Protected aperture in HL-LHC with CuCD TCTs

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Acknowledgement: G. Arduini, R. De Maria, M. Giovannozzi
Introduction

- Continuous effort to improve collimation hierarchy and hence reach in $\beta^*$
  
- Tighter collimators => smaller protected normalized aperture => smaller $\beta^*$ allowed

- Main limitation in the LHC was in Run I and Run II the risk of damaging TCTs / triplets during asynchronous beam dumps
Introduction

- Significant improvement in $\beta^*$-reach in the LHC in 2016 - 2018
  - matched phase advance between MKD-TCT
  - Removes risk of TCTs being hit and damaged by primary impacts during asynchronous beam dumps
Matched phase in HL-LHC

- Applied matched MKD-TCT phase to HL-LHC as from optics v1.3
  - Key to recovering $\beta^*=15$ cm after re-baselining
  - See talks in HL-LHC annual meeting 2017, Madrid
  - Protected aperture vs phase advance shown in CERN-ACC-2017-0051

<table>
<thead>
<tr>
<th>$\Delta \mu$ MKD-TCT</th>
<th>Protected aperture ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LHC, $\epsilon_n = 3.5 , \mu\text{m}$</td>
</tr>
<tr>
<td>$0^\circ$</td>
<td>9.5</td>
</tr>
<tr>
<td>$10^\circ$</td>
<td>9.5</td>
</tr>
<tr>
<td>$20^\circ$</td>
<td>9.5</td>
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<tr>
<td>$30^\circ$</td>
<td>10.0</td>
</tr>
<tr>
<td>$40^\circ$</td>
<td>10.9</td>
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<tr>
<td>$50^\circ$</td>
<td>11.7</td>
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<tr>
<td>$60^\circ$</td>
<td>12.3</td>
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<tr>
<td>$70^\circ$</td>
<td>12.3</td>
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<tr>
<td>$80^\circ$</td>
<td>12.3</td>
</tr>
<tr>
<td>$90^\circ$</td>
<td>12.3</td>
</tr>
</tbody>
</table>

CERN-ACC-2017-0051
Benefit from new materials?

- In parallel, pursued studies on new robust TCT materials
  - Gain: TCTs could be kept close to the beam further away from the optimal phase advance => increased optics flexibility
  - Omitting 5th axis in collimator design – should be able to withstand single-bunch impact

- Best candidate material: copper-diamond (CuCD)
  - Present baseline for robust TCTs
  - See talk F. Carra in 2019 collimation review for details
CuCD characteristics

- Lighter than present TCT material (Inermet180 - W alloy)
  - CuCD more robust to beam impacts than W
  - CuCD less absorbing than W => larger leakage to downstream elements (Q4-Q5, triplets, experiment).
    - Not believed to be problematic – see talk H. Garcia at 2019 collimation review

- Damage limit in terms of impacting beam energy estimated to be factor 14 higher than for Inermet180 (G. Gobbi et al., Mechanics of Advanced Materials and Structures, DOI: 10.1080/15376494.2018.1518501)
  - Numbers inferred from HiRadMat experiments

- What is the impact on the protected aperture if the TCT is a factor 14 more robust?
Studies of TCT losses during asynch dump

- As for LHC, use phase-space integration to estimate losses on TCTs for each bunch during dump failure (type 2 single-module pre-fire – worst case).
  - Integrate beam distribution over phase space area caught by studied bottleneck
  - Fast study which does not require full optics for every studied case – phase can be freely varied
  - Disadvantage: does not treat secondary impacts.
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
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

Best case: aperture=11.2 σ below 20 deg for W and below 30 deg for CuCD

Note: 2.5 um emittance
### Protected aperture vs MKD-TCT phase

<table>
<thead>
<tr>
<th>MKD-TCT phase (deg)</th>
<th>Allowed aperture $W$ ($\sigma$)</th>
<th>Allowed aperture CuCD ($\sigma$)</th>
<th>Gain with CuCD ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>11.2</td>
<td>11.2</td>
<td>0</td>
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<tr>
<td>20</td>
<td>11.2</td>
<td>11.2</td>
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<td>30</td>
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<td>60</td>
<td>14.5</td>
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<td>70</td>
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<tr>
<td>80</td>
<td>14.6</td>
<td>14.3</td>
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<tr>
<td>90</td>
<td>14.6</td>
<td>14.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

- For 0-20 deg: no gain, asynch dump is not limiting
- Gain up to 1 $\sigma$ for intermediate phases
- Only small gain close to 90 deg (very steep rise of losses at smaller TCT settings)
Conclusions

- Examined gain in TCT setting and protected aperture form the use of a more robust TCT material
- Assumed copper-diamond (CuCD) with factor 14 higher damage limit in terms of impacting beam energy
- Studied how limitation varies as function of MKD-TCT phase
- Gain up to $1\sigma$ in aperture margin for intermediate phases
  - Could e.g. allow 40 deg instead of 30 deg MKD-TCT phase, keeping present collimator settings and protected aperture
- To be seen what this gives in terms of optics flexibility
Backup
Phase space integration

- Integrate area in phase space outside the aperture cuts

\[ f_i = \iiint_{R^*_i \cap R_{i-1} \cap \ldots \cap R^*_1} \rho(X_0, P_0, \delta) dX_0 dP_0 d\delta. \]

- To be inside \( R_i \), horizontal coordinate should fulfil

\[ |X_i| \geq A_i \iff |C_{0i} X_0 + S_{0i} P_0 + S_{0i} \theta + D_i \delta| \geq A_i. \]

- Assumed distribution

\[
\rho(X_0, P_0, \delta) = \frac{1}{2\pi\sigma^2} \exp \left( -\frac{X_0^2 + P_0^2}{2\sigma^2} \right) \times \frac{1}{\sqrt{2\pi}\sigma_\delta} \exp \left( -\frac{\delta^2}{2\sigma^2_\delta} \right).
\]