Beam Induced Damage – What is a Safe Beam?

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[Authors listed]
and had to be replaced.

A LHC injected batch is $3.2 \times 10^{13}$ protons at 450 GeV. The full intensity is $3 \times 10^{14}$ protons which will be ramped to 7 TeV (360 MJ).

- How much beam can we lose in the LHC before damaging equipment at the different energies? Is there a SAFE BEAM LIMIT?
- Do our protection devices protect against beam loss?
- WHAT ARE THE DAMAGE LIMITS OF OUR EQUIPMENT?
A lot of metal in the LHC....

TT40 material damage test” was carried out

Experimental cross-check of damage limits of metals derived with FLUKA simulations

four intensities:

\[ A = 1.3 \times 10^{12}, \quad B = 2.6 \times 10^{12}, \quad C = 5.3 \times 10^{12}, \quad D = 7.9 \times 10^{12} \]

Perpendicular impact

Damage = “clear sign of melting”
Safe Beam Limit = Intensity where interlock inputs can be masked.

From TT40 experiment: @ 450 GeV: safe limit = $1 \times 10^{12}$ protons (intensity A)

Maximum temperature for intensity A in TT40 experiment: ~ 500º C

Cu melting point: 1083º C

Limit energy dependent:

Scaling law from FLUKA simulations

Safe Beam Limit

$1 \times 10^{12} \times (450/E)^{1.7}$

$E_{dep} \propto E^{1.7}$

(includes effect of emittance reduction)

For nominal emittance!!
Example: LHC secondary collimators

Allowable stress level: $\sigma_s = 86$ MPa

Studied worst case impact scenarios: injection error, 7 TeV asynchronous dump, 7 TeV pre-filamentation.

**FLUKA result**

Melting point of C ~ 3500° C. Mechanical limit already reached at 551° C. Factor 7 below melting point.

<table>
<thead>
<tr>
<th>Material</th>
<th>Jaw length [cm]</th>
<th>Max. temperature [°C]</th>
<th>Stress $\sigma_{equiv}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon-Carbon</td>
<td>20</td>
<td>335</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>345</td>
<td>12.7</td>
</tr>
<tr>
<td>Carbon-Carbon</td>
<td>20</td>
<td>212</td>
<td>20.8</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td><strong>551</strong></td>
<td><strong>82.0</strong></td>
</tr>
</tbody>
</table>

R. Ass.

Example: TPSG in the SPS: absorber in front of the extraction septa for fast extraction.

TPSG in LSS6: 3.5 m long sandwich of different materials (graphite, titanium, INCONEL)

Safety limit for material integrity: 305° C in one of the graphite blocks.
Example: LHC Secondary Collimator: TT40 robustness tests

Considered accident case at injection:

- 2.4 MJ/mm²: \(3.2 \times 10^{13}\) protons @ 450 GeV
- 4 MJ/mm²: \(3.2 \times 10^{13}\) protons @ 450 GeV

Graphite jaw survived as predicted.

But: thermal shockwave in Cu support bar deformed the whole jaw.
- Cu reached 70°C
- Now: GlidCop® support bar instead of Cu

Revised design: temperature rise too high

Example: TPSG in the SPS

TPSGs needed re-designing to survive stresses during impact.

However: design had to be adjusted again.

- Temperature rise 50 K → 250 bar pressure rise in water cooling system of septa too high during impact.
The tertiary collimators close to experiments are made of W to protect triplets with squeezed beams at 7 TeV.

J. Blanco Sales

Maximum energy deposition in W

Number of particles where melting is reached
Safe Beam Intensity is required as “set-up” intensity, **not** as intensity which can be safely lost **under all conditions**!

Set-up” intensity for collimator setting-up, optics measurements,...with relaxed machine protection constraints (masking)

- Constraint #1: needs to be safe for slow losses (BLMs will protect)
- Constraint #2: needs to be measureable with instrumentation
  - pilot intensity at 7 TeV

Proposal: change name from Safe Beam Intensity/Flag → **Set-up Beam Intensity/Flag**
Need to know the “REAL” damage levels of equipment to:

- set operational limits for equipment: e.g. Screens, wire scanners

  - Already fairly well-known and agreed

- set BLM thresholds to protect the element: e.g. TCT

  - Example: Transfer line collimation system

    - Damage level of magnets: coil > 100° C

    - Beam loss on the collimators heats up downstream magnets: FLUKA simulations

      → masks had to be introduced
Protection devices in the LHC: similar situation as in the LHC

Injection protection: TDI – TCDD (mask) – D1 (superconducting)

Dump protection: TCDQ – TCDQM (mask) – Q4 (superconducting)

HOW WELL DO WE KNOW THE DAMAGE LEVELS OF SC MAGNETS?

Is there one for all?

4.5 K and 1.9 K magnets, MBs and triplets?

HC Project Note 141 (O. Bruning and J.B. Jeanneret), 1998

Damage level of superconducting magnet

The equation (21) solves with \( T_c = 104 \) K. The critical energy deposition per unit volume is obtained by integrating numerically (22) between \( T = 0 \) and \( T = T_c \), or

\[
\Delta Q_c = 87 \text{ Jcm}^{-3}.
\]  

Further down they state [required number of protons to be lost at one location to damage]:
This damage level for SC magnets has been used for designing the TDI-TCDD protection...

### CASE GRAZING: comparison

<table>
<thead>
<tr>
<th>TCDD</th>
<th>TDI</th>
<th>Energy deposition on D1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$GeV/cm^3/p$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.1 \times 10^{11}p$</td>
</tr>
<tr>
<td>Absent</td>
<td>New</td>
<td>$7.35 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>Old</td>
<td>$1.4 \times 10^{-2}$</td>
</tr>
<tr>
<td>1500 mm²</td>
<td>New</td>
<td>$5.90 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>Old</td>
<td>$8.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>3600 mm²</td>
<td>New</td>
<td>$2.76 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

- New TDI geometry seems to be better than the old one, according to the simplified configuration results ([a factor 2 due to the BN used has to be considered!!](#)).
- Safety factor 1.5 (damage level = 87 J/cm³) TCDD is still needed to prevent damage in all conditions.
- With an identical TCDD configuration (but different position) the improvement due to TDI is still evident, in spite of the worsening due to the position of TCDD.
- Enlarging the TCDD opening to the actual size, it can be seen that the overall effect is negative.
During an asynchronous dump the Q4 is protected by the TCDQM. The levels used for the dump protection design were also used for the asynchronous dump. The table below summarizes the instantaneous load due to asynchronous dump at 7 TeV.

<table>
<thead>
<tr>
<th></th>
<th>Peak Load (J/cm²)</th>
<th>ΔT (K)</th>
<th>Energy Flow (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCDQ (front)</td>
<td>2139</td>
<td>712</td>
<td>-</td>
</tr>
<tr>
<td>TCS (right)</td>
<td>2283</td>
<td>679</td>
<td>-</td>
</tr>
<tr>
<td>TCDQM</td>
<td>44.5</td>
<td>12.8</td>
<td>-</td>
</tr>
<tr>
<td>MCBY</td>
<td>26.2</td>
<td>-</td>
<td>262</td>
</tr>
</tbody>
</table>

During an asynchronous dumping, the Q4 is protected by the TCDQM. The levels used for the pump protection were also utilized for the asynchronous dump.
According to the experts...

We don’t know...

The only number available: 87 J/cc

Is that number conservative?

A. Siemko: temperatures for components of SC magnets to start degradation

1. ~ 180° C: Kapton

2. ~ 220° C: SnAg solder material
   - important for splices
   - and cross-contact resistance of strands, strands are coated with SnAg

3. ~ 350° C: NbTi
   - current carrying capacity starts degrading
   - probably a more long-term effect (days)

pilot @ 450 GeV: 360 J
Contacted people from the TEVATRON

‘We don't have and never had a damage limit for the Tevatron superconducting magnets specifically. We have the solid numbers for slow and fast quench limits [...]’ N. Mokhov
Would be useful to clarify whether or not 87 J/cc is conservative.

If not our protection might not be adequate.

Simulations should be carried out to address energy deposition from transient beam loss!

Experimental verification?

We might get some data from the LHC...clearly not preferred solution

**TT60 HiRadMat** (High Power Beam Test Facility)?

**Proposal for HiRadMat in TT60:**

- Address **immediate need** for LHC collimator upgrade.
- **Foster advances in basic understanding of beam-induced shock waves** in standard and advanced materials.

R.W. Assmann

- Could we irradiate a **COLD** SC magnet there?
Simulations with Geant4 by M. Sapinski

Distributed losses due to small impact angles:

Quench of MB in sector 23: impact angle: ~ 250 μrad, beam size: 1 mm

Energy deposition maxima in the old bore/beam screen.

Energy deposition in the coils of a main dipole after beam losses on vacuum chamber:
Injection: $1 \times 10^{12}$ p+: 150 J/cc $>$ 87 J/cc
From the TT40 incident we know: holes are “long” slits.

25th of October 2004: MSE trip during high intensity LHC extraction. Damage of QTRF pipe and magnet.

~25cm long hole in chamber

Is it possible to slice open an LHC SC magnet and recreate a S34 incident?

An LHC SSS

E.g. a hole long enough for:

- He: cold mass
- beam vacuum
- insulation vacuum
or the case studied on the previous slide, the energy deposition for the cold bore by M. Sapinski

Distributed losses: (assuming 316L, constant \( C_p \)):

Melting point for 316L: \( 1398^\circ C \)

Temperature Rise Estimate over several m:

- Injection: \( 1 \times 10^{12} \) \( p^+ \): \( \Delta T \sim 76 \) K
- \( 3.2 \times 10^{13} \) \( p^+ \): \( \Delta T \sim 2100 \) K
- Collision: \( 1 \times 10^{10} \) \( p^+ \): \( \Delta T \sim 13 \) K
- \( 1 \times 10^{12} \) \( p^+ \): \( \Delta T \sim 1050 \) K

Preliminary numbers. Outcome very sensitive to impact angle, input distribution, aperture details,...
Our “set-up” intensity limits derived from the damage experiment seem to be consistent with damage limits derived through other means (Note 141).

Not every equipment (RF cavities, injection kickers,...) has been studied.

Damage level of superconducting magnets?

Shock waves, dynamic effects, phase transitions,...: damage levels are difficult to estimate → experimental verification is useful → HiRadMat.

For some equipment (e.g. Tertiary Collimators at 7 TeV) our “set-up” intensity is not safe.

Plus: damaging potential depends very much on impact, emittance,...

Conclusions?

By-product of our investigation: beam loss in SC magnets

Very first result: during accidents with large beam oscillations and large enough intensities stored holes of several m length could be drilled into the cold bore...S34 incident?

More data soon from FLUKA studies using the IR7 dispersion suppressor model with realistic...
should take conservative approach: AT 7 TeV NO BEAM IS SAFE UNDER ALL CONDITIONS

But should not panic either: need to get to $3 \times 10^{14}$

Implications for operational strategy:

**AVOIDANCE**

- Make sure we stay within operational envelope (I, E, emittance)
- Make every effort to prevent operational errors: RBAC, critical settings, SIS,...
- Thoroughly prepare and follow the commissioning procedures

**MINIMISE CONSEQUENCES**

- Set up and use passive protection from very early on
- Even if cleaning is no issue yet, use collimators as passive protection
- Every new intensity/energy step: use pilot intensity first
- Minimise downtime: spares, He release valves,...

**CONTINUOUS FOLLOW UP**