Instabilities and Beam Induced Heating in 2016

Evian 2016

Instabilities: L.R. Carver, D. Amorim, G. Arduini, J. Barranco, N. Biancacci, X. Buffat, W. Hofle, G. Iadarola, G. Kotzian, T. Levens, K. Li, E. Maclean, E. Metral, T. Persson, T. Pieloni, G. Rumolo, A. Romano, B. Salvant, M. Schenk, M. Soderen, C. Tambasco, R. Tomas, D. Valuch, BI colleagues & OP colleagues.

Beam Induced Heating: All involved equipment groups.

Outline

- Linear Coupling
  - Effect on transverse beam stability
- Operation in 2016
  - Instabilities at injection
  - Instabilities during and at end of squeeze
  - Instabilities in adjust and stable beams
- Impedance and stability measurements at 6.5TeV
  - Single bunch measurements: Collimator Tune Shift MD's
  - Stability threshold at EOS: Q'' and non-linearities
  - Summary of stability margins
- Beam induced rf heating
  - Overview
  - BGI & VMSI
  - Beam Induced Heat Load
- Summary

Linear Coupling

Foreword

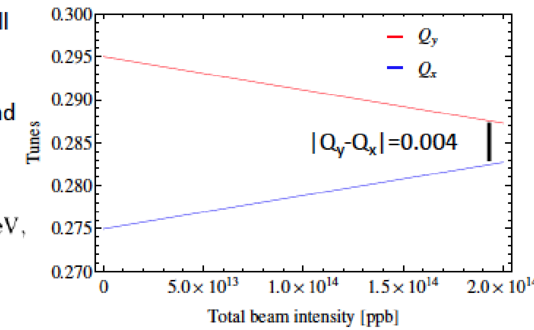
- Factor 4 more octupole needed to stabilise in 2012 at end of squeeze.
- Issues in 2015 at injection with emittance blowup when tunes not well separated (as reported at EVIAN15).
- Motivated a further study into effect of linear coupling on transverse stability.

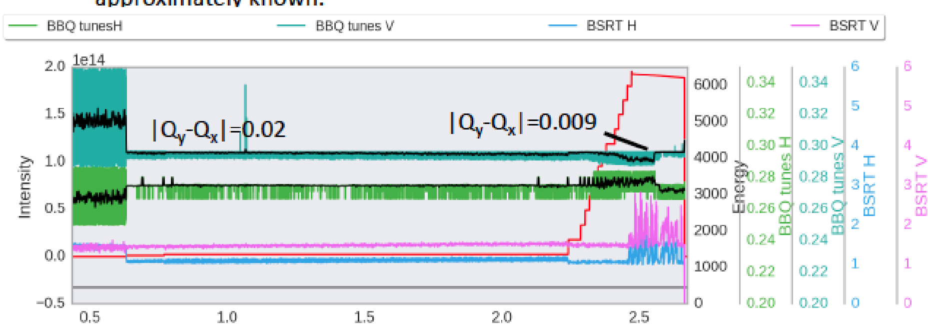
Injection – Tune Separation

- Key to preventing blowup at injection is maintaining well separated tunes.
- Laslett tune shift depends on total beam intensity.
- $N_b k_b$ = Beam intensity, β_{av}=ave. beta function, $\varepsilon_{1,2}$ depend on beam geometry with half height h and distance to ferromagnetic poles 2g.

$$\Delta Q_{\mathrm{Laslett}} = -\frac{N_b k_b r_p \beta_{av}}{\pi \gamma}\left(\frac{\varepsilon_1}{h^2} + \frac{\varepsilon_2}{g^2}\right) \simeq \begin{cases} -1.7 \times 10^{-2} & \text{at 450 GeV,} \\ -1.1 \times 10^{-3} & \text{at 7 TeV,} \end{cases}$$

- Tune shift measured (below) is approximately similar to analytical result (right). ε_1=0 but ε_2 and g are only approximately known.





Fill 4642, B2 (left) - tunes not separated, blowup observed.

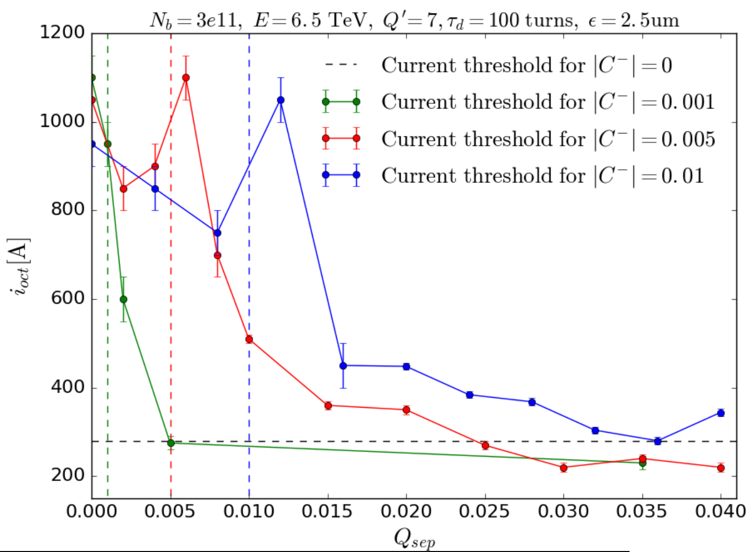
Fill 4643, tunes separated, no blowup observed.

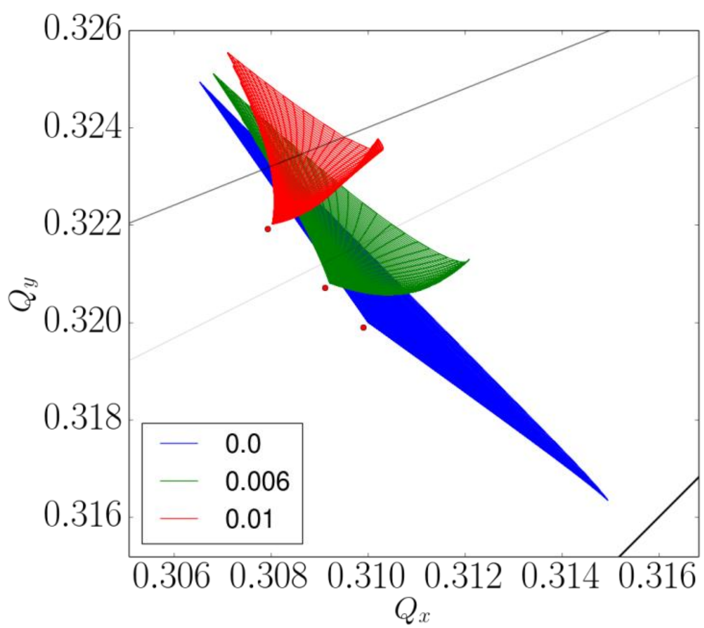
See ‘Single Beam Collective Effects in the LHC’ – F.Ruggiero
See ‘Analysis of intensity dependent effects…’ – T.Personn et al, IPAC15

16/12/15 Instabilities & Heating - Evian '15 8

Linear Coupling - Overview

- Unstable modes must be within the tune footprint to be Landau damped. Tune spread dominated by octupoles (when not in collisions).
- Studies on tune footprint and stability threshold using a variety of tools, each using a single skew quad model.
- Bottom left: PyHEADTAIL simulations showing required stabilising octupole current as function of the tune separation for different strengths of global coupling.
- Bottom right: MADX footprint as a function of |C-| tracked out to 10sigma.

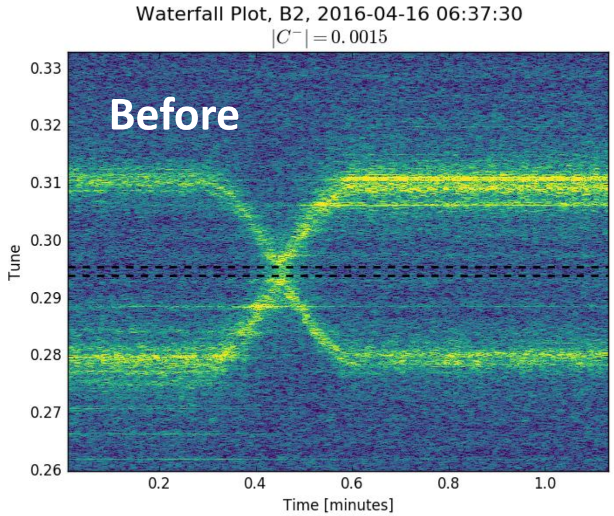


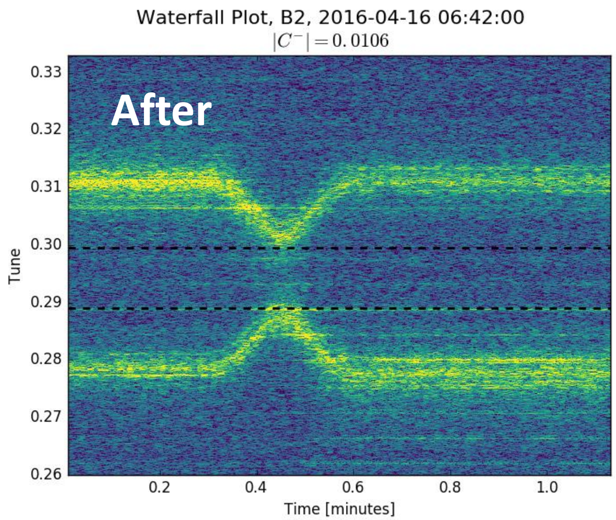


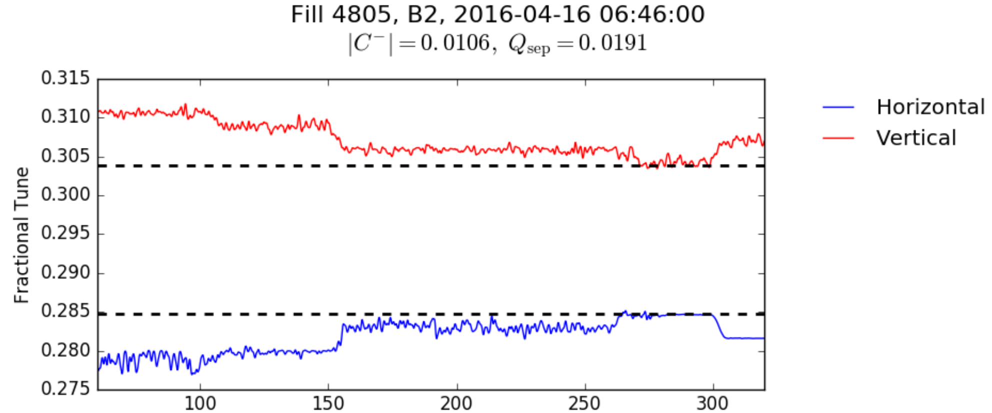
See L.R. Carver, "Role of linear coupling in beam stability", LBOC No. 57

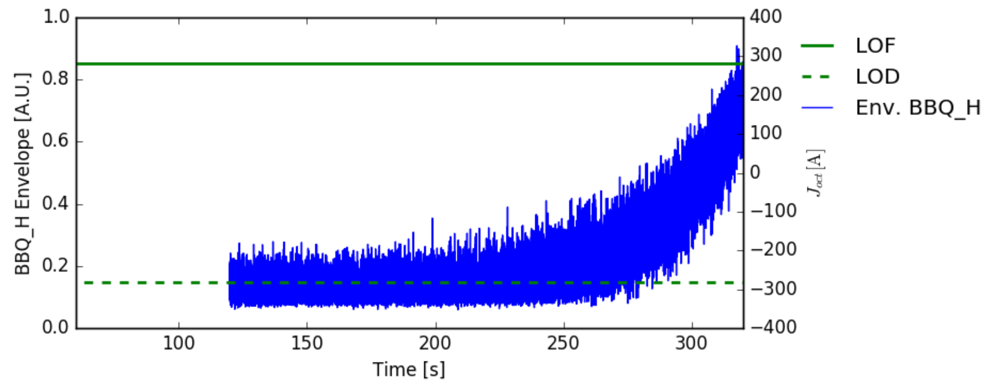
Linear Coupling – Single Bunch Measurement at Flat Top

Can we make a single bunch at flat top unstable using linear coupling?









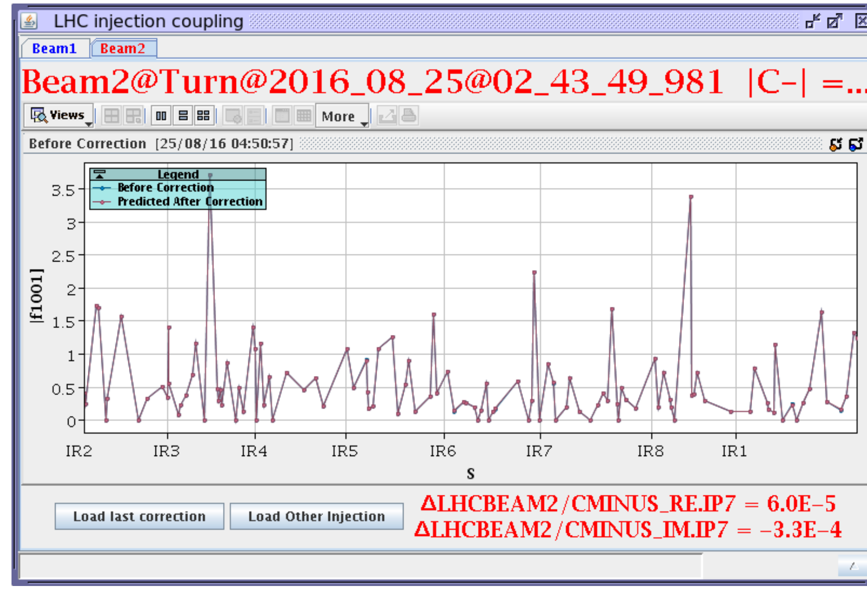
- Introduced coupling and measured by tune crossing.
- B2H became unstable when moving tunes together despite 283A in octupoles, norm. current of 254A.
- Norm. threshold for no coupling: 63.A. Expected factor 1.5 increase from PyHT with these settings, measured factor 4.
- **Still some work to do!**

See L.R. Carver, "Destabilising effect of linear coupling", 2nd Instability Review

Linear Coupling – Applications for Injection

- Two vital applications were developed to prevent coupling issues at injection.

Application for correction for Laslett tune shift – M. Schaumann



Application for coupling correction at injection – T. Persson

- **No issues with instabilities relating to coupling at injection in 2016.**

Operation in 2016

Strategy

- With less than 100b 25ns trains coming from the SPS, electron cloud wasn't going to be as dominant an effect as it was in 2015.
- The strategy this year was to start with parameters that we knew would work, and then try to check margins a few times throughout the year.
- Chromaticity is very effective at stabilising electron cloud instabilities.
- Octupoles can provide the tune spread which is required to Landau damp the unstable modes.
- In practice, a combination of the two is required in the presence of a strong ADT.

Injection

Injection - Overview

- With Q'=20/20, Joct=20A and nominal bunches with ε~3um, injection was going very smoothly.
- Switch to BCMS beams with ε~1.5um and the same settings, horizontal plane starts becoming unstable.
- **Double the octupoles (Joct=40A) to account for half the emittance**, problem solved.
- Measurements at the end of year show **little margin for chromaticity and octupole reduction.**
- Test with 8b4e show we can inject a full beam without e-cloud with optimal settings (Q'=5/5, Joct=6A) **without issues**.
- Confirms prediction from impedance.

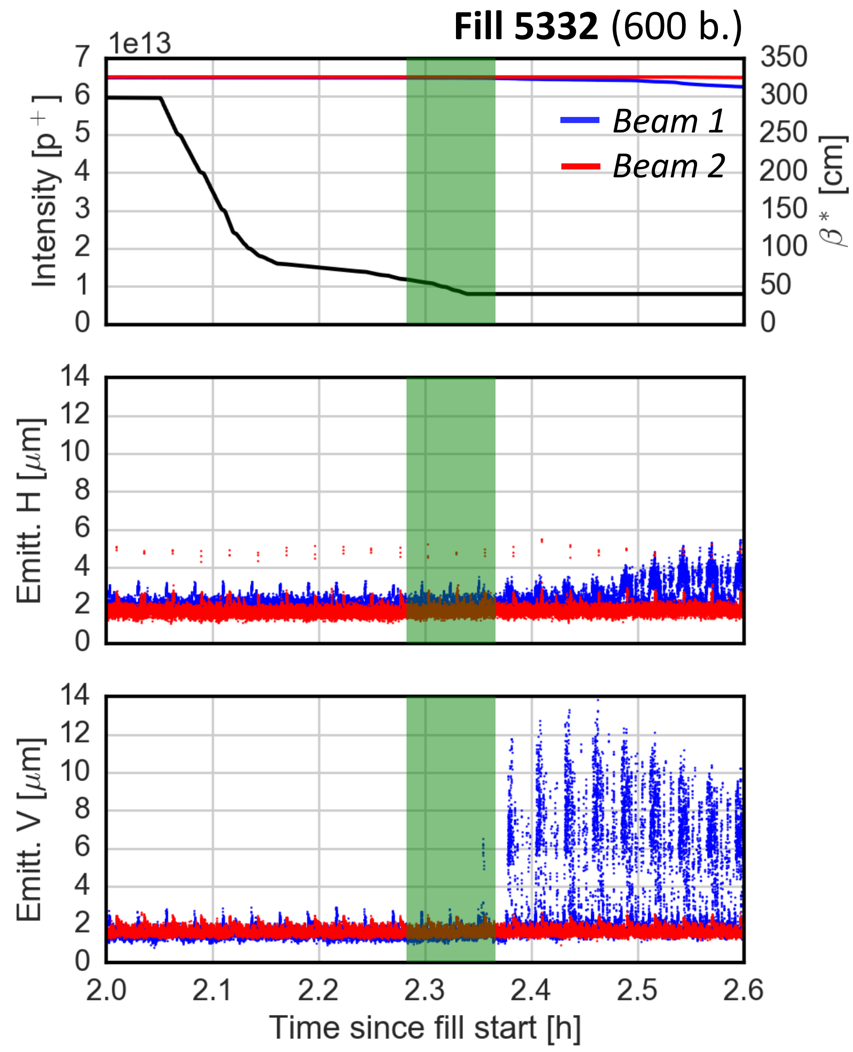
See K. Li, "Instabilities at injection", 2nd Instability Review

Squeeze

Operation in 2016 - Squeeze

Coupling during the squeeze is critical due to reduced Qsep

- Losses and emittance blow-up in beam 1 right after squeeze in fill 5332 (600b).
- Similar picture from BBQ, showing activity in H & V.
- Increase in BBQ $|C^-|$ for $\beta^* \leq 45$ cm.
- Optics measured in the next fill which showed large |C-| (~5e-3) at end of squeeze.
- Correction implemented, no more blowup observed in future fills.



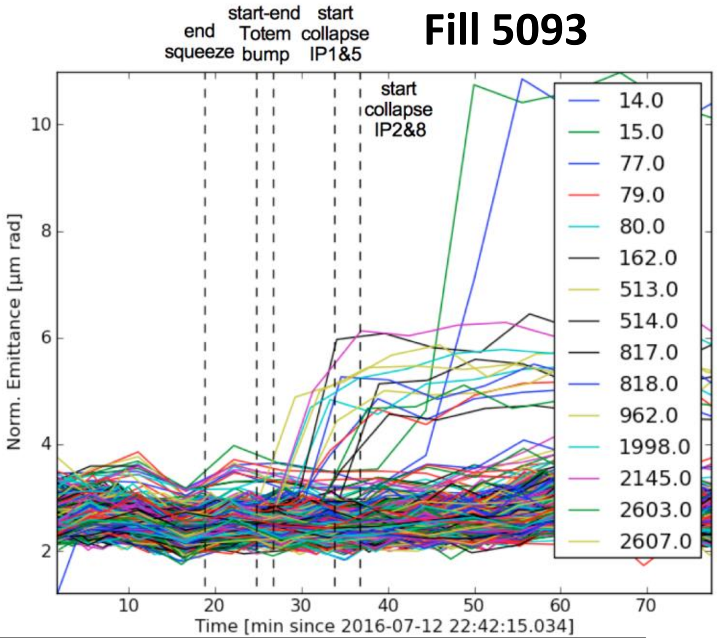
See M. Schenk, "Instabilities during the squeeze", 2nd Instability Review

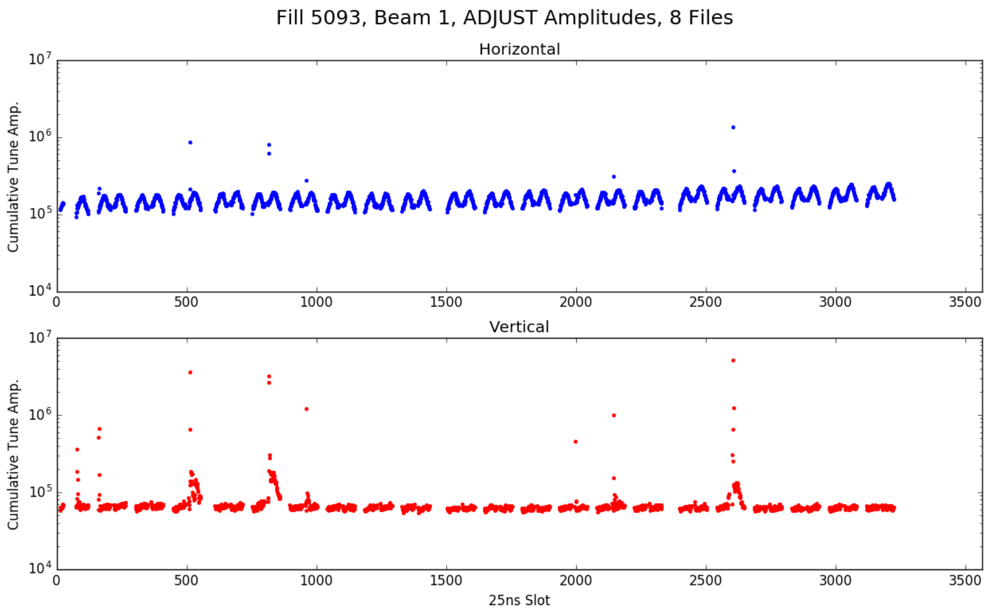
Adjust

Operation in 2016 – ADJUST Overview

- Lots of sporadic instabilities in ADJUST throughout 2016.
- Specifically in B1V and approximately correlated with the implementation of the TOTEM bump.
- Triggered ADTObsBox during ADJUST. Coherent activity seen on bunches at the start of the second batch of 48b. Typically mode 0 with rise times ~1-2 seconds.
- Expected to be stable for Joct=0A, more info later.

Fill 5093





See C. Tambasco, "Adjust Instability", HSC Section Meeting, 15/07/2016

Thanks to ADTObsBox team

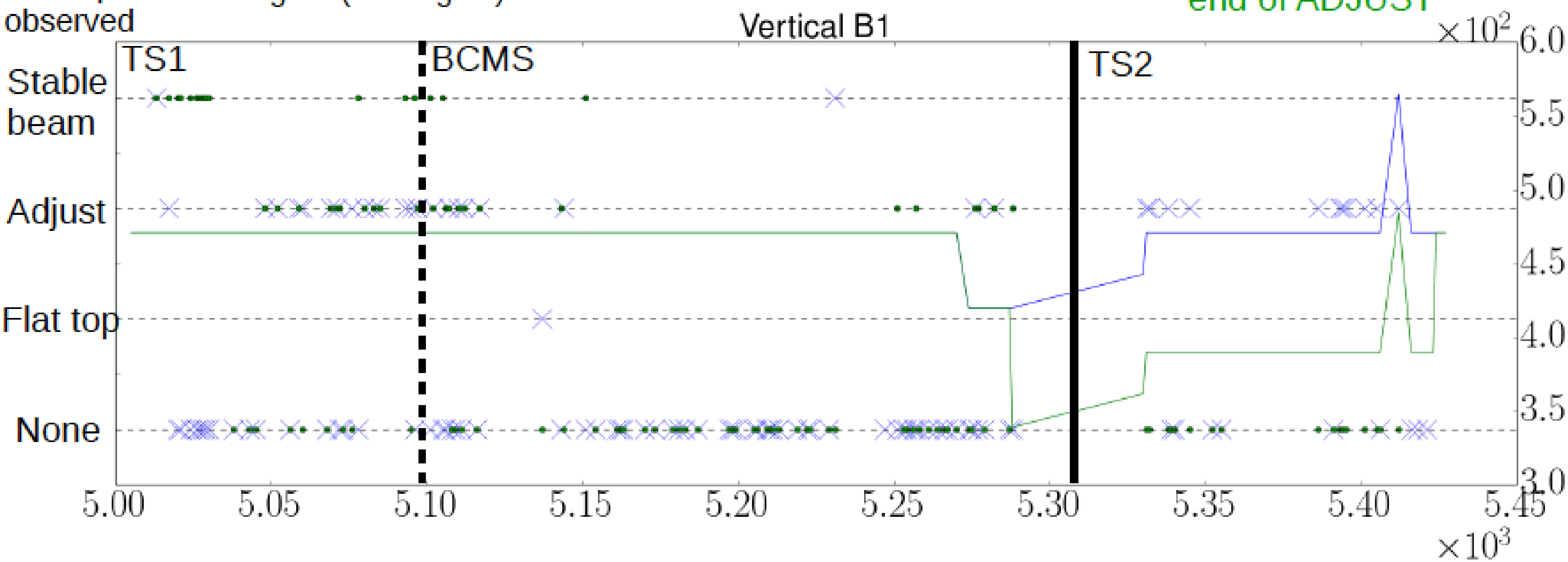
Operation in 2016 – ADJUST Overview

Beam mode during which blow up is observed

- Crosses corresponds to normal bunches
- Dots corresponds to bunches in the ADT gate (lower gain)

MOF current at start of ADJUST

MOF current At end of ADJUST



See X. Buffat, “Results from separation levelling and stability tests”, LBOC No. 70

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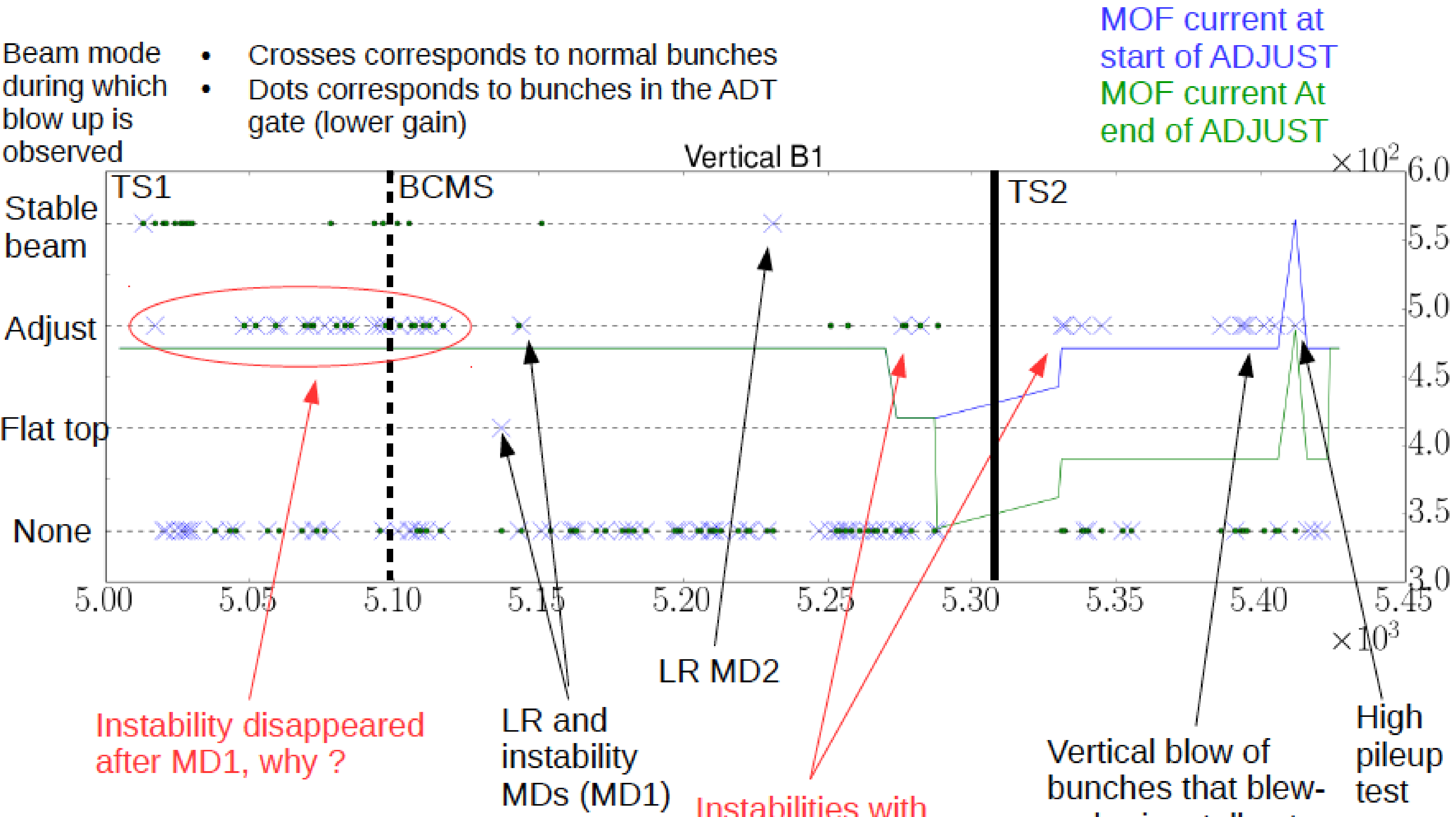
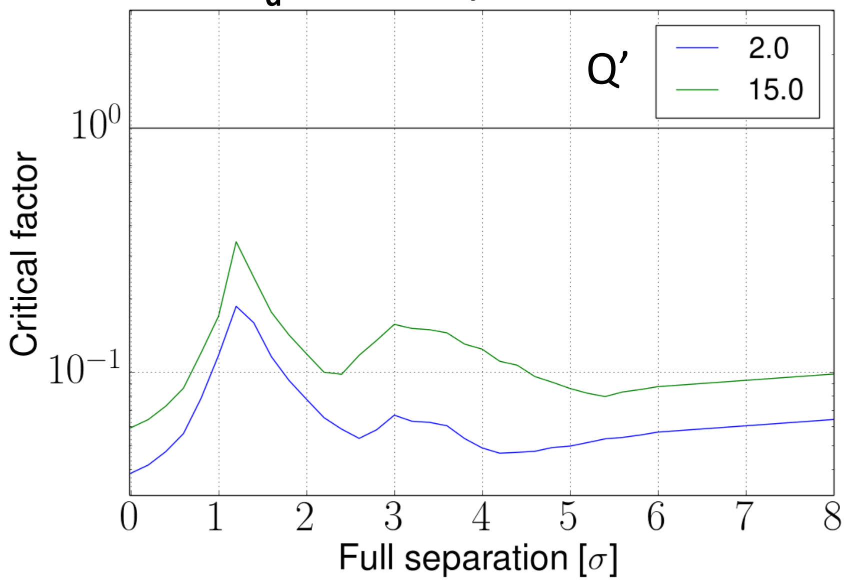


See X. Buffat, "Results from separation levelling and stability tests", LBOC No. 70

Operation in 2016 – Separation Tests

- Many separation tests performed this year.
- Below shows the stability prediction for Joct=500A and Q'=2 and Q'=15. It can be seen that for all separations it remains below 1 i.e. it is stable.
- **In fact, this occurs for all octupole currents including Joct=0A. i.e. long range only is enough to stabilise.** Measurements were performed that confirmed these predictions.

τ_d=50 turns, Joct=500A



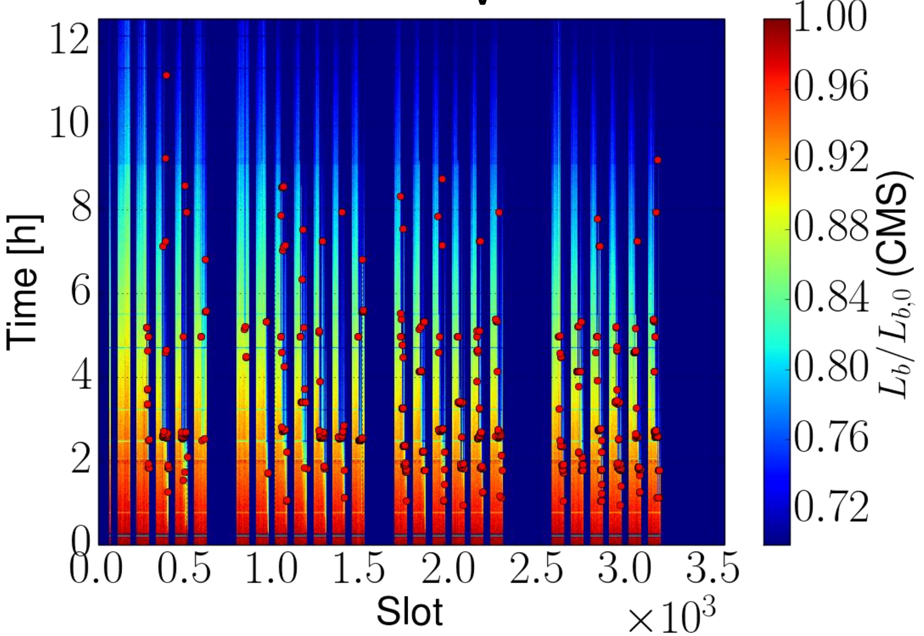
See X. Buffat, " Instabilities in Adjust", 2nd Instability Review, 29/11/2016

Stable Beams

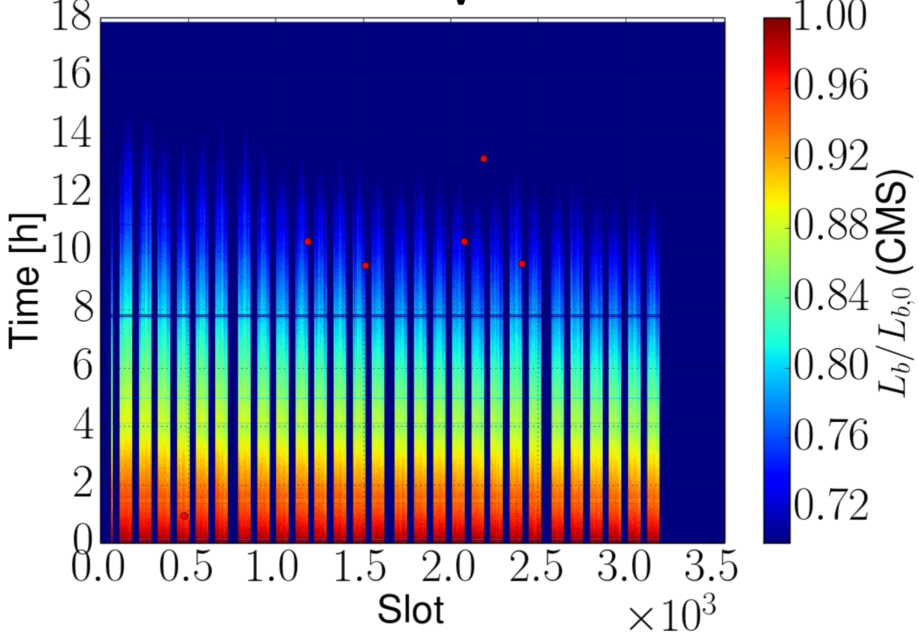
Operation in 2016 - Popcorn Instability

- Instabilities were observed in stable beams (typically after a few hours) in most of the fills with trains of 72b. (already with 600b. in the machine)
- Several bunches blew-up in the vertical plane, as observed on bunch by bunch luminosity and BSRT data
- Affecting only bunches at tails of the trains.
- Problem went away after several weeks (possible scrubbing).

Fill 4964, Q'$_v$ = 15



Fill 4988, Q'$_v$ = 22

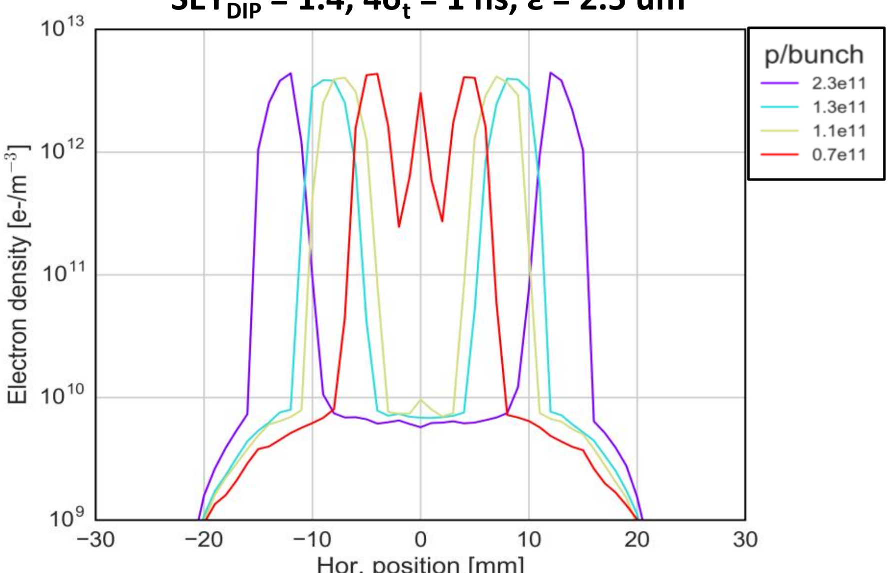


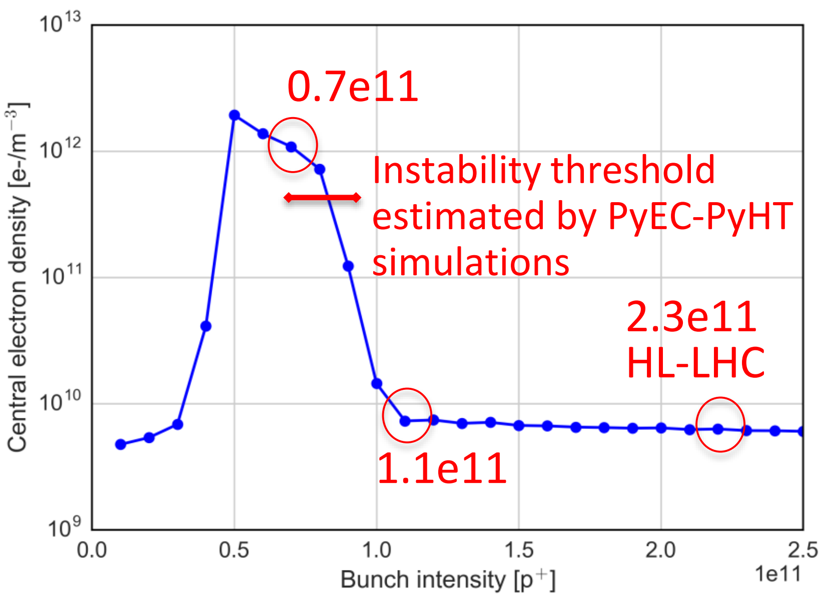
See X. Buffat, "Instability observations in stable beams", LBOC No. 62

Operation in 2016 - Popcorn Instability

- From PyECLOUD simulations we can estimate the electron density profile in the dipoles for different beam intensities
- When the bunch intensity decreases, the local electron density (close to the beam) increases significantly which has a much larger impact on the beam dynamics.
- The instability threshold does not change, and it can be seen that for intensities on the order of 0.7e11-0.8e11 the bunches could be unstable with the stated assumptions on SEY and beam parameters.
- Can be mitigated by increasing chromaticity or by scrubbing.

SEY_{DIP} = 1.4, $4\sigma_t$ = 1 ns, ε = 2.5 um





See A. Romano, "Instabilities in stable beams", 2nd Instability Review

Impedance and Stability Measurements at 6.5 TeV

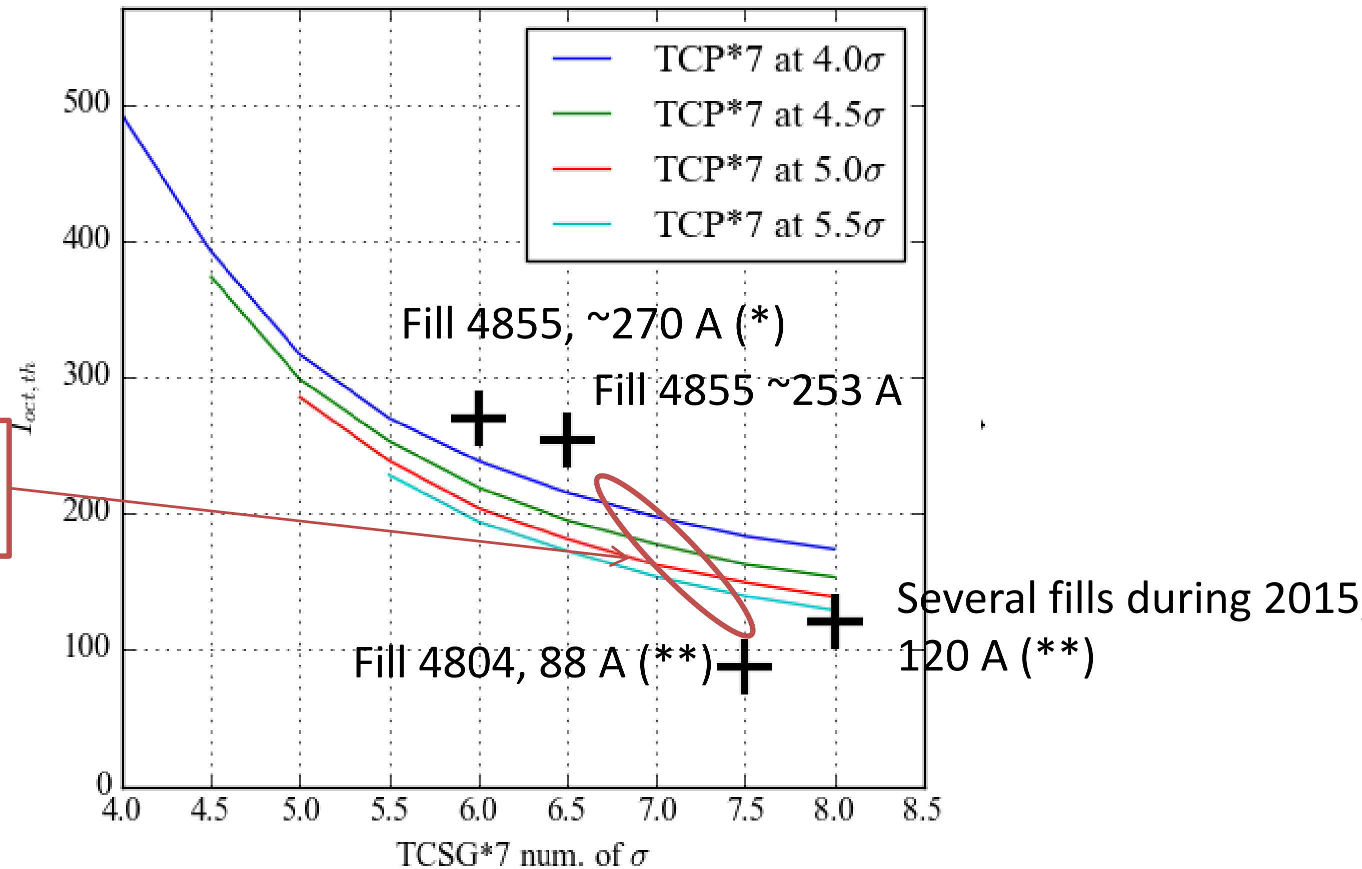
Impedance Tests in 2016 & Outlook for 2017

- Tune shift and instability measurements with different collimator settings can provide validation of impedance model.
- Some cases gave good agreement (TCSG.D4L7 and TCPs).
- Others were out by up to a factor of ~3, measurement techniques constantly being improved

LHC 40cm, Q'=10, τ_d =100 turns, N_b=1.2e11, ε=2um.

Measurements for TCP=5.5sigma

Discrepancy **7.5 -> 6.5** sigma to be understood



See N. Biancacci, "Impedance Model and Single Beam Instabilities", 2nd Instability Review

Measurements scaled to 1.2e11 in 2um emittance if needed.
(*) Scaled to H plane from V considering factor ~1.2 from impedance.
(**) Scaled to 40cm squeeze with the factor ~1.1 from impedance.

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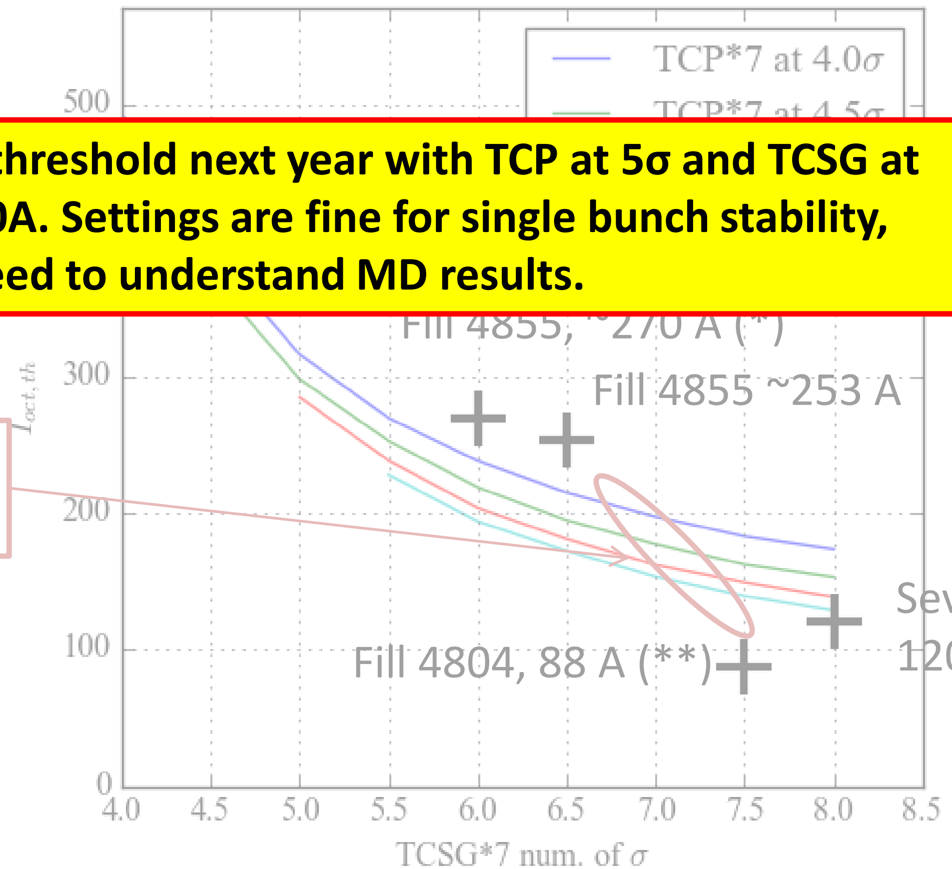


Measur... TCP=5.5...

Expected threshold next year with TCP at 5σ and TCSG at 6.5σ is 200A. Settings are fine for single bunch stability, but still need to understand MD results.

Discrepancy **7.5 -> 6.5** sigma to be understood

See N. Biancacci, "Impedance Model and Single Beam Instabilities", 2nd Instability Review

Measurements scaled to 1.2e11 in 2um emittance if needed.
(*) Scaled to H plane from V considering factor ~1.2 from impedance.
(**) Scaled to 40cm squeeze with the factor ~1.1 from impedance.

Beam Stability at 40cm in 2016

- Measurements **with a single bunch and a full single beam** at end of squeeze show we are stable at β^*=40cm for Joct=0A.

- This is in comparison with the threshold measured for a single bunch at flat top, which was ~70A and in good agreement with prediction.

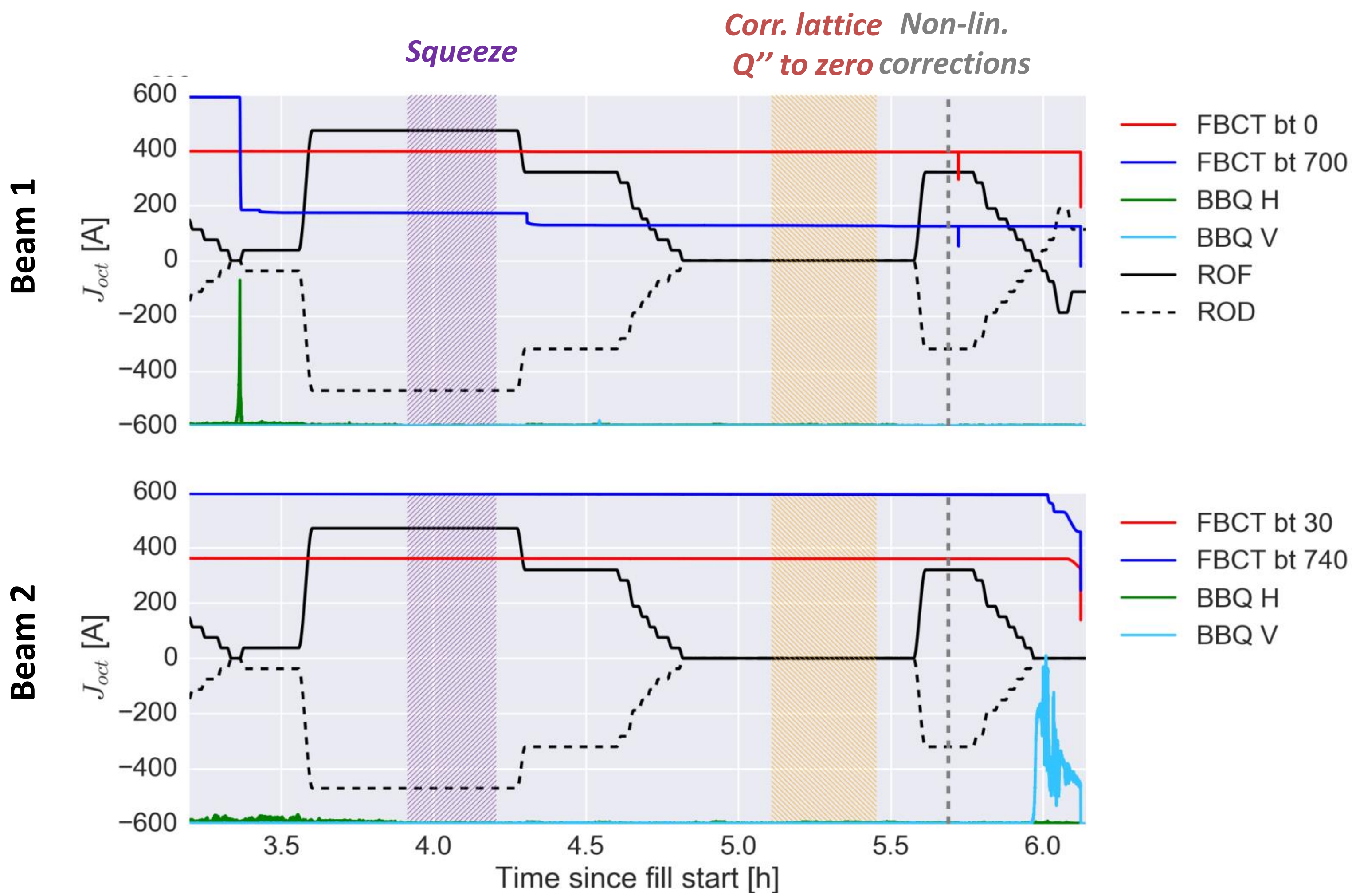
- Two possible explanations:
  - Q'' from the lattice (shown in backup)
  - Amplitude detuning from non-linearities in the IR's (see Evian talk by E. Maclean).

- MD1831 attempted to disentangle between the two effects.

See L.R. Carver, "News on stability margins from MD4", LBOC No. 69

Beam Stability at 40cm in 2016 – MD1831

- When correcting Q'' at EOS, single bunch was still stable (beware of sextupole spread).
- When implementing b4 corrections, B2V became unstable at 40A.



Summary of Stability Margins

Injection

- Q'=20/20 was needed to stabilise in 2016, if Joct is high enough (20A or 40A), should be stable. **Behaviour well understood – due to electron cloud.**
- This situation will be worse when we move to longer trains, no further margin expected.

Flat Top

- Q'=15/15 used throughout 2016. Octupole threshold is ~80A, we operated with 470A.
- **Behaviour well understood.**
- Next year with 144b+ trains, could try to run with ~250A (impedance threshold + some margin) during intensity ramp. Measurements of margin will be required.

Squeeze

- This year, there were a few cases of uncorrected coupling causing instabilities.
- If coupling is well corrected (|C-|~1e-3), no issues anticipated. Should be same as FT.
- If this is not possible, could consider squeezing with injection tunes. **Behaviour reasonably well understood**

Adjust and Stable Beams

- Did not observe an octupole dependence for adjust instabilities.
- Non-linearities should be corrected, amplitude detuning should come from octupoles only.
- Once in collisions, should be able to reduce octupoles to slightly above single bunch threshold (~200A). **Behaviour requires further study into possible mechanisms.**

Beam Induced Heating in 2016

Beam Induced Heating: Overview

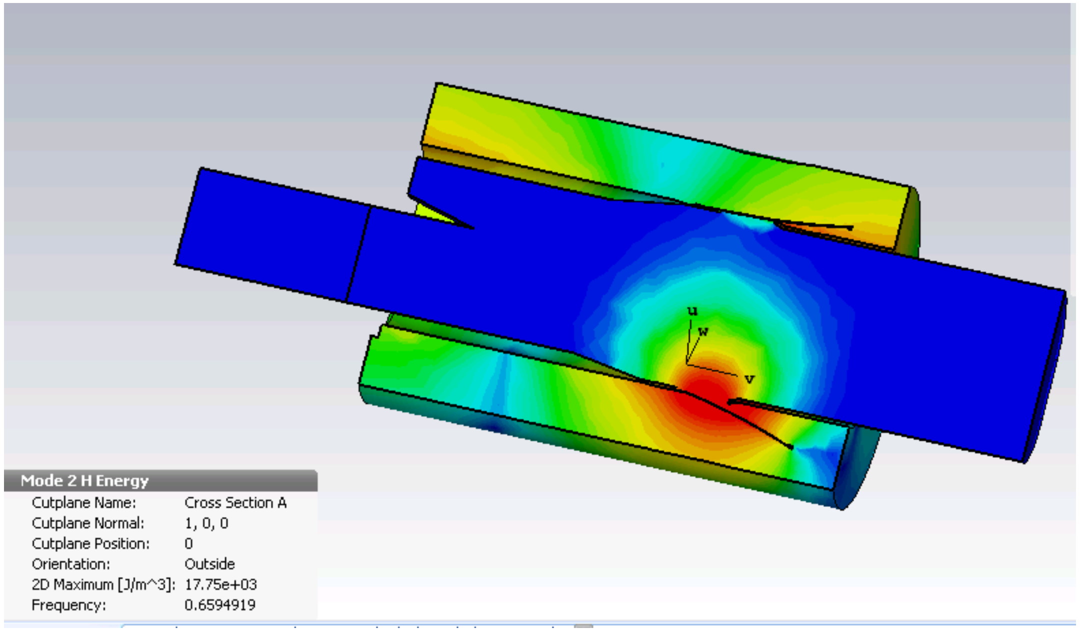
equipment	Problem	2011	2012	2015	2016
Vacuum modules	Damage		VMTSA removed		Spring on VMSI gone
TDI	Damage			Beam screen reinforced, non-conformity with hBN material	vacuum behavior with 55mm gap?
MKI	Delay			Beam screen upgrade and non conformity solved	ok
Collimators	Few dumps			Non conformity solved. TCTVB removed.	Several temperature probes perturbed by the beam → ok
Beam screen	Regulation at the limit	Q6R5 and TOTEM	Q6R5 and TOTEM	Upgrade of the valves +TOTEM ferrites baked out.	ok
ATLAS-ALFA	Risk of damage			New design + cooling	ok
BSRT	Deformation suspected			New design	ok
BGI	vacuum increase				BGI heats up

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

- **Some topics to follow up, but no limitation so far**

See B. Salvant, "Beam induced rf heating status", LMC No. 279

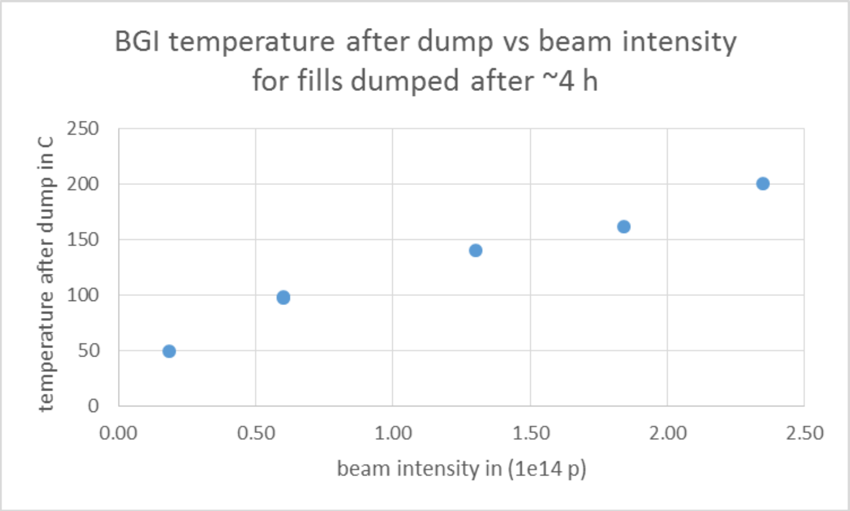
Beam Induced Heating: VMSI

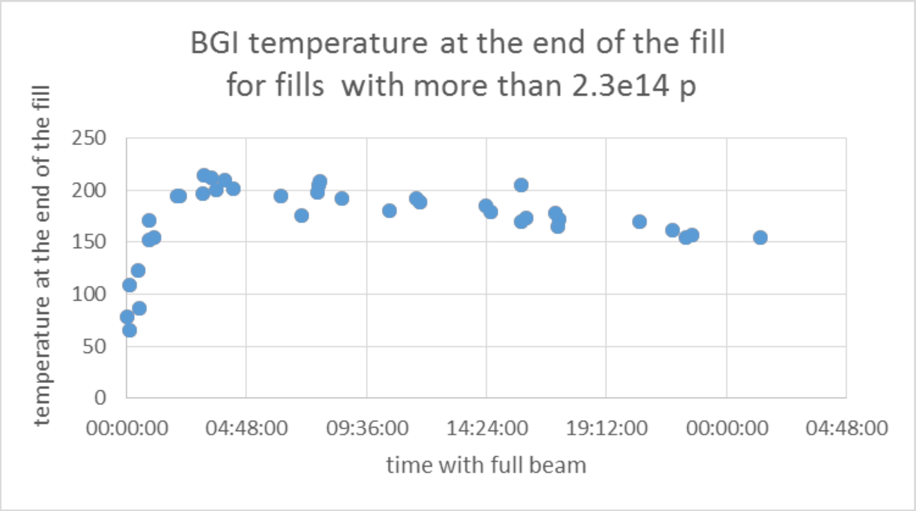


- RF fingers now hang and are not in contact anymore, due to missing spring.
- Significant resonant modes are found in impedance simulations
- Could potentially extract about 200W from the beam (of which 30% to 60% could go to the fingers sheet) if modes sit on beam spectrum.
- **Did not limit performance, will be replaced during EYETS.**

Beam Induced Heating: BGI

- BGI temperature probes were connected and confirm heating.
- Clear dependence with intensity, as shown on the left for fills dumped after ~4h.
- Can attempt to reconstruct the temperature at any time of a fill by combining all fills.
- Should be taken with care as should also depend on the initial temperature, work in progress.





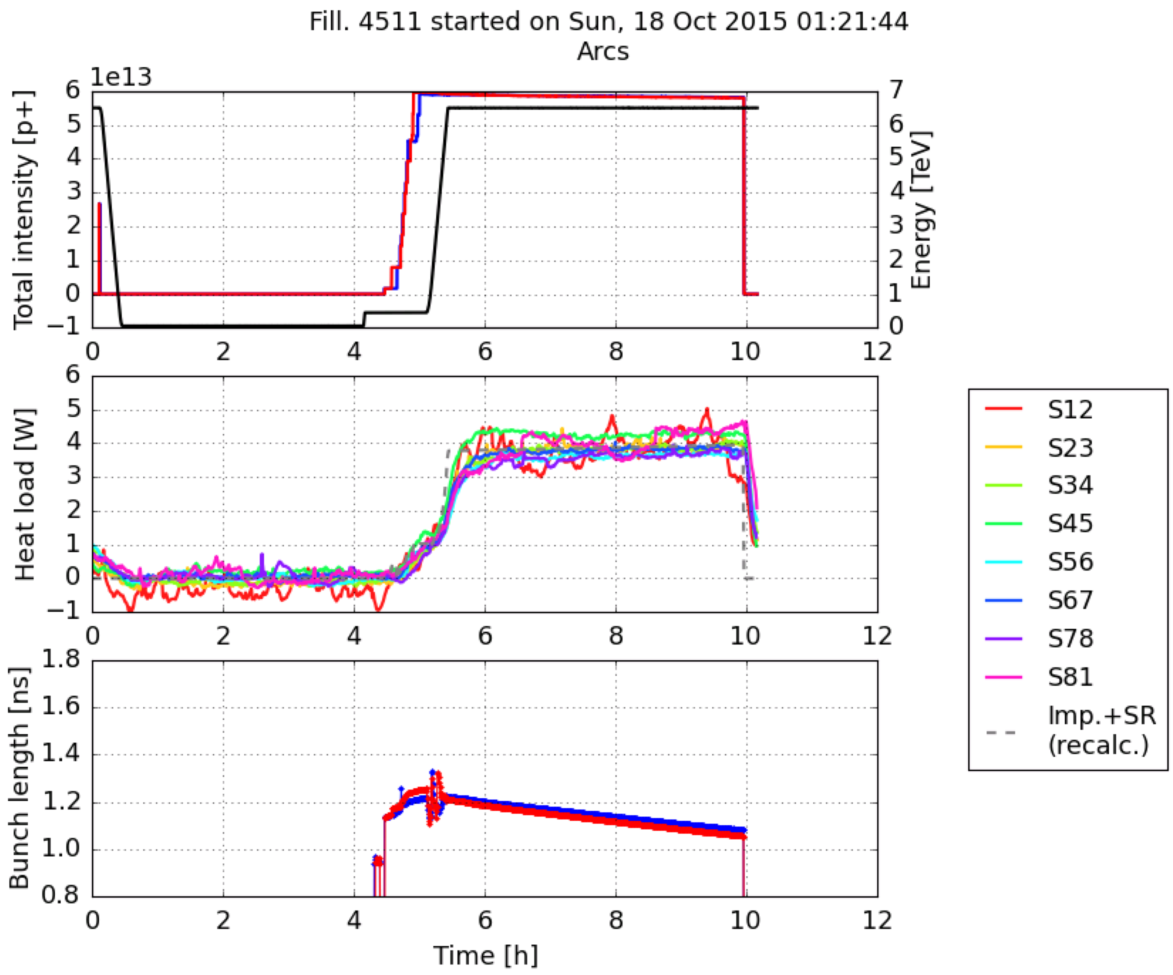
Recommendation:

- 2 BGI's will be removed during EYETS, 2 will remain in.
- Check for damage and work to improve temperature monitoring
- In case of issues (vacuum or damage), work on mitigation techniques
- Current design expects ~170 W if hitting narrow resonant modes around 500 MHz

Beam Induced Heat Load

- Estimations from **impedance and synchrotron radiation only** agree very well with data collected during machine operation in 2015 (without e-cloud).

Bunch spacing: 100 ns, b*=90m run in 2015



Summary

- Excellent performance w.r.t collective effects this year. **Reached ~1.4*HL-LHC brightness!**
- The instabilities that limited performance we could cure, the instabilities that did not limit performance require further study.
- Greater understanding of interplay between optics effects and beam stability both in general and at end of squeeze. Q'' as a possible stabilising knob has also been successfully tested at flat top.
- Gained valuable experience with the ADTObsBox in operation. Next step: application in the CCC.
- No limitations from beam induced heating in 2016 and no particular limitation expected in 2017, **but beware of non-conformities.**
- If all goes well, max possible intensity per bunch (1.25e11) and more bunches (2760) would increase power loss for all devices by ~40 % for all devices.

Thanks for your attention!

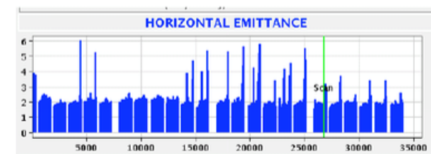
backup

Blowup in the ramp after MD4

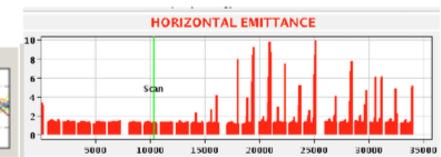
Beams going unstable with mode zero at the very beginning of the ramp
➔ blowup in B1H and B2H

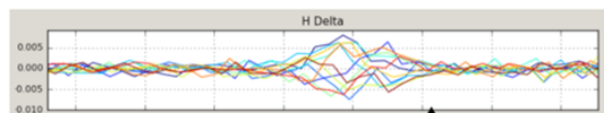
Simulations indicate it could be related to low (transient) Q' in the H plane
➔ critical bunches from e-cloud go unstable

As this seemed to only happen on "after-precycle" fills, it could be related to different incorporation timing for lattice sextupole ad b3 corrections

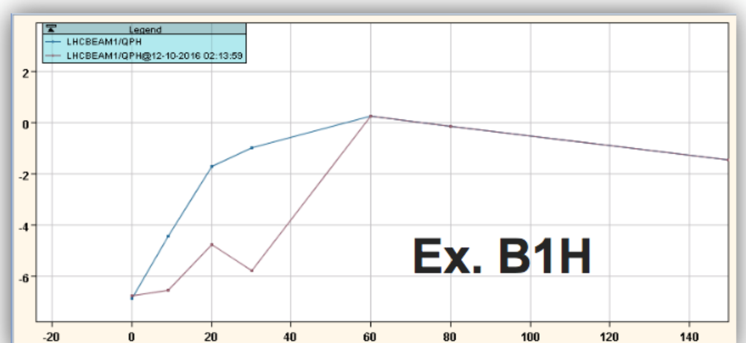


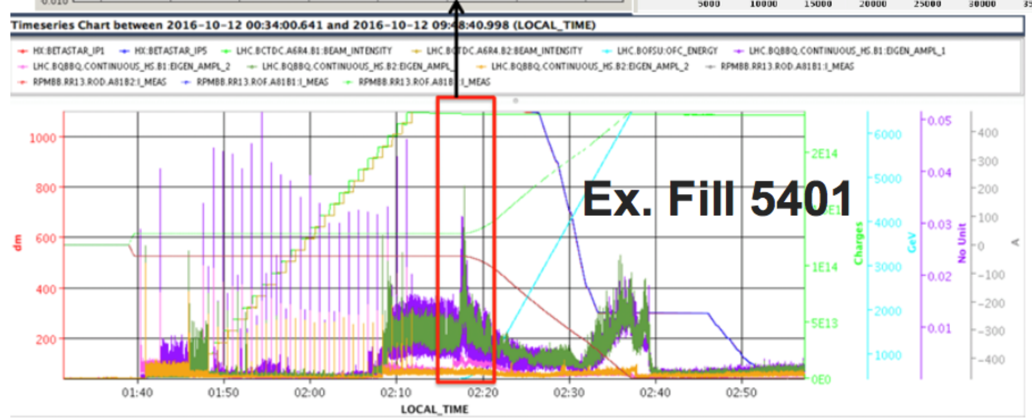
Cured by increasing Q'H corrections in the first seconds of the ramp by few units





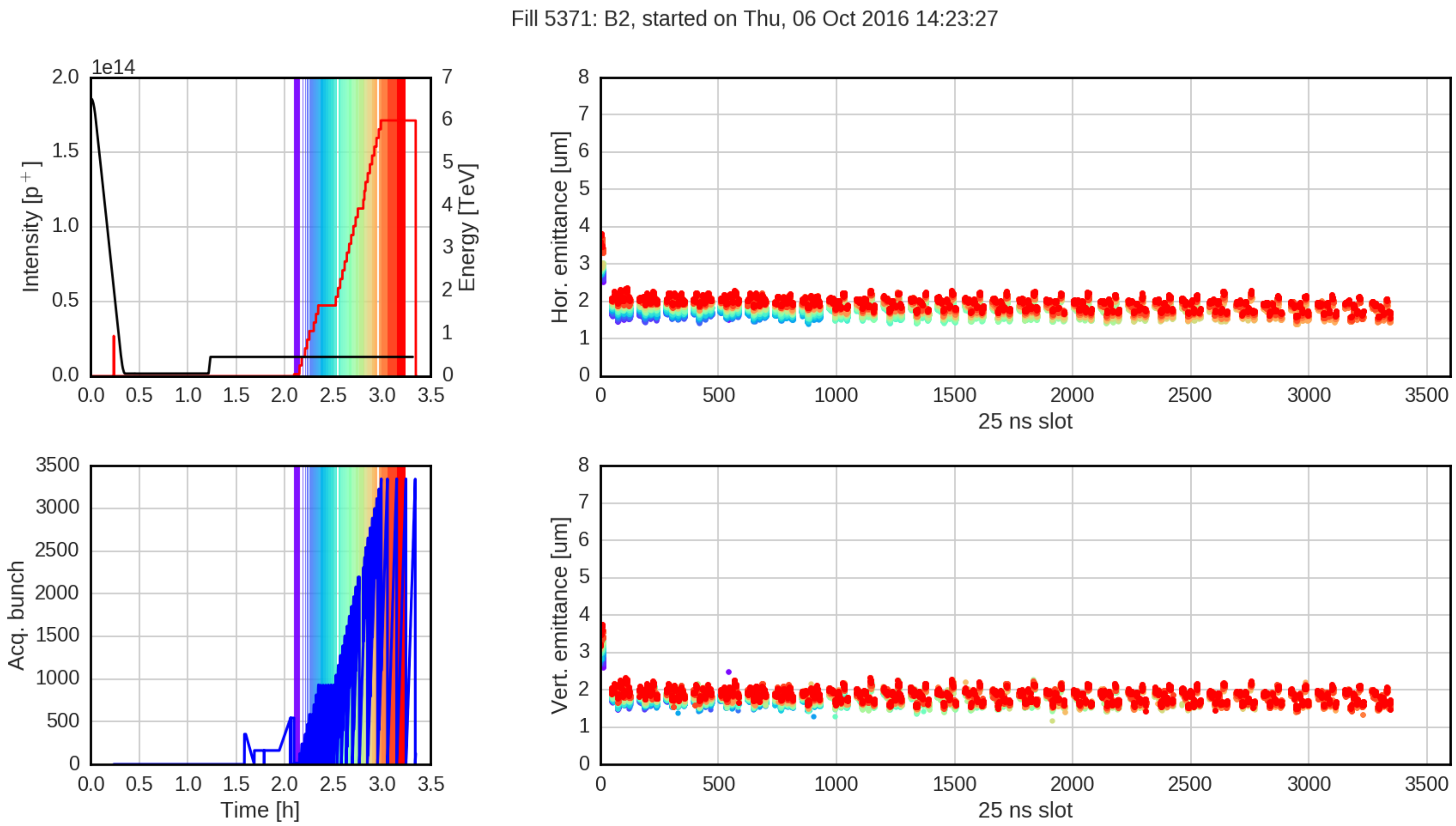
It is NOT CLEAR why the problem only appears now!!





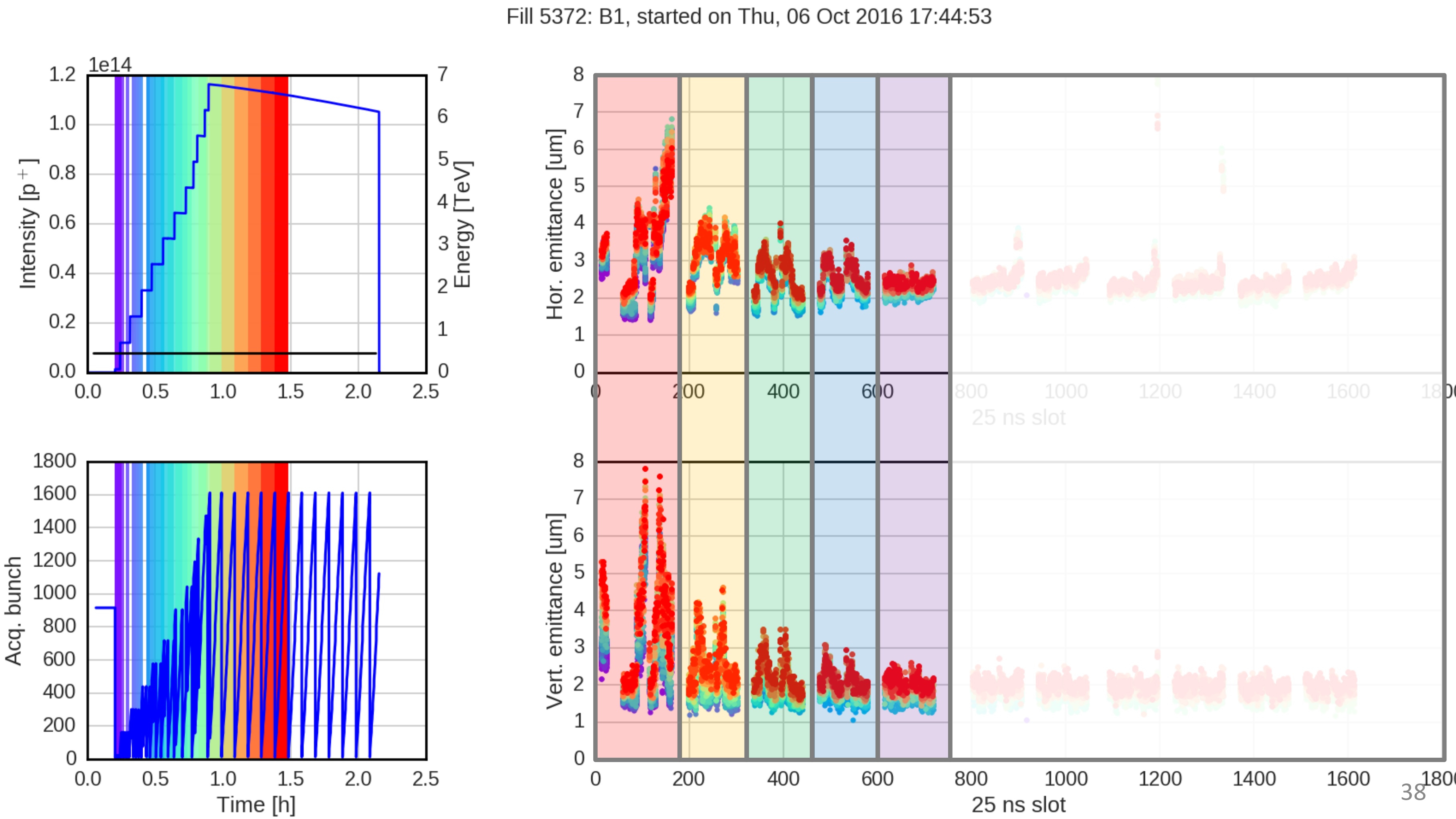
See M. Solfaroli contribution to, "Machine Status", LMC No.282

Operation in 2016 – Test with 8b4e



Operation in 2016 – Test with 25ns

Octupole knob	-0.5	-1.0	-1.0	-1.0	-2.0	-4.0	-4.0	-4.0
Chromaticity	5/5	5/5	10/10	15/15	15/15	15/15	10/15	20/15



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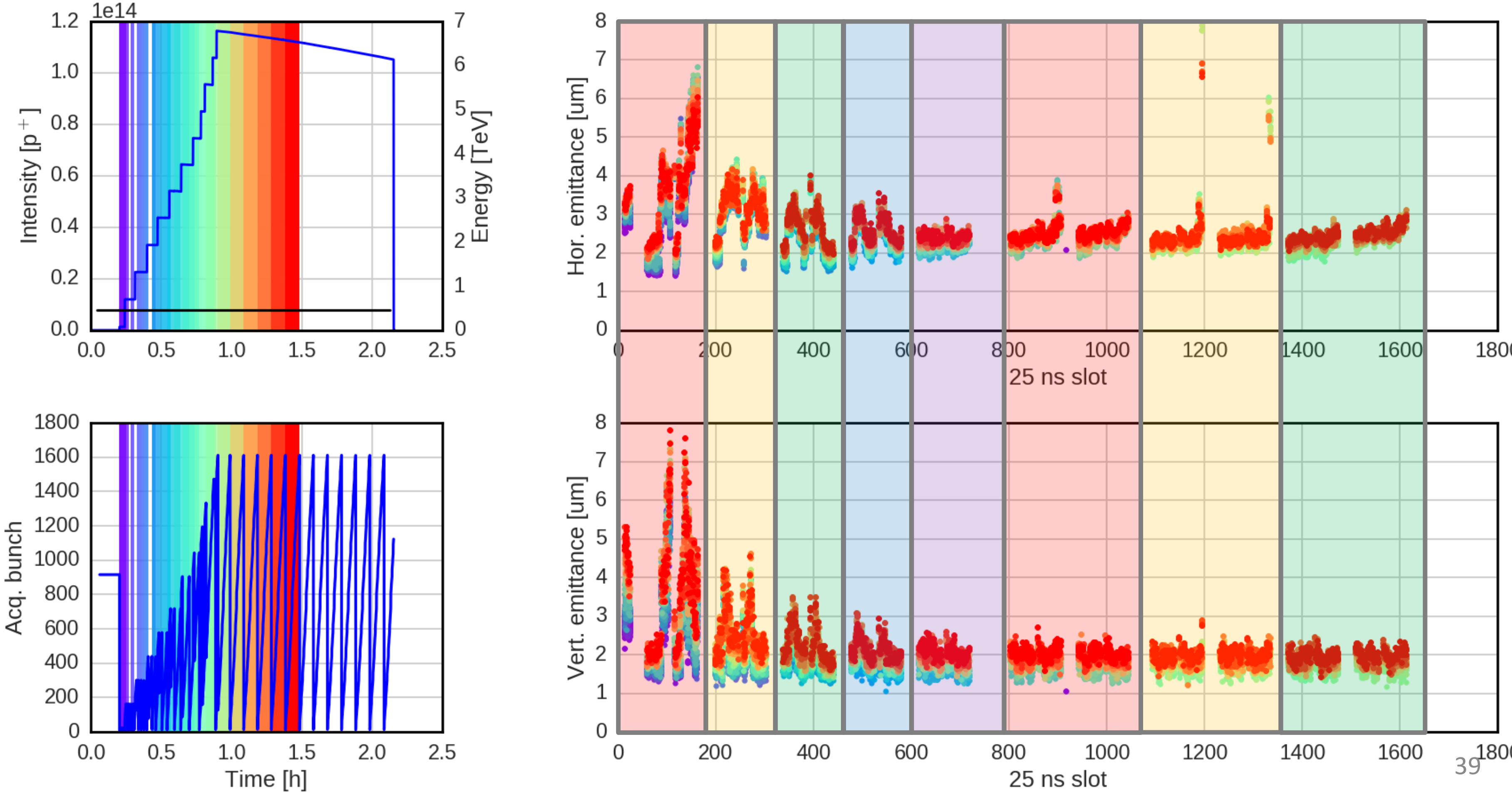
Chromaticity	5/5	5/5	10/10	15/15	15/15	15/15	10/15	20/15

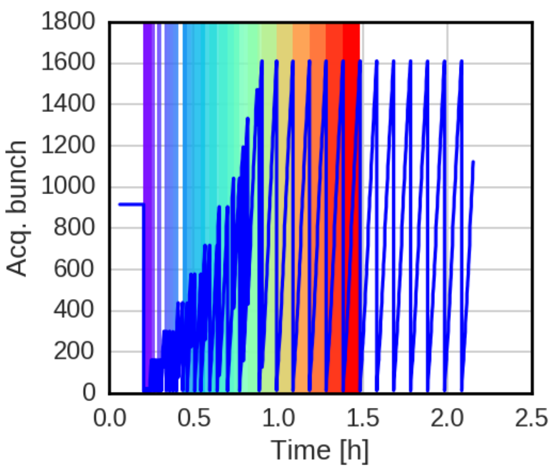
Fill 5372: B1, started on Thu, 06 Oct 2016 17:44:53

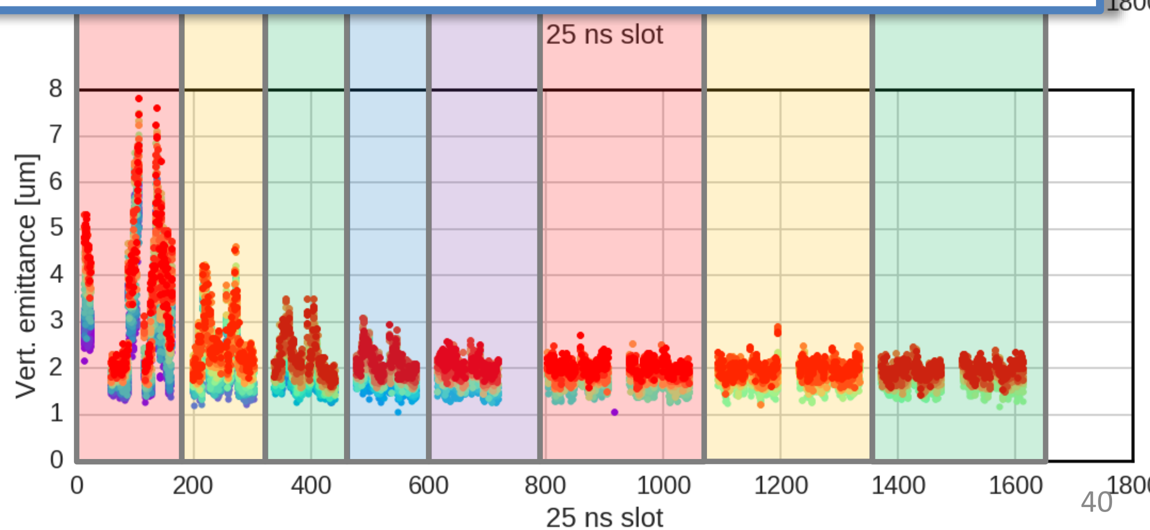


Operation in 2016 – Test with 25ns

Octupole knob	-0.5	-1.0	-1.0	-1.0	-2.0	-4.0	-4.0	-4.0
Chromaticity	5/5	5/5	10/10	15/15	15/15	15/15	10/15	20/15

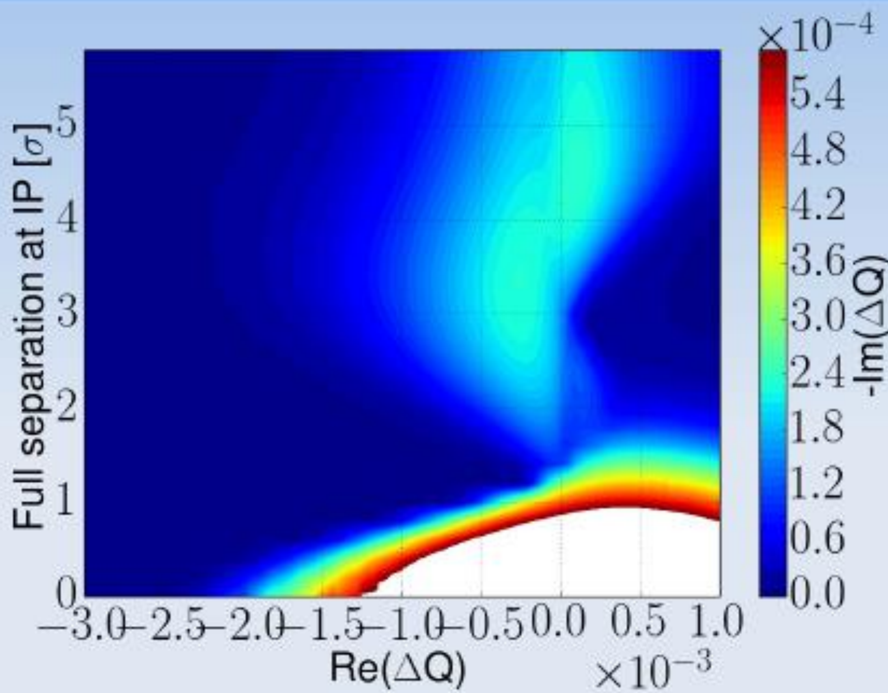
Fill 5372: B1, started on Thu, 06 Oct 2016 17:44:53

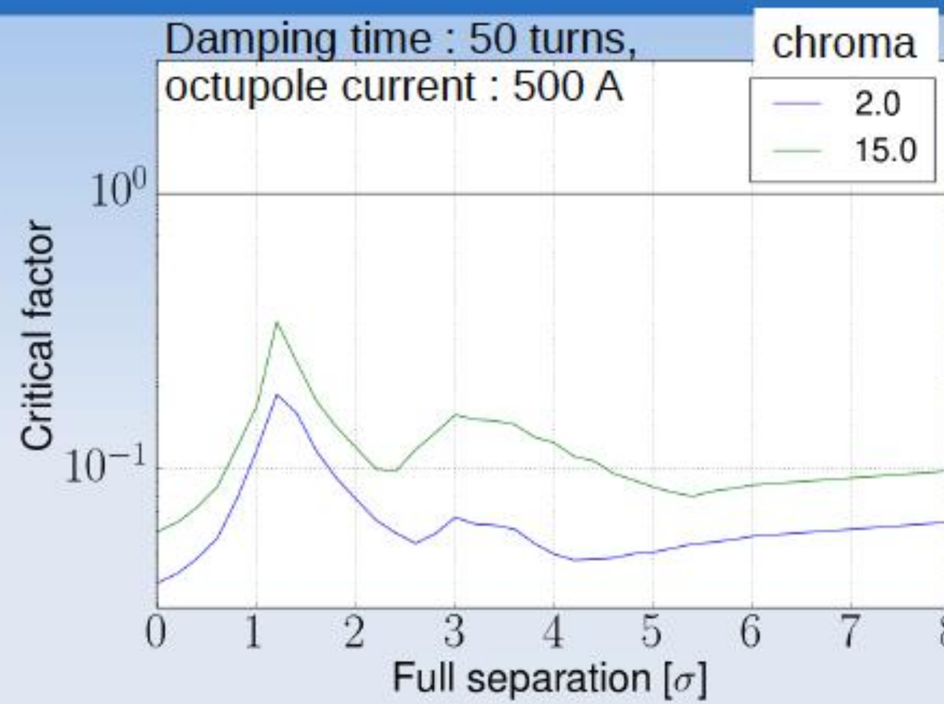




Pretty much looks like **e-cloud** – there appears to be **no margin** at injection!
We want to understand this better…

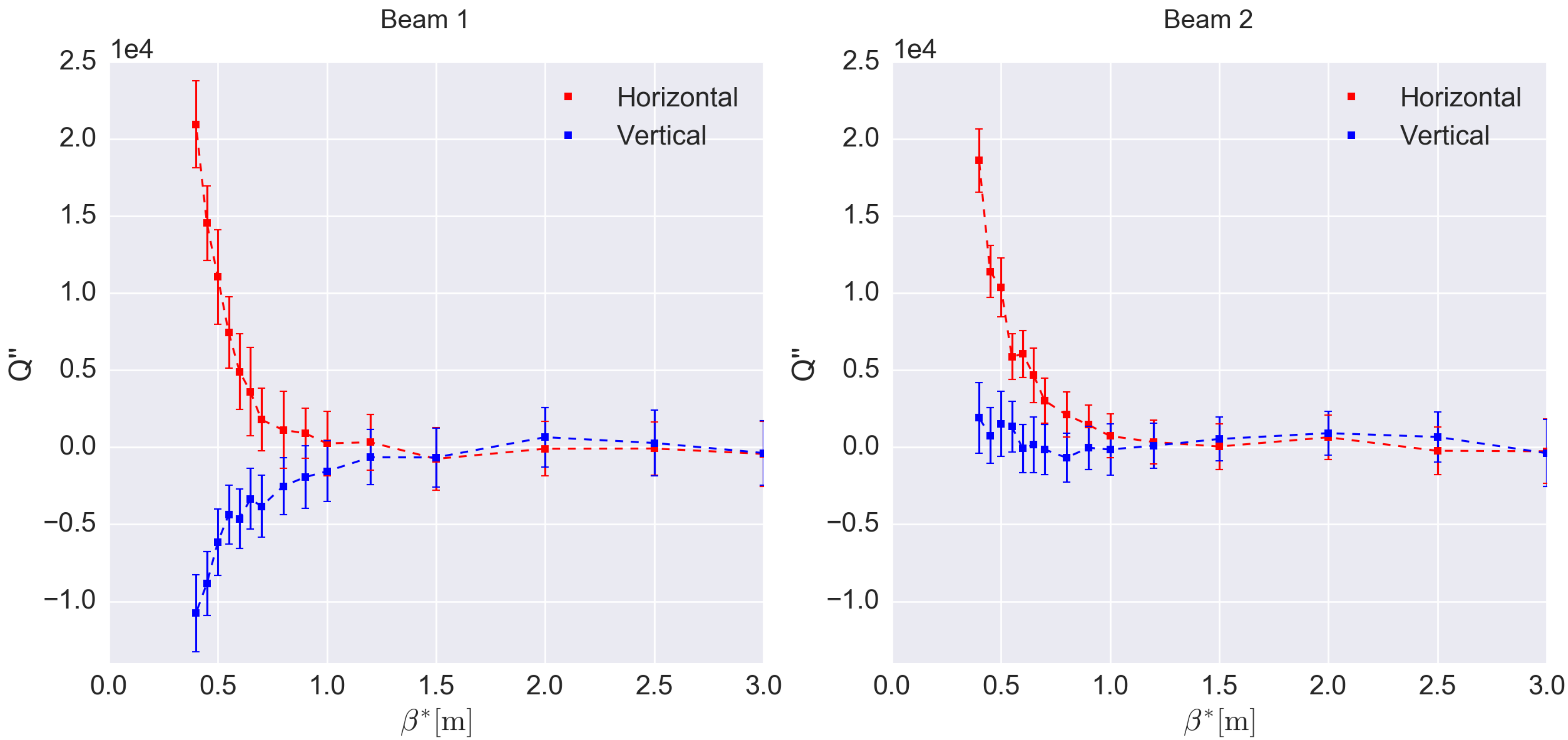
Coherent stability model





- The critical factor represents the beam stability margin (stable < 1, unstable > 1)
- The stability diagram has a minimum at about 1.5 σ, leading to and peak of the critical factor
  - Overall the beams remain well below the instability threshold during the process

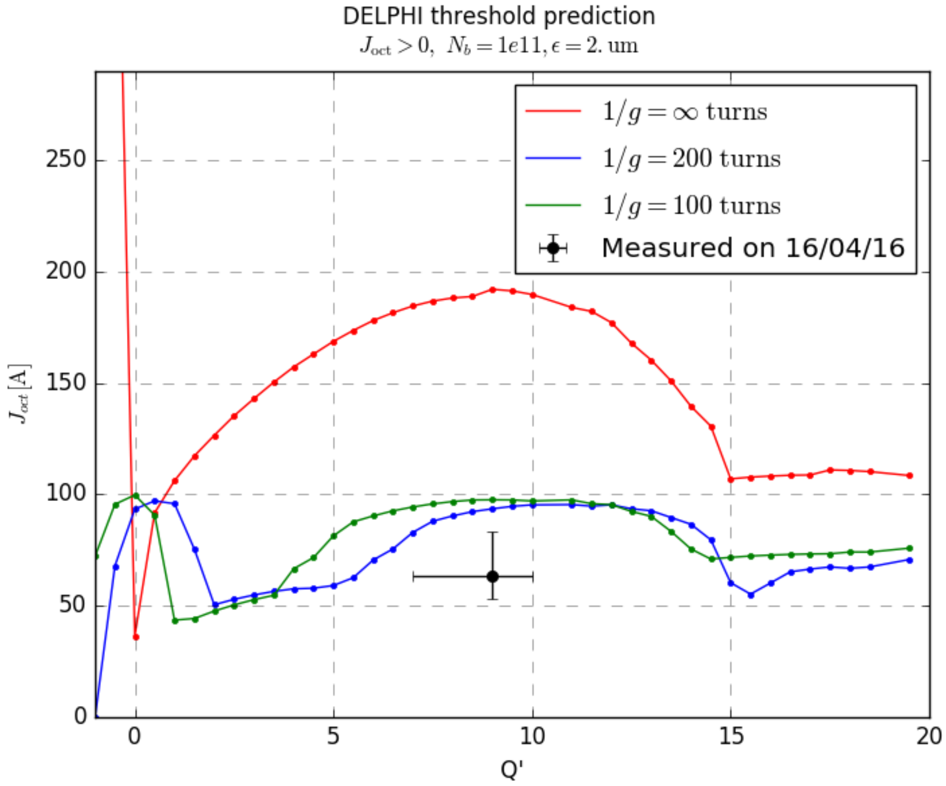
Measured lattice Q''



- Measured with pilot beams without LO (19.09.16).
- Good agreement with MAD-X.
- Contribution to Q'' from lattice is negligible for β* ≥ 80 cm, but becomes significant at β* = 40 cm.
- **One possible reason for better stability at EoS in 2016 compared to 2015.**

Single Bunch Stability Threshold - 2016

- EOF MD performed at start of 2016 to verify measurements from last year.
- Still have good agreement at flat top for a single nominal bunch with ADT ~150 turns.
- Instabilities seen in B1H and B2H with same characteristics at same threshold.



Beam Stability at 40cm in 2016

- Stability threshold measurements at end of squeeze showed that the bunch (or even a full beam with LR) is stable at β^*=40cm.
- Details of the specific measurements can be found below.
- Possible explanations are the Q'' from the lattice (see backup) or non-linearities from the IR's (see Evian talk by E. Maclean).
- MD1831 sought to distinguish between these effects.

Fill 4804 *(16.04.16)*

- **Flat top** (β* = 300 cm)
- Q' ≈ 9 / 8 (H/V)
- Single bunch threshold is **LOF ≈ 63 A** (norm.).
- Head-tail mode (0, 2).
- Consistent w. former MDs in 2015 (346, 751) and model predictions.

MD751 *(28.08.15)*

- **EoS** (β* = 80 cm)
- Q' ≈ 11 (H/V)
- Single bunch threshold is **LOF ≈ 80 A** (norm.).
- **Consistent with measurements at flat top.**

MD1751 *(02.08.16)*

- **EoS** (β* = 40 cm)
- Q' ≈ 13 / 16 (H/V)
- 2076 b. nom. BCMS as well as 964 non-coll. b. **stable w. LO off** (no beam-beam).
- Emittance blow-up in H (LOF ≈ 80 A), but no losses.

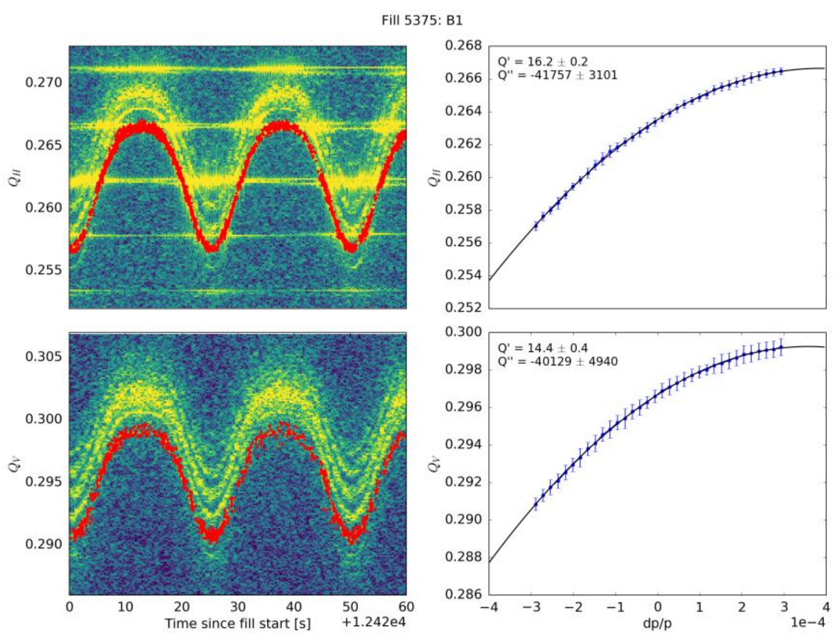
See L.R. Carver, "News on stability margins from MD4", LBOC No. 69

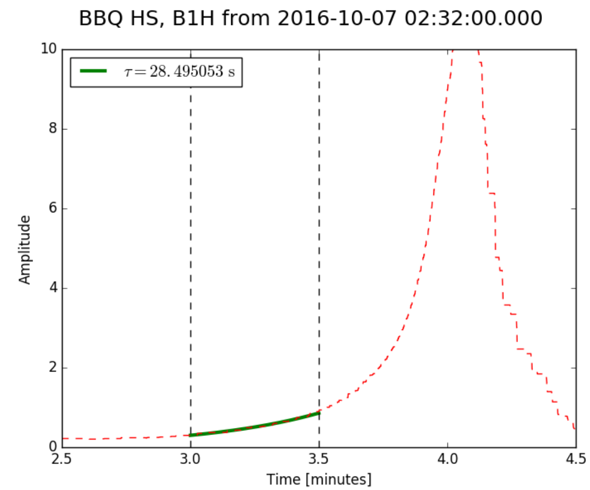
Q'' knob - 2016

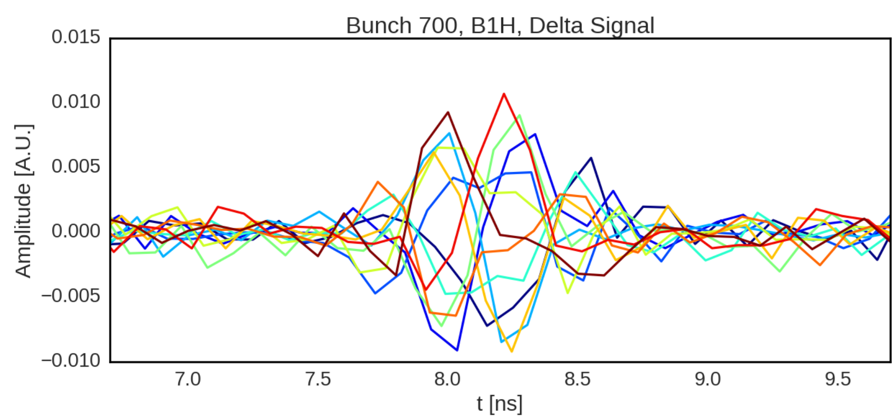
- During MD1831, introduced large Q'' at flat top in order to test new knob developed by R. De Maria.

- With Q' set to at 15/15 and two single bunches, large Q'' was introduced and octupoles reduced to 0A.

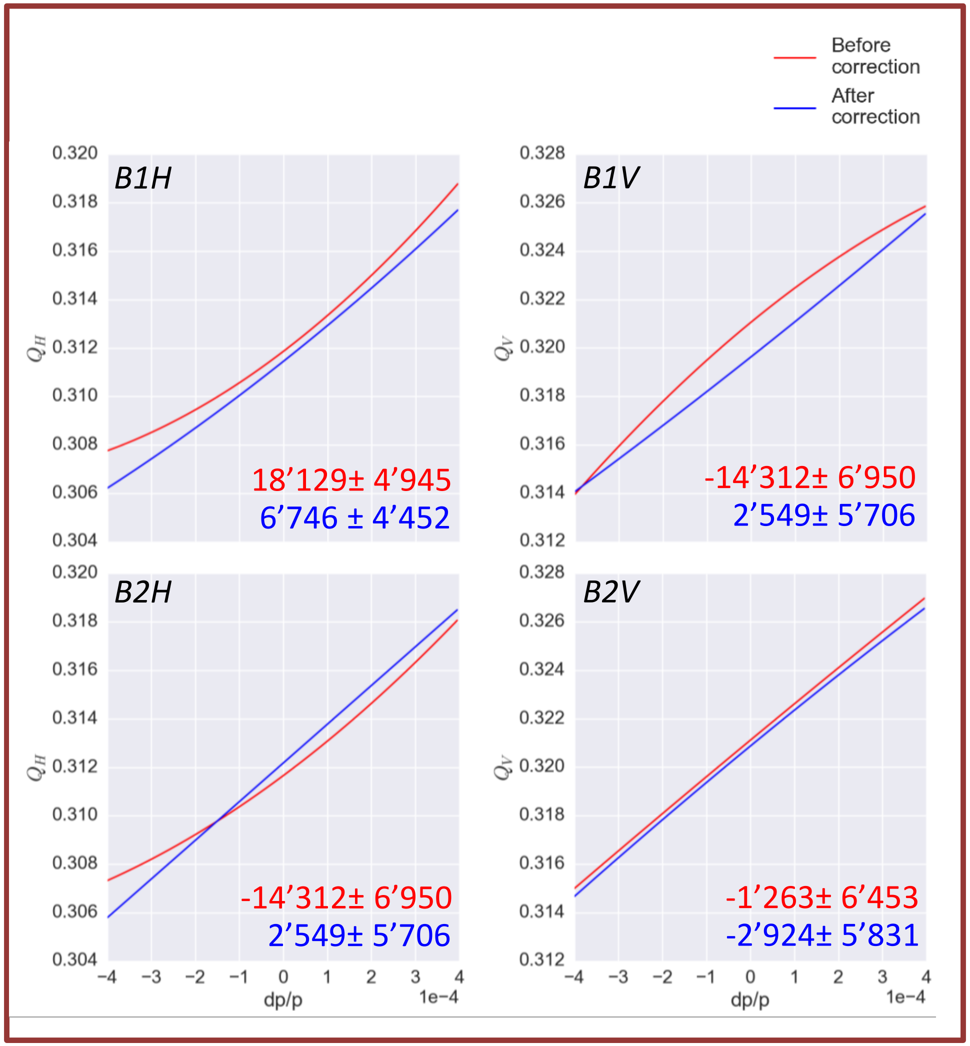
- One instability in B1H, but three planes stable with Q'' = -40k. PyHEADTAIL simulations are underway to explain the observation.







Q'' correction at EOS

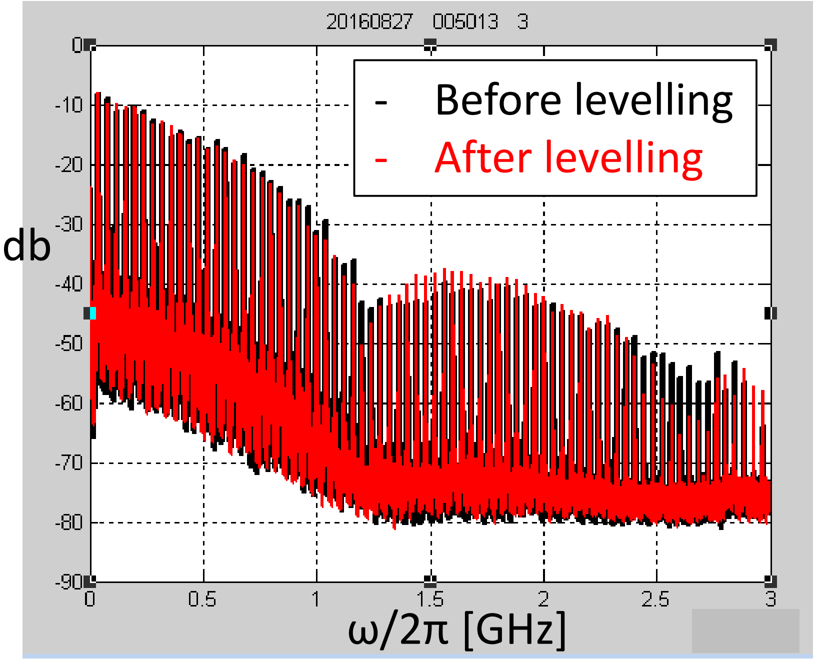


Beam Induced Heating: Miscellaneous

- Apparent dependence of temperature readings on TDI with beam intensity.
- This is based on dedicated tests with shielded probes and cables during the impedance measurements on the new spare TDIs (thanks to the help and support of BE-BI, EN-STI and TE-ABT).
- There is no indication that the TDI vacuum issues are related to heating, but no inspection of the TDI will take place during EYETS.
- Cannot know more nor can we predict its behaviour next year with longer trains.
- Issues with beam spectrum acquisition: RF experts have been working on it, but there seems to be an incompatibility of the scopes with the continuous acquisition with the CERN framework: may need to replace with other scopes (new or swapped).

Longitudinal Blowup & BCT Spectrum

- Clear impact of bunch length levelling: but not the way it is expected!
- Beam spectrum unfortunately not working most of the time
  (thanks a lot to Michael and Philippe for the numerous attempts at restarting the scopes)
- It would be important that it works after EYETS.



- Smaller amplitudes up to 1.2 GHz
- But larger beam spectrum amplitude between 1.3 and 1.7 GHz after levelling
- There are modes there for ALFA but it does not seem to explain the difference.
- Studies are ongoing but we are missing statistics.