EVALUATION OF RADIATION TO MACHINE COMPONENTS AND EQUIPMENT

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QUITE A BIT OF ENERGY

700 MJ per beam (7 TeV protons, $2.2 \times 10^{11}$ p per bunch, ~2800 bunches)

9.5 kW delivered in collisions (L=5$L_0$)

on each side of ATLAS and CMS, a 54mm aperture TAS absorber takes 500W and let 3.5kW impact the machine

by design, up to 500 kW can impact the primary collimators (in IR7)
WHICH IMPACT

radiation sources: regular collisions, collimator cleaning, beam-gas interaction
various accident scenarios (e.g. UFO)

Heating, stress  energy (power) deposition  →  thermomechanical analysis where needed

Degradation  energy (dose) deposition, particle fluence, DPA

Monitor response  energy (dose) deposition (→ charge collection), particle fluence

Background  particle fluence

Electronics  high energy hadron fluence, neutron fluence, energy (dose) deposition

Activation  residual activity and dose rate  →  S. Roesler’s talk
FROM MICROSCOPIC ...

Interplay of many physical processes described by different theories/models integrated in a Monte Carlo code.

6 GeV proton in liquid argon

- Low energy neutron reaction
- Hadron-nucleus reaction
- Electromagnetic shower
- Ionization
- Multiple scattering

Particle decay

Target nucleus

$\eta_c + \pi^+ K^0 K^-$
... TO MACROSCOPIC

LINAC4 and LHC proton beam on a 1 m long and 10 cm radius copper rod

160 MeV

7 TeV

1.680 TeV escaping

5.089 TeV

231 GeV into mass

2.45 MeV escaping

151.8 MeV

5.75 MeV into mass

dE/dx [GeV/mm per proton]

depth [cm]
in principle any relevant object can be implemented to a meaningful detail
LINE BUILDER

THE FLUKA LINEBUILDER AND ELEMENT DATABASE: TOOLS FOR BUILDING COMPLEX MODELS OF ACCELERATOR BEAM LINES

A. Mereghetti et al., IPAC2012

IR7, generated from the optics lattice
IR1

Long Straight Section and Dispersion Suppressor
Right of ATLAS

LHC-IR1, v6.503 nominal optics

Tracking accuracy within one micron
over several hundred meters in a 3D geometry
with various magnetic fields
HL-LHC IR IN FLUKA

beam screen gap (10 or 50 cm) in the middle of the interconnects

(coil) aperture 150mm
HL-LHC IR IN MARS

Q1  Q2A  Q2B  CP  Q3  D1

IP  TAS
DOSE TO THE BEAM SCREEN

several hundred MGy over the machine lifetime
QUADRUPOLES, CORRECTORS AND SEPARATION DIPOLE

Longitudinal peak power profile on inner coils @ $L=5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

- **Q1**, **Q2A**, **Q2B**, **Q3**, **MCBX3**, **D1**

- **Peak power (mW/cm$^3$)**
  - FLUKA
  - MARS

- **Peak dose (MGy/3000 fb)**
  - FLUKA (coils)
  - FLUKA (epoxy)
  - MARS (coils)
  - MARS (kapton)

**dose in the coils**

Critical dependence on the actual Inermet shielding **shape and gaps**

700 W in the cold masses + 550 W in the beam screen + 1.2 kW in the TAN
NOT HOMOGENEOUS DISTRIBUTION

7+7 TeV proton interactions, vertical crossing

Q1A @ non-IP side

monitor signal

$\sqrt{s} = 14$ TeV pp collisions - vertical crossing
inner
Point 1

[GeV/g per collision]
BLM MEASUREMENTS AND SIMULATIONS

- FLUKA is based, as far as possible, on well benchmarked microscopic models.
- However, first years of LHC operation also allowed to validate FLUKA dose predictions against Beam Loss Monitors (BLMs) measurements.
- BLMs measure dose from secondary showers in machine elements (magnets, collimators, etc.).
- Several thousand BLMs are installed around the ring (ICs, filled with N₂ gas, about 1500 cm² active vol.).

**Losses induced by beam wire scanner** (p≈3.5 TeV)
- Quench test 2010 in LHC IR4 (M. Sapinski et al.)
- Wire scans: showers due to collision products registered in BLMs installed on downstream magnets (∼35 from wire scanner)

**Direct losses on MQ beam screen** (p≈4 TeV)
- Quench test 2013 in arc sector 56 (A. Priebe et al.)
- Proton losses on beam screen (over ∼1.5 m) by means of orbit bump/beam excitation, dose measured by BLMs outside of MQ cryostat

[† input from V. Chetvertkova et al.]
LOOKING FARTHER FROM THE BEAM

High energy hadron equivalent fluence

Power Supply 24VDC 5A

F. Cerutti
June 13, 2014
HL-LHC Standards and Best Practices Workshop
RADIATION EFFECTS ON ELECTRONICS

Intermediate energy neutrons: low energy elastic/inelastic products

Thermal neutrons:
\[ n + ^{10}B \rightarrow ^{7}Li + ^{4}He, \text{etc.} \]

Low energy charged hadrons: direct ionization
(relevant for very sensitive technologies)
## RADIATION EFFECTS ON ELECTRONICS

<table>
<thead>
<tr>
<th>Single Event effects</th>
<th>Single Event Upset (SEU)</th>
<th>Memory bit flip (soft error) Temporary functional failure</th>
<th>High energy hadron fluence [cm(^{-2})] (but also thermal neutrons!)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Random in time)</td>
<td>Single Event Latchup (SEL)</td>
<td>Abnormal high current state Permanent/destructive if not protected</td>
<td>High energy hadron fluence [cm(^{-2})]</td>
</tr>
<tr>
<td>Cumulative effects</td>
<td>Total Ionizing Dose (TID)</td>
<td>Charge build-up in oxide Threshold shift &amp; increased leakage current Ultimately destructive</td>
<td>Ionizing dose [Gy]</td>
</tr>
<tr>
<td>(Long term)</td>
<td>Displacement damage</td>
<td>Atomic displacements Degradation over time Ultimately destructive</td>
<td>Silicon 1 MeV-equivalent neutron fluence [cm(^{-2})] {NIEL -&gt; DPA}</td>
</tr>
</tbody>
</table>
Numerous systems with commercial components are affected (powering, control, cooling, monitoring, etc.), several are critical for beam operation, some have to be located in “high-radiation” areas.

Presently about 50 different system, half of them undergoing new developments, others upgrades. Number of parts per system range from a few to a some thousand.

\[ N_{\text{failures}} = \int \phi(x) \sigma(x) dx \times N_{\text{devices}} \sim \Phi(x > X) \sigma \times N_{\text{devices}} \]

Reliability = low number of failures → short down-times!
BEST PRACTICES

Radiation tests are a phase of a new component development
Radiation constraints to be considered from day-0

REQUIREMENTS
- Electrical system
  - Radiation environment and effects
  - Timeline

DESIGN
- Specifications
- Selection
- Design

TEST
- System
- Component Qualification

PROCUREMENT
- Test boards
- Prototype
- Production
LOOKING FARTHER FROM THE IP

D2: 65 W

in its Nb-Ti coils peaks of 2 mW/cm³ @ 5L₀ and 35 MGy /3000 fb⁻¹
(to be improved)

protection based on the TAN absorber, TCL debris collimators and tungsten masks
ANOTHER ELECTRONICS ALCOVE

250 m downstream CMS

23 fb⁻¹ @ 4+4 TeV

2012 operation neutron fluence

<table>
<thead>
<tr>
<th>$F_{H&gt;20\text{MeV}} , [\text{cm}^{-2}]$</th>
<th>5RM08S</th>
<th>5RM09S</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLUKA</td>
<td>$6.1 \times 10^8$</td>
<td>$3.0 \times 10^7$</td>
</tr>
<tr>
<td>DATA</td>
<td>$4.56 \times 10^8$ (256 upsets)</td>
<td>$4.32 \times 10^7$ (25 upsets)</td>
</tr>
</tbody>
</table>

Agreement within 30%
Currently used *physics and geometry models* allow to reliably simulate *secondary particle showers* to many purposes (*beam intercepting device design, cold and warm magnet protection, monitoring, radiation to electronics, operation assistance, background, ..., activation*). *next talk*

Think about the radiation field and let us know if you need its characterization.

Systematic uncertainties imply to consider suitable design margins.
WHATEVER