FLUKA Monte Carlo modelling of the FCC arc cell: radiation environment and energy deposition due to beam-gas interaction
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FCC Week 2017, 29 May 2017 - 2 June 2017, Berlin, Germany
Introduction: R2E studies applied to FCC

- Consists of experts in various fields related to electronics damage
- Coordinates studies to minimize all risks of radiation-induced failures at CERN accelerators
- The main goals of the R2E-oriented studies are:
  - to define and quantify the effects of the radiation on the electronics;
  - to monitor and/or estimate the radiation levels in the concerned area;
  - to test and develop radiation-hard or sufficiently tolerant electronics;
  - to implement mitigation options.

- Integrated in the R2E mission
- Based on the well-consolidated experience from LHC
- Study of the radiation levels in critical areas for electronics
- Extensive use of FLUKA Monte Carlo simulation

- Increase FCC reliability by factors to reach performance goals
- Design of “optimized” areas for electronics
- (First) Evaluation of the requirements and constraints
- Lifetime and choice of critical components
Radiation sources critical for electronics:
• Particle debris from collisions in IPs (LSS)
• Direct Losses in collimators and absorbers (DS)
• Beam-gas interaction (ARC)

Cumulative Effects

- **Deterministic Effects**, Easy to predict
- Proportional to Total Ionizing Dose (TID)
- LHC absolute values typically not critical (especially in shielded areas)
- Scaling of components positive for TID (smaller oxides)

Single Event Effects

- **Stochastic Effects**, Hard to predict
- Proportional to High Energy Hadrons fluence
- Absolute levels are high, even in shielded areas (neutrons)
- Most effects are constant with scaling but they can also increase (proton direct ionization, etc.)
Considerable amount of work done in 2016 within the FLUKA team in the FCC framework

- Scaling form LHC data
  [Link](https://indico.cern.ch/event/486275/contributions/1164475/subcontributions/197611/attachments/1282506/20160601_FCCScaling.pdf)
- FLUKA MC simulation of a full arc cell: Radiation Levels
  [Link](https://indico.cern.ch/event/580163/contributions/2351810/attachments/1360751/2065629/20161103_FCC_Rad_Lev_ICRSup.pdf)

Significant update of the infrastructure in 2017

- Assessment of different relevant quantities for the design of the arc:
  - **R2E: radiation levels in critical areas for electronics**
    - Dose -> Cumulative Effects
    - Fluence: p, K, π, μ, n, High Energy Hadrons (HEH, >20 MeV) -> SEE
  - **Magnet and Cooling**
    - Peak power density
    - Total power in the cold mass and beam screen
    - Peak dose

**AIM OF THE WORK**

- Significant update of the infrastructure in 2017
- Assessment of different relevant quantities for the design of the arc:
FCC FLUKA modelling: 2017 update

What’s new?
- New layout of the tunnel
- First tentative layout of the alcove
- Up-to-date tentative gas-density profile
- Latest design of the main dipole

FCC FLUKA model
- Full arc cell: $\phi_{int}=6$ m single tunnel + 21 m long alcove
- 12 dipoles (14.3 m) + 2 quadrupoles (6.3m); Total length ~213 m
- (Tentative) Gas-density profile [Courtesy of R. Kersevan]
- 2x Proton beam 50 TeV/c
- Source term: Beam-gas interaction
Model of the arc cell: Tunnel & Alcove

Fresh air duct
Smoke/He extraction
Raw water firefighting
Demineralized water
QRL
Drain

Maze: 900 mm concrete wall
Shielding door: 800 mm concrete
Equipment Rack: 3x row inside the alcove
(Note: Each row divided in 3 blocks in FLUKA)

Original drawings courtesy of Fani Valchkova-Georgieva (EN/INT)
Tentative Gas-Density Profile

\[ \tau = \frac{1}{\sigma_cn} = 100h \]

Gas-Density Profile: Courtesy of R. Kersevan & L. Bellafont (TE-VSC-VSM)
Radiation Levels in the FCC tunnel & alcove
Radiation Levels in the Tunnel

Scoring:
- HEH & DOSE: tunnel & alcove
- Cartesian mesh: ~3M elements
- Particle Spectra in the alcove
- Variance Reduction technique

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Radiation Levels in the Alcove

Simulations confirmed the feasibility of the chicane-shielded door solution.

- HEH fluence, \(3\times10^7\) to \(4\times10^7\) LHC RE areas

- \(10^5 \text{n/cm}^2/\text{y}\) is the atmospheric neutron flux at ground level

- On going studies with RP for finalizing the design of the alcove shielding (thickness of the maze’s wall, materials, etc)

Note: \(10^7\) seconds in data taking – Statistical uncertainty < 5%

*See LHC Project note 363
Radiation Levels in the Alcove

Convergence of the simulation very slow compared with HEH -> more efforts are needed

Dose at the entrance of the maze ~3-6 LHC RE areas*

*See LHC Project note 363
Radiation Levels in the Alcove

- **Note:** $10^7$ seconds in data taking – lethargy plot

- **Tunnel**
  - Maze: before wall
  - Maze: after wall
  - Alcove: after shielding door
  - Alcove: Rack

- **Maze:** Before wall
- **Alcove:** Rack(s)

- **Differential particle distribution in energy for SEE rate calculation**
- **Unknown SEE-cross section**
- **Tunnel:** HEH fluence drives the SEE rate -> potential direct ionization from charged particle [A. Infantino et al., IEEE Transactions On Nuclear Science, 64(1), 2017]
- **Alcove:** particle environment dominated by neutrons -> indirect ionization

\[
\text{SEU rate} = \int_{E_{\text{min}}}^{E_{\text{max}}} dE \left( \frac{d\Phi(E)}{dE} \right) \sigma_{\text{SEU}}(E)
\]

[JEDEC Standard No. 89A]
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Dose [Gy]
Radiation Levels in the Tunnel

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Scoring:
- Average HEH & DOSE profile
- Cartesian mesh: power converter location
- Normalization: $10^7$ s data taking

Note: Statistical uncertainty < 10%
Energy Deposition in the Magnets
MB and MQ magnet
MB and MQ coils

MB

MQ

FCC Beam Screen

\[ \text{Nb}_3\text{Sn} + \text{Cu} + \text{S}2\text{-glass} \]

(\( \frac{1}{3} \) + \( \frac{1}{3} \) + \( \frac{1}{3} \))

Ti-alloy

SS316L

Fe

204 mm

\[ \text{Nb}_3\text{Sn} + \text{Cu} + \text{S}2\text{-glass} \]

Austenitic Steel

Epoxy

Low Carbon Steel
Energy deposition on MB and MQ coils

Note: Beam 1 – Estimated quench limit for Nb₃Sn: 40 mW/cm³
**Energy deposition on MB and MQ coils**

### Total Power [W]

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Cold Mass</th>
<th>Beam Screen</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>2.73</td>
<td>0.48</td>
</tr>
<tr>
<td>B2</td>
<td>3.69</td>
<td>0.83</td>
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<tr>
<td>B3</td>
<td>2.79</td>
<td>0.60</td>
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<tr>
<td>B4</td>
<td>2.78</td>
<td>0.60</td>
</tr>
<tr>
<td>B5</td>
<td>2.76</td>
<td>0.59</td>
</tr>
<tr>
<td>B6</td>
<td>2.77</td>
<td>0.59</td>
</tr>
<tr>
<td>Q1</td>
<td>1.30</td>
<td>0.31</td>
</tr>
<tr>
<td>B7</td>
<td>2.47</td>
<td>0.42</td>
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<tr>
<td>B8</td>
<td>3.57</td>
<td>0.80</td>
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<td>B9</td>
<td>2.74</td>
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<tr>
<td>B10</td>
<td>2.72</td>
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<tr>
<td>B11</td>
<td>2.70</td>
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<tr>
<td>B12</td>
<td>2.71</td>
<td>0.58</td>
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<tr>
<td>Q2</td>
<td>1.31</td>
<td>0.32</td>
</tr>
</tbody>
</table>

**Note:** Beam 1 (0.5 A)

**Average power loss per unit arc-cell length:** ~233 mW/m

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### Total Power [W]

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Cold Mass</th>
<th>Beam Screen</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>5.31</td>
<td>1.05</td>
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<td>B2</td>
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<td>5.81</td>
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<tr>
<td>Q1</td>
<td>2.34</td>
<td>0.53</td>
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<td>B7</td>
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<td>0.99</td>
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<td>1.04</td>
</tr>
<tr>
<td>Q2</td>
<td>2.31</td>
<td>0.53</td>
</tr>
</tbody>
</table>

**Note:** Beam 1 & 2 (1.0 A)

**Average power loss per unit arc-cell length:** ~466 mW/m

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01.06.2017

20
Energy deposition on MB and MQ coils

Note: Beam 1 – Baseline SC magnets dose limit: 30 MGy

Note: 10^7 seconds in data taking

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*Take-Home Message:*

- **Consolidated** experience within the FLUKA team in the evaluation of the *radiation levels* in critical areas for electronics as well as the *radiation load* for magnets

- FLUKA simulation allow for an *accurate modelling of the particle transport at (very) high energy* taking into account all the physics effects, the source term (*Beam-gas interaction*) and the actual geometry of the infrastructures & magnet/coils

- **Radiation levels** in critical areas for electronics
  - **DOSE** (*long term effects*):
    - Tunnel: factor ~200 LHC (power converter locations)
    - Alcove: factor ~3-6 LHC RE areas at the entrance of the maze, more efforts needed for the rack locations
  - **High Energy Hadrons** (*Single Event Effects*):
    - Tunnel: HEH ~500 LHC
    - Alcove: HEH ~3-4 LHC RE areas, *neutrons* dominate the particle environment

- **Radiation load** for the magnets:
  - Peak power density: max value ~0.85 mW/cm³ (<<< estimated quench limit for Nb₃Sn)
  - Total Power: 2nd and 8th are the most stressed magnets
  - Peak dose: ~1.1 MGy in one year of operation (<<< baseline dose limit for SC magnets)
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