Accelerator Technology Challenges (Part 3) : Accelerator operation and design challenges (2/2)

Francesc Salvat Pujol

Yesterday: beam losses and their challenges to accelerator operation
Today: challenges in the design of particle accelerators

With precious input from many CERN colleagues, especially A. Lechner, B. Humann, D. Calzolari
Plan ahead

- Yesterday: beam losses
  - Operational implications, microscopic description, macroscopic effects (heating, displacement damage, activation, etc).
- Beam-matter interaction
- Monte Carlo simulation tools
- Today: MC as a tool to overcome challenges in accelerator design

Radiation shower set up by a single 450 GeV p loss
Specifically

- A more detailed introduction to **Monte Carlo simulation** of particle transport for beam-matter interaction problems:
  ![FLUKA](image1.png)
  ![Geant4](image2.png)

- **Application**: design of components for the present LHC and its upgrade // limits on lifetime of components

- Basic interaction mechanisms of e-, e+, and photons

- **Applications** in the design future lepton machines:
  - FCCee
  - Muon collider

- Hadrons
- Leptons
An introduction to the Monte Carlo method for the simulation of beam-matter interaction
The radiation transport problem

- Thus far: beam losses and beam-matter interaction for particle accelerator components
- Underlying problem is much more general: **radiation transport**

![Diagram of radiation transport](source: Wikipedia)

- Governed by the **Boltzmann transport equation** (not trivial to solve)
- We want instead a **general solution method** that works for arbitrary sources, arbitrary geometries, and which allows to score a large number of observables: energy deposition, particle spectra, activation, etc
Two basic ingredients: cross section and mean free path

- **Cross section**: measure of the likelihood of an interaction

  \[
  \frac{d^2\sigma}{d\Omega \ dW} = \frac{\dot{N}_{\text{count}}}{|J_{\text{inc}}| \ d\Omega \ dW}
  \]

  Dimensions of \(L^2/E/\text{solid angle}\)

  Typical unit: 1 barn = \(10^{-24}\) cm\(^2\)

- **What? A surface to measure likelihood of interaction?**

- **Usefulness becomes clear if you think of a volume with \(N\) targets per unit volume. Mean free path (\(\lambda\)): average distance to the next interaction**

  \[
  \lambda = \frac{1}{N\sigma}
  \]

  Dimensions of \(L\)

Derivation and figures: PENEOLOPE manual (NEA 2018)
The Monte Carlo method

- List of particles: e-, e+, g, p, n, …
- List of interaction mechanisms (integrated and diff cross section for each)
- Define radiation source and material geometry
- Evaluate mean free path $\lambda(E)$
- Sample random step length $s$ to next interaction
- Decide kind of interaction: A, B, C, D,…
- Sample final state (possible secondaries)
- Contribute to statistical estimator of desired observables
- Sample an ensemble of particle trajectories

Ex: 10 MeV e- in Cu, 50 histories
Scale: few mm depth
Photons: long steps/range (e-e+ pair produced!)
Electrons: multiple interactions, corrugated trajectories

MARS, PHITS, MCNP, PENELOPE, EGS, …
“The purpose of simulation is insight, not numbers”

- Artistically pleasing as simulated radiation showers may be, one does not perform MC simulations for aesthetic purposes.

- The purpose is to gain insight into a given problem.

- In order to assess the effect of beam losses in materials, we want to extract relevant physical observables from MC simulations.
### Relevant quantities from MC simulations for beam-loss effects

**Short-term effects**
- Relevant quantity: Energy/Power deposition
- Allows to assess e.g.:
  - If a given beam loss is sufficient to bring a SC magnet beyond its quench limit
  - Whether a beam loss leads to sufficient energy deposition to melt target material

**Long-term effects**
- Dose during e.g. one operational year:
  - E.g., dose imparted to SC magnet insulators -> degradation and long-term failure
- Displacements per atom (DPA):
  - Recoil -> Frenkel pairs
  - Correlates well with displacement damage
  - Microscopic structural defects
Example for HL-LHC
Power leakage from ATLAS collision to the LHC

- ATLAS is huge: L~44 m, h~22 m, several 1000 tonnes
- Two counter-rotating beams collide at the IP
- Purpose: study new/exotic particles
- But one should not forget about the rest / known particles!
- **Question:** how much power is released in these collisions?

One first needs to know the collision rate

**Peak luminosity (2018):** \( \mathcal{L} \approx 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)

**Inelastic pp x-section:** \( \sigma_{\text{inel}} = 80 \text{ mb} \) (=80 \times 10^{-27} \text{ cm}^2)

\[ \Rightarrow \mathcal{L} \cdot \sigma_{\text{inel}} = 1.6 \times 10^9 \text{ collisions/s} \]

\[ \Rightarrow 2 \cdot 6500 \text{ GeV} \cdot 1.602 \times 10^{-10} \frac{\text{J}}{\text{GeV}} \cdot 1.6 \times 10^9 \text{ coll/s} = 3.3 \text{ kW (≈kJ/s)} \]

**This is the released power in collisions at the ATLAS interaction point**

- **Does it affect nearby machine components, e.g. superconducting magnets?**
Typical collision products from p-p collisions in ATLAS

- p-p collision at 14 TeV CMS energy:
  - Plenty of photons (nearly 100), from decay of produced pi0
  - Charged pions, kaons, p, n, pbar, nbar: ~1-10

- Interesting particles are much rarer: 1e-10 probability for producing a Higgs boson (hence need for ever higher luminosities – HL-LHC!)

- While collisions are performed to search for new/exotic particles, a large fraction of secondaries are well known particles

- No new exciting physics, but they pose a serious problem

- In blue: number of particles leaving the ATLAS chamber through the vacuum chamber back into the LHC.
Particles and power leakage from the ATLAS IP back to the LHC

Roughly 5% of the secondary particles reach the LHC machine

but:

they carry about 70% of the power released in the collisions!!!

Let that sink in: of the available 3.3 kW released per collision, 2.4 kW goes back into the LHC

Where does this power go? Where is it eventually deposited? Does it put superconducting magnets at risk / constrain their operation? How do we protect them accordingly?
Our sentinels: beam-loss monitors (BLM)

Beam loss monitor: ionization chambers (they measure dose rate in a given time window)

There are a few thousand of them along the LHC.

If BLM signal(s) go above threshold, this may lead to an extraction of the beam (dump)

Collision debris from the interaction point can be seen 700 m downstream at either side

Most delicate equipment nearby: inner triplet quadrupoles (they squeeze the colliding beams into the interaction point). These are superconducting magnets(!)
Inner triplet W shielding for HL-LHC

- Inner triplets are exposed to energetic charged hadrons leaking from IP, now impacting on the magnet.
- These are strong magnets: they capture charged particles.
- Without protection: immediate quench of the magnet.
- In view of increased luminosity (HL-LHC), it was suggested to insert W inserts inside the vacuum chamber to shield the SC coils of the inner triplet magnets.

HL-LHC upgrade:
Inner triplet W shielding for HL-LHC

- Intention: ensure that inner triplet lifetime is not compromised by radiation damage for the duration of the HL-LHC project

Plot below: dose distribution at peak cumulated luminosity of 3000 fb\(^{-1}\) in presence of the W shield
- This is below limit for long-term operation known for cold magnets in the LHC, \(~30\) MGy.
- The shielding does its intended job! It was recently prototyped and tested.

Beam loss / radiation source → MC simulation → Mitigation strategy

**Key element during design → shielding:**
- avoid quenches
- avoid that magnet fails due to long-term radiation damage

Dose < 30 MGy
Thus far we’ve just spoken about hadron machines

What about lepton machines?

Interlude: relevant interaction mechanisms of e−, e+, photons
Short recap - Electron and positron interactions

- Elastic scattering
- Inelastic scattering
- Bremsstrahlung emission
- Positron annihilation

*Synchrotron radiation emission in B fields!

*most relevant mechanisms for the examples below

Figures: PENEOLOPE manual (NEA 2018)
Energy loss / slowing down of $e^+$-$e^-$: stopping power

- Stopping power: average energy loss per unit path length
- At high energies: **Bremsstrahlung emission** dominates
- At low energies: Ionization losses dominate

If you want to attenuate $e^-$ beams, the higher the Z, the better

https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html
Most relevant interaction mechanisms of photons

- Photonuclear reactions:
  - $(\gamma, n)$, $(\gamma, 2n)$, …
  - $\mu^\pm$ pair production

*most relevant mechanisms for the examples below

Figures: PENELlope manual (NEA 2018)
Photon interaction cross sections

- Photoelectric effect dominates at low energies (signatures from various ionization edges)
- Compton dominates at intermediate energies
- **Pair production is what matters at high energies**
- Photonuclear cross section is rather low
Photon mean free paths (same info, now in terms of avg interaction length)

- **MFP for e⁻/e⁺ pair production:**
  - **C:** $O(1 \text{ cm})$
  - **W:** $O(1 \text{ mm})$

In anticipation of an example below: if one wishes to produce e⁺ from energetic photons, the larger the Z of the target material, the better!
After this brief interlude on e-/e+ and photon interactions, we go back to the leitmotiv of this lecture: "...but now applied to the design of future particle accelerators."
FYI: ESPPU

- Feel free to take a look at the *European Strategy for Particle Physics Update*, to see where the particle physics world at large is going in the future.
- “The ESPPU identified five key areas where an intensification of R&D is required to meet scientific goals:

1. Further development of high-field superconducting magnet technology.
2. Advanced technologies for superconducting and normal-conducting radio frequency (RF) accelerating structures.
4. **Studies and development towards future bright muon beams and muon colliders.**
5. Advancement and exploitation of energy-recovery linear accelerator technology.

- We shall now close this lecture series with two examples: one on FCC, one on muon collider.

Ref: [https://e-publishing.cern.ch/index.php/CYRM/issue/view/146](https://e-publishing.cern.ch/index.php/CYRM/issue/view/146)
Future colliders

For today’s lecture we just need to recall two big ongoing projects:

- **FCC:** ~100 km long circular collider
- **Muon collider**

More details, machine specs, aims, etc., see B. Dalena’s lectures on Mon, Jul 10 and Tue, Jul 11: “Future High-Energy Collider Projects (1 and 2)"

We will here merely focus on a few open design challenges presently under study
Future Circular Collider (FCC)

- ~100 km length
- Lepton machine first: FCCee
- Same infrastructure for a posterior hadron-hadron collider (FCChh)

See this link for a few more details, conceptual design report, etc.

https://fcc-cdr.web.cern.ch/
FCCee Conceptual design report

- Freely accessible: https://link.springer.com/article/10.1140/epjst/e2019-900045-4
- 360 pages: gives you an idea of the amount of work that goes into the design of an accelerator (even if the injector chain at CERN can be reused for it)

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https://doi.org/10.1140/epjst/e2019-900045-4

FCC-ee: The Lepton Collider
Future Circular Collider Conceptual Design Report Volume 2
FCC ee: electron positron collider

- ~91 km tunnel enclosing the Saleve
- 6 GeV $e^-$ on heavy target $\rightarrow$ $e^+$ production
- Initial acceleration to 20 GeV
- Injection to booster ring (20 GeV to final energy of 45 GeV – 182.5 GeV)
- Injection to collider ring
Aspects we will focus on

- Emission of synchrotron radiation on the arc of the collider
- Positron production target
FCCee positron production target

- Basic idea (combination of 2 interaction mechanisms we saw):
  - 6 GeV e- on a target → Bremsstrahlung emission → pair production
- Let’s recover the photon cross section plots from a few slides ago, focusing at the GeV end. Suppose two candidate materials: C and W

Given GeV photons, would you take C or W for the e+ production target?
You want bremsstrahlung photons to generate e-/e+ pairs as copiously as possible

So indeed, you’d take W (highest pair-production cross section, by almost an order of magnitude)

 Turns out not to be far from the actual design, made of a W alloy
A more realistic schematic of the e\(^+\) production target

- **Electron beam** impinging on the target
- Once e\(^+\) are emitted, one needs to focus them (intense B field needed)
- For this there are SC magnet coils. Not conventional, but high-Tc superconductors (operating at liquid nitrogen temperature instead of liquid He temperature)
- Advantage: a higher power load can be sustained! More affordable quench limit
- Still, in order to protect the SC magnet coils, the target is surrounded by a shielding
- **Design challenges/questions:**
  - Vis a vis short term effects (quenching): what’s the power density delivered to the high-Tc superconducting coils?
  - Long-term effects (lifetime of the equipment): what is the dose delivered to the target per operational year? Will the insulators of the superconducting coils sustain operation?
In order to assess short-term effects (quenches), one may evaluate the power-deposition map a la MC, e.g. with FLUKA

Target is obviously where most power is deposited by the incoming e- beam

The shielding is doing its job reasonably: the power deposition in the coils \(~10-20\ \text{mW/cm}^3\)

This is within the quench limit for bending dipoles in the LHC (\(15-20\ \text{mW/cm}^3\)). This holds for conventional SC coils at liquid helium temperature.

There should even be some margin: the SC coils around the FCCee positron production target are high Tc (liquid nitrogen temperature)
To assess long-term radiation effects, one looks at the imparted dose over a given time (operational year).

Dose per year delivered to the coils evaluated with FLUKA

For conventional SC, dose limit before coil insulators break down is 30 MGy.

But we see a peak value: ~22 MGy

Factor 10 for expected runtime of FCCee project → 220 MGy

We’d appear to be exceeding the dose limit

But the dose limit for future HTS insulators is still an open question

Thanks to B. Humann for kindly making this material available!
Next challenging source of radiation: SR emission of e- in collider arc

- Remember your classical electrodynamics lectures?
- Accelerated charged particles radiate.
- In presence of acceleration normal to v, charged particles emit synchrotron radiation (SR)
- Strongly peaked around v, 1/\(\gamma\) spread
- Radiated power:
  \[ P = \frac{2}{3} \frac{e^2 c}{4\pi \varepsilon_0} \frac{\beta^4 \gamma^4}{\rho^2} \]  (bending radius)
- Putting in ~numbers for e- in FCCee orbit:
  - Radius \(\rho=10.76\) km, \(E=182.5\) GeV
  - Energy radiated by e- per turn in FCCee: \(9.2\) GeV

**SR is a major source of radiation in lepton machines like FCC-ee**
Representative arc cell for FCCee

- Length: ~140 m
- Comprising:
  - dipoles (MB),
  - quadrupoles (MQ),
  - sextupoles (MS)
- Circulating e- beam (B1) and e+ beam (B2)
- Central problem: copious emission of synchrotron radiation
- How does one protect equipment?
Absorbers

- A series of *absorbers* is placed along the beam pipe
- SR emission in the external beam pipe is intercepted
  - Secondaries emitted back into the chamber (some may impact on magnets!)
- SR emission in the internal beam pipe is intercepted:
  - Secondaries emitted back into the tunnel
- Questions:
  - *Where does the SR power end up?*
  - *Are the absorbers doing their job properly?*
  - *Do they catch everything? Is the inner side of the vacuum chamber sufficiently shielded?*

**CuCrZr absorbers**

External beam: reflected particle $\rightarrow$ magnet yoke

Internal beam: reflected particle $\rightarrow$ tunnel
Short-term effects (power load on absorbers and magnets)

- FLUKA simulations reveal that 78% of the radiated power is effectively deposited in the absorbers.
- Absorbers are indeed doing their job.
- Power loads elsewhere are acceptable (these are warm magnets, i.e. not superconducting!)

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<td><strong>Total</strong></td>
<td><strong>167 kW</strong></td>
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(Power radiated by SR by the 2 circulating beams in the 140-m long arc cell)

*https://edms.cern.ch/ui/file/2302154/1.0/HLLHC_Specification_Document_v1.0.pdf*, page 16
Long-term effects (cumulative dose)

- Preliminary dose estimate at inner side of vacuum chamber: **1 MGy**
- Dose estimate above/below the collider beam plane: **300 kGy**
- Such dose levels pose problems for electronics:
  - Guideline reference value* for HL-LHC arc: **1.4 Gy (orders of magnitude lower)**
- These findings imply that further shielding is necessary to protect electronics in the tunnel
- Studies ongoing.

*https://edms.cern.ch/ui/file/2302154/1.0/HLLHC_Specification_Document_v1.0.pdf*, page 16
Wrap-up of this FCCee block

- **Two radiation sources:**
  - Radiation environment in/near positron production target
  - SR emission in the arc

- **MC simulations allow us to:**
  - Quantify effects, both short and long term, as critical design/operational info
  - Propose mitigation strategies: shielding of electronics in FCCee arc, etc.
Last topic for today: application to the design of future particle accelerators (Muon Collider)

Thanks to D. Calzolari for kindly making this material available!
Muon collider

- It’s among the options recommended to be explored by ESPPU
- See B. Dalena’s nice talks:

  - **Future High Energy Collider Projects 1/2**
    - Speakers: Barbara Dalena (CEA-Irfu & Université Paris-Saclay (FR)), Barbara Dalena (Univ. + INFN)

  - **Future High Energy Collider Projects 2/2**
    - Speakers: Barbara Dalena (CEA-Irfu & Université Paris-Saclay (FR)), Barbara Dalena (Univ. + INFN)

- More details: [https://muoncollider.web.cern.ch/node/25](https://muoncollider.web.cern.ch/node/25)

- For our purposes: muon beams in a circular collider with 10 TeV CM energy
Synchrotron radiation

- As recalled in earlier slides, charged particles in a magnetic field emit synchrotron radiation (SR):
  - Radiated power goes like $1/m^4$:
  \[ P = \frac{2}{3} \frac{e^2 c}{4\pi \varepsilon_0} \frac{\beta^4 \gamma^4}{\rho^2} \]
- One would expect fewer SR problems from muons:
- But the story is a bit more subtle.
- Muons decay (tau~2.2 us):
- What is actually **challenging** is the SR emission by decay electrons/positrons (!)
Effect of decay-e+- SR on SC coils

- Simplified geometry:
  - Beam aperture, shielded
  - Surrounded by SC magnet

- Short term effects:
  - What’s the power load on the superconducting coils? Are we within the quench limit?

- Long term effects:
  - Dose delivered to SC coil insulators (organic materials) after 10 years?
  - What about displacement damage in the SC coils? What is the DPA after 10 years?
Short-term effects

- MC simulations with FLUKA for 2 scenarios:
  - 3 TeV CM energy
  - 10 TeV CM energy

- Power deposition in the SC coils:
  - Peak ~ 1-2 mW/cm³
  - Well below typical 15-20 mW/cm³ quench limit for bending dipoles of the LHC

- No problem expected in terms of magnet quenches

- Aperture shield is working as intended
Long-term effects over 10 years

- **Dose delivered:**
  - Peak values O(several 10) MGy
  - At / somewhat above customary limit of **30 MGy** above which coil insulators fail
  - This situation can be mitigated by the inclusion of further shielding in the vacuum chamber to lower dose in SC magnet coil insulators!

- **Displacement damage:**
  - DPA ~ 1e-4
  - Ref: Nb₃Sn critical temperature degrades after 1e-3 DPAs.
Summary
Summary and key points

- **Beam losses:**
  - Microscopic causes, macroscopic effects, and implications for operation of a particle accelerator (Lecture 1)

- **Monte Carlo** method as powerful tool to assess the effect of beam losses and other sources of radiation in the design/operation of particle accelerators
  - Quantities relevant for short-term effects (power deposition)
  - Quantities relevant for long-term effects (dose and displacements per atom)

- **Assessment of beam losses and general radiation challenges:**
  - Inner triplet shielding in view **HL-LHC** upgrade
  - **FCCee**: positron production target (implications of radiation field on HTS coils)
  - **FCCee**: implications of synchrotron radiation emission in the arc
  - **Muon collider**: radiation challenges on SC dipole magnet due to emission of SR
Farewell note

- Use the Summer Student opportunity to **approach people** at CERN working on topics you are genuinely interested in!

- While being exquisitely mindful of people’s working time, shoot them an e-mail, say hi, and you may get a valuable in-person chat and **precious information** on what’s going on in your field of interest!
Thanks for your attention!

Enjoy the rest of CERN’s Summer Student Lecture Programme!
## Muon collider machine parameters

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<th>$\sqrt{s}=10\text{ TeV}$</th>
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<td>Beam energy</td>
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<tr>
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