Expected impact of hardware changes on impedance and beam induced heating during run 2

G. Arduini, M. Barnes, O. Berrig, N. Biancacci, F. Caspers, H. Day, J. Esteban Mueller, A. Grudiev, J. Kuczerowski, E. Métral, N. Minafra, N. Mounet, A. Nosych, A. Passarelli, G. Rumolo, J. Varela, B. Salvant, E. Shaposhnikova, C. Vollinger, M. Wendt, C. Zannini for the impedance team

With the invaluable help of
equipment groups, experiments, as well as collimation, MPP, operation teams and
HL-LHC WP2.4 collaborators.

Main messages

- Significant impedance related issues during run 1:

  → Impressive effort by all involved equipment groups to assess and reduce impedance of their device (in particular TE-VSC, EN-STI, EN-MME, BE-BI, collimation team, BE-RF, ATLAS, ATLAS-AFP, ATLAS-ALFA, CMS, TOTEM, ALICE, LHCb)

- Concerning beam induced RF Heating:

  → Many problems in run 1 linked to unexpected non-conformities.

  → Mitigations put in place but new non-conformities likely in run 2.

  → Need for efficient monitoring and alarms

  → Known limitations that led to increase bunch length from 1 ns to 1.25 ns were removed.

  → Many devices will need careful follow up (e.g. TDI, BSRT, Roman pots, MKI, BGV).

- Concerning LHC impedance: changes are expected to be transparent, but keep an eye on:

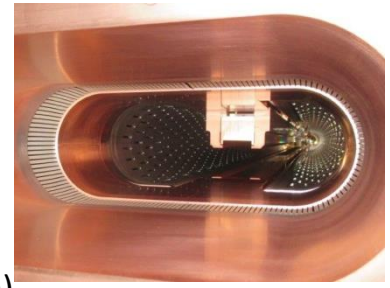
  → the new TCTP and TCSP collimators with BPMs and ferrites

  → the Roman pots, new TCL4 and especially TCL6 if they approach the beam to low gaps

Agenda

- Main messages
- Context:
  - Impedance and beam induced RF heating
- Hardware changes potentially affecting impedance during LS1
- Status of beam induced heating and instabilities
- Conclusions

Context: impact of beam impedance on performance

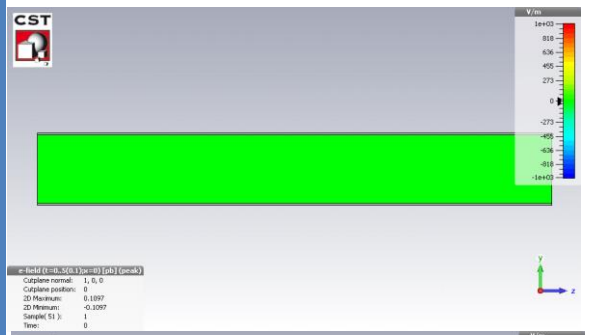


- When an ultrarelativistic beam of particles traverses a device which
  - is not smooth
  - or is not a perfect conductor,

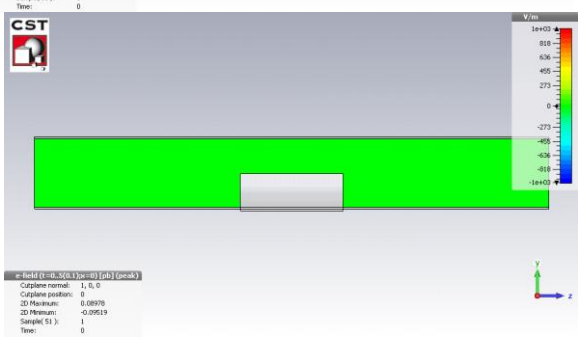
  it will produce wakefields that will perturb the following particles

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

- Example of perturbation caused by an obstacle in a beam pipe:



In a round beam pipe

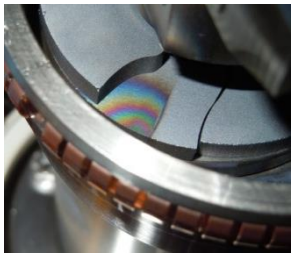


In a round beam pipe with sharp obstacle

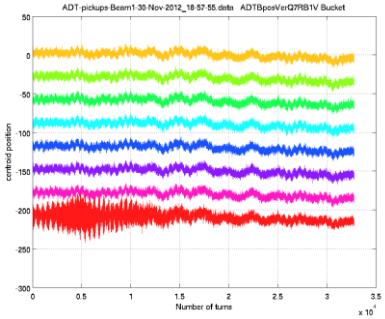
→ resonant RF mode

Context: impact of beam impedance on performance

- These electromagnetic perturbations are usually decomposed into longitudinal and transverse impedance
  - **longitudinal impedance** leads to energy lost from the particle and dissipated in the walls of the neighbouring devices
    → **heating** of beam surrounding
    → temperature interlocks or degradation of machine devices
    → during run 1, the LHC bunch length needed to be increased from 1 ns to 1.25 ns)



  - **Longitudinal/transverse impedance** leads to perturbation of the synchrotron/betatron oscillations
    → can excite **longitudinal/transverse instabilities**
    →degrades beam quality (beam losses, emittance growth and dumps)
    → many transverse instabilities occurred in LHC during run 1.



→ Current policy enforced by impedance team (when receiving a request):

(1) New equipment should by default remain in the shadow of the current LHC impedance

(2) New longitudinal resonant modes should have a shunt impedance below 200 kOhm

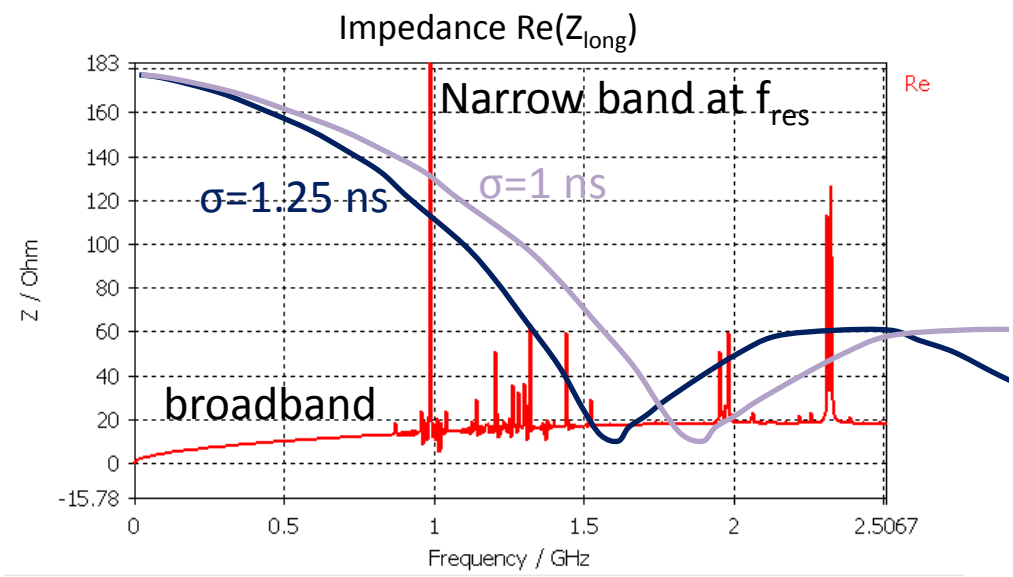
(3) Impact of new transverse resonant modes checked with beam synamics simulations

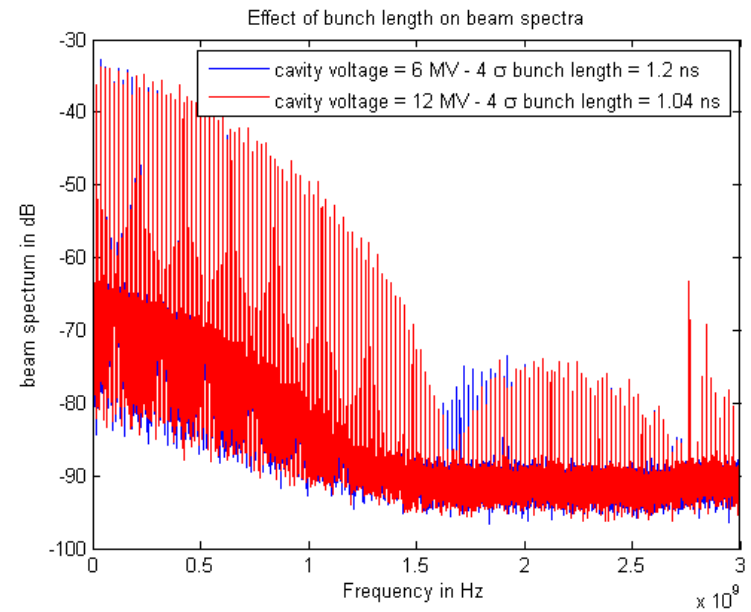
(4) Expected heat loads communicated to equipment owner to take appropriate action

Context: what can be done if heating is too large?

Power loss for M equidistant bunches: $P_{loss} = 2(eMN_b f_{rev})^2 \left(\sum_{p=1}^{\infty} \mathrm{Re}\left[Z_{long}(2\pi pMf_{rev})\right] \times Powerspectrum(2\pi pMf_{rev}) \right)$

- Reduce longitudinal impedance
- Reduce intensity per bunch (as efficient with broadband and narrow band impedances)
- Reduce number of bunches (less efficient with broadband impedances)
- Optimize the power spectrum (change bunch length but also bunch shape, e.g. with flat bunches)
- Extract the heat and/or improve the resistance to heat of the device





→ In case a problem is observed during a fill , the bunch length and/or bunch shape could be optimized, instead of dumping the beam.

Agenda

- Main messages
- Context:
- Hardware changes potentially affecting impedance during LS1
- Impact on beam induced heating
- Impact on instabilities
- Conclusions

Hardware changes during LS1 that may impact impedance

- Consolidation:
  - TDI beam screen consolidation
  - TCP replacement with spare
  - BSRT mirror design change
  - RF fingers consolidation, carroussel
- Upgrade:
  - Tertiary collimators with BPMs (TCTP and TCSP)
  - ATLAS-ALFA
  - “TOTEM consolidation” of existing Roman pots
  - MKI screen conductor upgrade
  - New experimental beam pipe in CMS and ATLAS
  - Schottky
- New equipment:
  - New TCL4 and TCL6
  - 3rd TCDQ module
  - BGV on B2
  - New “TOTEM upgrade” pots
  - New UA9 goniometer
- Non conformities:
  - Contacts in triplets
  - ~~RF fingers next to TCTH and TCTV in pt 5~~

Hardware changes during LS1 that may impact impedance

- Consolidation:
  - TDI beam screen consolidation
  - TCP replacement
  - BSRT
  - RF fingers consolidation, carroussel
- Upgrade:
  - TCTP and TCSP
  - ATLAS-ALFA
  - “TOTEM consolidation” of existing Roman pots
  - MKI
  - New experimental beam pipe in CMS and ATLAS
- New equipment:
  - TCL4
  - TCL6
  - 3rd TCDQ module
  - BGV
  - New “TOTEM upgrade” pots
  - UA9 goniometer

Modifications in order to reduce beam induced heating

Hardware changes during LS1 that may impact impedance

Issue to follow up

- Consolidation:
  - TDI beam screen consolidation ← heating
  - TCP replacement
  - BSRT ← heating
  - RF fingers consolidation, carroussel
- Upgrade:
  - TCTP and TCSP ← instabilities
  - ATLAS-ALFA ← heating
  - "TOTEM consolidation" of existing Roman pots ← Heating/instabilities
  - MKI
  - New experimental beam pipe in CMS and ATLAS
- New equipment:
  - TCL4 ← instabilities
  - TCL6 ← instabilities
  - 3rd TCDQ module
  - BGV ← heating
  - New "TOTEM upgrade" pots ← Heating/instabilities
  - UA9 goniometer

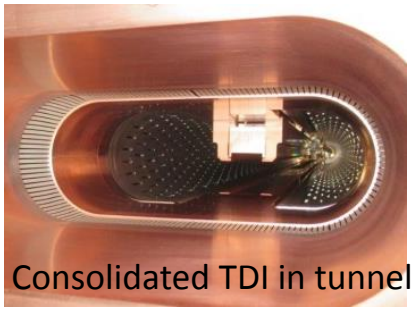
Modifications in order to reduce beam induced heating

Agenda

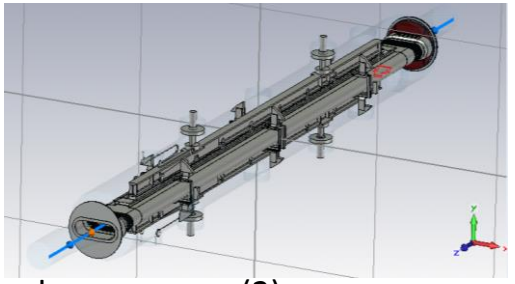
- Main messages
- Context:
- Hardware changes potentially affecting impedance during LS1
  - Focus on TDI, BSRT, Roman pots, MKI, TCTP, TCSPs, TCLs
- Status of beam induced heating and instabilities
- Conclusions

Impact on beam induced heating: TDI

- Significant issues before LS1:
  - Large outgassing with beam → **issues for background of experiments**
  - Deformation of beam screen → **issue for device integrity and machine protection**
  - Deformation of jaw → **issue for device integrity and machine protection**


Consolidated TDI in tunnel

- Causes:
  - No temperature monitoring, so difficult to understand what was going on
  - Water cooling eventually inefficient
  - Not easy to design as it is an internal dump (very long jaw, large volume, abrupt steps, dielectric material)



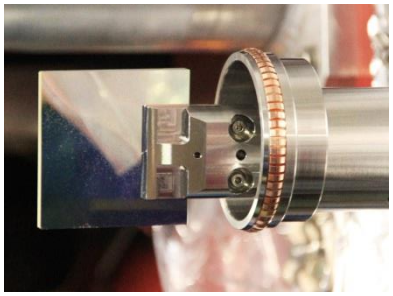
- Actions taken during LS1:
  - Stiffening of beam screen
  - More pumping power
  - Refurbishment of jaw mechanism
  - Removed copper coating on the beam screen (to reduce shunt impedance of
  - Temperature probes added on the lower jaw (4) on the support (2), and on the beam screen (2).
    - → **despite very large effort by EN-STI and TE-VSC, similar heat load as before LS1 expected for run 2**
    - → **heating issues may come back**
    - → **however, the refurbished TDIs should cope better with this heat load**

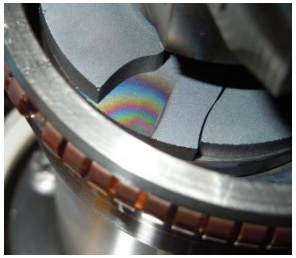
- What can we do if problems come back?
  - Spares with copper coating studied for installation in Christmas stop 2015/2016.
  - Decrease intensity per bunch
  - Additional diagnostics and impedance measurements before the installation should indicate the best mitigation mechanism (bunch length increase or bunch shape change)
  - Spend as little time as possible with TDI jaw gap closed (e.g. open after each injection if this does not jeopardize reliability).

→ To be monitored very closely in run 2

Impact on beam induced heating: BSRT

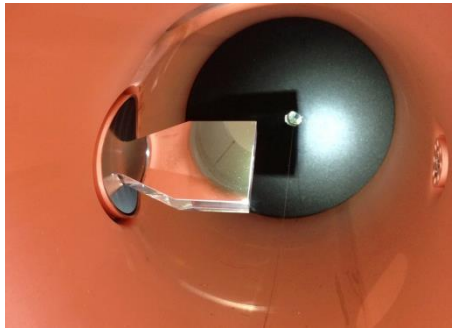
- Significant issues before LS1:
  - Deformation of mirror → problem for emittance measurement
  - Damage on holder and ferrite → problem for machine protection





- Causes:
  - ferrite to damp the RF mode due to the mirror and mirror holder, but difficult to evacuate the heat from the ferrite in vacuum

- Actions taken during LS1:
  - → mirror and mirror holder geometry modified to attenuate the RF mode
  - → RF mode expected to be small enough so that no ferrite is installed
  - → Ongoing RF measurements and RF studies to validate the design
  - → Simulations currently predict 50 to 200 W on the whole device
    (2 to 10 W on the mirror if the mode overlaps with the beam spectrum)

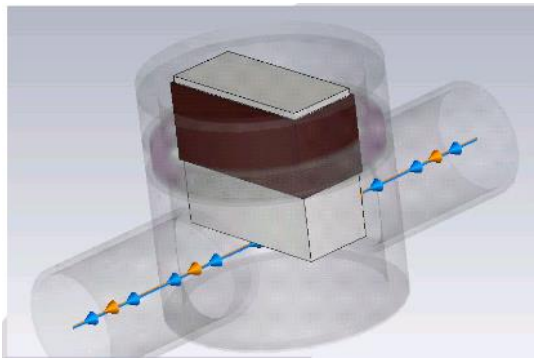


- What can we do if problems come back?
  - Increase bunch length, Decrease intensity per bunch
  - Try to cool from outside the vacuum chamber since a large proportion of the heat should be dissipated in the copper coated vacuum pipe.
  - Slightly move the mirror holder to try and avoid overlapping of RF mode with beam frequencies.

→ Changes should make things better but to be monitored very closely in run 2

Impact on beam induced heating: roman pots

- Significant issues before LS1:
  - Temperature of ATLAS-ALFA detector close to damage limit
  - Efficient cooling on TOTEM but related heating/outgassing may have generated Cryo regulation issues on neighboring Q6R5 (evidence of overheating of the ferrites were found during LS1).



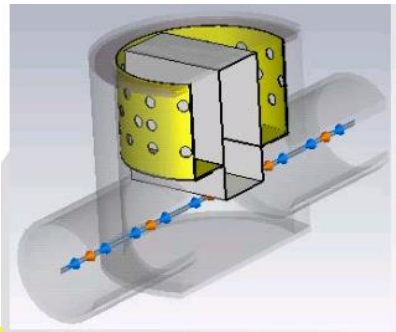
- Causes:
  - Design was not optimized to reduce heating
  - No cooling designed for ATLAS-ALFA
  - TOTEM pots wish to approach the high intensity beams

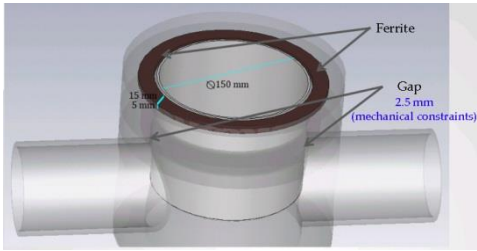
- Actions taken during LS1:

  → significant redesign of the Roman pots and relocation of ferrites where they can be cooled more easily

  → For ATLAS-ALFA, improvement of heat extraction and cooling capacity.

- What can we do if problems come back?
  - Increase bunch length, decrease intensity per bunch
  - Increase cooling capacity
  - Keep Roman pots far from the high intensity beam





→ Changes should make things better, to be monitored very closely in run 2 (in particular when approaching high intensity beam)

Impact on beam induced heating: MKI

- Issues before LS1:
  - Temperature of one kicker approached ferrite Curie temperature, which affected the kicker performance → need to wait before injection.

M. Barnes et al

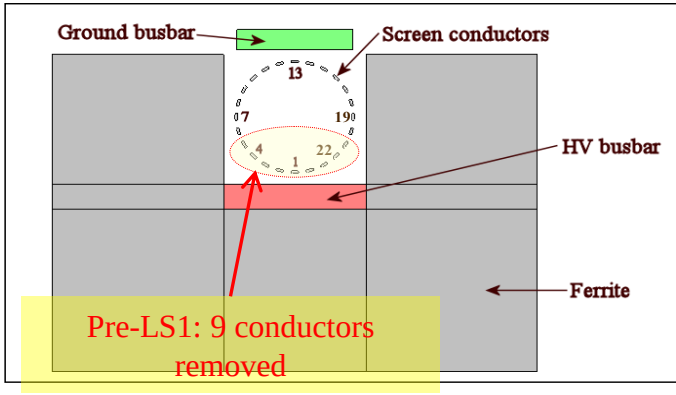
- Causes:
  - 9 screen conductors had to be removed with respect to design before run 1 to avoid electrical breakdowns.
  - Difficult to design cooling in vacuum together with the kicker high voltage.
  - Non-conformity of one MKI kicker (old MKI8D): screen conductors were twisted and not screening efficiently.

- Actions taken during LS1:

  → Implementation of results of pre-LS1 studies to redesign the screen conductors, to allow to install all 24 screen conductors (staggered without metallization at end)

  → systematic measurements of all MKIs before installation to detect non-conformities

M. Barnes et al



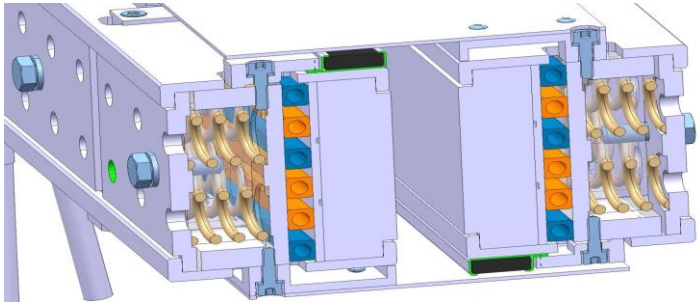
- What can we do if problems come back? (not expected)
  - Check if problem is a non-conformity or a design problem
  - Check if the temperature increase affects performance (softstart)
  - Decrease intensity per bunch
  - Increasing bunch length should help

→ Problem expected to be solved, but to be monitored in run 2

Impact on instabilities: new collimators with BPMs and ferrites

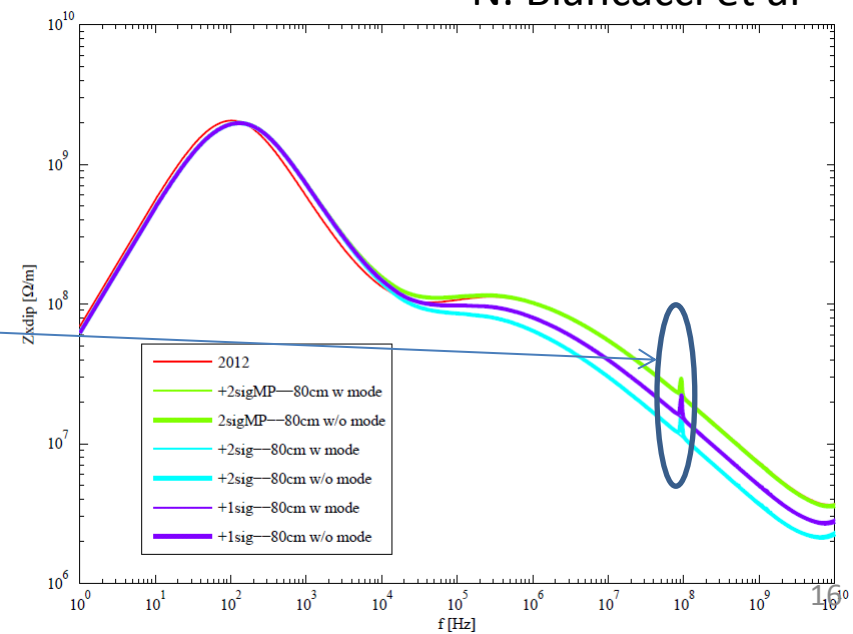
- Potential issues:
  - Transverse RF mode enhanced by the large beta function at the tertiary collimators
  - ferrite heating

- Causes:
  - New design with BPMs made the design of lateral RF contacts difficult
    → following all the issues with RF contacts in 2011, recommendation by the impedance team in 2011 to leave the gap open and install ferrites (only for the 8 TCTPs and 1 TCSG in 6 per beam, provided the gap is not too small).



Consequence: TCTP transverse mode at ~100 MHz (~30% above the impedance baseline at that frequency)

N. Biancacci et al



→ Impact on beam dynamics?

Impact on instabilities: new collimators with BPMs and ferrites

- Expected consequences on beam dynamics:

  → DELPHI, HEADTAIL and NHTVS simulations performed by N. Mounet and A. Burov (TCTP meeting in April 2013) and rechecked by N. Biancacci et al (in 2014). → small impact on beam stability expected.

  → Most of the beam induced heat load on the jaw and not the ferrites (~1 W expected on the ferrites after LS1)

- Actions during LS1:
  - Heavy simulation and measurement campaign to characterize fully the new collimator design (with the help of EN-MME, A. Mostacci (La Sapienza), M. Zobov and O. Frasciello, INFN Frascati and HL-LHC WP2 funding).

- What can we do if there are still problems?
  - Check if problem is a non-conformity or design problem to decide if useful to change with spare
  - Decrease intensity per bunch
  - For **stability**, increase jaw gap, or at constant gap decrease beta function at the TCTs.
  - For **heating**, increasing bunch length and decreasing jaw gap (!) should help.
  - Future designs of collimators with BPMs should use lateral RF contacts instead of/in addition to ferrites.

→ Impact is expected to be small
→ Need to be monitored in run 2

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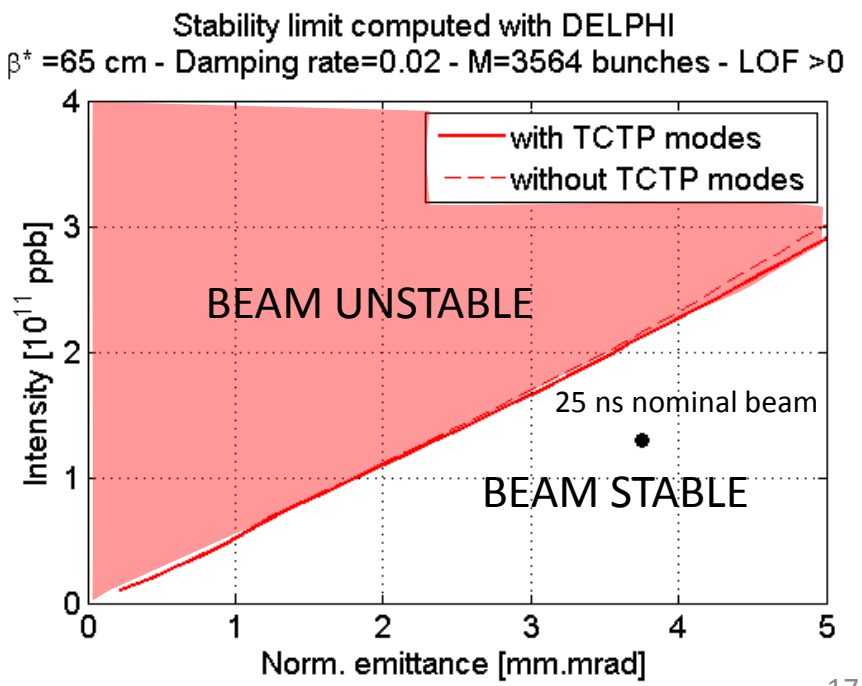
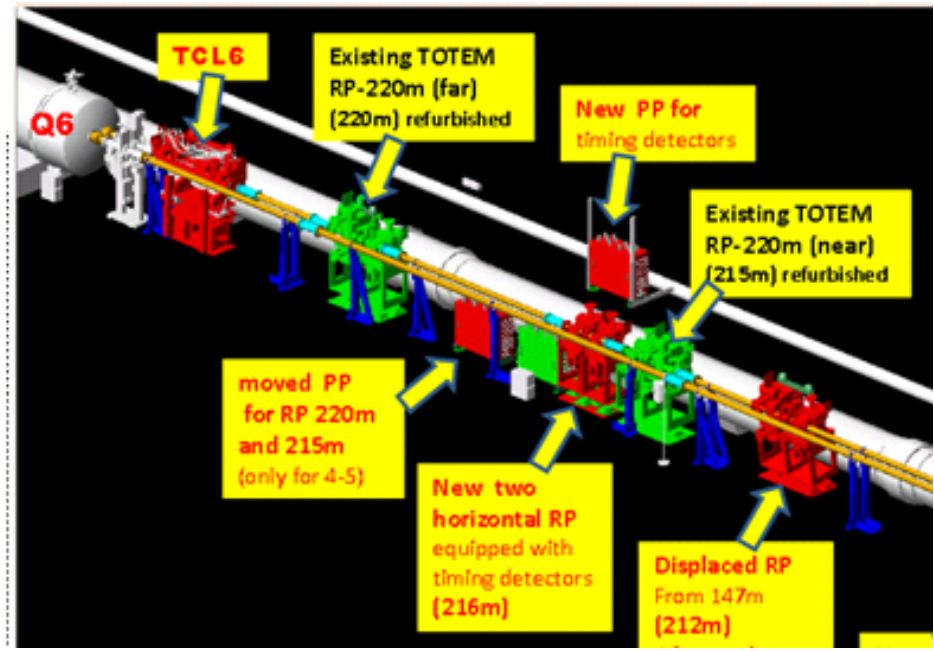


Impact on instabilities: new TCL4 and TCL6 + Roman pots

- Causes:
  - Very small gaps for Roman pots and TCL6 → high impedance
  - TCL4 has a smaller impact (metallic collimator at reasonable gaps)
  - Need to wait for the operational scenarios for these collimators and Roman pots (to be discussed at LMC: a tradeoff should be found between TOTEM protection and performance and requests by the impedance/energy deposition/collimation teams).

- What can we do if there are problems?
  - Retract the jaws and the Roman pots!
  - Decrease bunch intensity



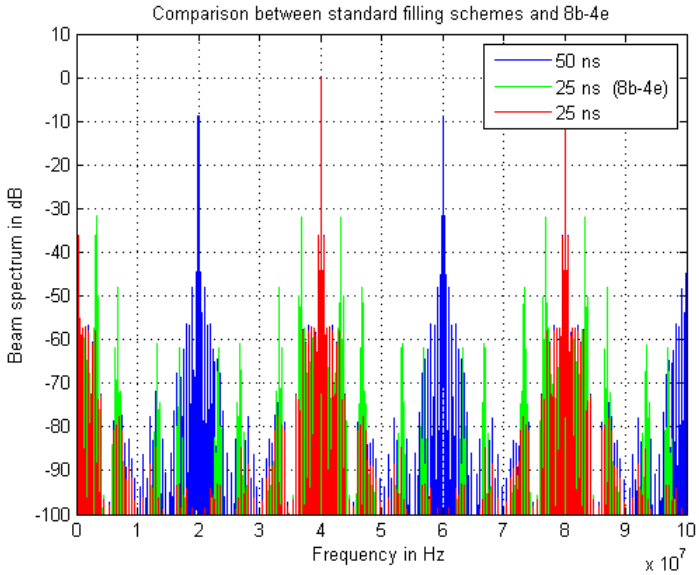
→ Impedance could limit the smallest operational gap
→ Need to be monitored in run 2

Other relevant information due to changes

- **3rd TCDQ module** → simulated impact on impedance expected to be small
- **BGV** → potential heating by RF mode at high frequency to be monitored
- **UA9 goniometer** → no impact expected since well shielded from the beam.
- **Passive absorbers in IR3** → no impact expected.
- **New beam pipe in CMS and ATLAS** → no issue expected.
- **TCP spare** that was overheating will be inspected this week with EN-STI colleagues.

- **8b4e beam** may lead to more heating due to the additional beam spectral lines that are not present with either regular 50 ns or 25 ns beams

- New studies account for the impact of 2 counter-rotating beams on beam induced heating in the beam screen (with weld)→ G. Iadarola, G. Rumolo and C. Zannini. The impact is small so far (for heating, 1 beam +1 beam ~ 2 beams).



Agenda

- Main messages
- Context:
- Hardware changes potentially affecting impedance during LS1
- Status of beam induced heating and instabilities
- Conclusions

Status of pre-LS1 beam induced RF heating issues

Element	Problem	2011	2012	2015 (expected)
Double-bellow VMTSA	Damage			All VMTSAs removed
Injection protection collimator TDI	Damage			Beam screen reinforced. Copper coating on the jaws abandoned
Injection kicker MKI	Delay (cold-down)			Beam screen upgraded
Primary collimator TCP B6L7.B1	Few dumps			Non-conformity should be removed (suspected cooling system issue)
Tertiary collimators TCTVB	Few dumps			All TCTVBs have been removed.
Beam screen standalone Q6R5	Regulation at the limit			Valves upgraded Neighboring TOTEM pot upgraded
ATLAS-ALFA roman pot	Risk of damage			New design being installed
Synchrotron light telescope BSRT	Damaged			New design being installed

→ All issues that led to increase bunch length from 1 ns to 1.25 ns in 2011 are expected to be solved:
- → All MKIs were upgraded, all now have 24 screen conductors.
- → Cryo margins on standalones were increased (L. Tavian, S. Claudet)
- → TCTVB collimators were removed

Status of beam induced RF heating:
Predicted impact of consolidations and changing bunch length on heating (ongoing work)

Element	Before LS1 (1.7e11 p/b – 1374 bunches- 1.25 ns)	Consolidation of design during LS1	After LS1 (1.2e11 p/b – 2748 bunches - 1.25 ns)	After LS1 (1.2e11 p/b – 2748 bunches -1 ns)
TDI (resistive wall at 55 mm)	36 W	Yes (but not on the jaw)	36 W (~)	48 W (+33%)
Arc beam screens	186 mW/m	No	215 mW/m (+15%)	300 mW/m
Triplet beam screens (Q1/Q2-Q3)	286/360 MW/m	No	331/419 mW/m (+15%)	460/590 mW/m
MKI	70 W/m (*) 160 W/m (**)	Yes	To be computed	36 to 55 W/m (-79% to -67% c.f. non-conforming)
MKD	22 W	No	22 W (~)	30 W (+35%)
TCP collimator	62 W	No	60 W (~)	92 W (+48%)
TCTP (at +/-5 mm)	-	-	3 W	5W
TOTEM** at 40 mm at 2 mm	10 W 57 W	Yes for some	5 W (-50%) 10 W (-80%)	13 W (+30%) 27 W (-32%)
ATLAS-ALFA at 40 mm	37 W	Yes	7 W (-80%)	20 W (-45%)
BSRT mirror (broadband/narrow band)	30 W (/0 W)	Yes	1 W (/1 to 4 W potential)	4 W (/2 to 8 W potential)
BGV (potential modes)	-	-	50 W (potential)	1 kW (potential)
ALICE cone (mode at 750 MHz) CMS cone (mode at 530 MHz) LHCb (mode at 630 MHz)	200 W (potential) 55 W " 50 W "	No	400 W (potential) 110 W " 100 W "	640 W (potential) 300 W " 190 W "

→ Significant improvements expected after LS1 consolidation on many equipment
→ Should be checked with temperature and power spectrum monitoring

(*) for conform MKI with 15 screen conductors
(**) for non-conforming MKI
(***) resistive wall not included

Status of longitudinal stability

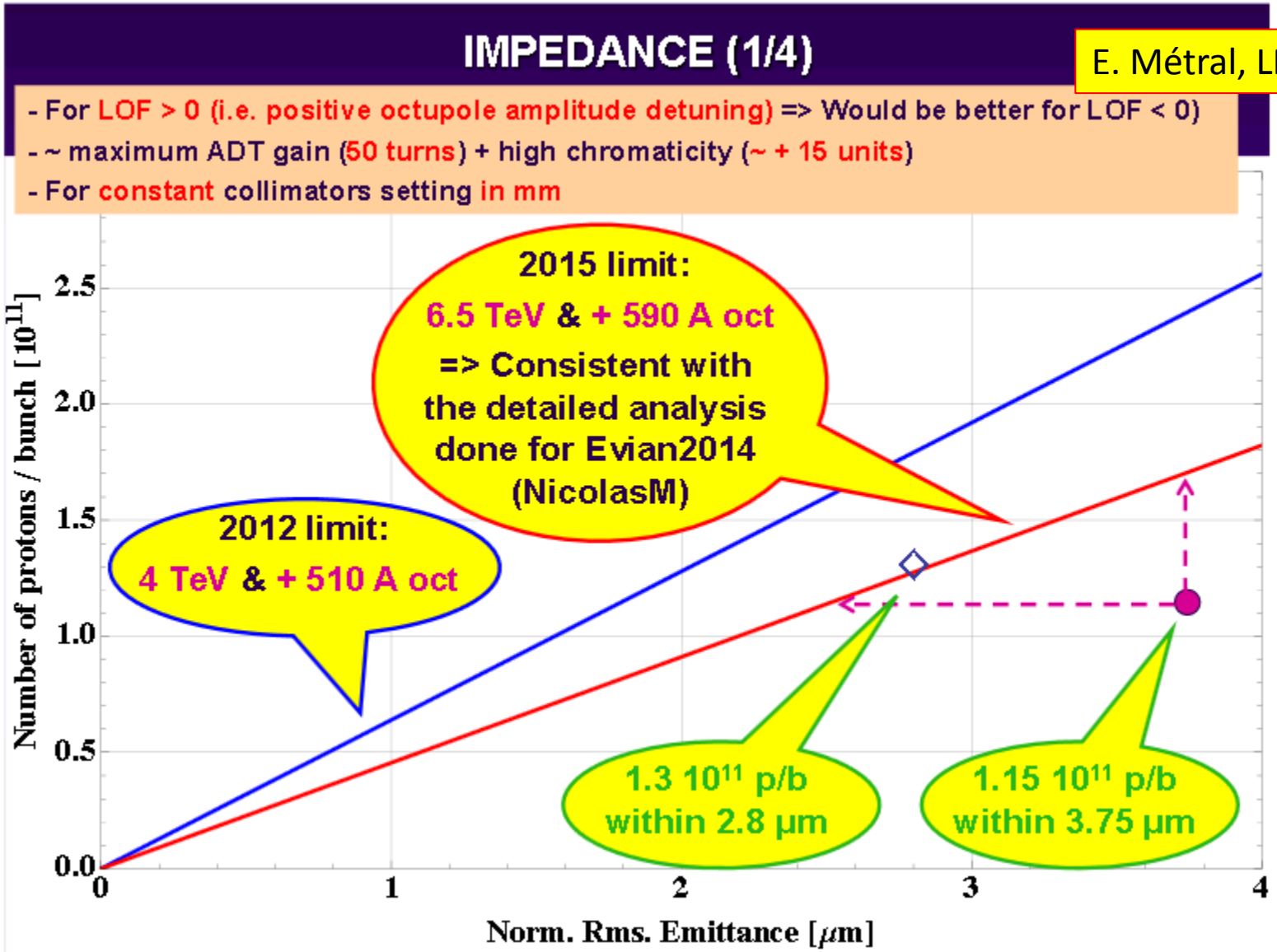
Evian 2014 talk of J. E. Mueller et al

Conclusions

- Margin in longitudinal stability → Lower emittances are tolerable:
  - Improved beam lifetime
  - Effect of IBS is expected to be not significant
  - Possibility of luminosity levelling
- Improvements in heating
  - Known issues expected to be solved
  - More temperature monitoring and alarms available after LS1
  - Flat bunches and bunch length levelling as possible mitigations

→ Shorter bunches (1.0 ns) are probably feasible
Are they interesting for experiments?

Status of transverse impedance related instabilities



→ Nominal 25 ns beam should be stable with both octupole polarities, high chromaticity and maximum ADT gain.

Status of transverse impedance related instabilities

CONCLUSION (3/3)

E. Métral, LMC188

- Expected limitations in bunch intensity & emittance (assuming no Collide & Squeeze) with LOF > 0
  - ~ 1.3E11 p/b within ~ 2.8 μm (with the same collimator settings as 2012)

Corresponding to β* ≈ 65 cm (RoderikB, Evian2014) => β* could be reduced if we do not reach this brightness limit

  - Brightness could be increased by
    - Opening the collimators BUT then smaller β* reach
    - Changing to LOF < 0 BUT then also smaller β* reach
  - With LOF < 0 and Collide & Squeeze, the brightness could be increased to the 1-beam limit (~ 1.6 times larger than above => to be checked…) or the β* further decreased (~ nom. coll. sett.)

Elias Métral, LMC meeting, 03/09/2014 14/14

Agenda

- Main messages
- Context:
- Hardware changes potentially affecting impedance during LS1
- Status of beam induced heating and instabilities
- Conclusions

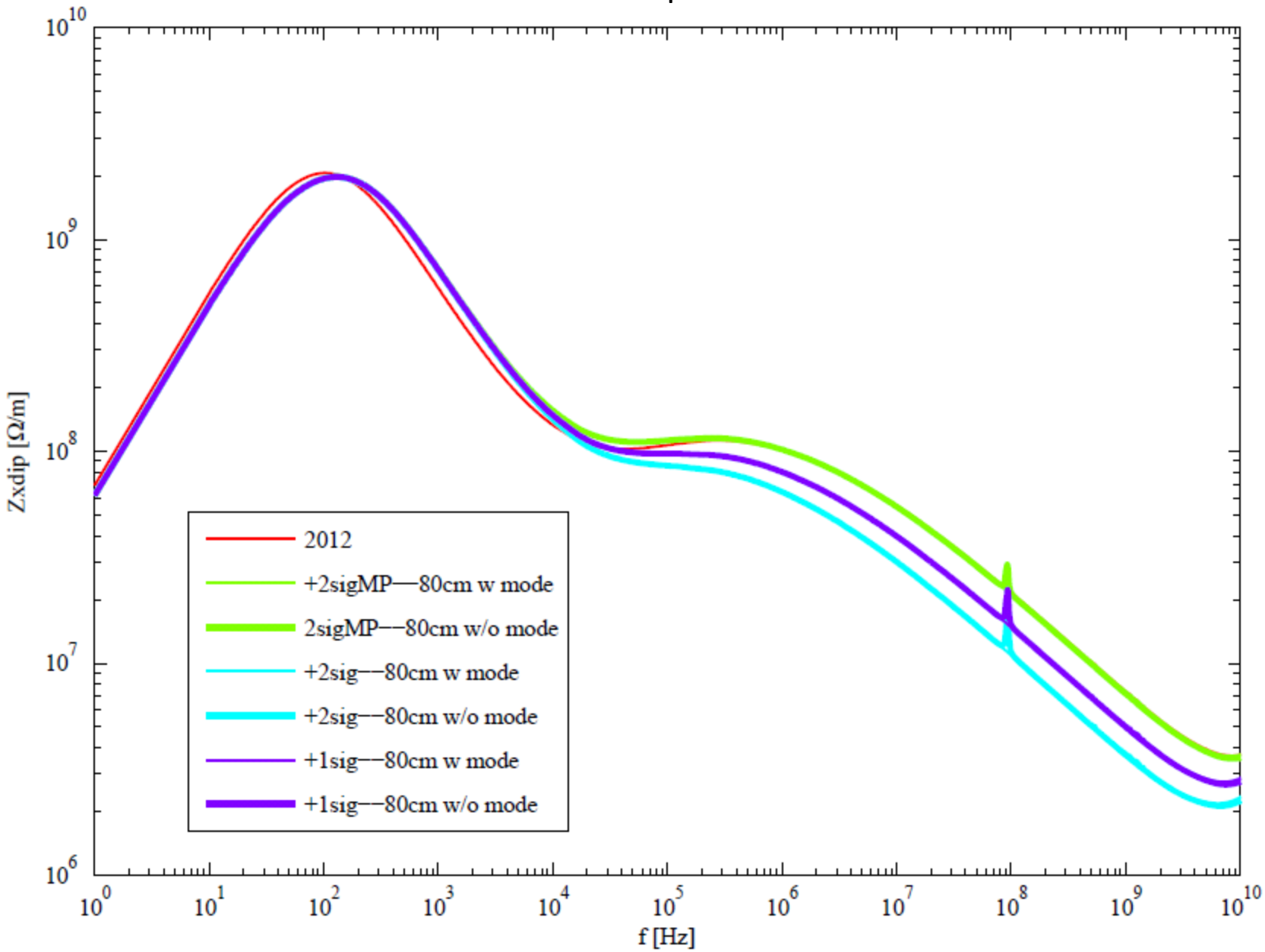
Main messages

- Significant impedance related issues during run 1
- Impressive effort by all involved equipment groups to assess and reduce impedance
- Beam induced RF heating: most issues should be solved, but careful follow up is needed
- Global LHC impedance: changes are expected to be transparent, but careful follow up is needed
- Longitudinal stability: no limitation expected so far, to be checked in dedicated MDs at 6.5 TeV.
- Transverse stability: it is difficult to predict where the limit will be, but strategies could be put in place in case the stability limit is lower than expected.

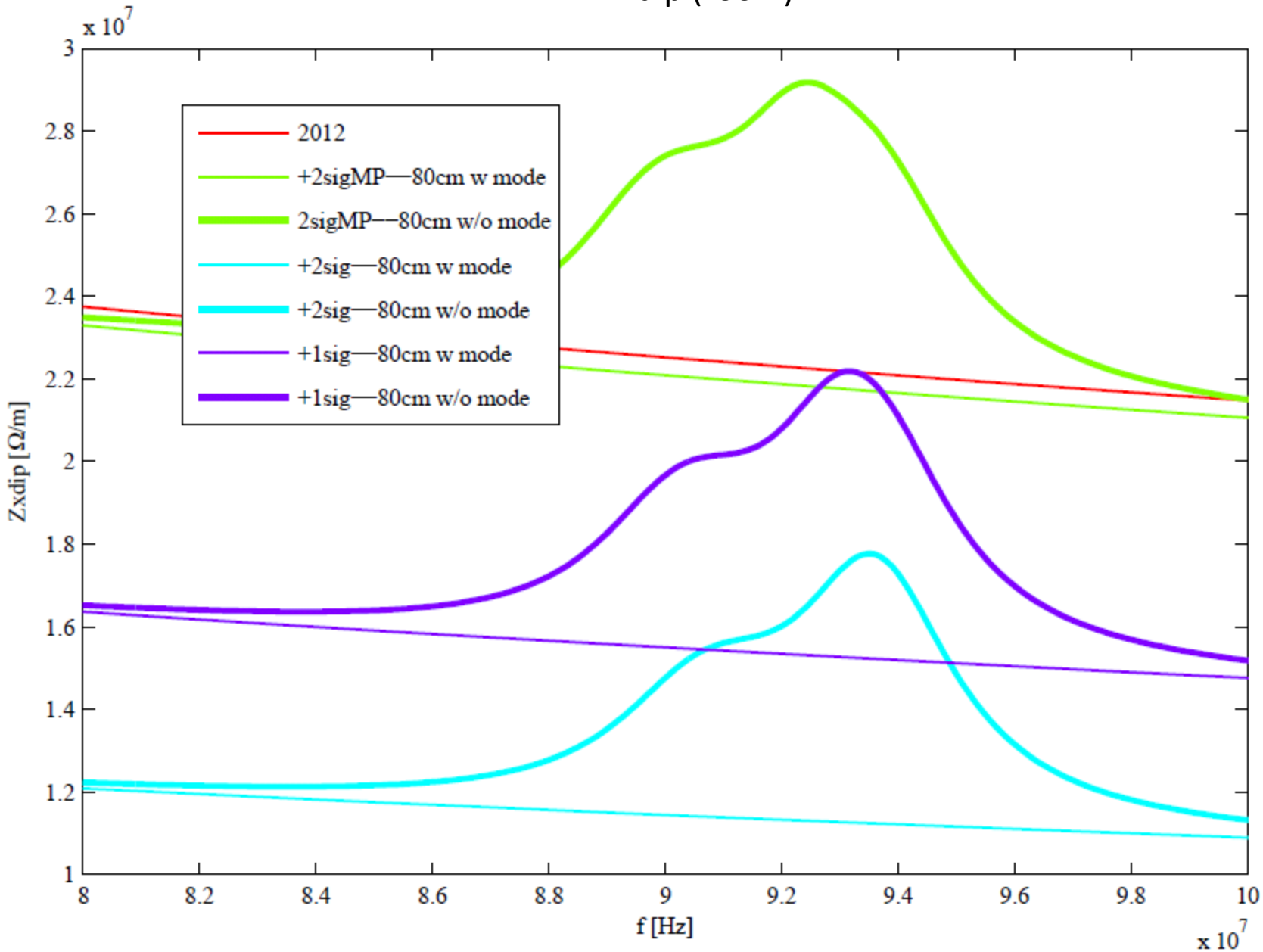
→ Heating and stability diagnostics improvements will be crucial after LS1 to diagnose and mitigate potential issues.

Many thanks for your attention!

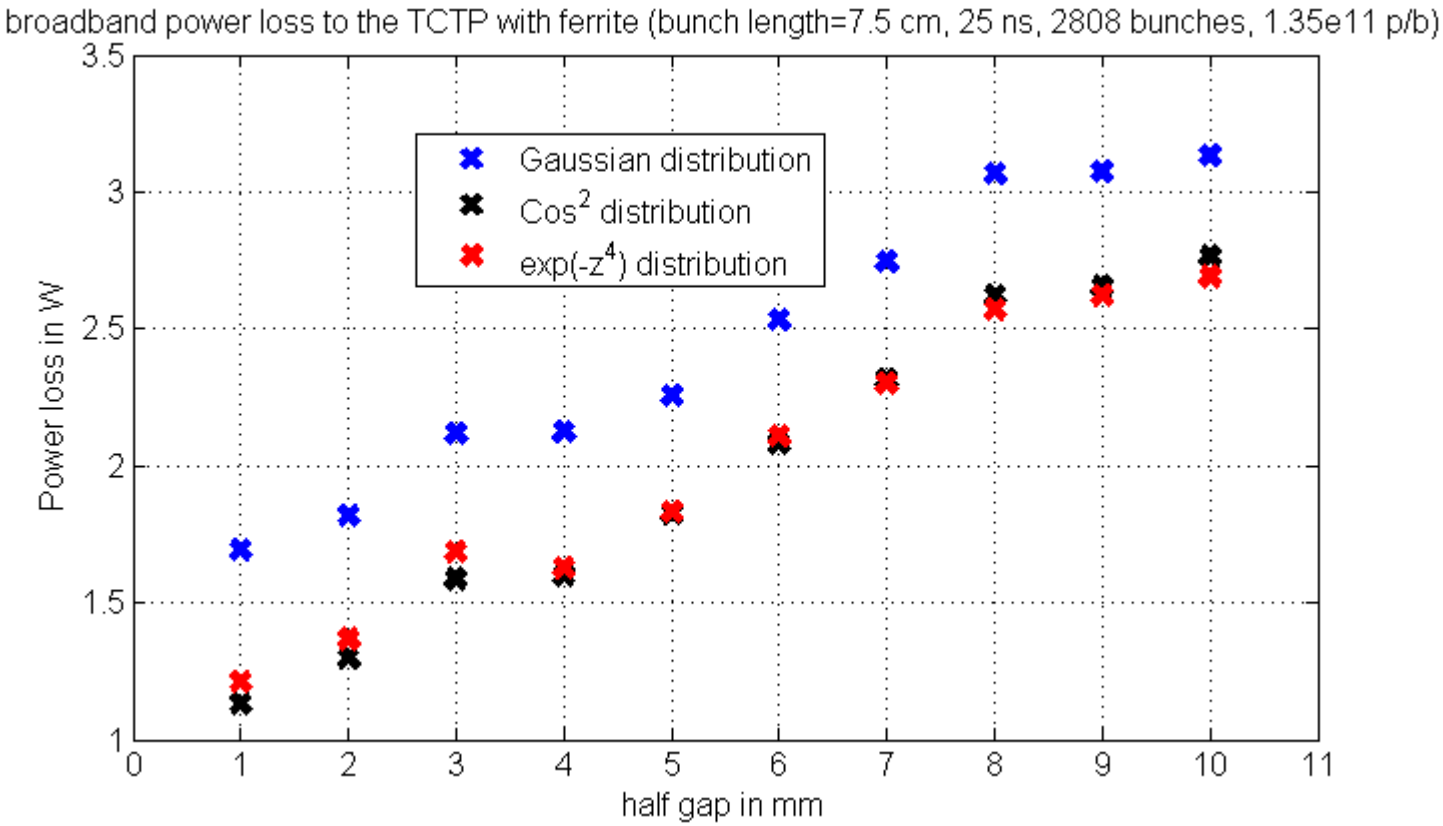
Zx dip


Zxdip [Ω/m]
f [Hz]
2012
+2sigMP—80cm w mode
2sigMP—80cm w/o mode
+2sig—80cm w mode
+2sig—80cm w/o mode
+1sig—80cm w mode
+1sig—80cm w/o mode

Zx dip (zoom)


x 10^7
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
Zxdip [Ω/m]
8
8.2
8.4
8.6
8.8
9
9.2
9.4
9.6
9.8
10
f [Hz]
x 10^7
2012
+2sigMP—80cm w mode
2sigMP—80cm w/o mode
+2sig—80cm w mode
+2sig—80cm w/o mode
+1sig—80cm w mode
+1sig—80cm w/o mode

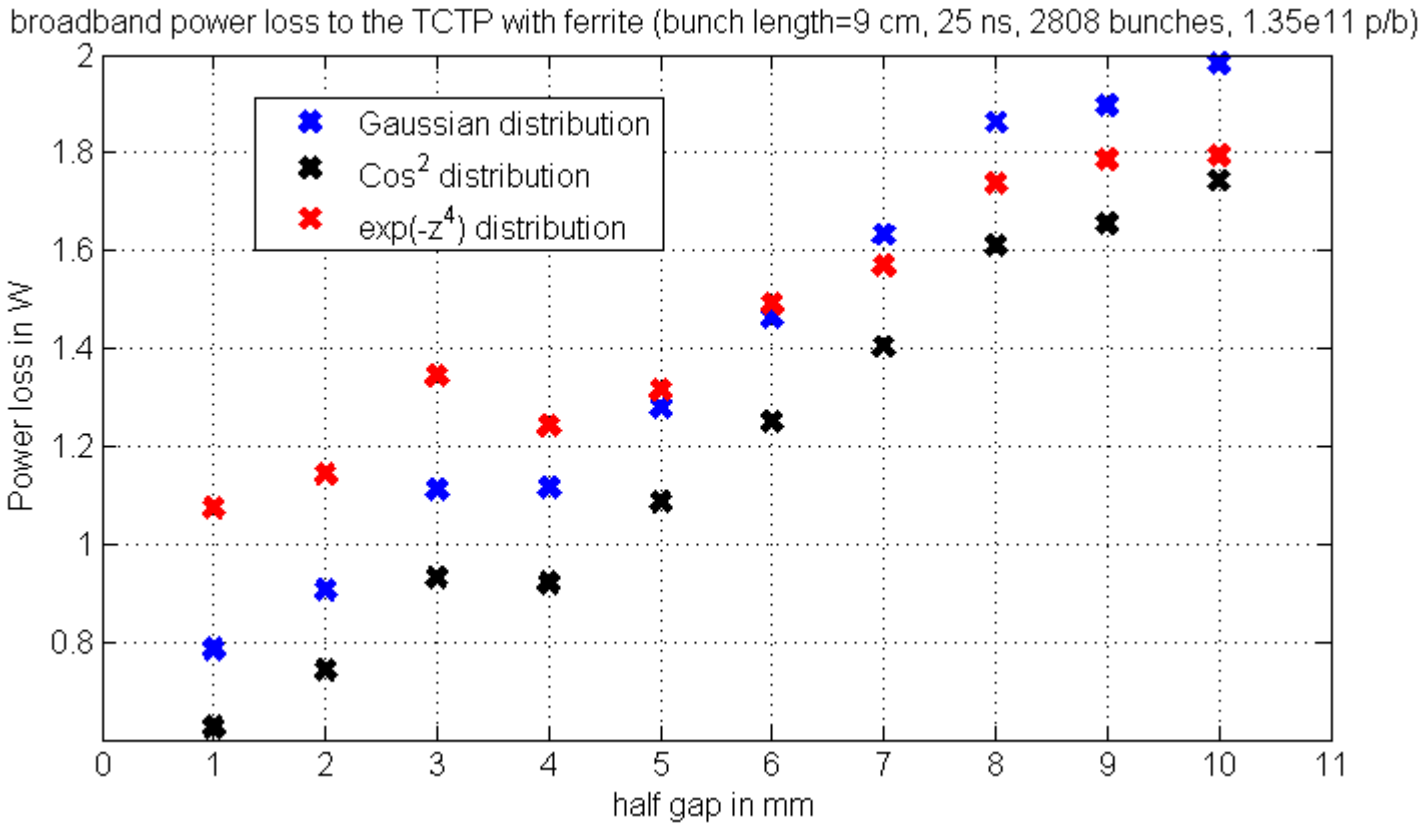
Power loss TCTP
(post-LS1, 25 ns, bunch length = 7.5 cm)



→ 50% to 100% of this heat load goes to the two lines of ferrite

Power loss TCTP

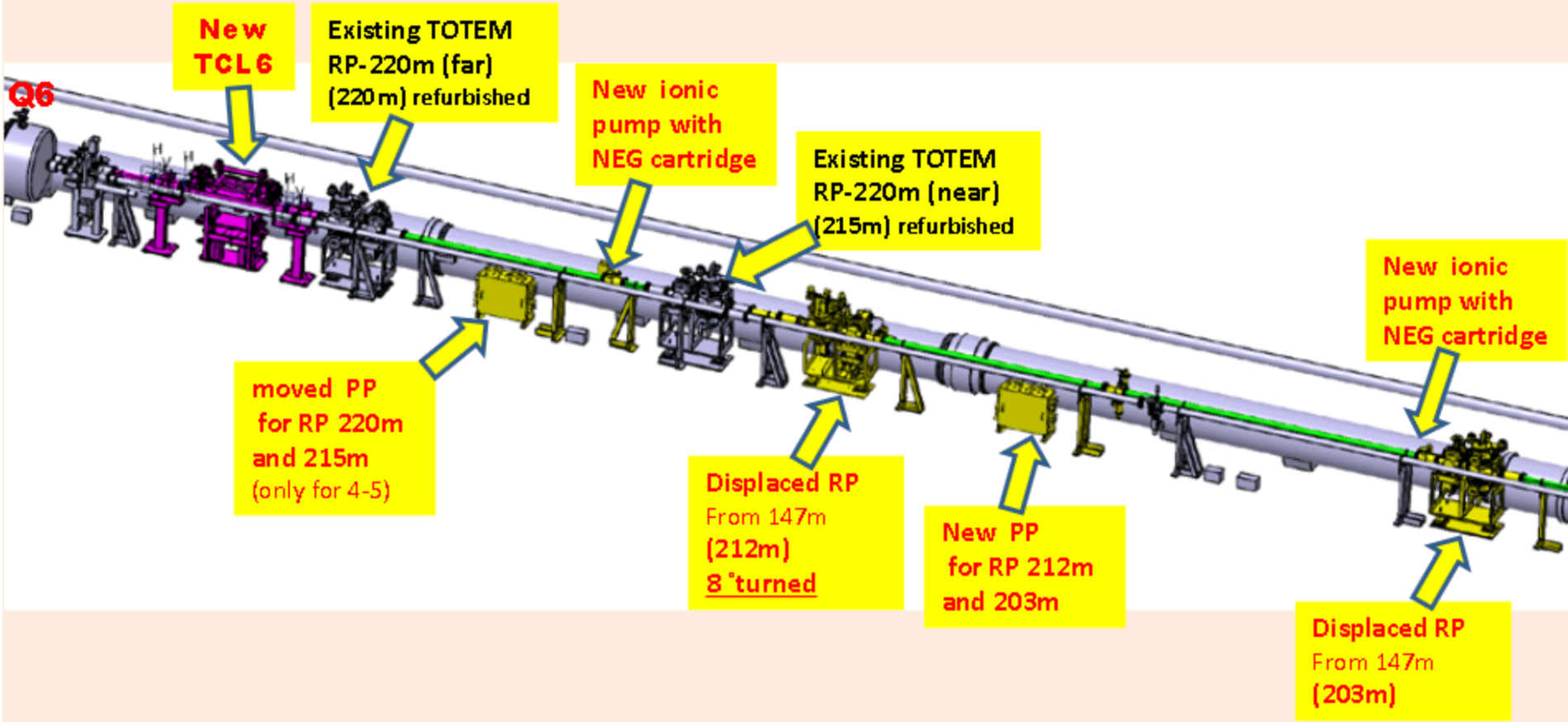
(post-LS1, 25 ns, bunch length = 9 cm)



→ 50% to 100% of this heat load goes to the two lines of ferrite

2. Consolidation project

D.Druzhkin (NIKIET, Moscow, Russia)



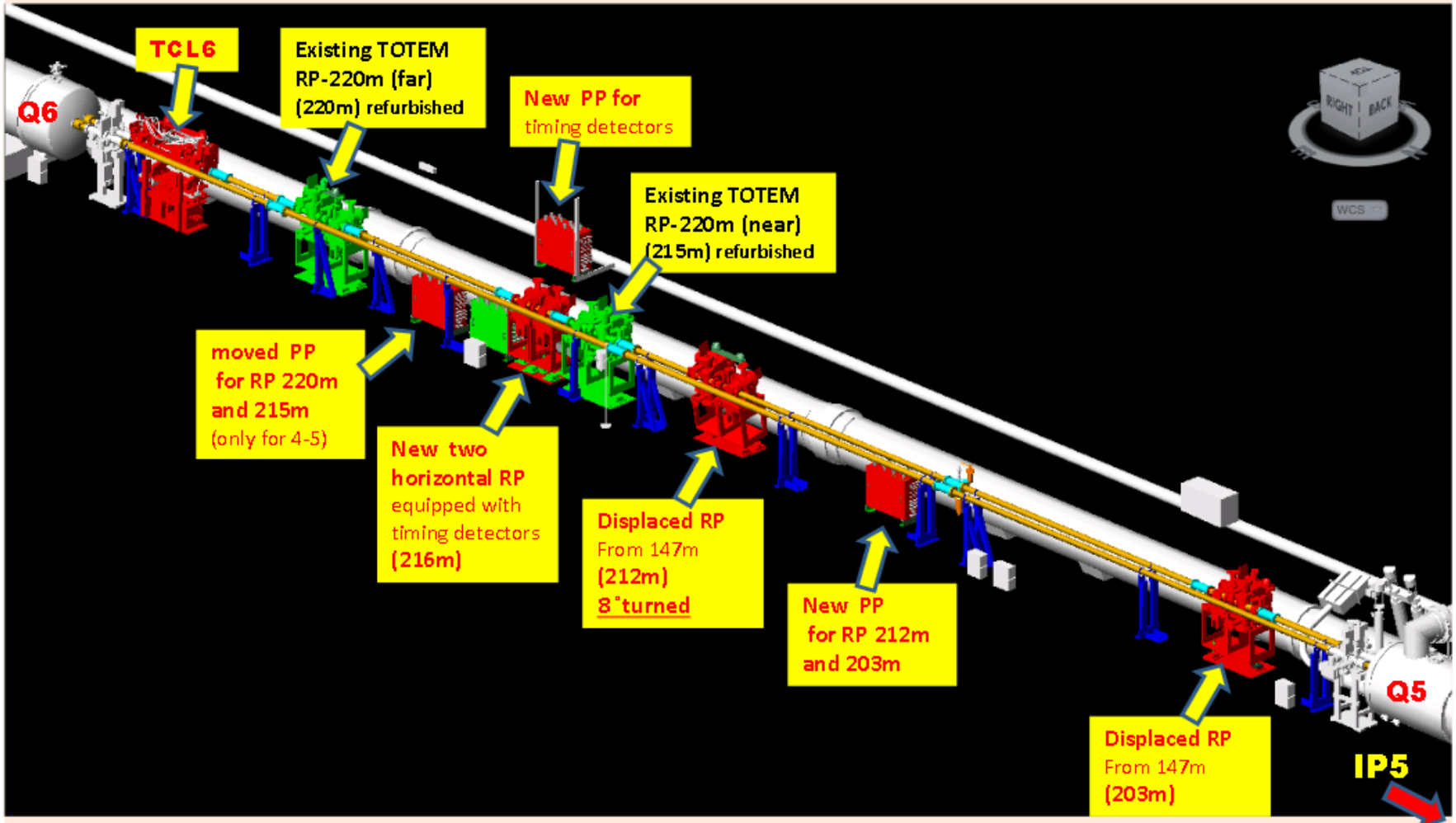
Works of the consolidation project are actually started at the beginning o

- **Remove RP147 m stations and patch panel to allow the installation of T (protection of D2–Q4);**
- **Relocation of RP147 m stations in 210m LSS region;**
- **Exchange the type of ferrites for all RPs; integration of ferrite support s**
- **Integration of RF fingers shield in the bellow between horizontal and ve**

3. Upgrade project

CMS-TOTEM Precision Proton Spectrometer (CT-PPS)

D.Druzhkin (NIKIET, Moscow, Russia)



Works of the upgrade project are actually started at the end of 2013 with production of several prototypes and sets of tests. The order of components has been done mostly in this February.

- Installation of additional new RP stations (horizontal) in 220 m LSS region;
- Integration of RF optimized horizontal Roman Pots in relocated horizontal stations in 210 m region;
- Works in the tunnel (cooling, radiation limiter, cabling, ...).

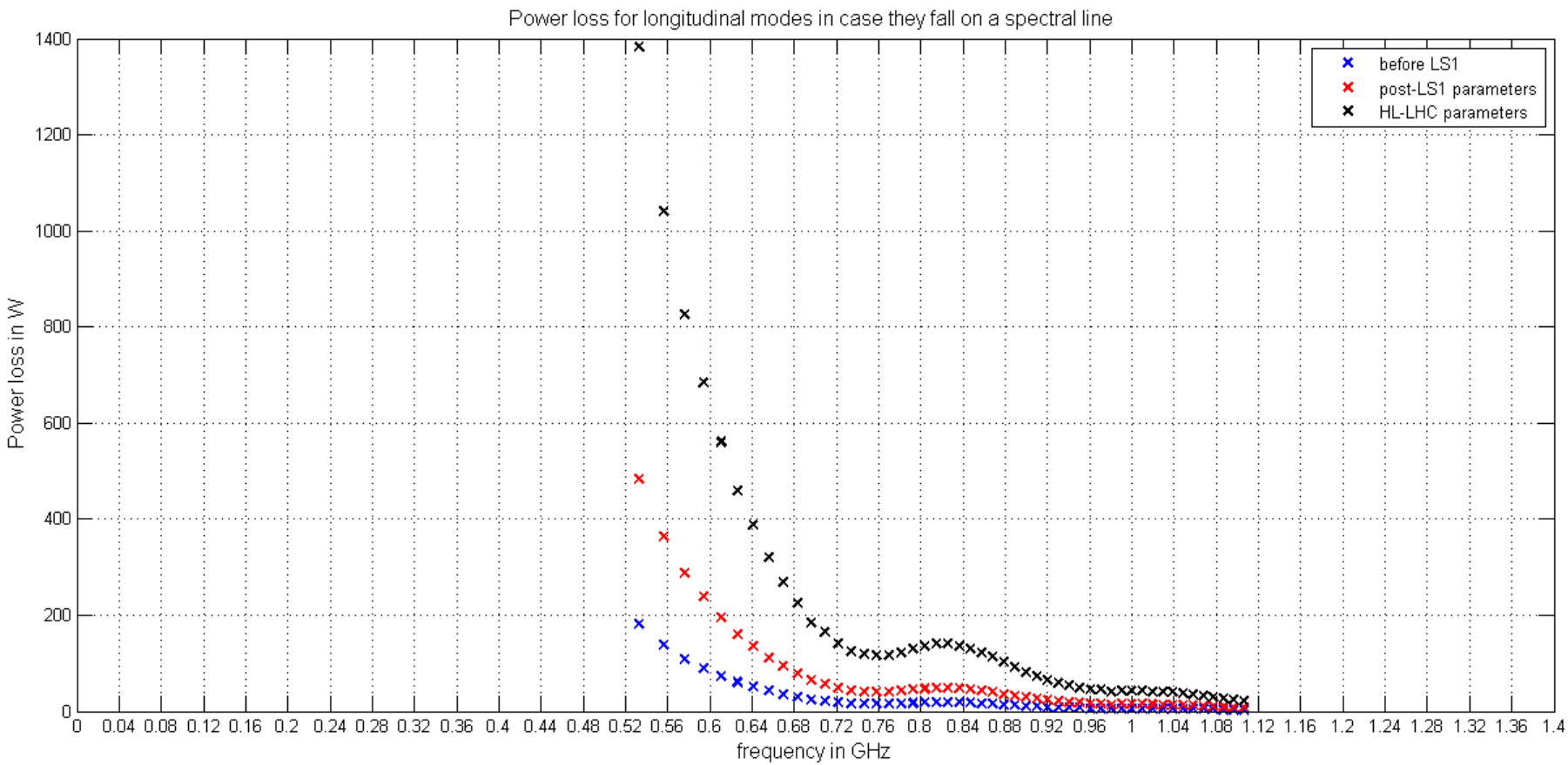
- Check parameters for high beta runs
- Pressure during fills
- TDI measurements
- TCTP heat load and impedance
- MKI upgrade
- TCP issue
- BSRT upgrade
- 8b 4e problem

TDI probes

- 2.2 TEMPERATURE SENSORS
- Temperature sensors (PT100) will be installed at eight different locations on the beam screen and jaws:
  - four sensors will be installed on the aluminum frame of the lower jaw (at the position of the first and fourth hBN absorber assembly, as well as at the position of the aluminium and copper-beryllium block assemblies, respectively);
  - two sensors will be installed on the stainless steel I-beam of the lower jaw (at the upstream extremity of the jaw as well as at the jaw center);
  - two sensors will be installed on the beam screen on the passage side of the machine (upstream and downstream).

Power from resonant modes

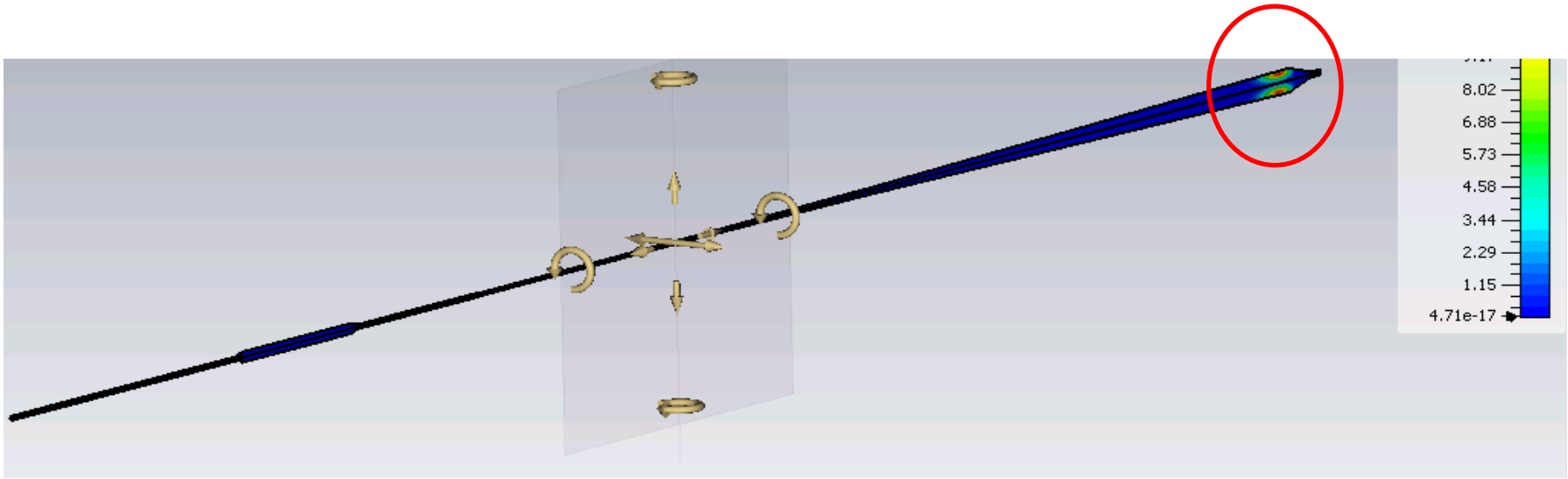
Modes from R. Wanzenberg and O. Zagorodnova



Significant increase of power loss with HL-LHC parameters

→ even the modes at higher frequencies are significant (of the order of 20 to 50 W)

Location of modes?



Linked to the large diameter of the cone → localized there
No changes foreseen in this area, so these modes are not affected by the upgrade

BGV

3.5 IMPEDANCE

Impedance studies were performed with several iterations of the design of the BGV.

These studies have shown that the impedance of the BGV is significant and should be minimized. In particular, the incoming and outgoing tapering angles as well as the outer diameter should be minimized from the impedance point of view, but a trade-off should of course be found with the performance of the instrument. Several iterations

were performed to assess this trade-off and the diameter reduction in particular proved very effective to reduce impedance contributions.

From wakefield simulations, the current design (see Figure 10) is expected to have longitudinal and transverse effective impedances that would stay in the background of the rest of the machine (< 1% of the effective low frequency impedance: longitudinal effective impedance was estimated at 0.74 mOhm, and weighted transverse effective impedance at 10 kOhm/m).

Also the longitudinal modes should be within the limit set for longitudinal instabilities (see Figure 11 for a limit set to 200 kOhm [9]).

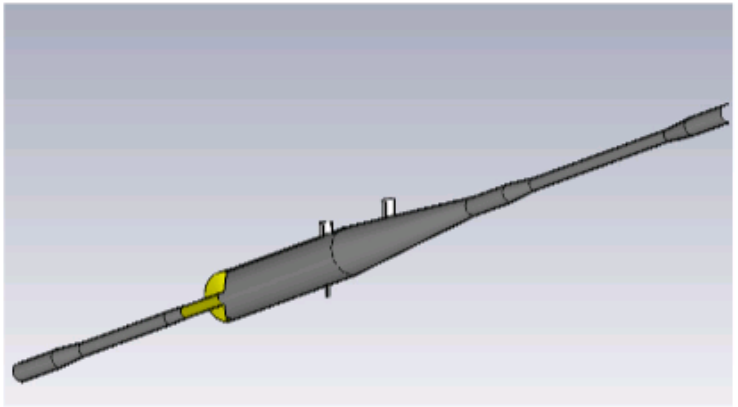


Figure 10: Model used to assess the impedance of the BGV (with CST Studio). The grey parts are in stainless steel of conductivity 1.35 10^6 S/m and the yellow part in aluminium with

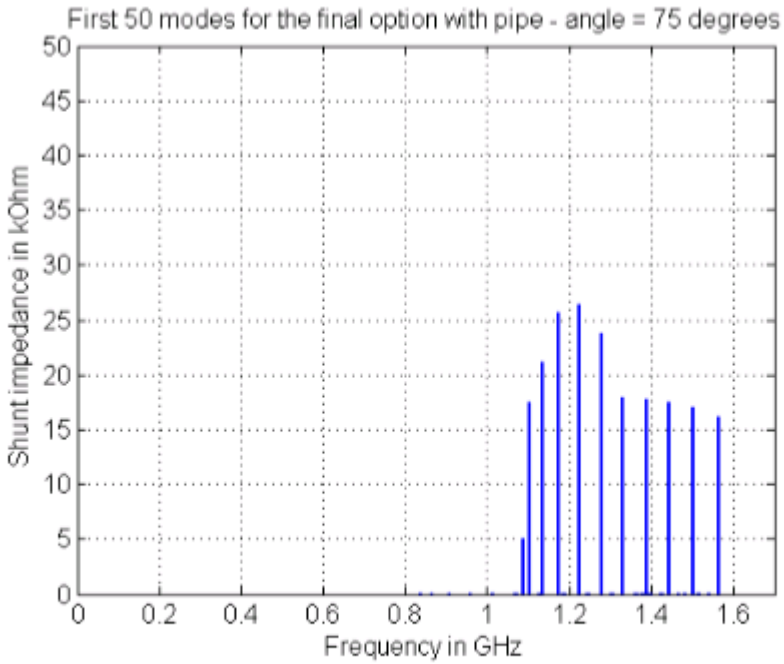


Figure 11: Shunt impedance of the longitudinal resonant modes as a function of frequency for the BGV model shown in Figure 10.

Power loss estimated for the BGV with foreseen post-LS1 parameters (25 ns: 2748 bunches with 1.15 10^{11} p/b; 50 ns: 1374 bunches with 1.6 10^{11} p/b) is shown in the following table, assuming that:

- Either all lines fall on a main beam spectrum line (spaced every 20 MHz for 50 ns beam or 40 MHz for 25 ns beam), and would lead to the "power loss (total)"
- Or, only the main resonance falls on a beam spectrum line, and would lead to the "power loss (main mode)"

Beam distribution	Scheme	Bunch length	Power loss (total)	Power loss (main mode)
Gaussian	25 ns	1 ns	3 kW	600 W
$\cos^2$	25 ns	1 ns	1 kW	270 W
Gaussian	50 ns	1 ns	1.5 kW	300 W
$\cos^2$	50 ns	1 ns	500 W	130 W
Gaussian	25 ns	1.25 ns	420 W	100 W
$\cos^2$	**25 ns**	**1.25 ns**	**50 W**	**8 W**
Gaussian	50 ns	1.25 ns	200 W	50 W
$\cos^2$	**50 ns**	**1.25 ns**	**23 W**	**4 W**

The most likely situation ($\cos^2$ distribution with 1.25 ns bunch length) is highlighted in red. However, lower bunch lengths and/or more critical longitudinal distributions can occur during the ramp, during MDs and also unexpectedly (as observed in October 2012). It is important to note that there are many assumptions undertaken in this estimation, and that appropriate safety factors should be applied by the designers to ensure that the BGV will sustain such power losses. It is acknowledged here that this device is a prototype and it is not required to be compliant with HL-LHC parameters (in the worst case, 10 kW are predicted).

Temperature probes should be installed on the stainless steel tank to measure the temperature during the run.

Eigenmode simulations predict that at least 97% of this loss should be sustained by the Stainless steel part of the BGV, while up to 3% would be sustained by the aluminium window.

Concerning the transverse resonant modes, with a β-function of about 165 m at the location of the BGV, the weighted shunt impedance of these modes would stay below 100 kOhm/m (see Figure 12). For the BGV, this contribution is at least two orders of magnitude smaller than the LHC impedance model at such frequencies [10], and the BGV should therefore remain in the background of the machine.

Finally, bench measurements are required with the final device to validate the simulation results and check for unexpected issues.