CuCD-based tertiary collimator

R. Bruce and S. Redaelli for the WP5 collimation team

Inputs: WP2 (G. Arduini, R. De Maria, R. Tomàs); Machine protection team (J. Uythoven, D. Wollmann, M. Zerlauth); OP (J. Wenninger); EN/MME for material calculations and HiRadMat results (A. Bertarelli, F. Carra).

Thanks: R. Schmidt. Many studies in the past years with EN/STI (fluka).

HL-LHC TCC meeting, 04/07/2019

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Introduction

International Review of the HL-LHC Collimation System

https://indico.cern.ch/event/780182

11-12 February 2019
CERN

Review Panel
Ralph Assmann (DESY), Wolfram Fischer (BNL), Mike Lamont (CERN), Mike Seidel (PSI, Chair), Alban Sublet (CERN), Walter Venturini (CERN).

The schedule of the 11 T magnet production is rather tight and presents a risk that installation in LS2 cannot be achieved. The possibility of installation in EYETS is a backup.

The IR1/5 cleaning scheme will be less constrained after Run-3 in the HL era, due to absent Roman pots.

TCTs in cells 4 and 6, made either from W or CuCD, are fully safe over a realistic range of setting. Thus Tungsten can be chosen as cost effective solution. In the unlikely case of a single bunch impact the collimator had to be exchanged. If the team decides to pursue the CuCD variant, the case for this solution should be strengthened.

Crystal collimation shows excellent performance for ions. This option should be further developed especially for ions, but not be considered as a replacement for DS collimators.

What is CuCD

- Developed by **RHP-Technology** (Austria)

Composition :

- $60\%_v$ diamonds (90% 100 μm, 10% 45 μm)
- $39\%_v$ Cu powder (45 μm)
- $1\%_v$ B powder (5 μm)

Composition and processing (Rapid Hot Pressing) did not change during R&D program

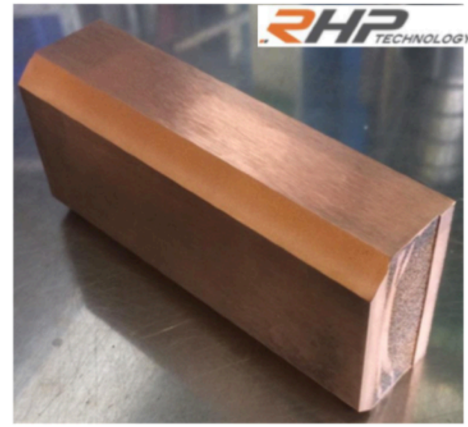
⬆ No diamond degradation

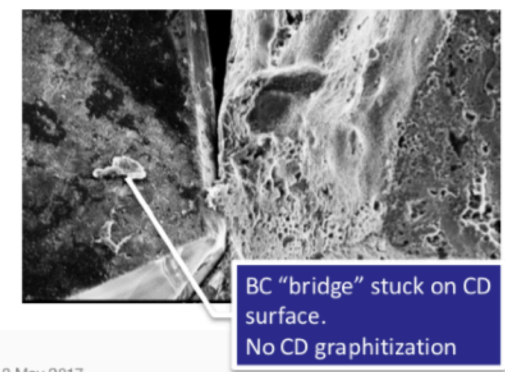
⬆ Thermal (**~490 $Wm^{-1}K^{-1}$**) and electrical conductivity (**~12.6 MSm^{-1}**)

⬌ No direct interface between Cu and CD (lack of affinity) impairs mechanical strength. Issue partly offset by limited bonding assured by Boron Carbides (**~120 MPa**).

⬇ Cu low melting point (**1083 °C**)

⬇ CTE increases significantly with T due to high Cu content (from ~**6×10^{-6} K^{-1} at RT** up to **~12×10^{-6} K^{-1} at 900 °C**)





7 A. Bertarelli – Collimation Material and Design Readiness for LS2 – 2 May 2017

Development started under funds of EuCARD and the LHC Collimation Project. HL-LHC since 2015 (mainly funding the validation phase: tests + HRM).

Scope: CuCD for tertiary collimators replacing the present inermet180 (tungsten heavy alloy).

Scope for Run III and HL-LHC

- Specific scope for higher-robustness collimators:
  <u>horizontal tertiary collimators (TCTs) of IR1/5</u>
  → Affected by the asynchronous dump case (only horizontal)
  → Critical in the transverse betatron hierarchy for **β* reach** of the collider
  → Close to the **experiments** (collateral damage, even at low-loss levels, is more a concern than other LHC insertions)
  → Critical gymnastics in collisions around the IP: local changes for levelling (β*, crossing, separation)

- <u>Following limitations/concerns at the start of Run II</u>, we requested a LHC-CONS program to replace the 4 TCTs in the horizontal planes of IR1 and IR5 with new ones that use CuCD as active material
  → Status: request still active, pending approval
  → Re-iterated at the last CONS day (May 2019)
  → IR2/8 not considered with the present target β*

- **HL-LHC : Scope is to equip with CuCD as active material 8 TCTs in the horizontal planes of IR1 and IR5**

General status of the CuCD development

- Technical validation of the material for usage in an accelerator well advanced:
  → Extensive validation without beams
  → Tests of samples in HiRadMat
  → Irradiation tests at BNL and Kurchatov
  → Tested in HiRadMat a complete jaw built with CuCD inserts
  → Vacuum compliance out-gassings (EDMS 1964788) + SEY measurements

- Extensive performance studies for HL-LHC layouts (see H. Garcia at WP5 review)
  → Various studies at Annual meeting addressed critical aspects:
    → Cold magnet protection in IRs
    → Experiment protection (electronics)
    → Effect on QPS (voltage to ground)
    → **Green light for CuCD on all fronts!**
  → WP5 studies triggered an important follow up from experiments on electronics

- Validation / price / potential production
  → Qualified companies for industrial production (process launched in 2017)
  → CINEL production option for 4 collimators (can decide until 2020)

- Actions recently triggered, following the WP5 review in Feb.
  → *Organised a price inquire, just out this week, to **assess reliably the price***
  → *News studies: can the improved robustness be used to push the performance?*

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Ballpark budgetary figures < 350 kCHF
(being assessed through a price inquiry)

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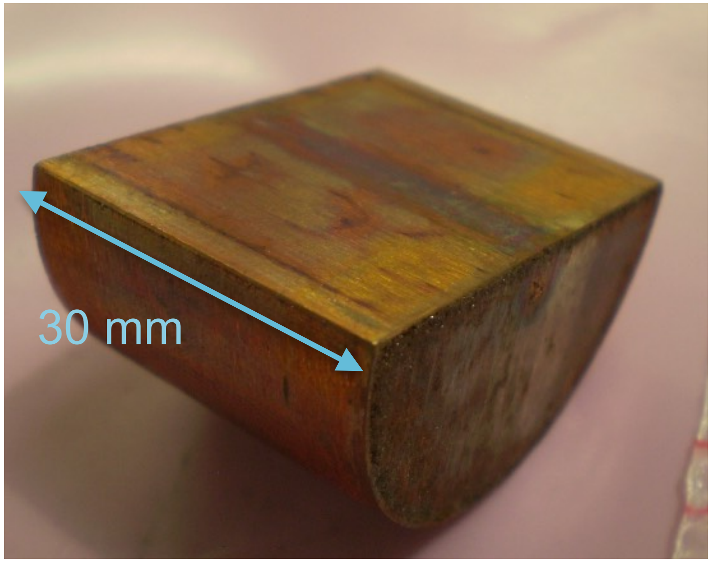
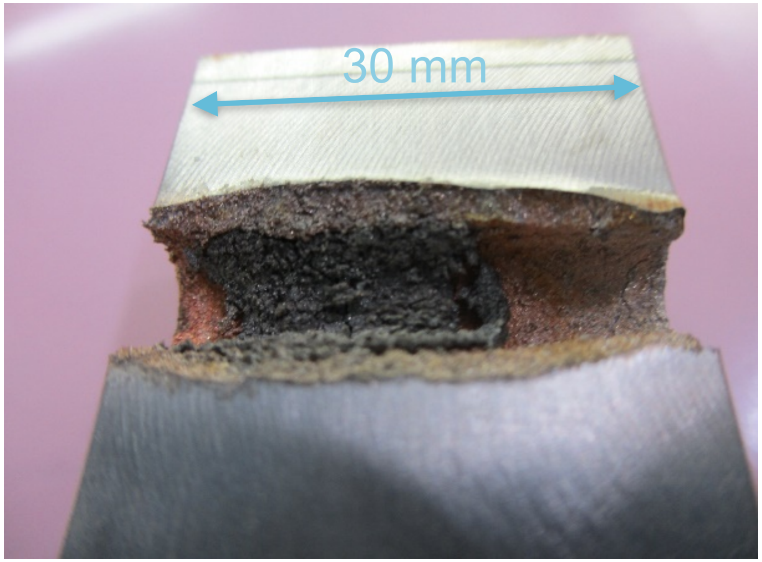
- Introduction
- What is CuCD
- Scope: Run III and HL-LHC
- **Comparative assessment: CuCD vs W**
- Other considerations
- Conclusions

Copper diamond

Inermet180 (W heavy alloy)



VS



HiRadMat: 440GeV equivalent of 3 x 1 nominal HL-LHC bunch

HiRadMat: 440GeV equivalent of 1.5 x 1 nominal HL-LHC bunch

Onset of plastic deformation ~ **1.3e11**

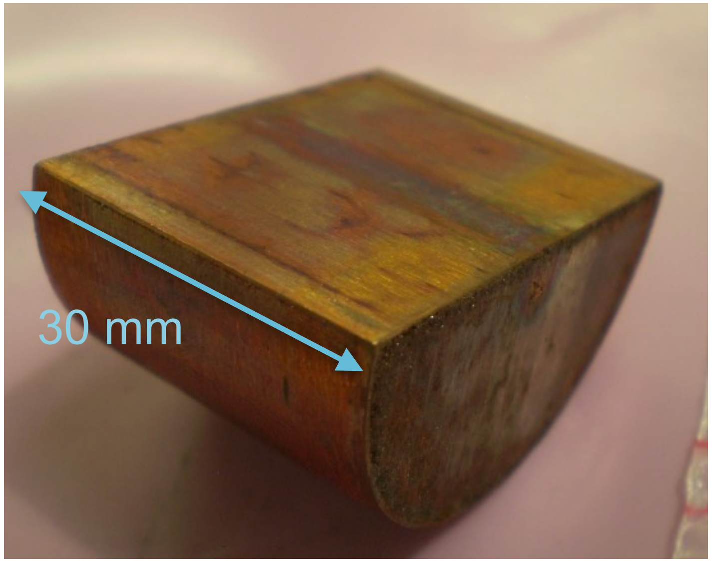
Onset of plastic deformation ~ **5e9**

Fragment ejection ~ 2.2e11p!
(not seen in HRM for bulk)

Fragment ejection ~ 2e10p!
(an LHC pilot bunch)

See also: Recent review by F. Carra at the MP workshop at Bossey
Nucl. Instrum. Methods Phys. Res., Sect. B 308, 88 (2013).

Copper diamond | Inermet180 (W heavy alloy)



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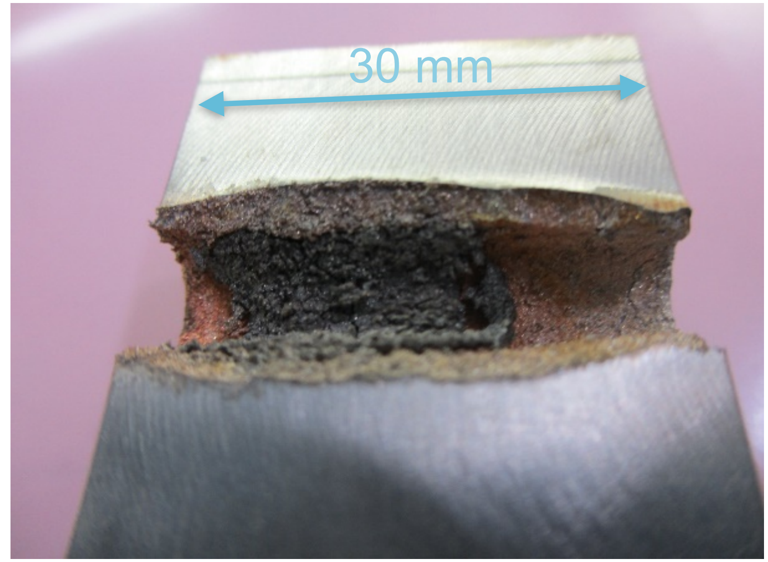


HiRadMat: 440GeV equivalent of *<u>3 x 1 nominal HL-LHC bunch</u>*

HiRadMat: 440GeV equivalen… 1.5 x 1 nominal HL-LH…

Onset of plastic deformation ~ **1.3e11**

Fragment ejection ~ 2.2e11p!
(not seen in HRM for bulk)

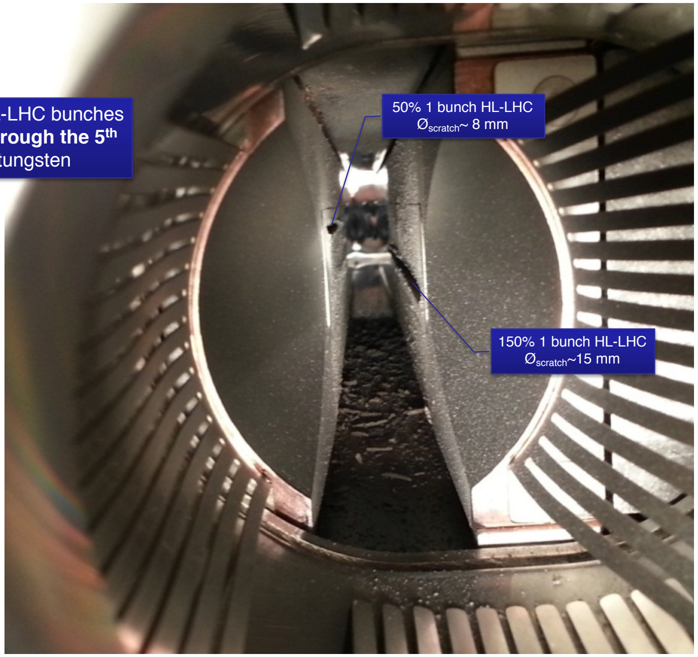
Onset of … **…9**

…ion ~ 2e10p!
…C pilot bunch)

Complex calculations behind these numbers: rely as much as possible on measurements, but scaling on some parameters (e.g. beam size) not trivial.

See also: Recent review by … MP workshop at Bossey
Nucl. Instrum. Met… …ys. Res., Sect. B 308, 88 (2013).

Behaviour of a TCT collimator (HRMT-09, 2012)



Note the debris and dust particles.

Phys.Rev.ST Accel. Beams 17 (2014) no.2, 021004

Joint recommendation from MP + CWG to design for single-failure, and/or mitigate impact on machine for this case.

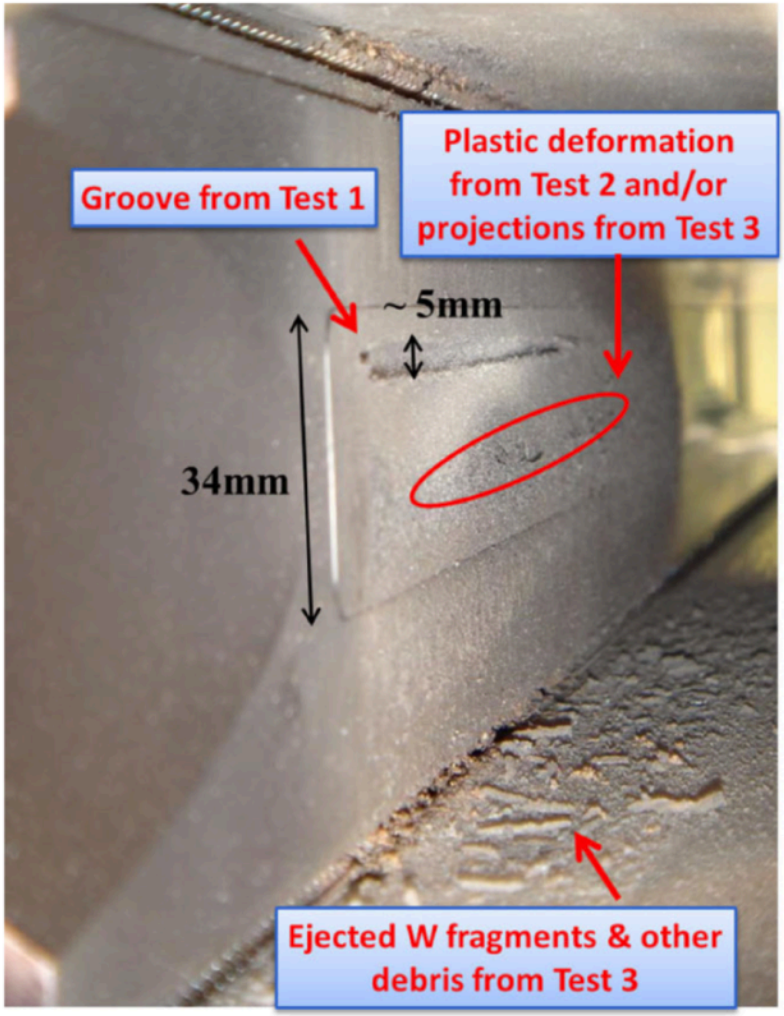
This triggered the question at the review

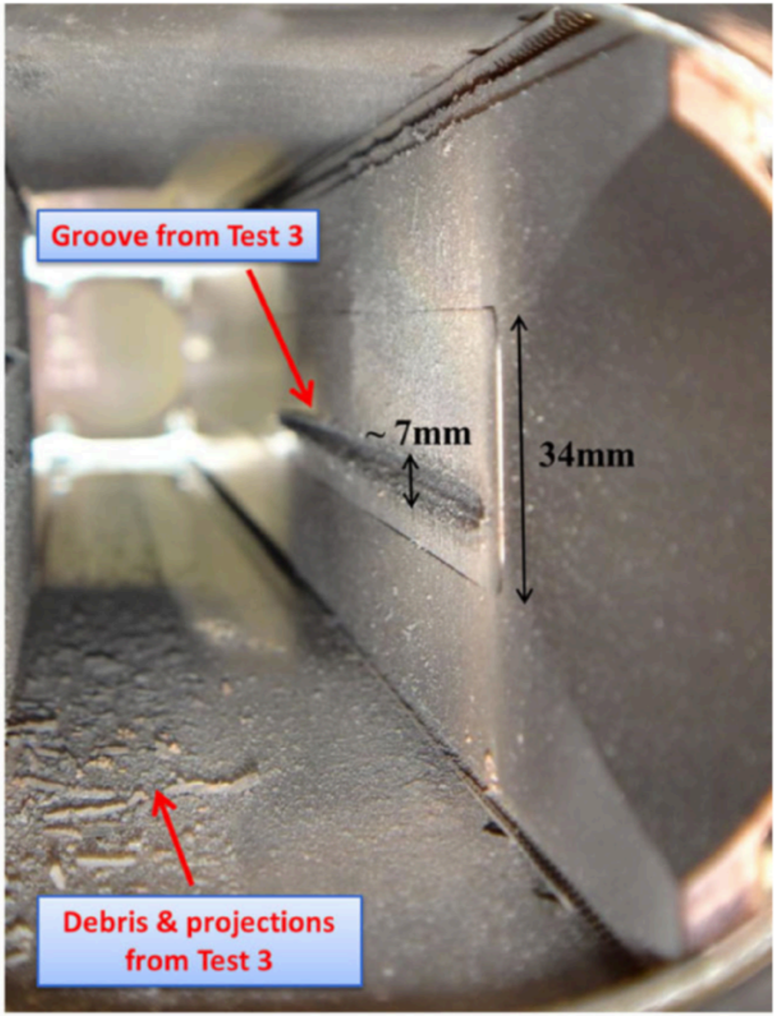
Tungsten alloy maximises absorption but has a low damage limit against beam impacts and the collateral damage from fragment ejection is important.
Issue known since Run I and confirmed experimentally by these HRM tests in 2012:

— Impact on LHC β* performance
— Mitigated since 2016 with zero-phase, worked well so far!

BUT:
— Never had an asynchronous dump in operations with machine full but expected to have ~ 1 / year; un-known scaling to from 6.5TeV to 7TeV
— Single-bunch losses (or equivalent intensity), unlikely but **cannot be** fully excluded from the failure scenario.
— Zero-phase optics not always respected, often close to tolerance (30 deg)

More pictures for Inermet180

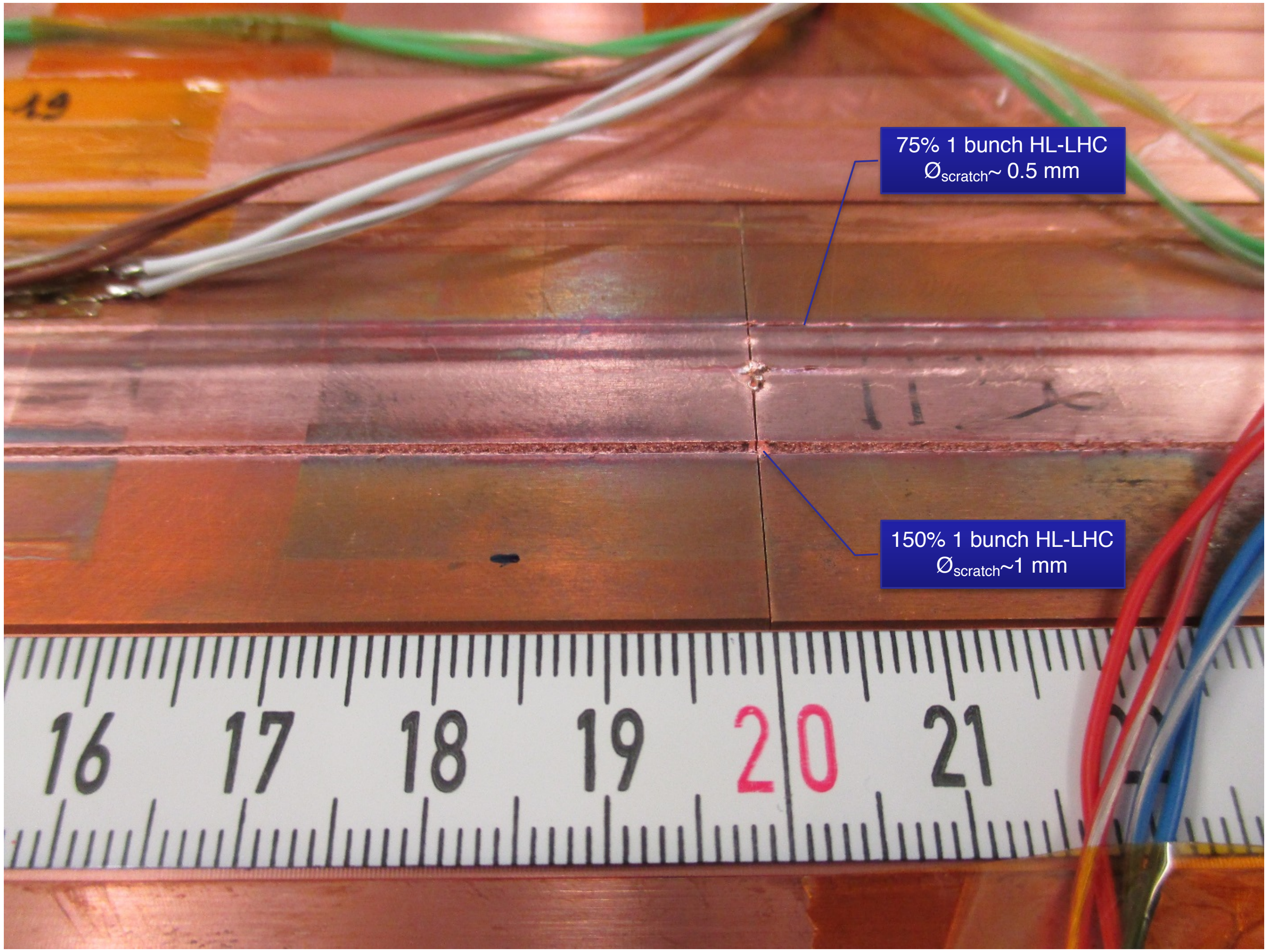




"Test 1" = 7 TeV equivalent of **~1.3e11p** = **0.02%** of HL-LHC design intensity

Phys.Rev.ST Accel. Beams 17 (2014) no.2, 021004

Results of a CuCD jaw (HRMT-23, 2015)



Small surface stripe for the case tested with 75% of 1 HL-LHC bunch
(Cu layer removed for 150% of the HL-LHC bunch)

Some considerations

- Inermet180
  → Well-established material for usage in the LHC
  → Higher absorption: “sacrificial”, but risks a severe damage
  → Long downtime in case of even small uncontrolled losses:
  fragment ejections starts at 2 x 10^{10} p

- CuCD
  → More robust: can withstand a much broader range of beam
  losses without damage requiring a replacement.
  → Collateral damage minimal also for (unlikely) worst scenario
  (Note: removed the 5th axis functionality for the TCTPHX)
  → Provides more flexibility for different optics/commissioning scenarios
  if one relies on the higher robustness to tighten the collimation
  hierarchy! See next slides

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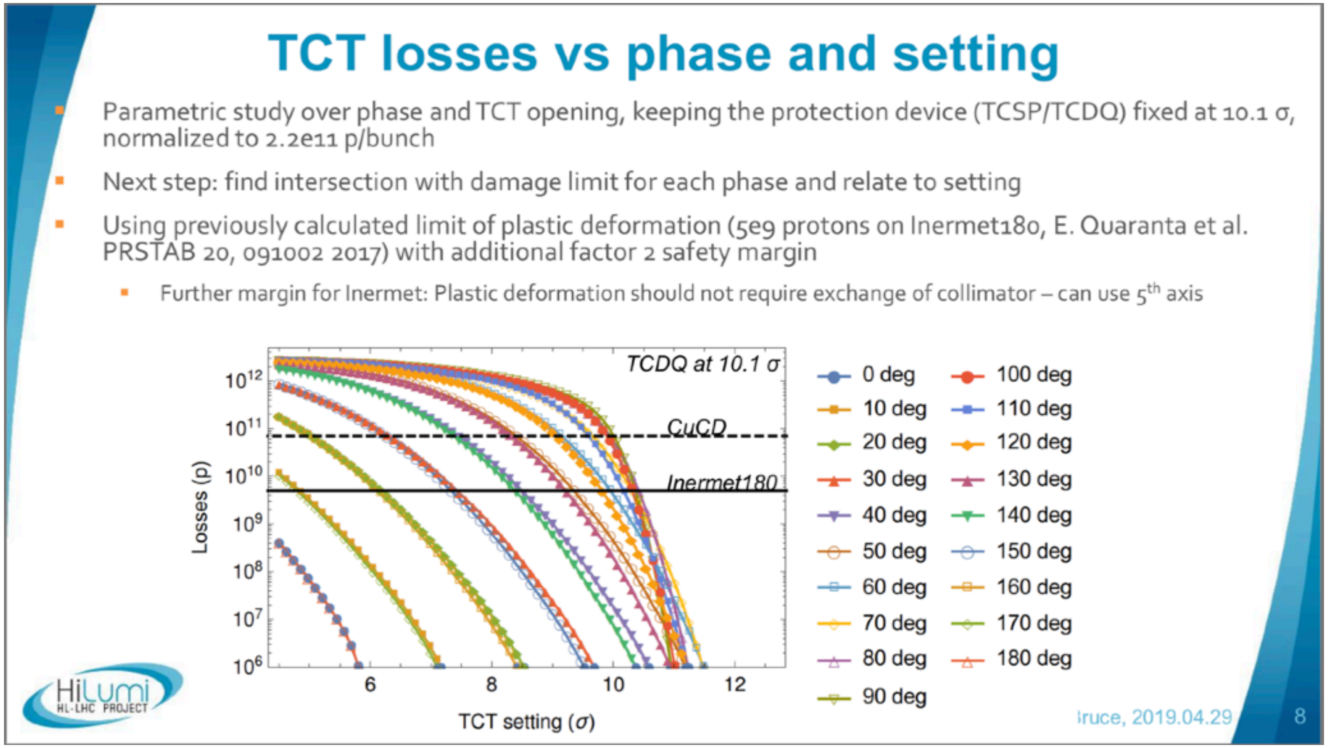
TCT losses and gain from material



R. Bruce,
115th ColUSM

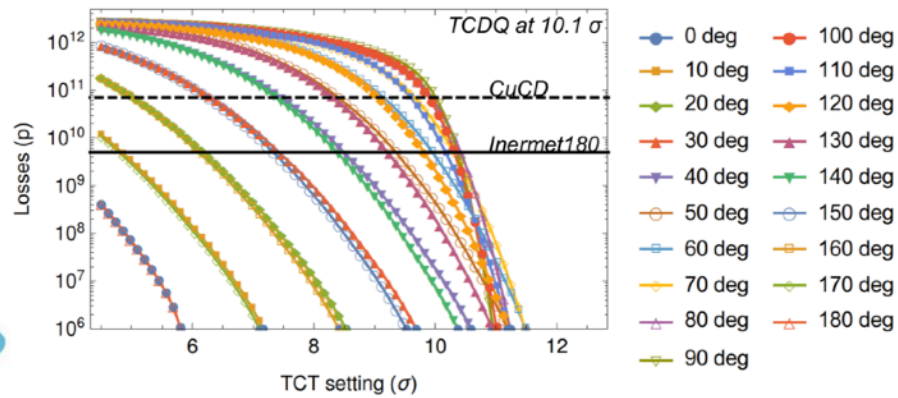
Rationale for this study:

— Allow increased losses at the TCT by the improvement factor from CuCD
— Translate into gain in phase advance and/or protected aperture
— Assess how we can use this to improve performance (or mitigate unexpected issues with aperture)

TCT losses and gain from material

TCT losses vs phase and setting

- Parametric study over phase and TCT opening, keeping the protection device (TCSP/TCDQ) fixed at 10.1 σ, 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 on Inermet180, E. Quaranta et al. PRSTAB 20, 091002 2017) with additional factor 2 safety margin
  - Further margin for Inermet: Plastic deformation should not require exchange of collimator – can use 5th axis



HiLumi HL-LHC PROJECT

ıruce, 2019.04.29 8

R. Bruce,
115th ColUSM

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MKD-TCT phase (deg)	Allowed aperture W (σ)	Allowed aperture CuCD (σ)	Gain with CuCD (σ)
10	11.2	**11.2**	0
20	11.2	**11.2**	0
30	11.9	**11.2**	0.7
40	12.9	**11.9**	1
50	13.8	**12.8**	1
60	14.5	**13.6**	0.9
70	14.6	**14**	0.6
80	14.6	**14.3**	0.3
90	14.6	**14.3**	0.3

Aperture gains and optics flexibility

Optics, aperture, crossing plane

	Round	Flat	FlatCC	FlatCCHV	FlatCCHV
β* Xing/Sep [cm]	15/15	30/7.5	18/7.5	18/9	18/7.5
Xing angle [μrad]	±250	±245	±240	±240	±240
Crossing plane IP5	V (or H)	H	H	V	V
Aperture Xing plane [σ]	13.1	15.6	14.2	14.2	14.2
Aperture Sep plane [σ]	16.5	12.7	12.7	13.9	12.7
H Aperture Point 1/5	13.1/16.5	12.7/15.6	12.7/14.2	14.2/13.9	14.2/12.7
MKD-TCT [°] IP1 [B1/B2]	5/19	23/10	4/6	13/22	13/22
MKD-TCT [°] IP5 [B1/B2]	30/31	14/22	27/25	40/45	39/54
H Ap. Protected IP1 W/Cu	11.2/11.2	11.4/11.2	11.2/11.2	11.3/11.2	11.3/11.2
H Ap. Protected IP5 W/Cu	11.9/11.2	11.3/11.2	11.7/11.2	13.3/12.3	14.1/13.1
Ap. Margin W [σ]	1.9 (or 1.2)	1.3	1.5	0.6	-1.4
Ap. Margin CuCD [σ]	1.9 (or 1.9)	1.5	1.5	1.6	-0.4

Assuming different settings for TCTH and TCTV, which is under study (R. Bruce):
- IR6 optics is constraining only for flat optics and V crossing in Point 5.
- CuCD collimators:
  - Improve β* reach for flat optics with crab cavities from about 8.7 cm to 7.8 cm (based on scaling).
  - Allow H crossing in Point 5 without performance losses (but CMS forward physics preferred V).
  - Allow ±10° additional potential flexibility in IP1 to IP5 for flat optics with crab cavities phase advance for lifetime optimization without compromising β* reach.

R. De Maria, [115th ColUSM]

A short summary:
— no obvious gain with the present optimised round optics including optimised phase advance; Note that remote alignment system promises ~1 sigma gain.
— gain in aperture is beneficial for flat optic, as it allows recovering about 1 sigma!
Reminder: HL-LHC performance dependance on beta* not big!

Other considerations

- Use optics flexibility to improve phase conditions between IP1 and IP5 for baseline optics
    - Potentially beneficial but not yet studied.
- Idea to use the flexibility to change the betas in IP6 to relax constraints of dump.
    - Do we know what improvement factor we need in beam size at TDE?
- New material adds more margins in a range of low intensities that is relevant for commissioning
- Much reduced particle debris compared to tungsten
    - Inermet : significant pollution with unclear consequences for the operation
    - Note that replacing a collimator induced a down time of 2-3 week (bake out)
- If not deployed: more pressure on OP and commissioning teams in critical beam manipulations at the IRs.
    - Support from LHC machine panels (MP, CWG, …) to make the machine more robust by using CuCD for the TCTs

Conclusions

- CuCD developed as high-robustness alternative to more conventional high-Z collimator materials
  - Solid experimental validation, not reviewed in detail here.
- Recent WP5 review triggered a re-evaluation of needs for HL-LHC.
  - Reviewed here the experimental comparison to inermet for robustness
  - Several arguments in favour, after having demonstrated that the reduced absorption is tolerable.
- There is a strong recommendation by WP5 and relevant LHC machine panels (MPP, CollWG, WP2) to have it deployed
- Budgetary assessment ongoing: expect all information from price inquiry by the end of August

  Ballpark figure of 200-380kCHF for the whole production, i.e. about 2% of WP5 IR upgrade;
  Inermet180 = 50-100kCHF for the whole production;
  Note: work foreseen anyway: talking here about the choice of material.
- Possible implementation strategy (looking for synergies HL/CONS):

  — *Use the present production option for building 4 TCT units with CuCD.*
  — *Install them in a YETS of Run III !*
  — *Re-use them in Run IV for the HL-LHC (standard TCT design in cell 6).*
  — *Build the remaining collimators in CuCD (2-in-1 + spares) for HL-LHC*