Beam induced RF heating… …including TDI

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Special thanks to our collaborators
at INFN Frascati, la Sapienza, DESY, TU Darmstadt and IHEP Beijing!

Main questions for this talk

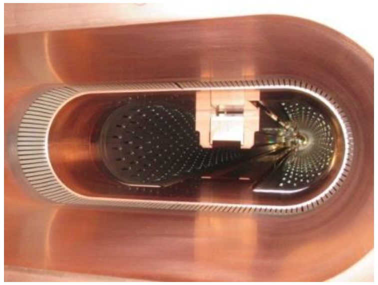
- Is beam induced RF heating expected to be a limitation in 2016?
- What about injection protection collimator TDI8 that was still a significant limitation in 2015?
- Will we need to implement bunch length control in 2016?

Note: heating due to electron cloud is not addressed here. See the previous talk from Gianni.

Agenda

- Recap on beam induced RF heating
- Reminder of issues before LS1
- Situation in 2015
- Outlook for 2016
- Proposed actions

Beam induced RF heating?

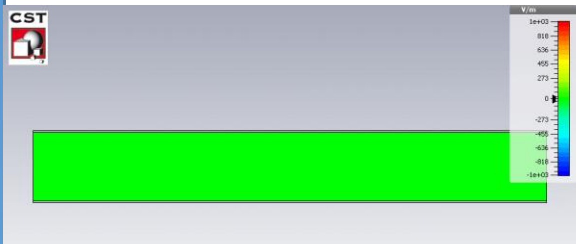


- When the LHC beam traverses a device which
  - is not smooth
  - or is not a perfect conductor,

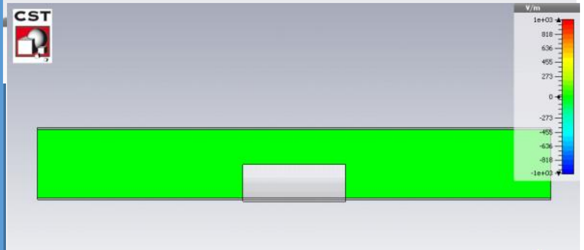
  it will produce wakefields that will perturb the following particles

  → resistive or geometric wakefields (in time domain) and impedance (in frequency domain).

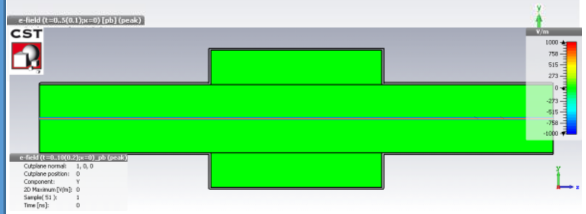
- 3D simulation of electromagnetic perturbation caused by an obstacle or a dispersive beam pipe:



In a round beam pipe



In a round beam pipe with sharp obstacle
→ resonant RF mode
→ energy left behind by the bunch
→ eventually dissipates in the surrounding walls



In a round beam pipe made of dispersive material
→ fields penetrate inside the material
→ dissipation of energy inside the surrounding walls

→ Energy lost by the bunch heats up the surrounding walls

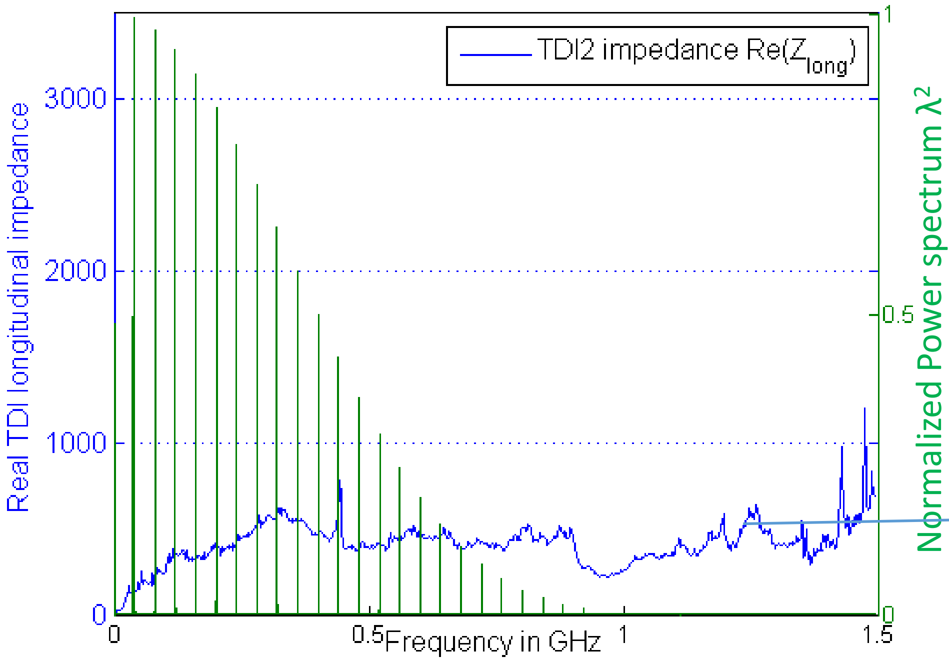
Beam induced RF heating?

- Can be computed from the impedance and the longitudinal beam spectrum

Power lost by a beam of intensity I_{beam} and normalized power spectrum λ^2 in a device of longitudinal impedance Z_{long}

$$P_{loss} = 2 \sum_{f=f_{rev}}^{\infty} \mathrm{Re}\left[Z_{long}(f)\right] \times I_{beam}^{\ 2} \times \lambda^2(f)$$

Power spectrum for 25 ns beam (cos² distribution and 9.75 cm) and measured 2015 TDIs impedance vs frequency



For 2248 bunches with 1.15 p/b, we would compute:

TDI2: Ploss ~ 2 kW

Beam induced RF heating?

- Can be computed from the impedance and the longitudinal beam spectrum

Power lost by a beam of intensity I_{beam} and normalized power spectrum λ^2 in a device of longitudinal impedance Z_{long}

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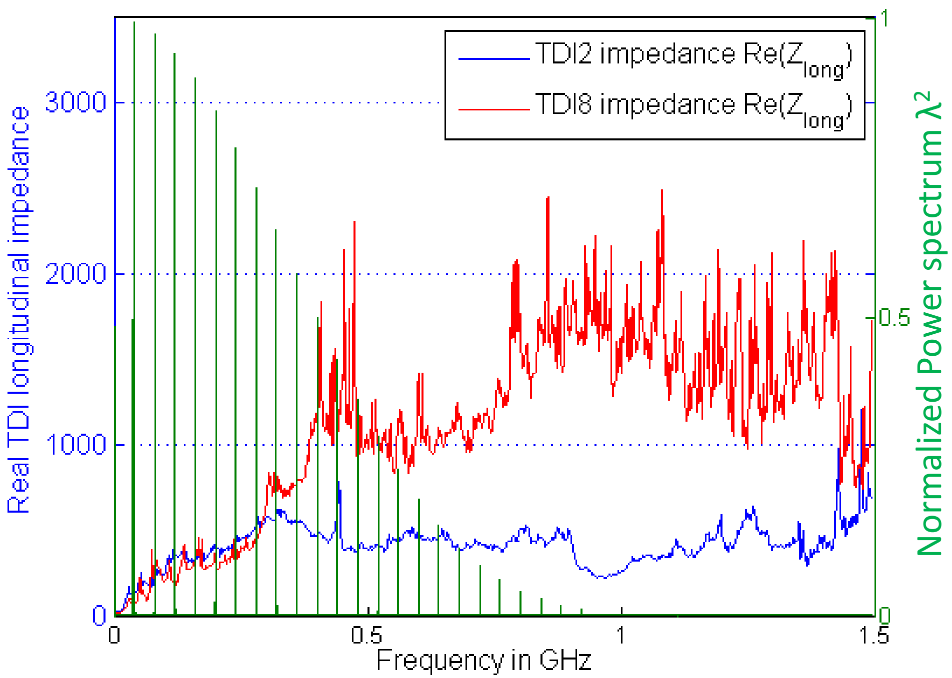
Power spectrum for 25 ns beam (cos² distribution and 9.75 cm) and measured 2015 TDIs impedance vs frequency



For 2248 bunches with 1.15 p/b, we would compute:

TDI8: Ploss ~ 3 kW

TDI2: Ploss ~ 2 kW

Depending on available cooling at the location of the dissipated power, could lead to problems or not (e.g. outgassing, structural issues)

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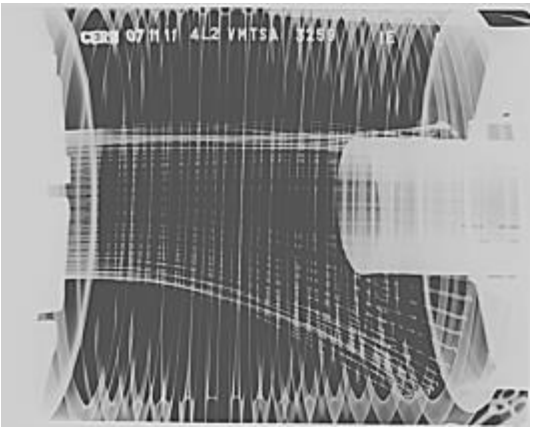
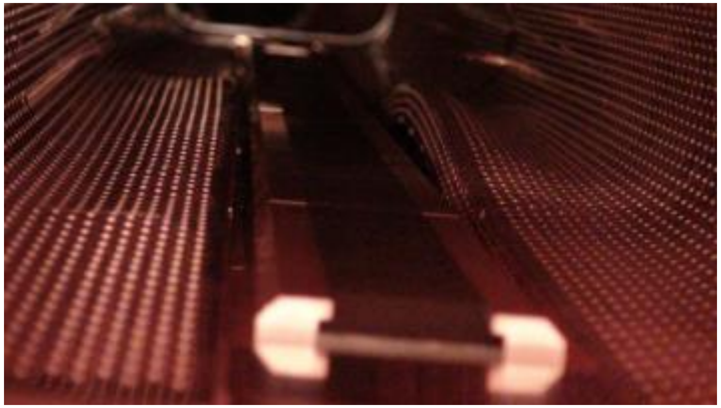
Reminder: heating issues in LHC before LS1

Damaged vacuum modules
→ Design not robust

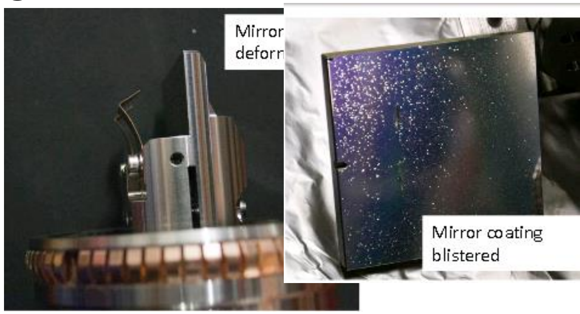


Damaged injection collimators
→ Design not robust



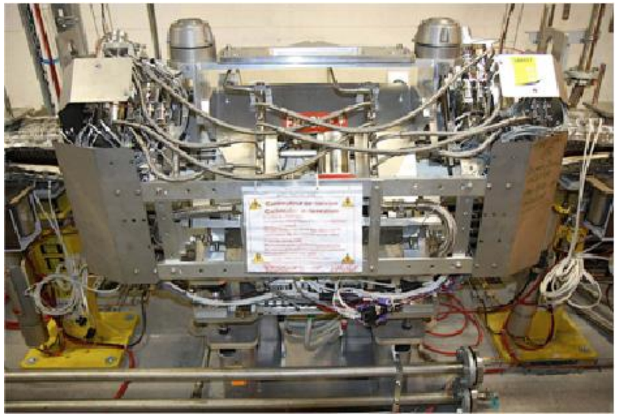
2 collimators reached temperature interlock dump levels
→ Cooling non conformity
→ Spurious temperature readings

Damaged synchrotron light monitor
→ Design not robust

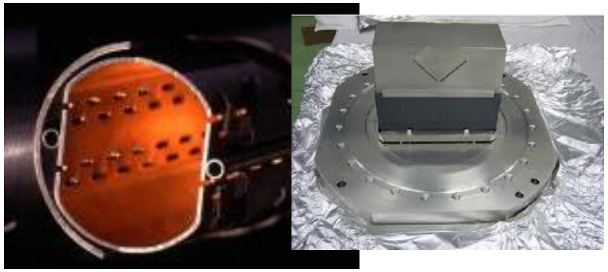


ATLAS-ALFA detector almost reached damage level
→ Design not robust

One injection kicker delays injection
→ Non conformity



One single cryogenic module (Q6R5) has no margin for cooling, likely linked to TOTEM outgassing.
→ TOTEM ferrite not baked



Summary table of heating issues in LHC before LS1

equipment	Problem	2011	2012
Vacuum module VMTSA	Damage		removed
TDI	Damage		
MKI	Delay		
Collimators	Few dumps		2 TCTVB removed
TOTEM/Q6R5 Beam screen	Regulation at the limit		
ATLAS-ALFA	Risk of damage		
BSRT	Damage		

→ Beam induced heating: major LHC limitation before LS1.
→ A lot of effort invested by equipment groups before and during LS1 to mitigate these issues

- Damaged
- Limited operation
- Worry that can limit operation
- Was fine fine

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    - The TDI
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    - Bunch length
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Summary table

equipment	Problem	2011	2012	2015
VMTSA	Damage			removed
TDI	Damage			Beam screen reinforced, ~~copper coating on the jaw~~
MKI	Delay			Beam screen upgrade and non conformity solved
Collimators	Few dumps			Non conformity solved. TCTVB removed.
Beam screen	Regulation at the limit	Q6R5 and TOTEM	Q6R5 and TOTEM	Upgrade of the valves + ferrites baked out.
ATLAS-ALFA	Risk of damage			New design + cooling
BSRT	Deformation suspected			New design
BGI	vacuum increase			To be followed up

Non conformity with TDI8, most likely the hBN jaw and its coating

→ All the efforts paid off: 2015 went much better!

- Damage
- Limits operation
- Worry that can limit operation
- Should be fine

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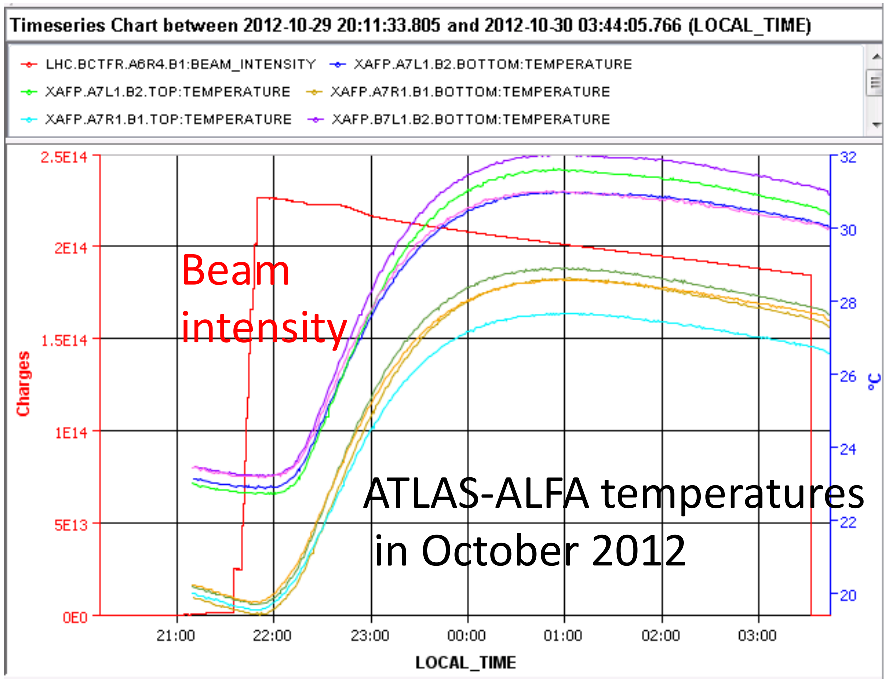
Situation of beam induced heating in 2015

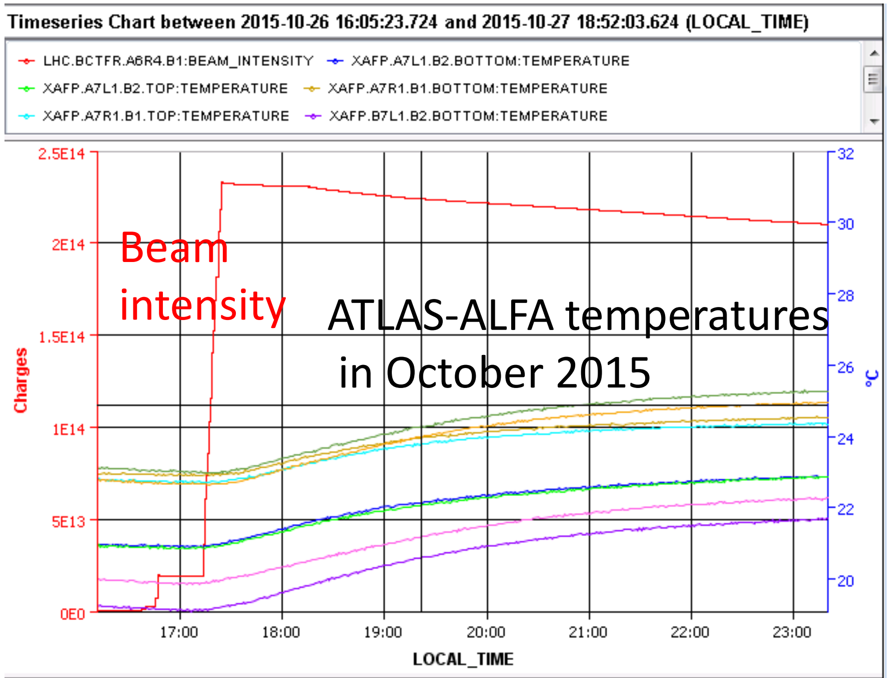
- Great success and big relief that new designs have worked so far!
  - Shielded and cylindrical Roman pots (both ATLAS-ALFA and TOTEM)

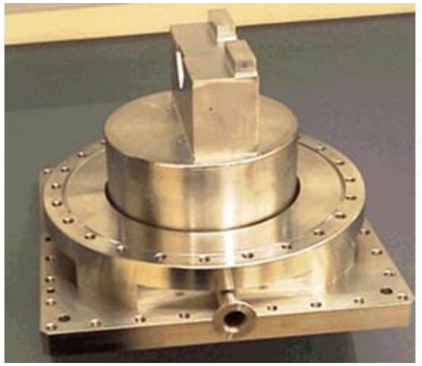
    → a lot of margin gained in 2015 for ALFA

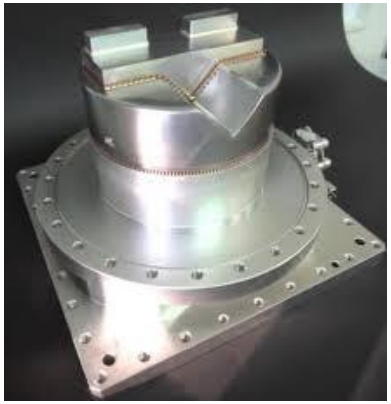
    → no vacuum problems with Q6R5 for TOTEM

2012 vs 2015: ATLAS-ALFA Roman pots





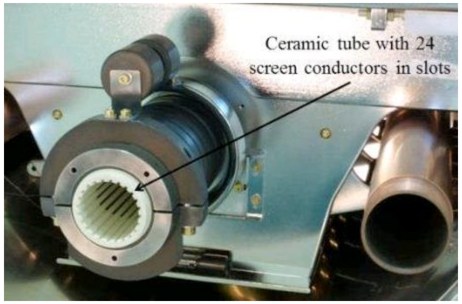




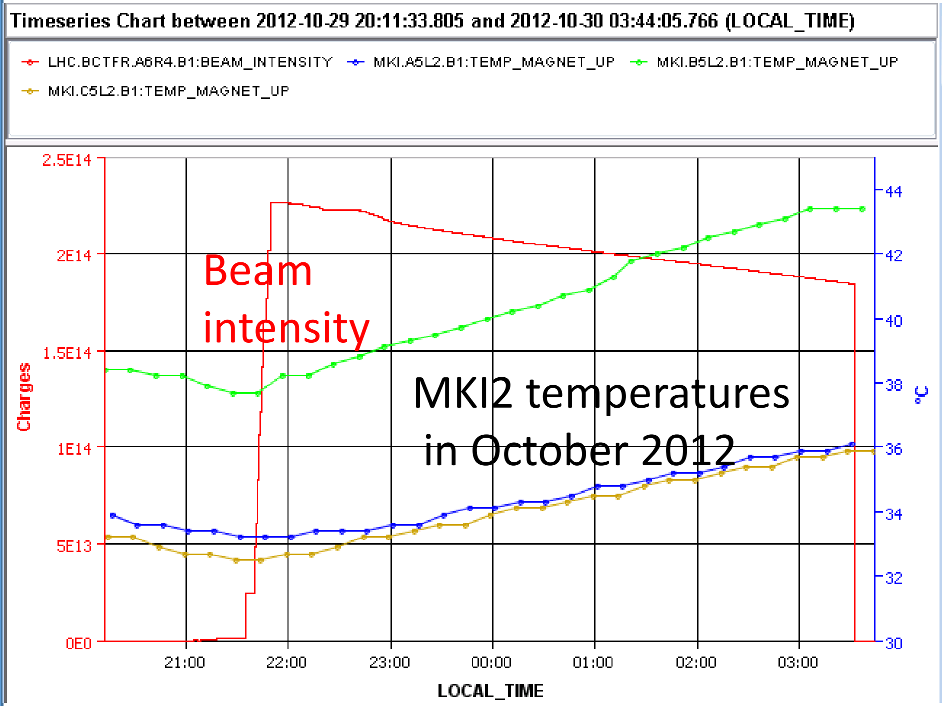
→ Clear gain with new shielded design

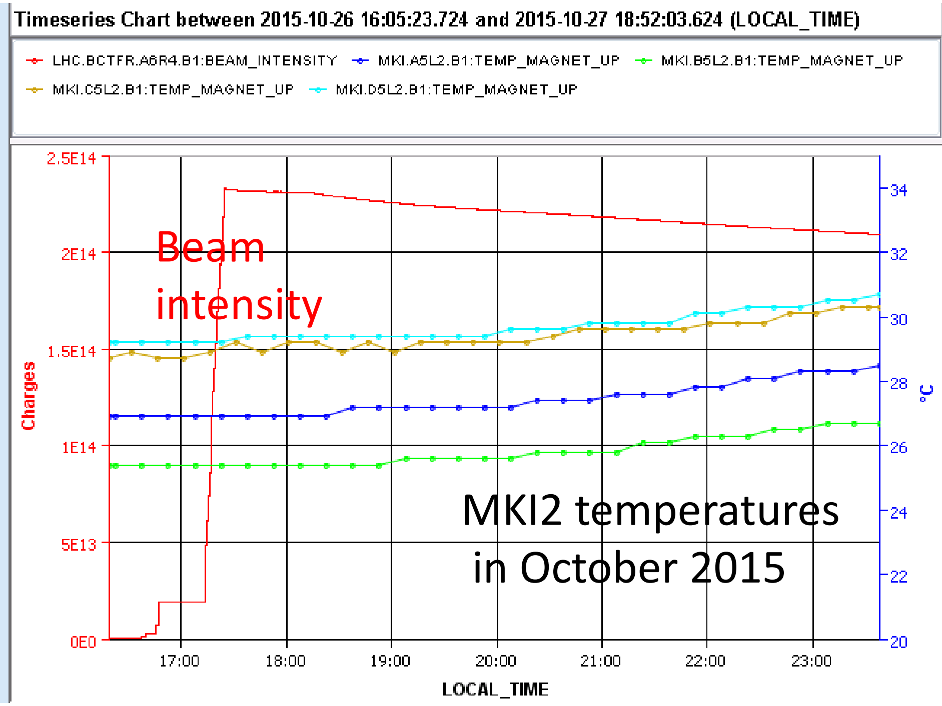
Situation of beam induced heating in 2015

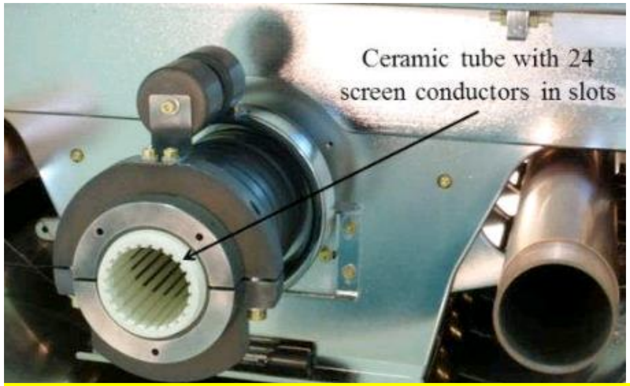
- Great success and big relief that new designs have worked so far!
  - Shielded and cylindrical Roman pots (both ATLAS-ALFA and TOTEM)
    → a lot of margin gained in 2015 for ALFA
    → no vacuum problems with Q6R5 for TOTEM
  - New design for **synchrotron light telescope** (BSRT) *followed up with BI-TB*
    → barely any temperature increase (compared to more than 300C in 2012)
  - New **collimator design with ferrite** (TCTP), *followed up with collimation WG*
    → no significant difference observed so far with respect to the design without ferrite
  - **Full shielding of ceramic tube for injection kickers** (MKI) – 24 instead of 15 screen conductors.
    followed up with MKI strategy meetings
    (see talk of Lee at Evian 2015)



2012 vs 2015: injection kicker MKI







→ Significant reduction of the temperature slope, but temperature has reached 50C after series of long fills.

→ Injection interlock kept low by TE-ABT (55C), but threshold can be incrementally increased once kicker behaviour is checked using softstarts.

→ MKIs are not expected to be a hard limitation for Run2 parameters.

→ In case it becomes too hot, it is then advised to keep the bunch length above 1 ns.

→ **We should be ready to control bunch length by bunch flattening**

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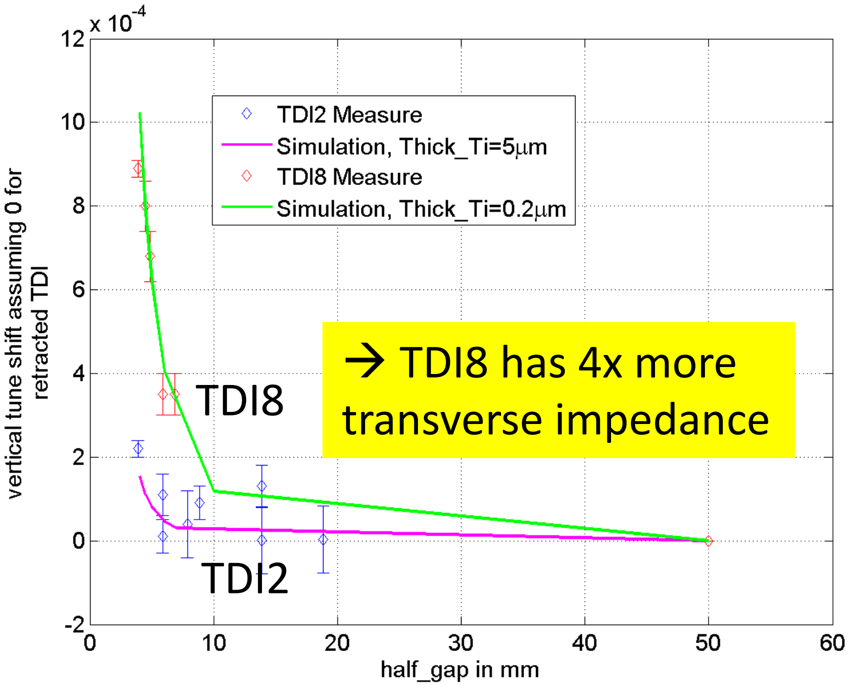
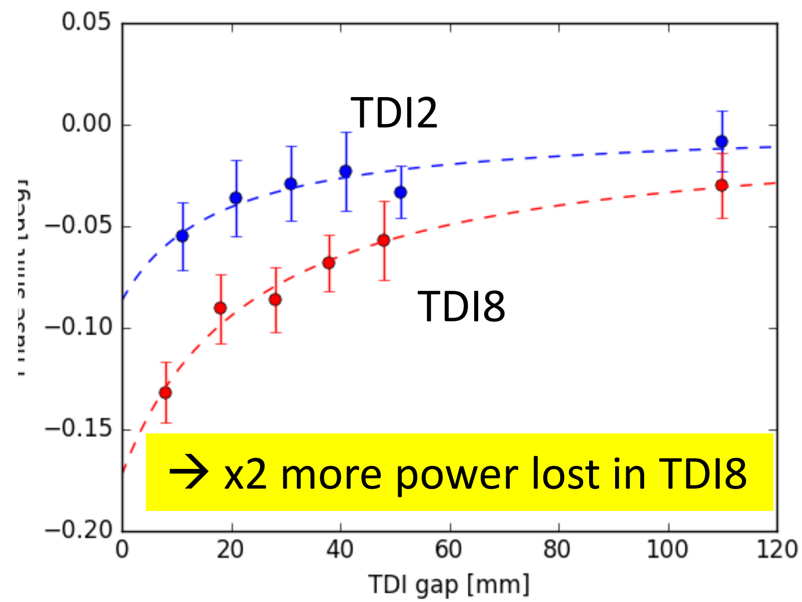
TDI issues

- Technical issues with implementing our recommendation to apply copper coating to reduce TDI impedance.
- Abnormal vacuum behavior on TDI8→ serious limitations during scrubbing and injection
- Abnormal impedance observables (both longitudinal and transverse) observed during the run.



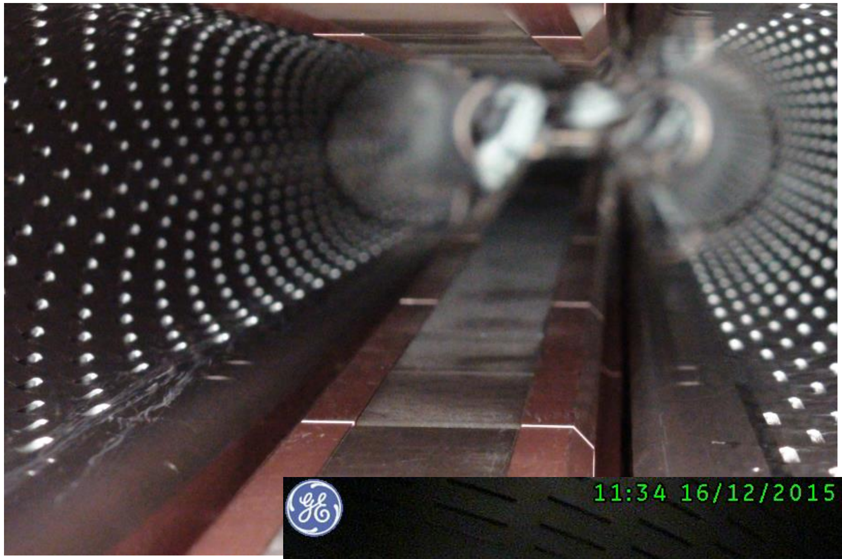


→ Observations point towards a coating issue for TDI8 (LMC237 in Sept 2015).

TDI issues

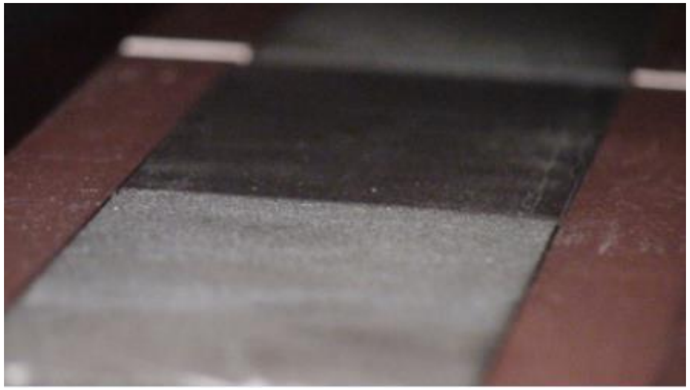
- TDIs were taken out of the machine in December.
- Indeed the coating on TDI8 is heavily compromised.

TDI2

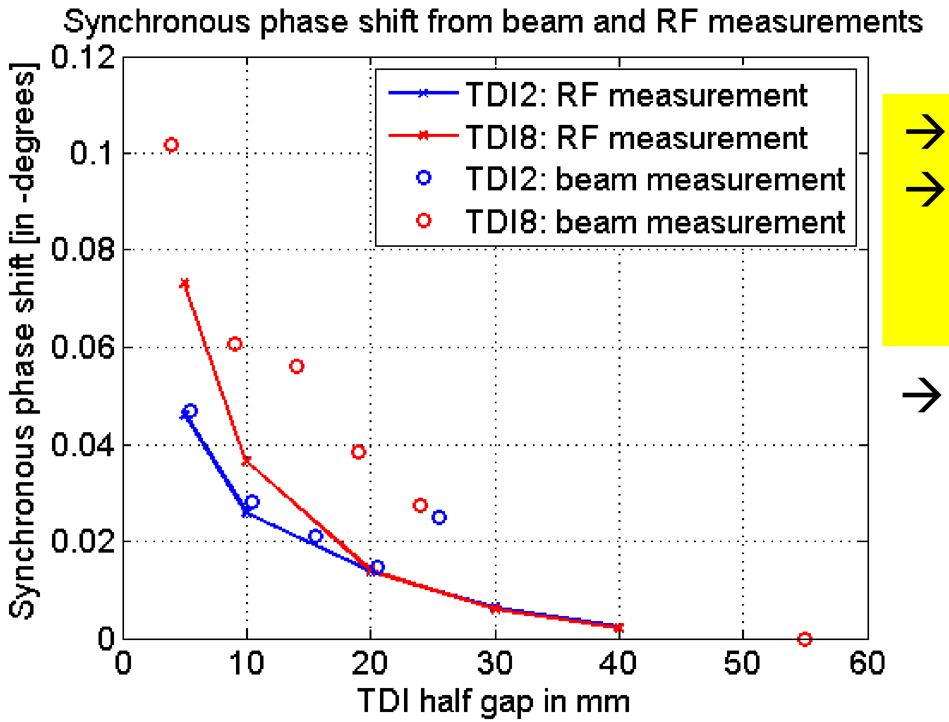


TDI issues

TDI2



TDI8



→ Something somewhere went terribly wrong.
→ More damage analysis (electromagnetic, chemical, structural) are planned to understand the origin of this non conformity.

→ Last week, bench impedance measurements confirmed the measurements with beam: the main suspect is the jaw material and its coating.

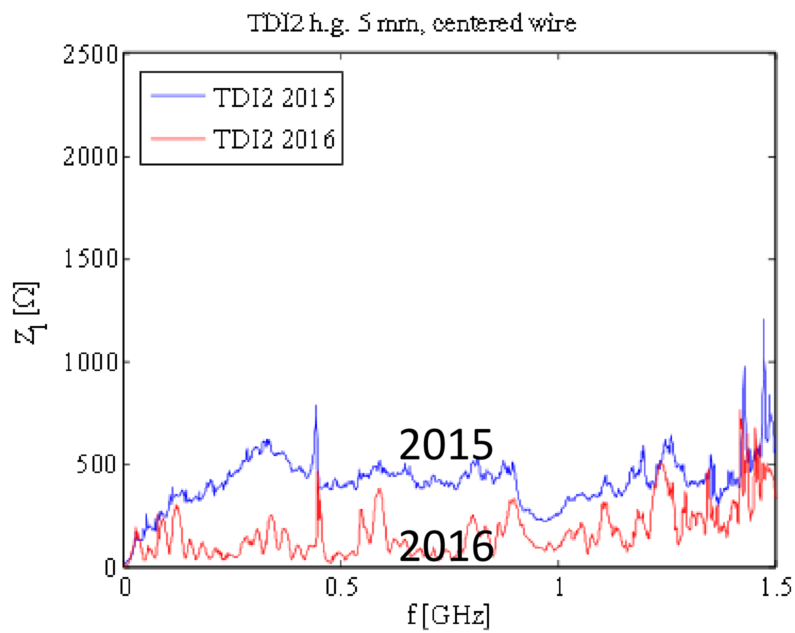
see N. Biancacci et al at LMC247.

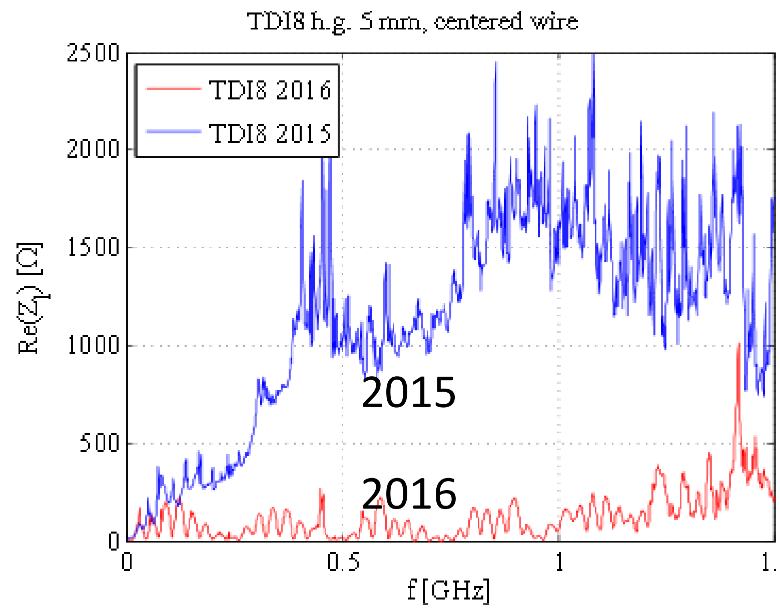
TDIs: what about 2016?

N. Biancacci et al, LMC247

Wire measurements on TDI2 and TDI8 for 2016 LHC run

Preparing 2016 run: The same set of measurements was performed on the new TDI going into the machine (Cu coated Graphite jaws in place of Ti coated HbN ones).





- The impedance is considerably reduced w.r.t. 2015 thanks to the improved jaw coating.
- Even in presence of coating problems the Graphite bulk losses are lower than in HbN.
- Still presence of HOMs (geometry has not changed).

→ The 2016 TDIs are better in terms of impedance and more robust in case of coating issues

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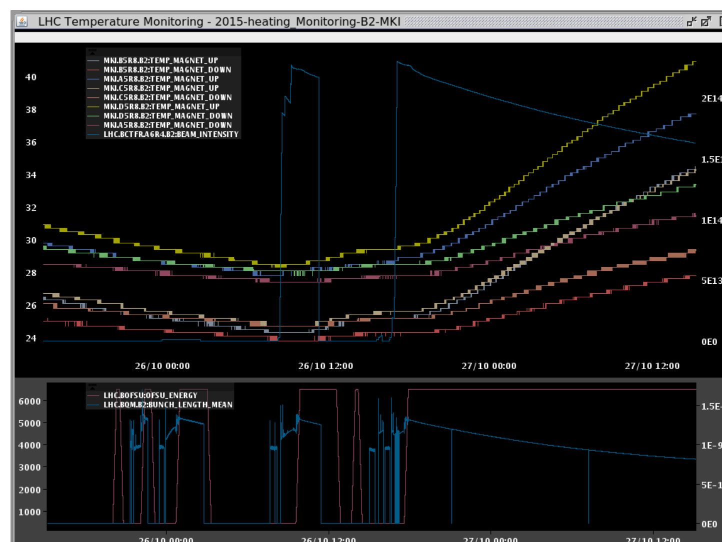
Heating monitoring in 2015

- Action from Chamonix 2014

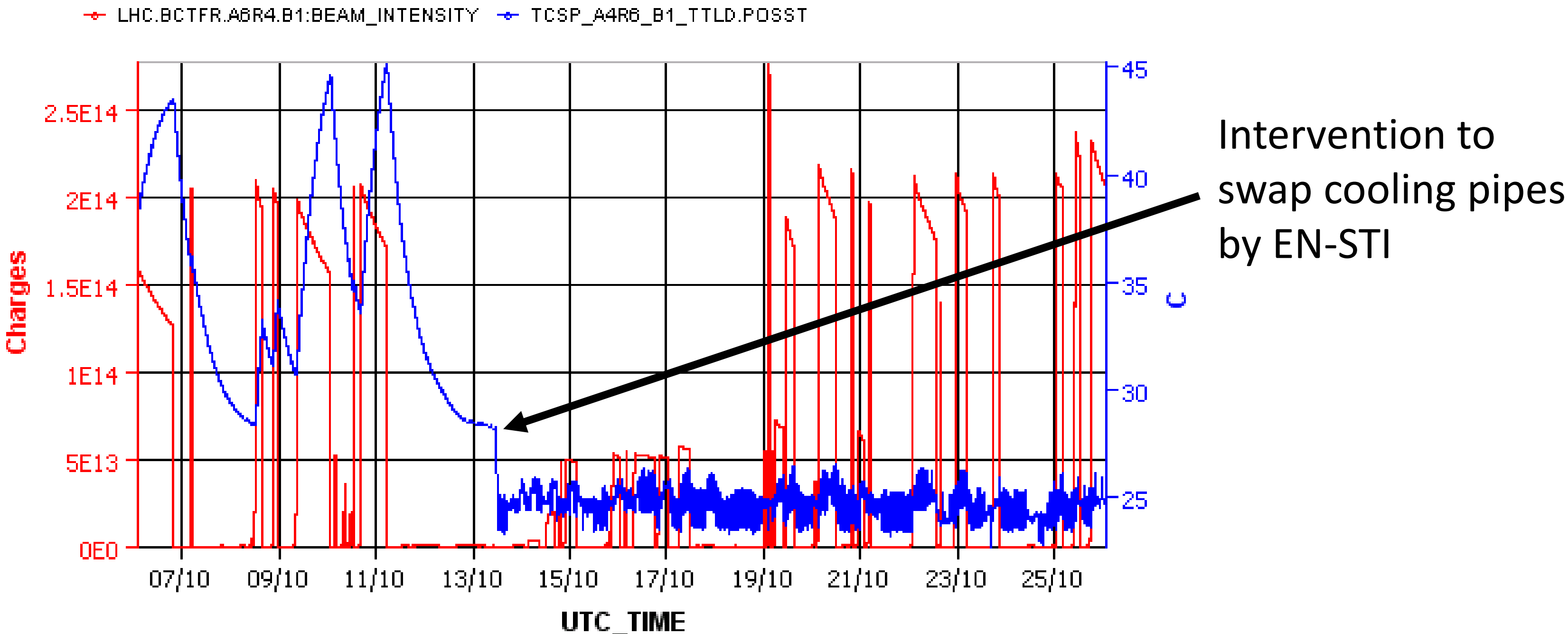
  → put surveillance tools in place for Run 2

- Available tools during 2015:
  - Temperature fixed displays (many thanks to our BE-CO colleagues!)
  - Systematic fill analyzer
  - Collimator webpage
  - Synchronous phase error with observation box (for TDI)
  - BigSISter can send prewarning text messages (no dump threshold).
  - Beam spectrum fixed display, but unfortunately there is a serious issue with the scopes and they crash very often



Heating monitoring in 2015

- Cooling connection non conformity on one secondary collimator:
  → Minor issue that was identified early and solved before it could lead to limitation.



- Heating monitoring working well but technical issues remain to be solved:
  - Several temperature probes of some collimators seem strongly perturbed by beam presence (especially TDI and TCLIA probes)
    → Measured ΔT of 10C to 100 C in 10 s when beam is dumped → not physical
    → Problem not addressed for the new TDIs and should still be there in 2016.
    → studies ongoing to understand and mitigate these issues

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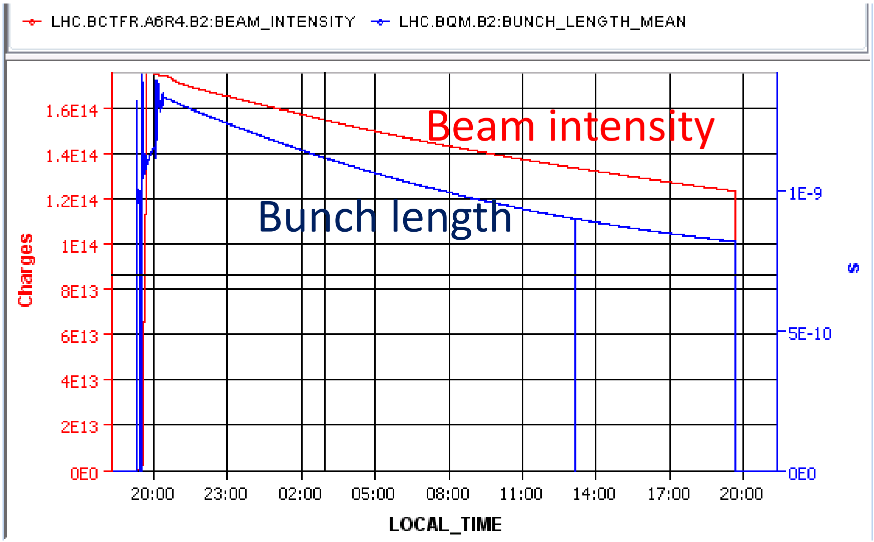
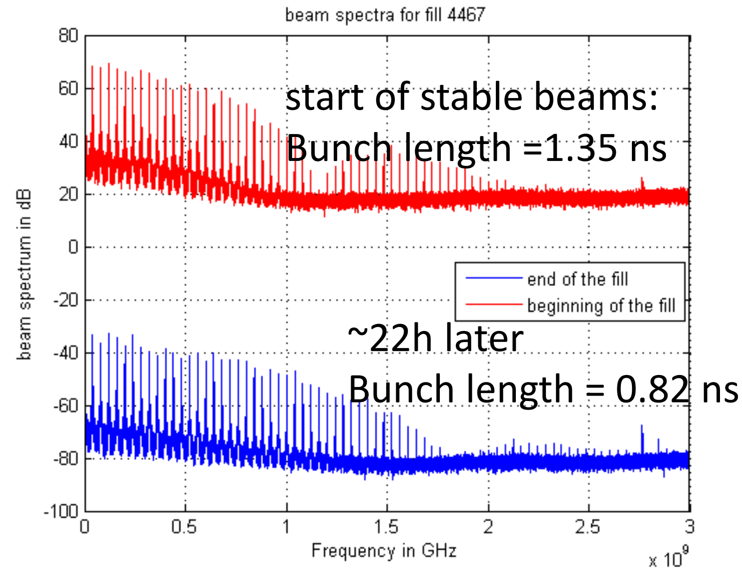
Impact of bunch length reduction during the fill:



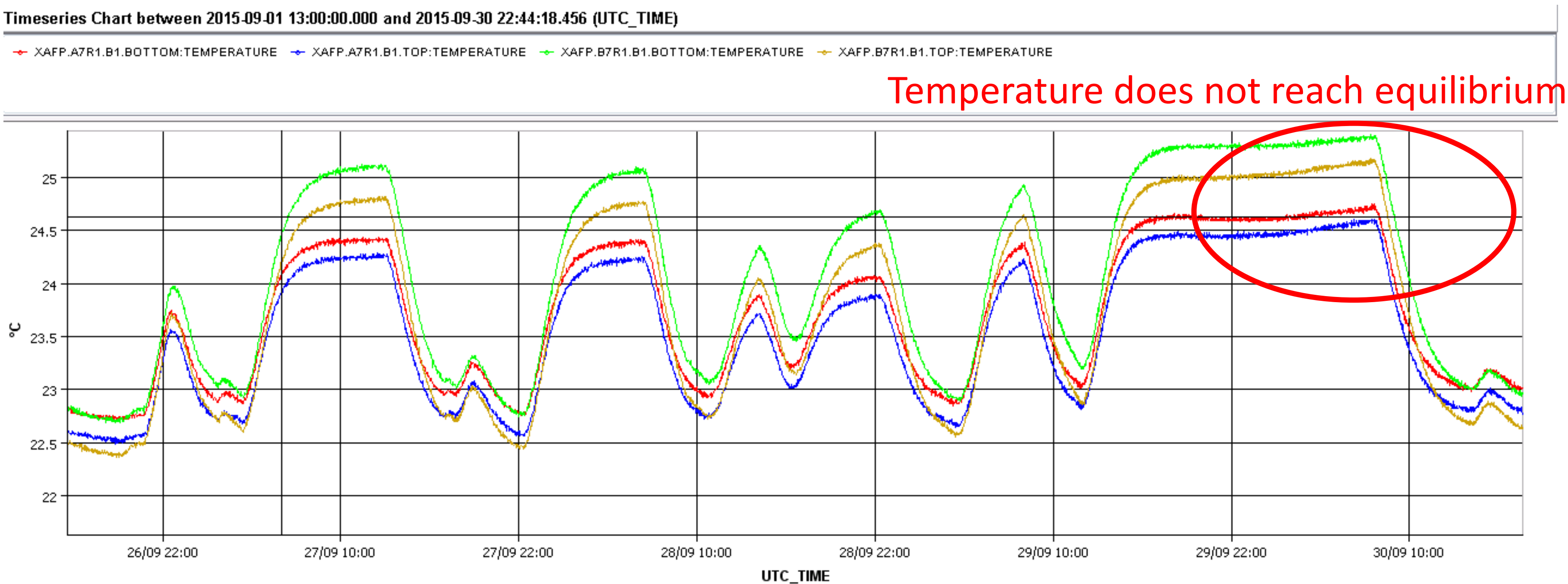


- **Power spectrum extends to higher frequency → more beam induced heating**
  → not a showstopper so far as intensity also decreases.
- **More luminosity**
  → not a showstopper either (!): expected gain with 2016 parameters ~2 % (from Fanouria's model).
- **Reducing luminous region** *(input from Jamie)*
  → request of LHCb/ALICE to keep the luminous region more constant.
  → ATLAS and CMS do not mind too much as long as there is a gain in luminosity.
- **Longitudinal instabilities at very low bunch length**
  → not an apparent issue in 2015 from bunch by bunch luminosity

→ It would be useful to be ready to control bunch length by bunch flattening

No adverse effect of bunch length reduction?

→ Case of ATLAS-ALFA in September 2015.



→ This observation did not come back after the target bunch length was increased
→ Mild increase in any case

→ We should be ready to control bunch length by bunch flattening

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Heating issues in LHC before LS1

equipment	Problem	2011	2012	2015	2016
VMTSA	Damage			removed	removed
TDI	Damage			Beam screen reinforced, ~~copper coating on the jaw~~	New design should solve problems
MKI	Delay			Beam screen upgrade and non conformity solved	
Collimators	Few dumps			Non conformity solved. TCTVB removed.	
Beam screen	Regulation at the limit	Q6R5 and TOTEM	Q6R5 and TOTEM	Upgrade of the valves +TOTEM ferrites baked out.	~12 W/half cell predicted
ATLAS-ALFA	Risk of damage			New design + cooling	
BSRT	Deformation suspected			New design	
BGI	vacuum increase			To be followed up	Temperature monitoring will be added

→ 2016 looks "cool", but beware of non conformities!

- Damage
- Limits operation
- Worry that can limit operation
- Should be fine

Main questions for this talk

- Is beam induced RF heating expected to be a limitation in 2016?

  → no (with what we know).

- What about TDI8 (injection protection collimator) that was a significant limitation in 2015?

  → the new TDIs are expected and were measured to have a lower impedance than both 2015 TDIs.

  → the new solution should be more robust in case of coating issues

  → There is hope that TDIs will not be a limitation in 2016

- Will we need to implement bunch length control in 2016?

  →It is very likely and bunch flattening should be tested early in commissioning

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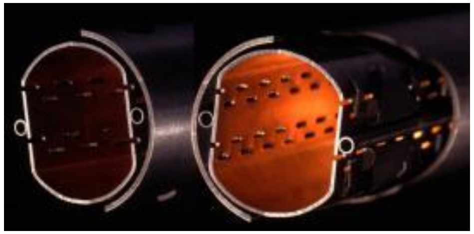
Recommendations for 2016

- Test and validate impedance of the new TDIs during commissioning (4h).
- Keep monitoring temperature, vacuum and beam spectra to identify issues in close collaboration with MPP and equipment groups.
- Find a mitigation for the spurious temperature readings.
- In view of HL-LHC, monitor in particular power lost in MKIs, TDIs, beam screen and ALICE beam pipe to assess the need for further modifications.
- Test and validate bunch flattening during intensity ramp up in case bunch length levelling at ~1 ns or ~1.1 ns would be required by either heating or experiments.

Thank you for your attention!

Beam screen heat load from impedance (LHC and HL-LHC)

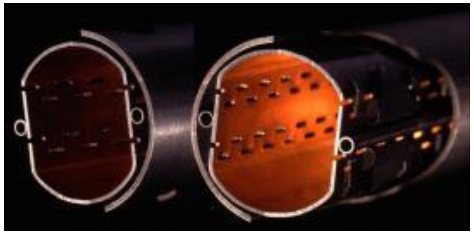


Power dissipated by the beam in the beam screen in mW/m (for 2 beams)

Beam screen	Radius (mm)	2012 4TeV 1374b 1.7e11 1.25 ns	2015 6.5 TeV 2248b 1.2e11 1.25 ns	2016 6.5 TeV 2748b 1.2e11 1.25 ns	Nominal 7TeV 2808b 1.15e11 1 ns	HL-LHC 7TeV 2748b 2.2e11 1.08 ns
Arc(*)	18.4	187	176	216	290	927
Current Q1(*)	24	143	135	165	222	710
Current Q2-Q3(*)	18.95	181	171	209	282	900

(*) Assumes 1 weld (2mm wide) on the side of the beam screen

Beam screen heat load from impedance (LHC and HL-LHC)



Power dissipated by the beam in the beam screen in W/half cell (for 2 beams)

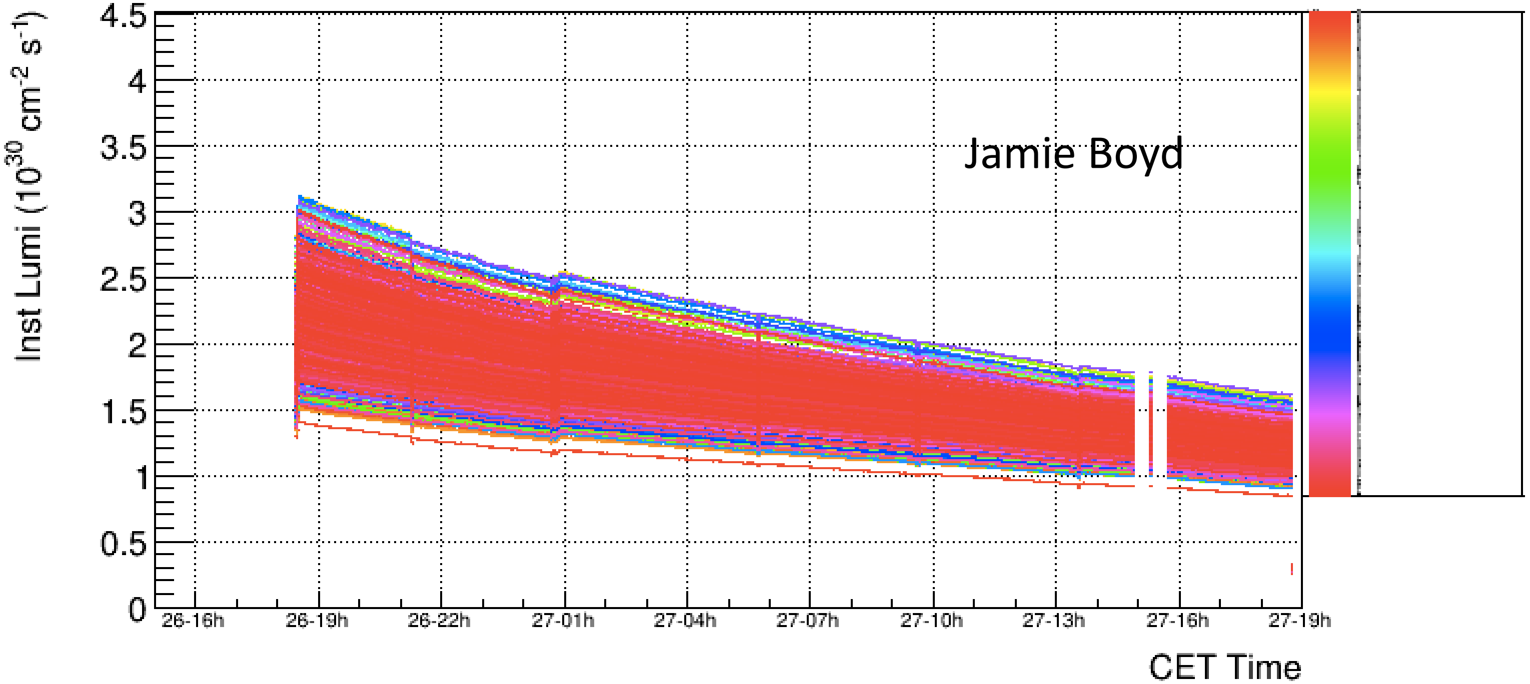
Beam screen	Radius (mm)	2012 4TeV 1374b 1.7e11 1.25 ns	2015 6.5 TeV 2248b 1.2e11 1.25 ns	2016 6.5 TeV 2748b 1.2e11 1.25 ns	Nominal 7TeV 2808b 1.15e11 1 ns	HL-LHC 7TeV 2748b 2.2e11 1.08 ns
Arc(*)	18.4	10 W	9 W	11.5 W	15.5 W	49 W

(*) Assumes 1 weld (2mm wide) on the side of the beam screen

References

- Beam induced heating at Chamonix (Elias, 2012), (Benoit, 2014)
- Evian talk by Lee (2015)

ATLAS instantaneous luminosity with longitudinal instabilities

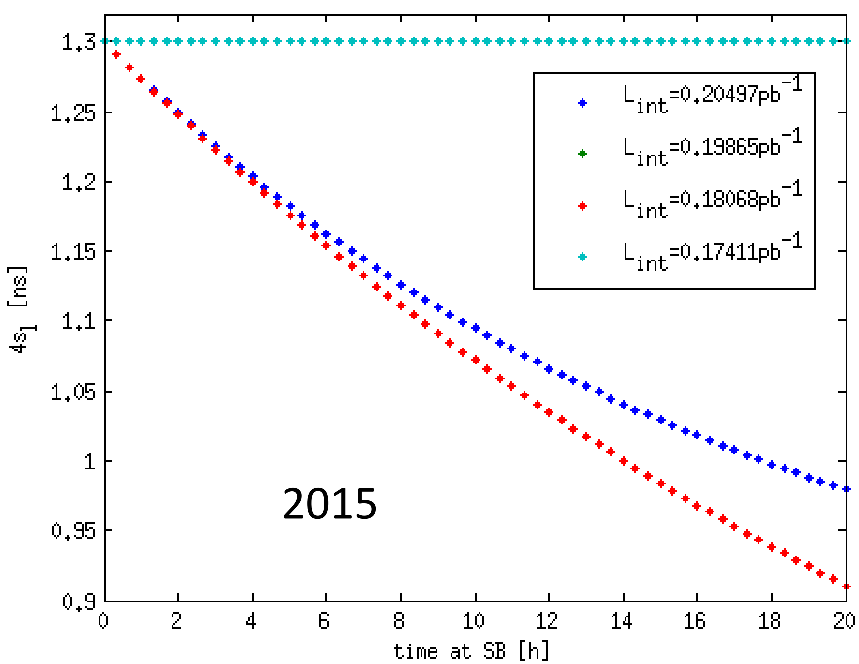


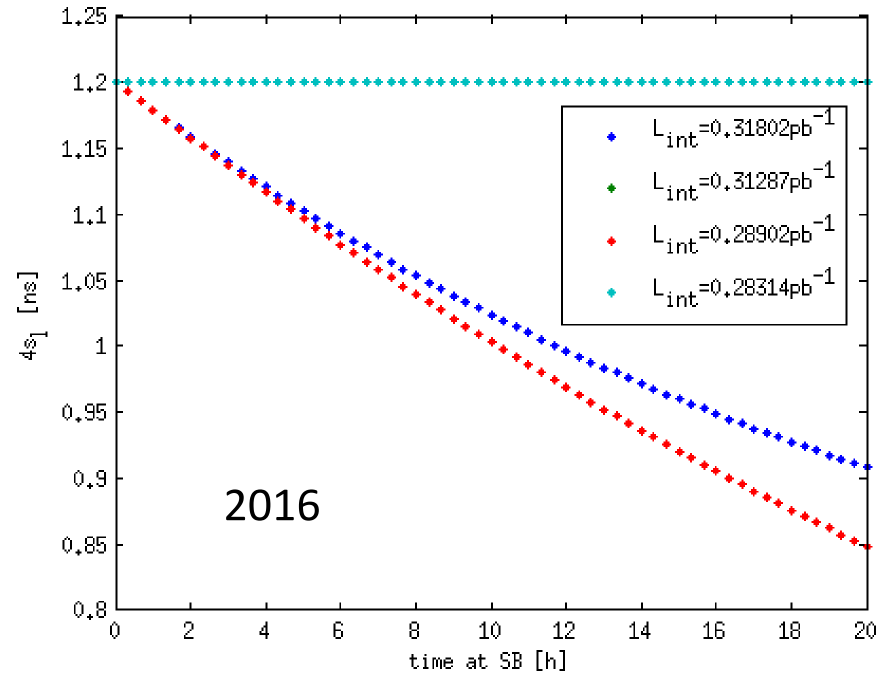
→ Even looking at bunch by bunch individually, no striking change of slope visible on the curve.

→ However, should be quantified if one needs % level.

Effect of bunch length levelling on integrated luminosity

From Fanouria Antoniou's model (for fills of 20h)





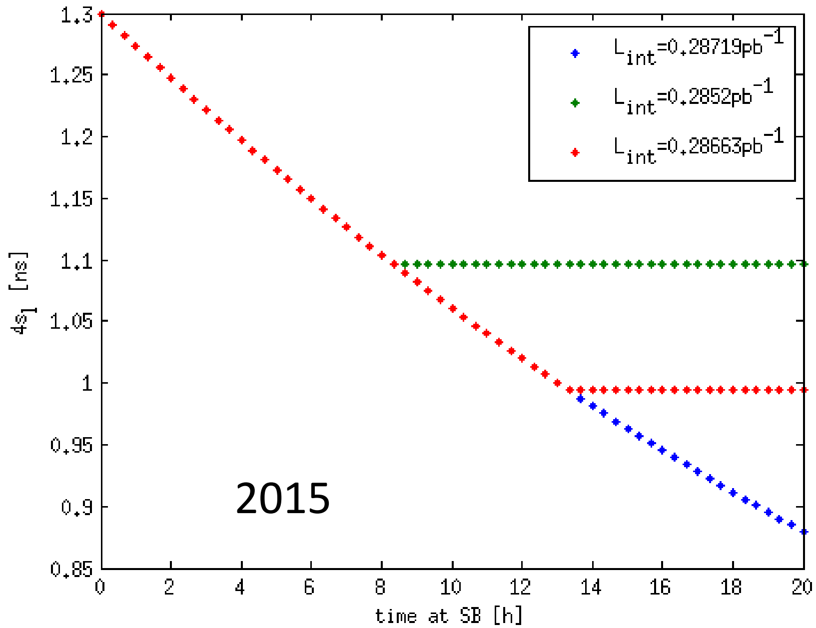
Keeping bunch length constant at 1.3 ns would have led to 3.1% to 3.6 % loss in integrated luminosity compared to leaving the bunch length decrease freely

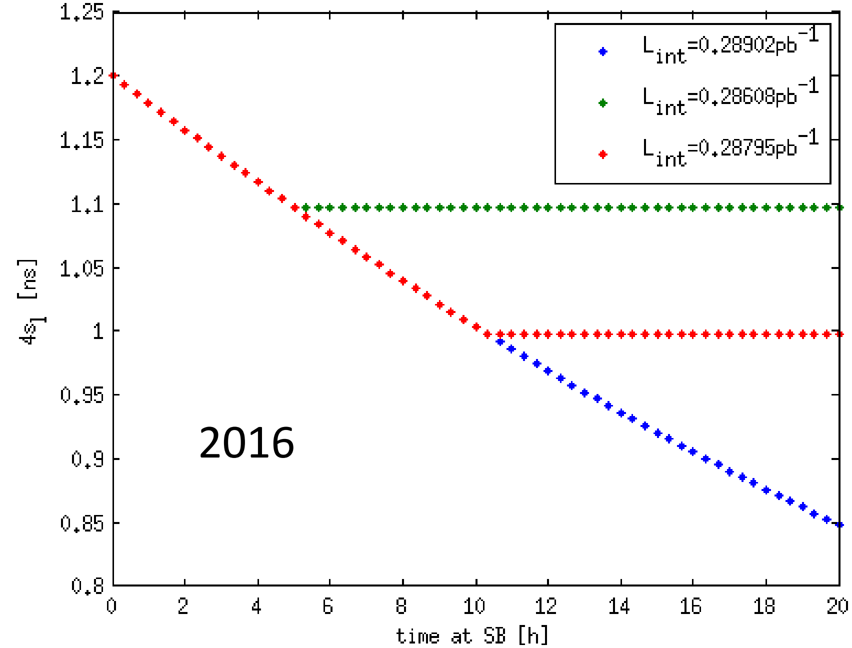
Keeping bunch length constant at 1.2 ns would lead to 1.6 to 2% loss in integrated luminosity compared to leaving the length decrease freely

3.1%: full model IBS+SR+Burnoff
3.6%: bunch length follows model but transverse emittance evolves slowly

Effect of bunch length levelling on integrated luminosity

From Fanouria Antoniou's model (for fills of 20h)





Starting from 1.3 ns and levelling at 1.1 ns or 1 ns would lead to resp. 0.1% to 0.6 % loss in integrated luminosity compared to leaving the bunch length decrease freely.

Starting from 1.3 ns and levelling at 1.1 ns or 1 ns would lead to 0.3 to 1% loss in integrated luminosity compared to leaving the length decrease freely

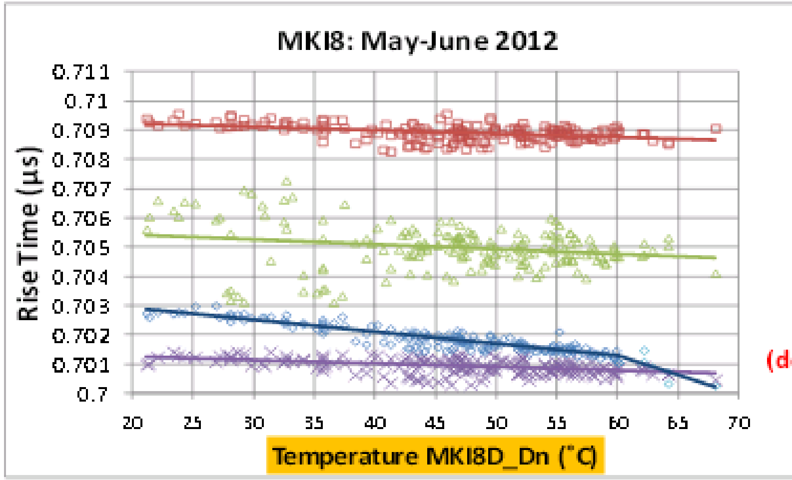
(bunch length follows model but transverse emittance evolves slowly)

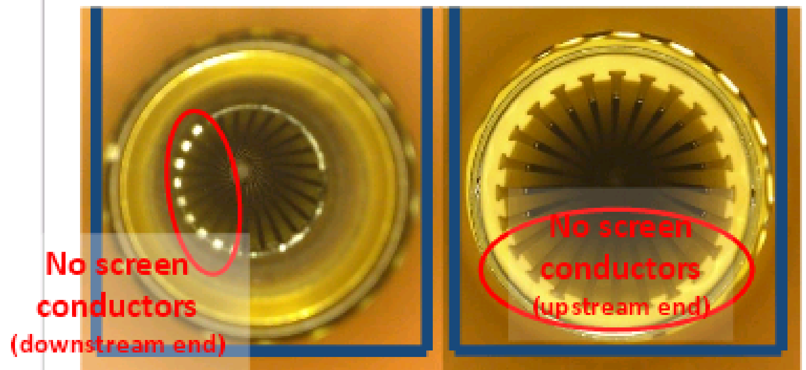
MKI Introduction

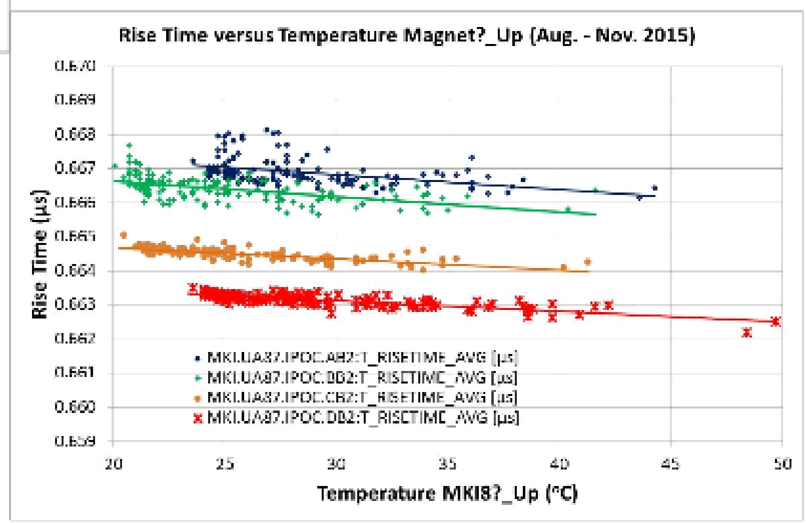
- Before LS1, there were 15 conducting screens in the aperture of each magnet.
- Until TS3 2012, MKI8D had 90 degree twist in conducting screens. Ferrite was exposed to wakefields, causing ~160W/m of heating, occasionally limiting LHC operation.
  - All other MKIs had maximum ferrite heating of ~70W/m and did NOT limit LHC operation.
- Temporary loss of magnetic properties of ferrite with prolonged periods of high intensity fills with power deposition of ~160W/m, motivated intense study into heating into all MKI's.
- After LS1, all MKI's have a full complement of 24 conducting screens. From measurements, maximum power deposition during run 2 is expected to be ~50W/m for all MKI's, i.e. less than MKI's that did not limit operation before LS1.
- Position of PT100 moved from end plates to side plates.

See 29th MKI Strategy Meeting 'Current status of LS1 work…–M. Barnes 17/12/14'

Check for non-linearity of Ferrite

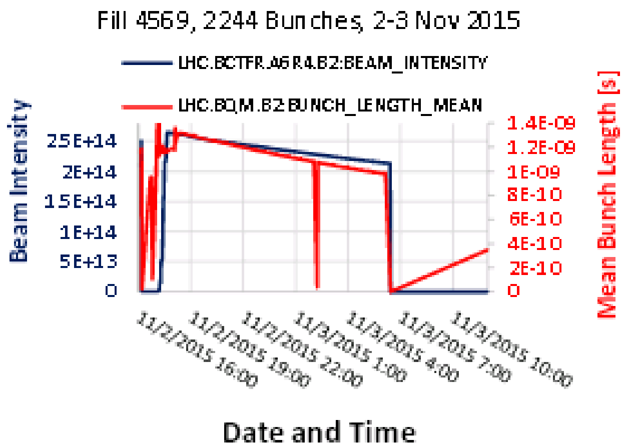


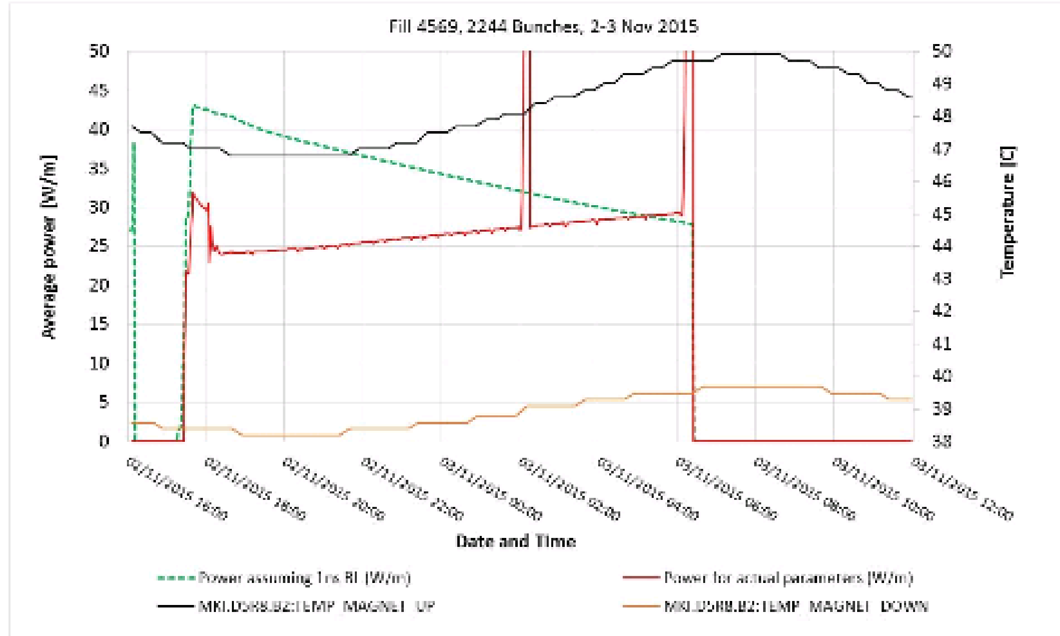




- Above: Until TS3 2012, MKI8D had "twisted" ceramic tube – causing high heating of ferrite yoke at downstream end ⇨ started to exceed Curie temperature and hence non-linearity in current rise-time above ~60˚C measured.
- Right: MKIs now have full complement of screen conductors. As expected, ferrite yoke is below Curie temperature i.e. no non-linearity seen.
- SIS interlock level gradually increased with experience, to avoid risk of mis-injection due to high ferrite temperature.

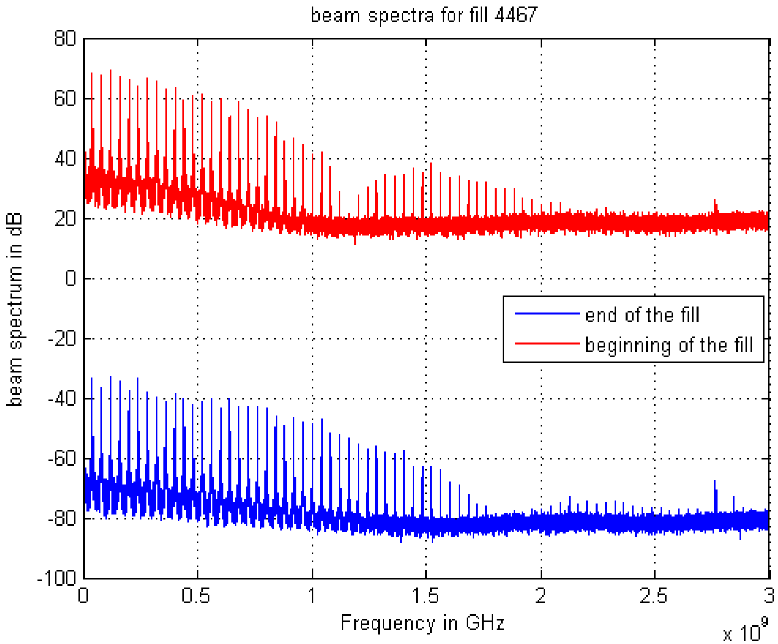
MKI Temperature During Long Fills



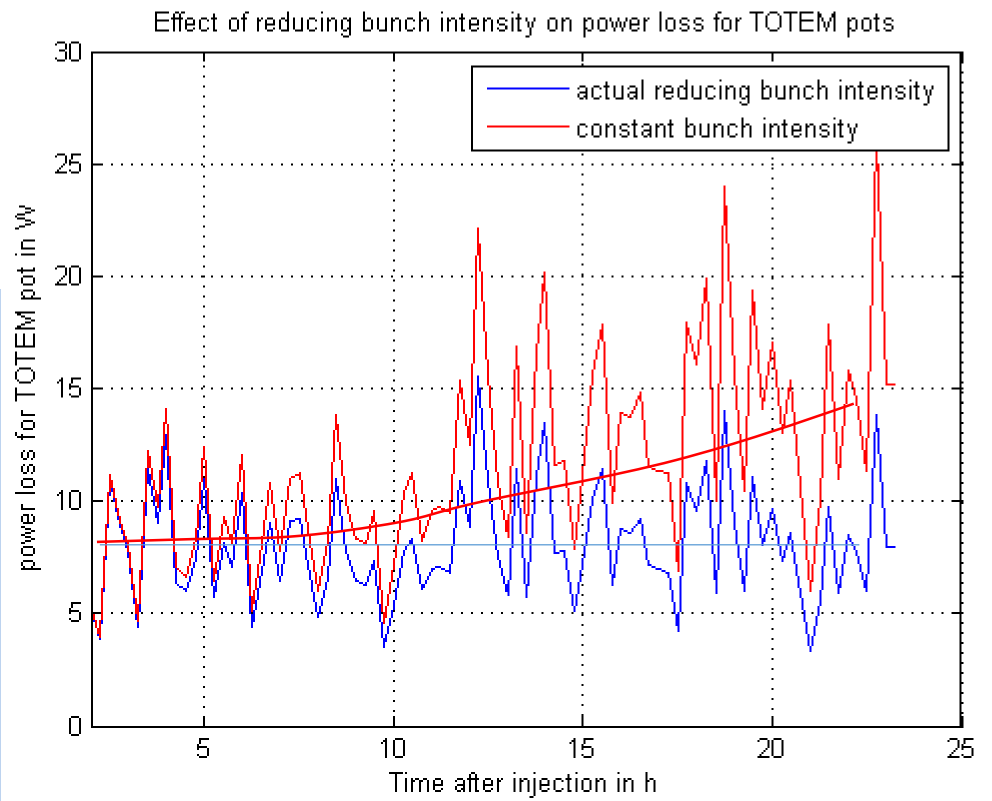


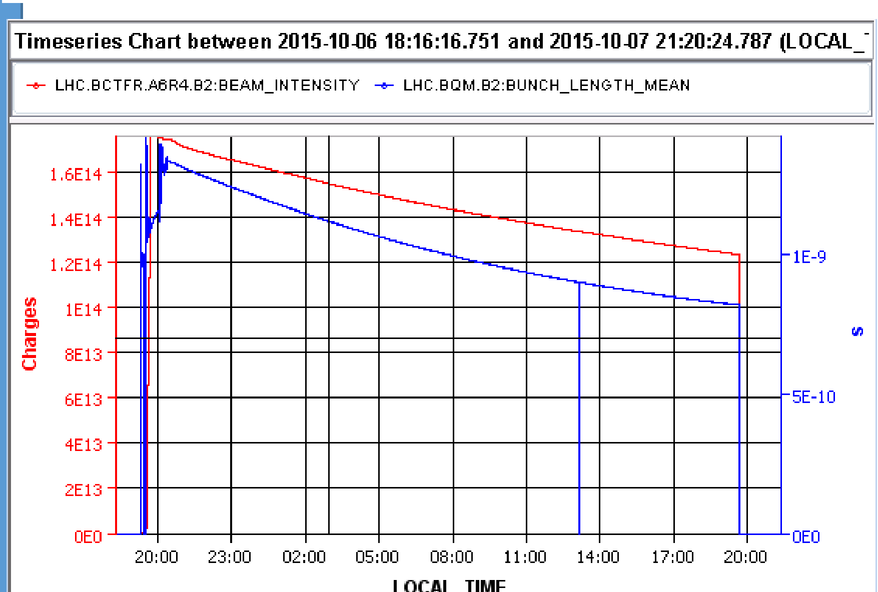
- Post LS1: upstream temperature readings, for all MKIs, are higher than downstream end.
- MKI8D Magnet_Up, as expected, has the highest PT100 reading.
- For MKI8D, average power loss estimated for above fill is ~26W/m [scaled from 52W/m for 1.15×10^{11} ppb, 2808 bunches, 1ns beam by ppb^2 and $(1/BL)^2$ to 1.16×10^{11} ppb, 2244 bunches].
- 40°C measured at downstream end corresponds to ~26W/m power deposition.
- ~50°C measured at upstream end corresponds to ~43W/m (and max. ferrite temp. of ~75°C)

Impact of bunch length on beam induced heating



Bunch length decreases
but intensity also decreases
→ Power loss leveling (here for TOTEM pot)





True for most devices, but…