Radiation environment assessment in the Experimental Insertion Region and Betatron Cleaning insertion

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R_2E

Introduction

- Experimental Insertion Region (IP A and G)
- Betatron cleaning insertion (IP J)

FLUKA model

- Total Ionizing Dose
- High Energy Hadrons fluence
- 1MeV neutron equivalent fluence
- Comparison with HL-LHC

Radiation Levels

Summary

DISCLOSURE:
Due to time constraints, only main achievements from FCC week 2017 will be presented in this talk. More material in the backup slides or related talks.

A. Infantino (Thursday April 12th, 10:30)
Radiation environment assessment in the FCChh and FCCee machines
Special Technologies session
"R2E": What, How, Why?

Radiation to Electronics -> Coordinates studies to minimize all risks of radiation-induced failures at CERN accelerators

+20 years

R2E strategies and actions

Particle environment

Electronic components

Particle debris
from collisions in IPs (LSS)

Physics models

Direct losses
in collimators and absorbers (DS)

Beam-gas
interaction (ARC)

Failures

- 2011
- 2012
- 2015
- 2016
- 2017
- HL-LHC

\[\text{SEE Induced LHC Dumps} \]

\[\text{Annual Cumulated Luminosity [fb}^{-1}]\]

~12 dumps/fb^-1

~3 dumps/fb^-1

~2 dumps/fb^-1

~1 dumps/fb^-1

~0.5 dumps/fb^-1

~0.1 dumps/fb^-1
**Relevant quantities for R2E-studies**

**DETERMINISTIC EFFECTS**
Cumulative 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 (HEH) fluence*. LHC absolute levels are high, even in shielded areas (neutrons). Most effects are constant with scaling but they can also increase (proton direct ionization, etc.).

**DISPLACEMENT DAMAGE**
Cumulative effects proportional to *1MeV neutron equivalent fluence*. Relevant for the experiments (detectors).
Simulations triggered and finalized the design of dedicated alcoves for the electronics [Link FCC Week 2017 ppt]

Studies of R2E-quantities -> HEH fluence & DOSE ~3-4 LHC RE areas*

Vacuum quality: $\sim 10^{15} \text{ H}_2 \text{ m}^3$ (pessimistic scenario) -> A better vacuum quality can further reduce the radiation levels

*See LHC Project note 363
EXPERIMENTAL INSERTION REGION (IP A and G)
Model of the experimental insertion region

Elements of the EIR

- Latest optics ($L^* = 40\,m$)
- **Complex FLUKA model (~500m)** of the IR including:
  - TAS ($\phi=34\,mm$)
  - Triplet: Q1 ($\phi=164\,mm$), Q2 ($\phi=210\,mm$), Q3 ($\phi=210\,mm$)
  - Correctors ($\phi=210\,mm$)
  - D1 ($\phi=170\,mm$)
  - TAN ($\phi=48\,mm$)
  - D2 ($\phi=80\,mm$)
- Triplet: 35mm thick tungsten **shielding** to protect magnet coils
- **Energy deposition on magnets**: model already used for studies in FCChh general design WG*

*See F. Cerutti at FCC Week 2018.

Infrastructure: tunnel

- Tunnel based on the latest design (**FCCee cross section**)
- Study case: FCCee infrastructure and FCChh machine

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“Review: Operation, reliability, radiation” session - FCC Week 2018, 9-13 April 2018, Amsterdam (NL)
Detector cavern based on the “latest” design (Feb. 2018)
See J. Osborne at FCC week 2018 for latest layouts
Model of the detector already used and optimized in the past from the FLUKA team (link FCC Week 2017)

FLUKA model – This presentation (A. Infantino)
Courtesy of Fani Valchkova-Georgieva (EN-ACE-INT)
Infrastructure: TAS shielding

FLUKA model – This presentation (A. Infantino)

Details of the FLUKA simulations in the backup slides

Infrastructure: cavern

- **TAS:**
  - Located at **35 m from the IP** (according to latest optics with $L^* = 40$ m);
  - Since cavern head wall will be concave, TAS will actually be **inside the detector cavern**;
  - “**Blockhouse**” solution around (**2m concrete** on all sides)

- **Blockhouse adapted to match** optics, machine protection and civil engineering constraints:
  - Inner width: 240 cm (to accommodate partially the Q1)
  - Front wall extended till the end of the balcony

Courtesy of Fani Valchkova-Georgieva (EN-ACE-INT)
Results: High Energy Hadrons & Dose

**Normalization**

**HEH fluence**: Normalized to ultimate conditions and worst case year (2500fb⁻¹/year)

**DOSE/1MeV nₑq fluence**: Normalized to ultimate conditions \( L_{int}=30ab⁻¹ \)
Results: Total Ionizing Dose

Total Ionizing Dose | Ultimate conditions (2500fb^{-1}) | -10cm < Y < 10cm

Distance from the IP [m]

Distance from the IP [m]

R1 - Dose [MGy/250fb^{-1}] , -10cm < Y < 10cm

Distance from IP [m]

HL-LHC courtesy of Andrea Tsinganis (EN-STI-BMI)
Ref: CERN-2017-007-M, p.278-279
Results: Total Ionizing Dose

Total Ionizing Dose

Different Operation Scenarios | X=100cm, Y=0cm

Interconnects

~7MGy

~580kGy

TAN

End of D1

Design 30ab⁻¹ (25 years)
Ultimate 2500fb⁻¹ (17.5 months)

Dose [MGy]

10^3

10

1

10⁻¹

10⁻²

10⁻³

0

50

100

150

200

250

300

350

400

450

500

Distance from the IP [m]

7000 kGy

200 kGy

= 35 < 30000 fb⁻¹

3000 fb⁻¹ × (50 TeV)⁻¹

7 TeV

≈ 48

Scaling: Exponent m=0.75-0.87

HL-LHC courtesy of Andrea Tsinganis (EN-STI-BMI)
Results: 1-MeV Neutron Equivalent fluence

1MeV Neutron Equivalent fluence

Different Operation Scenarios | X=100cm, Y=0cm

~7.0×10^{16} \text{ cm}^{-2}

~5.6×10^{15} \text{ cm}^{-2}

Ultimate 2500fb^{-1} (17.5 months)

Design 30000fb^{-1} (25 years)

\[
7 \times 10^{16} \text{ cm}^{-2} = 70 \times \frac{30000 \text{ fb}^{-1}}{3000 \text{ fb}^{-1}} \times \left( \frac{50 \text{ TeV}}{7 \text{ TeV}} \right)^{m=0.8} \approx 48
\]

1MeV neutron equivalent fluence profile in the tunnel (X=−1.6m, Y=0) (L_{int} = 3000 fb^{-1})

~10^{15} \text{ cm}^{-2}

HL–LHC V1.3 vertical 255 μrad

HL–LHC V1.3 horizontal 255 μrad

HL–LHC courtesy of Andrea Tsinganis (EN-STI-BMI)
Results: High Energy Hadrons fluence

Different Operation Scenarios | X=100cm, Y=0cm

- $5.8 \times 10^{13}$ cm$^{-2}$
- $1.8 \times 10^{14}$ cm$^{-2}$
- $4.8 \times 10^{14}$ cm$^{-2}$
- $2.0 \times 10^{15}$ cm$^{-2}$

Ultimate 2500fb$^{-1}$ (17.5 months)
Design 30000fb$^{-1}$ (25 years)

High energy hadron fluence profile in the tunnel (X=−1.6m, Y=0) ($L_{int} = 250$ fb$^{-1}$)

$4.8 \times 10^{14} \text{cm}^{-2} = 48 \approx \frac{30000 \text{fb}^{-1}}{3000 \text{fb}^{-1}} \times \frac{507 \text{TeV}}{7 \text{TeV}}^{m=0.8}$

HL-LHC courtesy of Andrea Tsinganis (EN-STI-BMI)
Results: Tentative UJs/RRs alcove

100cm Fe + 300cm CC 5x Φ=90cm ducts
Results: Tentative UJs/RRs alcove

High Energy Hadrons fluence | Ultimate conditions (2500fb⁻¹) | Z = 70m

Note: Artefact to speed-up the simulation!
Results: Tentative UJs/RRs alcove

High Energy Hadrons fluence | Ultimate conditions (2500fb⁻¹) | -10cm < Y < 10cm

Note: white part just out of the scale, i.e. <10⁸ HEH cm⁻²

~10^8-10^9 cm⁻²
-> same as HL-LHC!!!

Disclosure:
This is an extreme case to show how it could be possible to reuse the space available in the tunnel! A real optimized engineering solution must be discussed in the IOWG and iterate with different groups (CE, RP, CV, EL, ...). A factor 10-100x HL-LHC UJ can be expected in real life.

BETATRON CLEANING INSERTION
(IP J)
Model of the betatron cleaning insertion

**Elements of the Betatron IR**

- **2.7 km LSS** ≈ 5x LHC
- Main elements:
  - 8 Warm Dipoles (MBW)
  - 24 Warm Quadrupoles (MQW)
  - 2 Primary Collimators (TCP)
  - 11 Secondary Collimators (TCS)
  - 4 Long Absorber (TCLA)
  - 3 Passive Absorbers (TCAP)
- Normalization: $10^{16}$ lost protons/year/beam -> $\sim 10^{15}$ lost protons/year/beam in LHC in 2016/2017*
- Model already used in energy deposition studies**: [M. Varasteh at FCC Week 2018](Tuesday 10th - 14:30)

**Infrastructure**

- No dedicated infrastructure is currently available
- Tentative tunnel cross-section based on the arc-layout

*Courtesy of E. Skordis (EN-STI-BMI)
**Ref: M. Varasteh et al., Energy deposition studies: 30cm TCPs with thicker jaws and no skew
Results: High Energy Hadrons fluence

High Energy Hadrons fluence | $10^{16}$ lost protons | X=100cm, Y=0cm

Note: 2D map refers to Beam 1 only at the level of the second TCP
Results: Total Ionizing Dose

Note: 2D map refers to Beam 1 only at the level of the MBW just after the 1st TCAP
Results: Total Ionizing Dose

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TCP | TCS | TCAP
---|---|---
1010 | 430 | 200 | 80 | 5.4
810 | 980 | 160 | 100 | 9.8
725 | 1330 | 145 | 80 | 16.6

FCC/HL: 7x10^{15} lost p/year/beam based on intensity scaling

FCC:
- Assumption of 10^{16} lost p/year/beam: beam intensity difference FCC/HL < 2
- Shift of the peak dose w.r.t. HL-LHC: Skew TPC removed, TCP jaws shorten (60->30cm) and thicken (2.5->3.5cm), TCS thicken

Note: numbers rounded for presentation purposes; *absolute distance from the IP
Results: LHC UJs/RRs alcoves looking at FCC

LHC IR7 Dashboard:

- 100cm Fe in LHC IR7 Tunnel
- 40cm Fe + 40cm CC in LHC RR73
- 40cm Fe + 200cm CC in LHC UJ76

For a FCC UJ-like:
- Expected ~10x Dose and ~10³x HEH impinging the entrance wall
- To be discussed in IOWG

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Results: Radiation Levels maps

High Energy Hadrons fluence $|10^{16}$ lost protons $|$ Beam 1

$\sim 10^2-10^3 \times$

$\geq 20$ MeV hadron fluence RR77 7 TeV

Distance from the IP [m]

Ref: K. Røed, IR7 FLUKA Simulation Update (2010). Normalization: $1.5E+16$

$\geq 20$ MeV hadron fluence UJ76 7 TeV

Ref: K. Røed, IR7 FLUKA Simulation Update (2010). Normalization: $1.5E+16$

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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 -> e.g. **strong impact** in the design/optimization of **alcoves** in the FCChh arc.

- FLUKA simulation allows for an **accurate modelling of the particle transport at (very) high energy** taking into account all the physics effects, the source term (**particle debris, direct losses, beam-gas interaction**), beam optics and the actual geometry of the infrastructures.

- **Two IPs accurately modelled** including: beam line elements (magnets, collimators, absorbers, ...), FCChh detector, latest infrastructure -> EIR: ~42x40x46m half-detector cavern and 500m LSS; Betatron insertion: ~2.7km LSS -> **significant modelling and computational effort**!

- **Experimental Insertion Region:**
  - Radiation levels expected to be **factors higher** than HL-LHC -> difference given from **integrated luminosity + beam energy**.
  - **Need for a dedicated and optimized areas for electronics** -> possibility to **embed a UJ-like alcove in the LSS enlargement** which reduces, in an extreme case, the radiation levels to HL-LHC (UJ14/16) -> **factor 10-100x higher** can be expected in **real life**.

- **Betatron cleaning insertion:**
  - Differences in the collimation layout lead to a **shift (and increase) of the maximum dose peak** to the last passive absorber
  - Assuming **$10^{16}$ lost protons/year/beam** -> **~16x HL-LHC** at the maximum dose peak (TCAP passive absorber).
  - Assuming a HL-LHC UJ/RR-like layout, expected **~10x Dose** and **~$10^3$x HEH impinging the entrance wall** -> **need for a new/optimized design**.
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BACKUP SLIDES

www.cern.ch
Experimental Insertion Region

- **Source Term:**
  - p-p collisions $\rightarrow \sigma_{pp} (50 \text{ TeV}) = 108 \text{ mb}$
  - Vertical crossing $\rightarrow 89 \mu\text{rad}$
- **Event generator:** *DMPJET-III* (hh/hN $> 20 \text{ TeV/c}$)
- **Variance reduction techniques:**
  - *Multiplicity Bias:* Hadrons & Muons
  - *Leading Particle Bias:* cut-off 1 GeV ($e^-/e^+/\gamma$)
- **Statistics:** 4.8M collisions (HEH); 1M collisions (DOSE/1MEV $n_{eq}$)
- **Normalization:** *Integrated Luminosity* (different operation scenarios $\rightarrow 2500 - 30000 \text{ fb}^{-1}$)

Betatron Cleaning

- **Source Term:** *Loss map* (SixTrack) on primary collimator
- **Event generator:** *DMPJET-III* (hh/hN $> 20 \text{ TeV/c}$)
- **Variance reduction techniques:**
  - *Multiplicity Bias:* Hadrons & Muons
  - *Leading Particle Bias:* cut-off 1 GeV ($e^-/e^+/\gamma$)
- **Statistics:** 1M primary (HEH/1MEV $n_{eq}$); 600k primary (DOSE)
- **Normalization:** $10^{16}$ lost protons/year/beam $\rightarrow$ beam lifetime $\sim 280 \text{ hours}$
Normalization: Integrated Luminosity

**Target Luminosity**

- **Design**: Baseline integrated luminosity $5 \, ab^{-1}$ -> Ultimate integrated luminosity $30 \, ab^{-1}$
- **25 year of operation**:
  - Phase 1 (Baseline): $2.5 \, ab^{-1}$ in the first 10 years -> $250 \, fb^{-1}$/year
  - Phase 2 (Ultimate): $15 \, ab^{-1}$ in the last 15 years -> $1000 \, fb^{-1}$/year
- **pp physics** periods of 17.5 months (max 9.5 months/year)
  - Phase 1 (Baseline):
    - Worst year (9.5 months) -> $\sim 365 \, fb^{-1}$
    - Worst period (17.5 months) -> $\sim 670 \, fb^{-1}$
  - Phase 2 (Ultimate):
    - Worst year (9.5 months)* -> $\sim 1397 \, fb^{-1}$
    - Worst period (17.5 months)* -> $\sim 2570 \, fb^{-1}$

*Note: Rounded to 1400 and 2500 fb$^{-1}$ in this presentation."
EIR: 1-MeV Neutron Equivalent fluence

1 MeV Neutron Equivalent fluence | Ultimate conditions (2500 fb⁻¹) | -10 cm < Y < 10 cm

Distance from the IP [m]

1 MeV neutron equivalent [cm²/250 fb⁻¹]

R1 - 1 MeV neutron equivalent [cm²/250 fb⁻¹], -10 cm < Y < 10 cm

Distance from the IP [m]

1 MeV neutron equivalent [cm²/250 fb⁻¹]

HL-LHC courtesy of Andrea Tsinganis (EN-STI-BMI)
Ref: CERN-2017-007-M, p.278-279
EIR: High Energy Hadrons fluence

High Energy Hadrons fluence | Ultimate conditions (2500fb^-1) | -10cm < Y < 10cm

R1 - High energy hadrons [cm^-2/250fb^-1], -10cm < Y < 10cm

HL-LHC courtesy of Andrea Tsinganis (EN-STI-BMI)
Ref: CERN-2017-007-M, p.278-279
EIR: High Energy Hadrons fluence

High Energy Hadrons fluence

Different Operation Scenarios | X=100cm, Y=0cm

~1.2x10^{15} \text{ cm}^{-2}

~4.7x10^{14} \text{ cm}^{-2}

~1.8x10^{14} \text{ cm}^{-2}

~2.0x10^{12} \text{ cm}^{-2}

High energy hadron fluence profile in the tunnel (X=-1.6m, Y=0m) (L_{\text{int}} = 3000 \text{ fb}^{-1})

~1.2x10^{15} \text{ cm}^{-2}

HL-LHCV1.3 vertical 255 urad

HL-LHCV1.3 horizontal 255 urad

\begin{align*}
5.8 \times 10^{15} \text{ cm}^{-2} & \approx 48 \\
1.2 \times 10^{14} \text{ cm}^{-2} & \approx 30000 \text{ fb}^{-1} \\
& \times \left( \frac{50 \text{TeV}}{7 \text{TeV}} \right)^{m=0.8} \\
& \approx 48
\end{align*}

HL-LHC courtesy of Andrea Tsinganis (EN-STI-BMI)
EIR: Tentative UJs/RRs alcove

High Energy Hadrons fluence | Ultimate conditions (2500 fb⁻¹) | -10cm < Y < 10cm

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Betatron: 1-MeV Neutron Equivalent fluence

1-MeV Neutron Equivalent fluence | $10^{16}$ lost protons | X=100cm, Y=0cm

Distance from the IP [m]

Note: 3D map refers to Beam 1 only at the level of the TCP/TCAP
Betatron: Radiation Levels maps

High Energy Hadrons fluence | $10^{16}$ lost protons | Beam 1

Total Ionizing Dose | $10^{16}$ lost protons | Beam 1

1-MeV Neutron Equivalent fluence | $10^{16}$ lost protons | Beam 1

Distance from the IP [m]
Assuming a scaling $(6.5/3.5)^{0.8} \approx 1.6 \Rightarrow \Phi_{\text{HEH}}(\text{RML703}) = 3.2 \times 10^{10} \text{cm}^{-2} \text{y}^{-1}$

Factor $\sim 10^4$ K. Røed’s LHC IR7 FLUKA simulations

Overall, FCC will see fluences a factor $10^3$-$10^4$ higher

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Normalization: 2.0E+16 lost protons/year (M. Brugger et al., CERN-AB-Note-2008-031-ATB)