FCCee collimator materials brainstorming and reflections

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Aim of presentation

- Summarise material selection considerations for FCCee collimators from mechanical + impedance perspective (focussed on primary collimators for now)
- Promote discussion regarding next steps for material studies, and seek discussions and exchanges with relevant teamss
- Collectively down select the few key material options for further study

Overview

Primaries:

- Low density material (for survivability)
- MoGr proposed, but does not appear to meet impedance requirements
- Proposal: Consider other material options/coatings for jaws with high conductivity metal
- **Work:** Explore coating options + bulk materials

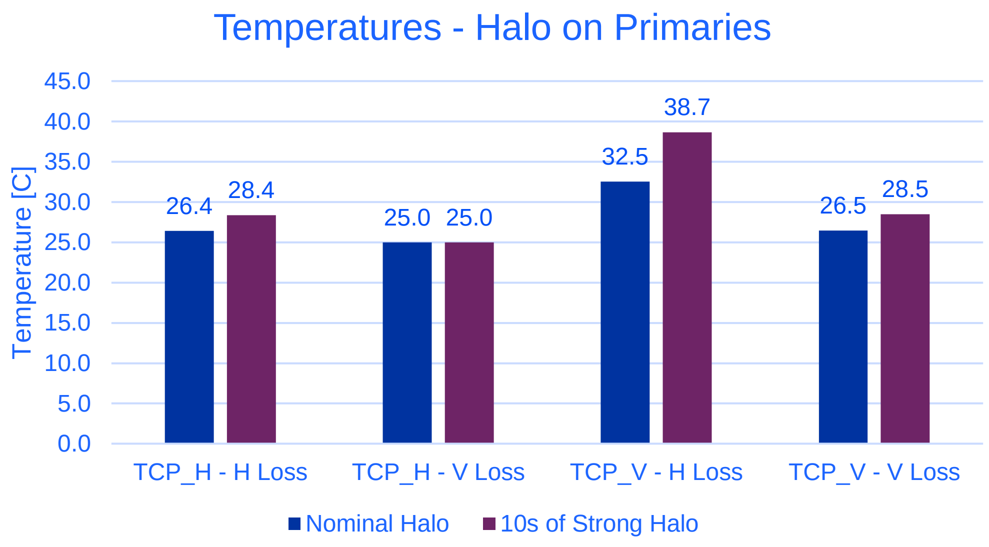
Secondaries:

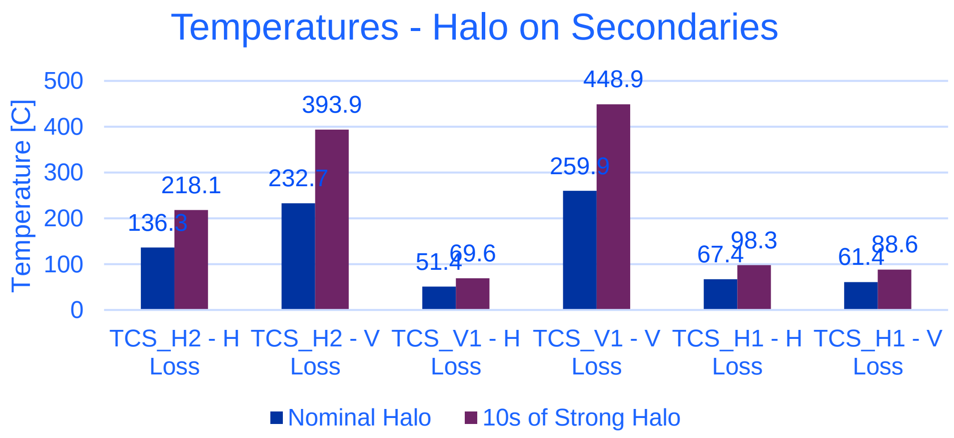
- High density material (for absorption?)
- TZM proposed, but does not appear to survive some accident scenarios (contentious)
- Proposal: Does this need solving at this stage? - discuss

Requirements:
Not yet defined!

- Requirements for the collimation material are not yet fully defined, mainly due to the difficulty in identifying accidental scenarios at this early stage
- However, cases around the nominal are reasonably well-defined for this stage:
  - Remove particles/clean beam
  - Do not exceed impedance budget
  - Do not exceed temperature/stress/deformation limits
  - Have established nominal case and some pseudo-nominal accident cases (meaning a scaled version of nominal, e.g. 5 min lifetime)

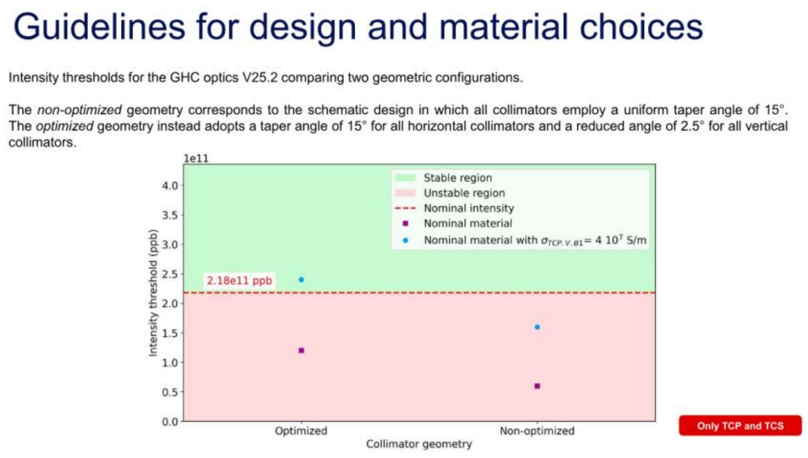
Nominal case + pseudo-nominal case – temperatures of primaries and secondaries at last study (GHC v23)



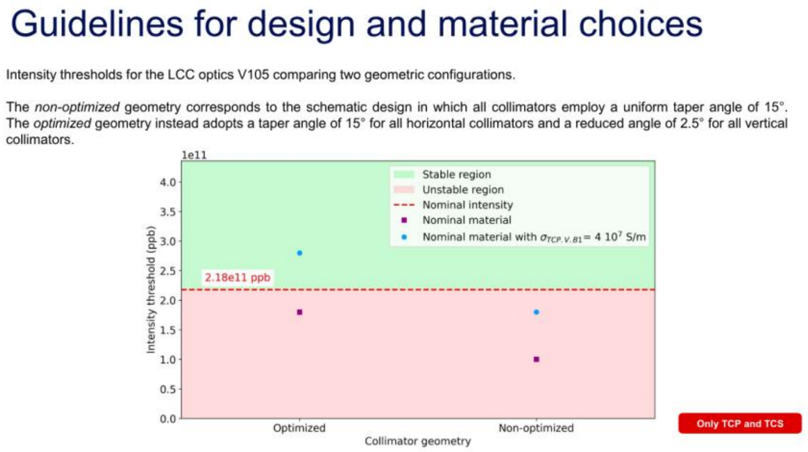


Impedance

- Impedance studies have concluded MoGr **does not** have enough conductivity *for the current design*
  - This is largely due to the **very small half gap** for vertical collimators.
- This means we should explore either **coatings** or **higher conductivity bulk materials**.
  - Or, consider significant changes to collimation system – vertical scraper, perhaps 2-phase?
- If we must coat it, our requirements for the bulk material change.
  - We no longer strictly require a high conductivity material,
  - but prefer greater survivability, good through-thickness thermal conductivity and good coating attachment
- Geometry optimisation can affect this – but if we are this close to instability we want more margin!



GHC ^ / LCC v – Dora Gibellieri - https://indico.cern.ch/event/1604870/



Material options - Primary

A number of materials have been proposed for the primary collimators.

- Low density, high survivability materials
  - Graphite
  - Molybdenum Graphite
  - Carbon-Fibre-Reinforced Carbons (CFRCs)
- Most current studies focus on MoGr or Graphite
- Chosen for ability to survive beam impact
- **Low to medium conductivity**
  - Nothing suggested has sufficient conductivity
  - CFRC best suggested is only equivalent to MoGr.

Engineering Values	Units	Graphite	Molybdenum Graphite	CFRCs
Density	kg/dm^3	1.8	2.5	1.8
Conductivity	MS/m	0.1	1 IP, 0.05 OOP	Unknown – up to 1 IP?
Strength (Bending)	MPa	60	70-80 IP, 5 OOP	100 IP, 50 OOP
CTE	10^-6/K	11	~2 IP, ~10 OOP	~0 IP, ~10 OOP
Specific heat capacity	kJ/kg/K	0.7	0.6	0.7 ?
Absorbed energy†	Arb. Units. [~kJ/cm3]	1	~3	~1
Through-thickness k	W/m/K	105	40	50
Melting Temp	C	3600	2600?	3000?

Qualitative factors	Graphite	Molybdenum Graphite	CFRCs
Beam impact survivability	High	Quite High?	High, but high-conductivity variant not tested
In-beam experience	Lots	Numerous HiRadMat experiments. Some collimation experience?	Lots for CFRCs in general, none for high conductivity variant
Coating questions	Lots of knowledge, well defined process. Used in Hi-Lumi collimators I think?	Some evidence of higher than expected surface melting, poor adhesion compared to graphite	Some poor adhesion under beam impact, dependent on surface fiber structure

†Table 5; Pasquali, M., Bertarelli, A., Accettura, C. *et al.* Dynamic Response of Advanced Materials Impacted by Particle Beams: The MultiMat Experiment. *J. dynamic behavior mater.* **5**, 266–295 (2019). https://doi.org/10.1007/s40870-019-00210-1

Coating options - Primary

Coating must have good conductivity and a high survivability is preferred

- Current materials considered
  - Copper – high conductivity
  - Molybdenum – high survivability
  - Be? – low stopping power, med melting temp
- A denser coating than the bulk material is less survivable,
  - but a denser collimation layer leads to a shorter collimator and **less impedance**.

Material	Units	Copper (pure)	Molybdenum (pure)
Rho	kg/dm^3	8.9	10.3
Conductivity	MS/m	40	19
Strength	MPa	200	320
CTE	10^-6/K	17	5
Specific heat capacity	kJ/kg/K	0.385	0.255
Stopping power (1/rad length)	cm^-1	0.70	1.04
Melting point	C	1080	2600
Beam impact survivability	N/A	Low	Medium
In-beam experience	N/A	Some	Unsure

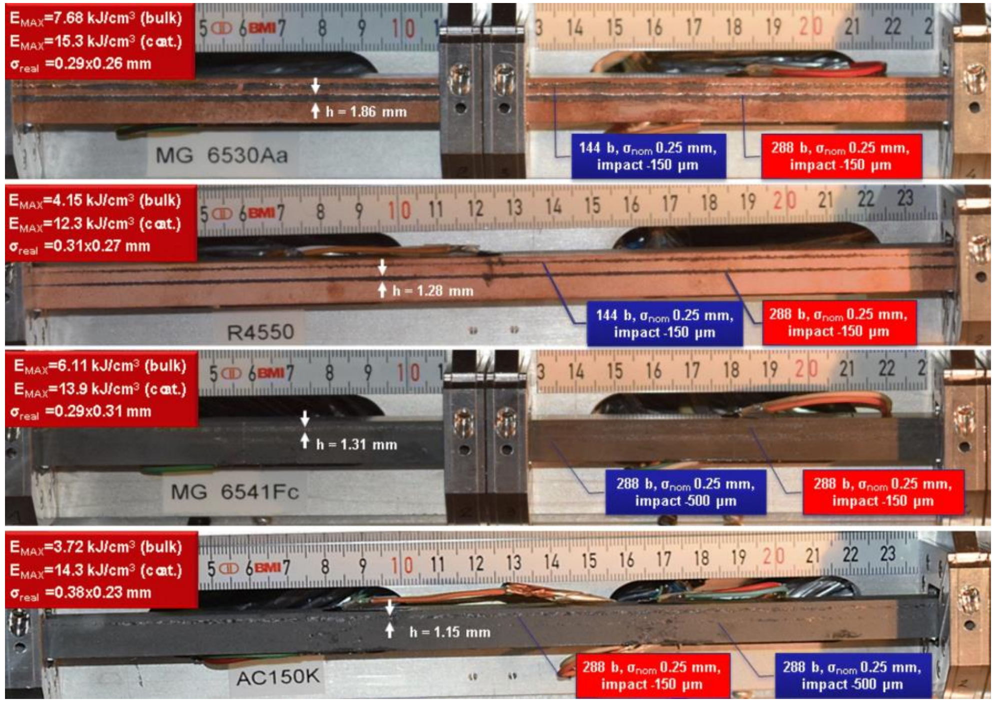


Fig 33; Pasquali, M., Bertarelli, A., Accettura, C. *et al.* Dynamic Response of Advanced Materials Impacted by Particle Beams: The MultiMat Experiment. *J. dynamic behavior mater.* **5**, 266–295 (2019). https://doi.org/10.1007/s40870-019-00210-1

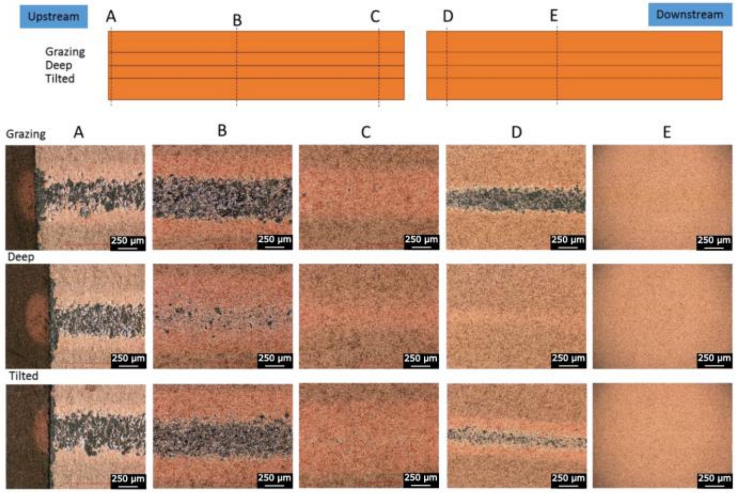


Figure 17. Optical microscope images of the Cu-coated graphite jaw acquired at different points along the beam impact axes, showing an overview of the coating damage for the three different kinds of impact. Note that the positions along the blocks where the images were taken is shown in the schematic illustration at the top of the figure.

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Future Work

It would be good to see the effect on the collimation system of:

- **Cu-coated** primary
- **Mo-coated** primary

These would presumably affect the collimation length required and somewhat affect downstream heating.

We can consider even higher-conductivity bulk materials:

- Copper-impregnated Graphite?
  - Currently ~0.3MS/m but could perhaps be improved
- Metals? Be bulk jaw?
  - Very good conductivity but how much less resistant to damage than a coating?
- Taking suggestions …

Separately, we will undertake studies of beam impact effect on coated collimators. This seems like a reasonable first step to work on for now.

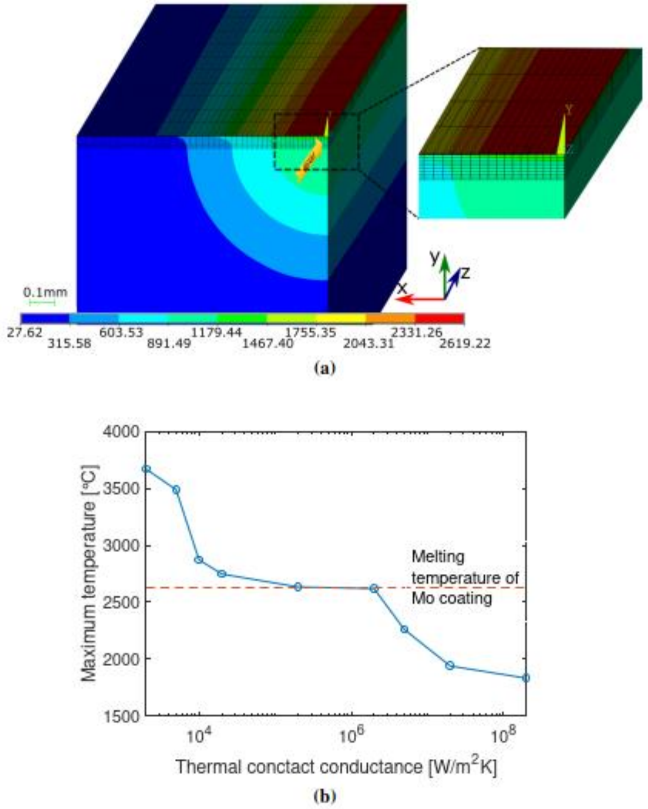

Figure 10. a) Temperature distribution in the molybdenum-coated graphite block after a grazing beam impact for a $TCC^*_{Mo-Gr} = 2.00 \cdot 10^6$ [W/m^{2}K] (half model considering YZ symmetry plane). b) Maximum temperature in the molybdenum coating under a grazing beam impact versus the thermal contact conductance between the coating and graphite substrate.

Previous work on simulation of impacts on coated jaws - J. Maestre *et al* 2022 *JINST* **17** P01019

Secondaries

- For a future discussion … more work needed.

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