LHC bunch charge limitation from beam induced RF heating

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Many thanks to all equipment groups!

Thanks in particular to Lotta Mether, Carlo Zannini, Giovanni Rumolo, Gianni Iadarola, Francois-Xavier Nuiry, Marko Milovanovic, Roderik Bruce, Vasileios Vlachodimitropoulos, Oskar Bjorkqvist and the IWG.

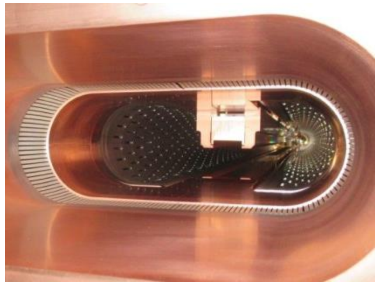
Joint Accelerator Performance Workshop

December 6th 2022

Agenda

- Beam induced RF heating
- Status before LS2
- Status in 2022
- Plans for 2023
- Conclusion

Beam induced RF heating?

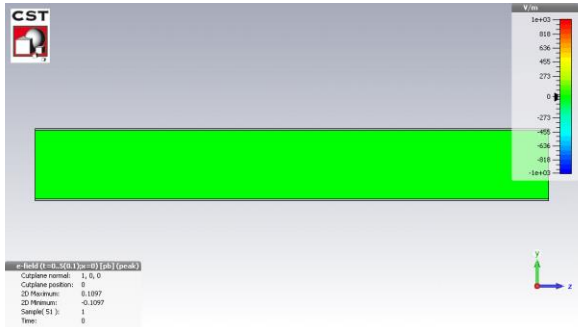


- When the LHC beam traverses a device which
  - is not smooth
  - or is not a perfect conductor,

  it will produce wakefields that will perturb the following particles

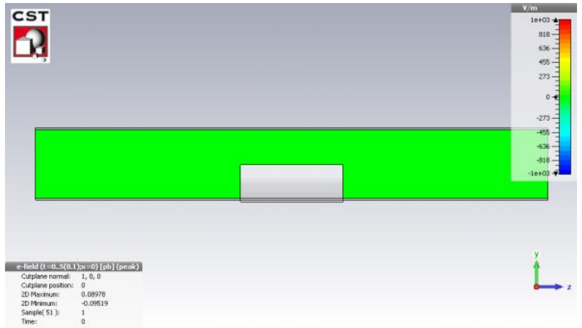
  → resistive or geometric wakefields (in time domain) and impedance (in frequency domain).

- Example of 3D simulation of electromagnetic perturbation caused by an obstacle beam pipe:



e-field (t=0..5(0.1);x=0) [pb] (peak)
Cutplane normal: 1, 0, 0
Cutplane position: 0
2D Maximum: 0.1097
2D Minimum: -0.1097
Sample(51): 1
Time: 0

In a round beam pipe



e-field (t=0..5(0.1);x=0) [pb] (peak)
Cutplane normal: 1, 0, 0
Cutplane position: 0
2D Maximum: 0.08978
2D Minimum: -0.09519
Sample(51): 1
Time: 0

In a round beam pipe with sharp obstacle

→ resonant RF mode

→ energy left behind by the bunch

→ eventually dissipates in the surrounding walls

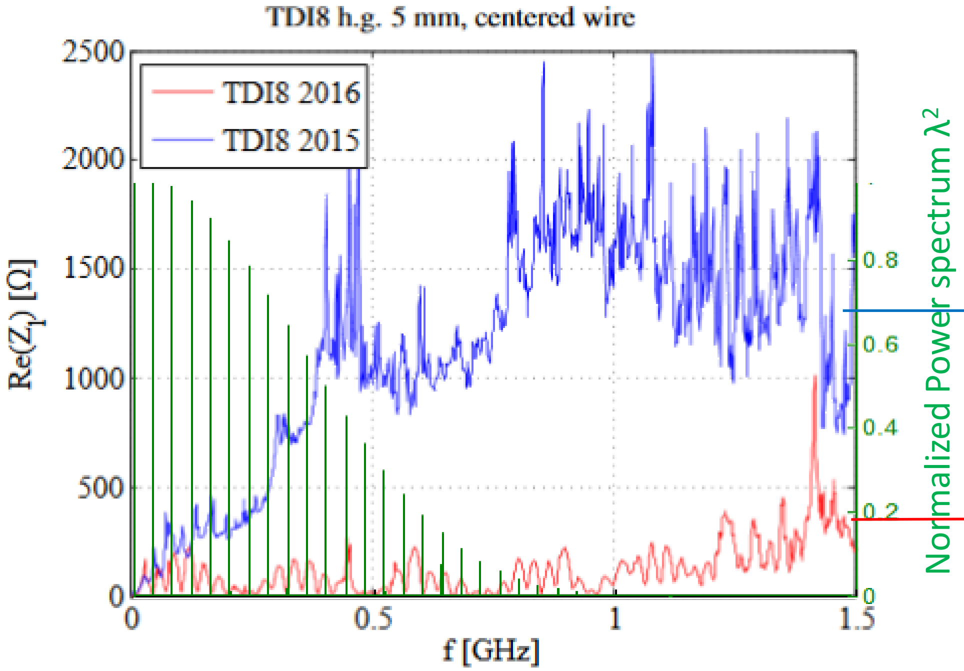
→ Energy lost by the bunch will eventually heat up the surrounding walls

Beam induced RF heating?

→ Can be computed from the impedance of the device and the beam power spectrum

Power lost by a beam of intensity $I_{beam} = M*N_b*e*f_{rev}$ and normalized power spectrum λ^2 in a device of longitudinal impedance Z_{long}

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



For 2248 bunches with 1.15 10^{11} p/b, we have measured:

TDI8 in 2015: P_{loss} ~ 3 kW

TDI8 in 2016: P_{loss} barely measurable

In order to reduce beam induced RF heating, one can:

- reduce the impedance of the device (as done on TDI8 in 2016)
- reduce the intensity of the beam
- change the power spectrum to reduce its interaction with the device impedance (change bunch length, bunch distribution and filling pattern)

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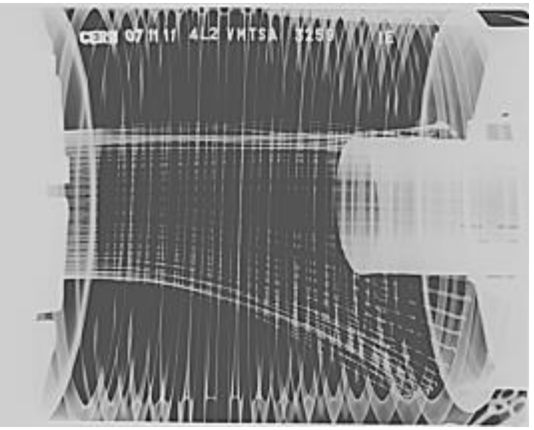
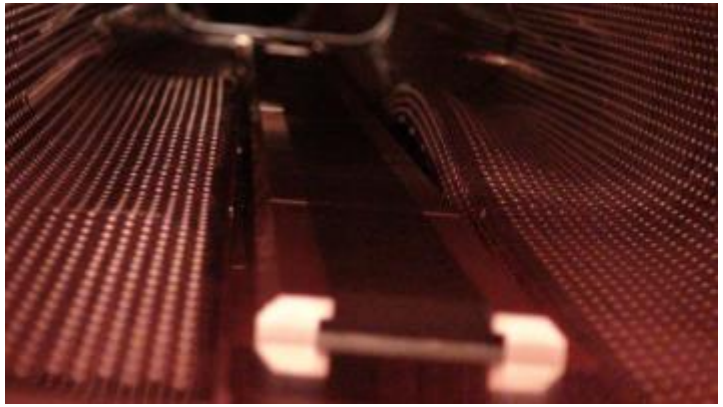
Reminder: heating issues since LHC startup

Damaged vacuum modules
→ Design not robust



Damaged injection collimators
→ Design not robust

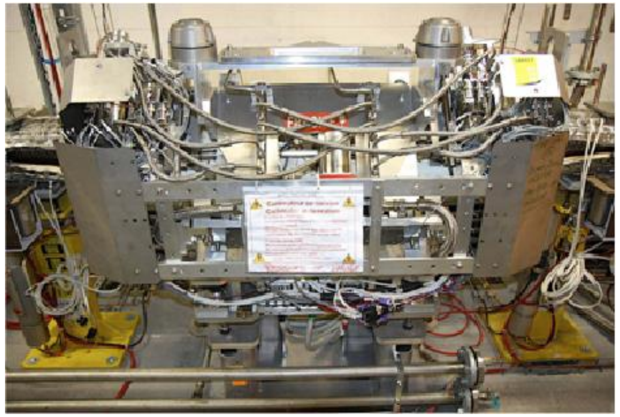


Damaged synchrotron light monitor
→ Design not robust

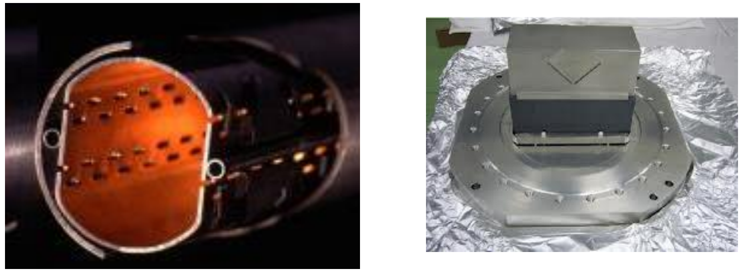
ATLAS-ALFA detector almost reached damage level
→ Design not robust

One injection kicker delays injection
→ Non conformity

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



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



→ Many actions taken by all involved equipment groups (especially during LS1 and 2015-2016 YETS)!

Beam induced heating status before LS2

equipment	Problem	2011	2012	2015	2016	2017 and 2018
Vacuum modules	Damage	⬛	🟩 VMTSA removed	🟩	🟩 Spring on VMSI gone	🟩 Spring on VMSI gone again
TDI	Damage	⬛ Beam screen bent	⬛ Beam screen bent	⬛ non-conformity with hBN material	🟩 vacuum behavior with 55mm gap, could be e-cloud related	🟩
MKI	Wait for injection or reduce intensity	🟥	🟥	🟩 Beam screen upgrade and non conformity solved	🟩	🟩
Collimators	Few dumps	🟥	🟨	🟩 Non conformity solved. TCTVB removed	🟩	🟩
TOTEM	Beam screen regulation at the limit	🟨 Q6R5 affected by TOTEM	🟥 Q6R5 affected by TOTEM	🟩 Upgrade of the valves + TOTEM check	🟩	🟩
Roman pots (ALFA and AFP)	Risk of damage and outgassing	🟨 ATLAS-ALFA close to limit	🟥 ATLAS-ALFA close to limit	🟩 New design for ATLAS-ALFA + cooling	🟩	🟩
BSRT	Deformation suspected	🟨	⬛ Mirror damage	🟩 New design + cooling	🟩	🟩
BGI	vacuum increase	🟩	🟩	🟩 To be followed up	⬛ BGI heats up and damaged	🟩 BGIs removed

→ Some topics to follow up, but no limitation anymore

⬛ Damage
🟥 Limits operation
🟨 Worry that can limit operation
🟩 Should be fine

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  - What has changed
  - MKI
  - Vacuum spikes in TCLDs, LHCb Velo, 5R4
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What has changed after LS2

- Steady increase of intensity per bunch from 1.15-1.2 10^{11} p/b to ~1.45-1.5 10^{11} p/b

  → Beam induced heating increased by ~50% compared to Run 2

  → Another ~50% increase expected to reach 1.8 10^{11} p/b

- Relevant equipment installed during LS2
  - Low impedance collimators
  - TDIS
  - LHCb Velo upgrade
  - TCLD
  - New experimental chambers

Beam induced heating status at the end of 2022

equipment	Problem	2011	2012	2015	2016	2017 and 2018	2022
Vacuum modules	Damage	⬛	🟩 VMTSA removed	🟩	🟩 Spring on VMSI gone	🟩 Spring on VMSI gone again	🟩 Need to check vacuum spikes in 5R4
TDIS	Damage	⬛ Beam screen bent	⬛ Beam screen bent	⬛ non-conformity with hBN material	🟩 vacuum behavior with 55mm gap, could be e-cloud related	🟩	🟩
MKI	Wait for injection or reduce intensity	🟥	🟥	🟩 Beam screen upgrade and non conformity solved	🟩	🟩	🟩 Temperature interlocks increased with experience
Collimators	Few dumps	🟥	🟨	🟩 Non conformity solved. TCTVB removed	🟩	🟩	🟩 Need to check TCLD vacuum spikes
TOTEM	Beam screen regulation at the limit	🟨 Q6R5 affected by TOTEM	🟥 Q6R5 affected by TOTEM	🟩 Upgrade of the valves + TOTEM check	🟩	🟩 Some sectors heating more	🟩
Roman pots (ALFA and AFP)	Risk of damage and outgassing	🟨 ATLAS-ALFA close to limit	🟥 ATLAS-ALFA close to limit	🟩 New design for ATLAS-ALFA + cooling	🟩	🟩	🟩 AFP pots are getting close to 50 C
BSRT	Deformation suspected	🟨	⬛ Mirror damage	🟩 New design + cooling	🟩	🟩	🟩
BGI	Vacuum increase	🟩	🟩	🟩 To be followed up	⬛ BGI heats up and damaged	🟩 BGIs removed	🟩
LHCb Velo	Vacuum spikes	🟩	🟩	🟩	🟩	🟩	🟩 Need to check vacuum spikes

→ Some topics to follow up, but still no limitation despite the significant increase in bunch intensity

⬛ Damage
🟥 Limits operation
🟨 Worry that can limit operation
🟩 No limitation during operation

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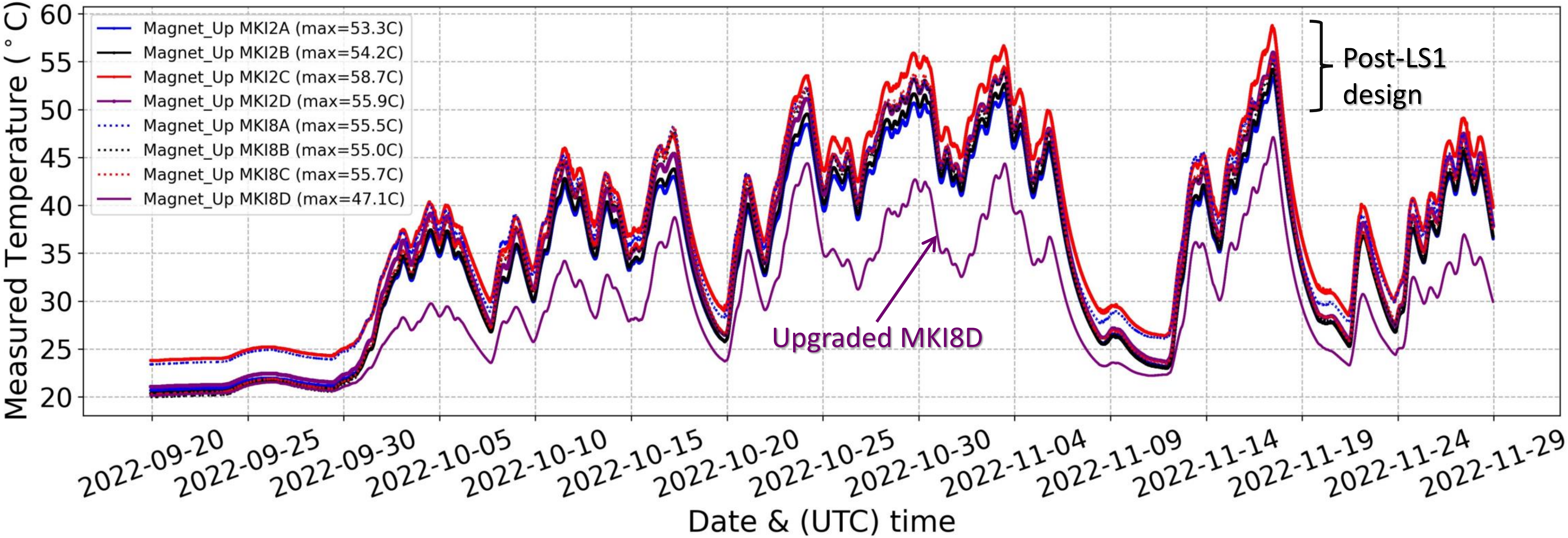
MKI temperature



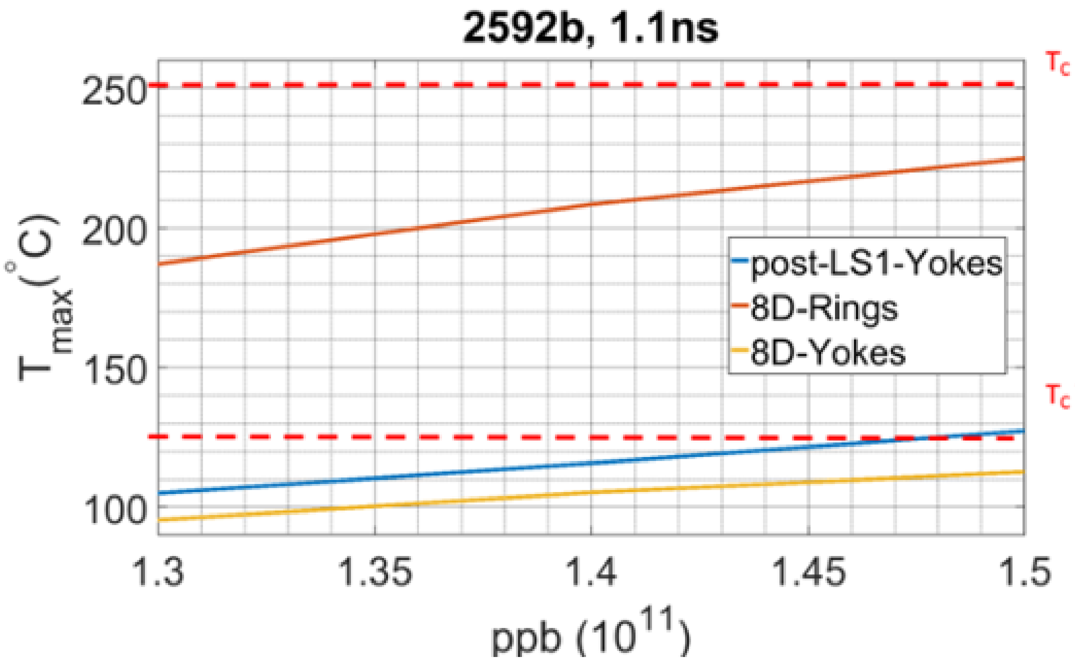
- Measured temperatures increase as expected with higher intensity and long fills
- Procedures followed, with fast turn-around, to increase SIS interlock thresholds as necessary.
- MKI8D (installed YETS 2017/18) included an upgrade to relocate a significant portion of beam induced power from the yoke to the ‘**RF damper**’: this element is not at pulsed high voltage.

  → Lower yoke temperature for MKI8D

  → effectiveness of the upgrades demonstrated during LHC operation.

MKI temperature: simulations

- Talk of Francesco Velotti at Evian 2019 and Mike Barnes at Chamonix 2022
- Recall of steady state thermal simulations for currently installed MKIs



T_C Rings (4B3) = 250°C

Notes:
-MKI8D as upgraded in YETS17/18
-Expected hottest post-LS1 magnet: 8C

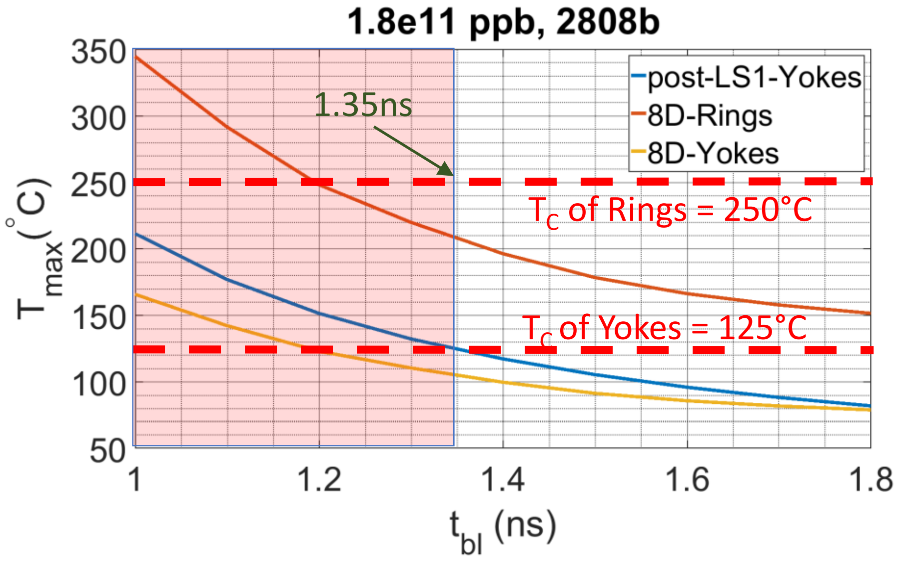
T_C Yokes (CMD5005 or 8C11) = 125°C

→ We are now very close to the limit for steady state heat load

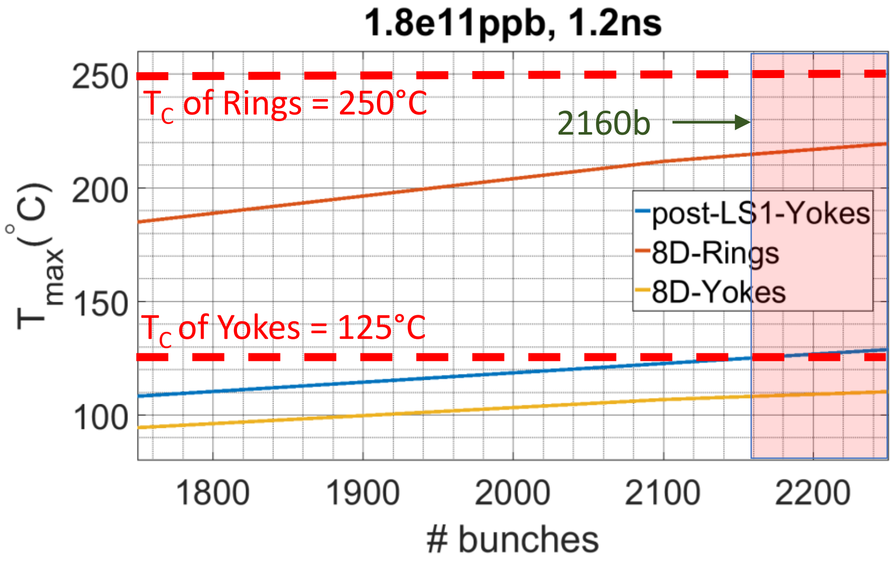
MKI temperature: simulations

- Talk of Francesco Velotti at Evian 2019 and Mike Barnes at Chamonix 2022
- Recall of steady state thermal simulations for currently installed MKIs

1.8e11 ppb, 2808b



1.8e11ppb, 1.2ns

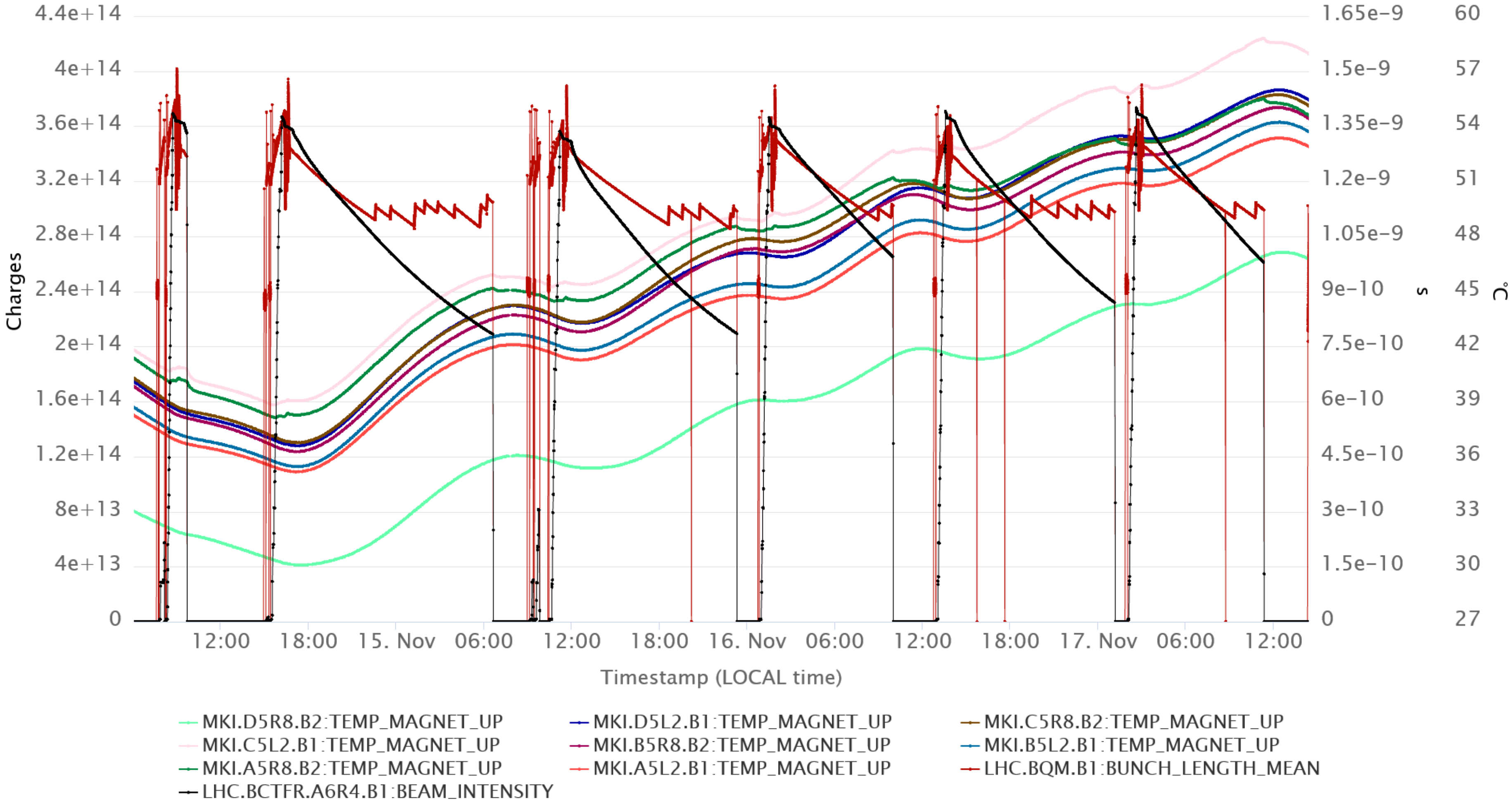


→ Limit expected with 2808 bunches and 1.8 10^{11} p/b at 1.35 ns for steady state heat load

→ Increasing bunch length will help

MKI temperature

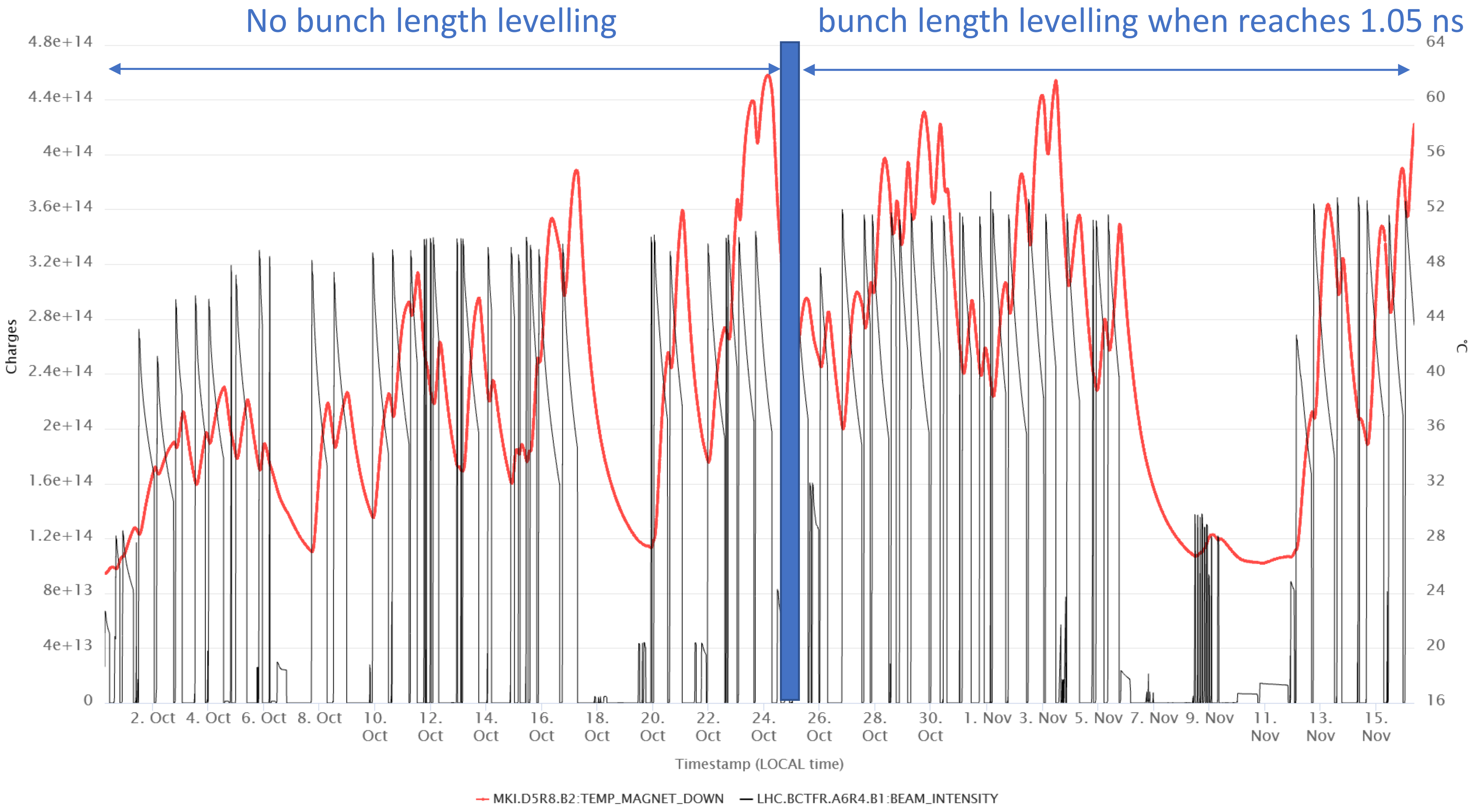
→ Limit expected with 2808 bunches and 1.8 10^{11} p/b at 1.35 ns for steady state heat load



→ Limit not reached yet for MKI8D or post-LS1 MKIs with series of consecutive fills with 2462 bunches at 1.45 10^{11} p/b levelled at ~1.1 ns (mid November)

MKI temperature

- Bunch length leveling has been efficient at limiting heating of MKIs (around 1.1 ns)

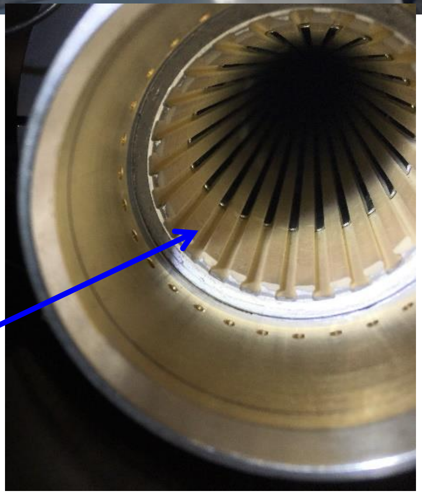


MKI temperature outlook for 2023

- MKI-COOL will replace MKI8D in YETS 2022/23
  - MKI8D is the coolest installed kicker… but…
  - … issues with quality of produced alumina tubes
  - … need to recuperate the alumina tube of MKI8D for installation of another MKI-COOL in the YETS 2023/24

- No significant difference expected from BCMS/8b4e/mixed schemes (see next slides)

- Increasing bunch length target would help in case we reach the limit in physics before 1.8 10^{11} p/b



Cr_2O_3 coated alumina

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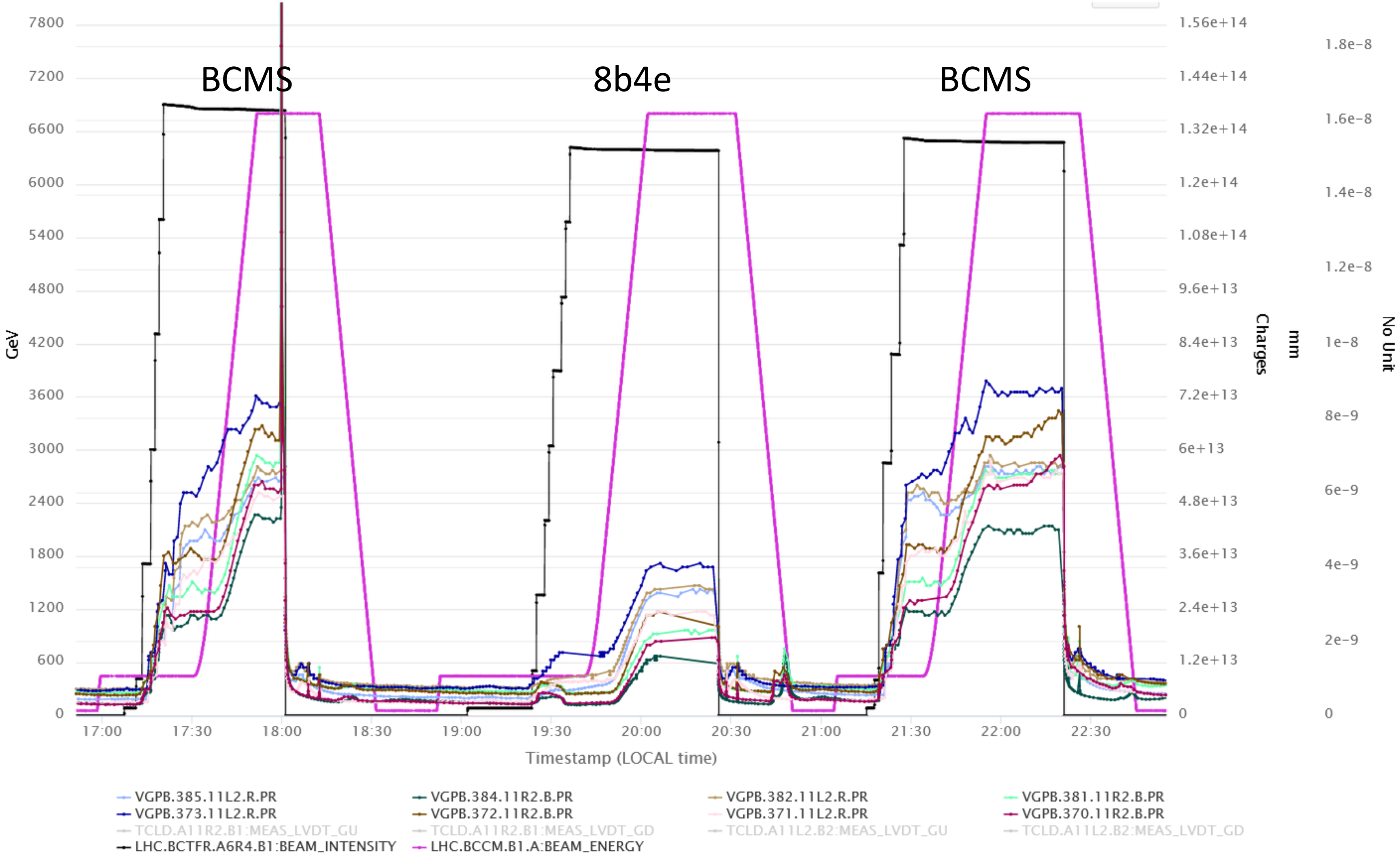
Vacuum spikes observed during the run:

- TCLDs
  - Vacuum spikes observed on both 11R2 and 11L2 throughout the year (randomly in the fill) (largest during the scrubbing run in June)
  - No correlation to movement of collimator, but some correlation observed with losses
  - Xrays were performed during the LHC stop in Summer, will be redone on 11R2 during the YETS to investigates shadows seen on the Xrays

- 5R4
  - Vacuum spikes observed at almost every fill during injection or the first part of the ramp, one dump at flat top during high intensity BCMS MD.
  - Xrays will be performed on vacuum modules to check status of RF fingers (Dec 8th)

- LHCb Velo
  - Vacuum spikes observed when moving the Velo IN and OUT during stable beams
  - Temperatures increase measured on the SMOG side with beam
  - Visual inspection will be performed on the wakefield suppressor side during the YETS

Vacuum spikes near TCLDs



→ Dynamic pressure significantly better with 8b4e on both 11R2 and 11L2

→ Dynamic pressure rise most likely from electron cloud, which could favour vacuum spikes

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Changes for 2023

- Hardware
  - MKI-COOL should replace MKI8D
    → no significant impact on expected limitations

- Beams
  - Intensity increase
    → ramp up to 1.8 10^{11} p/b → ~50% more heating than during 2022

  - Various filling patterns envisaged:
    - BCMS
    - 8b4e
    - Mixed BCMS/8b4e

Expectations for 2023

Vacuum modules	Damage	⬛	🟩 VMTSA removed	🟩	🟩 Spring on VMSI gone	🟩 Spring on VMSI gone again	🟨 Need to check vacuum spikes in 5R4
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Collimators	Few dumps	🟥	🟨	🟩 Non conformity solved. TCTVB removed	🟩	🟩	🟩 Need to check TCLD vacuum spikes
TOTEM	Beam screen regulation at the limit	🟨 Q6R5 affected by TOTEM	🟥 Q6R5 affected by TOTEM	🟩 Upgrade of the valves + TOTEM check	🟩	🟩 Some sectors heating more	🟩
Roman pots (ALFA and AFP)	Risk of damage and outgassing	🟨 ATLAS-ALFA close to limit	🟥 ATLAS-ALFA close to limit	🟩 New design for ATLAS-ALFA + cooling	🟩	🟩	🟩 AFP pots are getting close to 50 C
BSRT	Deformation suspected	🟨	⬛ Mirror damage	🟩 New design + cooling	🟩	🟩	🟩
BGI	Vacuum increase	🟩	🟩	🟩 To be followed up	⬛ BGI heats up and damaged	🟩 BGIs removed	🟩
LHCb Velo	Vacuum spikes	🟩	🟩	🟩	🟩	🟩	🟩 Need to check vacuum spikes

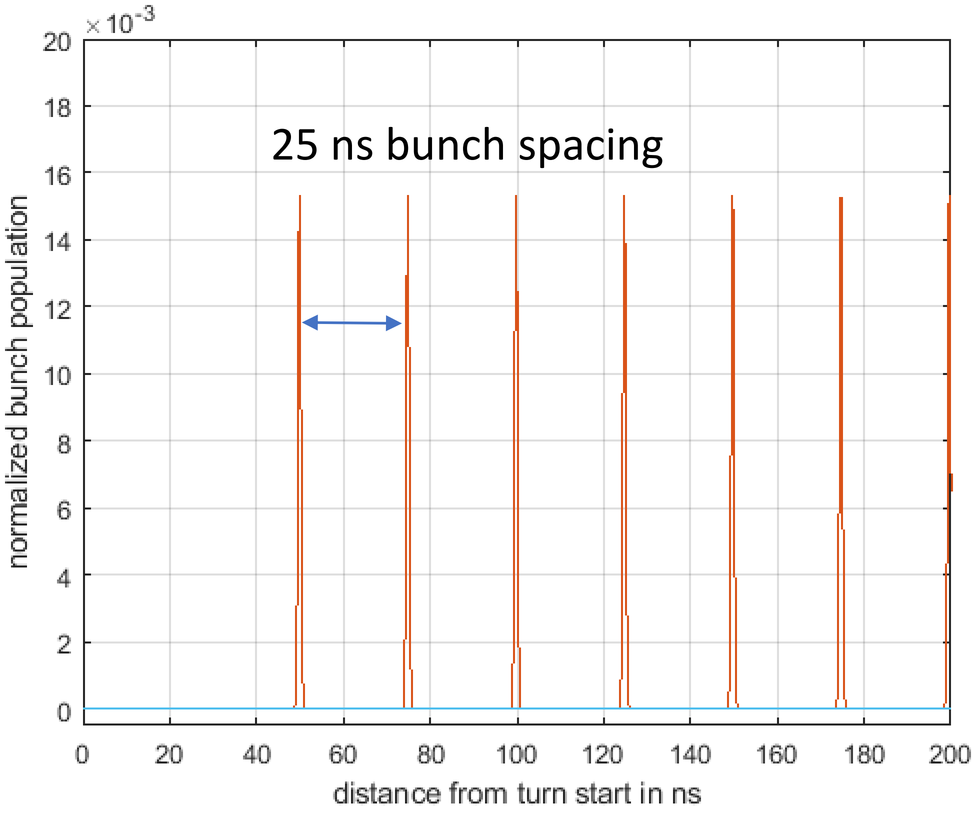
→ Xrays planned

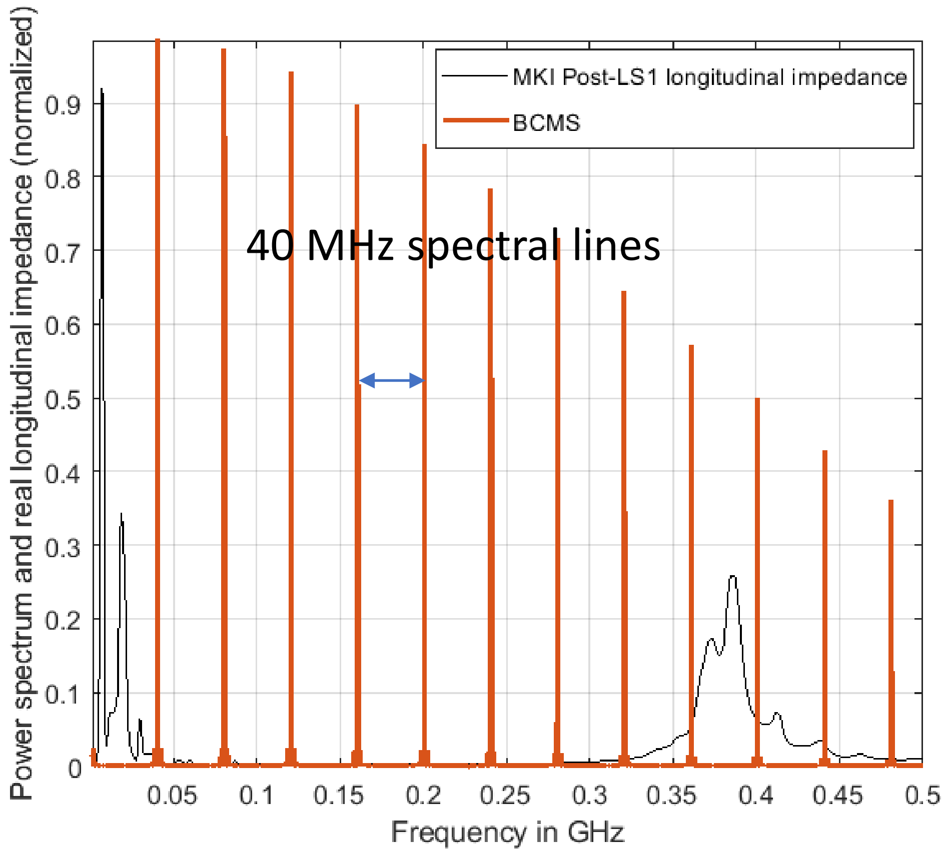
→ Soft limitation
Prevents injection

⬛ Damage
🟥 Limits operation
🟨 Worry that can limit operation
🟩 Expected to be fine

Impact of filling scheme: BCMS

- Changing the filling scheme can have a significant impact on the sidebands of the beam power spectrum
- 25 ns bunch spacing → main spectral lines every 1/25 ns = 40 MHz





Impact of filling scheme: 8b4e

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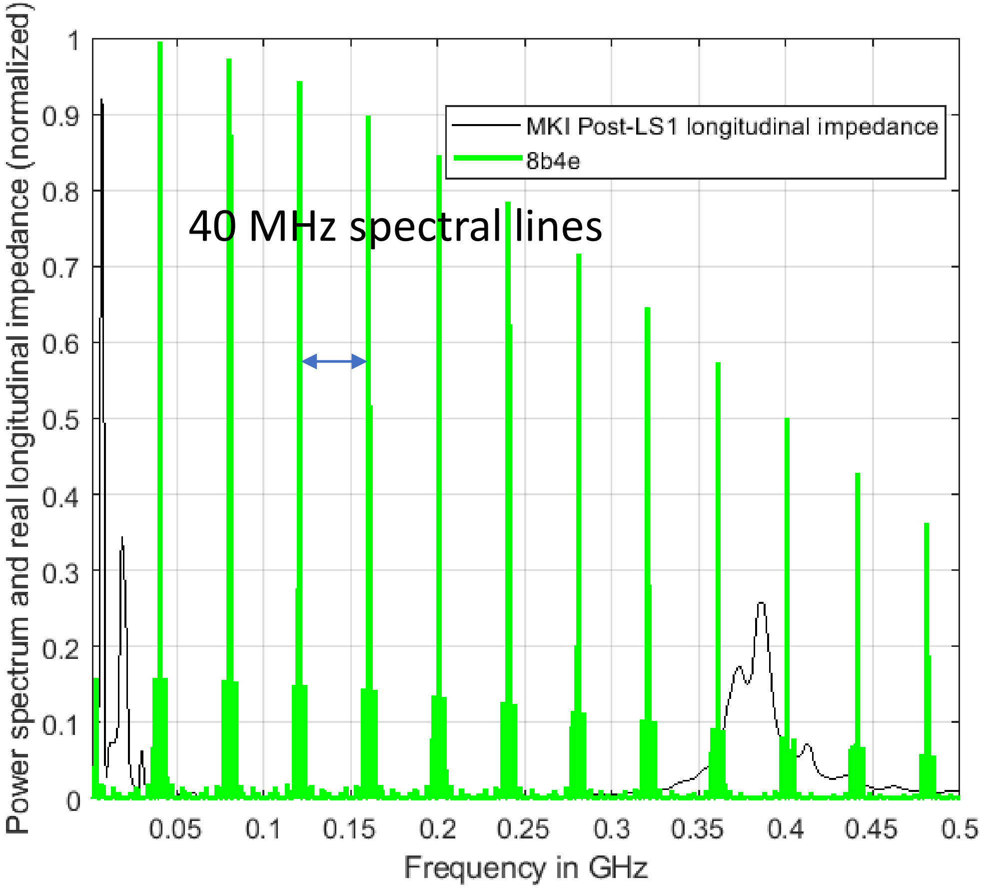
- 25 ns bunch spacing → main spectral lines every 1/25 ns = 40 MHz
- Filling with 8b4e → same spectral lines with major sidebands every 1/(12*25ns)=3.3 MHz



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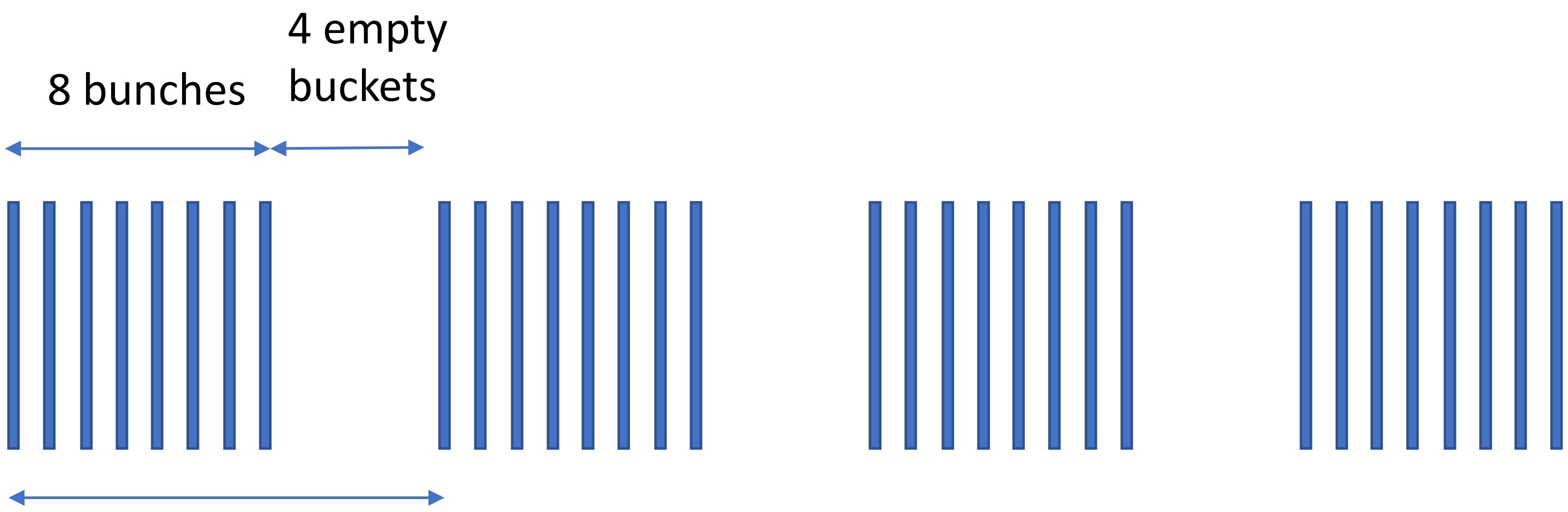
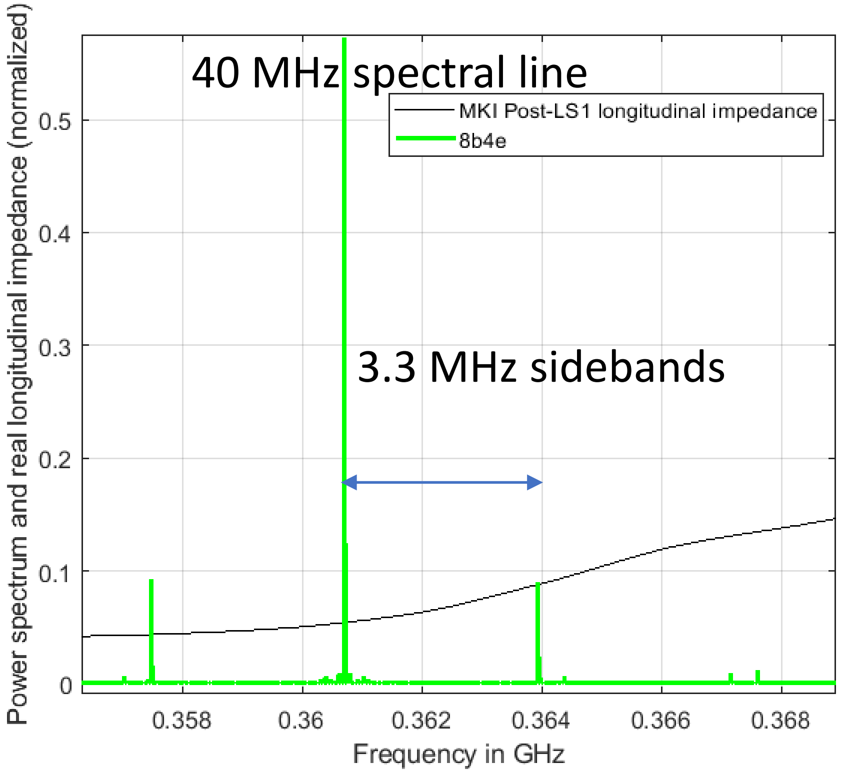

8 bunches

4 empty buckets

Periodicity of 12 buckets
→ modulation period of 300 ns
→ Sidebands at 1/300ns =3.3 MHz from the main lines


40 MHz spectral line

3.3 MHz sidebands

Impact of filling scheme: 8b4e

- Changing the filling scheme can have a significant impact on the sidebands of the beam power spectrum
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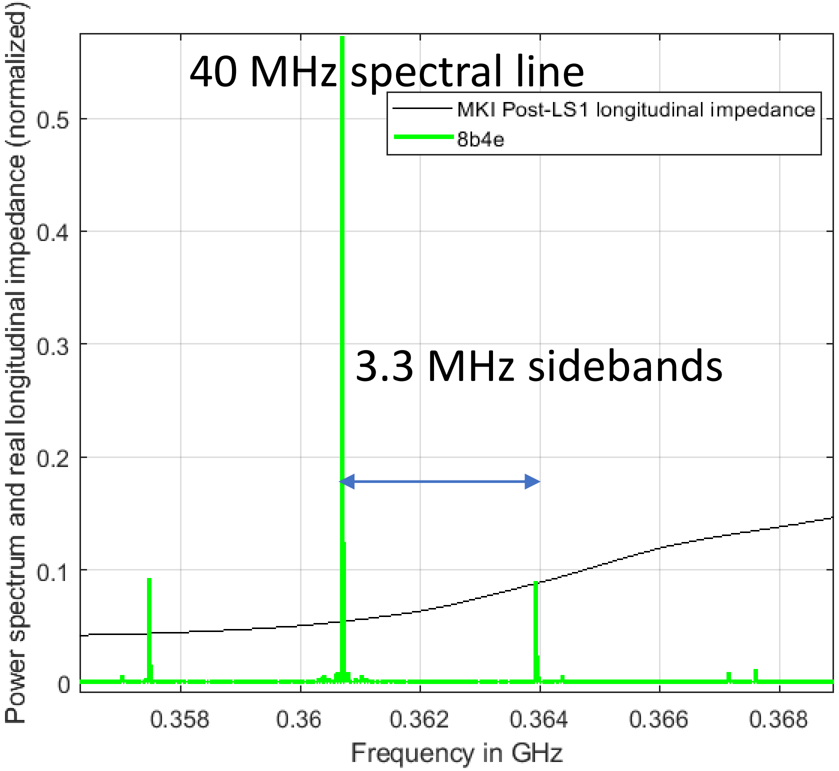
$$P_{loss} = 2 \sum_{f=f_{rev}}^{\infty} \mathrm{Re}\left[Z_{long}(f)\right] \times I_{beam}{}^{2} \times \lambda^{2}(f)$$

Power loss is an infinite sum over frequency,

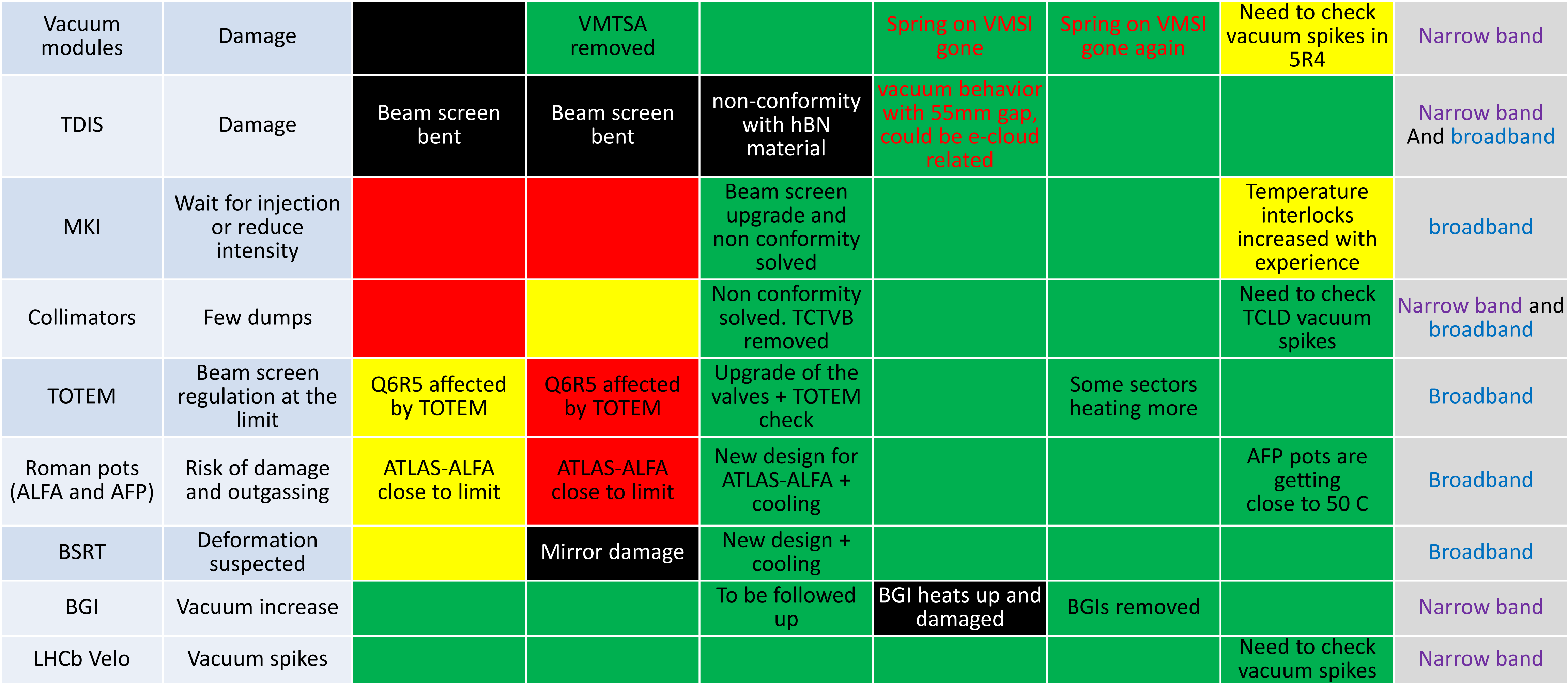
→ impact of sidebands is small for impedances that are varying slowly with frequency (broadband impedance)

→ Impact of sidebands can be very large for peaked impedances (narrow band impedance)



→ Moving to 8b4e can excite narrow band resonances that are not excited by the BCMS beam

Impact of filling scheme: 8b4e



Vacuum modules	Damage	⬛	🟩 VMTSA removed	🟩	🟩 Spring on VMSI gone	🟩 Spring on VMSI gone again	🟨 Need to check vacuum spikes in 5R4	Narrow band
TDIS	Damage	⬛ Beam screen bent	⬛ Beam screen bent	⬛ non-conformity with hBN material	🟩 vacuum behavior with 55mm gap, could be e-cloud related	🟩	🟩	Narrow band And broadband
MKI	Wait for injection or reduce intensity	🟥	🟥	🟩 Beam screen upgrade and non conformity solved	🟩	🟩	🟨 Temperature interlocks increased with experience	broadband
Collimators	Few dumps	🟥	🟨	🟩 Non conformity solved. TCTVB removed	🟩	🟩	🟩 Need to check TCLD vacuum spikes	Narrow band and broadband
TOTEM	Beam screen regulation at the limit	🟨 Q6R5 affected by TOTEM	🟥 Q6R5 affected by TOTEM	🟩 Upgrade of the valves + TOTEM check	🟩	🟩 Some sectors heating more	🟩	Broadband
Roman pots (ALFA and AFP)	Risk of damage and outgassing	🟨 ATLAS-ALFA close to limit	🟥 ATLAS-ALFA close to limit	🟩 New design for ATLAS-ALFA + cooling	🟩	🟩	🟩 AFP pots are getting close to 50 C	Broadband
BSRT	Deformation suspected	🟨	⬛ Mirror damage	🟩 New design + cooling	🟩	🟩	🟩	Broadband
BGI	Vacuum increase	🟩	🟩	🟩 To be followed up	⬛ BGI heats up and damaged	🟩 BGIs removed	🟩	Narrow band
LHCb Velo	Vacuum spikes	🟩	🟩	🟩	🟩	🟩	🟩 Need to check vacuum spikes	Narrow band

→ Moving to 8b4e can excite resonances that are not excited by the BCMS beam

→ We will have to monitor closely the temperature and vacuum signals during the ramp up

⬛ Damage
🟥 Limits operation
🟨 Worry that can limit operation
🟩

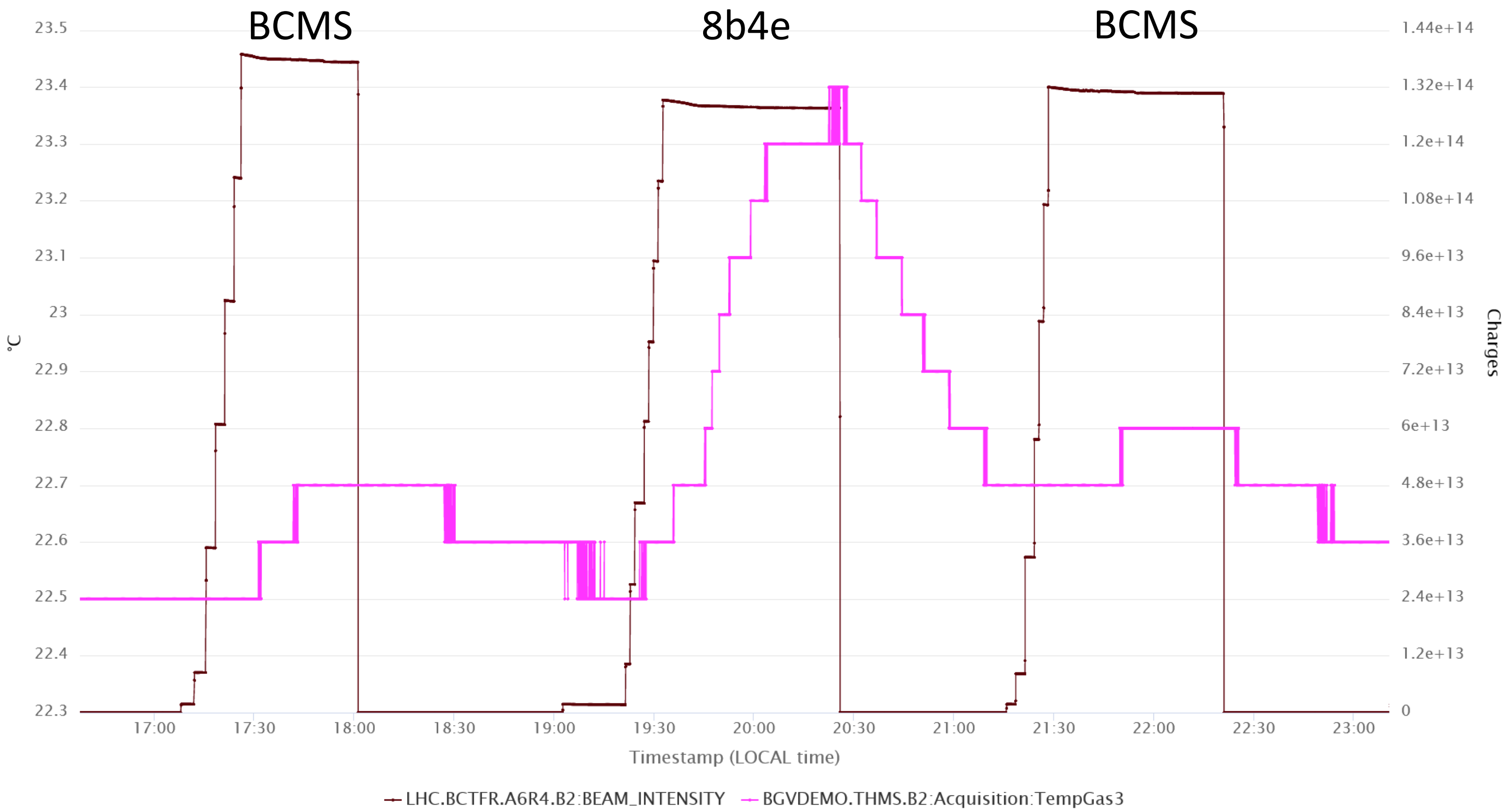
Example of BGV with 8b4e

- For most of the machine, moving from BCMS to 8b4e during the high intensity MD reduced significantly the dynamic pressure rise
- … for everyone except the BGV

- It is known BGV is full of resonant modes, and it will be replaced by LS3

- No other issue identified

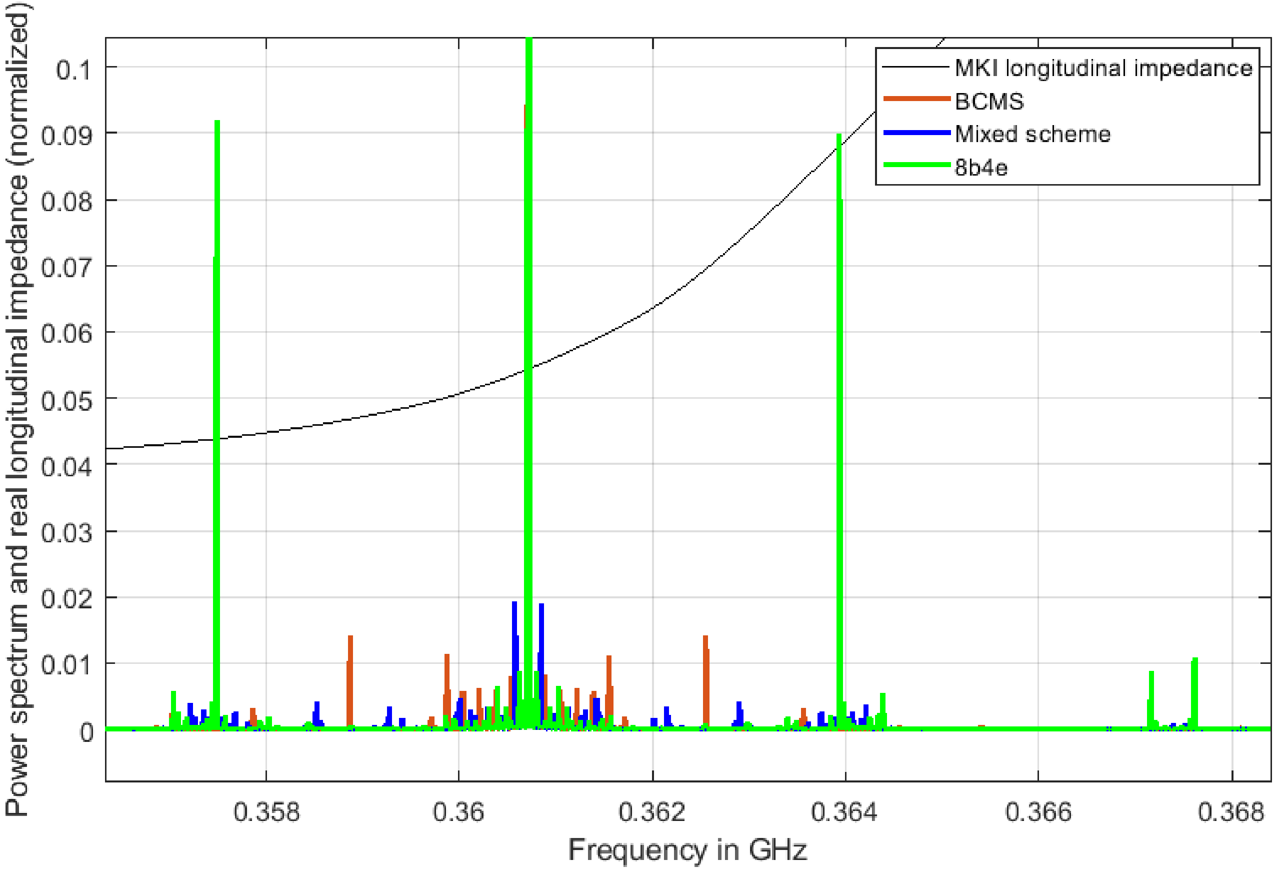
- Warning: the Velo was not moved IN during the MD



Impact of filling scheme

- 8b4e/BCMS mixed scheme breaks the modulation pattern

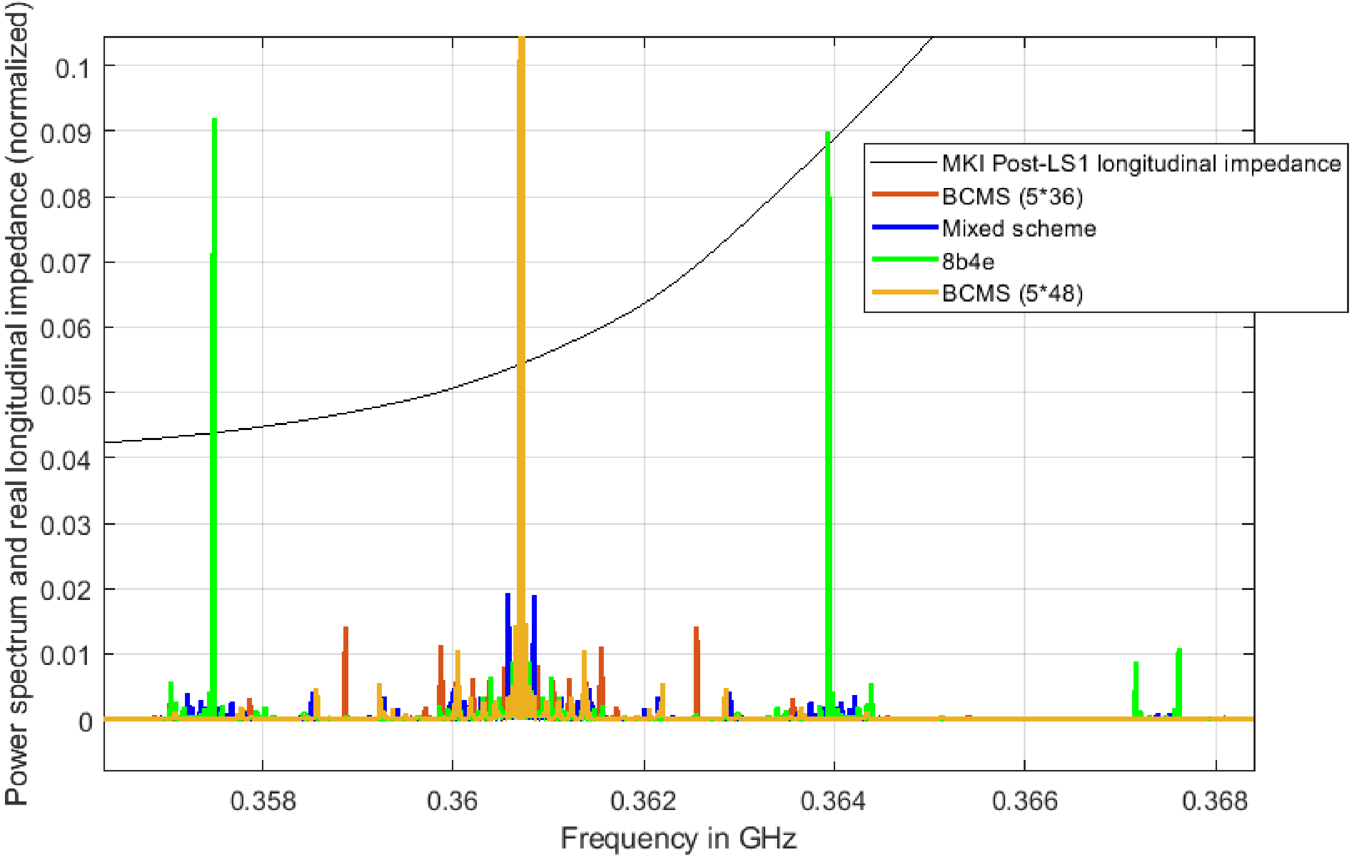
→ much smaller sidebands, of the same order than existing sidebands of the BCMS scheme



Impact of filling scheme

- 8b4e/BCMS mixed scheme breaks the modulation pattern

→ much smaller sidebands, of the same order than existing sidebands of the BCMS scheme (with 36 and 48 bunches)



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Outlook

- 2022:
  - So far so good!
  - LHCb VELO and RF fingers will be checked in some locations during the YETS (5R4, TCLDs)

- 2023:
  - 50% more heating with 1.8 10^{11} p/b
  - Will need to continue monitoring
  - MKI temperature may become a limitation, and may require waiting for injection
  - Continue what worked well:
    - Intensity ramp-up checklists
    - Bunch length leveling
    - New Timber performance ramp up

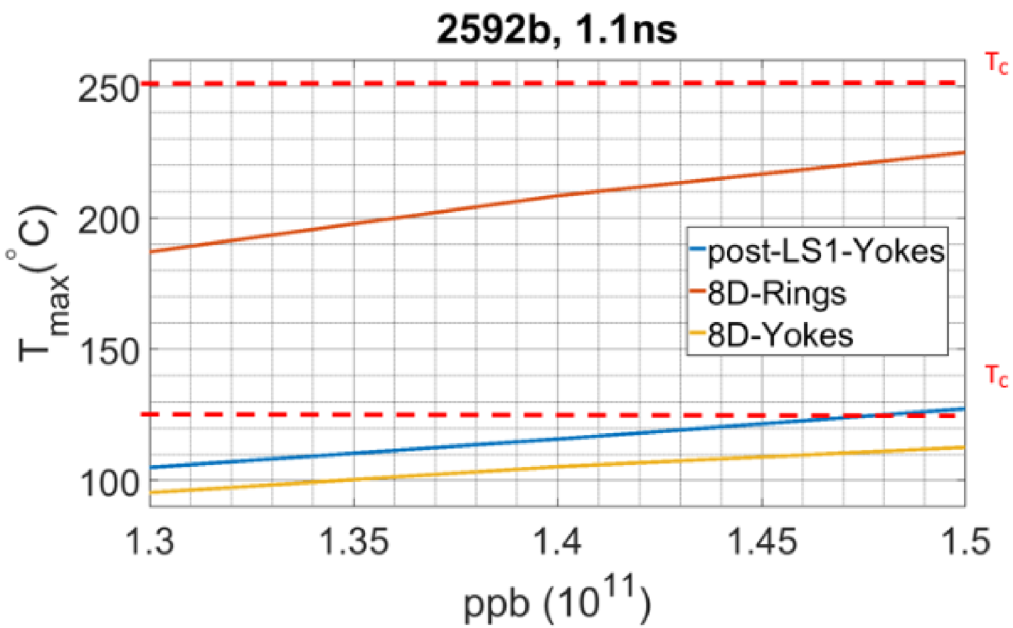
  - Possible improvements:
    - Get the beam spectrum measurement and logging back as before LS2
    - See if target bunch length for leveling can be increased
    - See (again) if interlocks on unreliable temperature measurements are really worth the risk of dumps

Thank you very much for your attention

Limitations from injection devices post-LS2

Francesco Velotti
Evian 2019

- → Limit to LIU/HL-LHC baseline parameters for transported/injected beam from the SPS to the LHC
  - ↳ New TCDIL and new TDIS
- → MKI limits for injected beam:
  - ↳ Up to 7.8 us pulse length operated so far - OK for 240 bunches per train (8.2 us might be in reach, if needed, but to be evaluated in MD first)
- → MKI limits to max number of storable bunches given by post-LS1 magnets installed
  - ↳ Details in: V. Vlachodimitropoulos, “Hardware limitations at injection” (https://indico.cern.ch/event/663598/) and “Update on MKI impedance studies” (https://indico.cern.ch/event/734086/)

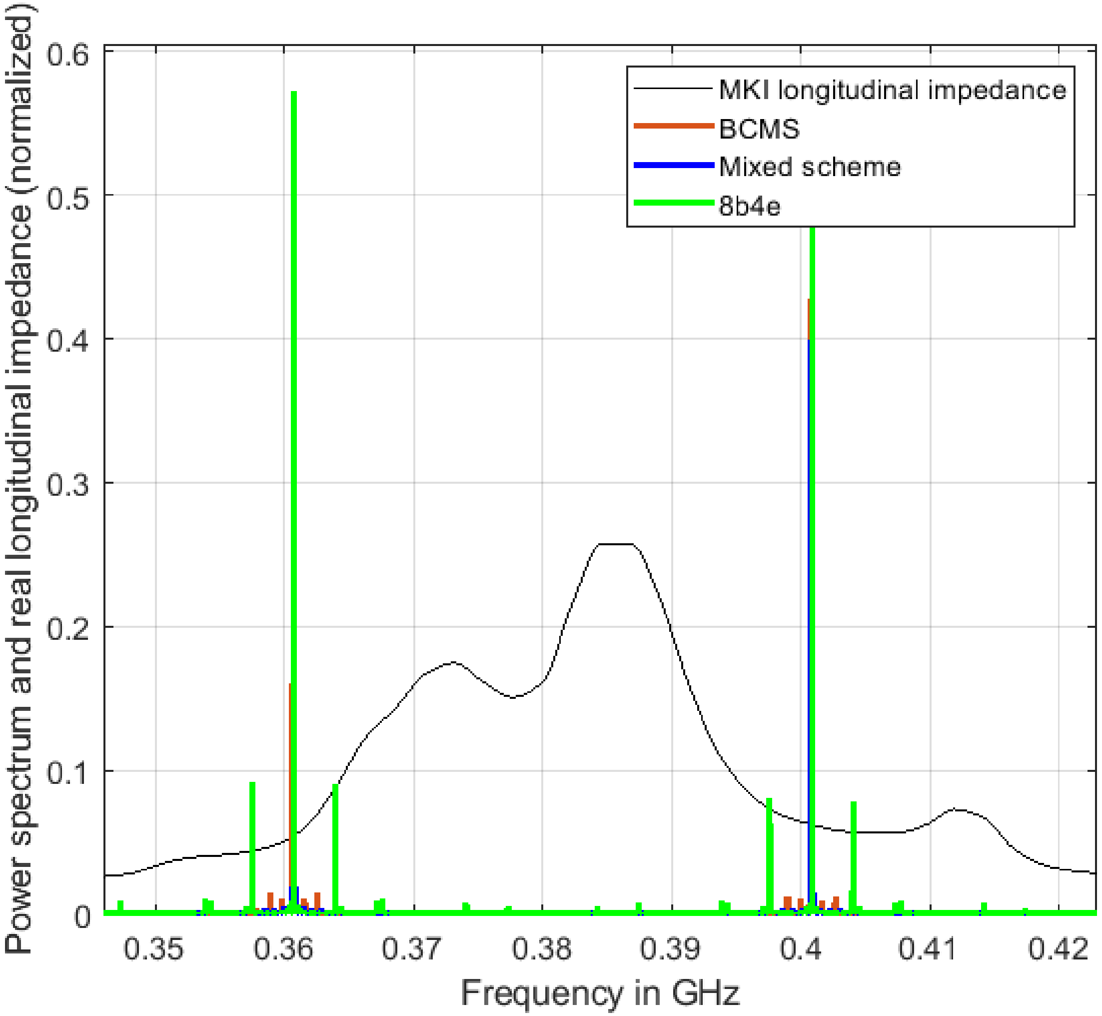


T_C Rings (4B3) = 250°C

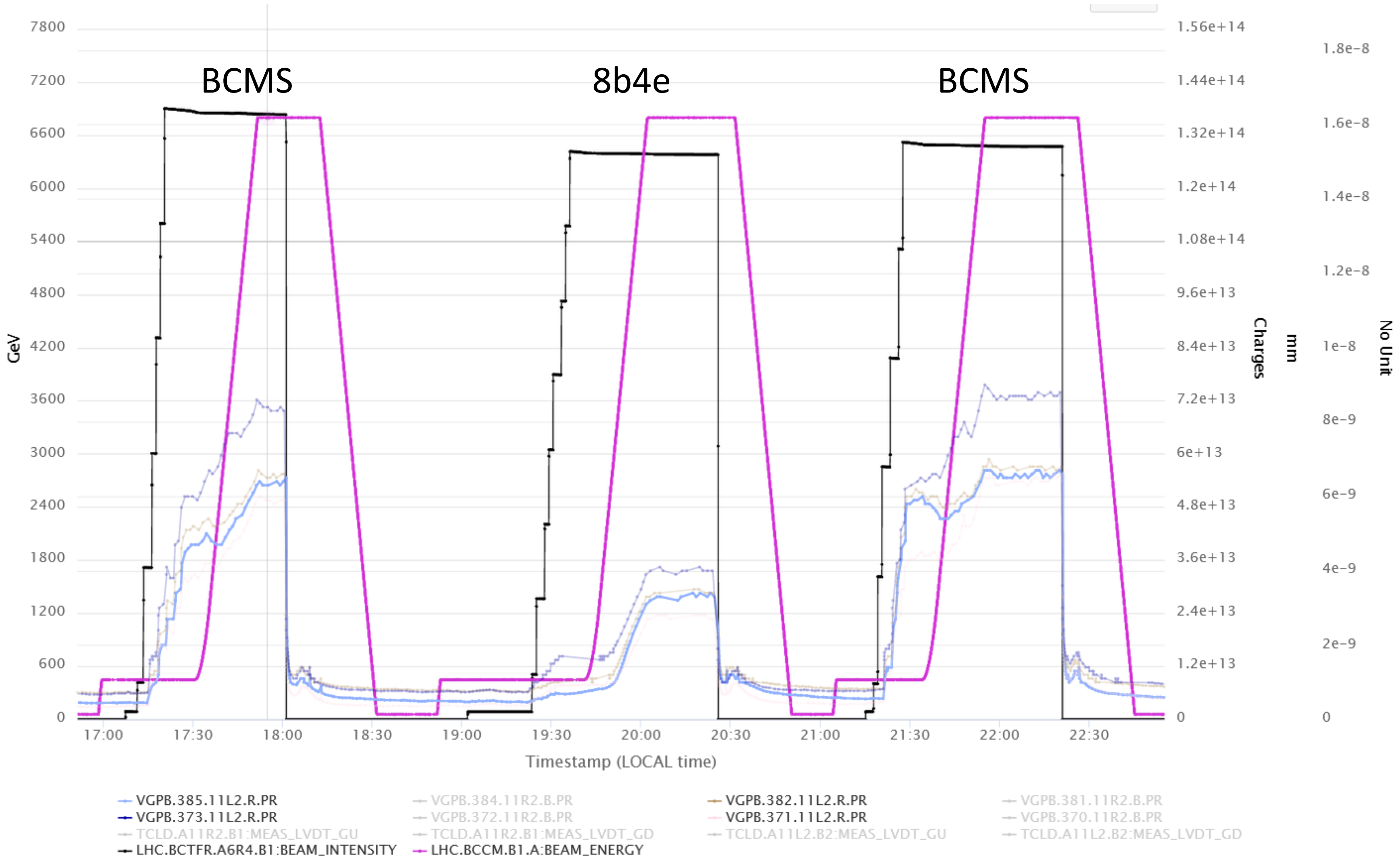
Notes:
-MKI8D as upgraded in YETS17/18
-Expected hottest post-LS1 magnet: 8C

T_C Yokes (CMD5005 or 8C11) = 125°C

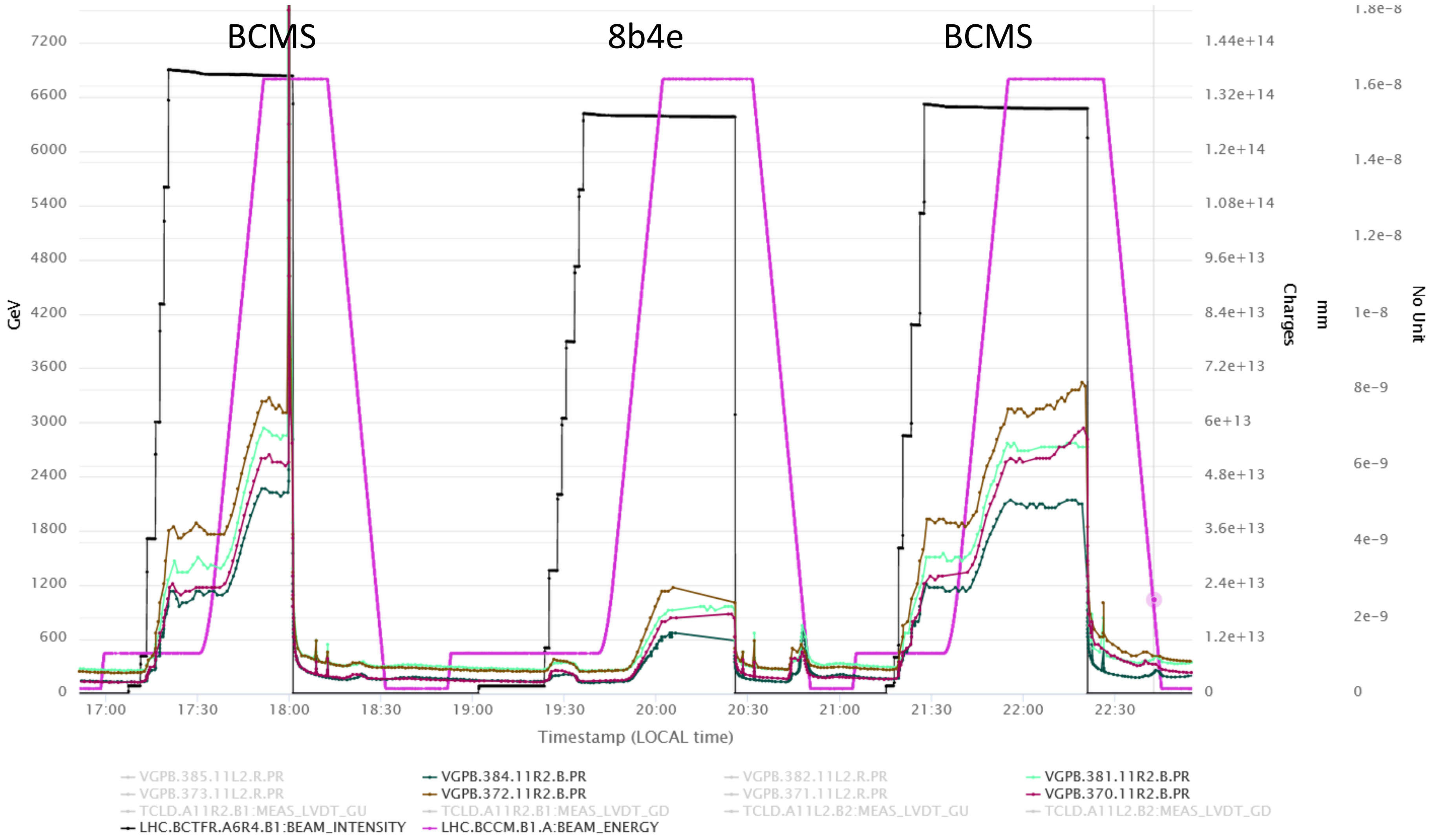
MKI temperature outlook for 2022



Vacuum spikes near TCLDs



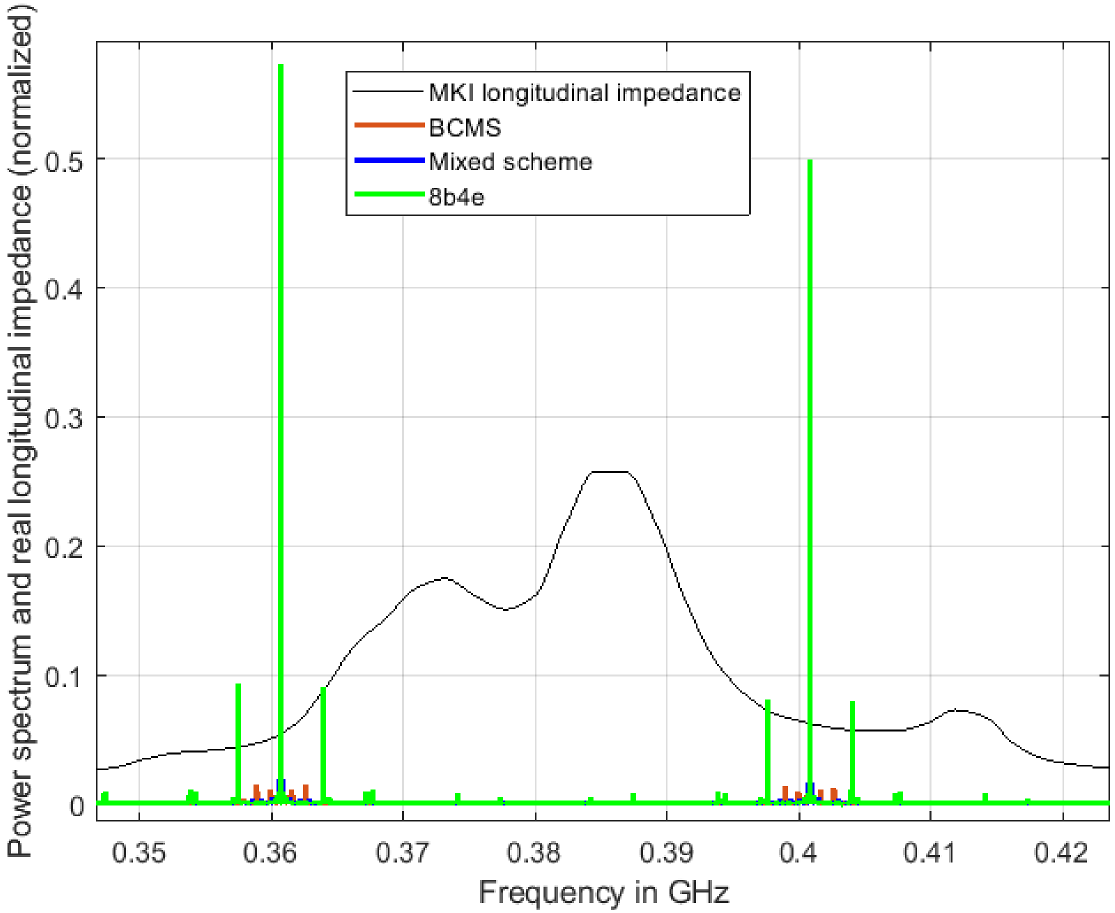
Vacuum spikes near TCLDs



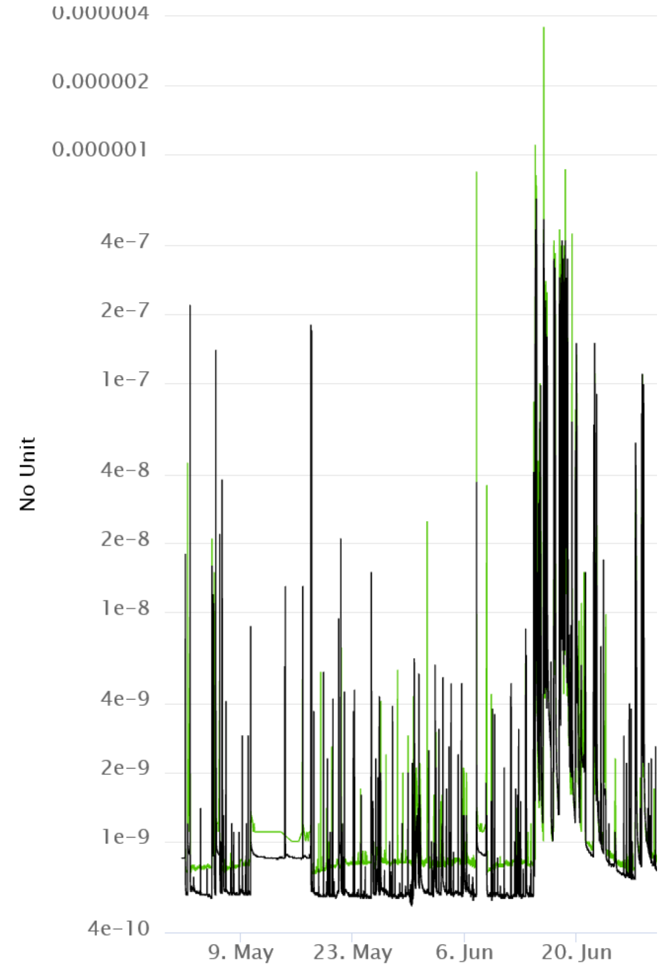
Impact of filling scheme: mixed schemes

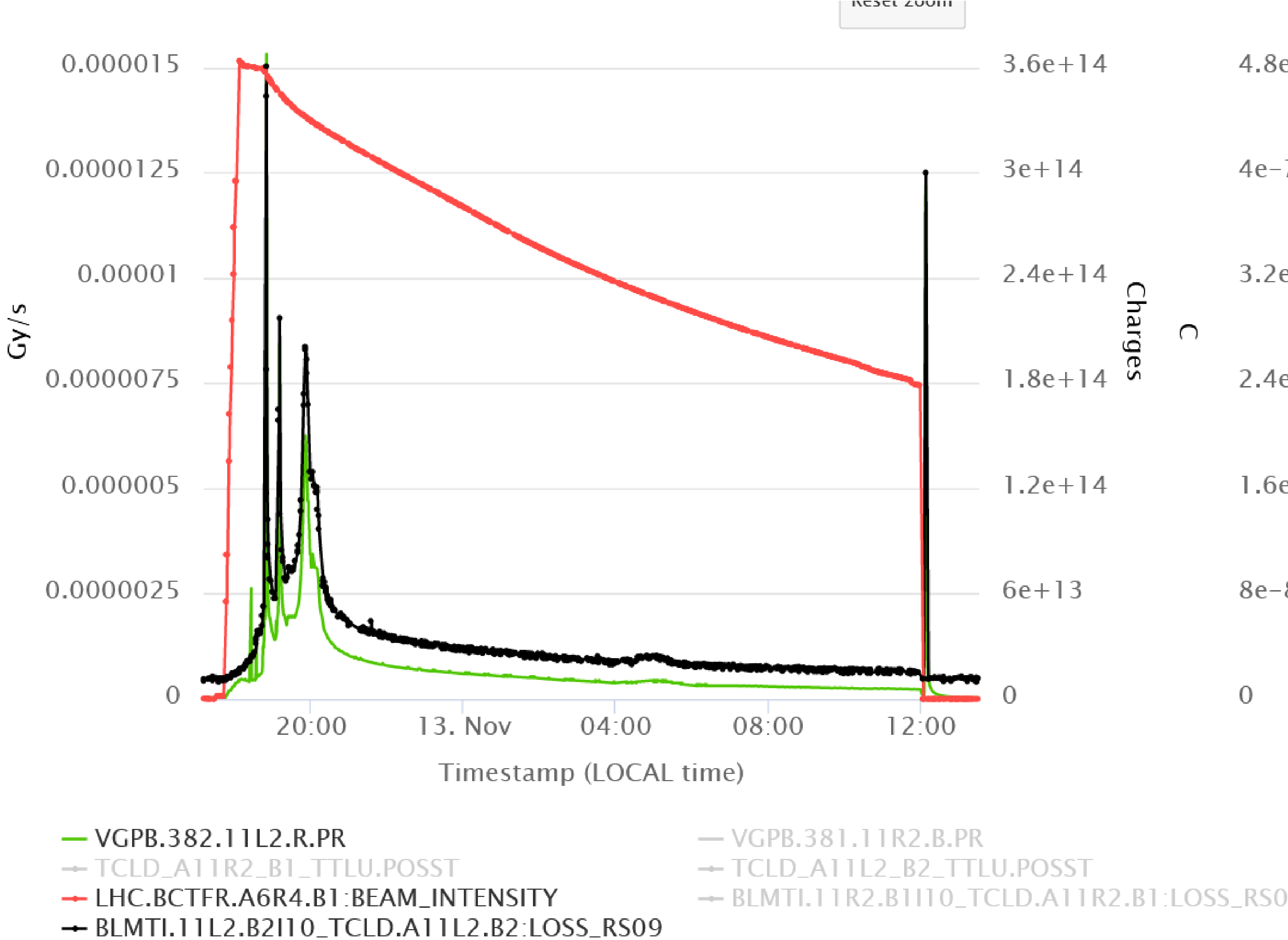
- 8b4e/BCMS mixed scheme breaks the modulation pattern

  → mush smaller sidebands



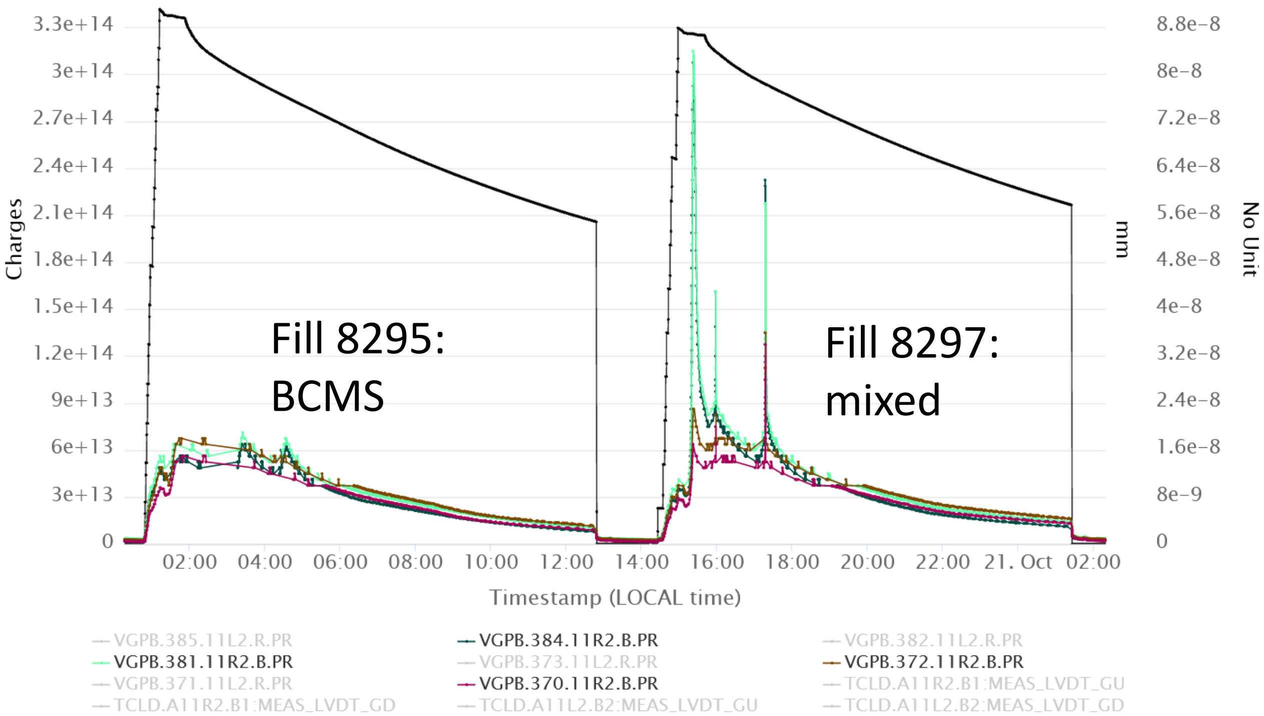
Vacuum spikes observed during the run: TCLDs





Vacuum behaviour near TCLDs

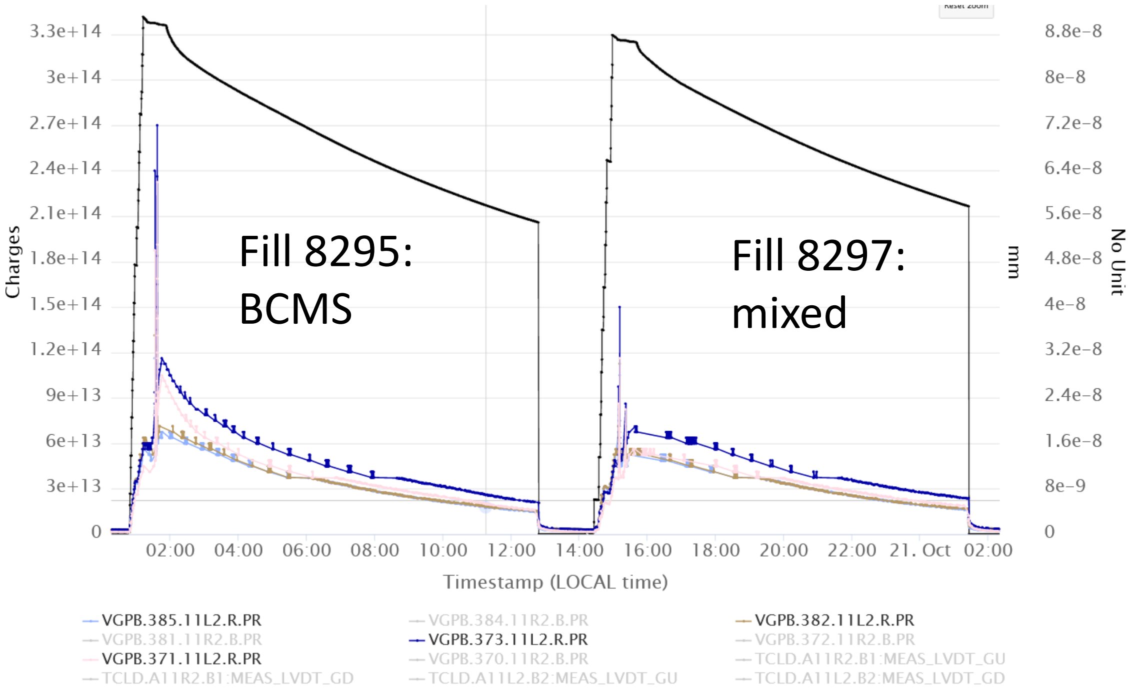
Vacuum pressure in 11R2



Fill 8295: BCMS

Fill 8297: mixed

Vacuum pressure in 11L2



Fill 8295: BCMS

Fill 8297: mixed

→ Mixed scheme does not look better than BCMS for 11R2

→ Mixed scheme similar to BCMS for 11L2

→ These locations will be checked with Xrays