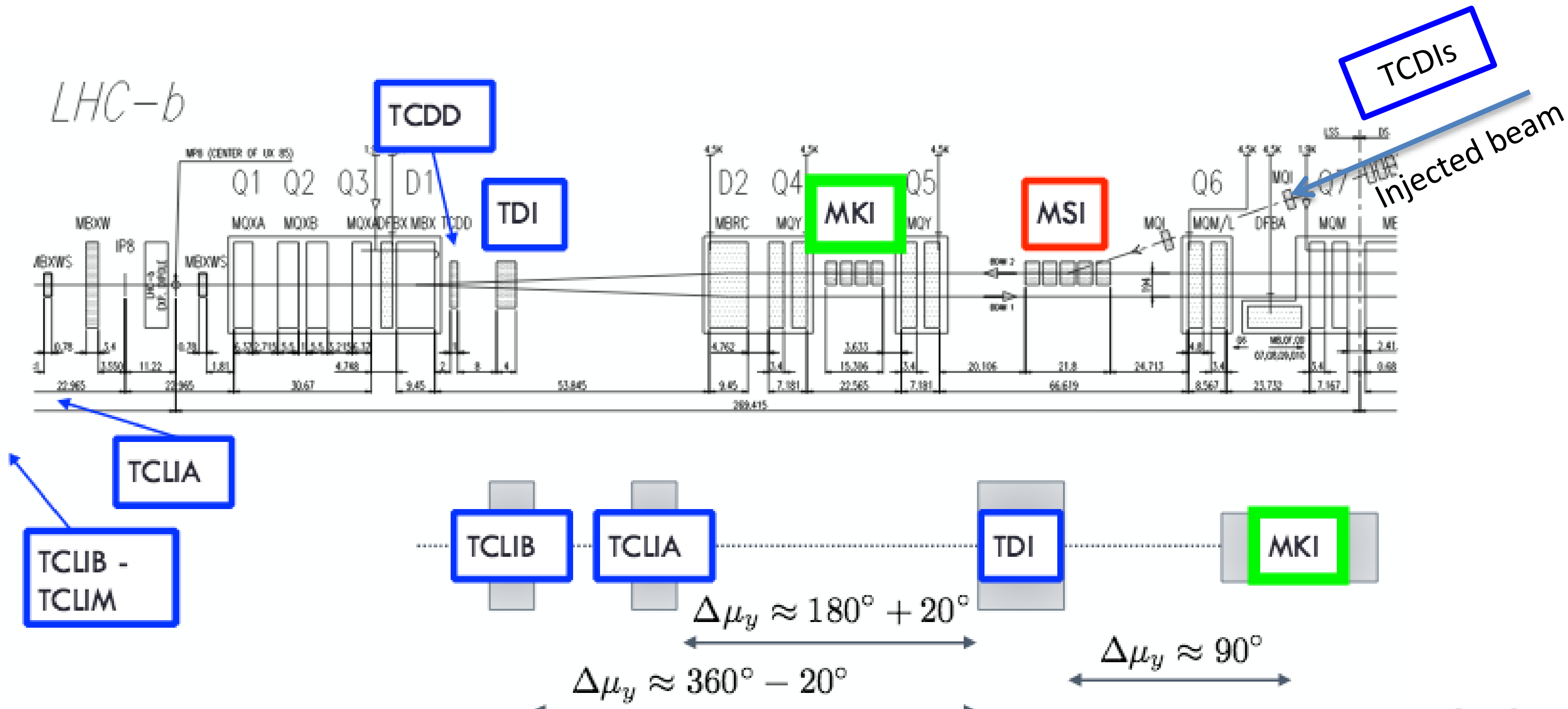
For LHC injection system and LDBS:

- General description
- LS1consolidation works
- LBDS reliability runs
- 2015 performance - comparison with Run1
- Forecasts for Run2 ➔ Run3 ➔ HL-LHC (operation at 7TeV)
- Conclusions

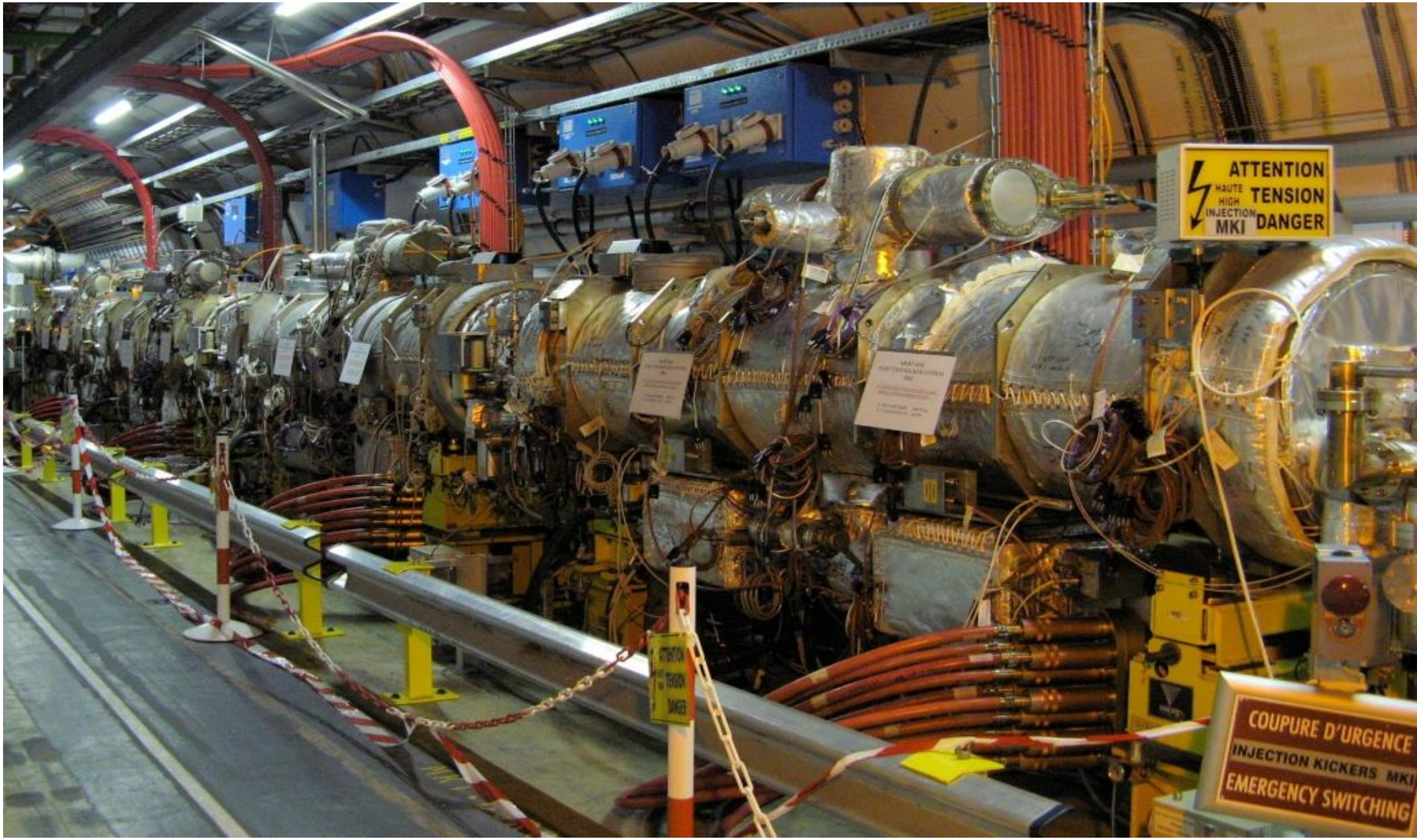
Injection System

The LHC injection system is composed by:

- Horizontal septum – MSI (5)
- Quadrupole - Q5
- Vertical kicker – MKI (4)
- Protection devices (TDI, TCDD, TCLIA and TCLIB)



MKI


ATTENTION
HAUTE TENSION
HIGH
INJECTION
MKI DANGER
COUPURE D'URGENCE
INJECTION KICKERS MKI
EMERGENCY SWITCHING

MKI – LS1 Activities

Main goals:

- Improve high voltage performance (reduce flashovers of screen conductors)
- Reduce: ferrite MKI yoke heating, pressure rise and e-cloud, number of UFOs at MKI

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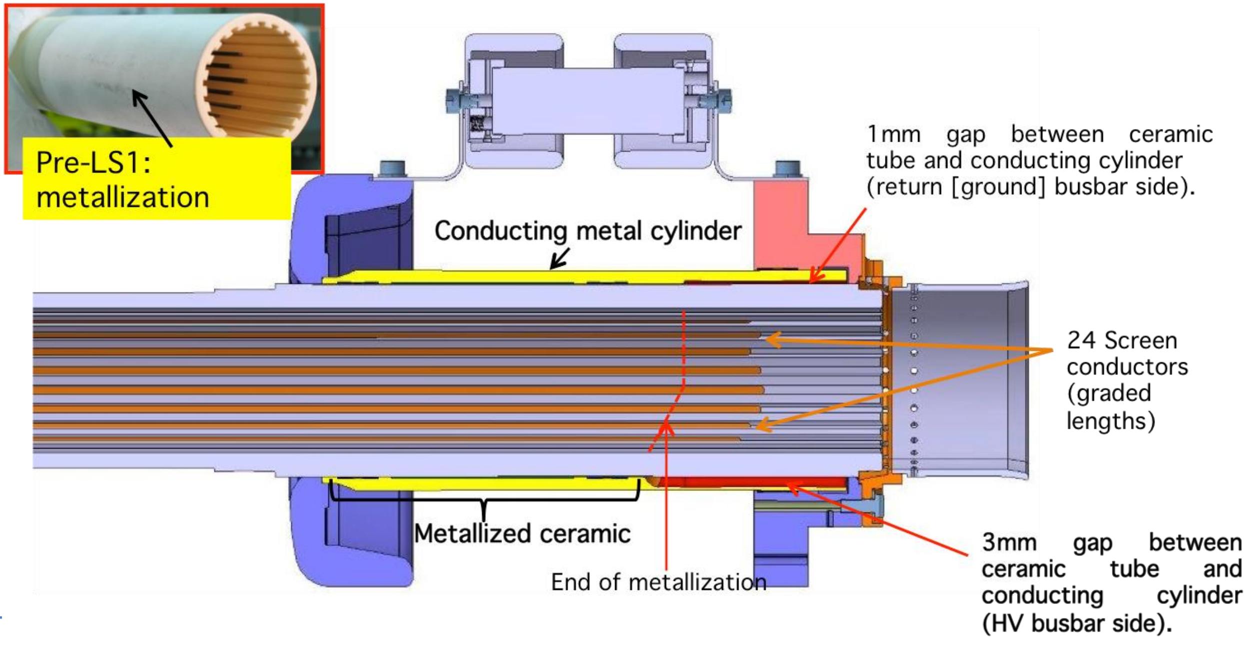

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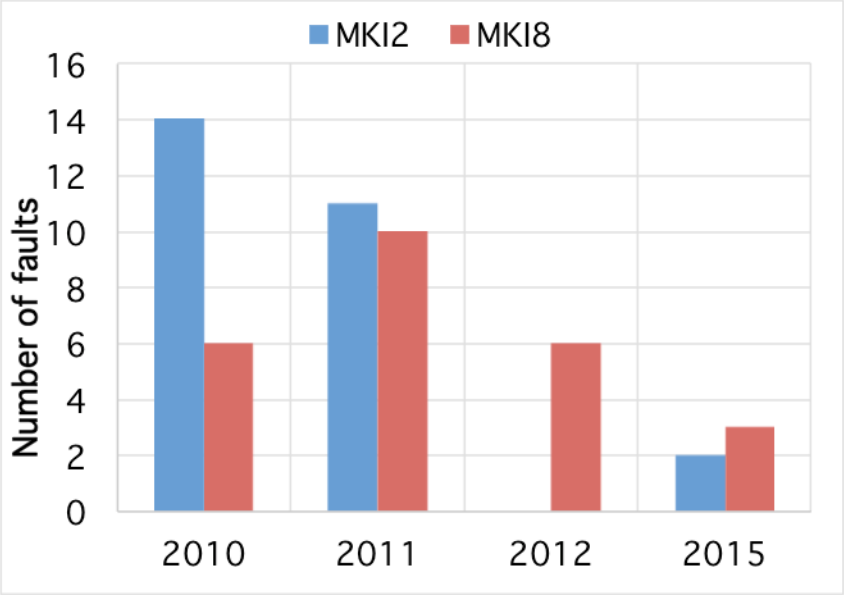
- Improved cleaning procedure for ceramic tubes => reduce UFOs
- NEG coating and cartridges (cold-warm transitions, bellows close to MKIs, MKI interconnects, bypass tubes, BTVs and BPTX).

MKI Performance 2015 vs Run 1

High Voltage MKI performance (erratics and sparks)



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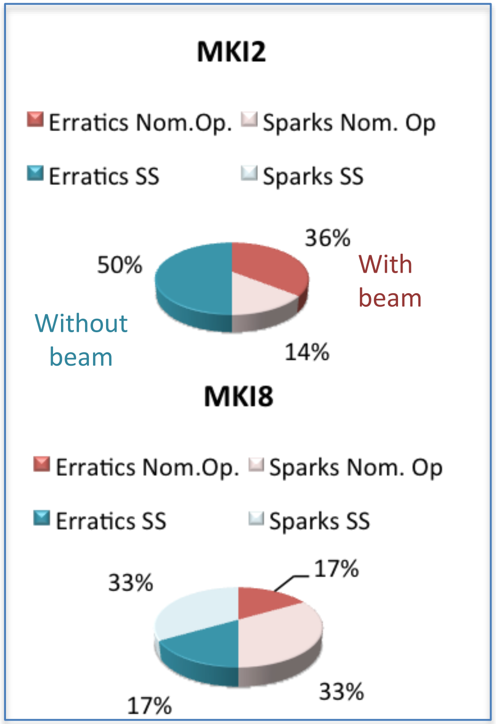

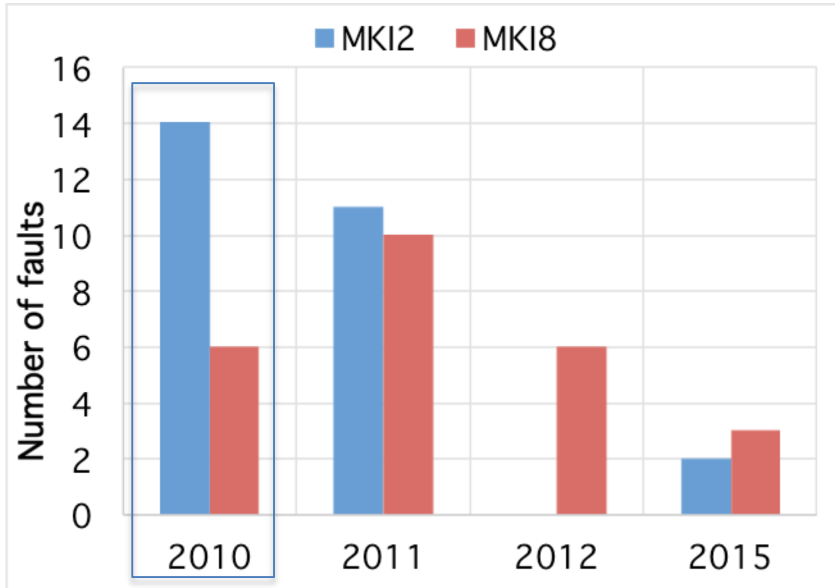

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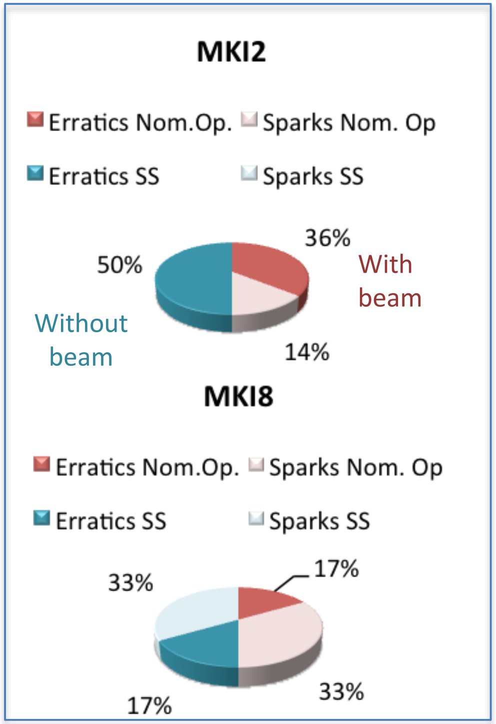

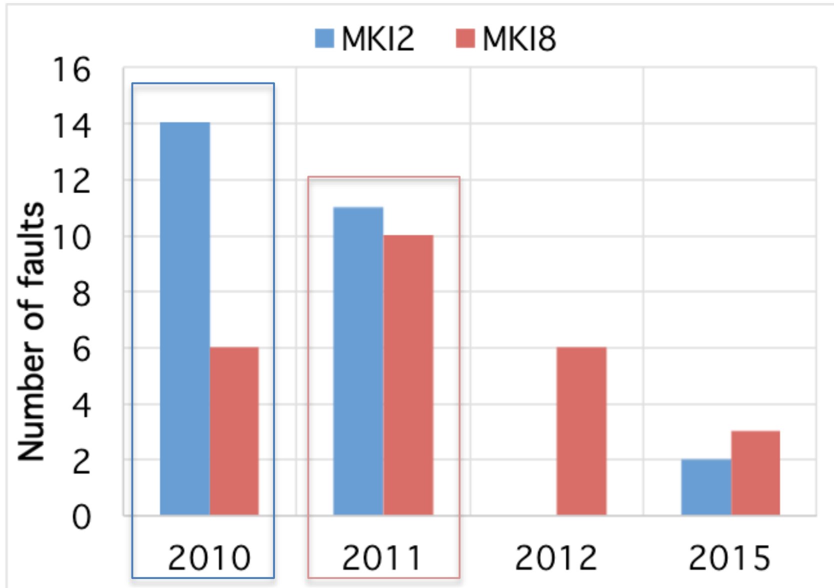

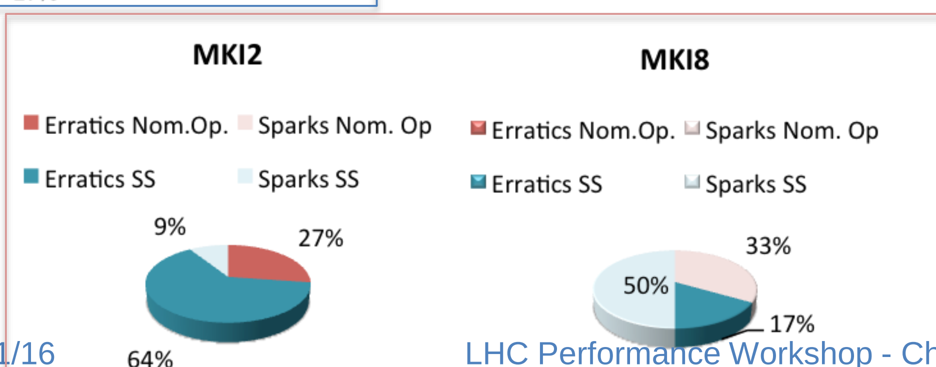

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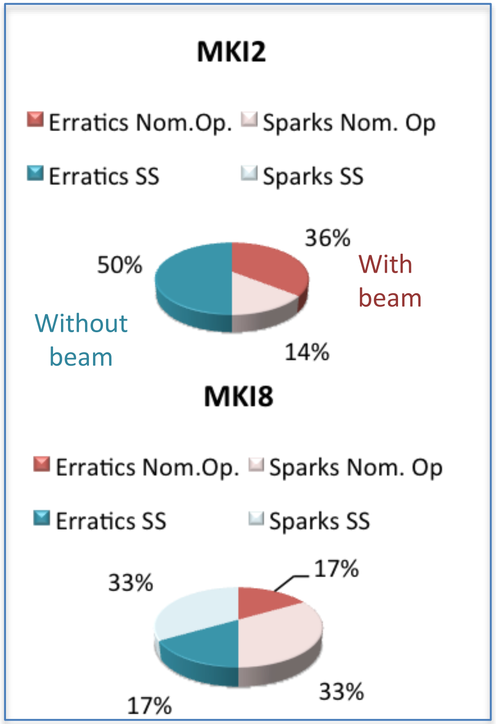

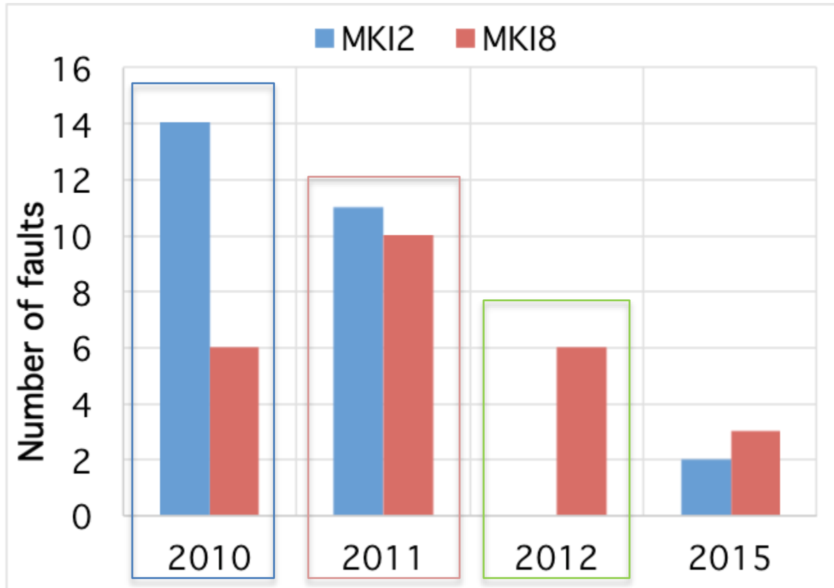

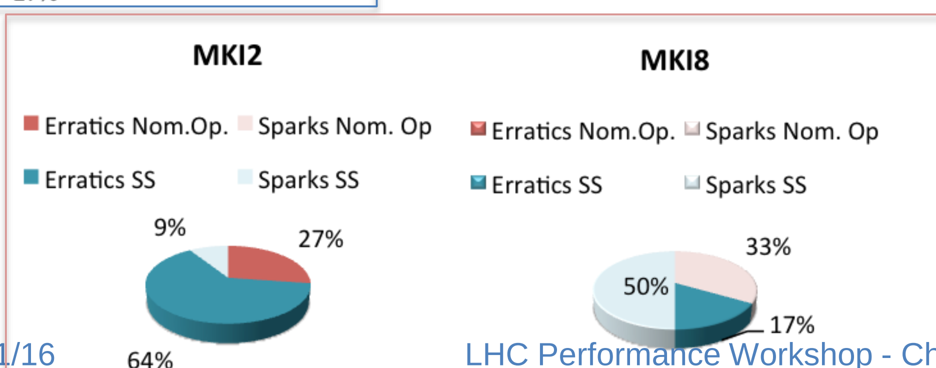

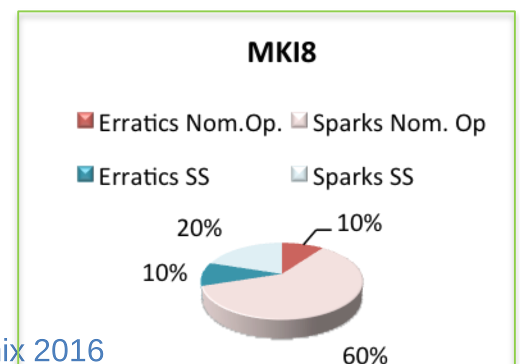

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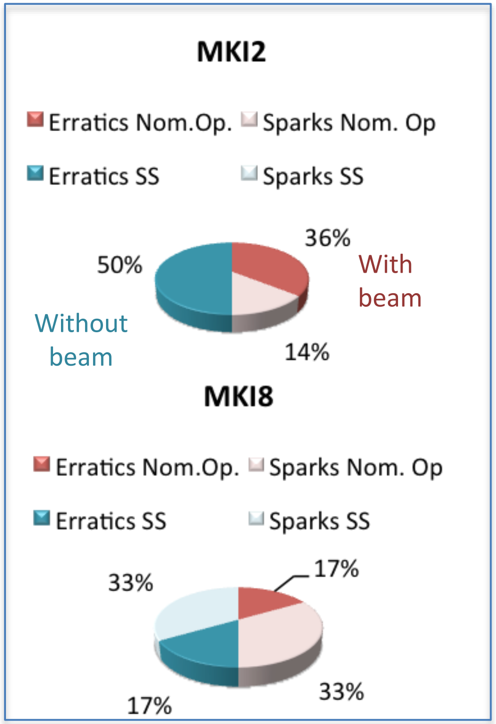
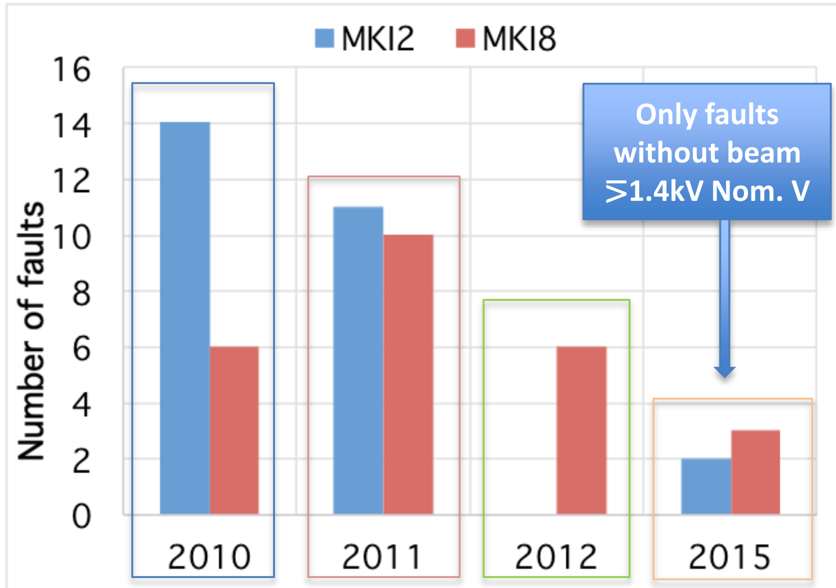
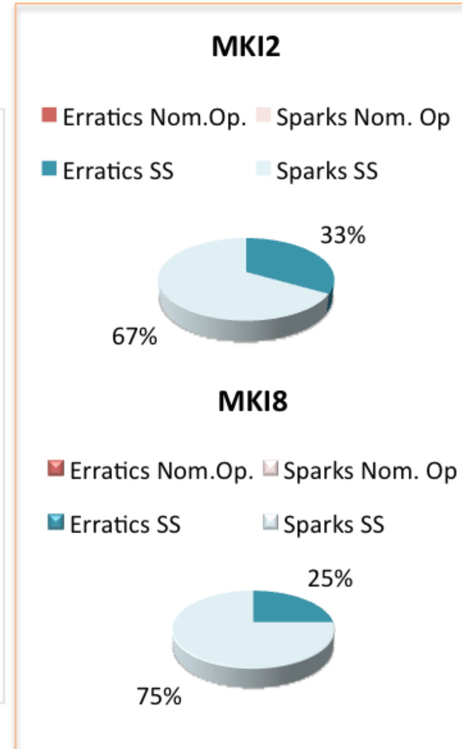
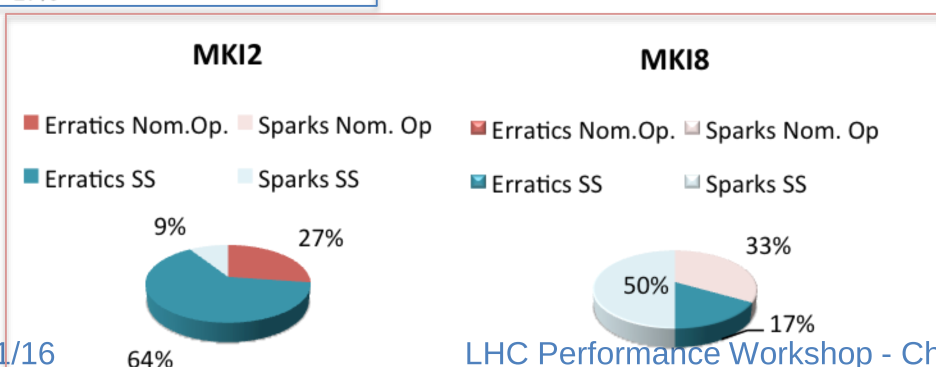
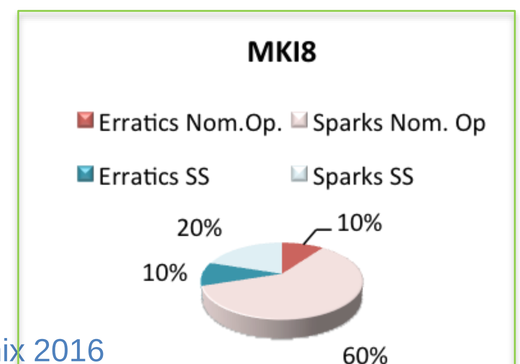




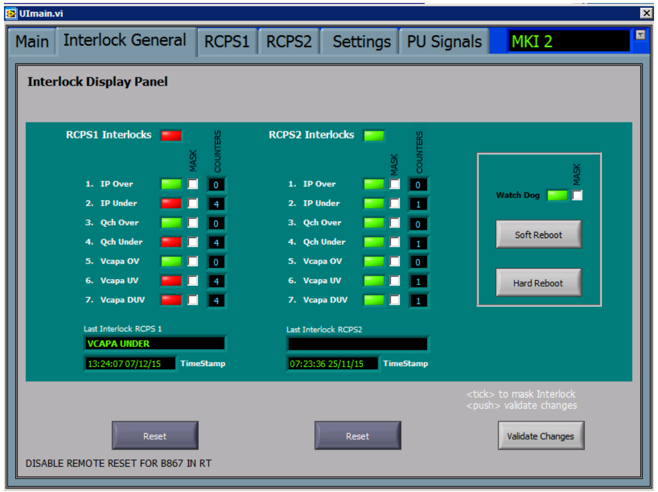




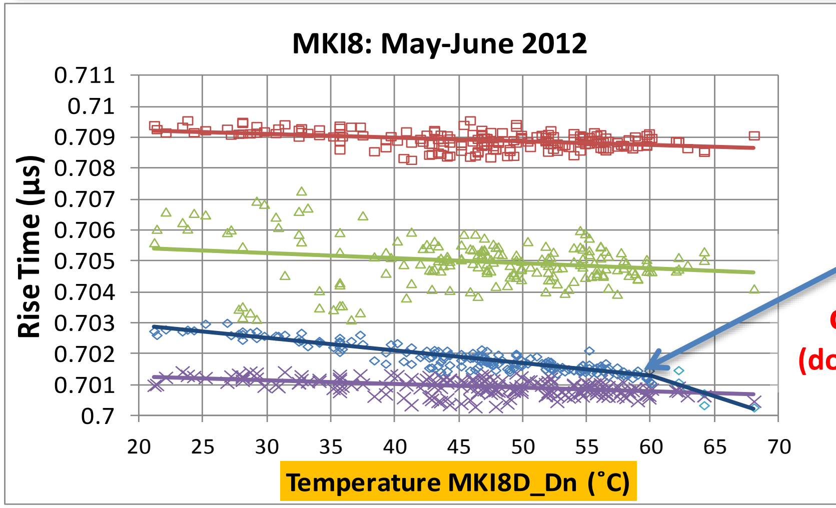


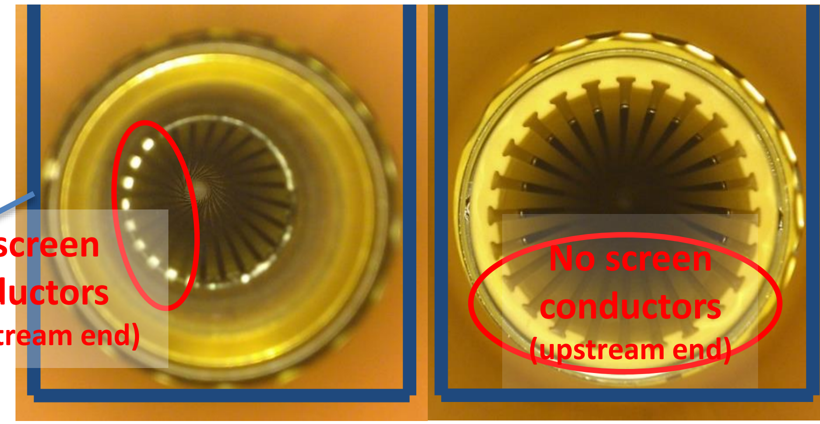
MKI 2015 Faults

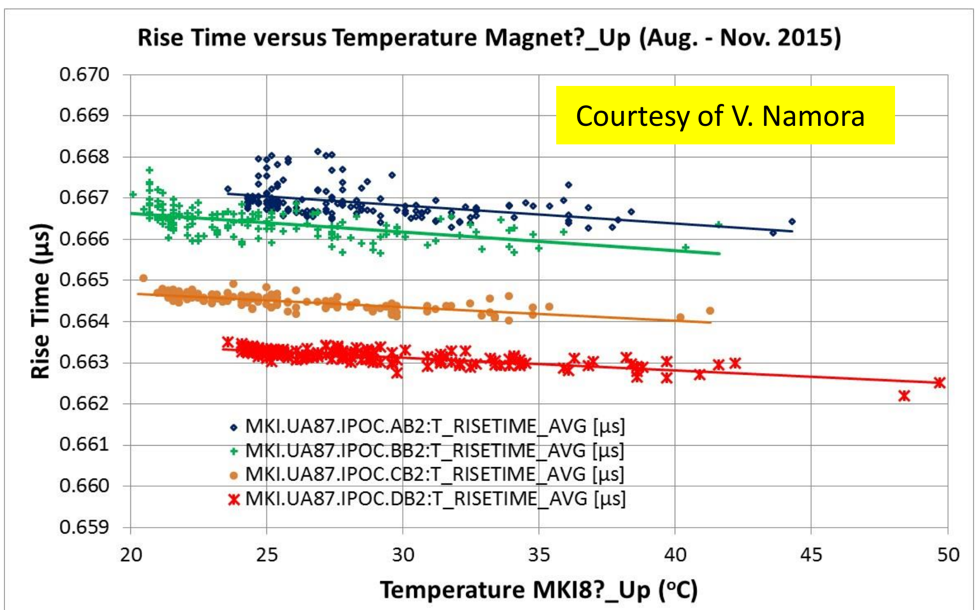
- 22 faults (8 Controls, 14 hardware) 4 faults required access (BETS-AGK reconnection, fix oil leakage, replace fuse, replace heater module ➔ 9h 45 min.), 8 faults prevented injection (sparks during MKISS, vacuum spikes, etc.➔ 6h 38 min).
- Almost all faults correctly detected and understood (BETS and IQC)
- A fault appeared twice (28/10 and 7/12) on MKI2 RCPS monitoring (new diagnostics software on Resonant Power Supply) after Terminating Dump Resistor (TDR) replacement at the end of September 2015. This fault is not fully understood and investigations are on going: real fault or just noise? (TDR replaced, cables checked, etc.).



MKI Heating





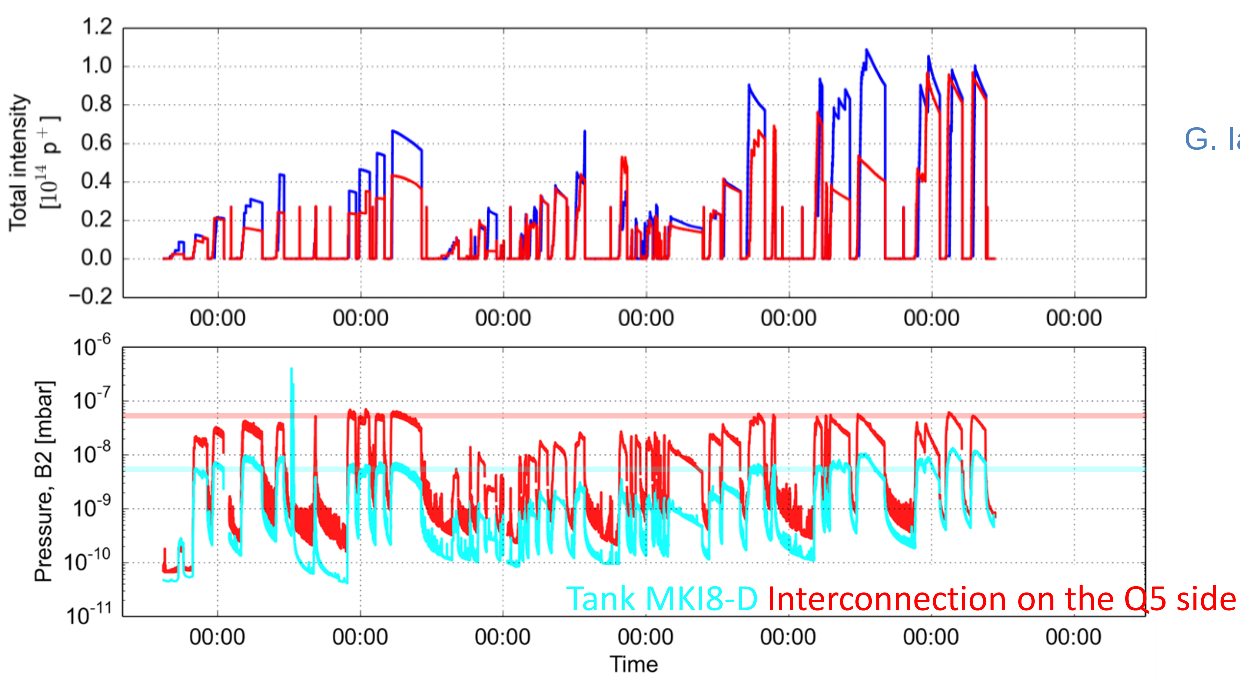


Now complete set of conductors. Ferrite Yoke below Curie Temperature ➔ no non-linearity seen

No stop/delay in operation during 2015 (SIS interlock threshold gradually increased following SS after beam dump).

MKI Vacuum and e-cloud

- High pressure in the kicker magnet tank, and near the capacitively coupled end of the beam screen, when pulsing the kickers, increases the probability of an electrical breakdown ➔ SIS interlock on instantaneous and integrated pressure
- Interconnect on Q5 end of MKI8D occasionally limited operation this year, due to high pressure in cold-warm transition:
  - During scrubbing runs (increase SIS limit in steps + extended SS)
  - When reaching 2244 stored bunches (limited to injections of 36 bunches)



G. Iadarola

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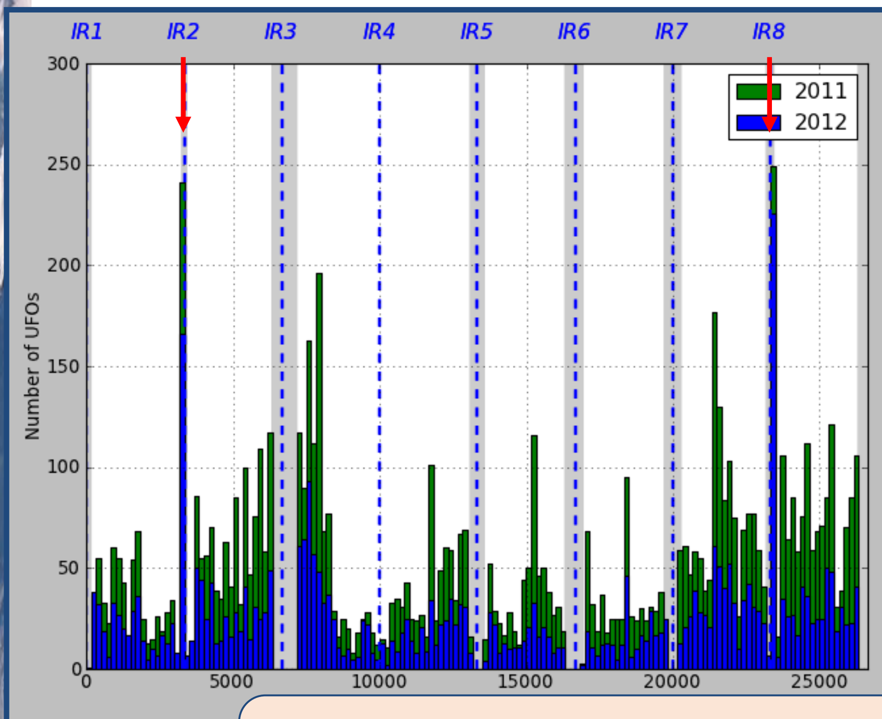
  - When reaching 2244 stored bunches (limited to injections of 36 bunches)
- Need to periodically perform sublimation (either during each TS or in shadow of other interventions) – after this YETS, remote sublimation of MKIs possible (VSC)
- Possibility of rotating MKI8D by 180° to expose to Q5 the “less sensitive” grounded end is being studied (during EYETS? need ECR)
  - Better scrubbing at Q5 (improve efficiency of e-cloud solenoids)
- Increase the SIS limits during operation TBD!➔ could increase number of breakdowns ➔ increase probability of damage to the magnet.

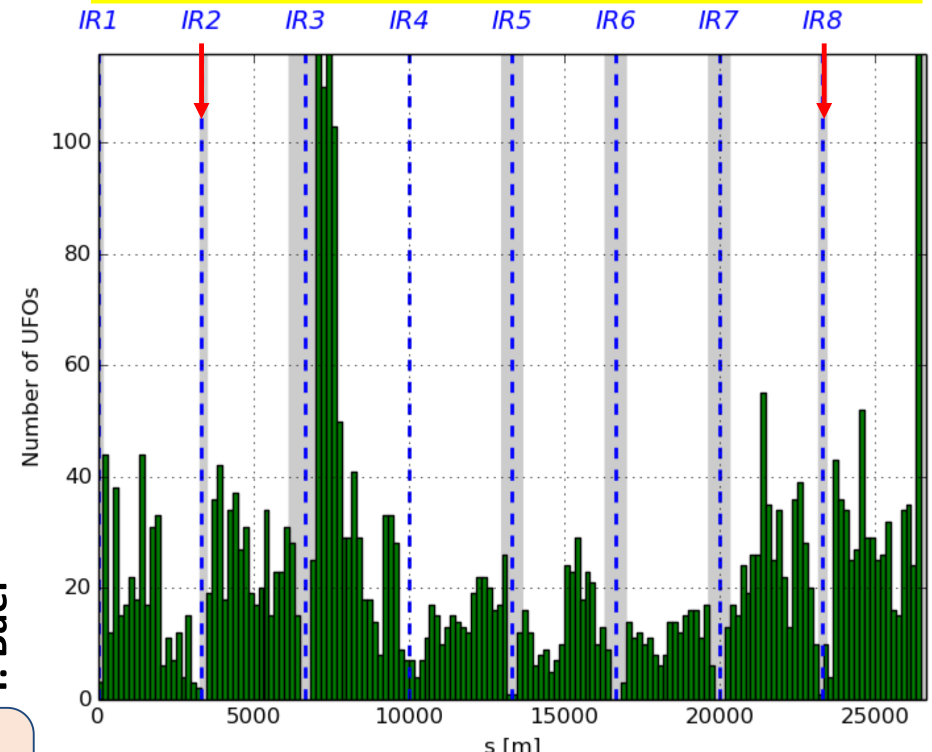
UFOs Longitudinal Distribution

Plot courtesy of G. Papotti et. al, "Busting UFOs – part 1", LMC 22/07/2015



T. Baer

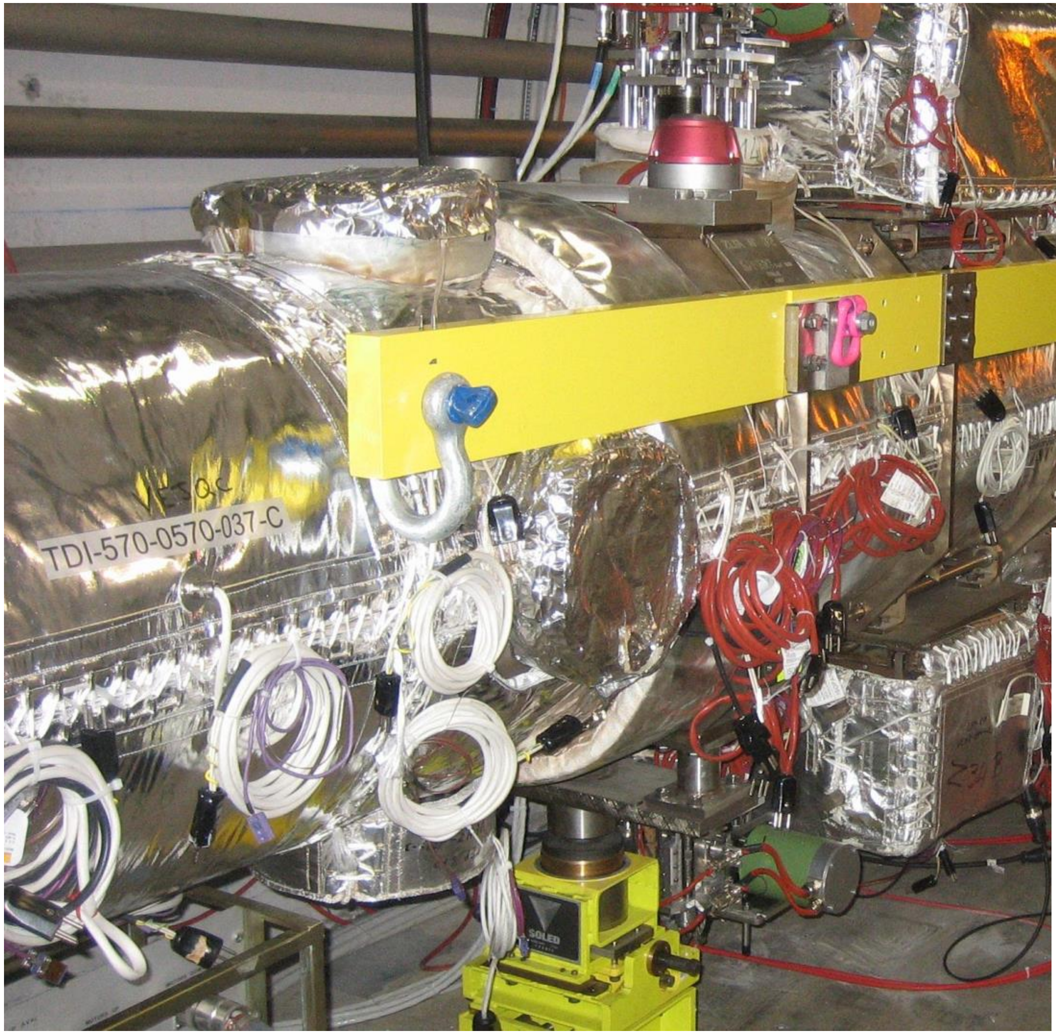
2011: 7668 UFOs at 3.5 TeV.
2012: 3719 UFOs at 4 TeV.
Signal RS04 > $2\cdot10^{-4}$ Gy/s.
Grey areas around IRs are excluded from the analysis.

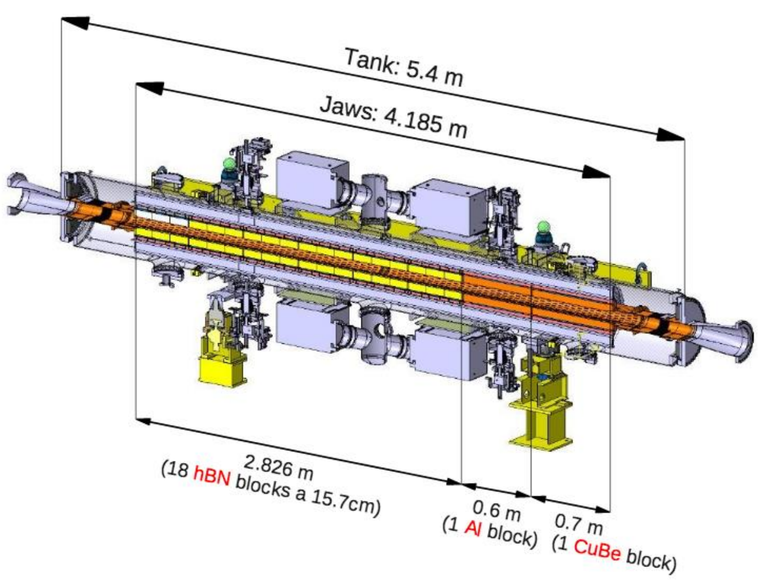


2015: 3621 UFOs at 6.5 TeV.
Signal RS04 > $2\cdot10^{-4}$ Gy/s.

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

TDI


TDI-570-0570-037-C

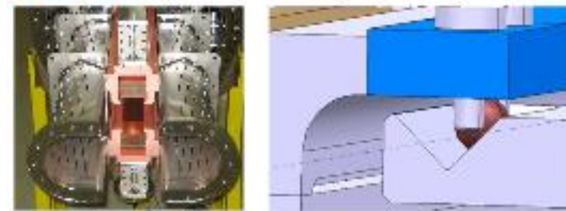

Tank: 5.4 m
Jaws: 4.185 m
2.826 m
(18 hBN blocks a 15.7cm)
0.6 m
(1 Al block)
0.7 m
(1 CuBe block)

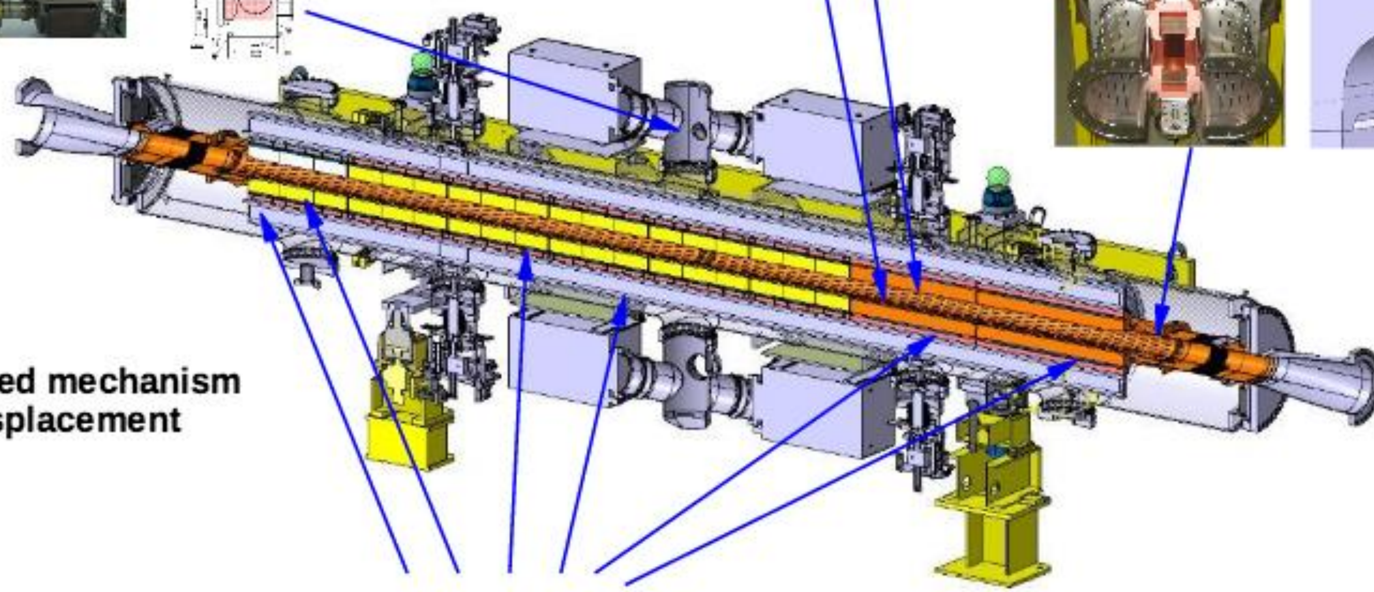
TDI – LS1Activities

NEG cartridges

Ti coating on Aluminium blocks to reduce SEY

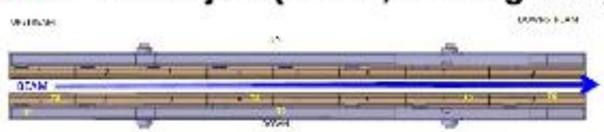
Reinforced beam screen made of stainless steel and improved sliding contacts (ceramic spheres)





Refurbished mechanism for jaw displacement

Temperature probes on lower jaw (frame, beam girder) and beam screen

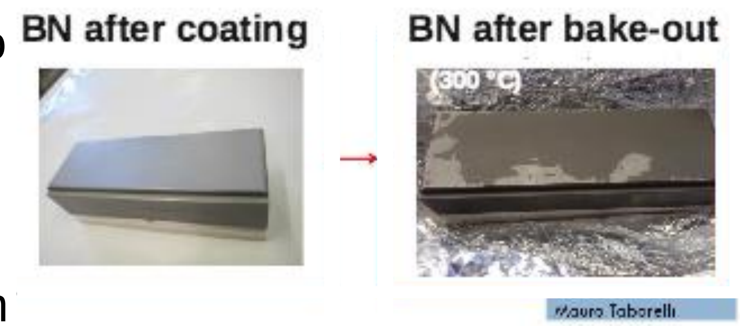


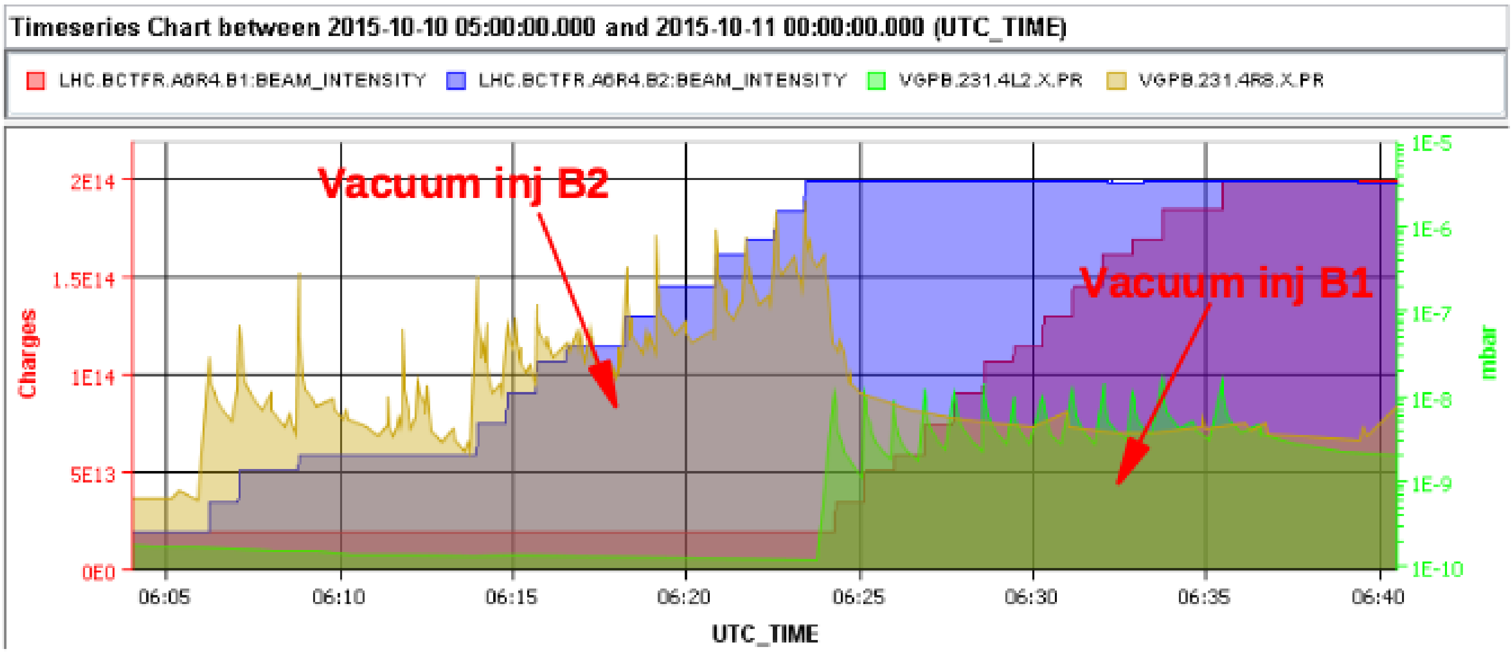
Sensor positions jaw

Sensor positions beam screen

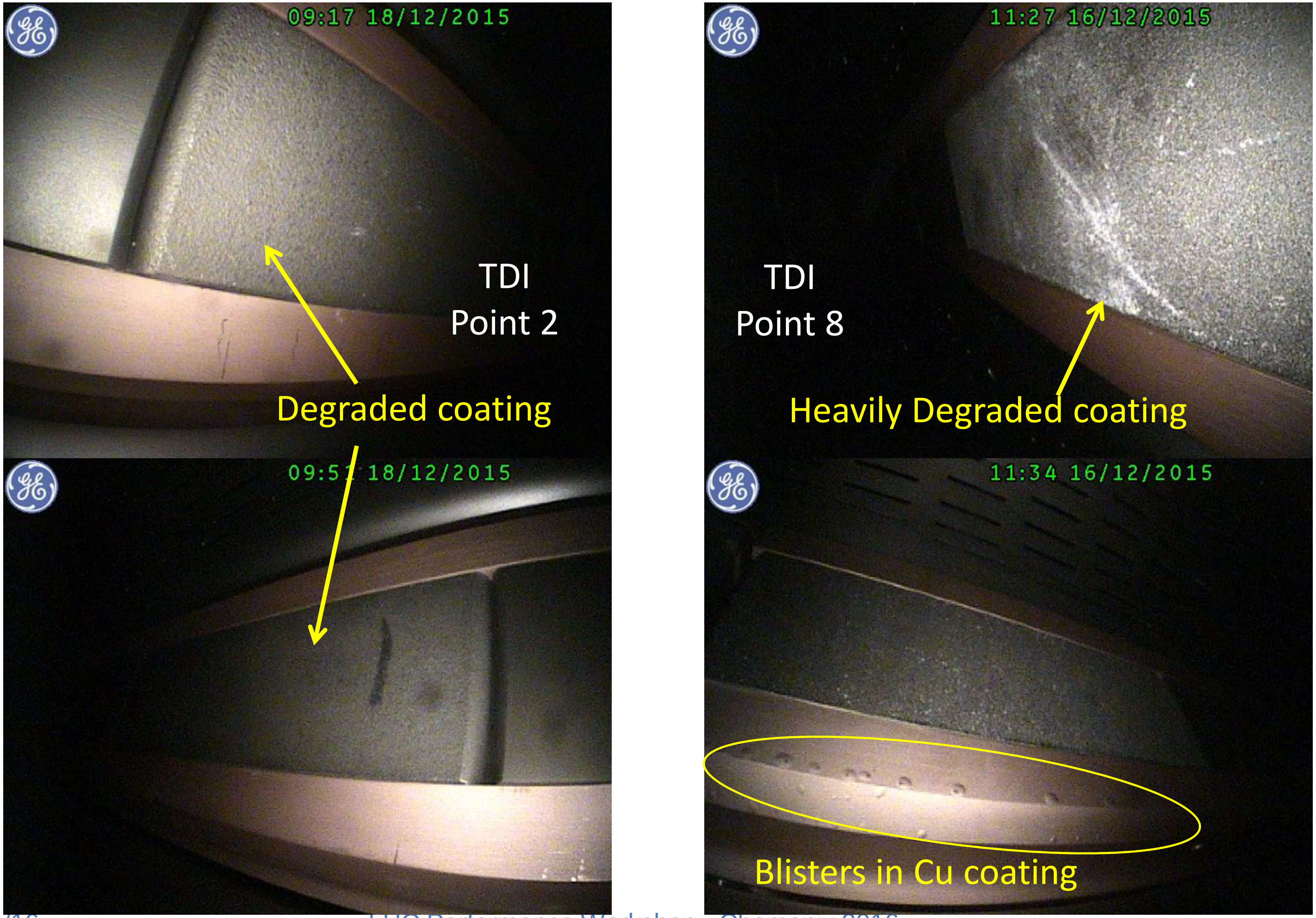
TDI Performance

- Limited in number of bunches per injection due to hBN non-conformities
- Significant pressure rise during injection and spurious spikes during fill with jaws retracted
- Much worse behavior for TDI in point 8 (also from impedance and heating point of view)





TDI Inspection

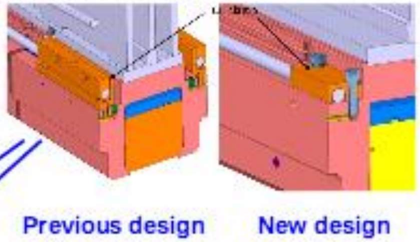


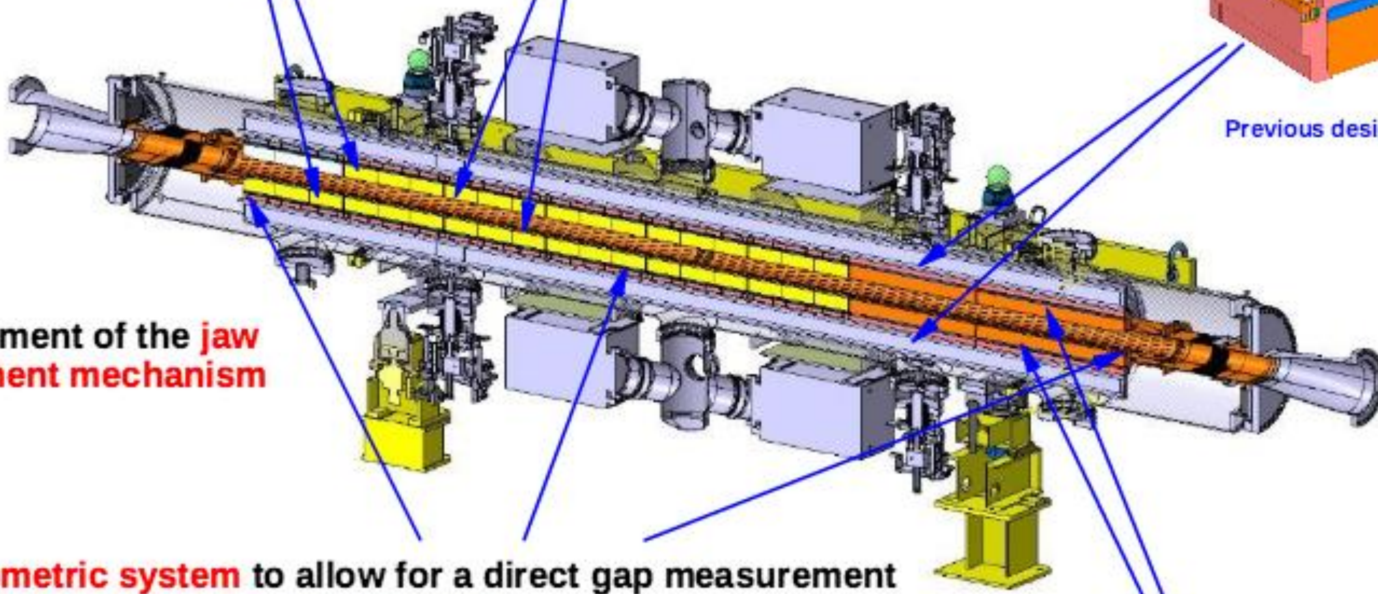
TDI Upgrade for 2016

Replacement of the hBN blocks with **Graphite R4550 blocks** to improve the robustness to beam impact

2 μm Copper coating on R4550 blocks to reduce the resistive heat load (2015: 5 μm Ti on hBN)

Modified clamping of cooling pipes to improve their contact with the frame





Refurbishment of the **jaw displacement mechanism**

Interferometric system to allow for a direct gap measurement

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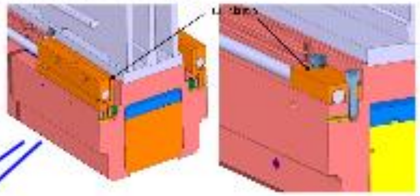

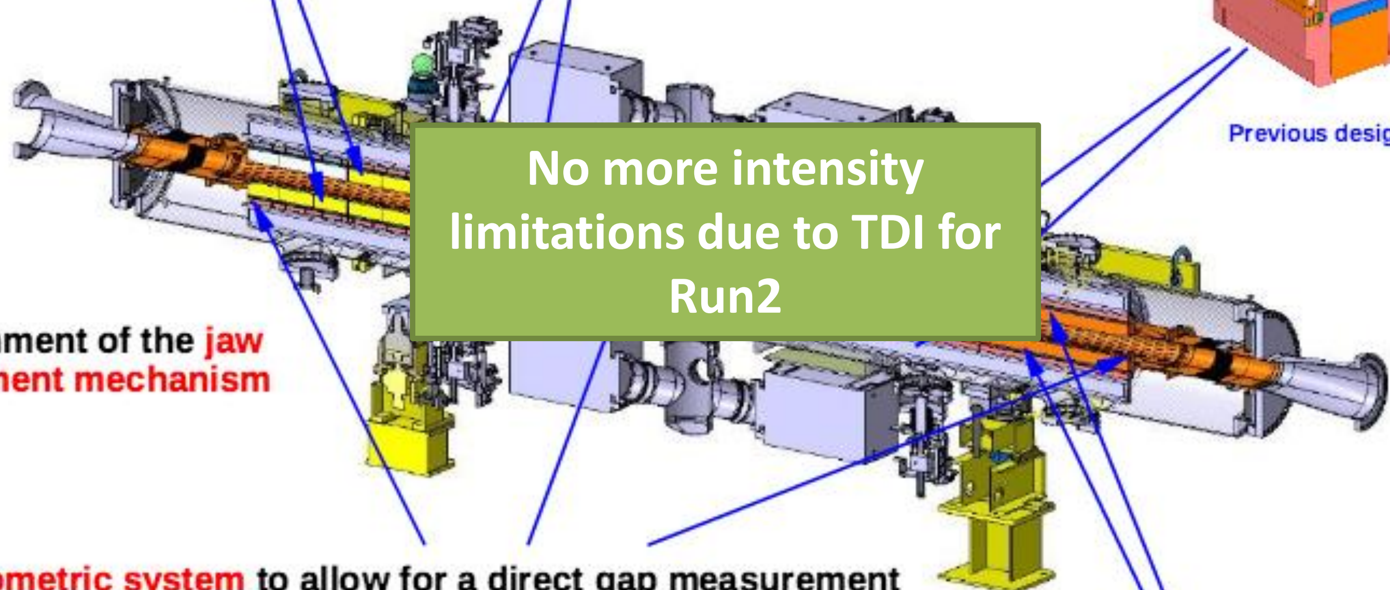

No more intensity limitations due to TDI for Run2

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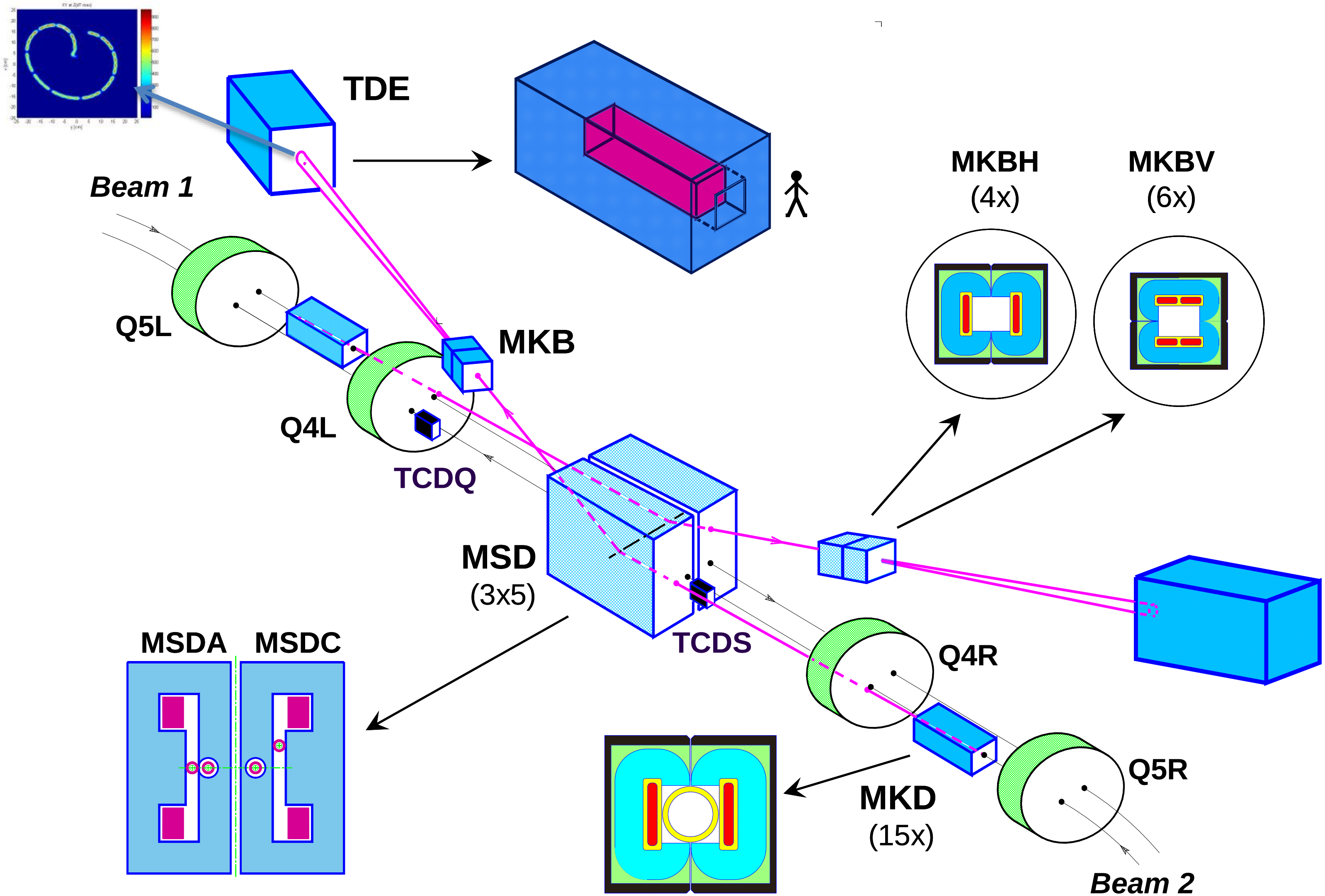
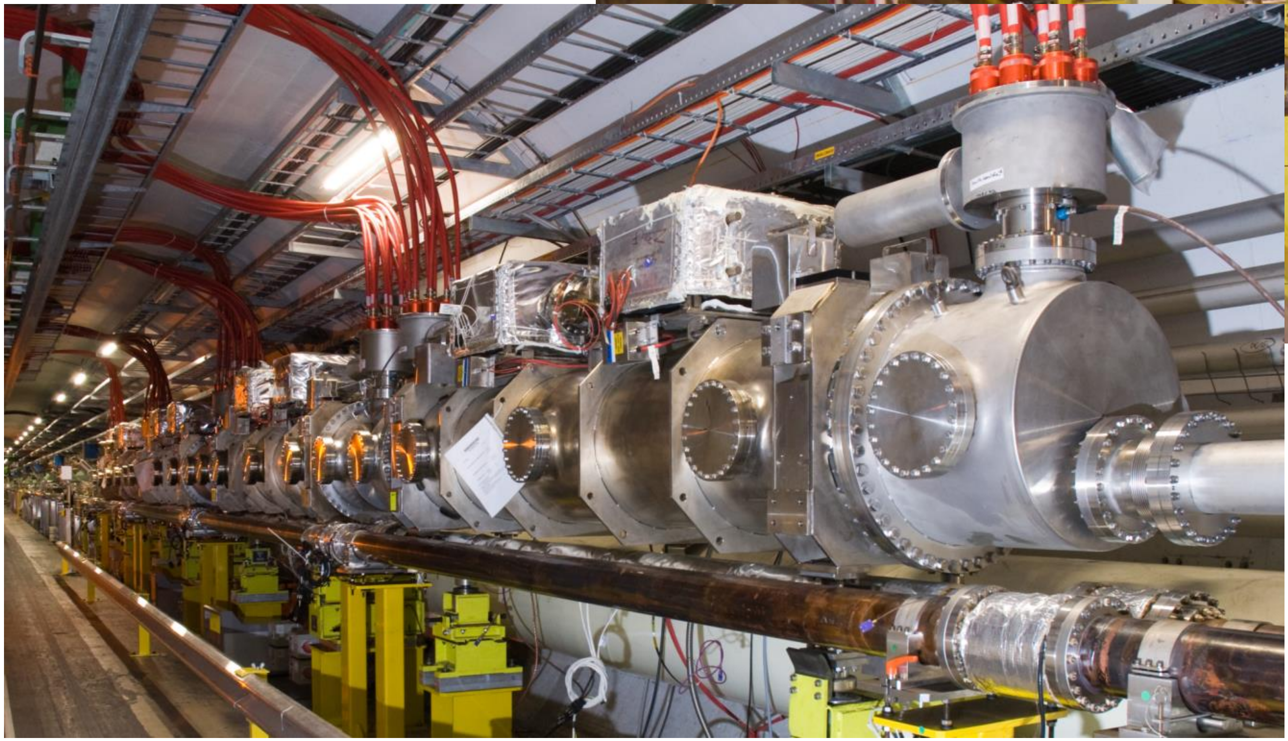
LBDS


TDE
Beam 1
MKBH
(4x)
MKBV
(6x)
Q5L
MKB
Q4L
TCDQ
MSD
(3x5)
TCDS
Q4R
MSDA
MSDC
MKD
(15x)
Q5R
Beam 2

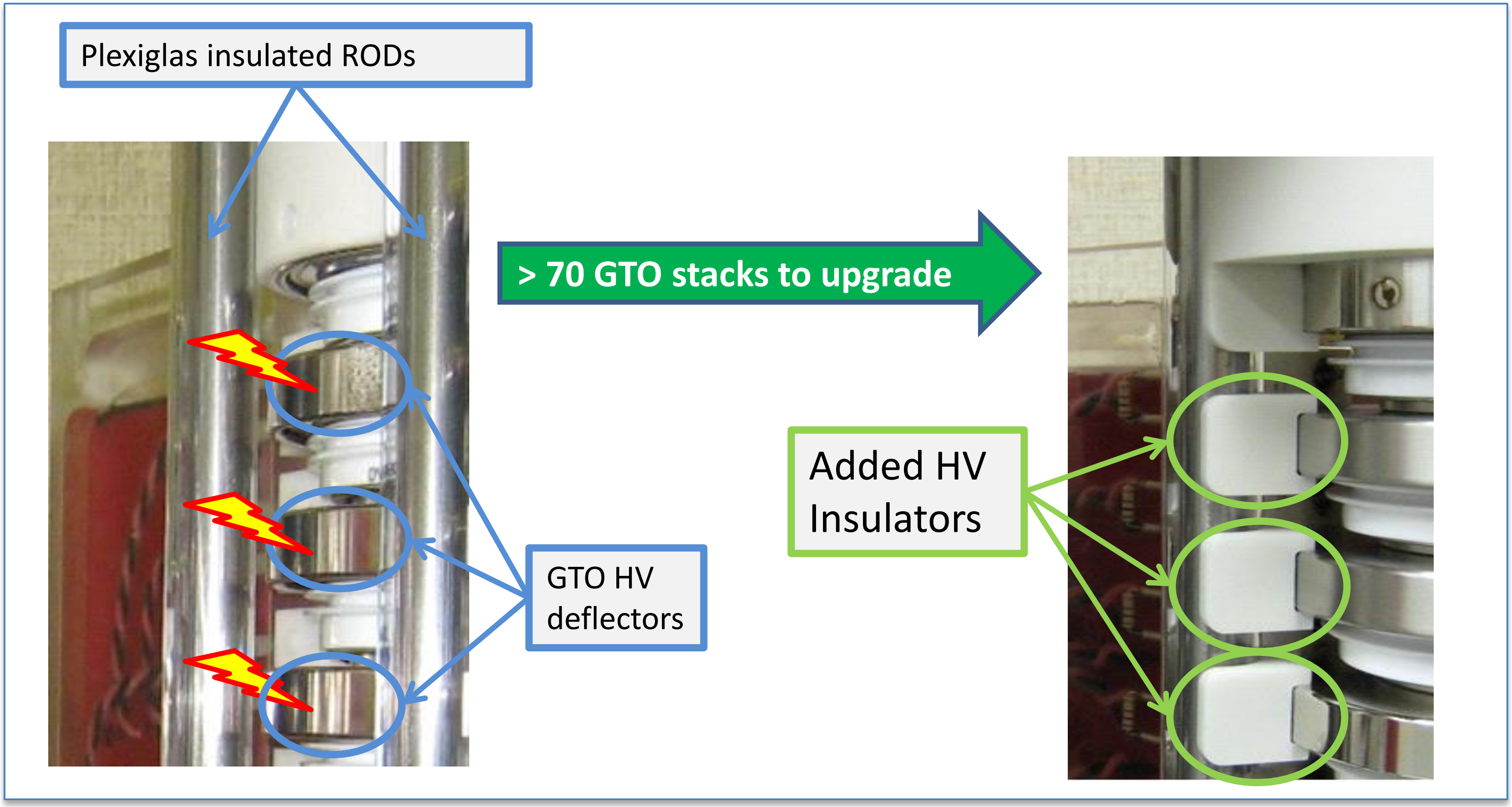
MKD/MKB



LBDS – LS1 Activities

Main aim: increase reliability (reduce rate of spontaneous triggers), safety and resistance to radiation

- HV generator GTO consolidation (MKD and MKB)



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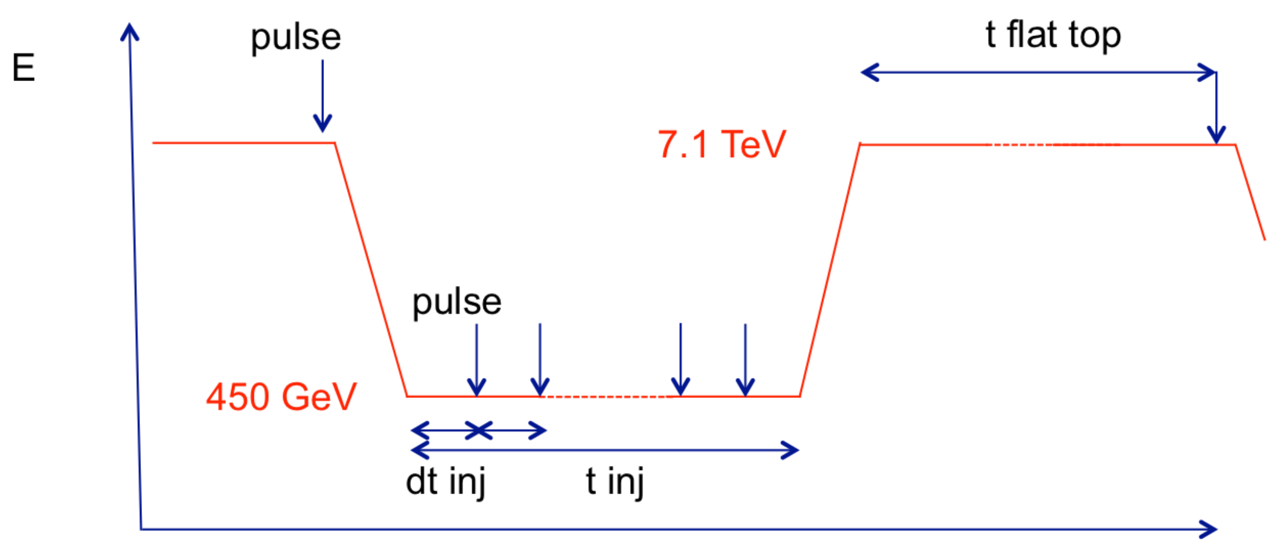
- SW upgrade (FESA3 migration and for operation at 6.5 TeV)

MKD Reliability Runs

Vital tests!

- Slow control – test of correct voltage readings inside generator and correct control functions
- HV test :
  - Dynamic - measurements of internal current transformer signals waveforms (at 450 GeV, 1 TeV, 2 Tev, 5 TeV)
  - Static - Sparking test: DC test at 7.1 TeV (48h) with recording of sparking activity of GTO seen by retrigger pick-up
  - Ramp test during 5 days: 400 GeV (10 min) -> ramp to 7.1 TeV (10 min) –> plateau 7.1 TeV (90 min) and pulse at the end –> rump down to 400 GeV (10 min) s

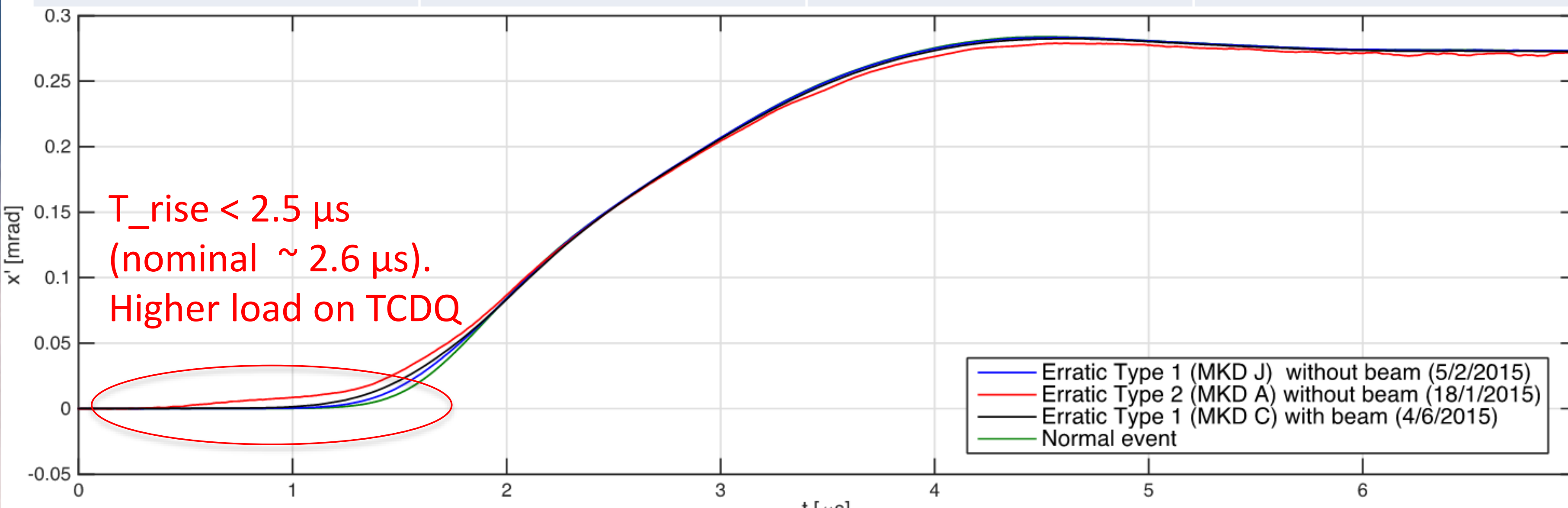


MKD Non-Conformities

Beam 1		Beam 2	
Erratic Type 1	Erratic Type 2	Erratic Type 1	Erratic Type 2
Gen H – 8x		Gen D – 25x	Gen G – 1x
Gen O – 4x		Gen B – 3x (6 GTO broken)	Gen N – 1x
		Gen J – 3x (2 GTO broken)	Gen A – 1x
		Gen N – 2x	
		Gen A – 3x	

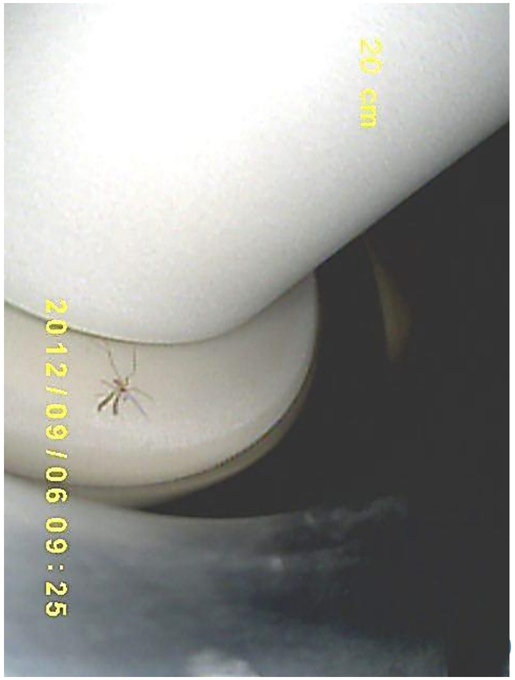
1 spark/Gen/24h

4 sparks/Gen/24h



MKD Non-Conformities

- Generally, the generators that undergo erratic triggering presented higher sparking activity
- Found correlation between dust presence/quantity inside generators and sparking activity
- Dust penetrates into generator via perforated side panels (for PTU cooling) and when deposited in “sensitive area” contributes to sparking.



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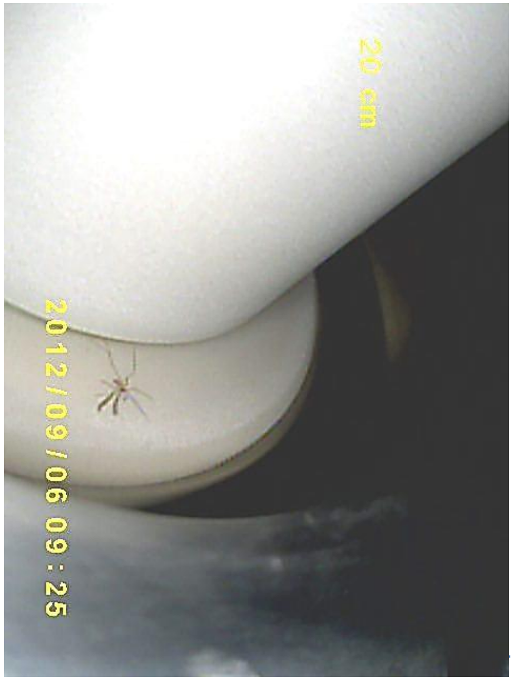
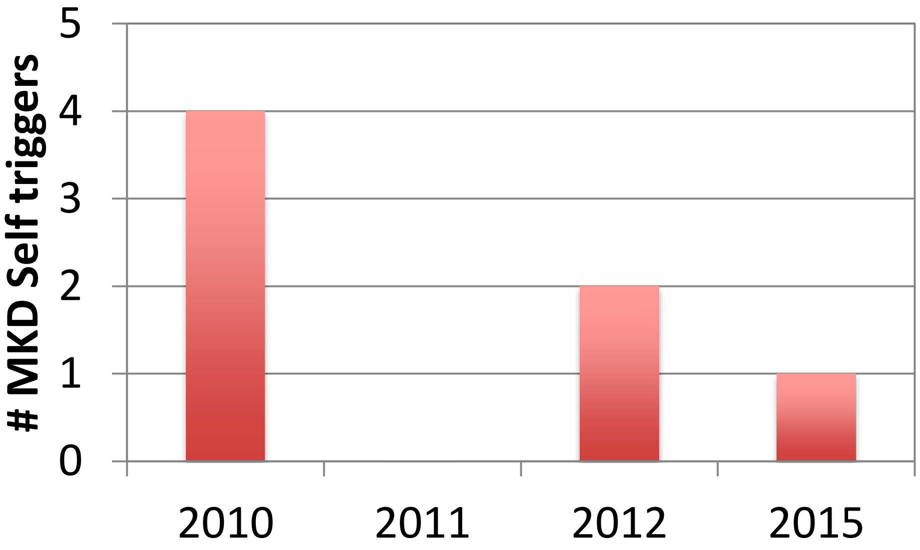
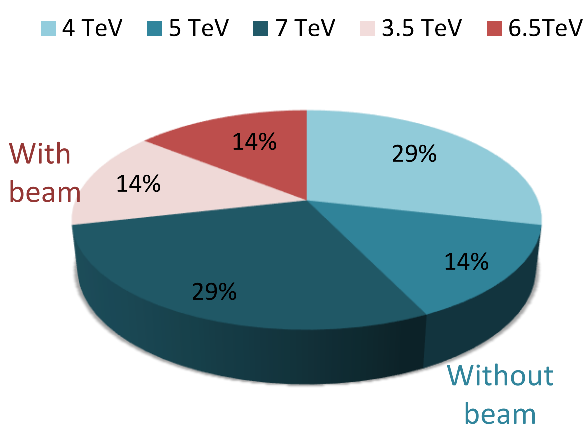


Mitigation measurements:

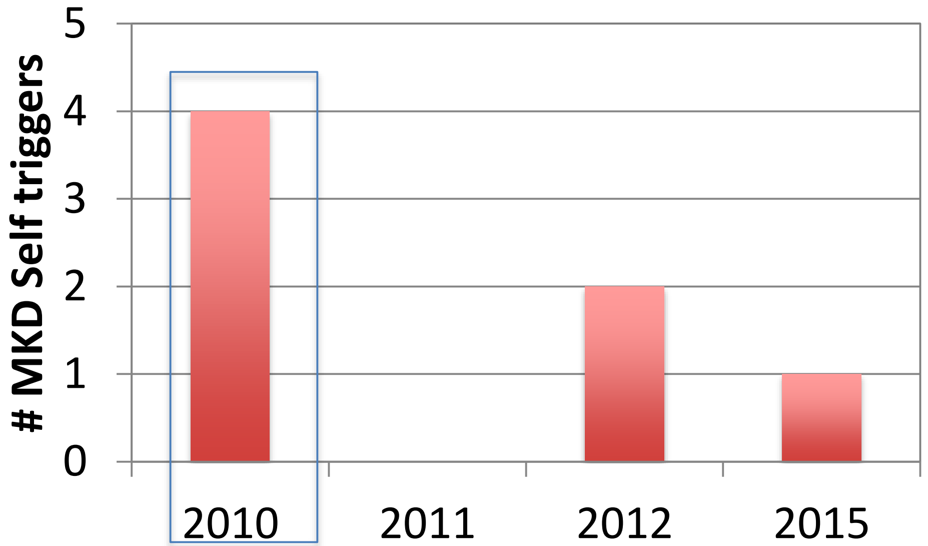
- Endoscopic inspection and cleaning of dust inside generators (repeated during YETS and EYETS)
- Exchanged perforated with non-perforated panels (on going activity)
- **Several modifications will be put in place to allow operation at 7 TeV (during LS2)**

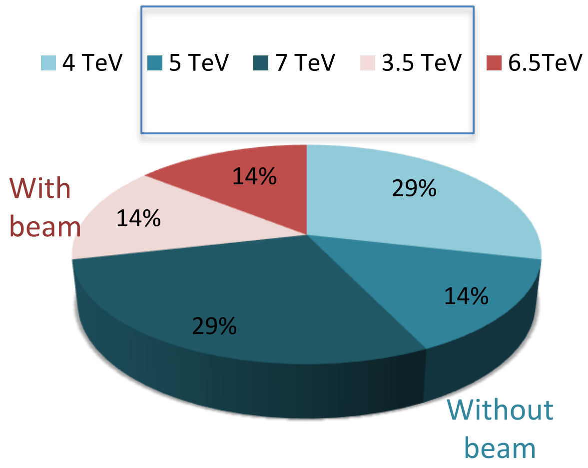
MKD Performance 2015 vs Run1



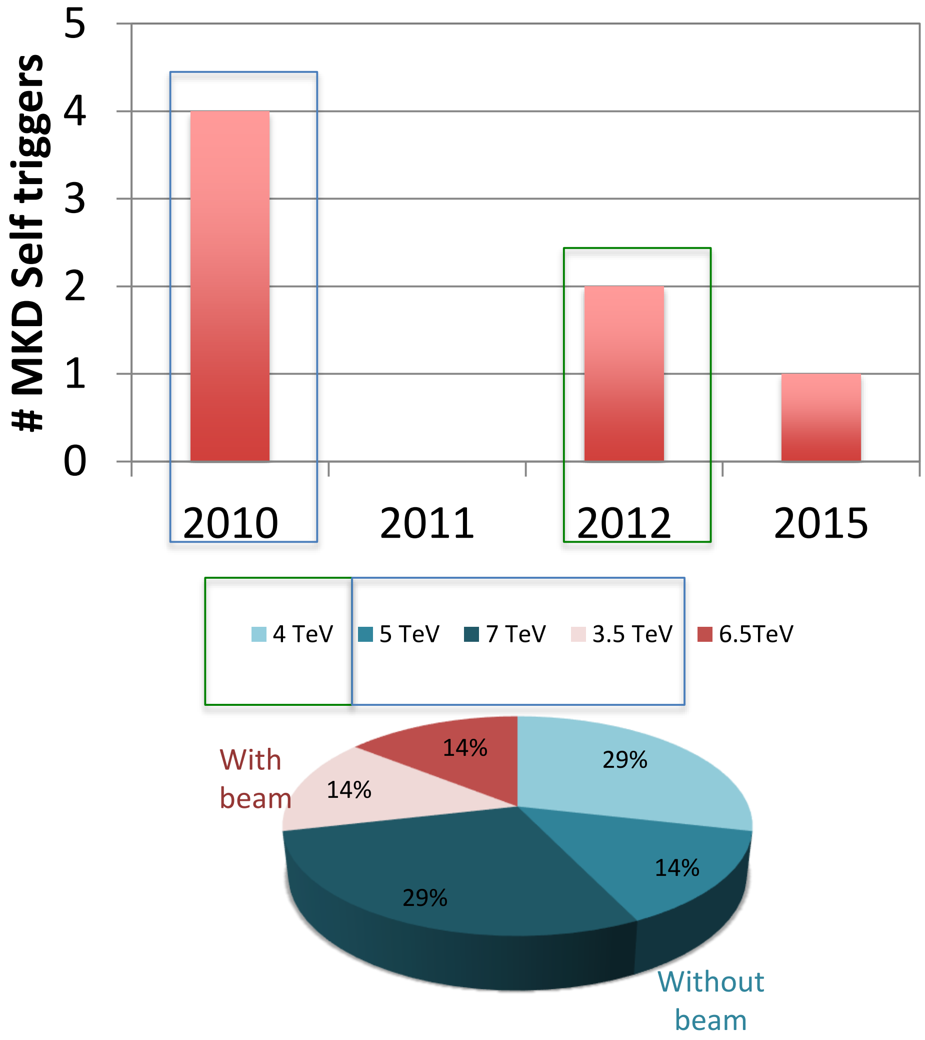


MKD Performance 2015 vs Run1

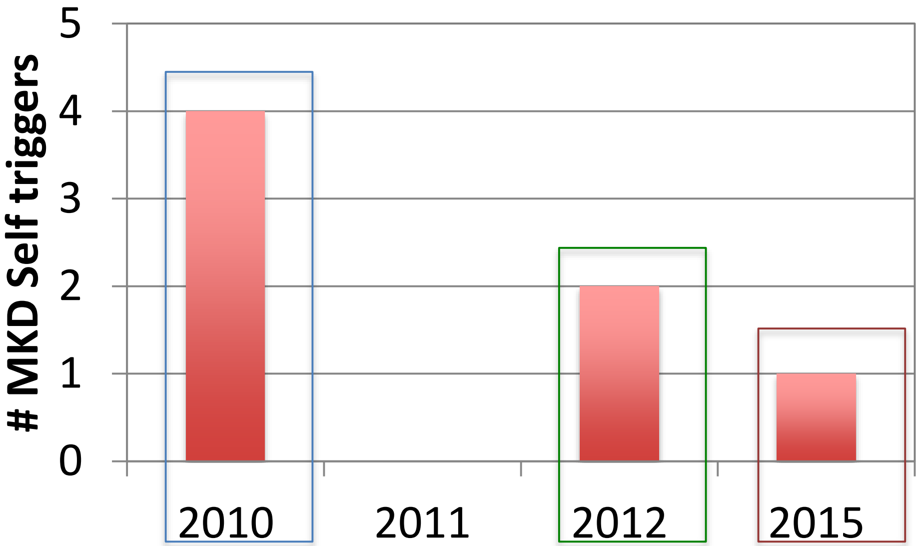


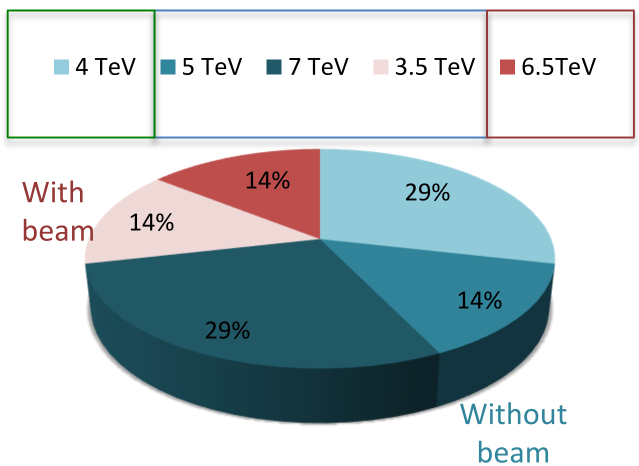


MKD Performance 2015 vs Run1

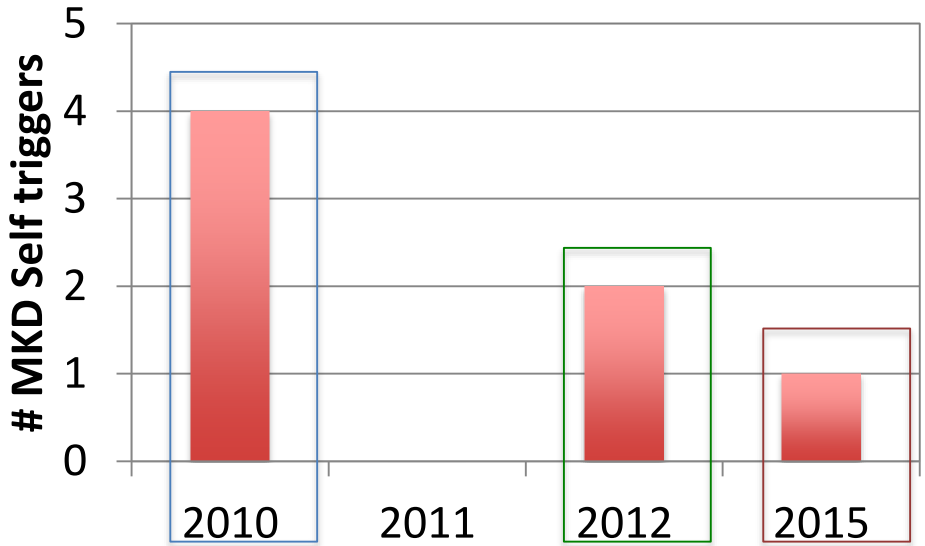


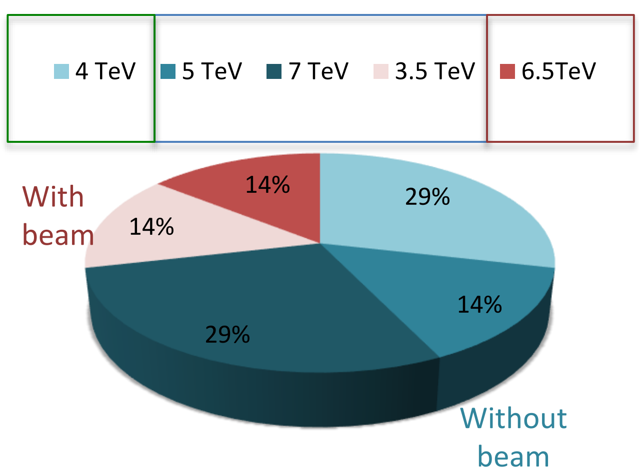
MKD Performance 2015 vs Run1





MKD Performance 2015 vs Run1





Estimated async. beam dumps @ 6.5 TeV: 3 per beam per year

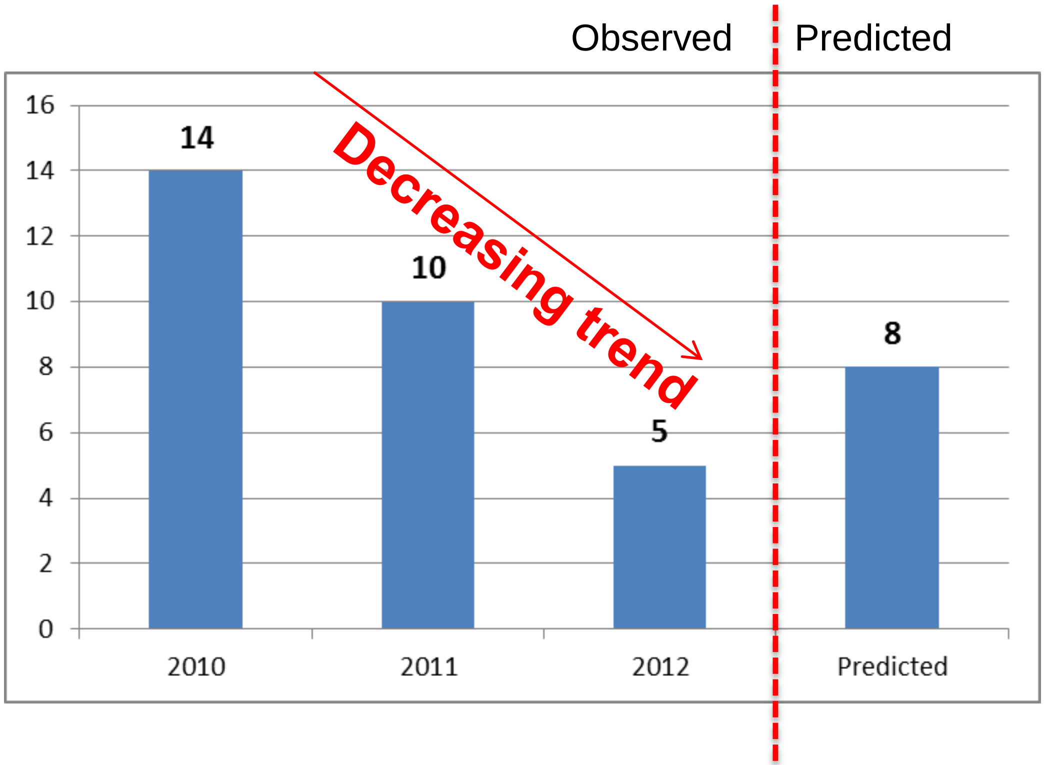
Only one async. dump with beam on 4th June 2015:

- No beam seeing the MKD rising edge.
- **MKD switch changed**, total intervention time with tests:17 h

One MKD generator exchanged at the end of TS1 (broken current pick-up) in the shadow of a cryogenics problem.

LBDS Performance 2015 vs Run1

- Estimates for false dumps (internal triggers): 8 (±2) per year ➔ 24 false dumps foreseen for 3 years of LHC operation (2010-2013). Observed 29 false dumps (continuous improvement over the years)



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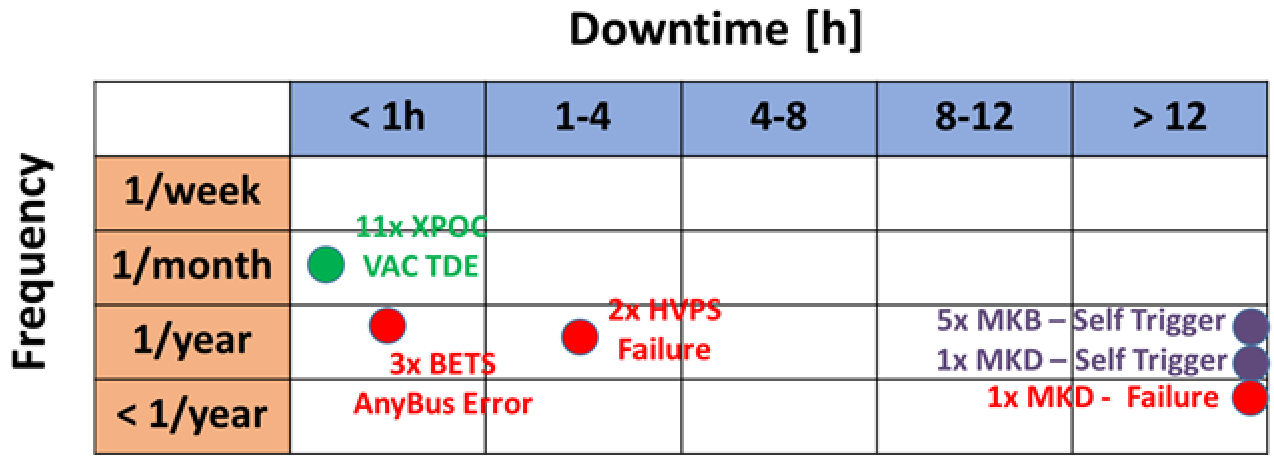

Green: mitigated/not expected to re-appear
Red: not yet mitigated/no need for mitigation
Violet: partially mitigated

- All faults correctly diagnosed (XPOC, IPOC, BETS) and understood. Plans to improve IPOC triggering to capture MKB erratics (LS2).

R2E

	6.5 TeV	7 TeV	7 TeV (without LS1 modifications)
	2.7 kV/GTO (MKD) 2.5 kV/GTO (MKBH)	2.9 kV/GTO (MKD); 2.7 kV/GTO (MKBH)	
ABB SEBc-s [cm^2] (MKD GTO)	2e-10	8e-9	8e-9
Dynex SEBc-s [cm^2] (MKB GTO)	3e-8	1e-7	1e-7 (5e-7 if used in MKD =2.9kV/GTO)
IXGN100N170 SEBc-s [cm^2] (IGBT)	5e-9	5e-9	1e-7 IXDN75N120
HEH fluence estimation [HEH.cm-^{2}.y]	5e4	5e4	4e5
	Failure probability		
MKD (GTO) [y^{-1}]	6e-3	0.2	61 (60 due to Dynex GTO)
MKD (IGBT) [y^{-1}]	9e-2	9e-2	15
MKBH (GTO) [y^{-1}]	0.12	0.4	3.2
MKB (IGBT) [y^{-1}]	3e-2	3e-2	5
Total AD (MKD GTO + IGBT) [y^{-1}]	0.1	0.3	76
Total SD (MKB GTO + IGBT) [y^{-1}]	0.15	0.43	8.2

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Dynex SEBc-s [cm^2] (MKB GTO)	3e-8	1e-7	1e-7 (5e-7 if used in MKD =2.9kV/GTO)
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Target 0.2 y^{-1}

R2E

	6.5 TeV	7 TeV	7 TeV (without LS1 modifications)
	2.7 kV/GTO (MKD) 2.5 kV/GTO (MKBH)	2.9 kV/GTO (MKD); 2.7 kV/GTO (MKBH)	
ABB SEBc-s [cm²] (MKD GTO)	2e-10	8e-9	8e-9
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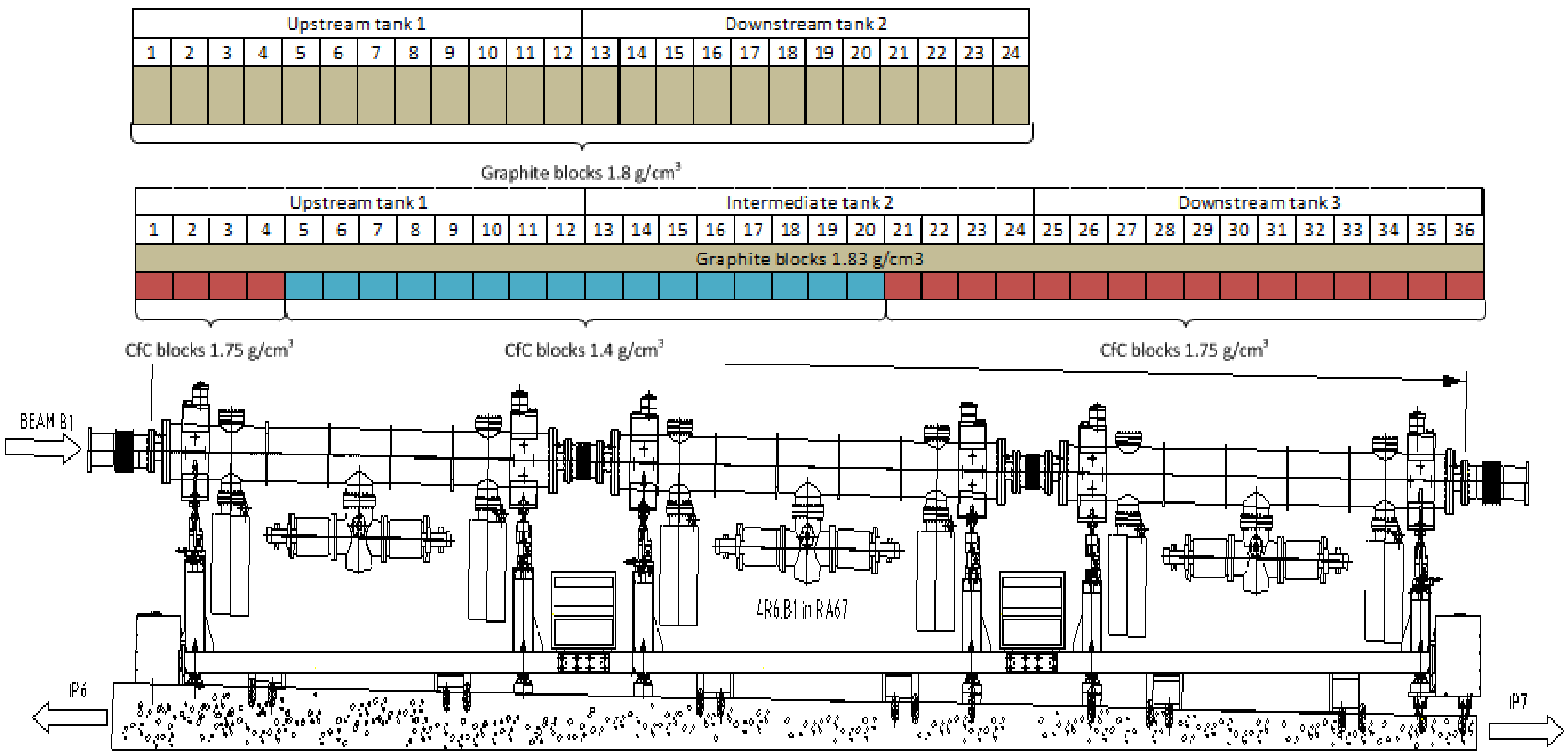
MKD (IGBT) [y^{-1}]			
MKBH (GTO) [y^{-1}]			
MKB (IGBT) [y^{-1}]			
Total AD (MKD GTO + IGBT) [y^{-1}]			
Total SD (MKB GTO + IGBT) [y^{-1}]			

- No SEB event in 2015
- No main limitations to go to 7 TeV (after completing shielding installation)
- More sensitive RAD monitors installed in the area for a better estimate of HEH → possible to extrapolate for HL-LHC

TCDQ

Hardware

- TCDQ length increased by 50% (added a third tank).
- The graphite absorbers were replaced by:
  A sandwich of graphite and Carbon Fiber reinforced Carbon (CFC)



TCDQ

Hardware

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- The graphite absorbers were replaced by:
  A sandwich of graphite and Carbon Fiber reinforced Carbon (CFC)

Controls:

- Deployment of the two functions into two separated PLCs:
  - Motor Drive and Control (MDC)
  - Position Readout and Survey (PRS)
  - TCDQ position in BETS

No beam dump induced by TCDQ, no mechanical problems

Two Controls faults (load settings) solved by rebooting the FEC.

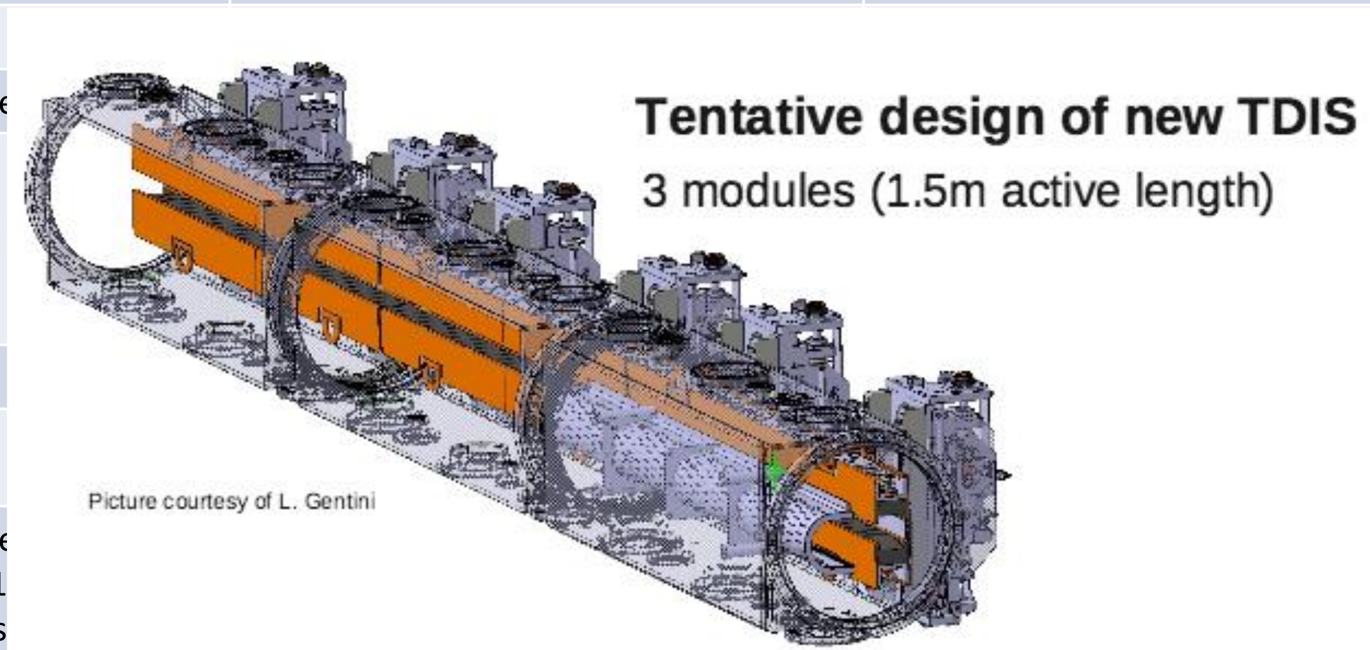
(2011:10 dumps due to TCDQ!)

Injection: Run3 → HL-LHC

	Run 2 Nom.	Run 3 Nom.	HL-LHC	Comments
MKI	OK	OK	Ceramic chamber treatment to reduce SEY (LS2). New capacitively coupled end design, of beam screen, to further reduce flashovers (LS2).Coating of vacuum tank to increase emissivity (LS2). New ferrite with higher Curie T (LS3).	
MSI	OK	OK	OK	
TDI	OK	New HW (LS2)	OK	
TCLIA	OK	OK	OK	Allow more gap when at parking to increase Alice crossing angel (HW modifications or moving → IP)
TCLIB	OK	OK	OK	
TCDD	OK	OK	OK*	*Additional mask at D1
TCDI	OK*	New HW (LS2) 2.1 m long jaws in stead of 1.2 m	OK	*< 144 BCMS bunches before LS2 (transmission problems)

Injection: Run3 ➔ HL-LHC

	Run 2 Nom.	Run 3 Nom.	HL-LHC	Comments
MKI	OK	OK	Ceramic chamber treatment to reduce SEY (LS2). New capacitively coupled end design, of beam screen, to further reduce flashovers (LS2).Coating of vacuum tank to increase emissivity (LS2). New ferrite with higher Curie T (LS3).	
MSI	OK			
TDI	OK	Ne		
TCLIA	OK			
TCLIB	OK			
TCDD	OK			
TCDI	OK*	Ne 2.1 in s		



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MSI	OK	OK	OK	
TDI	OK	New HW (LS2)	OK	
TCLIA	OK	OK	OK	Allow more gap when at parking to increase Alice crossing angel (HW modifications or moving → IP)
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Courtesy: H. Day

MKI Magnet	Pre-LS1 (W/m)	Post-LS1 (W/m)	HL-LHC, 50ns (W/m)	HL-LHC, 25ns (W/m)
MKI11-T13-MC03 (24 screen conds.)	34	**52**	**240**	**191**
MKI12-T12-MC01 (24 screen conds.)	20	34	151	124
MKI08-T11-MC09 (24 screen conds.)	26	43	192	157
MKI07-T08-MC08 (24 screen conds.)	27	45	199	163
MKI06-T07-HC12 (24 screen conds.)	22	37	168	137
MKI10-T06-HC13 (24 screen conds.)	25	43	184	149
MKI2A **pre-LS1**: 15 screen conds.	**68**[a]	117	538	432
MKI8D **pre-LS1**: 15 (twisted) screen conds.	**161**[b]	N/A	N/A	N/A

[a]: Did not limit LHC operation: maximum measured temperature 53˚C.

[b]: Occasionally necessary to wait for yoke to cool-down (yoke close to Curie temperature), maximum measured temperature 63˚C

Injection: Run3 → HL-LHC

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MSI	OK	OK	OK	
TDI	OK	New HW (LS2)	OK	
TCLIA	OK	OK	OK	Allow more gap when at parking to increase Alice crossing angel (HW modifications or moving → IP)
TCLIB	OK	OK	OK	
TCDD	OK	OK	OK*	*Additional mask at D1
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LBDS: Run3 → HL-LHC

	Run 2 Nom.	Run 3 Nom.	HL-LHC	Comments
MKB	OK	MKBH switch modifications (LS2)	OK	Not possible to go to 7 TeV without switch modification
MKD	OK	Switch modifications (LS2)	OK	Not possible to go to 7 TeV without switch modification
TCDQ	OK	OK	Ongoing studies, to define optics constraints and if any HW issues also with BCMS beams (June '16)	If need to close TCDQ during squeeze → **Integration of β^* interlock in BETS (New system, no money and manpower allocated)**
TCSP	OK	OK	Ongoing studies, to define optics constraints and if any HW issues also with BCMS beams (June '16)	
TCDS	OK	OK	Ongoing studies, to define optics constraints and if any HW issues also with BCMS beams (need for 1 additional module?) (June '16)	
TDE	OK*	OK	Ongoing studies, to define optics constraints and if any HW issues also with BCMS beams (June '16)	* HW interlock on pressure asap! Impact on window, TDE block evaluated. One option could be add dilution (more MKBs)

LBDS: Run3 ➔ HL-LHC

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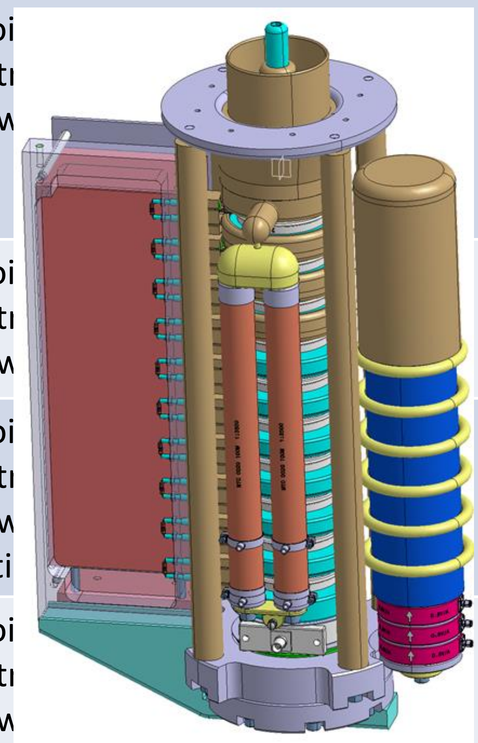
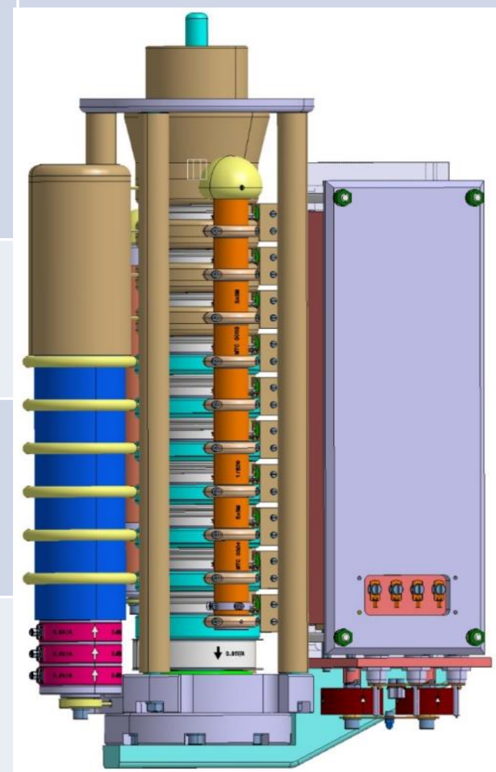
MKD	OK	Switch modifications (LS2)	OK	Not possible to go to 7 TeV without switch modification
TCSP	OK	OK	Ongoi constr also w	
TCDS	OK	OK	Ongoi constr also w additi	
TDE	OK*	OK	Ongoi constr also w	p! e

Make the installation less critical (reduce both max electrical fields and air ionization by 50%)





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TCSP	OK	OK	Ongoing studies, to define optics constraints and if any HW issues also with BCMS beams (June '16)	
TCDS	OK	OK	Ongoing studies, to define optics constraints and if any HW issues also with BCMS beams (need for 1 additional module?) (June '16)	
TDE	OK*	OK	Ongoing studies, to define optics constraints and if any HW issues also with BCMS beams (June '16)	* HW interlock on pressure asap! Impact on window, TDE block evaluated. One option could be add dilution (more MKBs)

Conclusions

- The most critical failure scenarios for LHC machine protection concern the injection and dump systems ➔ need high reliability and safety ➔ possible impact on machine availability ➔ find optimum trade off
- Several activities were carried out during LS1 to improve reliability, safety and availability of LHC injection and dump systems
- Machine checkout and reliability run are vital for injection and LBDS (find non-conformities and unexpected faults in time to react) ➔ enough time need to be allocated.
- 2015 run proved that some goals were reached (MKI HV performance, heating and UFO rate, TCDQ, etc.) but non conformities were also observed (TDI, MKD switches etc.)
- Further upgrades were/are being put in place for the rest of Run2.
- Studies are ongoing for the final designs for Run3 ➔ HL-LHC and in general operation at 7 TeV and higher intensity.

References

MKI:

https://indico.cern.ch/event/287487/contribution/0/attachments/534936/737578/Barnes_LBOC_21Jan2014.pdf

TDI:http://indico.cern.ch/event/434129/session/4/contribution/18/attachments/1193321/1756866/2015_12_16_eviantdi.pdf

LBDS

https://indico.cern.ch/event/310353/session/4/contribution/17/attachments/593654/817077/LBDS.pdf

lhc-mpwg.web.cern.ch/lhc-mpwg/MPP-Meetings/No98-31-10-2014/MPP_31.10.2014_-_LBDS.pptx

https://indico.cern.ch/event/405842/contribution/3/attachments/1135740/1625081/MKD_4August.pdf

TDE N2 Leak

- TDE normally runs at 1.2 bar Nitrogen overpressure
- Nitrogen leak on TDE B2. Fixed by tightening the flange after some days
- Manometer on the bottle was found closed, causing initial pressure drop
- The only ‘interlock’ is presently in the XPOC
- The only gauge is far away from the dump block, on a long line. Gives the correct pressure in stable conditions…
- To consider
  - Separate TDE N2 overpressure more clearly from other signals in XPOC
  - Install a second, hardware interlock on the TDE pressure
  - Consider a second pressure gauge on the TDE for complementary information (LS2)