Collimation performance and protection: Can we go to 15 cm?

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Can we go to 15 cm?

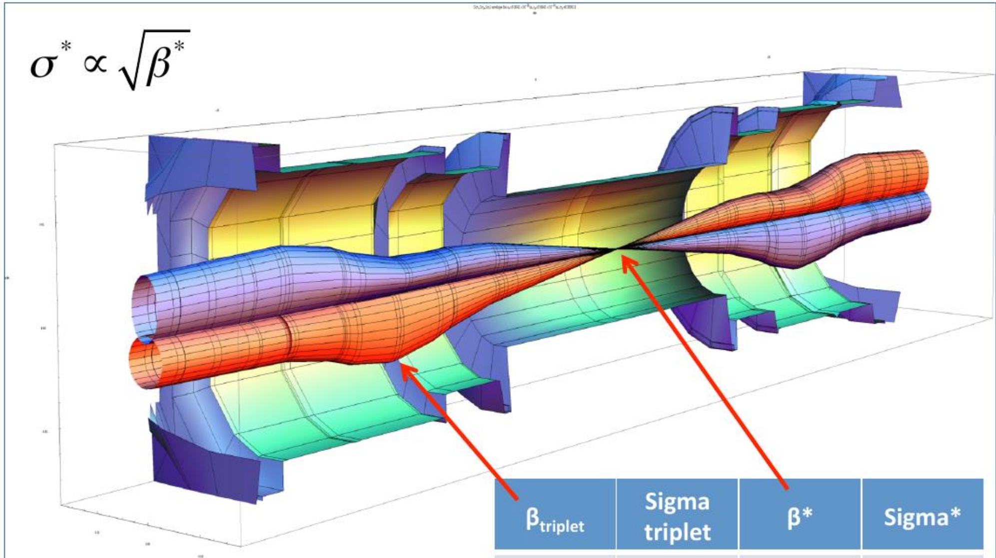
YES!

Outline

- Relation between collimation hierarchy and machine performance
- Increased LHC performance using MKD-TCT phase advance
- Application to HL-LHC optics v1.3
- Calculations of losses in HL-LHC from asynch dump
- Protected aperture as function of phase advance
- New baseline of collimator settings and protected aperture
- Verification of performance for asynchronous dump and cleaning
- β*-reach with new collimator settings and v1.3 optics

Introduction

- Collimation system needs to protect aperture => important for machine performance
- Reduced β* => Reduced aperture aperture margin in triplet
  - must be protected by collimators
- Protecting the aperture has been major limitation for β*-reach in LHC
  - Limiting case: Asynchronous dump

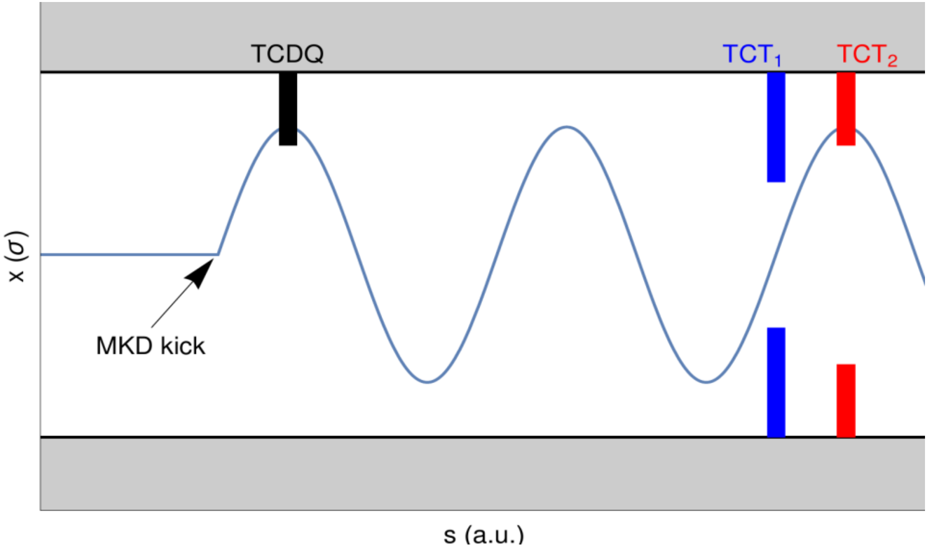


$\beta_{triplet}$	Sigma triplet	β*	Sigma*
~4.5 km	1.5 mm	55 cm	17 um

Image courtesy John Jowett

Constraints from asynchronous dump

- Asynchronous beam dump: miskicked beam on oscillating orbit
- Single-turn losses risk to damage sensitive elements
  - Triplets, tungsten collimators (TCTs)
- Significant improvement in β*-reach in the LHC in 2016 / 2017
  - Matched phase advance between MKD-TCT mitigates risk of TCT hits
  - Based on 2015 MD experience
  - Mitigated risk of TCTs being hit and damaged by primary impacts during asynchronous beam dumps



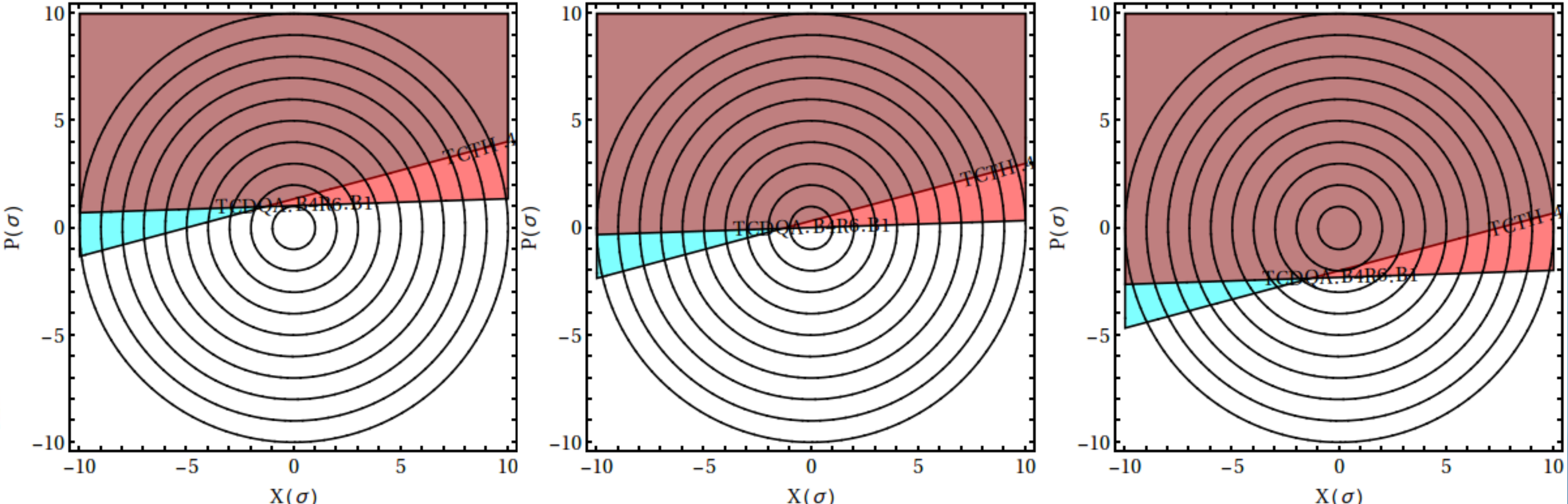
Nuclear Instruments and Methods in Physics Research A 848 (2017) 19–30

Application to HL-LHC?

- Can we profit of this experience to improve the β*-reach in the HL-LHC?
  - References: R. De Maria in WP2 meeting 1/11/2016, R. Bruce in ColUSM 11/11/2016, R. Bruce at Chamonix 26/1/2017, R. Bruce et al. CERN-ACC-2017-0051
- For HL-LHC, study what TCT setting and aperture can be protected by the collimation system as a function of the phase advance during asynch. dump
- Method: phase space integration (*NIM A 848 (2017) 19–30*)

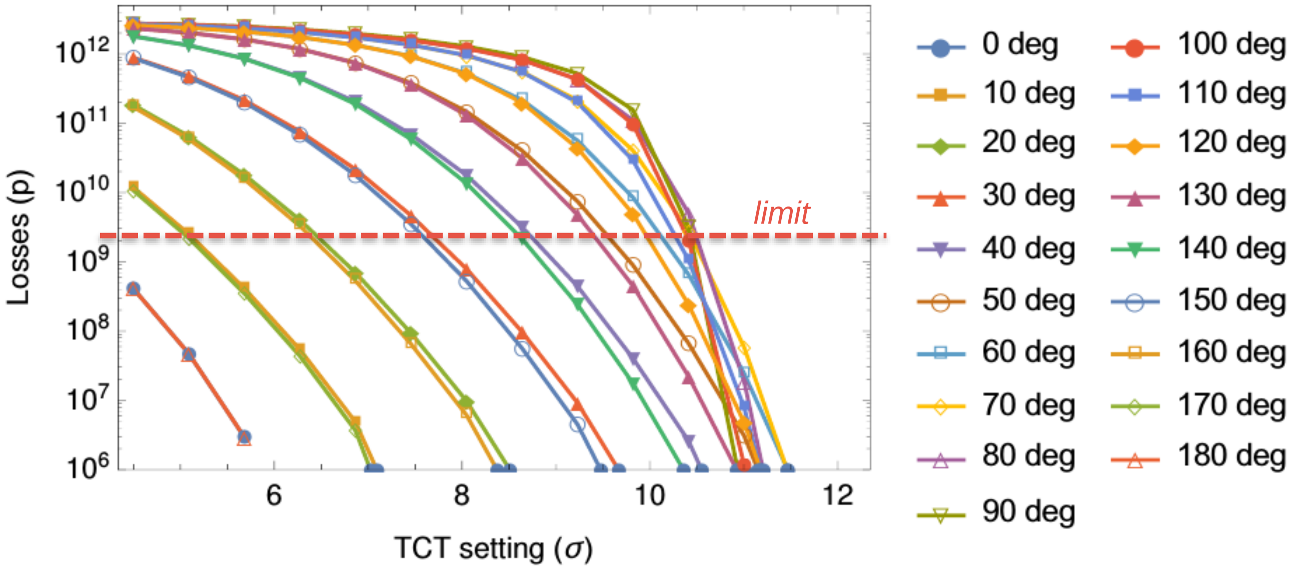
Phase space integration

- Estimate losses on TCTs for each bunch during dump failure (type 2 single-module pre-fire – worst case).
  - Integrate beam distribution over normalized phase space area intercepted by each bottleneck
  - Fast study which does not require full optics for every studied case
  - Disadvantage: does not treat secondary impacts.



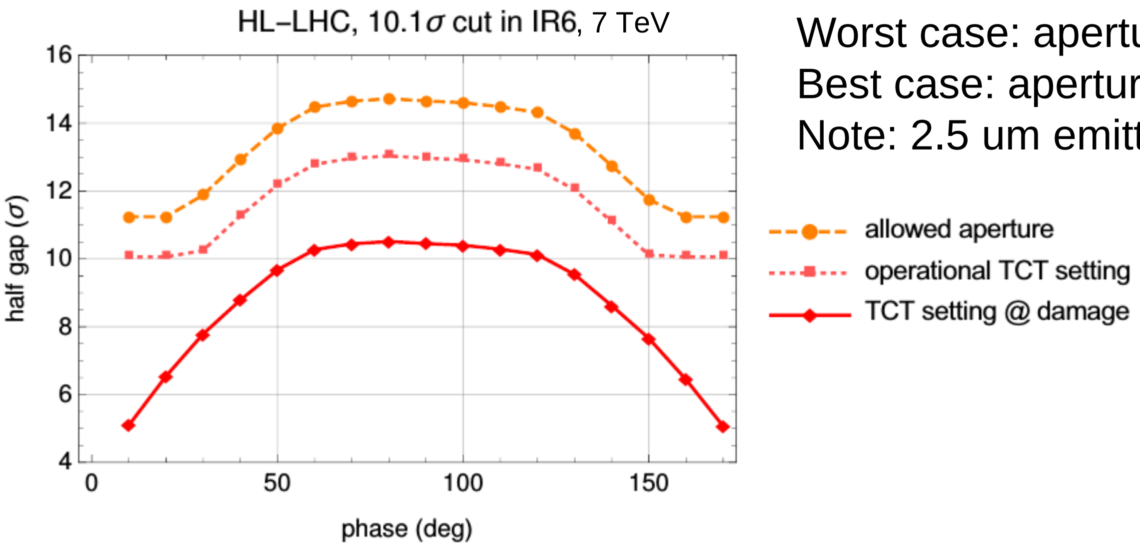
TCT losses vs phase and setting

- Parametric study over MKD-TCT phase and TCT opening, keeping the protection device (TCSP/TCDQ) fixed at 10.1 σ, β*=15 cm, normalized to 2.2e11 p/bunch
- Next step: find intersection with damage limit for each phase and relate to setting
- Using previously calculated limit of plastic deformation (5e9 protons, E. Quaranta et al. PRSTAB 20, 091002 2017) with additional factor 2 safety margin
  - Further margin: Plastic deformation should not require exchange of collimator – can use 5th axis



Allowed TCT setting and aperture in operation

- TCT must operate sufficiently far outside the setting @ damage
- Calculate operational setting and allowed aperture with methods used for LHC (*PRSTAB 18, 061001 (2015)*) accounting for orbit, β-beat, setup error etc.
- **Note: aperture from asynch dump only**. Cleaning limits anyway to around 10.1 sigma



Worst case: aperture=14.6 σ
Best case: aperture=11.2 σ below 20 deg.
Note: 2.5 um emittance

Protected aperture vs MKD-TCT phase

$\Delta\mu$ MKD-TCT	Protected aperture (σ)	
	LHC, ϵ_n =3.5 μm	**HL-LHC, ϵ_n =2.5 μm**
0°	9.5	**11.2**
10°	9.5	**11.2**
20°	9.5	**11.2**
30°	10.0	**11.9**
40°	10.9	**12.9**
50°	11.7	**13.8**
60°	12.3	**14.5**
70°	12.3	**14.6**
80°	12.3	**14.6**
90°	12.3	**14.6**

CERN-ACC-2017-0051

Phase advance in HL-LHC v1.3

- In HL-LHC v1.3: Optics matched by WP2 to have good MKD-TCT phase advance ! (see talk R. De Maria)

optics	TCT6 IR1 B1	TCT6 IR5 B1	TCT6 IR1 B2	TCT6 IR5 B2
HL-LHC v1.2 15 cm	106	285	137	101
HL-LHC v1.3 15 cm	180	155	154	152

- For **HL-LHC v1.2** optics: aperture should be above **14.6 σ**.
- For **HL-LHC v1.3** optics: aperture should be above **11.9 σ**.

Proposed new collimation hierarchy for v1.3

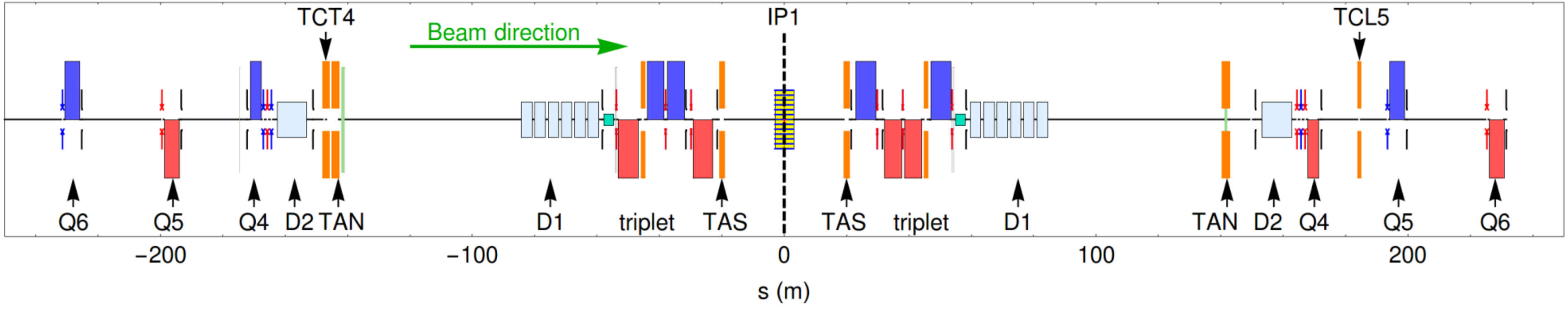
Collimator	Setting (LHC – 3.5 μm)	Setting (HL – 2.5 μm)
TCP7	5.7	**6.7**
TCS7	7.7	**9.1**
TCSP6	8.5	**10.1**
TCDQ6	8.5	**10.1**
TCT IR1/5	8.8	**10.4**
Aperture IR1/5	10.0	**11.9**

TCT asynch dump losses from SixTrack

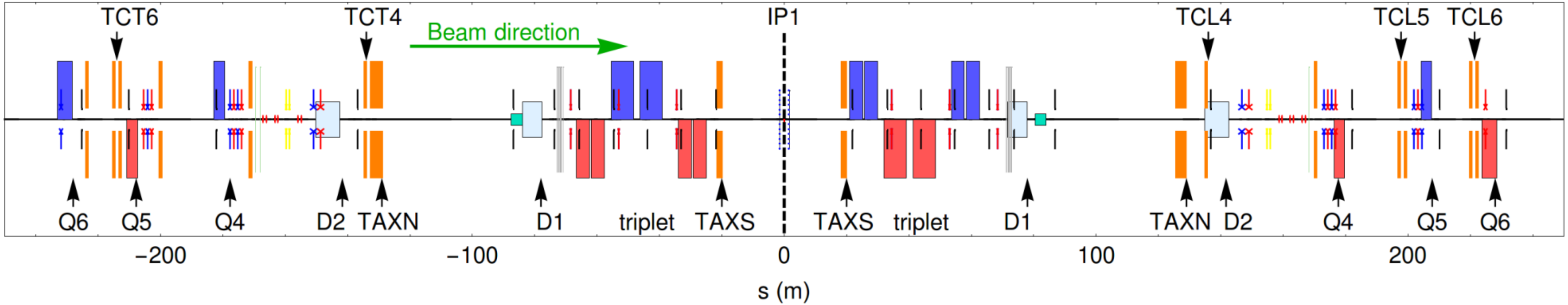
- Verify protection of sensitive elements in HL-LHC v1.3 during asynch. dump with more realistic simulation
- Type 2 single-module pre-fire simulated with SixTrack, kicker O firing first (most critical case)
- Waveform data from M. Fraser
- Full magnetic tracking in complete lattice, with collimation system in place
- Including scattering in collimators
- One simulation per bunch - each receives different kicks. Sum loss pattern over all bunches
- Method described in *NIM A 848 (2017) 19–30*

IR layout in HL-LHC v1.3

Nominal LHC

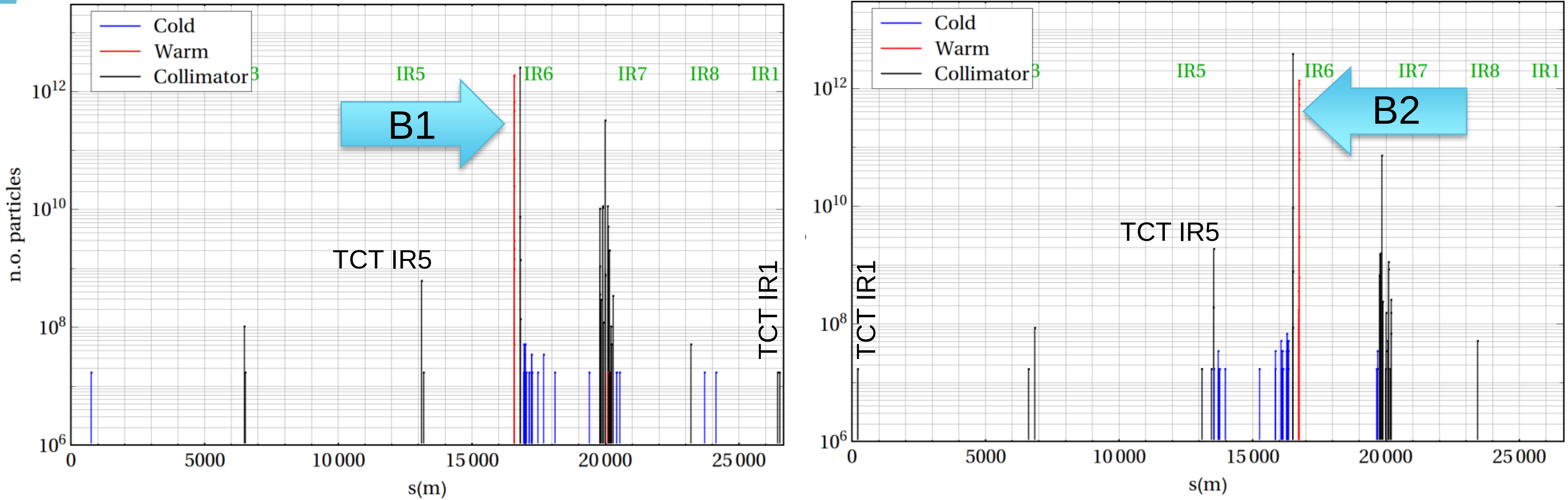


HL−LHC v1.3



SixTrack simulation of asynch. dump

- Simulation of the 35 most dangerous bunches only, normalized to 2.2E11 p / bunch, HL-LHC v1.3 optics and collimation settings, 7 Tev, β*=15 cm
- At baseline settings, no primary losses at TCTs, but some secondary (not worrisome)



TCT damage limit

- Damage limit depends strongly on the impact distribution on the TCT
- Detailed damage TCT limits from 3-step simulation
- "Secondary losses" (outscattered): generally more spread out and distributed over both jaws => larger number of protons tolerated before damage
- "Primary losses" (have not hit any upstream collimator): impacts in small spot => fewer protons needed to damage

Case 1: Dominated by spread-out secondary losses

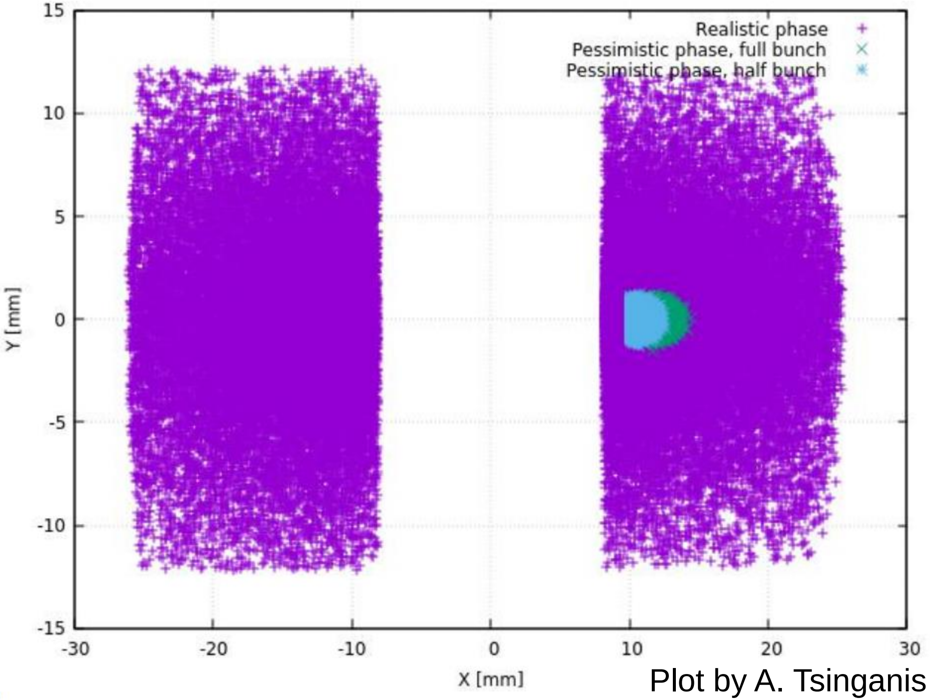
TABLE IV. Damage limits calculated for the tungsten collimator jaw for the three cases discussed in the paper.

Material damage	Thresholds (number of protons) Case 1	Case 2	Case 3
Plastic deformation	1.2×10^{11}	4.6×10^{9}	6.9×10^{9}
Fragment ejection	7×10^{11}	1.8×10^{10}	2.6×10^{10}
Catastrophic damage	1.1×10^{12}	1.4×10^{11}	1.7×10^{11}

E. Quaranta et al., Phys. Rev. Accel. Beams 20, 091002 (2017)

Comparison of impact distribution

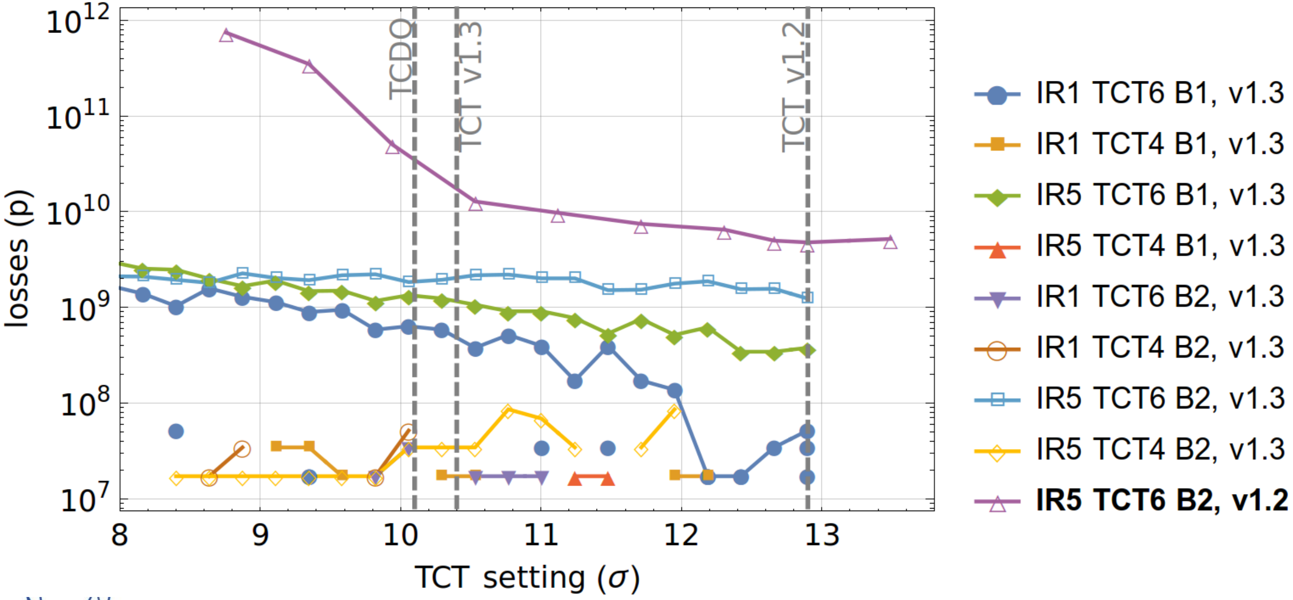
- Secondary losses much more spread out and impact both jaws



Plot by A. Tsinganis

TCT losses during asynch. dump, v1.3

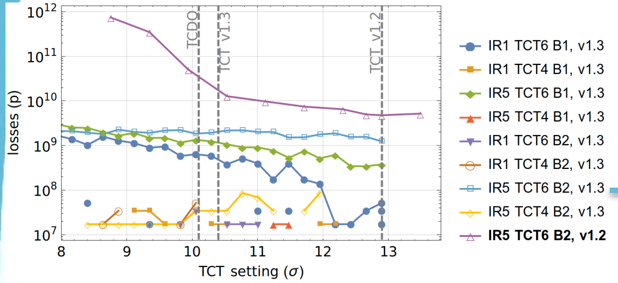
- Sensitivity study: Vary TCT setting at 7 Tev, β*=15 cm
- Sharp rise of losses at smaller setting in v1.2 with bad phase advance
- TCT losses are almost independent of setting in v1.3

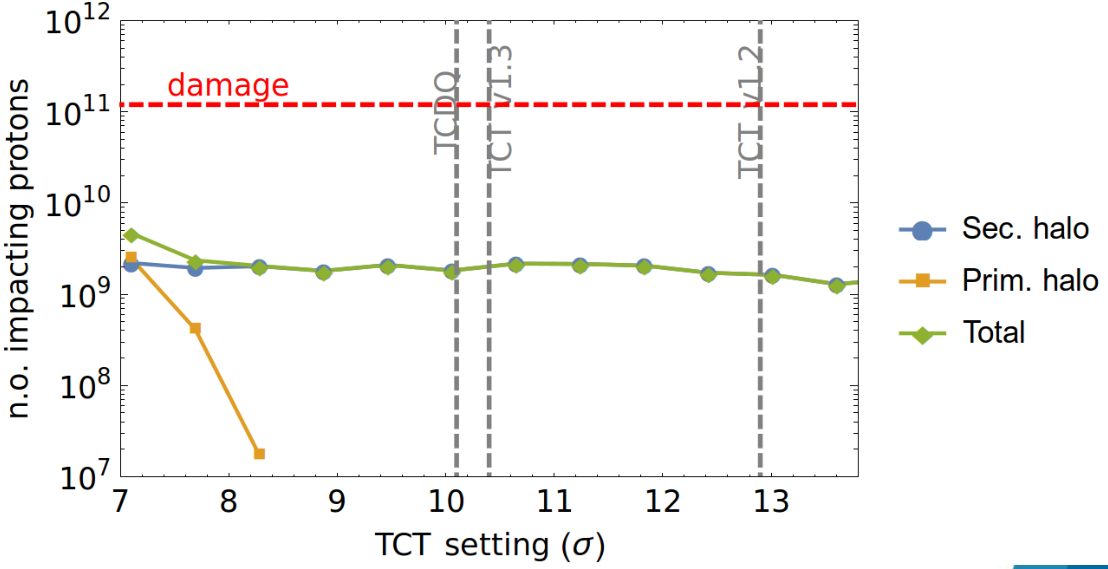


Primary and secondary TCT losses

- With HL-LHC v1.3, all losses are spread-out secondaries and well below corresponding damage limit, also with margin on operational setting

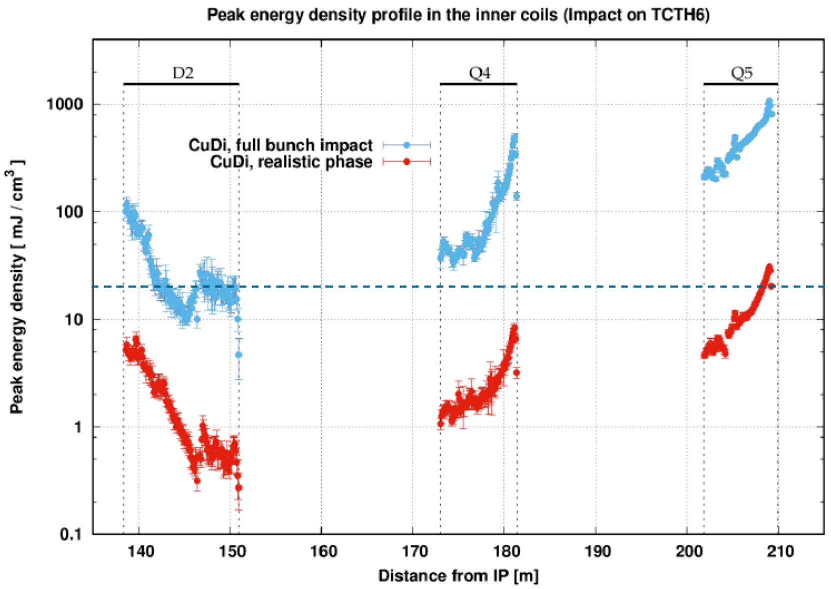
IR5 TCT6 B2, v1.3





Showering from TCT

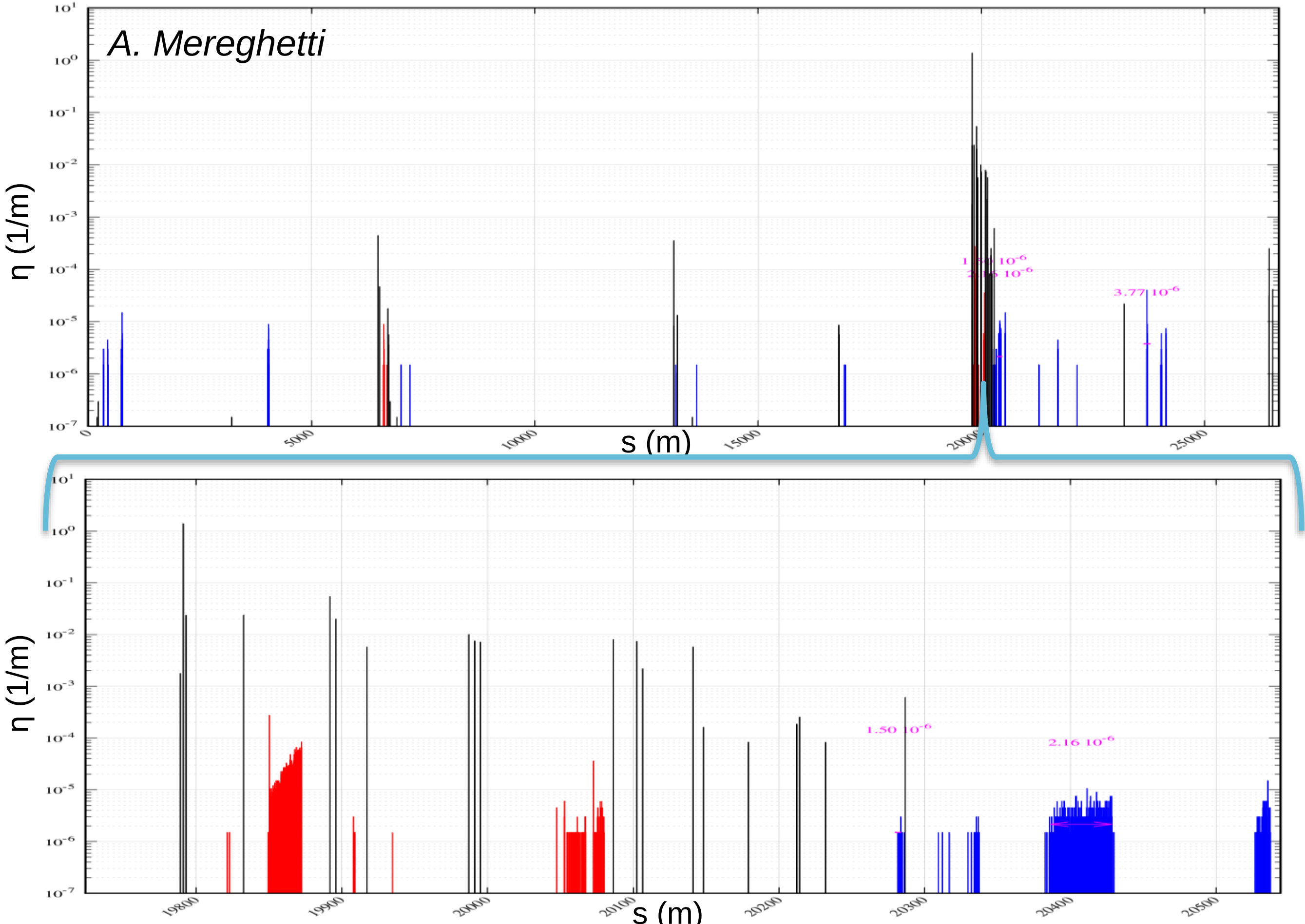
- Shower from TCT during asynch. Dump simulated with FLUKA – see talk A. Tsinganis
- Conclusion: With HL-LHC v1.3 phase advance, losses are low enough not to be problematic for the magnets or the experiments



A. Tsinganis et al.

Verification of cleaning performance

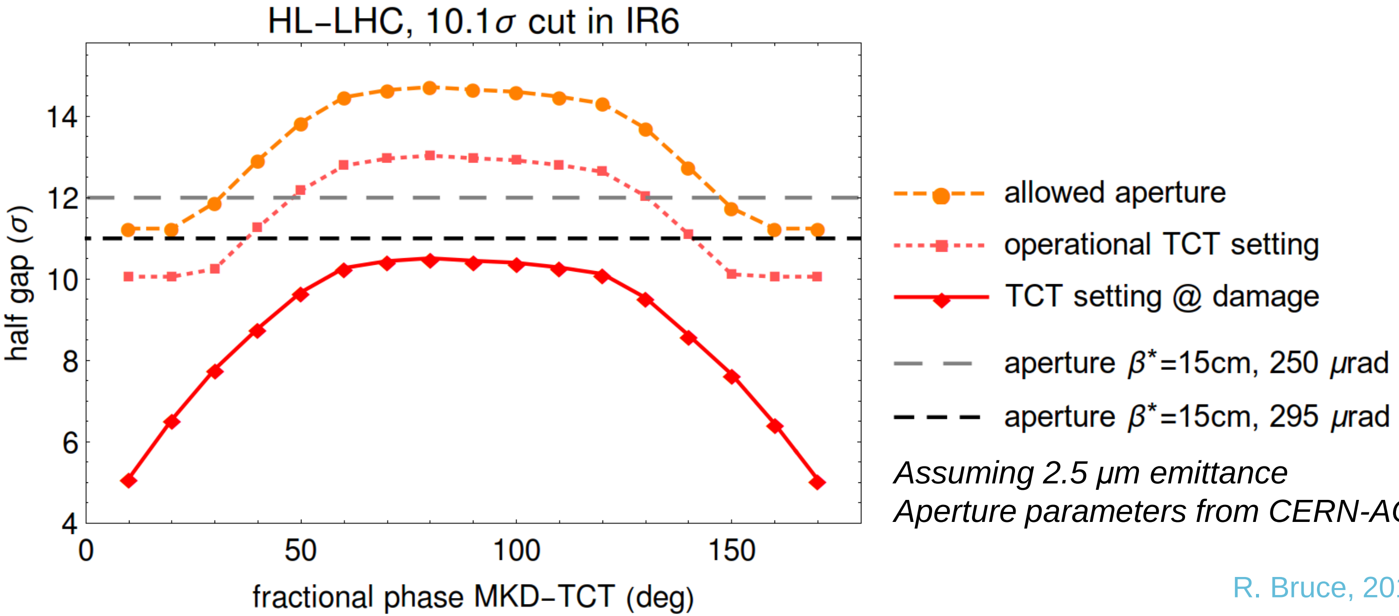
- Loss maps simulated with latest HL v1.3 baseline
  - More details in talks A. Mereghetti, H. Garcia
- Energy deposition of a few mW / cm^3 (talk C. Bahamonde)
  - Cleaning fulfills requirements, even accounting for underestimation of IR7 DS BLMs



HiLumi HL-LHC PROJECT
CERN

Translate aperture in β*-reach

- Below 20 deg phase advance, can almost recover 15 cm and 295 urad
- For 30 deg phase, reach in β* is between 16 cm and 17 cm. Need to also decrease crossing angle to recover 15 cm
- Talk N. Karastathis: 250 µrad half crossing possible (but tight) for beam-beam => at 30 deg MKD-TCT phase, **we can recover β*=15 cm !**



Assuming 2.5 µm emittance
Aperture parameters from CERN-ACC-2017-0051

Conclusions

- One main limitation for protected aperture and β* has been risk of damage on TCTs and triplets during asynch dumps
- In HL-LHC v1.3, mitigated with good phase advance MKD-TCT, as done in LHC.
- New collimator settings proposed and validated with simulations
  - Allows smaller protected aperture in HL-LHC v1.3: 11.9 σ
- With the new collimator settings and aperture, and with 250 μrad half crossing angle, **squeezing to β*=15 cm can be recovered in HL-LHC v1.3**
- Performance: resulting increase in integrated luminosity of ~3% for nominal scenario and ~6% for ultimate (talk R. Tomas)

β* is like oranges…

- If you try hard enough, you can always squeeze a bit more

Backup

HL-LHC collimator settings, v1.2

	Setting in σ, $\epsilon_n = 3.5\,\mu$m	Setting in σ, $\epsilon_n = 2.5\,\mu$m
TCP7	5.7	**6.7**
TCS7	7.7	**9.1**
TCSP6	8.5	**10.1**
TCDQ6	9.0	**10.6**
TCT	10.9	**12.9**
aperture	12.3	**14.6**

- Previous baseline: TCSP is at 10.1 σ, TCDQ at 10.6 σ (2.5 um emittance)
- TCDQ can be tightened to 10.1 σ but we don't think we can move it in further due to robustness constraints (C. Bracco, A. Lechner)
    - Decreasing margin TCP-TCSG doesn't bring a gain at the moment