Detection and Analysis of Uncontrolled Beam Loss in the High Luminosity LHC

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Scope of project

- Study of uncontrolled beam loss scenarios
  - How failure occurs
  - Effect on the beam
  - Subsequent beam losses (intensity, location)
  - Time scales
- Detection of failures
  - How to limit time between detection of failure and beam dump
- Mitigation of or protection against failures
- Simulations (mainly beam tracking and optics calculations)
- Experiments (using very fast diamond beam loss monitors)
- Also important to protect beam from unnecessary dumps!
Beam induced damage

- SPS beam shot at copper cylinders
- $1.5 \times 10^{11}$ protons per bunch @ 440 GeV

Target 3
144b
$\sigma = 0.2\text{mm}$

Target 2
108b
$\sigma = 0.2\text{mm}$

Target 1
144b
$\sigma = 2\text{mm}$

Courtesy of F. Burkart
Beam induced damage

- 144 bunches of $1.5 \times 10^{11}$ protons per bunch, 440 GeV

Courtesy of F.Burkart
LHC Injection Failure

- Before LHC commissioning, SPS beam hit aperture in LHC injection transfer line
- $3.4 \times 10^{13}$ protons @ 450 GeV
- Required changing chamber and a quadrupole

![Image showing a 25cm long hole in chamber with damage visible over 1 meter (melted steel).]
Magnet damage

- Decomposition of insulation
  - => short circuit
- Decomposition of superconducting strands
  - => degradation of superconducting properties
- Need replace magnet
  - => min. downtime ~3 months

Courtesy of V.Raginel
LHC overview

- Most of ring – periodic lattice of FODO cells
- Around interaction points, matching section
  - Triplet quadrupoles (Q1,Q2,Q3) – very large beta functions
  - Separation and recombination dipoles (D1 and D2)
High Luminosity LHC (HL-LHC) changes

- To attain higher luminosity, higher bunch intensity and smaller $\beta^*$ (bunch size in collision point)
- Many changes in layout (e.g. Triplet quadrupoles, crab cavities ... )

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td># bunches</td>
<td>2808</td>
<td>2808</td>
</tr>
<tr>
<td>Bunch intensity [protons per bunch]</td>
<td>1.15e11</td>
<td>2.2e11</td>
</tr>
<tr>
<td>$\beta^*$ [cm]</td>
<td>55</td>
<td>15</td>
</tr>
<tr>
<td>Stored Beam energy (@ 7 TeV) [MJ]</td>
<td>362</td>
<td>693</td>
</tr>
</tbody>
</table>
Failure Classifications

- Slow failures (> 1 s)
  - Cryogenics, failure of orbit/tune feedback...
  - Manual intervention possible
- Fast failures (> 15 ms)
  - Trip of RF system, superconducting circuit/magnet power problem
  - Protection by multiple systems
- Very fast failures (> 3 LHC turns, 270 µs)
  - UFOs (macroparticles entering beam), resistive magnet power problem, transverse damper failure, crab cavity failure
  - Protection by fastest systems
- Ultrafast failures (< 3 turns)
  - Injection/extraction failure, loss of beam-beam kick, quench heaters
  - Protection dump not possible (rely on passive protection)
Accelerator Physics – some basic concepts

- Beta function describes the oscillation of off-center particles, a function of the quadrupoles
  - Beta function is also related to the beam size
- Transverse bunch particle distribution can be modelled as sum of two 2d-Gaussians (beam core + beam halo)
- $1 \sigma [m] \sim 1$ standard deviation/width of distribution
  - $\sigma(s) = \sqrt{\beta(s)} \epsilon$
  - $s : \text{longitudinal distance}$
  - $\epsilon : \text{emittance, average transverse spread in phase space}$
- Off-center particles remain at constant radius in phase space
  - Normalized to beam $\sigma$ – convenient unit
  - Phase must be taken into account for very fast failures
Collimation system overview

- Smallest aperture bottleneck
- Designed to clean off-center particles
- First elements to intercept the beam for most failures
- Consists of three sets
  - Primary collimators (TCP, ~5.5 $\sigma$ aperture, ~2 mm)
    - Carbon
    - Diffuses protons
  - Secondary
    - Carbon
    - Shower creation
  - Tertiary
    - Tungsten
    - Absorbs showers
- Orbit excursion of ~3 $\sigma$ at 7 TeV enough to damage
Damage limits

- Collimator system
  - 288 nominal bunches (one SPS beam) at 450 GeV
  - 8 nominal bunches at 7 TeV
    - ~Half this for HL-LHC
- Magnets
  - Quench limit: ~1e9 protons @ 450 GeV, ~1e7 protons @ 7 TeV
  - Damage limit: 1e12 protons @ 450 GeV, 1.e11 protons @ 7 TeV
Magnet protection

- When a quench occurs
  - Usually localized
  - Must be spread quickly (~100 ms) to diffuse the resistive current loss throughout the magnet

- Quench heaters: resistive plates attached to magnet (current system)

- A new system for heating whole magnet at once in development – explained further down

- Both types induce magnetic field in beam area
  - Affects the beam!
Quench heaters in Dipoles

- From simulations: the QH cause a 0.7 mT field in the beam area
- Associated orbit change: +/- 400 µm, confirmed experimentally
- A delay of up to 3 ms (35 turns) between QH firing and dump
- In HL-LHC triplet quadrupole, up to 52 σ kick
  - Imperative to dump first

Measured and simulated orbit change
CLIQ – Coupling Loss Induced Quench

- CLIQ – a new type of quench protection system
- Capacitor discharges current in magnet circuit
- 2 kA of current going into the magnet coils – imperative to study its criticality
- Poles P3 and P1 see lower current
- Poles P4 and P2 see higher current
- Heat is deposited in the copper matrix via inter-filament and inter-strand coupling losses, causing a quench

![CLIQ Diagram](image)

**Q2 current – CLIQ discharge**

![Graph](image)

- Current, $I_{nominal}$
- Current flowing through CLIQ
- Current in poles
- CLIQ discharge time, $t$ [s]
CLIQ in Triplet (Q2 and Q3)

- Differences in connection, different magnetic fields.
- Q1 electrically same as Q3
- From optics, Q3 has larger beta function, and is thus more critical
- **Q2**: Symmetric discharge -> **Quadrupolar** field -> beta beating
- **Q1/Q3**: Asymmetric discharge -> **Skew dipolar** field -> orbit excursion

Q2, peak field (12 ms)

Q3, peak field (20 ms)
Q3 – orbit excursion

- Beam lost shortly after LHC turn 100

Normal LHC – D1 failure

$1 \sigma - 4 \text{ ms}$
Q2 – Beta Beating

- Beta beating of up to 100% at the TCPs
- Beam size changes -> losses at TCPs
Crab Cavities

- In HiLumi LHC, due to smaller $\beta^*$ and to limit beam-beam effects the crossing angle will be increased
- $\rightarrow$ Lower luminosity:

$$L = \frac{n_b f_{rev} N_p^2}{4\pi \sigma_x^* \sigma_y^*} \times F(\theta_c)$$

<table>
<thead>
<tr>
<th>Piwinski Reduction (Geometric) Factor</th>
<th>2012 LHC</th>
<th>2015 LHC</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_c$ [\mu rad]</td>
<td>313</td>
<td>290</td>
<td>590</td>
</tr>
<tr>
<td>$F(\theta_c)$</td>
<td>0.88</td>
<td>0.85</td>
<td>0.31</td>
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</table>

Geometric Factor
Crab Cavities

- Cavity with sinusoidal transverse kick - bunch is tilted - better overlap at crossing point

Phase advance:

- $0^\circ$ - kick in $x'$
- $90^\circ$ - max offset in $x$
- $180^\circ$ - $x'$ set to 0 with same voltage
Crab Cavities – failure modes

- Voltage drop (~4 LHC turns)
  - Residual crabbing outside Interaction Point large
- Phase change (must be driven by the RF control)
  - Kicks beam core out of orbit
- Quench (combination of the above)
Consequences of CC failure

- Phase shift causes beam core to be transversally kicked - can give fast beam loss

- If crabbing not compensated (e.g. voltage drop), transverse beam distribution wider - increases hazard of other failures

Nominal 180 µrad tilt

Bunch Distribution – double Gaussian (5%@1.8σ)

Integrated Intensity ratio above x σ – double Gaussian (5%@1.8σ)
Combined failures – beam beam effect

- The two beams interact with each other electromagnetically in crossing points
  - Transverse kick (orbit change, main issue)
  - Emittance growth
  - Tune spread
  - ...
- Dumping one beam gives sudden loss of beam-beam kick
- After a given failure, beams will always be dumped
  - -> this type of combined failure must thus always be considered
Current work...

- Experiment on Thursday
  - Studying UFO dynamics using diamond beam loss monitors
- Two IPAC papers *(preliminary titles)*
  - Results of UFO dynamics studies with beam in the LHC
  - Crab cavity failures combined with loss of beam-beam effect in the HL-LHC
- Article on ”Fast failures in the LHC and HL-LHC”
  - First draft by end of this year...
Thank you!
Introduction

- 16L2 refers to loss events in an interconnection in LHC sector 16L2
- Three types:
  - Steady state losses (resolved)
  - UFO-like losses causing beam instability (fast loss rise, beam dump, quench)
  - UFO-like losses not causing instabilities (do not dump)
Introduction

- 61 dumps since May until 25th Oct (7 more until 28th Nov)
- 294 dumps due to faults, 64 due to beam losses (incl 16L2)

<table>
<thead>
<tr>
<th>Period</th>
<th>Duration</th>
<th>SB Hours</th>
<th>Dump Count</th>
</tr>
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<tbody>
<tr>
<td>Period 1</td>
<td>2.5 months</td>
<td>589h</td>
<td>19 dumps</td>
</tr>
<tr>
<td>Period 2</td>
<td>1 month</td>
<td>299h</td>
<td>35 dumps</td>
</tr>
<tr>
<td>Period 3*</td>
<td>1 month</td>
<td>318h</td>
<td>5 dumps</td>
</tr>
</tbody>
</table>

*Courtesy of A. Lechner*
Observables and Goals

- **Hypothesis:**
  - Solid macro-particle enters beam -> gives UFO-like losses
  - Macro-particle evaporates -> charged particle cloud -> beam instability -> losses in TCPs

- Local dBLM: direct losses from 16L2 interaction (relatively low signal)
- IR7 dBLM: losses due to build-up of instabilities

- From local data, study the UFO dynamics
  - Bunch blow-up in H or V
  - Displacement of bunches in H,V or diagonally
    - Tells us which direction the UFO is coming from (see MD on UFO dynamics with wirescanner)

- From IR7 data, study how the instability develops

- Fastest losses observed in the LHC
16L2 Machine Development test (MD)

- Unique opportunity with UFOs on demand
  - High bunch intensity, many bunches and high energy seems to trigger them
- Foreseen to conduct MD before end of this run
  - Various combinations of blown up and displaced bunches
  - Study UFO dynamics as shown by previous MD2036 using wirescanner
  - Understand 16L2 in case it reoccurs

- Challenges for dBLM part:
  - Optimize signal
  - Use many bunches with set properties for better statistics
    - How many bunches required will be an outcome of current analysis
      - From understanding the histogram
    - How to combine signals from the different bunches to draw conclusions
      - Increasing statistics without destroying relevant data
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