Simulations of collimation upgrade scenarios with new materials for HL-LHC

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Limitations of present LHC collimation system

HL-LHC beam parameters pose strong concerns for present LHC collimators
(see R. Bruce's talk)

Limitations related to collimator materials:

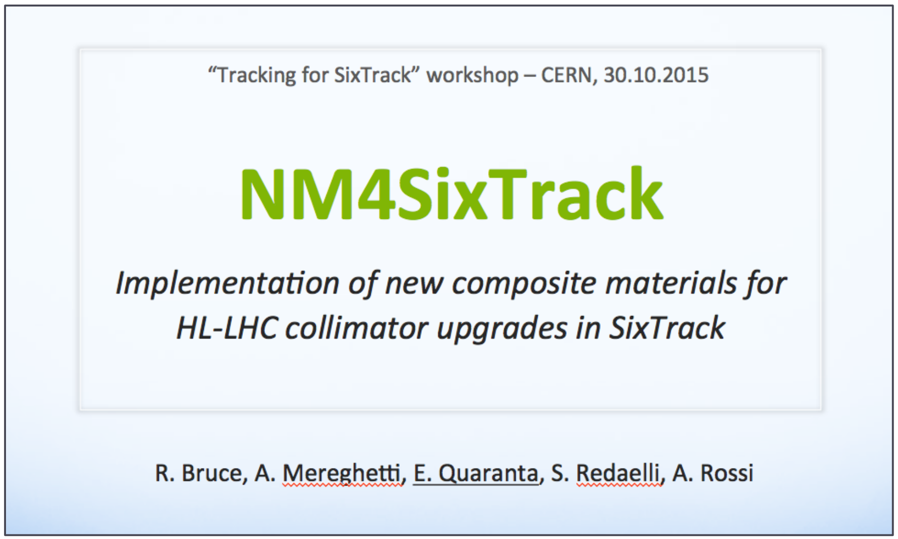
High contribution of non-metallic collimators (TCSG) to machine impedance → beam instability	Low-impedance TCSG in IP7
High losses of off-momentum protons in high dispersion locations (e.g.: IR7 DS) → limitation to collimation cleaning	DS collimators in IR7
Low robustness of collimators at LHC experiments (TCTs) against large beam losses → limitation in β^* and luminosity	Robust TCTs at the experiments

Baseline for HL-LHC collimation upgrade

SIMULATION MODEL OF COMPOSITE MATERIALS

Material implementation in SixTrack

SixTrack = standard tool for collimation studies.
Code modified to model composite materials used for LHC collimators:
MoGr, CuCD, Glidcop, Inermet180



For reference:

E. Quaranta et al.,
”Collimation cleaning at the LHC with advanced secondary collimator materials”,
IPAC15, Richmond, Virginia, USA

Approximation for composite material implementation in SixTrack:

composite materials treated by calculating off-line “effective” parameters based on material composition, then those values used as inputs for scattering process.

How to model composite materials in SixTrack? (I)

Atomic number Z and **atomic weight A**
as average weighted on the atomic fraction of the components:

	Z	A [g/mol]	ρ [g/cm^3]	σ_{el} [MS/m]	**at. content** [%]	χ_0 [cm]	λ_{tot} [cm]	λ_{inel} [cm]
CFC	6	12.01	1.67	0.14	100 C	25.57	35.45	51.38
MoGR	6.653	13.532	2.5	1	2.7 Mo_2C, 97.3 C	11.931	24.84	36.42
CuCD	11.898	25.238	5.4	12.6	25.7 Cu, 73.3 CD, 1 B	3.162	13.56	20.97
Glidcop	28.823	63.149	8.93	53.8	99.1 Cu, 0.9 Al_2O_3	1.442	9.42	15.36
Inermet180	67.657	166.68	18	8.6	86.1 W, 9.9 Ni, 4 Cu	0.385	6.03	10.44

$$p = \sum_i at_i \cdot p_i, \qquad (1)$$

- p = [Z,A] of compound to compute
- p_i = values of the property for i-th element in material (from [1])
- at_i[%] = atomic content of i-th element in compound

[1] K.A. Olive et al. Particle Data Group. Chin. Phys. C, 38, 090001, 2014

How to model composite materials in SixTrack? (II)

Density ρ and **electrical conductivity σ_{el}** are measured from available specimens

	Z	A [g/mol]	ρ [g/cm^3]	σ_{el} [MS/m]	**at. content** [%]	χ_0 [cm]	λ_{tot} [cm]	λ_{inel} [cm]
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Atomic content calculated after production process of materials

How to model composite materials in SixTrack? (III)

Mean excitation energy I, **radiation length χ_0**, **collision length λ_{tot}** and **inelastic length λ_{inel}** as average weighted on the mass fraction of the components:

$$\frac{1}{p} = \sum_i \frac{wt_i}{p_i},$$

	Z	A [g/mol]	ρ [g/cm^3]	σ_{el} [MS/m]	**at. content** [%]	χ_0 [cm]	λ_{tot} [cm]	λ_{inel} [cm]
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Deflection angle due to elastic collisions:

$$\theta_0 = \frac{13.6\ MeV}{\beta c p} z \sqrt{\frac{x}{\chi_0}} \left(1 + 0.038\ ln \frac{x}{\chi_0}\right)$$

Total cross section and inelastic cross section:

$$\sigma_{tot,inel} = \frac{A}{N_{Av}\ \varrho\ \lambda_{tot,inel}}$$

Considerations on NM4SixTrack routine

- Results from simplified model in SixTrack are being benchmarked with other codes (FLUKA, Merlin...)

- SixTrack implementation of composite materials has been used to study the effects of advanced collimators with novel materials on the collimation cleaning performance for the HL-LHC scenario.

CLEANING PERFORMANCE WITH ADVANCED COLLIMATORS IN IR7

Cleaning simulations with advanced collimators

According to present HL baseline: replacement of all TCSGs in IR7 with MoGr
→ 30% impedance reduction (up to 50% with 5μm Mo-coating)

- What would be the impact of this configuration on the cleaning efficiency?
- Does it worsen/improve the collimation performance?

3 cases simulated with SixTrack for HL-LHC scenario, where replaced:

1. All TCSGs in IR7 with MoGr/CuCD
1. All TCPs in IR7 with MoGr/CuCD
1. TCPs and TCSGs in IR7 with MoGr/CuCD

Might not be acceptable for injection failure scenario, but used in simulation for comparison with MoGr

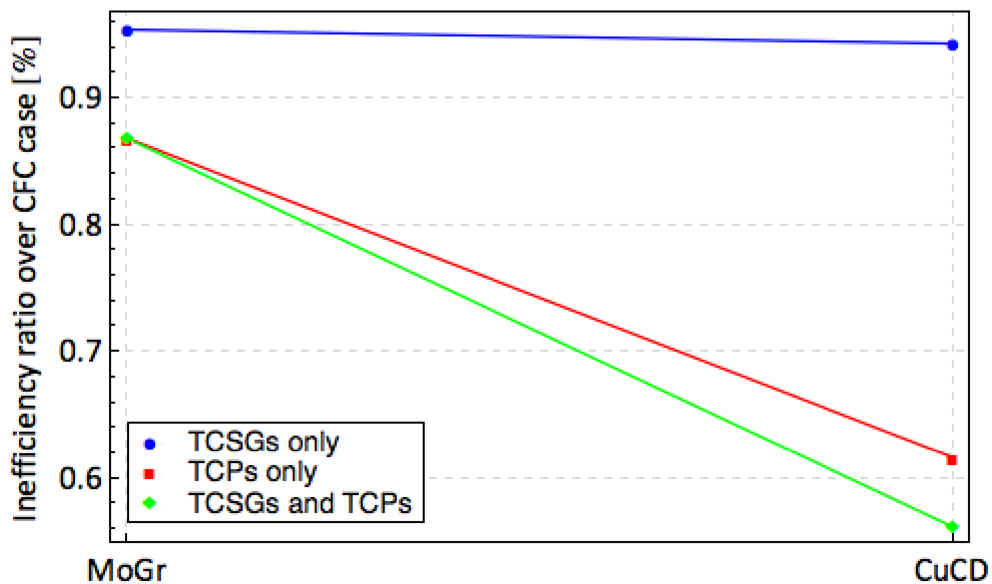
Cleaning inefficiency for various configurations

IR7 configuration	Cleaning inefficiency in DS1	Cleaning inefficiency in DS2
TCPs/TCSGs in CFC	1.07×10^{-5}	$0.85\pm\times10^{-5}$
TCPs in CFC TCSGs in MoGr	1.02×10^{-5}	$0.85\pm\times10^{-5}$
TCPs in CFC TCSGs in CuCD	1.01×10^{-5}	$0.84\pm\times10^{-5}$
TCPs in MoGr TCSGs in CFC	0.93×10^{-5}	$0.74\pm\times10^{-5}$
TCPs in CuCD TCSGs in CFC	0.66×10^{-5}	$0.50\pm\times10^{-5}$
TCPs/TCSGs in MoGr	0.93×10^{-5}	$0.71\pm\times10^{-5}$
TCPs/TCSGs in CuCD	0.60×10^{-5}	$0.44\pm\times10^{-5}$

Case 1 → / similar to CFC reference case

Case 2 → / = - 13% (MoGr), / = - 40% (CuCD)

Case 3 → same as Case 2 (MoGr), / = -50% (CuCD)

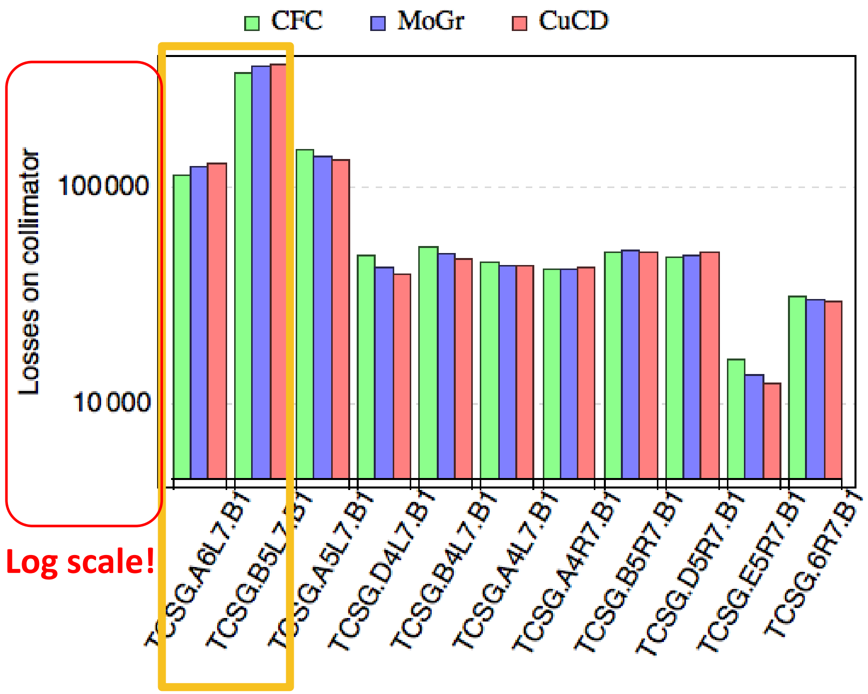


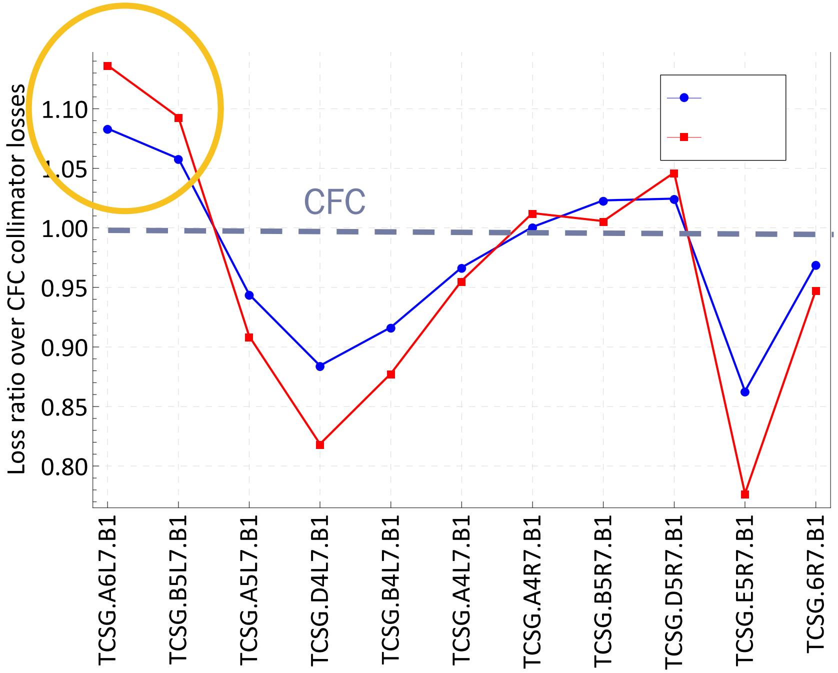
How does the loss sharing change in IR7 collimators in the different cases?

Replacement of IR7 TCSGs with novel materials

- Losses on first two TCSG: +11-18% than CFC
- Differences in losses on TCSGs further downstream less apparent

energy deposition studies needed to confirm if the increase of load is acceptable for robustness



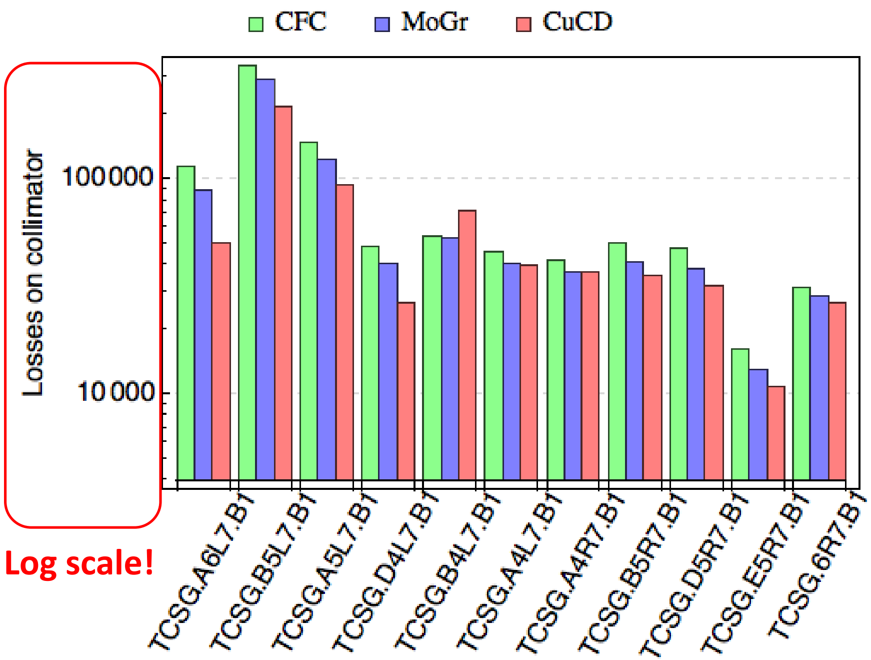


Replacement of IR7 TCPs with novel materials

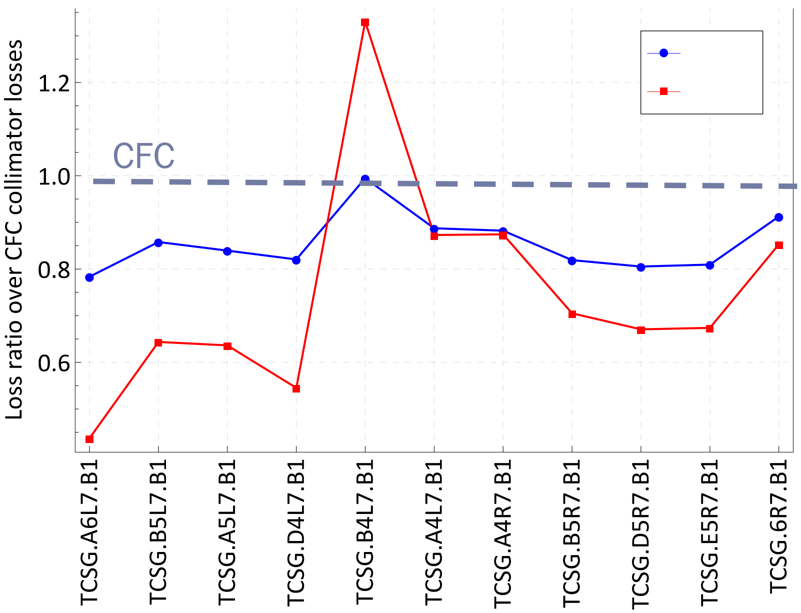
TCPs in MoGr →
- <10% more losses in TCPs
- ~10-20% loss reduction on TCSGs

TCPs in CuCD →
- 10-40% more losses in TCPs
- ~10-55% loss reduction on TCSGs
(TCSG.B4L7 to be further investigated)

energy deposition studies needed to confirm if the increase of load is acceptable for robustness

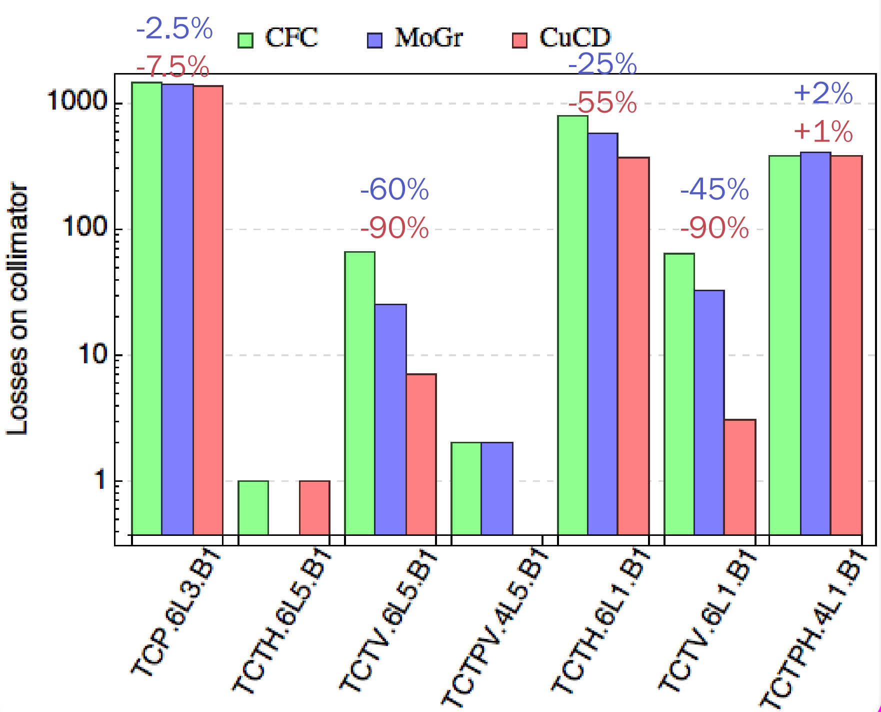


Log scale!

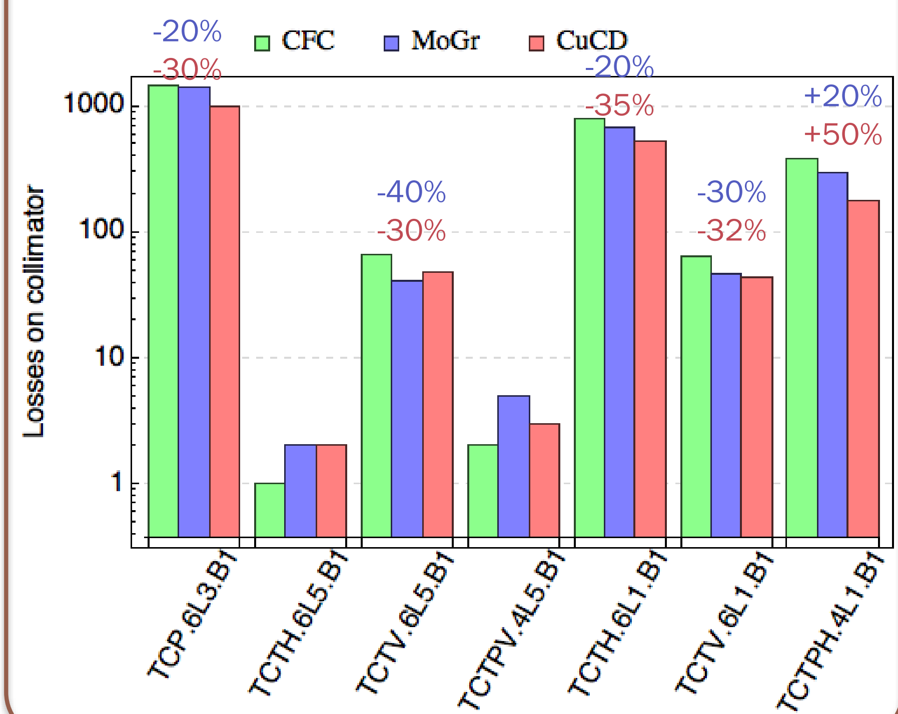


Losses at other collimator locations

IR7 TCSGs replaced



IR7 TCPs replaced

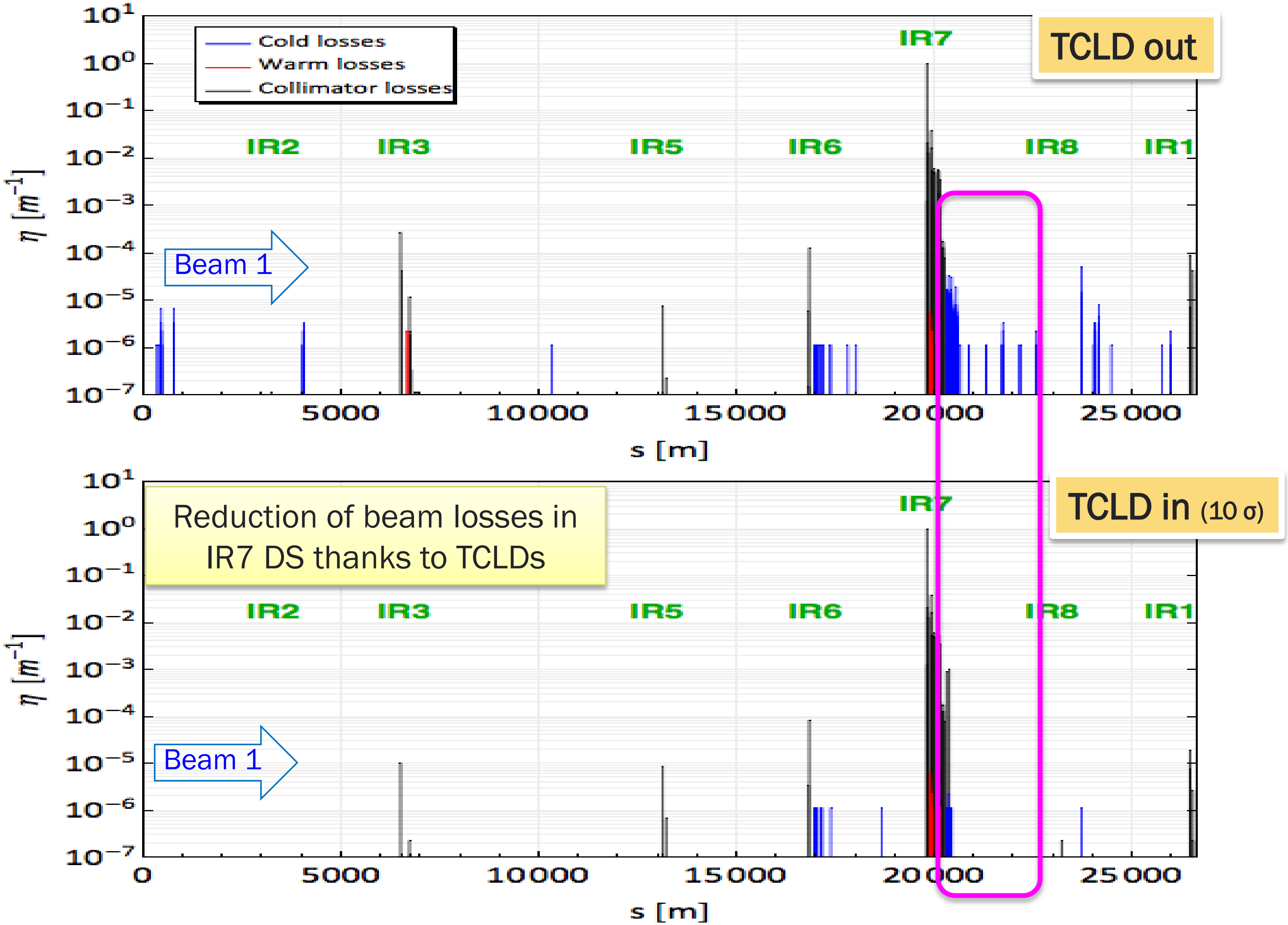


Load generally reduced in other collimators when advanced materials are used.

DISPERSION SUPPRESSOR COLLIMATORS IN IR7

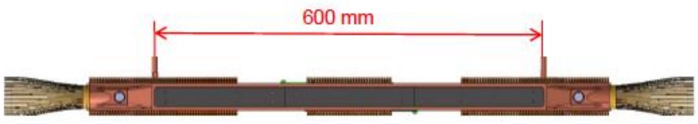
Effects of TCLDs on IR7 DS

Loss distribution B1 H (β*=15 cm, ε=3.5μm)

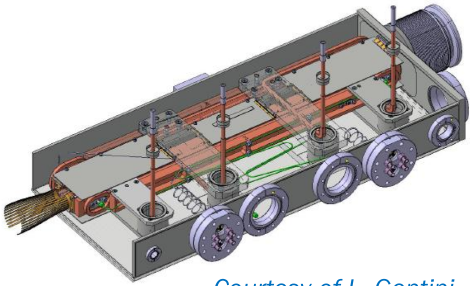


Dispersion suppressor collimators for IR7

- 60 cm long jaws
- Inermet® IT-180

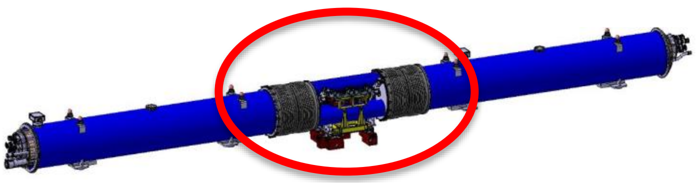


Courtesy of L. Gentini



Courtesy of L. Gentini

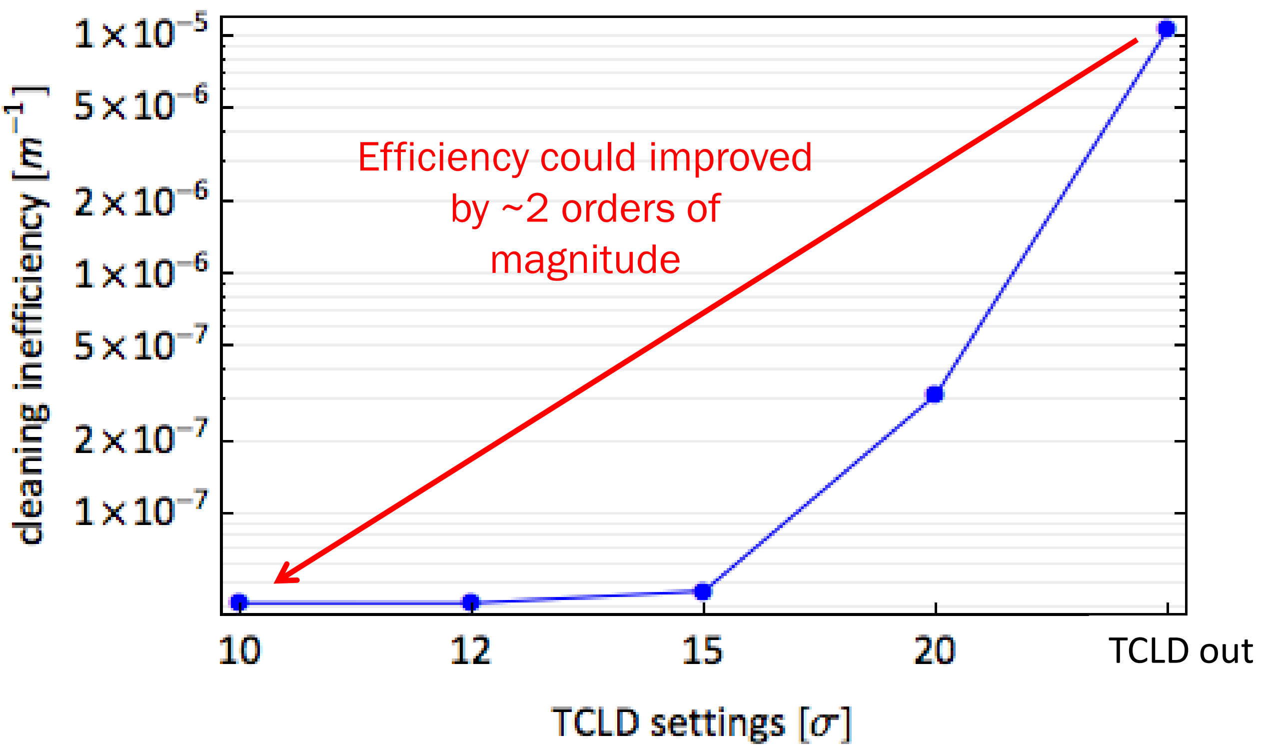
- Enclosed by shorter and higher field (11T) magnets to replace selected DS dipoles downstream of IR7
- 2 TCLDs for each beam (cell 8 and 10)



Courtesy of D. Duarte Ramos

- Staged installation starting from 2018

Cleaning efficiency with IR7 TCLDs B1 H (β*=15 cm, ε=3.5μm)

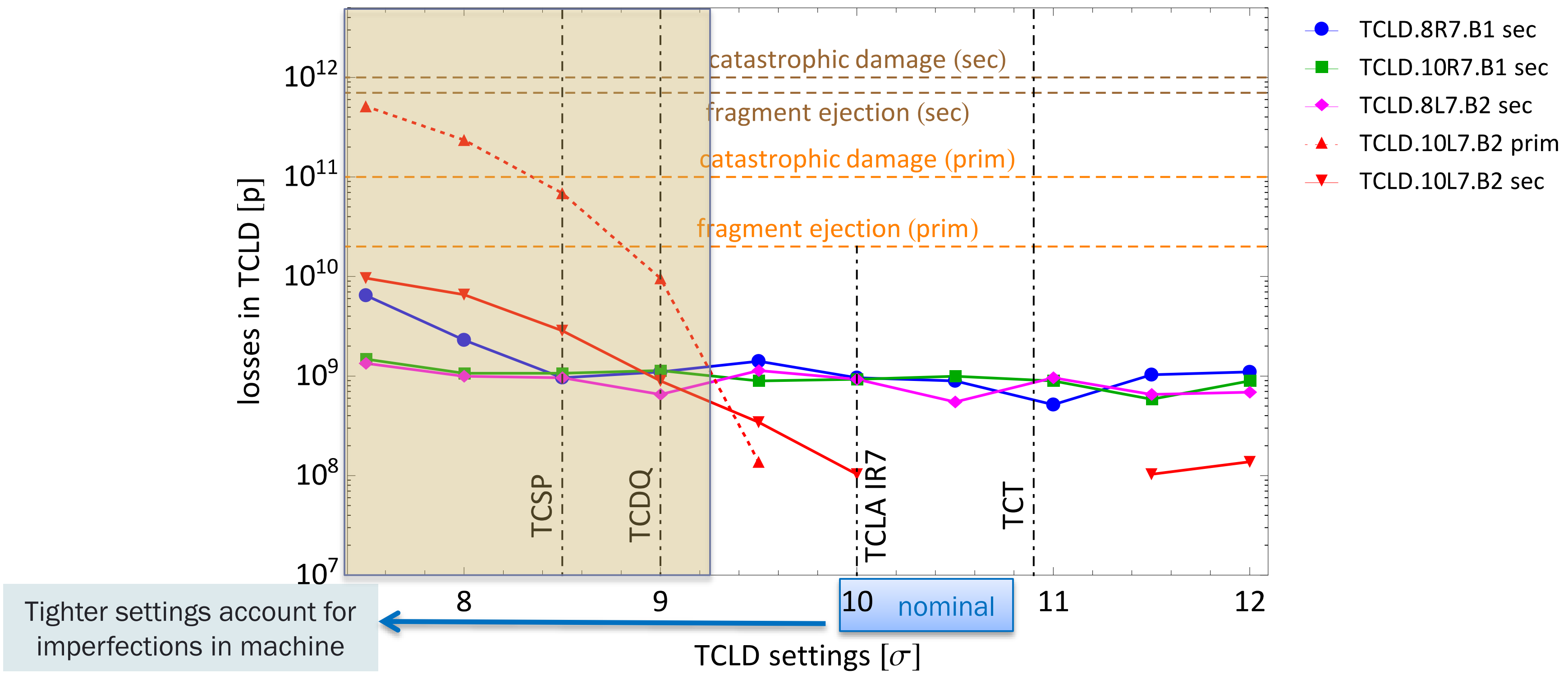


Operating at this settings, are TCLD tungsten jaws robust enough to withstand fast beam losses following a beam dump failure (most severe failure scenario)?

TCLD material robustness against fast beam losses

High beam losses at tight TCLD settings may expose IT-180 to severe damage

Assumption: same W damage limits for TCLDs as for calculated for TCTs (P. Gradassi, CWG meeting, CERN, 8/6/2015)

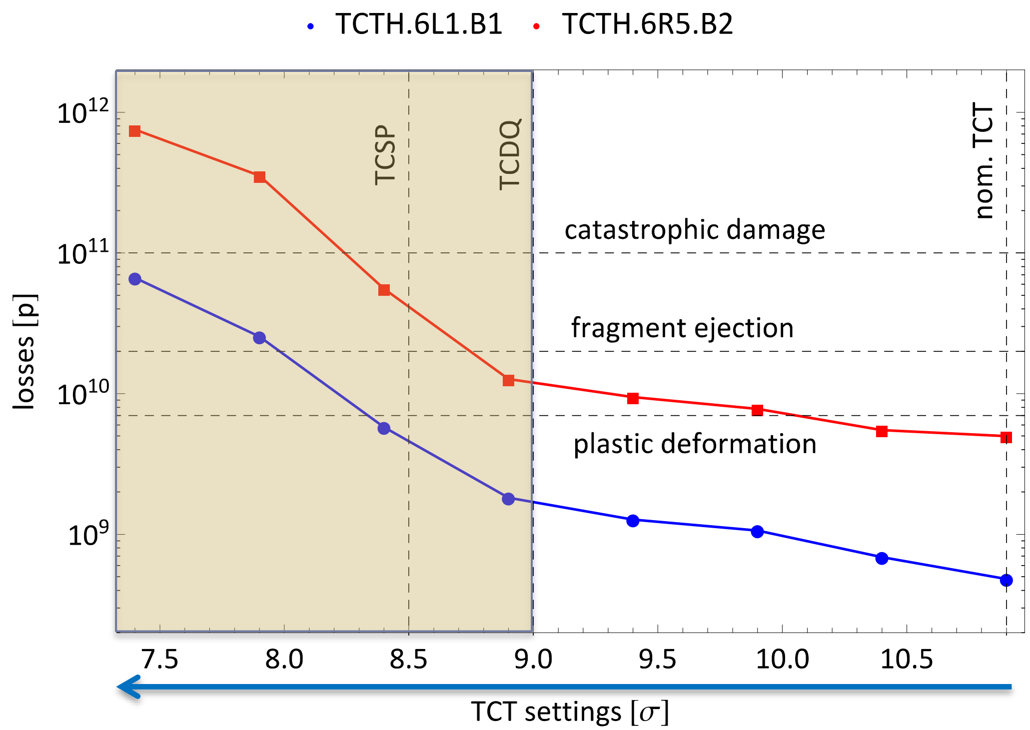


Other materials under consideration for DS collimators: CuCD, other W-allows (W-Re, W-La…)

ROBUSTNESS OF TERTIARY COLLIMATORS AGAINST FAST BEAM LOSSES

Losses in TCTs due to beam dump failure in HL-LHC

Loads from beam losses following an asynchronous beam dump were simulated as input to material choice for the upgraded TCTs at the experiments



Possible errors and orbit drift accounted by scanning down TCT positions

Going down to settings below dump protections, TCTs more exposed to losses

IT-180 jaws risk to be severe damaged

Considerations on material choice for TCTs

- Proposal to mitigate the constraints from TCT material robustness issues by replacing present IT-180 with CuCD.

- Results at HRMT-23 indicate that CuCD ~15 times more robust than IT180 against failure (see F. Carra's talk)

- Simulations ongoing to assess quantitatively the improvement in robustness

- Reduced absorption of materials lighter than tungsten may expose element downstream of TCTs to damage.

CONCLUSION

Summary

- Proposals for deploying new materials for upgrade of LHC collimation system were presented

- Low-impedance collimators made of Mo-Gr to replace present CFC secondary collimators in IR7 (HL-LHC present baseline)
  - → ~30-50% impedance reduction with MoGr
  - → small gain in cleaning efficiency
  - → up to +60% efficiency by replacing CFC primary collimators with CuCD
  - → load from beam losses increases with new materials: acceptable?

- Cleaning efficiency would benefit of the installation of DS collimators in IR7

- Improved robustness against large beam losses (failure scenarios) for tertiary collimators and DS collimators could be provided by Cu-CD

What's missing for final choice on collimator materials?

- Finalize the choice of coating technology for secondary collimators
- Define damage thresholds for MoGr and CuCD, based on HRMT-23 results.
- Verify with complete simulation chain (Sixtrack → FLUKA → ANSYS) if loss load in advanced TCPs and TCSGs in IR7 is compatible with damage limits.
- Simulate loss distribution for TCTs in CuCD in case of fast failures and compare with new limits.

Thank you all for your attention!

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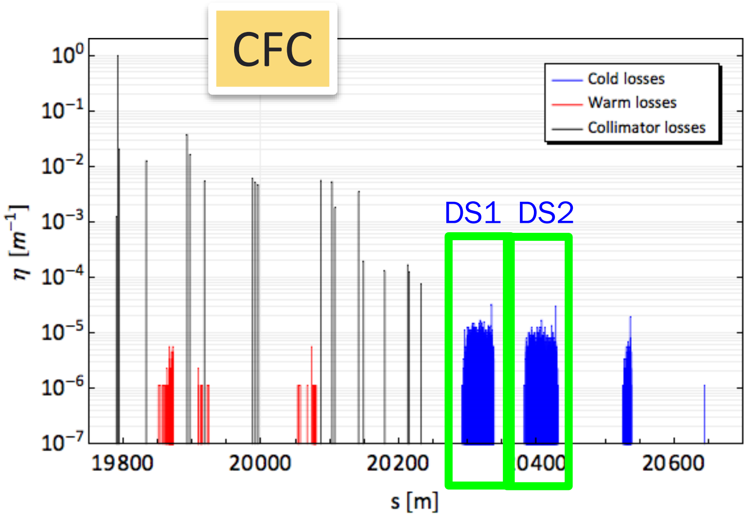
BACKUP SLIDES

Cleaning with advanced collimators: simulation setup

- Beam energy = 7 TeV
- HL-LHC v1.2 optics (β*=15cm)
- 3.5μm rad normalized emittance
- Beam 1, H halo
- Full LHC collimation system in place
- 2σ retraction between IR7 TCPs and TCSGs
  Collimator settings are listed in table.
- TCLDs added in cell 8 and 10 (IR7)
  (scan from open to 10σ)
- Pure W used so far for TCTs and Absorbers replaced by IT-180

Collimator families	Settings [σ]
IR7 TCP/TCSG/TCLA	5.7/7.7/10
IR3 TCP/TCSG/TCLA	15/18/20
IR6 TCSG/TCDQ	8.5/9
IR1/5 TCTs	10.9
IR2/8 TCTs	30

Looking at the losses in DS in IR7 to compare cleaning inefficiency in the proposed configurations…



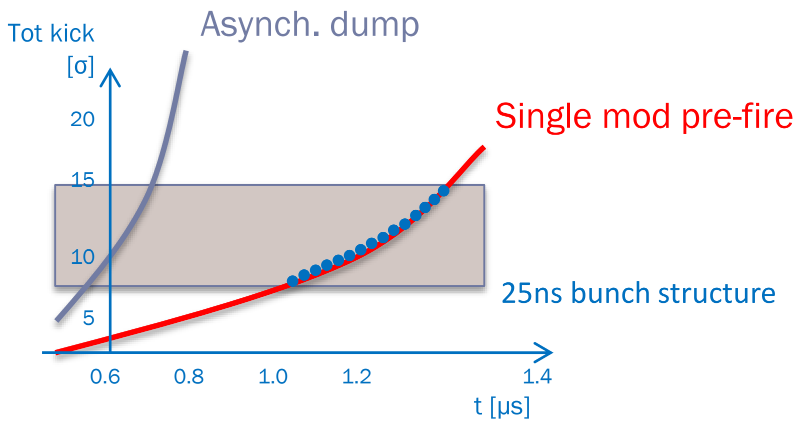
Beam dump failures

To allow a standard beam dump:

- 3 μs space without beam (abort gap) in LHC filling scheme
- 15 dump kickers (MKD) from zero to full field

Possible errors:

- *Asynchronous dump*: simultaneous firing of all 15 kicker modules, but outside the abort gap
- *Single module pre-fire*: one module misfires, followed by re-triggering of remaining 14 within a short delay



Pessimistic case

More bunches see intermediate kicks

Beam dump failure: simulation setup

Special SixTrack setup to simulate dump failure:

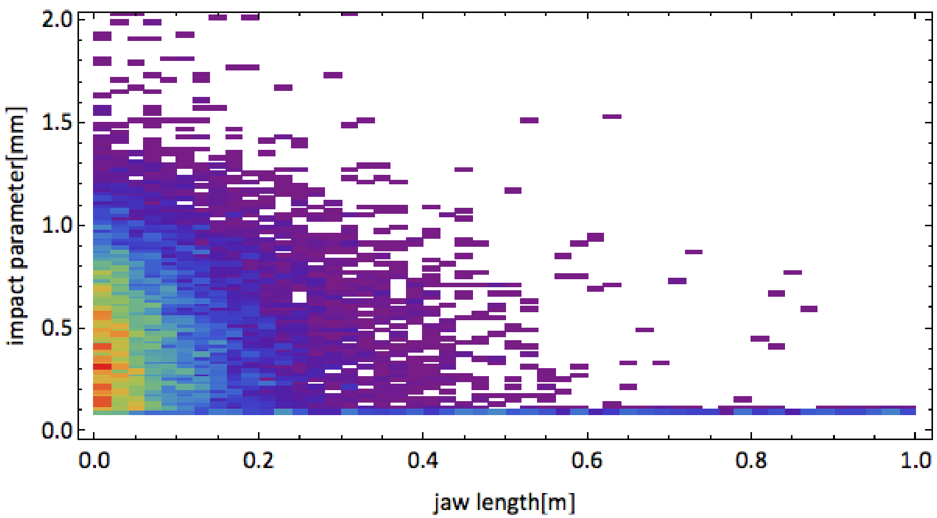
- Single module pre-fire, type 2 (M. Fraser)
- Gaussian bunches, not only halo as for cleaning (2.2e6 p/b)
- 25 ns bunch spacing structure:
  - Different kicks for each bunch: sum of 15 MKDs sampled every 25 ns
- 7 TeV protons, hor. Halo
- HL LHC optics v1.2
- Standard HL collimator settings (2σ retraction)

Collimator families	Settings [σ]
IR7 TCP/TCSG/TCLA	5.7/7.7/10
IR3 TCP/TCSG/TCLA	15/18/20
IR6 TCSG/TCDQ	8.5/9
IR1/5 TCTs	10.9
IR2/8 TCTs	30

Impacts on collimators for fast failure scenarios in HL

Note: contribution of both primary and secondary proton losses

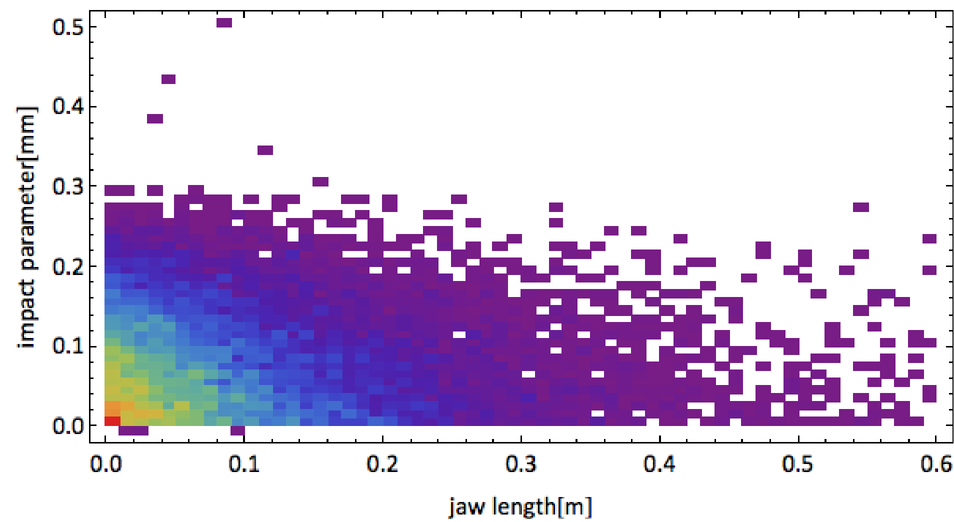
TCTH.4R5.B2



Case: no TCLD, TCT = 7.9 σ (ColUSM #45)

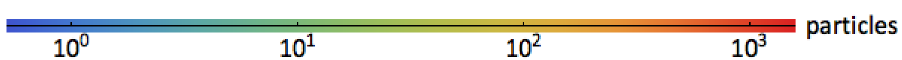
Used for estimation of damage level in W for HL scenario

TCLD.10L7.B2



Case: TCLD = 7.5 σ, TCT1/5=10.9σ

Factor 5 shorter tail in x:
→ Worth to recalculate damage threshold??



By how much can TCLDs be tighten?

Reference parameters (β^*=15 cm, ε=3.5μm)			
	β-func [m]	beam size [mm]	dispersion [m]
IR3 TCP B1	131.52	0.25	2.1
IR3 TCP B2	131.52	0.25	-2.1
TCLD 8 B1	31.37	0.12	0.22
TCLD 10 B1	45.73	0.15	0.90
TCLD 8 B2	34.77	0.13	-0.084
TCLD 10 B2	44.97	0.15	-0.84

Collimator setting [σ]	δp/p [10^{-3}]
	TCP IR3
15	1.77
14	1.66
13	1.54
12	1.42

Requirement: $(\delta p/p)_{cut} > (\delta p/p)_{TCP\ IP3}$

Collimator setting [σ]	δp/p [10^{-3}]			
	TCLD 8 B1	TCLD 10 B1	TCLD 8 B2	TCLD 10 B2
12	6.70	1.96	18.2	2.08
11.5	6.43	1.87	17.5	1.99
11	6.15	1.79	16.7	1.91
10.5	5.87	1.71	15.9	1.82
10	5.59	1.63	15.2	1.73
9.5	5.30	1.54	14.4	1.65
9	5.03	1.47	13.7	1.56
8.5	4.75	1.38	12.9	1.47
8	4.47	1.30	12.2	1.39
7.5	4.19	1.22	11.4	1.30
	OK		OK	