Radiation environment assessment in the FCChh and FCCee machines

Angelo Infantino, Rubén García Alía, Markus Brugger, Francesco Cerutti

CERN
FLUKA Team & R2E-Project

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Special Technologies session ‘Electronics & Instrumentation- FCC Week 2018, 9-13 April 2018, Amsterdam (NL)

Introduction

R₂E-FLUKA studies

- FCChh
  - Arc
  - Detector
  - Experimental Insertion Region (IP A and G)
  - Betatron cleaning (IP J)
- FCCee
  - Arc
  - HE-LHC

Radiation Levels

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

Summary

DISCLOSURE:
Due to time constraints, only results/main achievements will be presented in this talk. More information about the FLUKA models/simulations are reported in the backup-slides or related talks.
Introduction: “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**

[Diagram showing the radiation environment, electronic components, physics models, and particle environment]

[Graph showing SEE induced LHC Dumps vs. Annual Cumulated Luminosity [fb^-1] with data points for years 2011 to 2017 including HL-LHC.]
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.).

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).

DISPLACEMENT DAMAGE

Cumulative effects proportional to 1MeV neutron equivalent fluence. Relevant for the experiments (detectors).
FCChh: DETECTOR (IP A and G)
FCChh: Detector (FCC Week 2017)

Dose for 30 ab\(^{-1}\)

Hadronic calorimeter (scintillator):
- barrel: 6 kGy
- extended barrel: 8 kGy
- previous layout: 3 kGy, with 40% longer tracker and 10% deeper EM-calos

Central tracker:
- first IB layer (2.5 cm): \(-400\) MGy
- external part: \(0.1\) MGy

Forward calorimeters:
- EM-calos: \(5000\) MGy
- HAD-calos: \(-1000\) MGy
- at R=2 m the dose is \(-1\) MGy

Simulations courtesy of Maria Ilaria Besana (EN-STI-BMI)
Ref: FCC Week 2017
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1 MeV Neutron Equivalent Fluence for 30 ab⁻¹

- Barrel calorimeter:
  - EM-cal: 4 \times 10^{15} \text{ cm}² & HAD-cal: 4 \times 10^{14} \text{ cm}²
  - higher values wrt previous layout
- End-cap calorimeter:
  - EM-cal: 2.5 \times 10^{16} \text{ cm}²
  - HAD-cal: 1.5 \times 10^{16} \text{ cm}²
- Forward calorimeters:
  - maximum at \approx 5 \times 10^{18} \text{ cm}² for both the EM and the HAD-calos
  - \approx 10^{16} \text{ cm}² at R=2 m
  - previous simulations: 7 \times 10^{16} \text{ cm}²
  - EM-cal and 4 \times 10^{18} \text{ cm}² HAD calo
- Muon Chambers:
  - barrel: 10^{22} \text{ cm}²
  - end-cap: 10^{23} \text{ cm}²
  - forward: up to 10^{27} \text{ cm}², 10^{35} at R=2 m

Estimated levels of first pixel layers at r = 3.7 cm
- HL-LHC 3ab⁻¹ (Target for current Irradiation Facilities)
  - 1 MeV neq Fluence = 1.5 \times 10^{16} \text{ cm}², Dose = 5MGy
- For radi\lesssim 50-60 cm fluence exceeds the value expected at HL-LHC (10^{16} \text{ cm}²) by \approx 2 orders of magnitude

Simulations courtesy of Maria Ilaria Besana (EN-STI-BMI)
FCChh: ARC
FCChh: ARC (FCC Week 2017)

Ref: A. Infantino et al. (FCC Week 2017)

Note: $10^7$ seconds in data taking (both plot)

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Simulations triggered and finalized the design of dedicated alcoves for the electronics

Studies of $R^2E$-quantities -> HEH fluence & DOSE $\sim 3-4$ 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

Note: $10^3$ seconds in data taking – Statistical uncertainty < 5%
FCChh: EXPERIMENTAL INSERTION REGION (IP A and G)
**FCChh: Experimental Insertion Region (2018)**

Normalization

- **HEH fluence**: Normalized to ultimate conditions and worst case year (2500 fb\(^{-1}\)/year)
- **DOSE/1MeV \(n_{eq}\) fluence**: Normalized to ultimate conditions \(L_{int}=30ab^{-1}\)

Ref: A. Infantino et al. (FCC Week 2018)
FCChh: Experimental Insertion Region (2018)

Total Ionizing Dose

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

- Interconnects
- TAN
- ~7MGy
- ~580kGy

End of D1

Design 30ab\textsuperscript{1} (25 years)
Ultimate 2500fb\textsuperscript{-1} (17.5 months)

Dose profile in the tunnel (X=-1.6m, Y=0) (L\textsubscript{int} = 3000 fb\textsuperscript{-1})

- HL-LHV1.3 vertical 255 μrad
- HL-LHV1.3 horizontal 255 μrad

<200 kGy

Scaling: Exponent m=0.75-0.87

\[ \frac{7000 \text{ kGy}}{200 \text{ kGy}} = 35 \leq \frac{3000 \text{ fb}^{-1}}{3000 \text{ fb}^{-1}} \times \left( \frac{50 \text{ TeV}}{7 \text{ TeV}} \right)^{m=0.8} \approx 48 \]

HL-LHC courtesy of Andrea Tsinganis (EN-STI-BMI)

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High Energy Hadrons fluence

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

- $10^{16}$ cm$^{-2}$
- $10^{15}$ cm$^{-2}$
- $10^{14}$ cm$^{-2}$
- $10^{13}$ cm$^{-2}$

Distance from the IP [m]

- 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$^{-1}$)

- ~$1.0 \times 10^{13}$ cm$^{-2}$
- ~$4.8 \times 10^{14}$ cm$^{-2}$
- ~$2.0 \times 10^{15}$ cm$^{-2}$

Distance from IP [m]

$4.8 \times 10^{14} \text{ cm}^{-2} = 48 \approx \frac{30000 \text{ fb}^{-1}}{3000 \text{ fb}^{-1}} \times \left(\frac{50 \text{ TeV}}{7 \text{ TeV}}\right)^{m=0.8} \approx 48$

HL-LHC courtesy of Andrea Tsinganis (EN-STI-BMI)
FCChh: Experimental Insertion Region (2018)

100cm Fe + 300cm CC
5x Φ=90cm ducts
FCChh: Experimental Insertion Region (2018)

Note: Artefact to speed-up the simulation!
FCChh: Experimental Insertion Region (2018)

Note: white part just out of the scale, i.e. \(<10^7\) HEH cm\(^2\)

~\(10^8-10^9\) cm\(^2\)

\(\rightarrow\) 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 \(10-100\times\) HL-LHC UJ can be expected in real life.

HL-LHC courtesy of Andrea Tsinganis (EN-SEI-BM)
Ref: CERN-2017-007-M, p.278-279
FCChh: BETATRON CLEANING (IP J)
FCChh: Betatron cleaning insertion (2018)

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

**Note:** 2D map refers to Beam 1 only at the level of the second TCP

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A few considerations...

- HL-LHC: $7 \times 10^{15}$ 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

| TC(X) | $|Z|^*$[m] | $D[kGy]$ | $|Z|^*$/m | $D[kGy]$ | FCC/HL |
|-------|------------|----------|-----------|----------|--------|
| TCP   | 1010       | 430      | 200       | 80       | 5.4    |
| TCS   | 810        | 980      | 160       | 100      | 9.8    |
| TCAP  | 725        | 1330     | 145       | 80       | 16.6   |

Note: numbers rounded for presentation purposes; *absolute distance from the IP
LHC IR7 Tunnel: 100cm Fe  
LHC RR73: 40cm Fe + 40cm CC

For a FCC UJ-like: Expected ~10x Dose and ~10^3 x HEH impinging the entrance wall
-> To be discussed in IOWG

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FCChh: Summary

What we have:

- Excellent coverage of the machine with several IPs already studied:
  - High-luminosity experiments (IP A and G): detector + insertion region
  - Arc: FLUKA-R2E studies crucial in the design & optimization of safe-areas for electronics
  - Betatron cleaning (IP J): Overview of the radiation levels

What we need:

- Detector: new iterations planned for post-CDR
- EIR: Need for a suitable solution for safe-areas for electronics (UJ/RR-like? embedded alcove? Junction tunnel?)
- Betatron cleaning:
  - iterate in the IOWG for a dedicated infrastructure design which fits R2E-needs
  - DS: typically of interest for R2E
- Dump (IP D): dedicated studies are necessary, but information needed for R2E-studies are still partially available
- Injection: no specific requests at moment
FCCee: ARC
FCCee: Arc (FCC Week 2016)

Simulations courtesy of Maria Ilaria Besana (EN-STI-BMI)

Cell top view:

Dipole:

Absorber:

✓ Dose in the tunnel up to ~1-2 MGy (difference between internal/external beam due to absorbers)

Note on FCCee Experiments (IP A and G):

$e^-e^+$ event generator currently not implemented in FLUKA

--> possible 2-steps simulation with an external $e^-e^+$ event generator
FCCee: Arc – Update of the model (2018)

- Vacuum chamber cross section: 70 mm ID with “winglets” in the plane of the orbit (SUPERKEKB-like)
- More information on the vacuum system in [R. Kersevan at FCC Week 2018](#)
- Missing inputs/data necessary to perform FLUKA simulations!

Courtesy of Roberto Kersevan & Miguel Gil Costa (TE-VSC)

FLUKA model (2018) – Angelo Infantino
FCCee: Summary

**What we have:**

- First estimate (2016) of the radiation levels in the arc close to magnet

**What we need:**

- A *major revision/update* of the FCCee FLUKA model is *currently ongoing* in order to take into account:
  - Up-to-date lattice in the arc (usable twiss?)
  - Up-to-date design of magnets
  - Up-to-date vacuum chamber layout and absorbers
  - Up-to-date infrastructure (tunnel)
- With all the necessary inputs, an updated study might be performed for the second revision of the CDR
- *Event generator* for $e^+/e^-$ collisions at IP -> to be interfaced
HE-LHC
General lack of results/available studies up to a few weeks ago

Already some requests on the table of the FLUKA team but:

- Simulations rely on inputs/data coming from different groups (optics, CE, vacuum, magnets, etc) -> **up to today, many information are missing**!
- Need of resources in terms of manpower to cover all the requests (both R2E and non-R2E related studies)

What we have:

- ARC (Beam-gas interactions):
  - Already on the table of FLUKA team
  - Shopping list: Optics? Magnets? Vacuum?
  - Adapted tunnel layout available -> Radiation levels to be verified
- Other IR: EIR? Betatron cleaning? Dump?
Summary

**Take-Home Message:**

- **Consolidated** experience within the FLUKA team in R2E-related studies, particularly 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, synchrotron radiation*), beam optics and the actual geometry of the infrastructure
- Monte Carlo simulation is a very powerful tool but relies on the accurate description of the physics problem to be studied, i.e. *information from different groups are needed to perform accurate simulations!*
- **FCCChh:**
  - Good coverage of the main critical areas for electronics
  - Radiation levels expected to be factors higher than HL-LHC -> dedicated alcoves for electronics and R2E-qualification strategies are needed
  - FLUKA simulation already used in the design/optimization of safe-areas for electronics
- **FCCee:** ongoing major update of the arc model -> simulations ready by II-review of the CDR (if all inputs acquired)
- **HE-LHC:** requests already on the table of the FLUKA tam but several information are missing to perform simulations
- A **considerable** amount of work has been done in these years within the FLUKA team and even more is expected in the short-mid term, i.e. *FLUKA modelling doesn’t stop with the CDR -> manpower is needed to cover all these studies!*
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Angelo Infantino
CERN EN-STI-BMI
FLUKA Team - R2E Project
@ angelo.infantino@cern.ch
www.cern.ch
List of related talks

**FCCeh**
- M.I. Besana et al., *Update on Energy Deposition for L* 40 m*. WP3 meeting.
- A. Infantino et al., *Baseline EIR: Energy Deposition Studies for L* = 40m*. EuroCirCol Meeting.
- M.I. Besana et al., *Energy deposition studies: 30cm TCPs with thicker jaws and no skew*. FCC collimation design meeting #14.
- J. Keintzel et al., *Updated picture of the collision debris impact on the FCChh triplet-D2 region*. FCChh General Design meeting.

**FCCee**
FCChh: ARC - Radiation Levels in the Tunnel

Note: Statistical uncertainty < 10%

Note: Statistical uncertainty < 2%

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FCChh: ARC - Radiation Levels in the Alcove

Note: $10^7$ seconds in data taking

- Convergence of the simulation very slow compared with HEH
  -> more efforts were needed
- Dose at the entrance of the maze ~3-6 LHC RE areas*

*See LHC Project note 363

Note: EMF ON; Preliminary ~38k primary; Final 150k primary + average in the alcove
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
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FCChh: EIR - High Energy Hadrons fluence

Ref: CERN-2017-007-M, p.278-279

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

$\text{Equivalent fluence} \sim 10^{15}\text{ cm}^{-2}$

$7 \times 10^{16}\text{ cm}^{-2} = 30000 fb^{-1} \times \left(\frac{50 T eV}{7 T eV}\right)^{m=0.8} \approx 48$

HL-LHC courtesy of Andrea Tsinganis (EN-STI-BMI)
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A factor $10$-$100x$ HL-LHC UJ can be expected in real life.
FCChh: Betatron - Total Ionizing Dose

Total Ionizing Dose | $10^{16}$ lost protons | $X=100\,\text{cm}$, $Y=0\,\text{cm}$

Note: 2D map refers to Beam 1 only at the level of the MBW just after the 1st TCAP
FCChh: 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]
FCChh: Betatron - Radiation Levels maps

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

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

>20 MeV hadron fluence  RR77  7 TeV

Distance from the IP [m]

20 MeV hadron fluence  UJ76  7 TeV

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