Addressing of LHC 2024 Issues

A.Calia summarizing the excellent work done by many people, including:
M. Solfaroli, D. Mirarchi, J. Wenninger, M. Hostettler, T. Persson, G. Trad, S. Kostoglu, G. Sterbini, K. Parachou, B. Lindstrom, R. Bruce, S. Morales, B. Salvachua, X. Buffat, S. Kostoglou, K. Paraschou, S. Redaelli, F. Van Der Veken, D. Nisbet, S. Fartoukh, I. Efthymiopoulos, H.Timko, N.Gallou, B. Karlsen-Baeck

Outlook

- LHC Collimator Hierarchy Breakage
- FASER/SND Background
- LHC aperture: measurements and performance
- Intensity limits at LHC from RF vacuum modules

LHC Collimator Hierarchy Breakage

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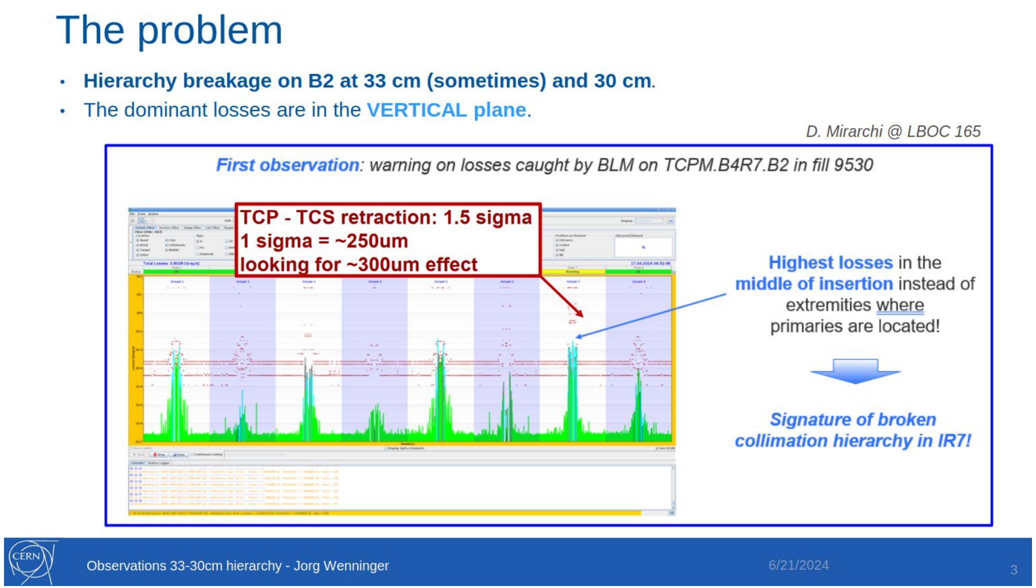
- Hierarchy breakage on B2 during B* levelling
- Nominal B* levelling paused at 36cm



Courtesy of J.Wenninger, LBOC 07/05/2024

LHC Collimator Hierarchy Breakage

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- Nominal B* levelling paused at 36cm
- Machine validation was OK
  - No issue identified during lossmaps
  - Working point for Q’ and MO different for SETUP beam vs trains

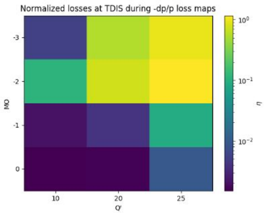
First thoughts

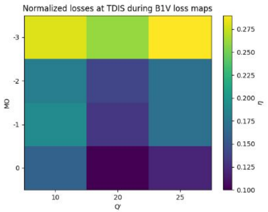
- **No issues** were observed in **validation loss maps**

  → **Main difference** in machine parameters between **validation** fills with single bunches and **physics** fill with long trains: **non linearity**!

Already observed in the past that large octupoles (MO) and chromaticity (Q’) can induce differences on relative losses between collimation stages

See **losses on TDIS** at injection in **2022**





- **MO and Q’ tuned** during intensity ramp up driven by beam **stability considerations**

  → **Very difficult to know working point a priory** and validate machine with those values

23/04/2024 D. Mirarchi | Investigation on broken hierarchy 3

It should be possible to foresee Q’ and MO operational working points, should we change the settings for validating the machine with closer operational conditions?

Courtesy of D.Mirarchi, LBOC 23/04/2024

LHC Collimator Hierarchy Breakage

- Hierarchy breakage on B2 during B* levelling
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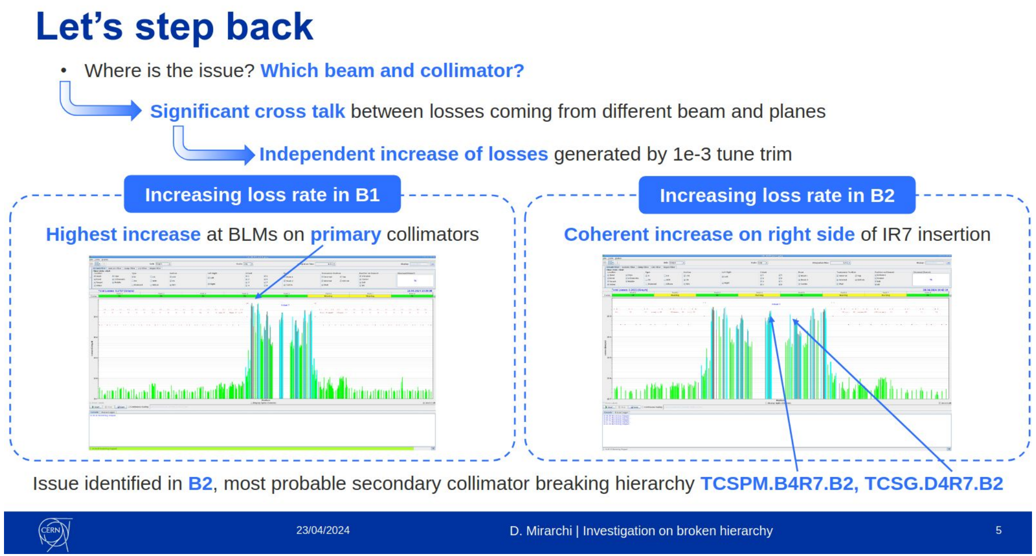
- Issue identified for B2
  - Significant crosstalk → beams and planes
  - Identified TCP.D6R7.B2 (primary) and TCSG.D4R7.B2 (secondary) as likely responsible for the hierarchy breakage



Courtesy of D.Mirarchi, LBOC 23/04/2024

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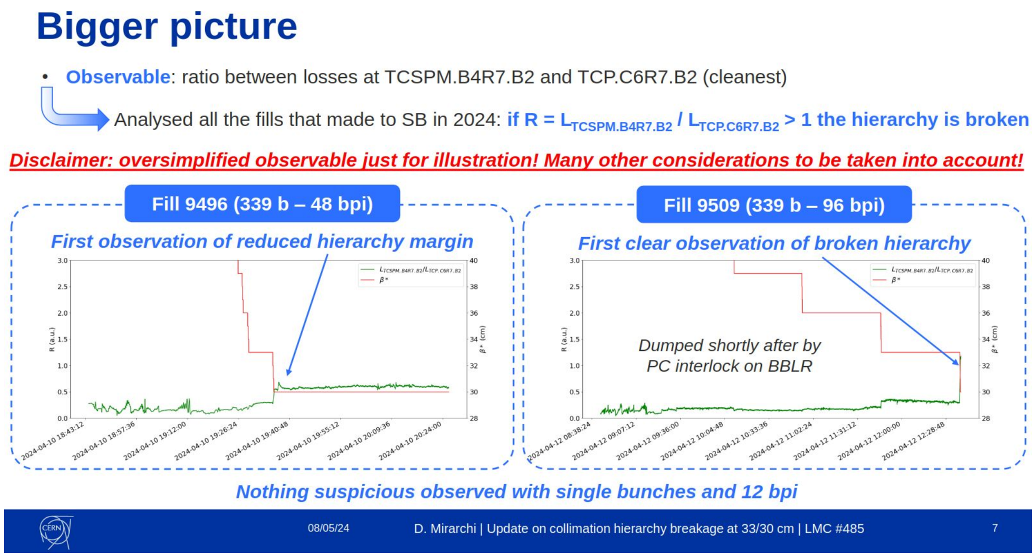

Courtesy of D.Mirarchi, LMC 08/05/2024

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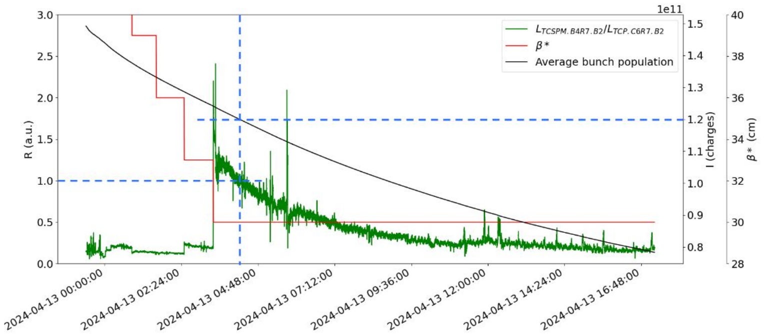
    - Defined the ratio of the losses at those collimators as observable for the hierarchy breakage
    - Phenomenon dependent on bunch intensity
    - Starting from ~1.2e11 ppb, hierarchy is restored according to the selected observable

Beam-beam signature (bunch charge dependency)

First clean and steady situation: fill 9512 (831 b – 96 bpi)



- Possible to evaluate ***bunch threshold of ~1.2e11 ppb to start recovering correct hierarchy***

→ **Similar** observations can be made looking at fills with **831 b – 144 bpi** and with **1215 b – 144 bpi**

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Courtesy of D.Mirarchi, LBOC 23/04/2024

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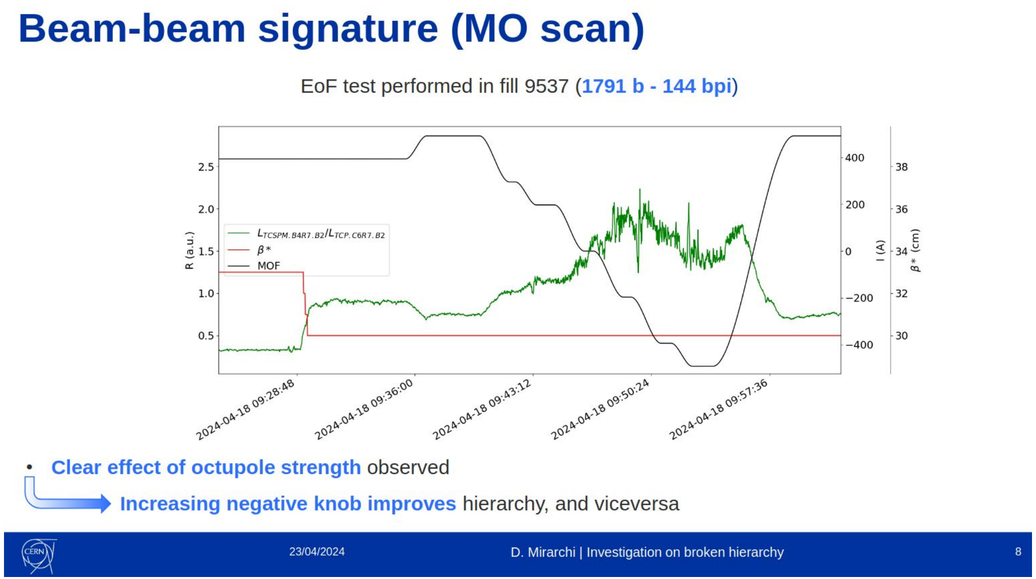

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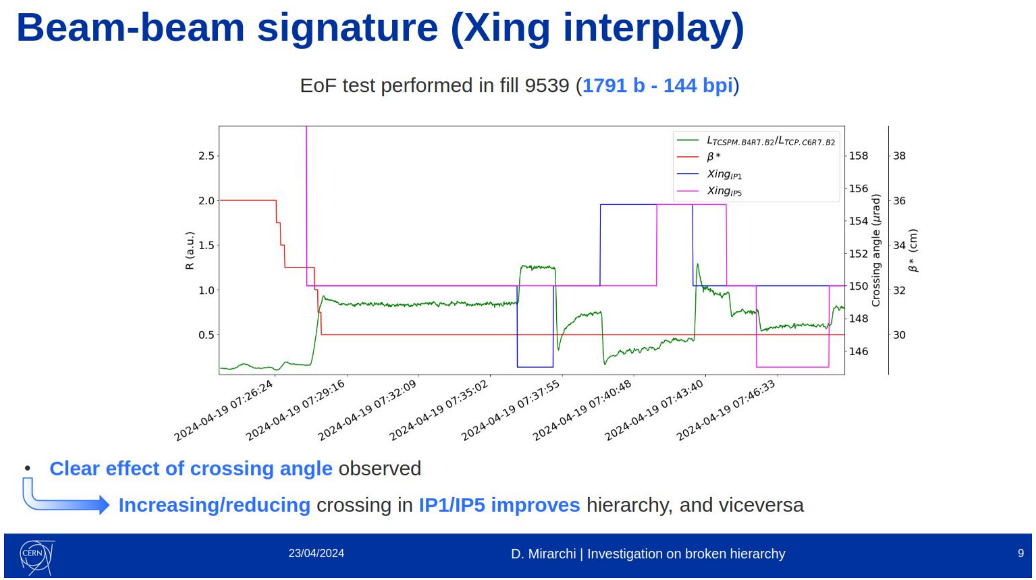
  - IP1/IP5 crossing angle affects hierarchy



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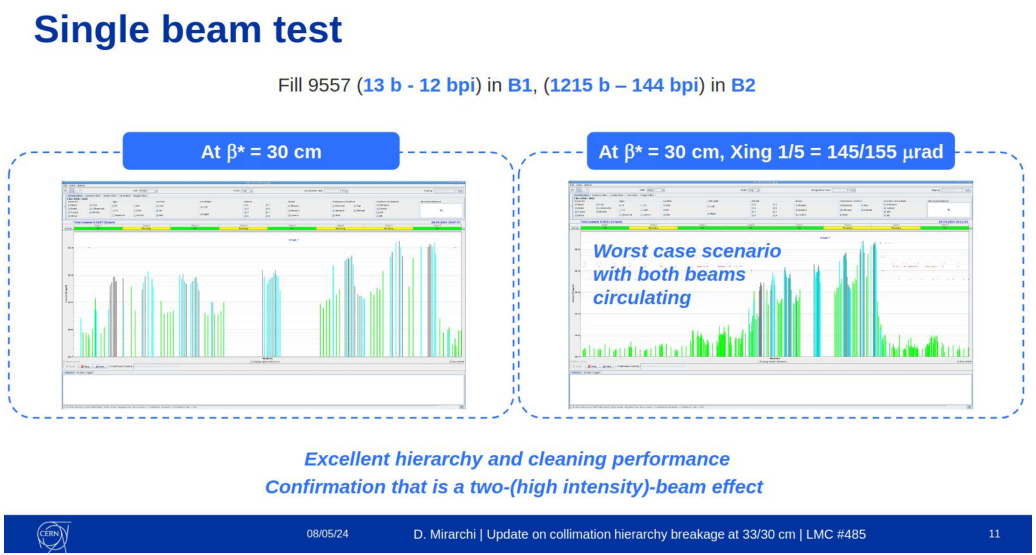
  - IP1/IP5 crossing angle affects hierarchy
  - Single beam test demonstrates it is a two beam effect with high intensity



Courtesy of D.Mirarchi, LMC 08/05/2024

LHC Collimator Hierarchy Breakage

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- Nominal B* levelling paused at 36cm
- Machine validation was OK
- Issue identified for B2
- End of Fill tests **confirmed that the hierarchy is broken due to vertical off-momentum halo particles**
- Different options on the table to gain margin
  - IR1 dispersion KNOB
  - Q’ setpoint optimization
  - a3 corrections
  - MO setpoint optimization

Conclusions

Measurement conditions:

- EoF with 2352 BCMS bunches (fill 9708)
- ~ 0.89e11 ppb
- Q2V optimized at each step and then pushed up by +2e-3 to observe hierarchy degradation

Knob	Aperture (σ)
Ref	~ 6.2
Ref + on_disp	~ 5.8
Ref + on_disp + Q’	~ 5.8
Ref + on_disp + Q’ + a3	~ 5.7
Ref + on_disp + Q’ + a3 + MO	~ 5.6
Ref + on_disp + Q’ + a3 + MO + LRBB	~ 5.6

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Courtesy of D.Mirarchi

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Conclusions

- Results achieved in different conditions but seems consistent:
  - ➢ Fill 9663: EoF at 30 cm with 1e11 ppb and Q2V pushed to 3rd order resonance
  - ➢ Fill 9701: Moved to ADJ and went to 30 cm with most similar op. conditions (~1.3e11 ppb and optimized Q)
- Main outcomes:
  - ✓ **Confirmed** that issues are linked to **+δp/p protons at large vertical amplitude** (should go to IR3 otherwise)
  - ✓ **Hierarchy breakage** taking place at **6.5-6.6 σ of TCSG.D4R7.B2**
  - ✓ **Gain of ~0.4 σ** by increasing **on_disp from 150 μrad to 250 μrad**
  - ✓ **Similar gain of ~0.2 σ** by reducing **Q’ from 20 to 10 units** (a bit more towards ~0.3 σ if reducing to 5 units), or introducing **a3 corrections** (planned to be deployed after TS1 anyhow)

We should be able to have > 0.5 σ margin between TCSG.D4 and TCP.D6 after TS1 by combining knobs
Do we all agree that this provides required confidence on operational stability?

- Additional thoughts:
  - ❑ Scraping check done also on TCSPM.B4R7.B2 (chosen randomly) and no issues observed
  - ❑ Observed beneficial effect of increasing MO from -2 to -2.5, missing scraping to asses effect on tails, next EoF?
  - ❑ Any check on D’?

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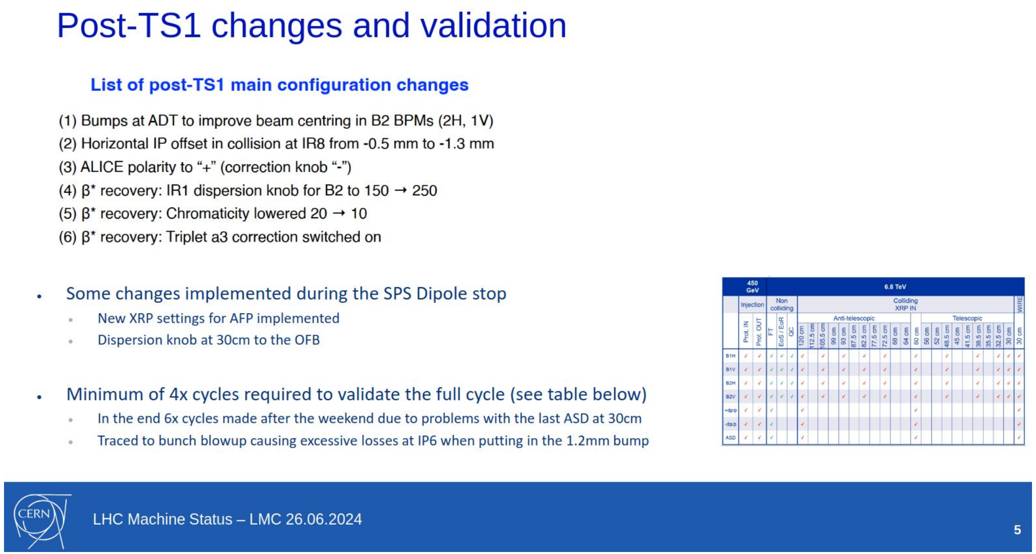
Courtesy of D.Mirarchi, LBOC 04/06/2024

LHC Collimator Hierarchy Breakage

- Road to B* 30cm after TS1
  - IR1 dispersion KNOB increased 150 → 250
  - Q’ lowered 20 → 10
  - Triplet a3 correction put in place



Courtesy of D.Nisbet, LMC 26/06/24

LHC Collimator Hierarchy Breakage

- Road to B* 30cm after TS1
  - IR1 dispersion KNOB increased 150 → 250
  - Q' lowered 20 → 10
  - Triplet a3 correction put in place
- Aperture was good and hierarchy restored

Post-TS1 changes and validation

- Aperture verified and confirmed good
  - B2V found to be 0.3sigma smaller @4L1
  - Source not yet identified (possibly effect of triplet movement during TS)
  - TCT GAP reduced to guarantee same margin to aperture

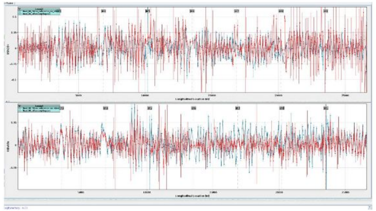
B1H:
Aperture bottleneck 2L5
Measured 11.5 to 12.0 sigma in CS
Measured 11.2 sigma with BBA

B1V:
Aperture bottleneck 4R1
Measured 9.5 to 9.6 sigma in CS
Measured 9.6 sigma with BBA

B2H:
Aperture bottleneck 2L1
Measured 12.0 to 12.5 sigma in CS
Measured 11.0 sigma with BBA

B2V:
Aperture bottleneck 4L1
Measured 9.0 to 9.1 sigma in CS
Measured 9.0 sigma with BBA
→ Pre-TS1 measured 9.3 sigma

- Optics verified and confirmed good within a few % of values measured in April



- BBLR wires now fully operational at 350A
  - Will be turned on once IP1/5 are head-on at 30cm

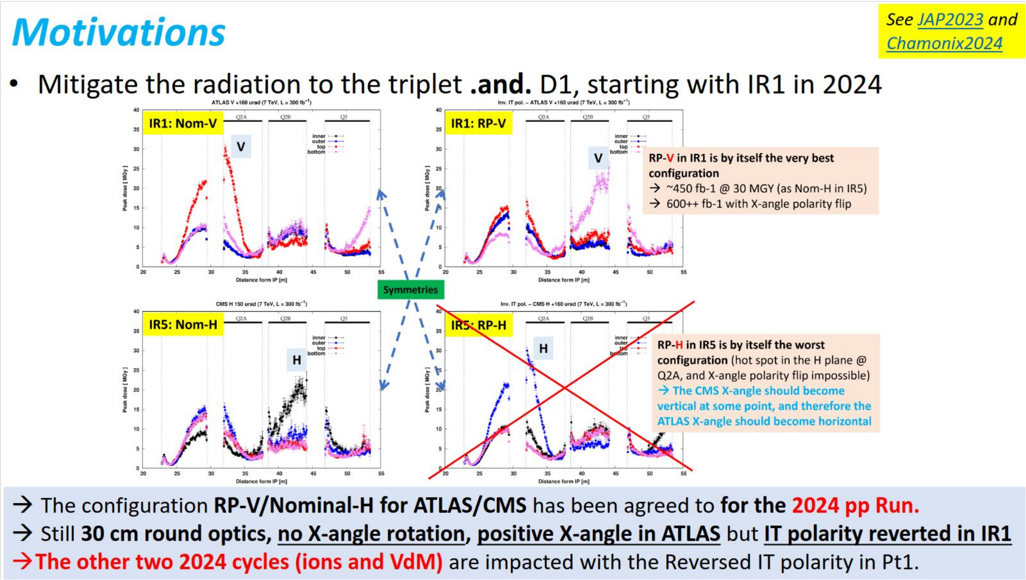
LHC Machine Status – LMC 26.06.2024 6

Courtesy of D.Nisbet, LMC 26/06/24

FASER/SND Background

FASER/SND Background Issue

- Agreed for 2024 with Reversed Polarity V (RP-V) crossing in IP1 and nominal H (Nom-H) crossing in IP5
- Reduce IR1 triplet and D1 radiation



Courtesy of S.Fartoukh, LMC 28/02/24

FASER/SND Background Issue

- Agreed for 2024 with Reversed Polarity V (RP-V) crossing in IP1 and nominal H (Nom-H) crossing in IP5
- Reduce IR1 triplet and D1 radiation
- Implications for the machine
  - RQX cable polarity reversed
  - **Q4 of IP1 is OFF**

RP optics vs. nominal optics

- **Main features and implications**

- Q4 is OFF (to recover the nominal polarity of the LHC quads as of Q5).

→ Q4 degaussing procedure put in place

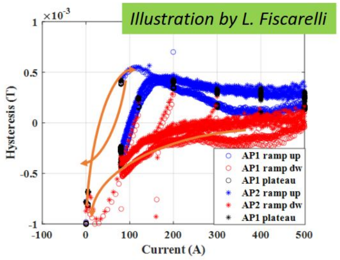
- The IT polarity is reversed in Pt 1 (the 3 circuits RQX, RTQX2 and RTQX1)

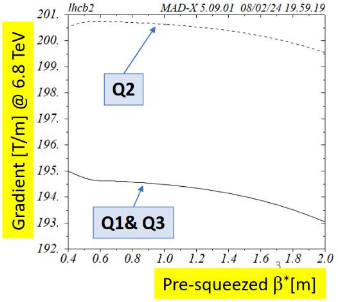
→ Polarity-wise, IT1 is now similar to IT2 & IT8

→ Due to the missing Q4, an *unusual gradient unbalance* (~6 T/m) is needed between Q1/3 (up to 195 T/m max) and Q2 (up to 201 T/m max), but all MQX's at ~nom. or below.

→ To accommodate this unbalance, the IPNO of RQX circuit has been reduced below nominal, while increased by 30 A above ultimate for the RTQX2 circuits (Pt1 only).

28/02/2024 S. Fartoukh, LMC





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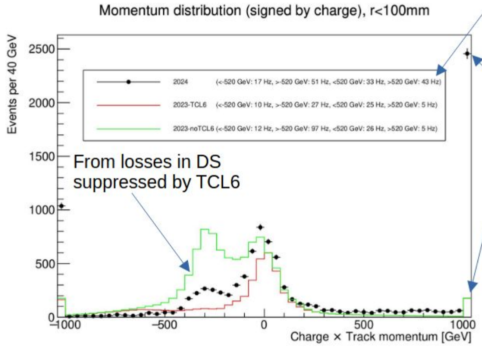
- Issue with forward physics experiments
  - High momentum muons from IP1 collisions are not deflected anymore by Q4

FASER Background Source

- Very new FLUKA studies show increase mainly due to high momentum positive muons from hadron decays before Q4 (and some additional loss in DS due to looser TCL6)
  - Thanks to Giuseppe Lerner and Francesco Cerutti
- Consistent with FASER observations of muon momenta and angular distribution

Rates scaled to 2x10^{34}



Main difference to 2022/23 is large increase in high momentum positively-charged muons

(note charge and momentum not well measured >1000 GeV)

Courtesy of FASER, LPC 08/04/24

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  - FASER reports a 2x background increase

Conclusions

- FASER backgrounds factor 2 higher than in 2022/23 and does not appear possible to mitigate for this year
(missing field from Q4 to bent away upstream muons)
- Will have to replace emulsion box every ~15/fb instead of 30/fb
  - Will need additional (parasitic?) access periods for these replacements
  - Some data will be with tungsten only as not enough emulsion available on short notice
- For electronic detector background is not a concern,
but we will need more disk space to store data
- For future major changes would be better to have enough to time to understand impact using simulation/MD etc.
  - We hope some mitigation is possible for 2025 as we will loose up to half of the luminosity for our neutrino measurements in 2024

Courtesy of FASER, LPC 08/04/24

FASER/SND Background Issue

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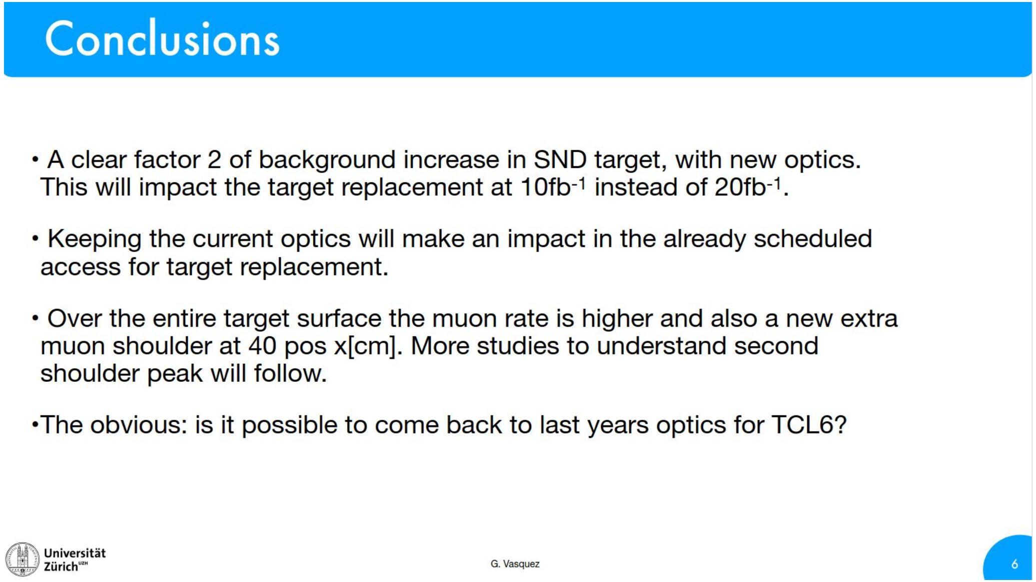
  - **Q4 of IP1 is OFF**
- Issue with forward physics experiments
  - High momentum muons from IP1 collisions are not deflected anymore by Q4
  - FASER reports a 2x background increase
  - SND reports as well a 2x background increase
- Experiments emulsion box need to be replaced every 10 fb-1 instead of every 20 fb-1



Conclusions

- A clear factor 2 of background increase in SND target, with new optics. This will impact the target replacement at $10fb^{-1}$ instead of $20fb^{-1}$.
- Keeping the current optics will make an impact in the already scheduled access for target replacement.
- Over the entire target surface the muon rate is higher and also a new extra muon shoulder at 40 pos x[cm]. More studies to understand second shoulder peak will follow.
- The obvious: is it possible to come back to last years optics for TCL6?

Universität Zürich[UZH]

G. Vasquez

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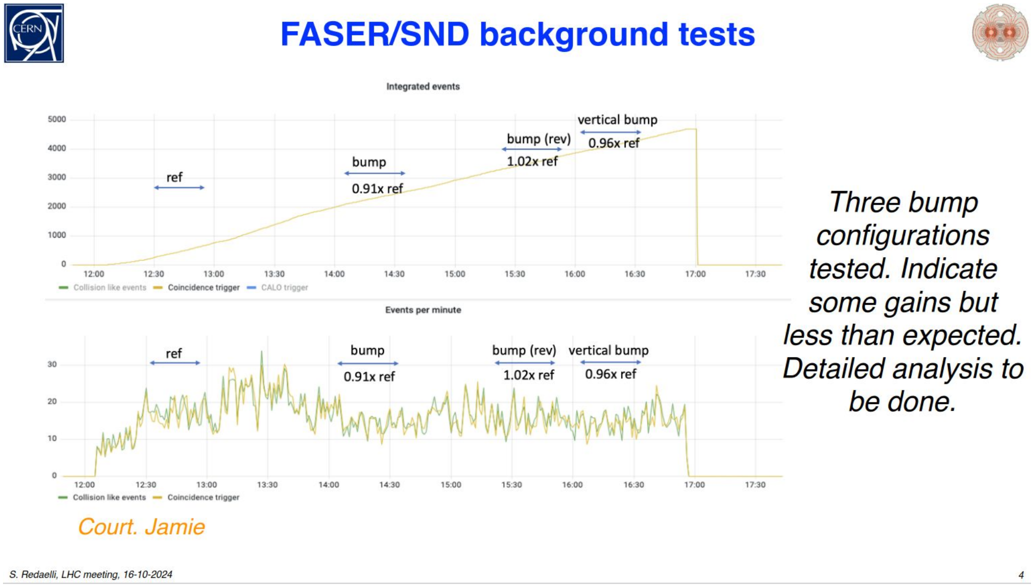
Courtesy of G.Vasquez, LPC 08/04/24

FASER/SND Background Issue

- Attempt with orbit bumps to deviate high momentum muons
- Non significant improvement
- Fortunately, 2025 configuration will restore the polarity in IP1 (same as 2023 but with inverted crossing plane)
  - **FASER/SND background is expected to be under control**
  - Back to nominal emulsion exchange rate (every 20 fb-1)



Three bump configurations tested. Indicate some gains but less than expected. Detailed analysis to be done.

LHC aperture: measurements and performance

Automated Aperture Measurements

- Aperture measurement is a crucial step in beam commissioning to define the acceptable clearance of the machine
- The bottleneck found must be protected by the collimation system along the cycle

Introduction

- **Aperture measurements** are one of the most **important activity** during beam **commissioning**
  - ✓ Provide final **operational feedback** on available **geometrical aperture**
  - ✓ Crucial input to **freeze collimation hierarchy**
- Ongoing **effort** to **automatize measurements** as much as possible
  - ✓ **Reduce load** on system **experts** while increasing commissioning efficiency

Long term aim:
measurement *could be carried out by* ***OP working on a 24/7 basis***, ***validation*** *always in hands of* ***experts***

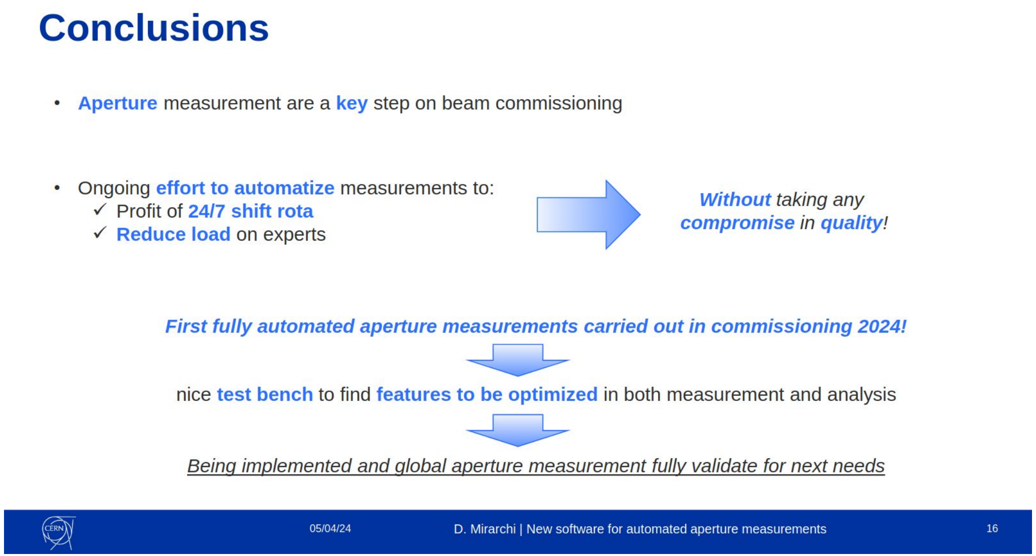
- *Available example:* ***LossMaps***
  - ✓ **Run 1 & 2**: **collimation expert** presence likely **required** (particularly for **dp/p** in Run 2), **several repetition** needed for betatron and ASD (**significant penalty** on cycles needed)
  - ✓ **Run 3**: **collimation expert** enter loss map matrix and **validate system performance**, while test **execution handled by OP** autonomously
- *First next step on collimation side:* *automatize* ***aperture measurements***

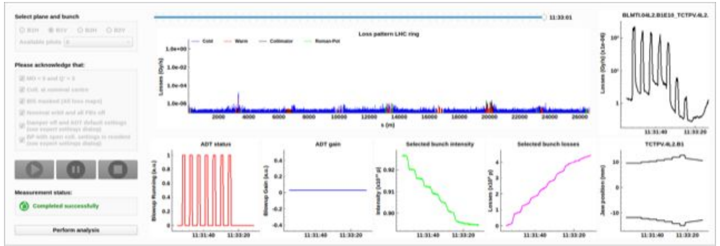
05/04/24 D. Mirarchi | New software for automated aperture measurements 2

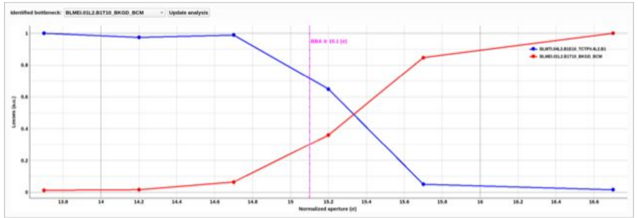
Courtesy of D.Mirarchi, LHC Collimation Working Group 05/04/2024

Automated Aperture Measurements

- Aperture measurement is a crucial step in beam commissioning to define the acceptable clearance of the machine
- The bottleneck found must be protected by the collimation system along the cycle
- For 2024, a new automated procedure allowed significant improvements in time and reproducibility
  - **2 experts for 4h → 1 expert for 1h**
  - Goal is to hand over the execution of the measurement to OP, while the experts will validate them offline







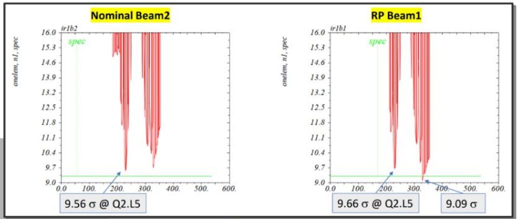
Courtesy of D.Mirarchi, LHC Collimation Working Group 05/04/2024

Aperture Measurements Results

- Agreed for 2024 with Reversed Polarity V (RP-V) crossing in IP1 and nominal H (Nom-H) crossing in IP5
- In this configuration, the aperture bottleneck of the machine in IR1 shifts from the triplets region to the D1 in physics

Measurements 2024

S. Fartoukh, Status of the 2024 RP optics (LBOC 161)



Energy [GeV]	Optics
450	Injection
6800	After IR8 crossing-angle rotation (1.2m)
6800	β*=30cm – colliding

N1 indicates aperture bottleneck Shift to D1 (Cell 4) in IR1

Confirmed in tracking simulations replicating aperture measurements

2024-04-05 Aperture Measurements 2024 | CollWG Meeting 6

Aperture Measurements Results

- Agreed for 2024 with Reversed Polarity V (RP-V) crossing in IP1 and nominal H (Nom-H) crossing in IP5
- In this configuration, the aperture bottleneck of the machine in IR1 shifts from the triplets region to the D1 in physics
- To gain aperture margin in 33 → 30cm B* step, crossing angle reduced from 160 urad to 150 urad
- TCL.6 at constant settings along B* levelling
    - Conservative compromise: FASER background (finally TCL.6 position had low impact on background), AFP dose and fixed interlock limits during B* levelling

Conclusions

- **Aperture Measurements 2024 completed!**
- Injection: expected aperture size and bottleneck → okay
- After IR8 crossing angle rotation: consistent with previous year → okay
- End of Luminosity Levelling (30cm):
    - As expected from simulations: shift of bottleneck to 4R1/4L1 + reduction by 0.5σ
    - With nominal IR1 X-ing angle (160µrad) insufficient margin in vertical plane
    - Solution: reduction of X-ing to 150µrad + TCTV setting of 8.3σ
- Observation: losses observed far downstream from D1 → might overestimate aperture from CS. New BLM at D1 could be envisaged for YETS24/25

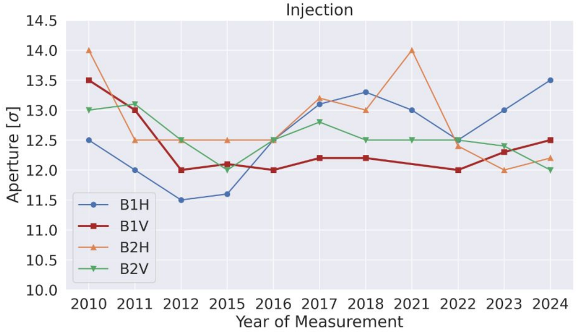
2024-04-05 Aperture Measurements 2024 | CollWG Meeting 16

Courtesy of P.Hermes, LHC Collimation Working Group 05/04/2024

Aperture Measurements Results

- Injection aperture is quite constant along the years and in the same region (IR6)
  - No surprises expected at injection for 2025 configuration
- **Expect aperture bottleneck at top energy will change again in 2025, new configuration**

Injection



No surprises – consistent with previous measurements and expected aperture

Plane	CS [σ]	BBA [σ]	Bottleneck
B1H	13.5 – 14.0	>12.3	4R6
B2H	12.5 – 13.0	>12.2	5R6
B1V	12.5 – 13.0	>12.9	4L6
B2V	~12.0	>12.0	4R6

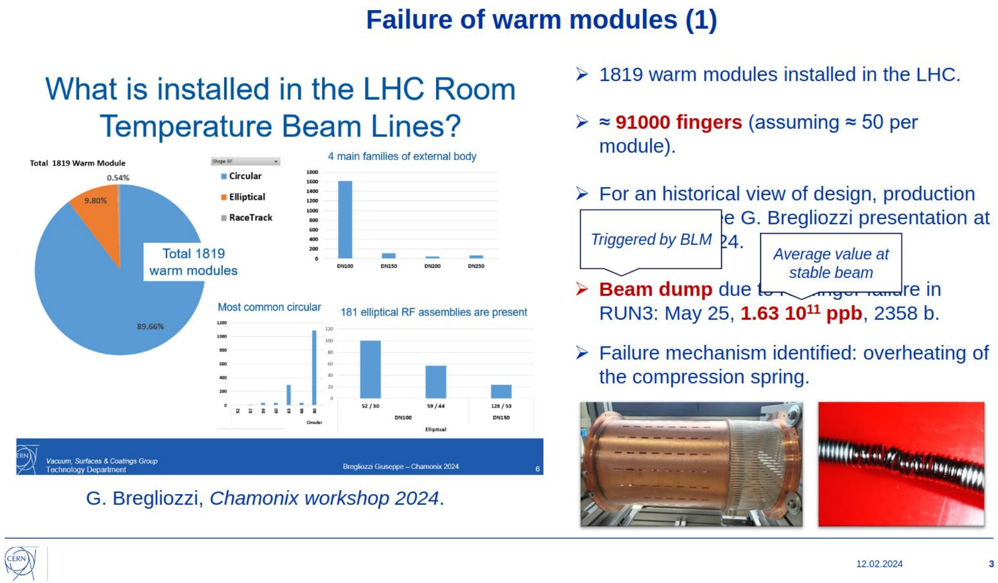
2024-04-05 Aperture Measurements 2024 | CollWG Meeting 12

Courtesy of P.Hermes, LHC Collimation Working Group 05/04/2024

Intensity limits at LHC from RF vacuum modules

Intensity Limitation

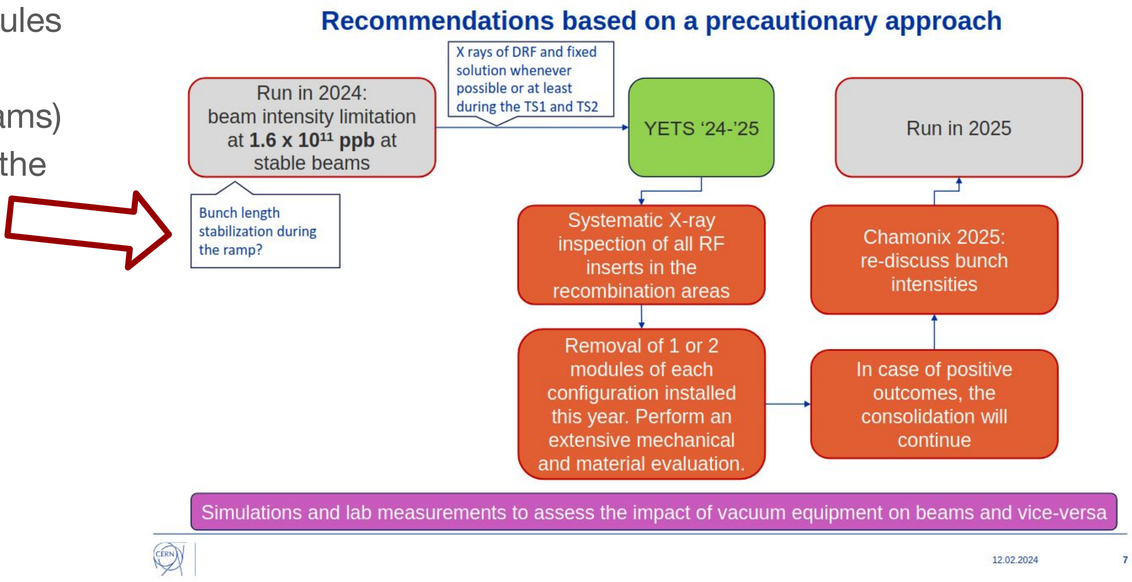
- Protect against failure of RF vacuum modules compression spring overheating



Courtesy of J.M. Jimenez & P.Chiggiato, LMC14/02/2024

Intensity Limitation

- Protect against failure of RF vacuum modules compression spring overheating
- Intensity limited to 1.6e11 ppb (stable beams)
- Bunch length has a significant impact on the local heating of the compression springs



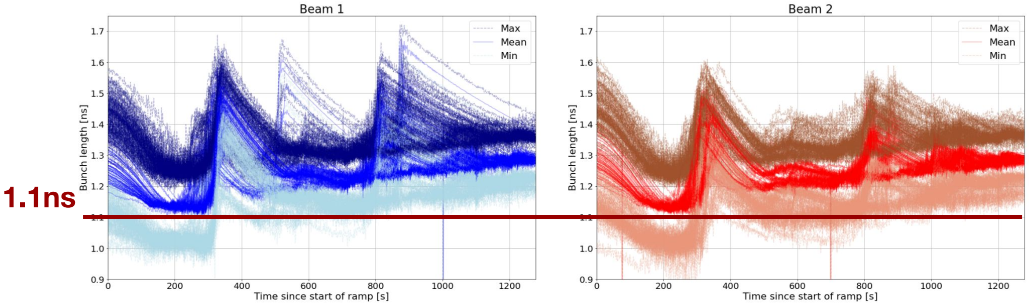
Courtesy of J.M. Jimenez & P.Chiggiato, LMC14/02/2024

Bunch Length Control

- Protect against failure of RF vacuum modules compression spring overheating
- Intensity limited to 1.6e11 ppb (stable beams)
- Bunch length has a significant impact on the local heating of the compression springs
- During a typical 2023, bunch length was frequently below 1.1ns at start of ramp

Bunch lengths

- **Minimum, average, and maximum bunch length in 2023 physics fills (> 200 bunches)**



Courtesy of B. Karlsen-Baeck

H. Timko | Bunch length during ramp, LBOC 26th March 2024 12

Courtesy of H.Timko, B. Karlsen-Baeck, LBOC 26/03/2024

Bunch Length Control

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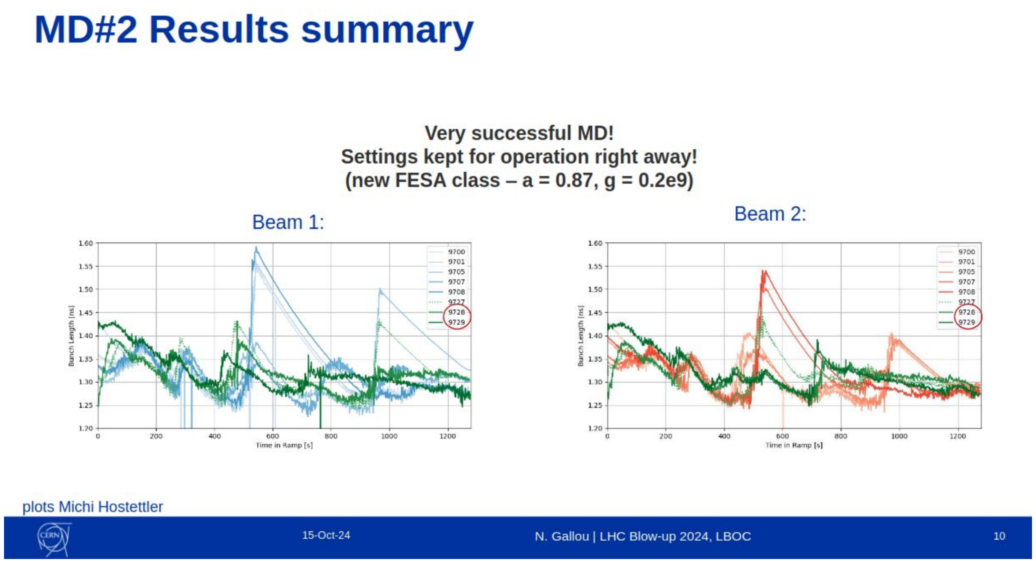
- Intensity limited to 1.6e11 ppb (stable beams)
- Bunch length has a significant impact on the local heating of the compression springs
- During a typical 2023, bunch length was frequently below 1.1ns at start of ramp
- Mitigations:
  - Started the year with long. blow up tweaks
  - Optimum RF setpoints following MDs and scans during ramps



Courtesy of N.Gallou, M.Hostettler, LBOC 15/10/2024

Bunch Length Control

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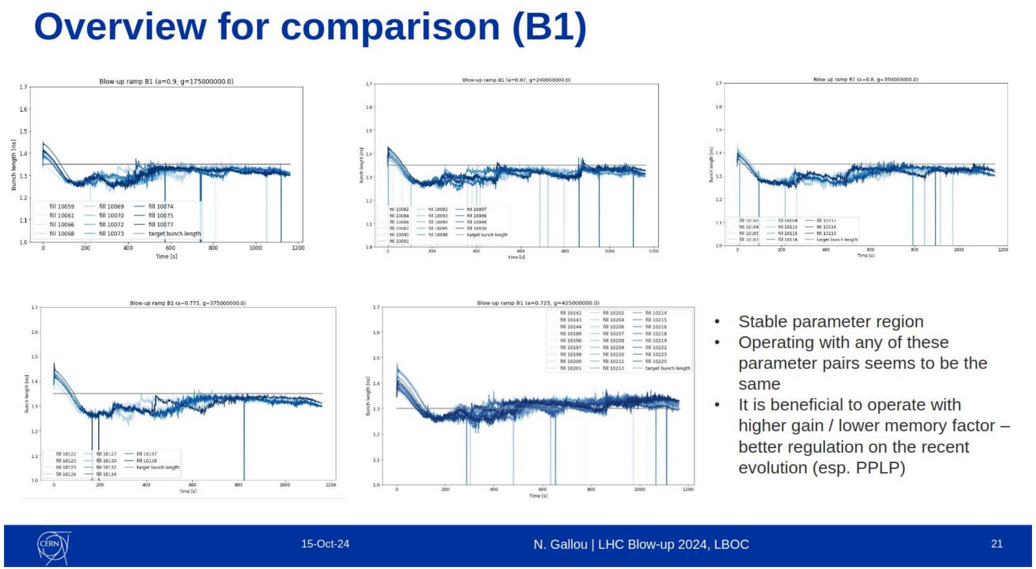
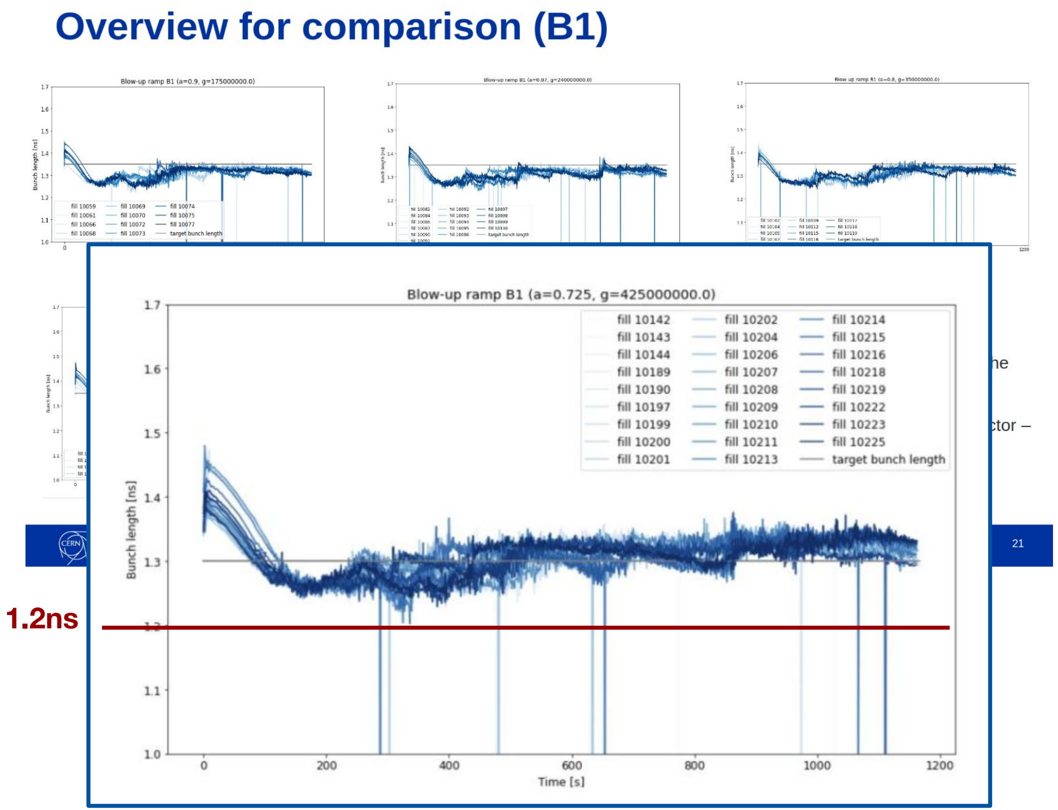


Courtesy of N.Gallou, LBOC 15/10/2024

Bunch Length Control

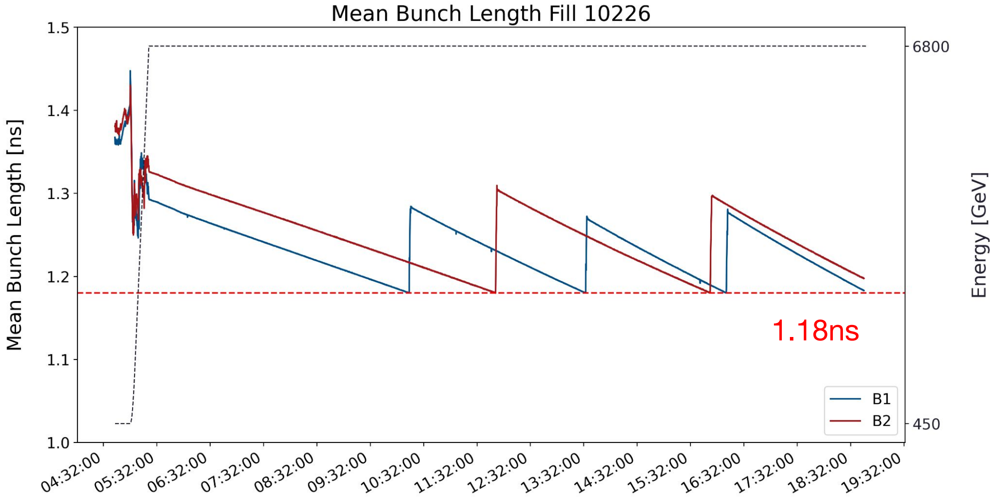
- Protect against failure of RF vacuum modules compression spring overheating
- Intensity limited to 1.6e11 ppb (stable beams)
- Bunch length has a significant impact on the local heating of the compression springs
- During a typical 2023, bunch length was frequently below 1.1ns at start of ramp
- Mitigations:
    - Started the year with long. blow up tweaks
    - Optimum RF setpoints following MDs and scans during ramps
- **Drastically reduced instantaneous heating during the ramp since bunch length is consistently above 1.2ns**

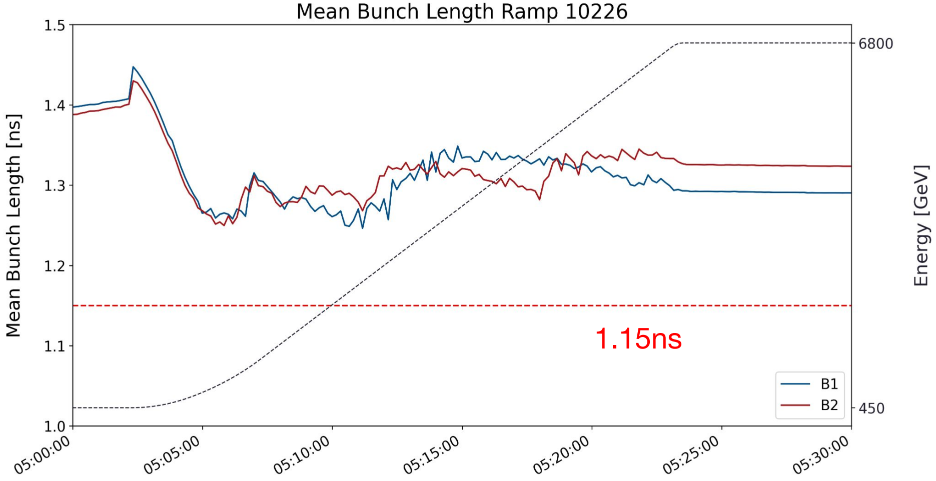


Courtesy of N.Gallou, LBOC 15/10/2024

Bunch Length Control

- Interlock in the ramp
  - Minimum average bunch length 1.15ns
- Optimized RF setpoints during the ramp
- Longitudinal blow up during physics
  - Average bunch length threshold ~1.18ns

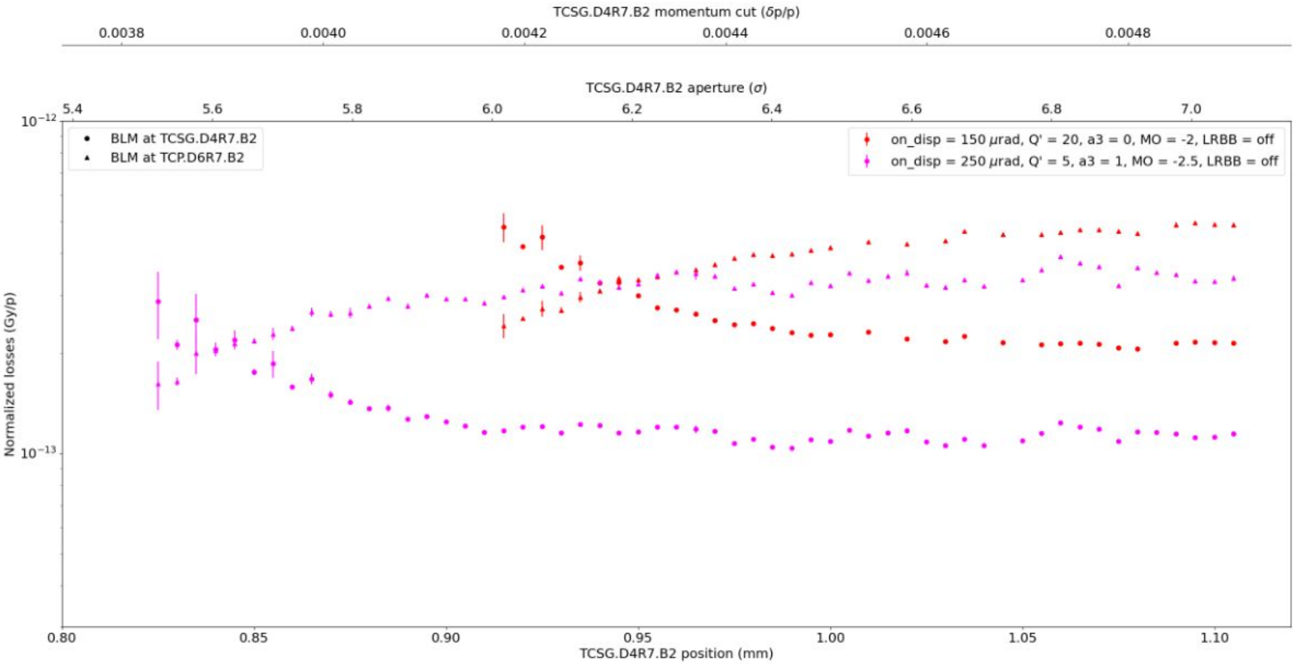




Thanks for your attention

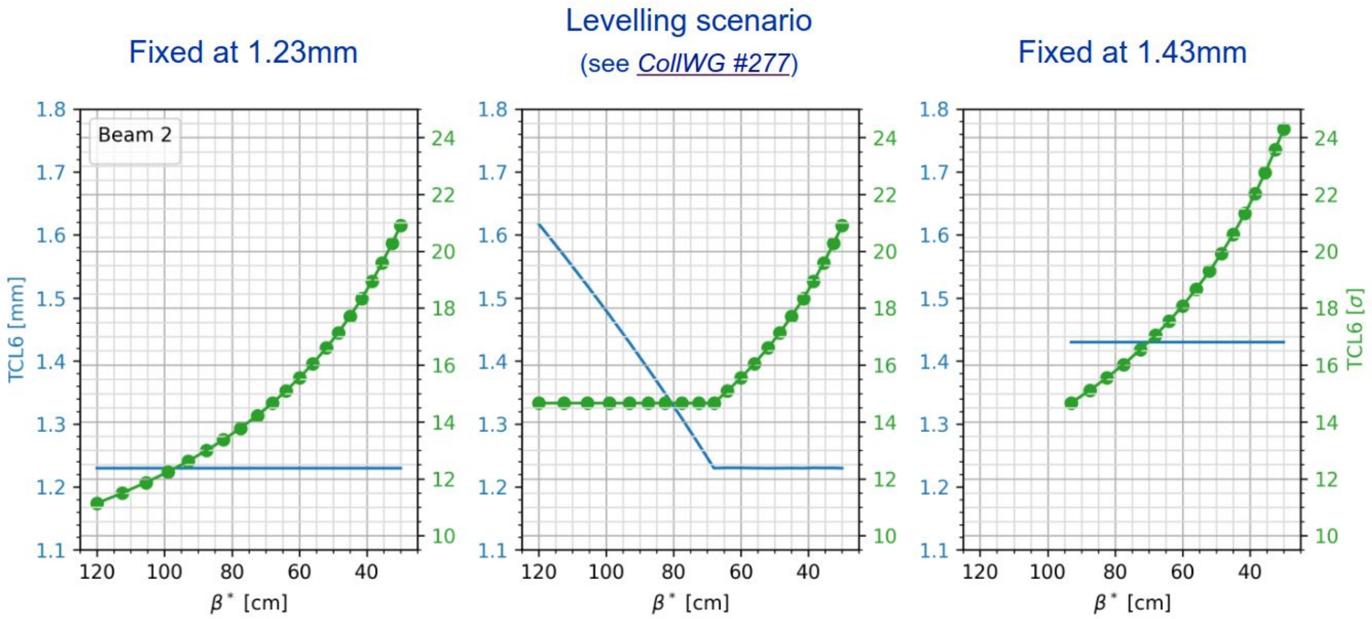
Backup

Ref ➔ Ref + on_disp + Q’ + a3 + MO



Courtesy of D.Mirarchi

TCL6 in IP1



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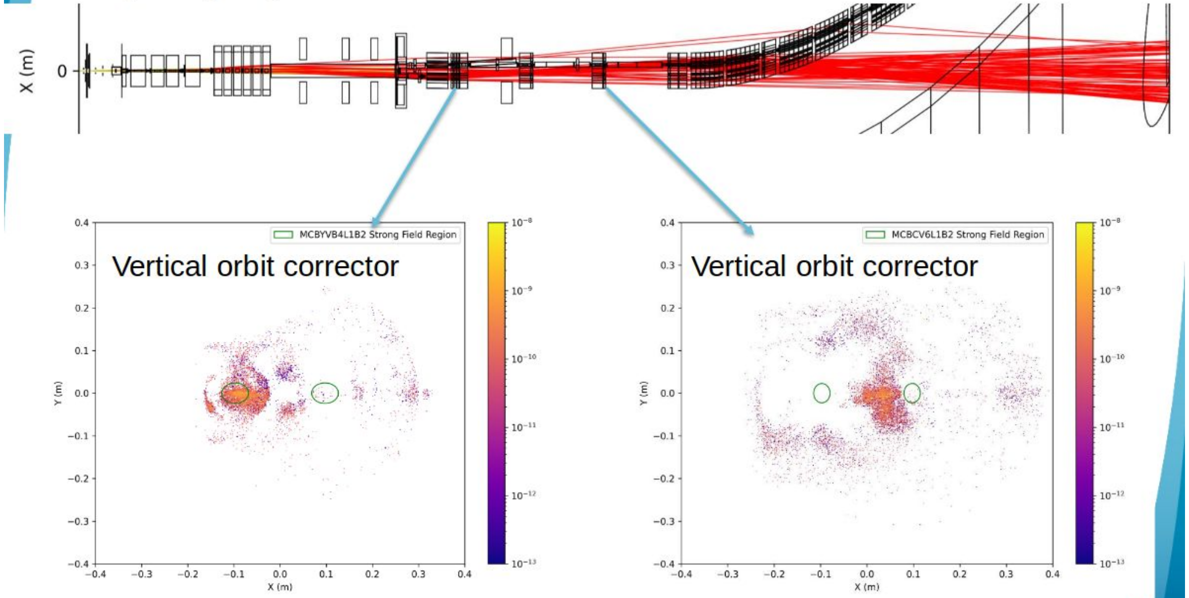
Courtesy of F.Van Der Veken, LHC Collimation Working Group #278

Potential mitigation

- Tracks of >1TeV pos. muons reaching FASER simulated with BDSIM (A. Keyken)



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Courtesy of B. Lindström, LPC 02/10/24