Energy deposition in IR6 magnets during regular and irregular beam losses

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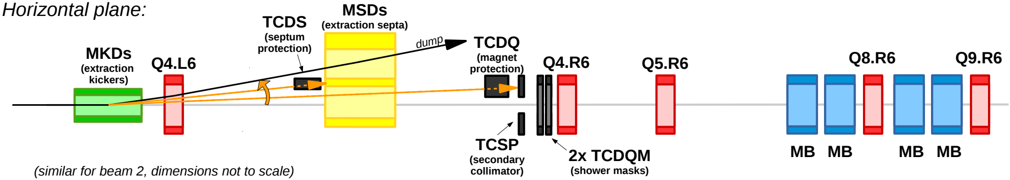
On behalf of **HL-LHC WP14**

With contributions from: G. Lerner, J.B. Potoine (R2E team)
E. Belli, R. Bruce (collimation team)

9th HL-LHC Collaboration Meeting

October 15$^{\mathrm{th}}$, 2019

Horizontal plane:



(similar for beam 2, dimensions not to scale)

Topics of this talk:

- Asynchronous beam dumps in HL-LHC: are SC magnets sufficiently protected against damage?
  - *"Benchmarks" of the simulation model against asynch. beam dump MDs*
  - *Update of energy deposition studies for HL beams (HL-LHC V1.3)*

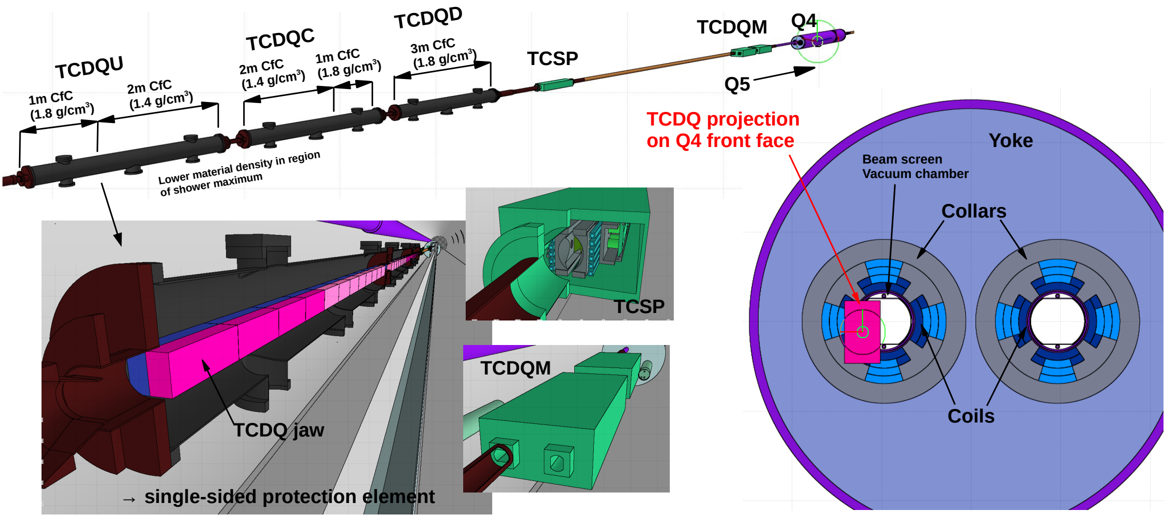
  → relevant for machine safety

- Halo losses on **TCDQ/TCSP** in HL-LHC: is there a risk of quench in case of lifetime drops?
  - *Was never studied before for HL-LHC*
  - *Profit from synergies with R2E studies of IR6 radiation levels*

  → relevant for operational performance

Not discussed in this talk: robustness of protection devices, protection efficiency of TCDS

TCDQ+Q4/Q5 model for energy deposition simulations



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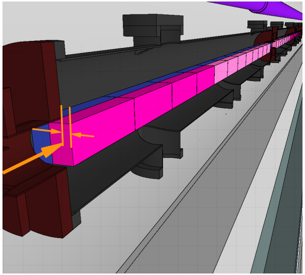
Asynchronous beam dump MDs at 6.5 TeV in Run 2 (C. Wiesner et al.)

MDs in Run 2 → **better understand the shower leakage to SC magnets**

		ASD test, 2016-05-15	MD4044	MD2930	MD2930	MD4044
Intensity		~3e10 on TCDQ (based on BSRA)	5e9 p+	1.8e10 p+	1.0e10 p+	5e9 p+
Bucket		Debunched beam	34611	34621	34631	34641
Estimated TCDQ impact parameter		Debunched beam	~0 mm (?)	~0.8 mm (?)	~1.6 mm (?)	~2.6 mm (?)
Magnet	T (K)	Quench?	Quench?	Quench?	Quench?	Quench?
MQY.4R6	4.5	No	Yes	Yes	No	No
MQY.5R6	4.5	No	No	No	No	No
MB.A8R6	1.9	Yes	Yes	Yes	No	No
MB.B8R6	1.9	(Yes)*	(Yes)*	(Yes)*	No	No
MQML.8R6	1.9	(Yes)**	(Yes)**	(Yes)**	No	No
MB.A9R6	1.9	No	No	No	No	No
MB.B9R6	1.9	No	No	No	No	No
MQM.9R6	1.9	(Yes)**	(Yes)**	(Yes)**	No	No

σ_x at TCDQ ≈ 0.4 mm

*quenched due to heat propagation
**quenched due to electro-magnetic coupling

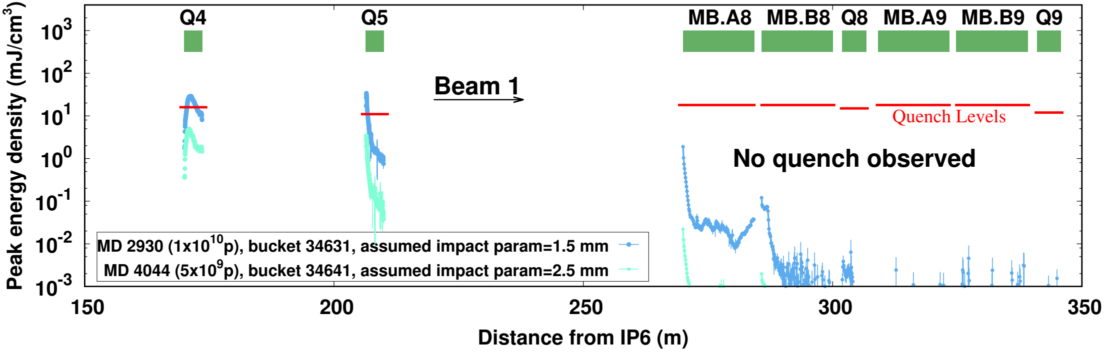


For details, see presentation of C. Wiesner in LSWG meeting 04/12/2018

- Presence or absence of a quench gives an indication about the energy deposition in coils
- **Can be used to "benchmark" the shower simulation model**

Reconstructed energy density in coils (for attempts **not** leading to a quench)

FLUKA results for MD2930/MD4044 vs quench levels:



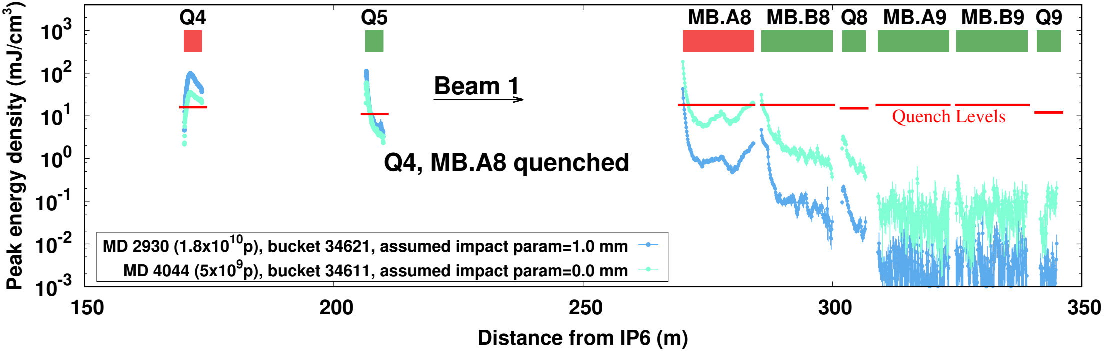
→ *in one case (MD2930) energy density in Q4 (Q5) 2× (3×) above assumed quench level, but no quench observed*

→ *reconstructed energy density in DS magnets well below quench level, compatible with absence of quench*

Based on input from C. Wiesner, A. Apollonio, simulations by M. Frankl.

Reconstructed energy density in coils (for attempts leading to a quench)

FLUKA results for MD2930/MD4044 vs quench levels:



→ *simulated energy density in Q4 and MB.A8 above quench level, compatible with observation of quench*

→ *reconstructed energy density in Q5 well above quench level, but no quench observed*

Based on input from C. Wiesner, A. Apollonio, simulations by M. Frankl.

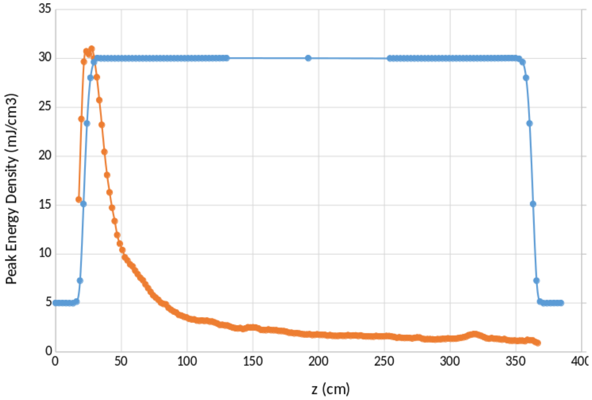
Conclusions from MDs wrt shower simulation model

- With the exception of the Q5, the simulation results can explain - within a factor of ∼2 - the presence or absence of observed quenches
- Possible explanations for Q5:

  → *highest energy density is around the return coils where quench behaviour could be different*

  → *Simplified FLUKA geomety might lead to an overestimation of the energy density in this region (i.e. simulation uncertainty could be higher than a factor of 2)*

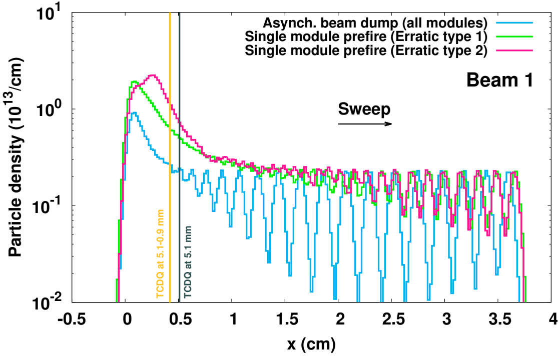
Longitudinal energy density profile in Q5 and *longitudinal magnetic field profile*:

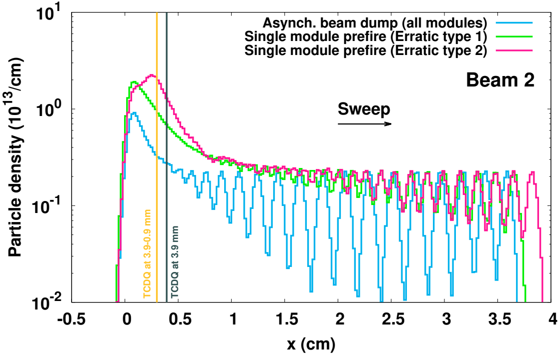


A. Apollonio, S. Izquierdo Bermudez

Proton impact distribution on TCDQ in case of asynchronous beam dumps

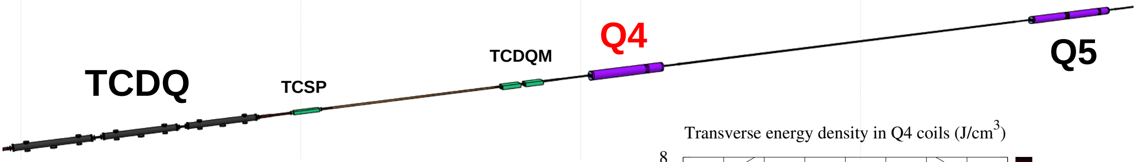
HL-LHC optics V1.3, 2.3$\times$10^{11} ppb, ε = 1.7 μm (BCMS) *Y. Dutheil*

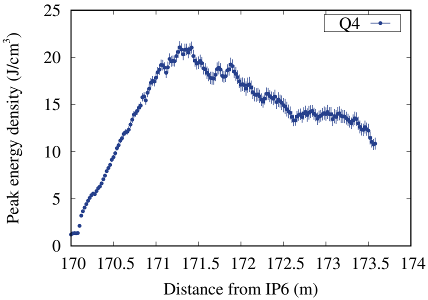


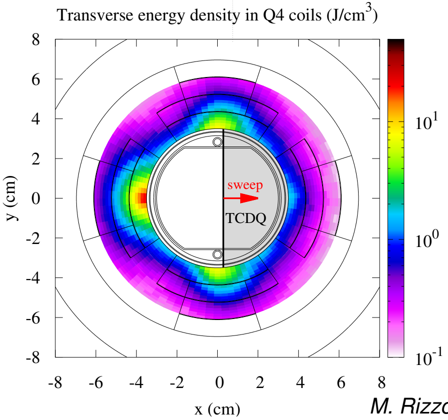


- $\rightarrow$ **Type 2 erratic** (single module prefire) yields the highest particle density (similar distribution for different beam modes)
- $\rightarrow$ Distributions similar for B1 and B2, but situation **worse for B2 due to smaller gap** (smaller β_x)
- $\rightarrow$ Gap assumed in HL-LHC energy deposition studies = nominal gap - 1.0 mm

Peak energy density Q4 coils (B2, T2 Erratic, 2.3×10^{11}ppb, TCDQ@2.9mm)



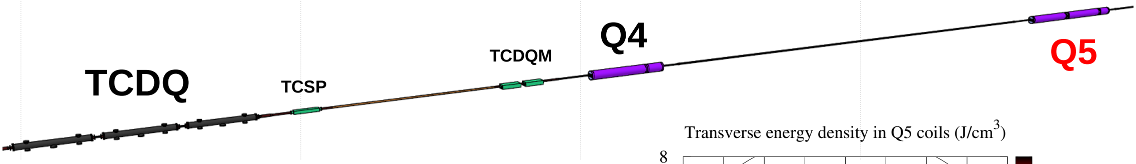


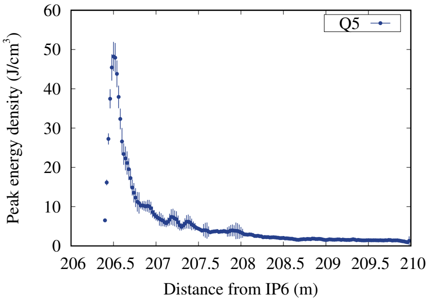


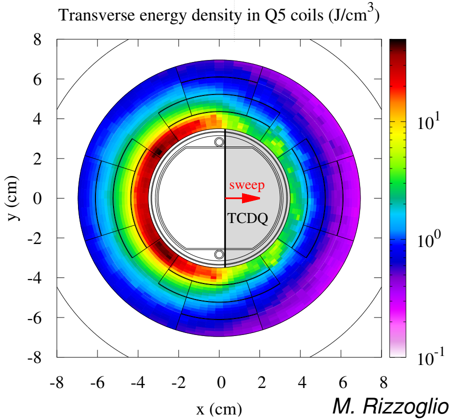
M. Rizzoglio

→ Predicted peak energy density in Q4 coils: ∼20 J/cm^3

Peak energy density Q5 coils (B2, T2 Erratic, 2.3×10^{11} ppb, TCDQ@2.9mm)







M. Rizzoglio

→ Predicted peak energy density in Q5 coils: ~40–50 J/cm^3

Remarks on the energy density in superconducting coils

- **Model calculations:**
  → **Should account for a sufficient safety margin** (at least a factor 3 below damage limit)

- **Damage limit of NbTi coils for ultra-fast losses:**
  → During the design of LHC protection devices a value of **~87 J/cm^3** was assumed, which however has to be revised
  → **HiRadMat test** on SC cables carried out by colleagues from TE/MPE (at room and cryogenic temperature) - see HL annual meeting 2019
  → These tests indicate that NbTi coils can sustain of the order of **1 kJ/cm^3**

- **Conclusions:**
  → **Considering the shower calculations and the HiRadMat tests, we should have ample margin in terms of magnet protection in IR6**
  → Even changes in optics/TCDQ half gap should not change this conclusion
  → One open point we would like to study: affect of angular misalignment

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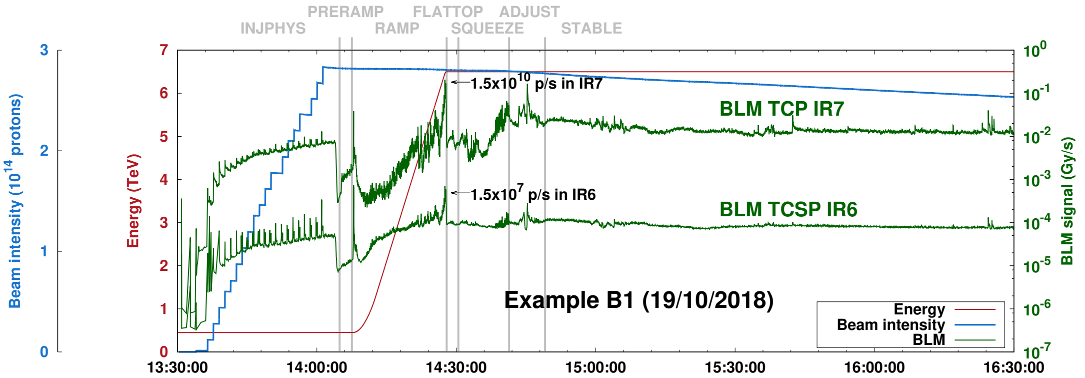
Halo losses on extraction protection devices

- **Beam halo losses:**
  - The IR6 protection devices need to be in place at all times $\rightarrow$ unavoidable that they intercept halo particles (outscattered from IR7 collimators)
  - **Is there a risk that halo protons impacting on the TCDQ/TCSP induce quenches in case of lifetime drops in HL-LHC?**
  - Remember: HL-LHC collimation upgrades in IR7 (TCLDs) $\rightarrow$ goal is to **sustain a beam lifetime of 0.2 h for 10 sec without quenching**
- **This talk:**
  - Analysis of proton losses on TCDQ+TCSP in Run 2 (in collaboration with R2E team, WP10) $\rightarrow$ determine halo fraction lost in IR6
  - Estimate of power density in Q4/Q5 for HL-LHC (tracking input from WP5)

Halo losses in IR6 vs IR7

Random physics fill in 2018 (#7320):



→ Halo losses in IR6 are expected to be mainly protons outscattered of IR7 collimators

→ **BLM signals in IR7 and IR6** (TCDQ+TCSP) indeed exhibit **similar but not fully identical time structure**

→ Differences could be due to time evolution of H and V loss sharing (IR6 losses mainly driven by H component)

Approach adopted in this study

To estimate the power deposition in IR6 magnets for HL-LHC, we use following normalization (loss rate):

$$\frac{\mathrm{d}N_{IR6}}{\mathrm{d}t} = \frac{\mathrm{d}N_{0.2\,h}}{\mathrm{d}t} \times f_{IR6} \qquad (1)$$

where

→ $\mathrm{d}N_{0.2\,h}/\mathrm{d}t$ is the proton loss rate in case of a 0.2 h beam lifetime, here: 8.8×10^{11} p/s[†],

→ **f_{IR6} is the halo fraction lost on TCDQ+TCSP**, which is determined **empirically** based on Run 2 experience:

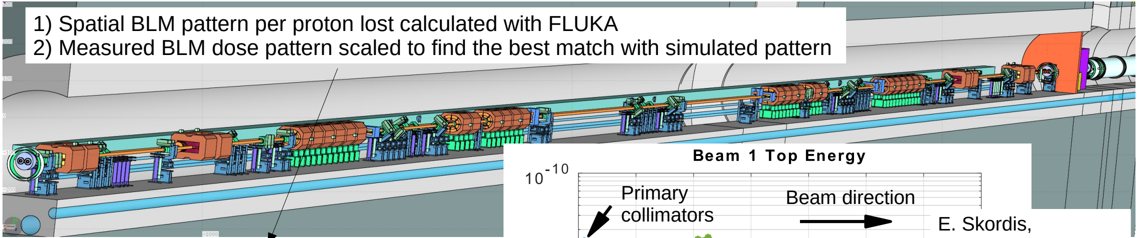
$$f_{IR6} = \frac{N_{IR6}}{N_{IR6} + N_{IR7}} \qquad (2)$$

where N_{IR6} and N_{IR7} are the estimated proton losses in IR6 and IR7 in a defined time period (reconstructed from BLM measurements and FLUKA BLM response simulations).

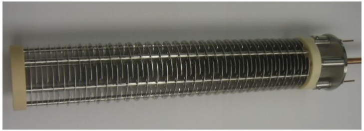
[†] 2760 bunches, 2.3×10^{11} protons per bunch

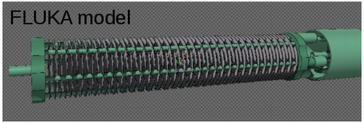
Determining the number of halo protons lost in IR7 (N_{IR7})

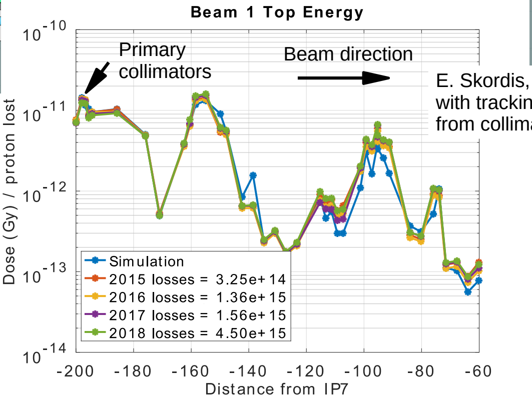
1) Spatial BLM pattern per proton lost calculated with FLUKA
2) Measured BLM dose pattern scaled to find the best match with simulated pattern



Scaling factor = number of protons lost in the time period of the measurements



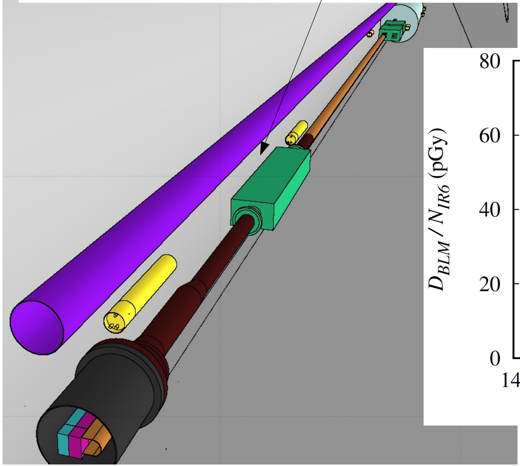


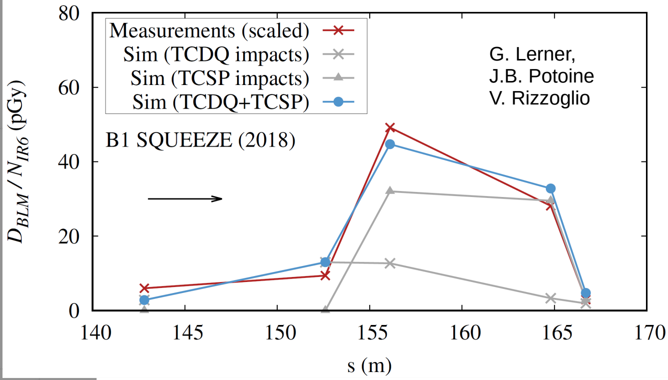


E. Skordis, with tracking input from collimation team

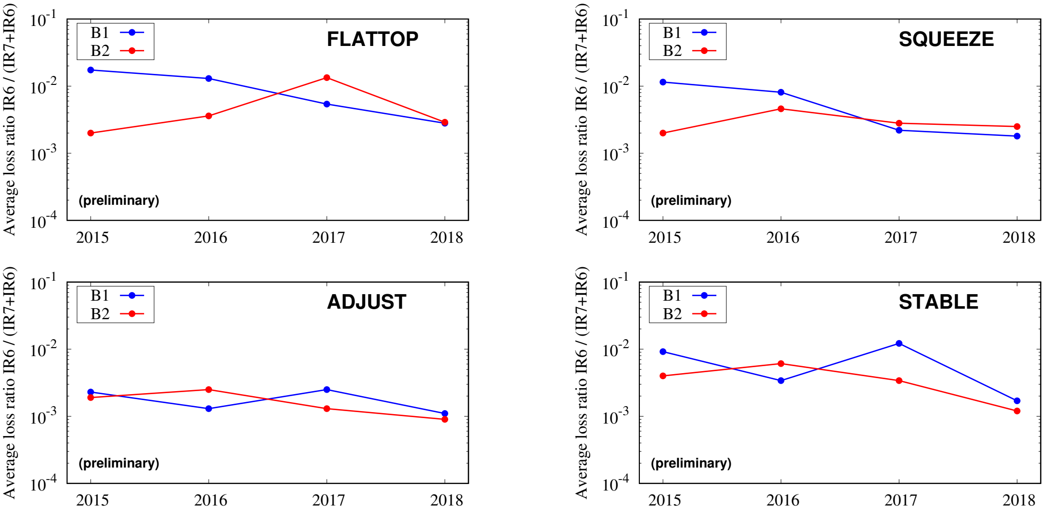
Determining the number of halo protons lost in IR6 (N_{IR6})

1) Spatial BLM pattern per proton lost calculated with FLUKA, separately for TCDQ and TCSP impacts
2) Measured BLM dose pattern scaled to find the best match with simulated pattern, using TCDQ/TCSP sharing as additional free parameter

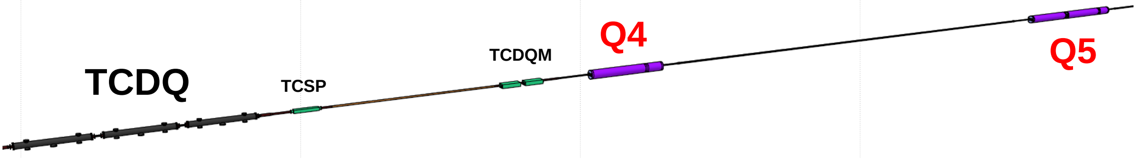




Average halo fraction f_{IR6} lost in IR6 (Run 2, different beam modes)

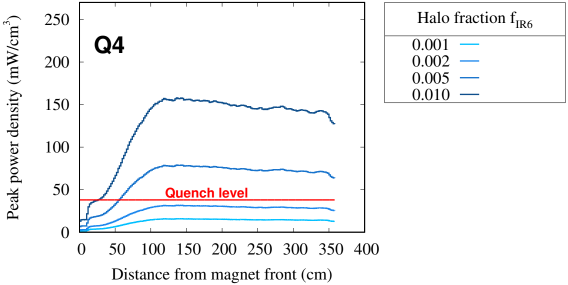


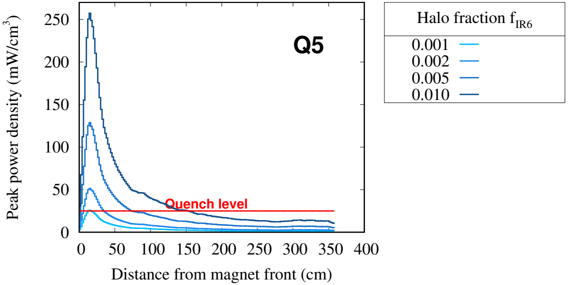
Halo-induced power density in Q4/Q5 coils for HL-LHC beams



Assumed halo losses in IR6 (50%TCDQ+50%TCSP): $f_{IR6} \times 8.8\times 10^{11}$ p/s (beam lifetime 0.2 h)

Impact distribution from E. Belli (optics HL-LHC V1.3), FLUKA simulations by V. Rizzoglio





→ **there is a potential risk of quench → halo leakage to IR6 to be studied/understood in more detail**

Contents

Conclusions

- **SC magnet protection in case of asynchronous beam dumps**
  - Shower simulations and results from HiRadMat tests show that the present protection devices provide sufficient protection of IR6 magnets in HL-LHC
- **Risk of halo-induced quenches in IR6 in case of 0.2 h beam lifetime**
  - Cannot be exluded, but needs further study
  - In particular the halo leakage from IR7 to IR6 in Run 2 needs to be better understood (tracking simulations for 2018 machine configuration ongoing by collimation team)