Criticality of fast failures in the HL-LHC with depleted transverse halo

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Outline

- Fast failures: definitions and classification
- Beam distributions with depleted transverse halo
- Beam losses from spurious discharge of Coupling Loss Induced Quench system (CLIQ) with depleted halo
- Other fast failures: quench heaters, symmetric triplet quench, ADT and BBCW
- Conclusions: criticality and protectability with depleted transverse halo

Fast failures

- Failures: events leading to uncontrolled beam losses
  - Protection from **ultra-fast failures** (damage limit reached within 3 turns) relies on passive absorbers
  - Protection from **fast failures** (damage limit reached within 10ms) relies on dedicated interlocks
- Machine protection **critical loss level** for fast failures: **1 MJ** deposited in IR7 within 10ms
- Key quantitative parameters:
  - time from failure onset to critical loss level
  - time from failure detection to critical loss level must provide sufficient margin to safely dump the beam

Fast failures

Classification	Failure	Detection	Elements
Beam effect of magnet protection equipment	QH	Direct	Triplets, D1, D2 (+ MB, MBH)
	CLIQ	Direct	Triplets IP1 & 5
Active device failure	ADT	Indirect	ADT H & V
	Crab cavities	Direct	IP1 & 5
Powering failure (resistive component)	BBCW	Direct	IP1 & 5
Powering failure (SC component)	Symmetric triplet quench	Direct / Indirect	Triplets IP1 & 5

Direct detection: external fault detection mechanism is interlocked
Indirect detection: protection relies on interlocked beam-based measurements

Machine parameters

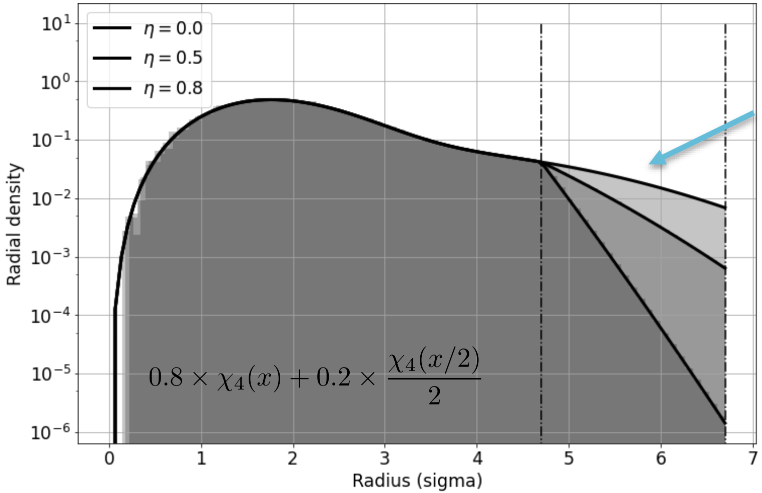
- HL-LHC layout v1.4 with round optics (β* 15 cm)
- Collimator settings: TCP @ 6.7 sigma

	Beam parameters
Beam energy	7 TeV
Beam stored energy	674 MJ
Bunch intensity	2.2 x 10^{11} p^{+}/bunch (2736 bunches)
Beam emittance	2.5 μm
TCP / E-lens settings	6.7 / 4.7 sigma
Crossing angle at IP1-5	500 μrad
BCCM threshold	3.0 x 10^{11} protons *

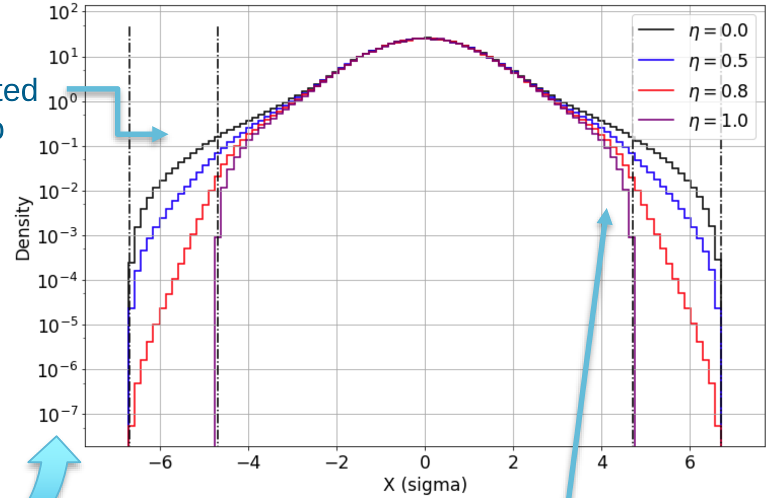
* for short integration windows (≤ 64 turns)

Partially depleted transverse halo

- 4 degrees of freedom beam distribution and halo depletion
- Modified radial chi-distribution: exponential decrease in the halo
- Partial depletion using a modified PDF: exponential decrease in the halo
- We define **η ≔ halo depletion factor** (η = 1 for fully depleted halo)



Depleted halo



Projection

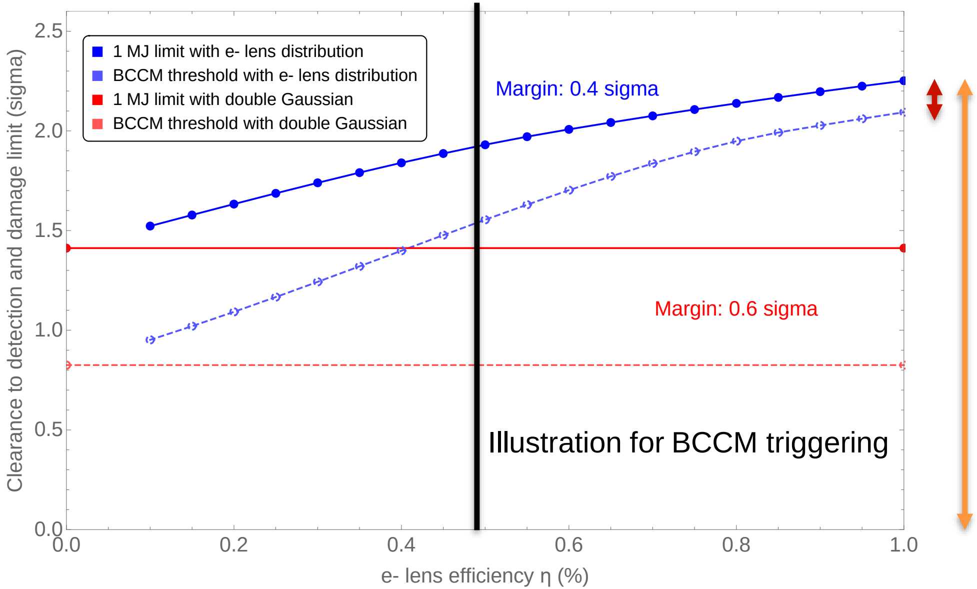
Depletion below 4.7 sigma from projection effect

Margins with depleted halo

- **Increased orbit excursion margin** to reach critical losses
- But **reduced margin between beam loss detection and reaching critical loss level**

Protection with dedicated interlock
→ gain, delayed losses

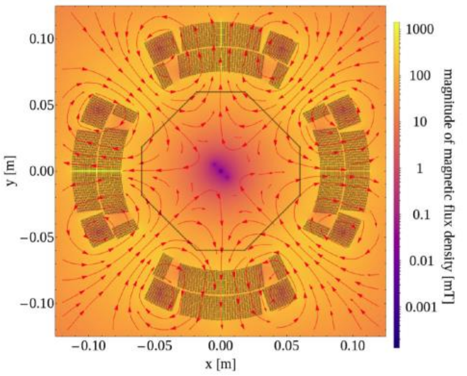
Indirect protection (beam losses)
→ reduced margin



CLIQ and impact of magnet protection on the beam

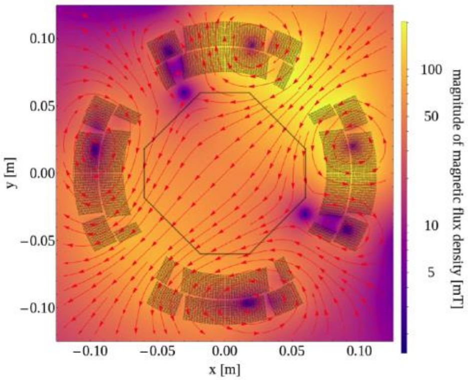
- Failure mode: erratic firing of CLIQ unit
  - In case of a quench, for HL-LHC, the QPS will trigger a beam dump before CLIQ firing (and QHs)
- Initial connection scheme for Q1-3 magnets exhibited a strong dipolar field *
  - Past studies concluded that this is not compatible with the protection of the machine
  - Baseline connection scheme now has a Q2-like connection for all magnets

Q2-like connection



Field dominated by a **skew-octupolar** component

Q1-3 connection

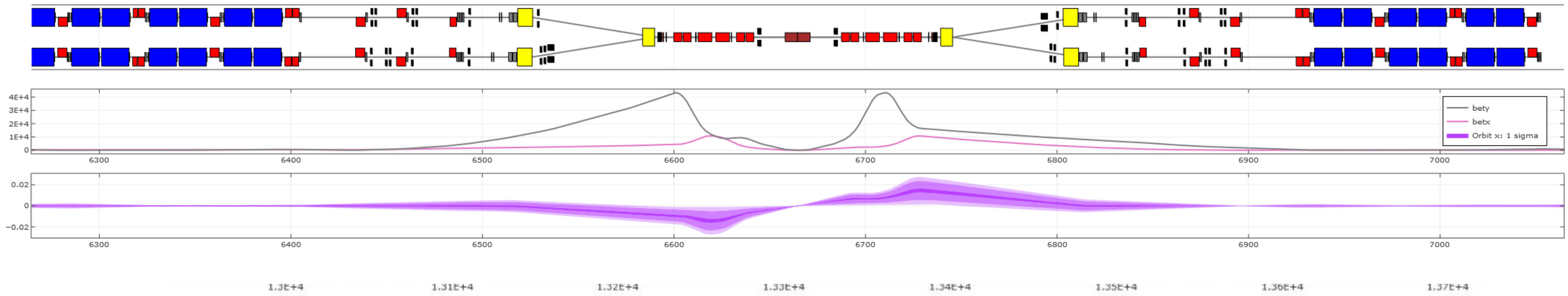


Field dominated by **normal and skew dipolar** components

LEDET/SIGMA simulations (E. Ravaioli) – Difference w.r.t main field after 5ms

(*) Additionally, in the old scheme for Q1-3, a single CLIQ unit would act on both halves of the magnet, doubling the effective length

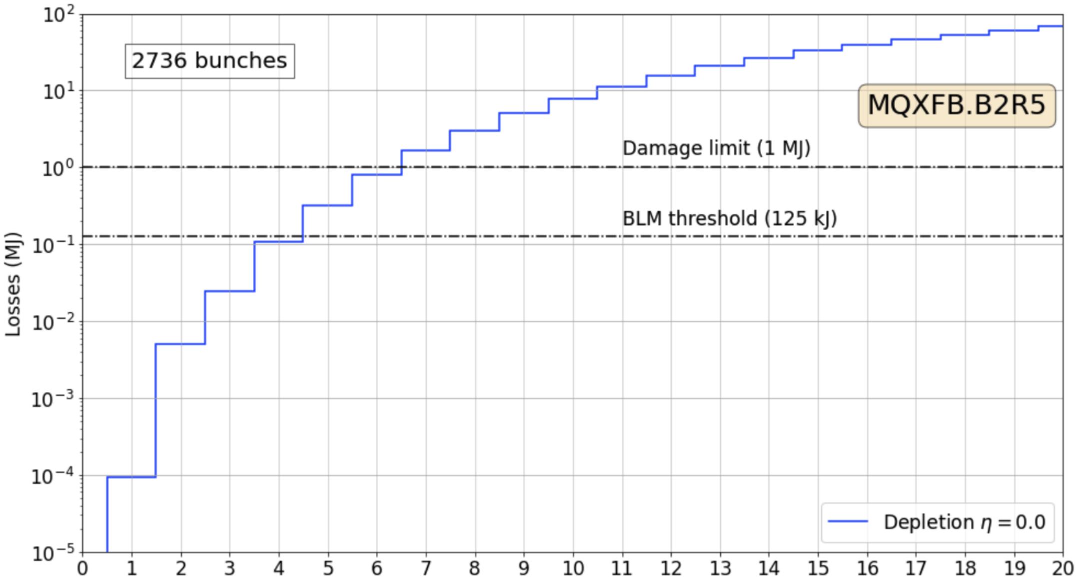
Impact on the beam



- Large amplification from the β function at full squeeze
- Important magnetic length (4.2m for Q1-3, 7.15m for Q2)
- Crossing angle (feed-down)

Beam losses

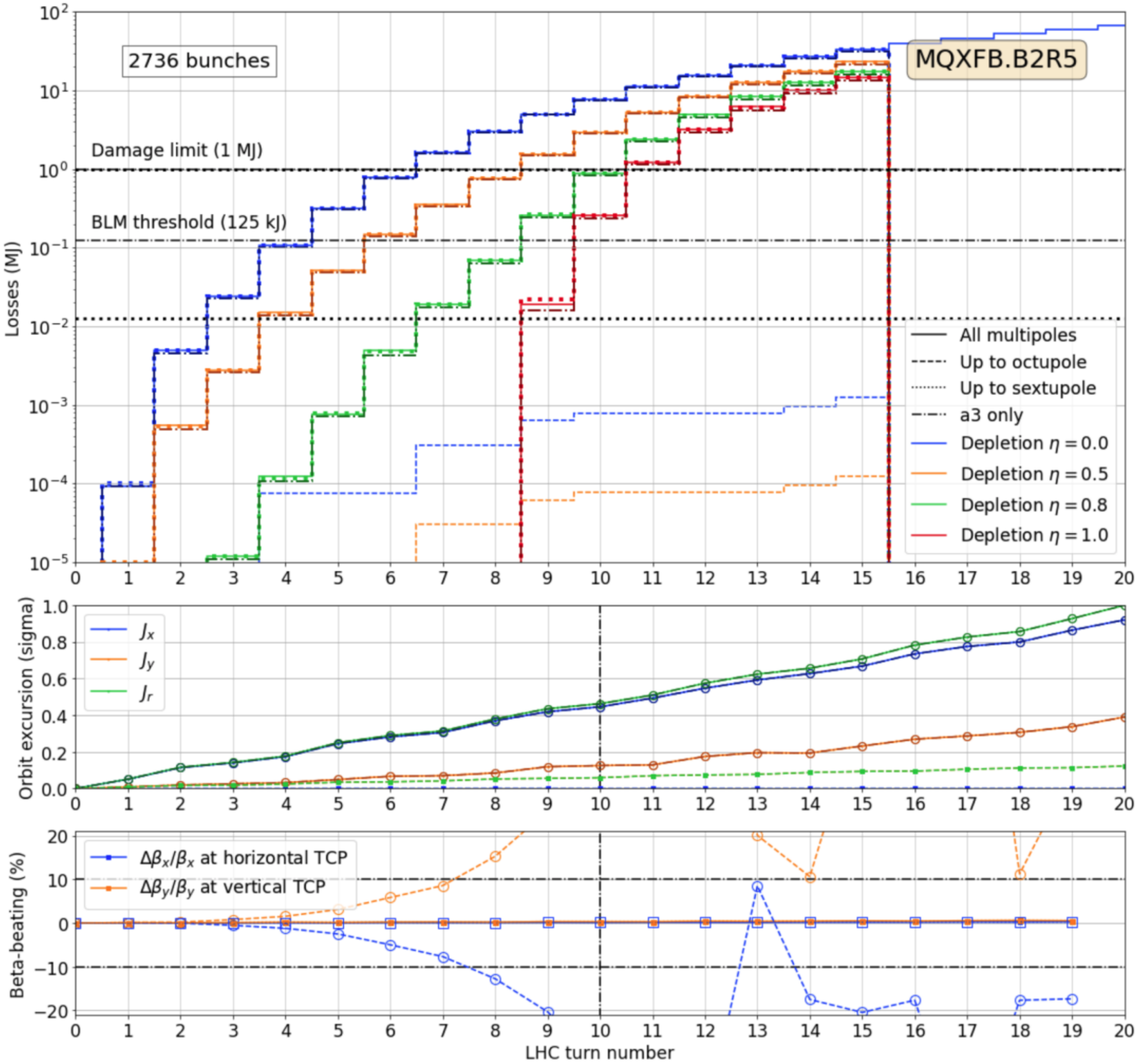
- Losses computed from multi-particle tracking simulations
- Worst case identified: MQXFB.B2R5, detailed simulation and analysis for different machine configurations



- Large losses compared to the initial understanding (based on orbit excursion and beta-beating)
- Critical level reached in **5 turns**
- Much faster than the 10-turn initially foreseen interlock

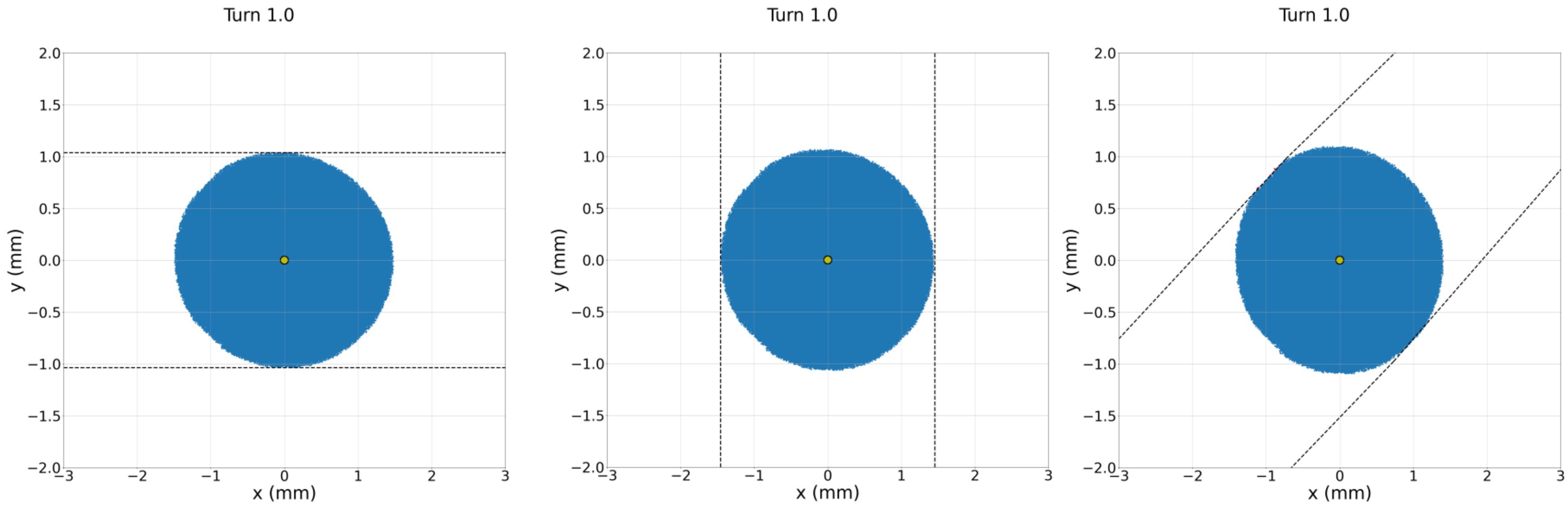
Beam losses Q2b R5

- Cannot correlate with orbit excursion nor beta-beating
- Isolate the multipoles and conclude that the skew-octupolar field is solely responsible
- Halo depletion (e-lens) effects:
  - Margin further reduced (1 turn at 50% depletion)



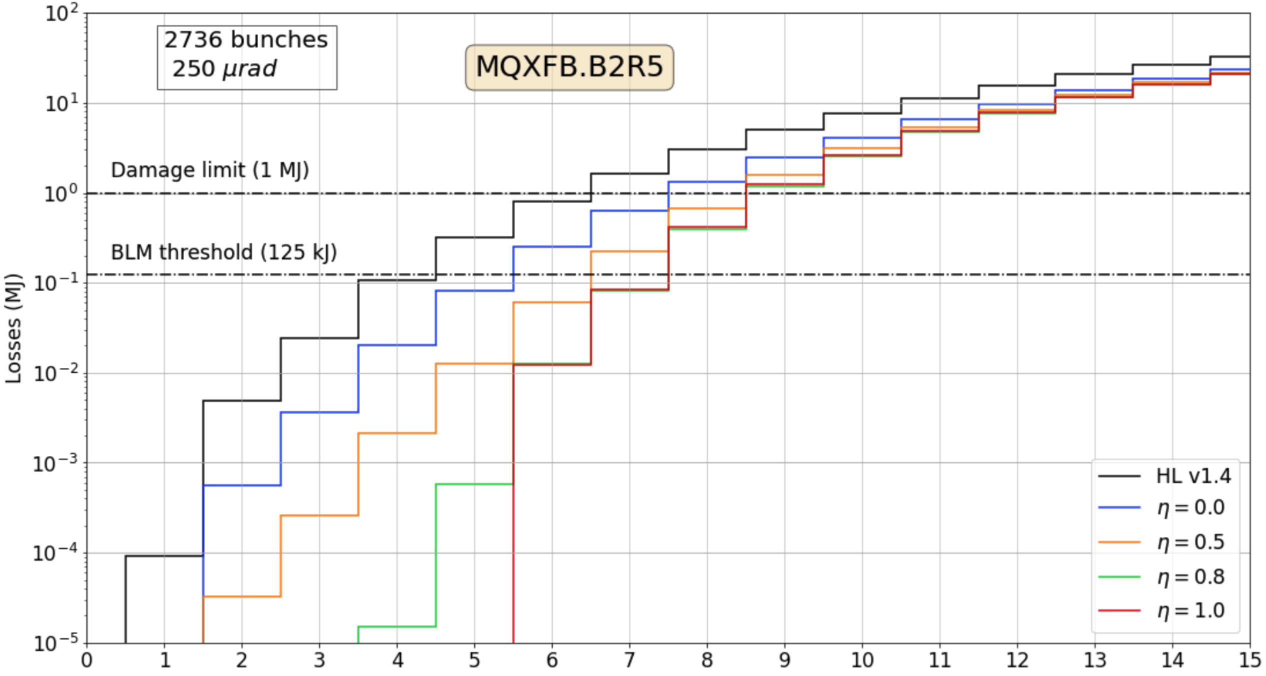
Beam losses at the TCPs

- Turn-by-turn losses at the TCPs in IR7



TCP.D6L7 (vertical) TCP.C6L7 (horizontal) TCP.B6L7 (skew)

HL-LHC v1.5 configuration with relaxed collimator settings



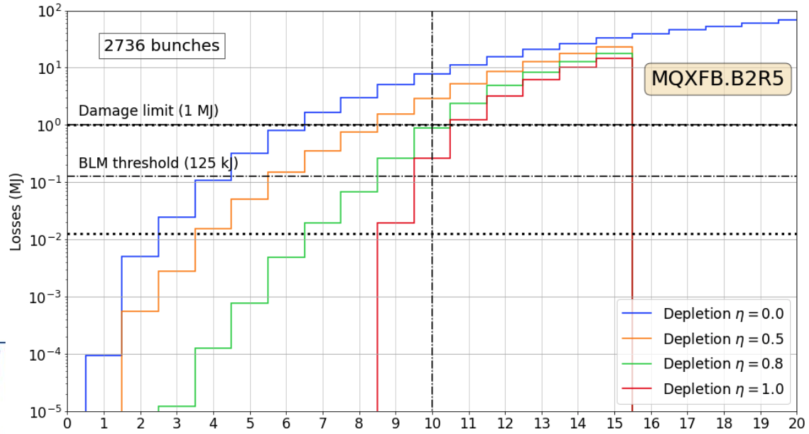
Open collimator settings (8.5 sigma) provide 1 turn additional delay but the failure detection to loss margin is not increased

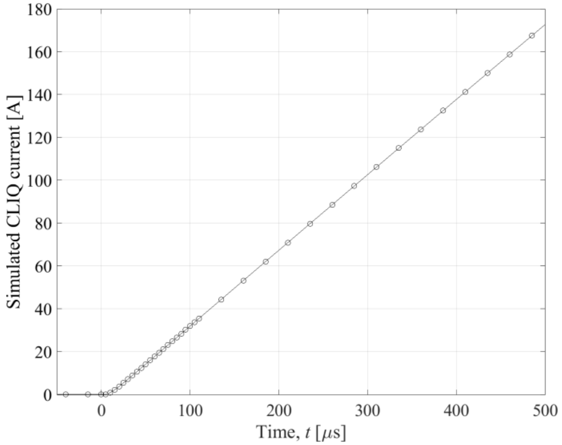
Conclusions on criticality and interlocking

- Need a very fast dedicated interlock
  - Interlock the capacitive discharge ➡ protects the worst-case scenario, also for depleted halo

See J. Uythoven's presentation: R2E development for PIC and BIS in HL-LHC

Onset to damage margin	450 μs
Propagation via BIS from P1 to P6	- 100 μs
LBDS synchro.	- 89 μs
Extraction	- 89 μs
Allowed interlock reaction time	**= 170 μs**

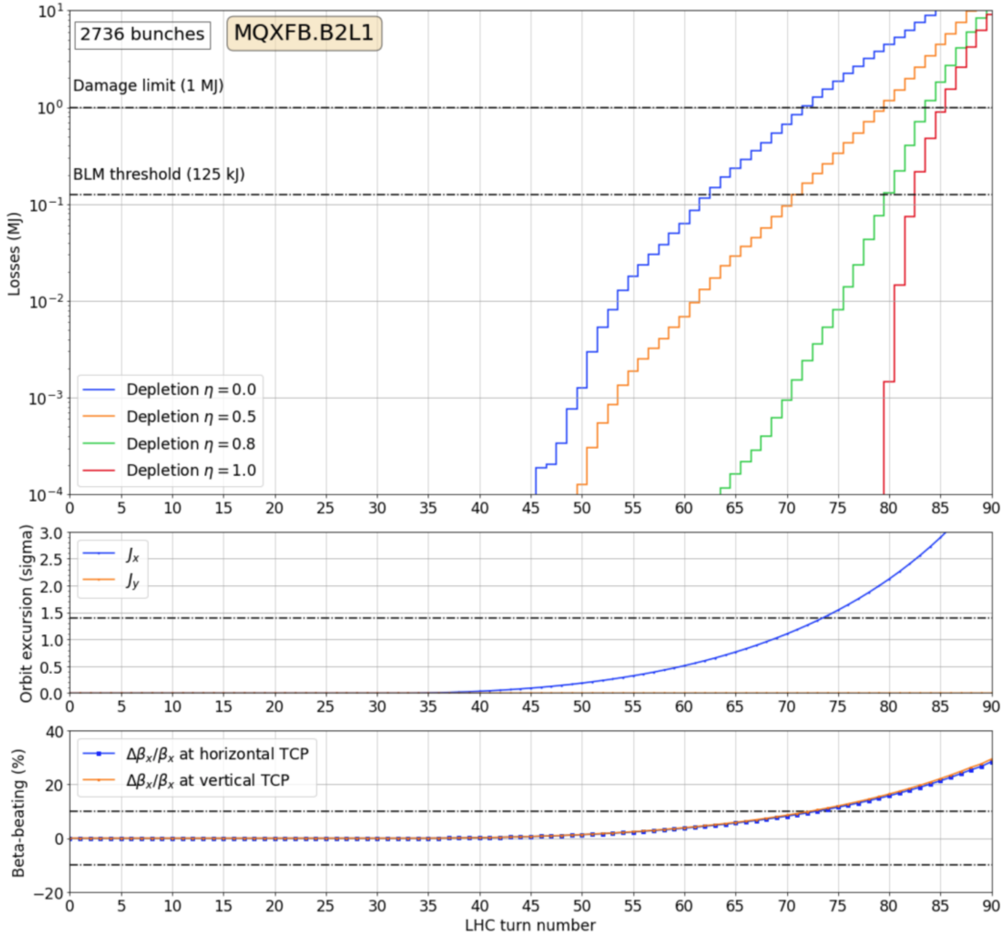




Symmetric triplet quench

- Use the orbit excursion estimates to identify the worst case (MQXFB.B2L1) and perform a detailed simulation and analysis

  - Tracking losses confirm the initial understanding
  - Critical level reached in **72 turns** (non depleted halo) or **85** turns (fully depleted)
  - **2-turn** margin for BLM interlock
  - Beta-beating does not play a major role, collimation hierarchy not an issue



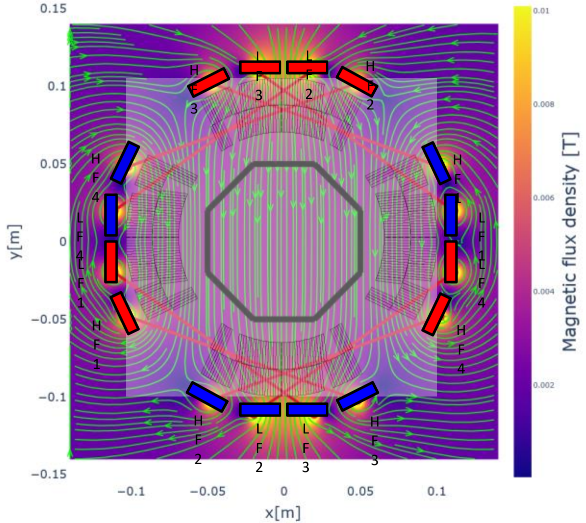
Conclusions on criticality and interlocking

Constraints on the symmetric quench detection	TCP @ 6.7	TCP @ 8.5
Onset to damage margin	6480 μs	7476 μs
Propagation via BIS from P1 to P6	- 100 μs	- 100 μs
LBDS synchro.	- 89 μs	- 89 μs
Extraction	- 89 μs	- 89 μs
Allowed interlock reaction time	**= 6200 μs**	**= 7200 μs**

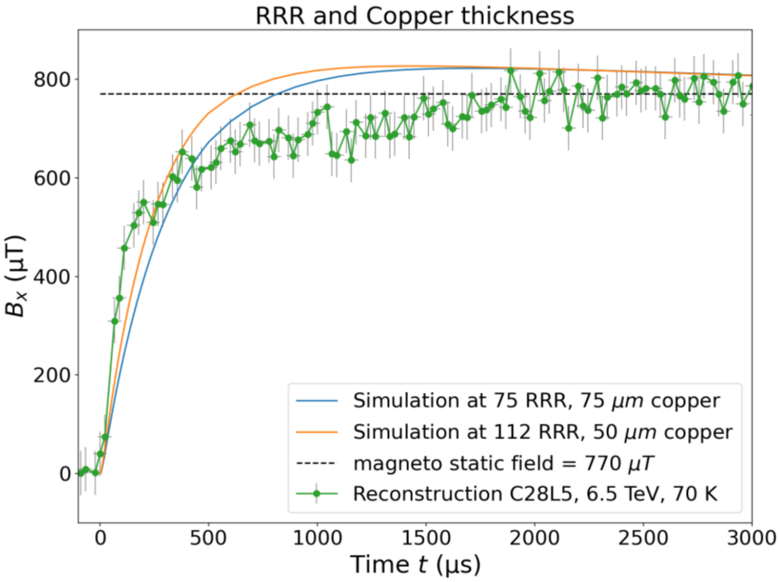
- For non-depleted halo, dumping on the BLM losses provides sufficient margin (10 turns)
- Maximum tolerable halo depletion at 50% to provide sufficient margin between beam loss detection and critical losses
- Dynamics of the symmetric quench and its detection is crucial for beams with depleted halo!

Quench heater effect on the beam

- Spurious triggering of one QH unit cannot be excluded
- Very fast current rise ~30 μs
- Beam oscillations observed at the LHC
- Field reconstruction from BPM data consistent regarding field levels and rise times



QH field reconstruction from BPM measurements

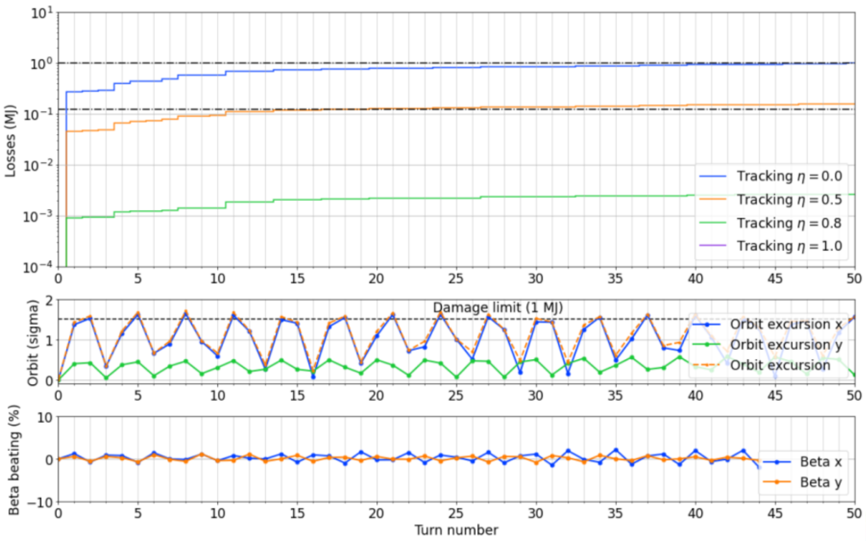


L. Richtmann, M. Sc. Thesis, 2021.

Quench heater spurious discharge

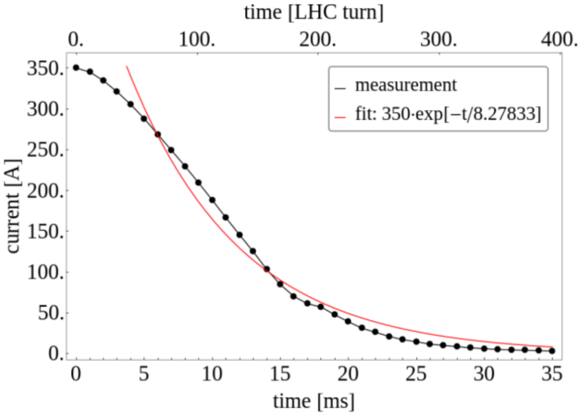
- For non-depleted halo, dumping on the BLM losses provides sufficient margin (10 turns)
- At full halo depletion, only 2-turn margin between BLM detection and damage
  Dynamics of the symmetric quench and its detection is crucial for beams with depleted halo!

D1 – Single QH circuit (worst case)



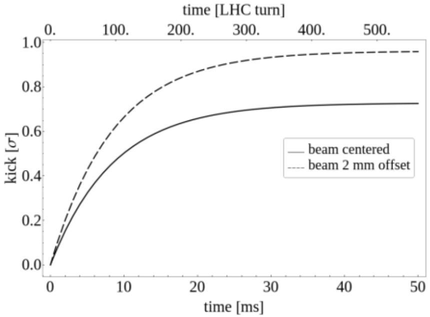
BBCW powering failure

- The powering failure implies a current decay modeled with an exponential fit on measured data



- We also consider the (hypothetical) case where the fields go to zero instantly
- In case of failure, we did not model
  - The reaction of the orbit feedback
  - The tune feedback

Dipolar effect

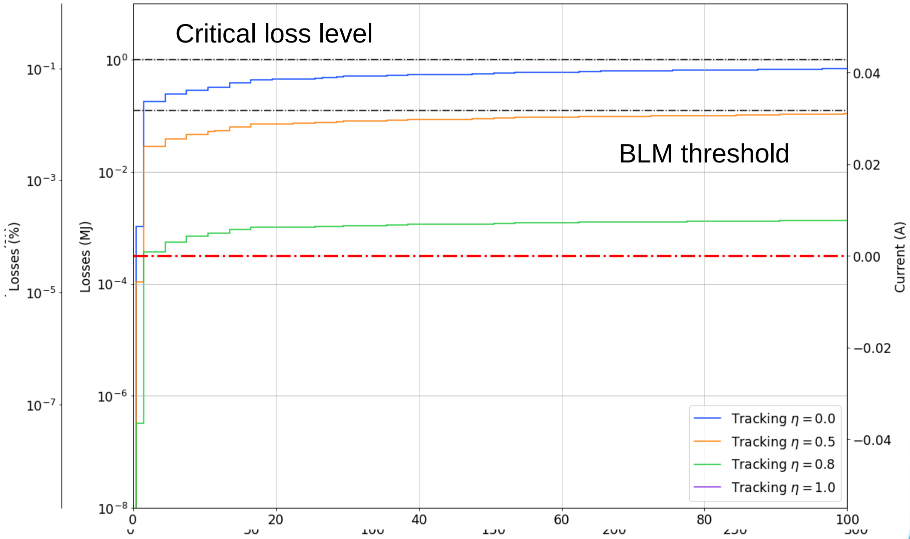


$$\alpha \approx \frac{Bl}{B\rho}\sqrt{\frac{\beta(s)}{\epsilon_g}} = \frac{\mu_0 I l}{2\pi B\rho\epsilon_g r[\sigma]}$$

But all multipoles present

Beam losses

- **Exponential decay starting at 150 A for wire installed in 4L5**
  - BLM threshold reached “asymptotically” (not before 300 turns, 26.7 ms)
  - Critical loss level not reached
- **Instantaneous switch off**
  - “Worst case” for the field decay
  - BLM threshold reached at turn 2
  - Critical loss level not reached



Conclusions on criticality and interlocking

- Criticality is low: losses remain below the critical loss level
- For an exponential decay, reaching BLM threshold would occur late (> 300 turns, 26.7ms) leaving enough time for the WIC interlock to act as protection

- **Halo depletion has a beneficial effect** !

ADT coherent excitation

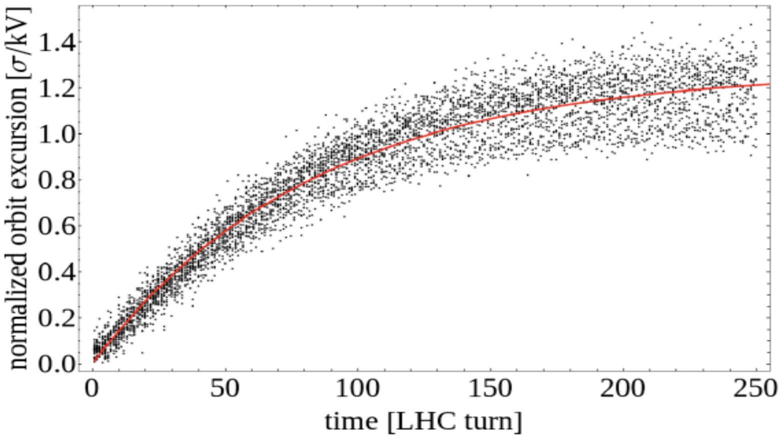
ADT operation in coherent excitation mode

- Potential fast-failure leading to beam losses reaching the critical loss limit within few milliseconds
- Orbit excursion is a superposition of coherent excitation and always-on damping

Objectives

- Determine the **operational envelope** for allowed operation with the ADT in coherent excitation for **HL-LHC with different halo depletion factor**

ADT model from measurements



Measured coherent excitation of the beam by the ADT normalized to the applied voltage at 6.5 TeV with fitted scaling law

$$\frac{d}{dt}\sigma(t) = k - d \cdot \sigma(t)$$

$$\sigma(t) = \frac{k}{d}\left(1 - e^{-d \cdot t}\right)$$

ADT coherent excitation

- Operational envelope (211th MPP) defined:
  - Limit the ADT active window length to 2 batches (480 bunches) for HL-LHC
    - Further restriction to 1 batch (240 bunches) if operating with depleted halo
  - Limit the maximum voltage at injection energy to 5.0 kV

Conclusions

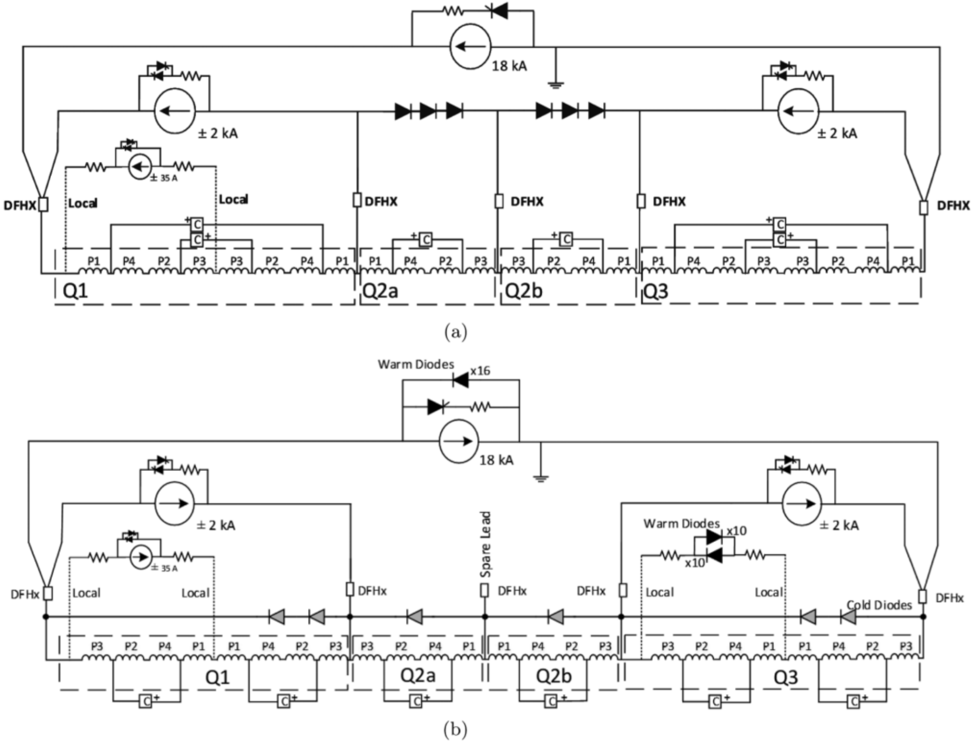
- Derived a parametric **beam model for partially depleted halo**
  - **Need to refine beam halo measurements at larger amplitudes during Run III**
- **CLIQ**
  - Most critical fast failure case identified for HL-LHC: **fast dedicated interlock foreseen** (PDSU-PIC)
- **Quench heater spurious discharge -** Beneficial effect from partial halo depletion, D1 most critical
- **Symmetric triplet quench -** Sufficient margin for non-depleted halo; 2-turn margin at full depletion
- **ADT coherent excitation -** ADT excitation window limited to 480 bunches; voltage limited at injection
- **BBCW -** Low criticality, protection from WIC sufficient - beneficial effect from halo depletion

HiLumi HL-LHC PROJECT CERN

Questions?

Back-up

CLIQ connection scheme



Old

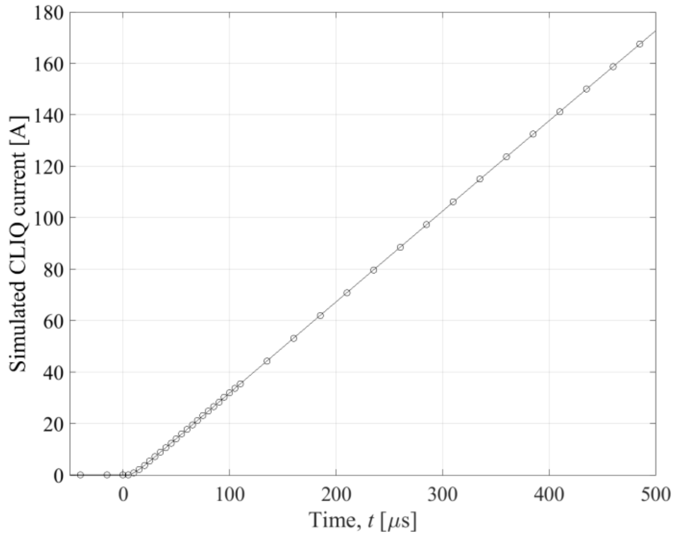
Baseline

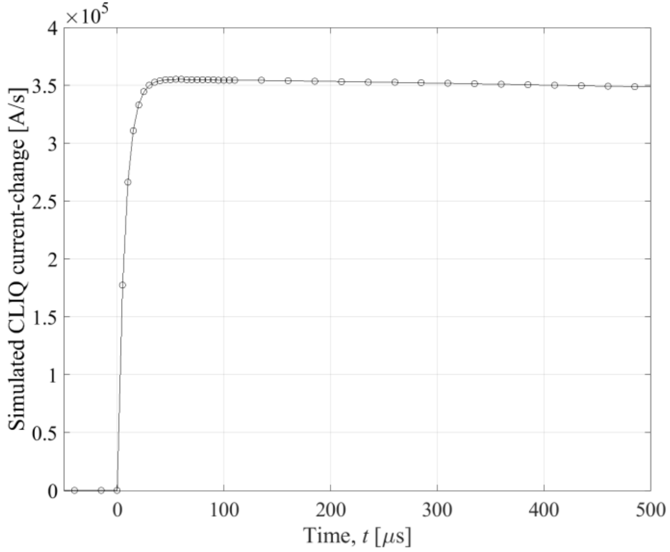
FIG. 9. The baseline CLIQ connection scheme (top) as of the writing of this article [29,45] vs the new baseline to be active from HLLHC TDR v. 1.0 [46]. The magnets, Q1, Q2, and Q3 are encircled by dashed lines. All three magnets consist of two identical halves, designated a and b, but only for Q2 the halves are separate. The magnet poles are designated by P1 to P4 and the CLIQ units by C. (a) Baseline in HLLHC TDR v. 0.1 (b) New baseline in HLLHC TDR v. 1.0.

For reference

CLIQ current

- Rise-time shown below for the first 5 turns

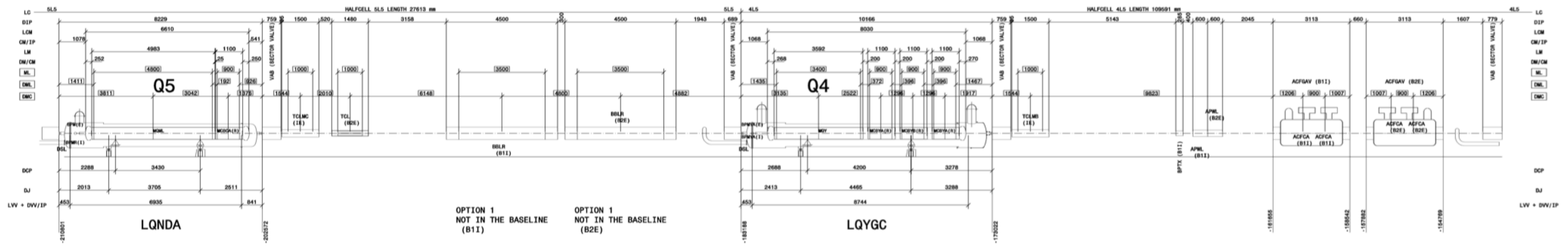




LEDET simulations (E. Ravaioli)

BBCW for HL-LHC

- Layout based on EDMS-2037987
- Space reservation request based on HL-LHC v1.3
- Drawings of space reservation
  - Left of IP1 & Right of IP1
  - Left of IP5 & Right of IP5



Q5

BBLR
B1 & B2

Q4

CC