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

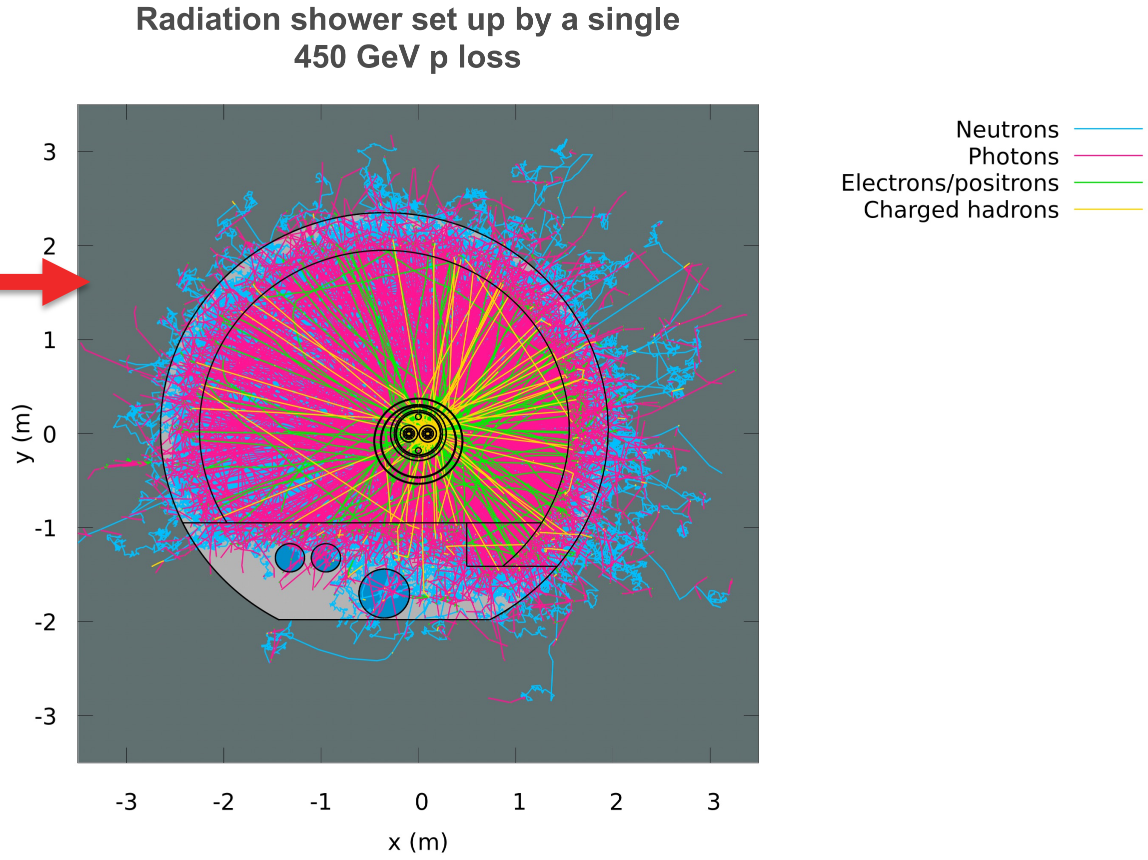
Francesc Salvat Pujol

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**



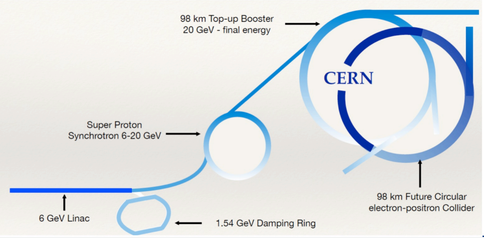
Specifically

Hadrons

- A more detailed introduction to **Monte Carlo simulation** of particle transport for beam-matter interaction problems:
- **Application**: design of components for the the present LHC and its upgrade // limits on lifetime of components

Leptons

- Basic interaction mechanisms of e-, e+, and photons
- **Applications** in the design future lepton machines:
  - FCCee
  - Muon collider

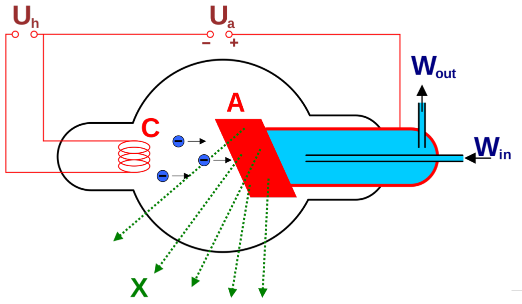


International MUON Collider Collaboration

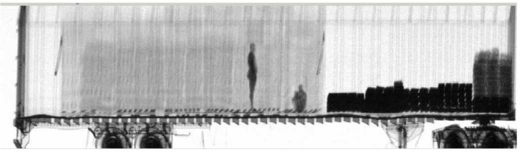
An introduction to the Monte Carlo method for the simulation of beam-matter interaction

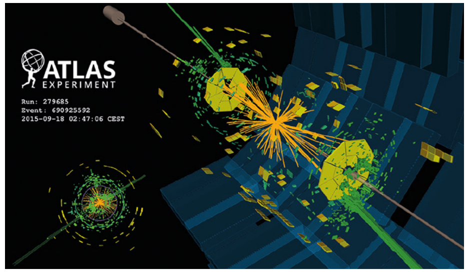
The radiation transport problem

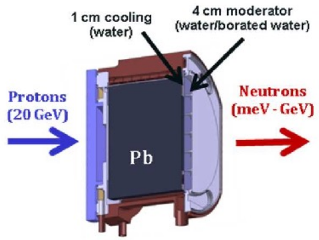
- Thus far: beam losses and beam-matter interaction for particle accelerator components
- Underlying problem is much more general: **radiation transport**

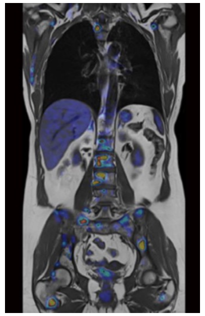


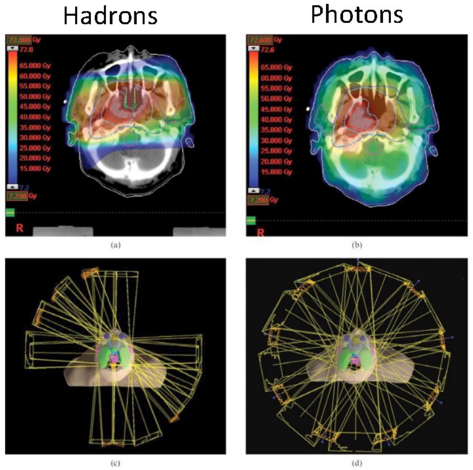
Source: Wikipedia









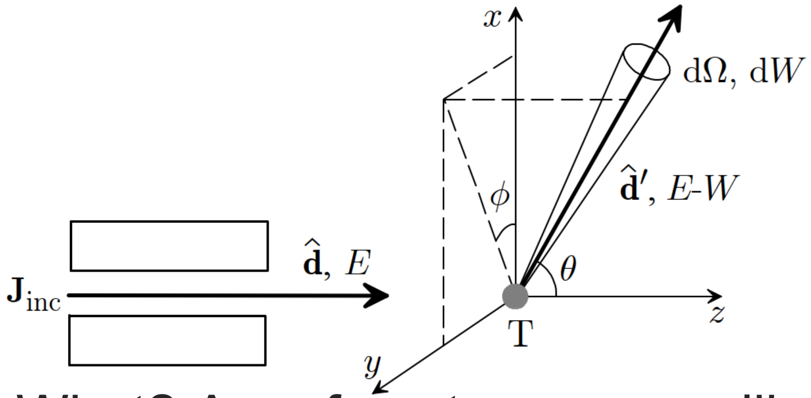


Radiation source → Propagation in matter → Detection

- Goverened 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



Differential cross section

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\,\mathrm{d}W} \equiv \frac{\dot{N}_{\mathrm{count}}}{|\mathbf{J}_{\mathrm{inc}}|\,\mathrm{d}\Omega\,\mathrm{d}W}$$

Dimensions of L^2/E/solid angle

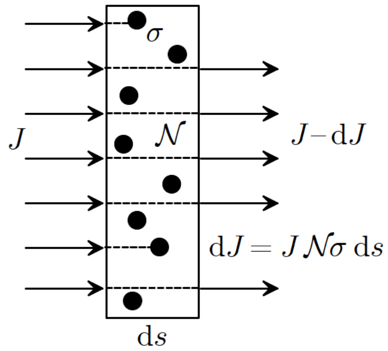
(Integrated) cross section

$$\sigma = \int_0^E \mathrm{d}W \int \frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\,\mathrm{d}W}\,\mathrm{d}\Omega$$

Dimensions of L^2

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 (λ)**: average distance to the next interaction



$$p(s) = \mathcal{N}\sigma\,\exp\left[-s\,(\mathcal{N}\sigma)\right]$$

Path length

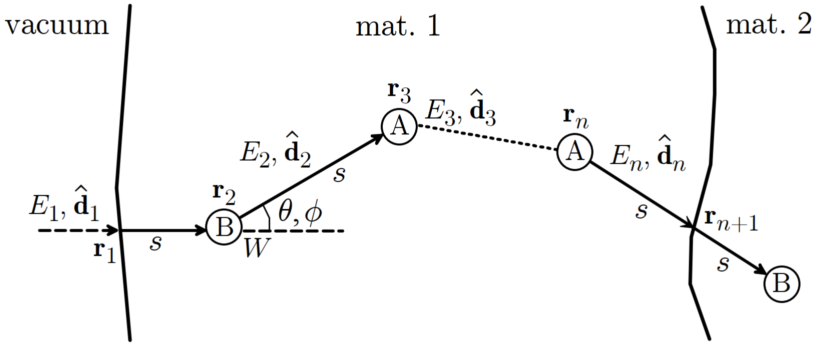
Number of atoms per unit volume

$$\lambda = \frac{1}{\mathcal{N}\sigma}$$

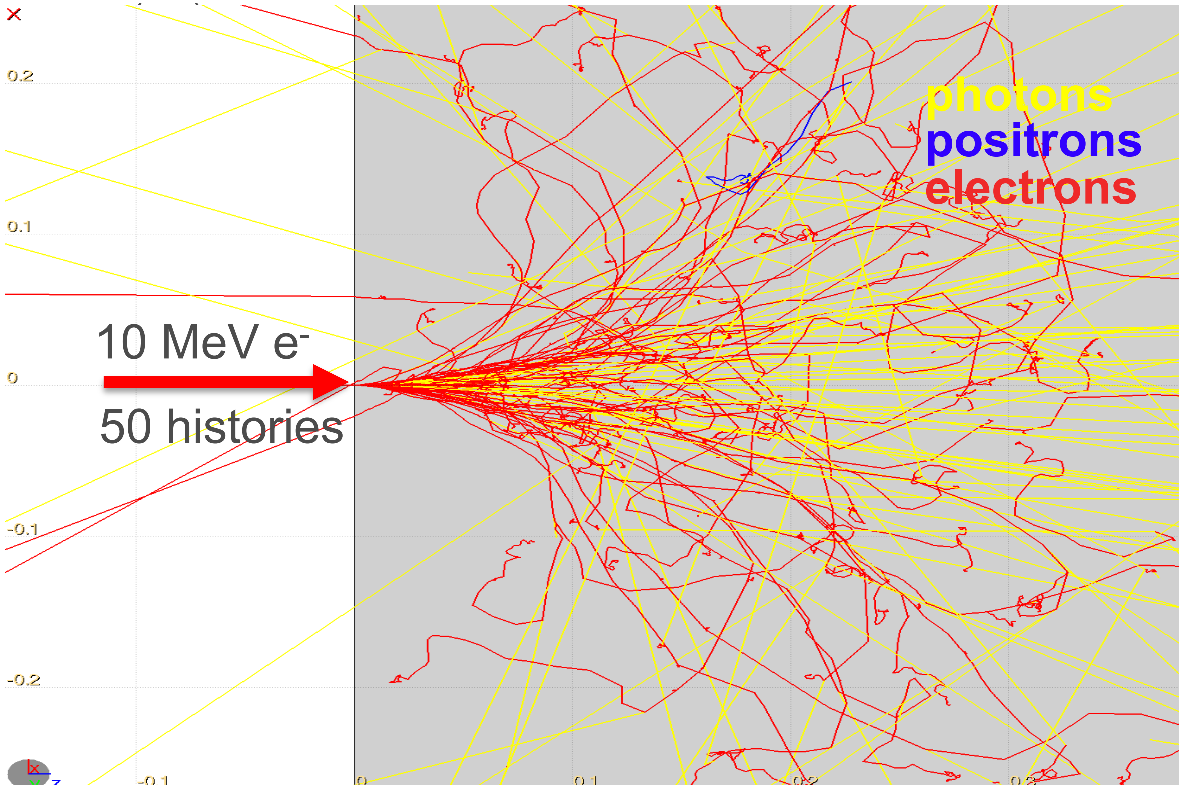
Dimensions of L

The Monte Carlo method

MARS, PHITS, MCNP, PENELOPE, EGS, …



- 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 λ(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

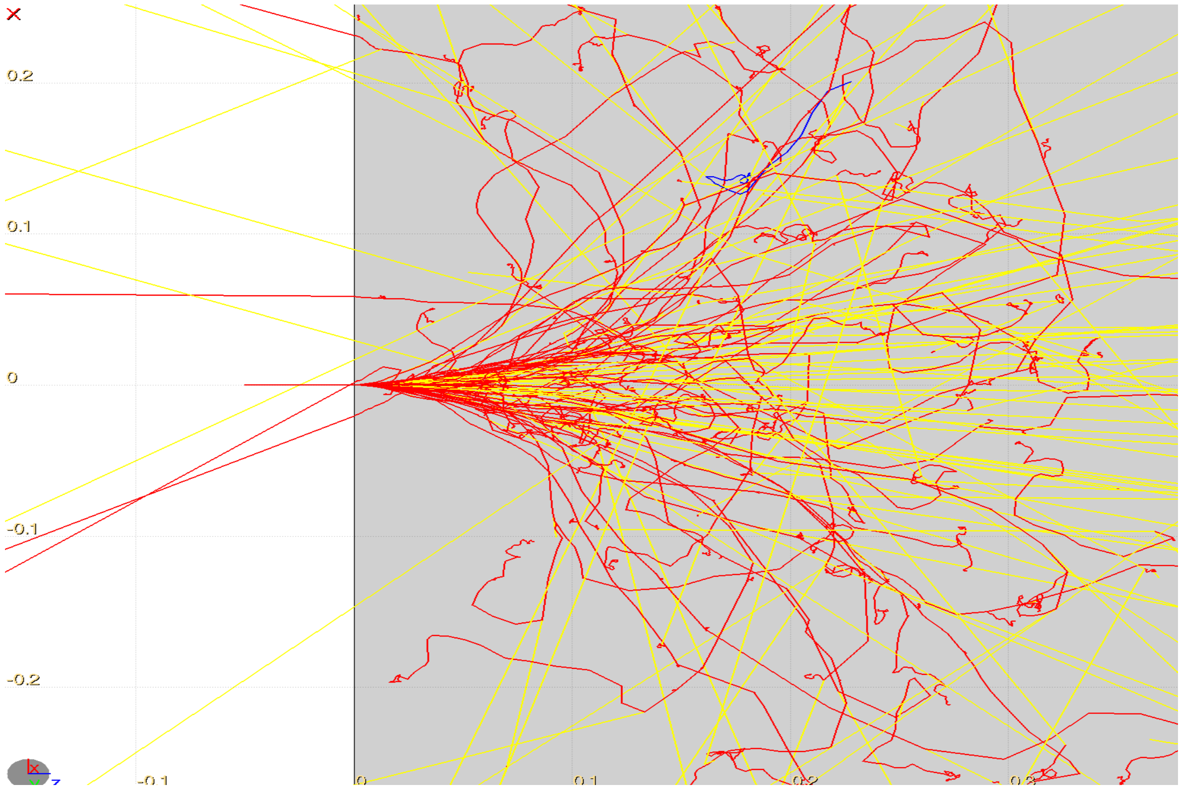
"The purpose of simulation is insight, not numbers"

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

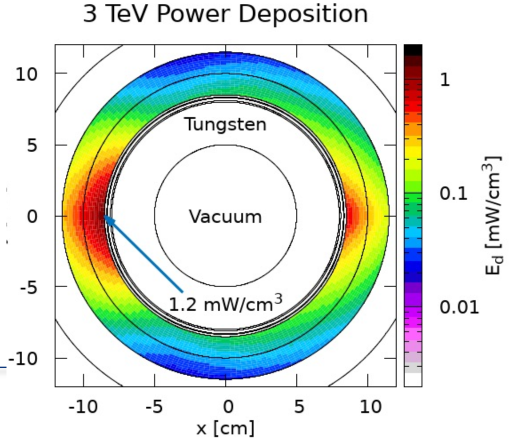
→



Relevant quantities from MC simulations for beam-loss effects

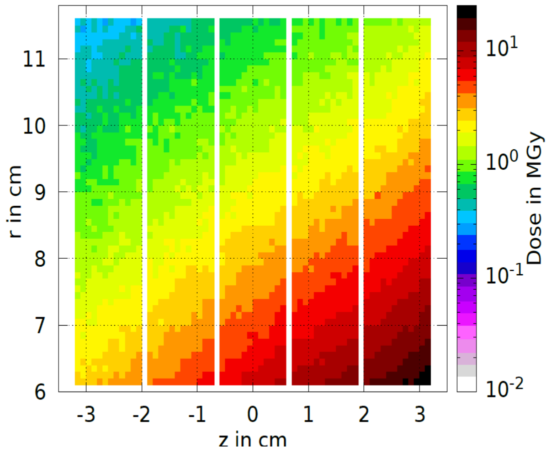
Short-term effects

- 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

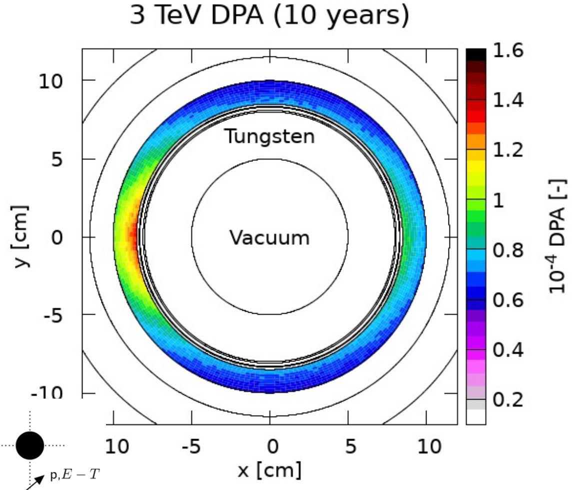


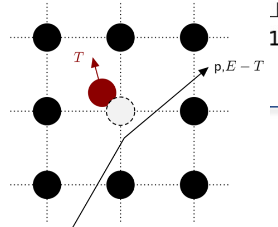
Long-term effects

- 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

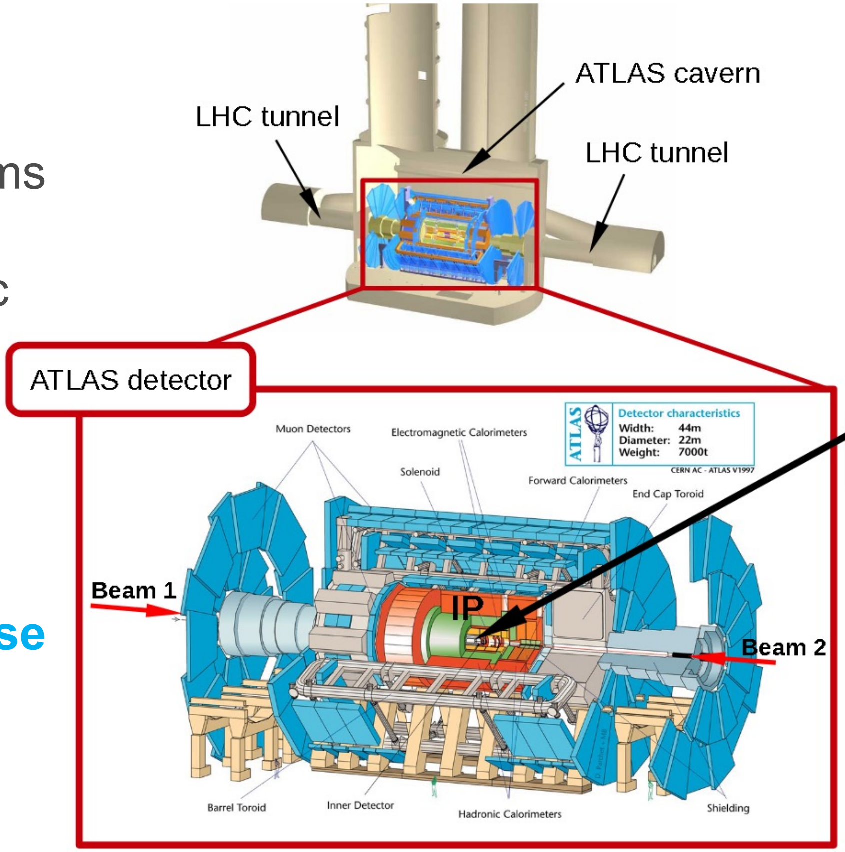


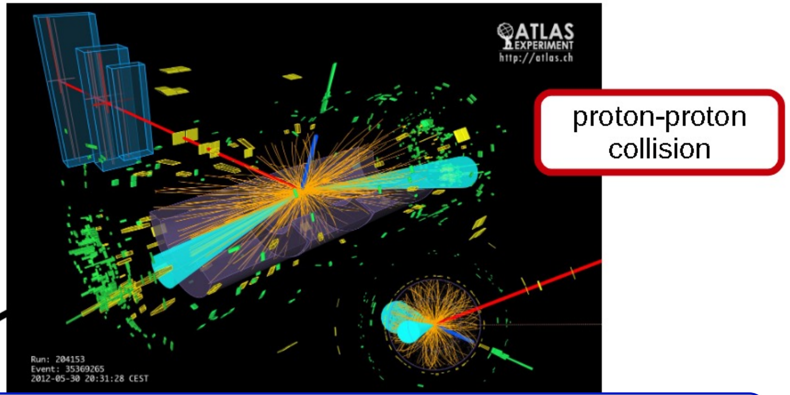


Example for HL-LHC

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): $\mathcal{L} \approx 2\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$
Inelastic pp x-section: $\sigma_{inel} = 80\ \mathrm{mb}$ $(=80\times10^{-27}\ \mathrm{cm^2})$

$\Rightarrow \mathcal{L}\cdot\sigma_{inel} = 1.6\times10^{9}$ collisions/s

$\Rightarrow 2\cdot 6500\,\mathrm{GeV}\cdot 1.602\times10^{-10}\,\frac{\mathrm{J}}{\mathrm{GeV}}\cdot 1.6\times10^{9}$ coll/s
$= 3.3\,\mathrm{kW}$ (=kJ/s)

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

- **Does it affect nearby machine components, e.g. superconducting magnets?**

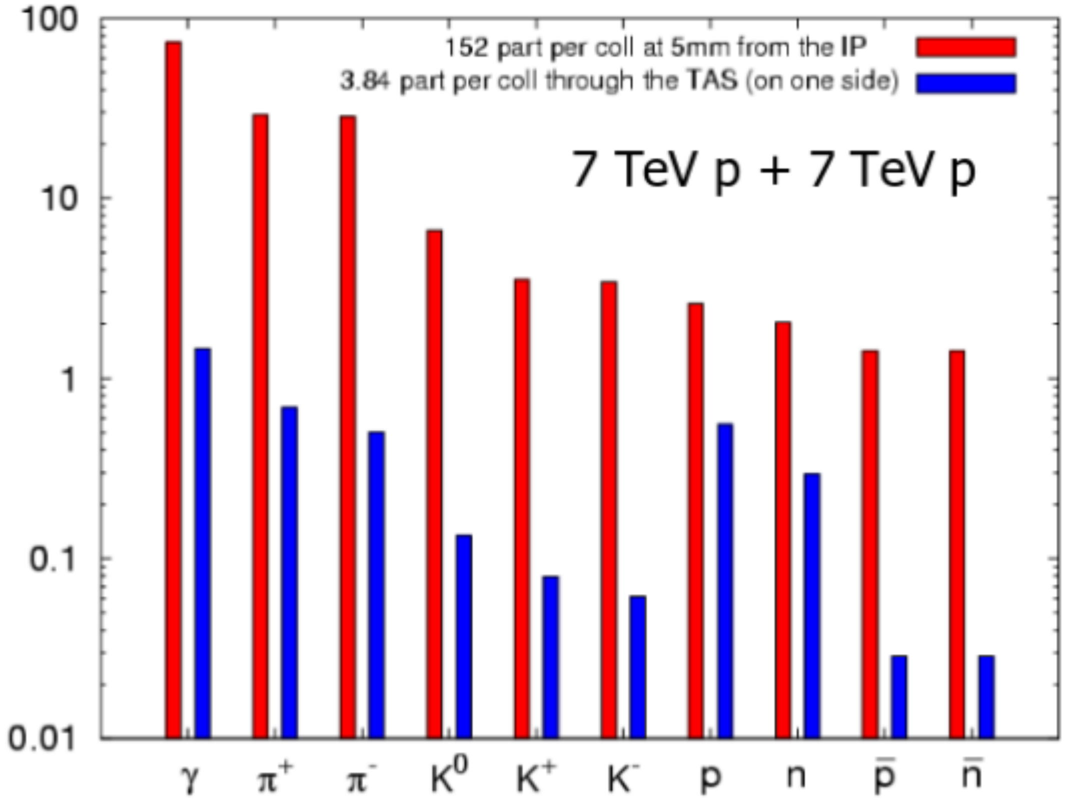
Typical collision products from p-p collisions in ATLAS

- 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

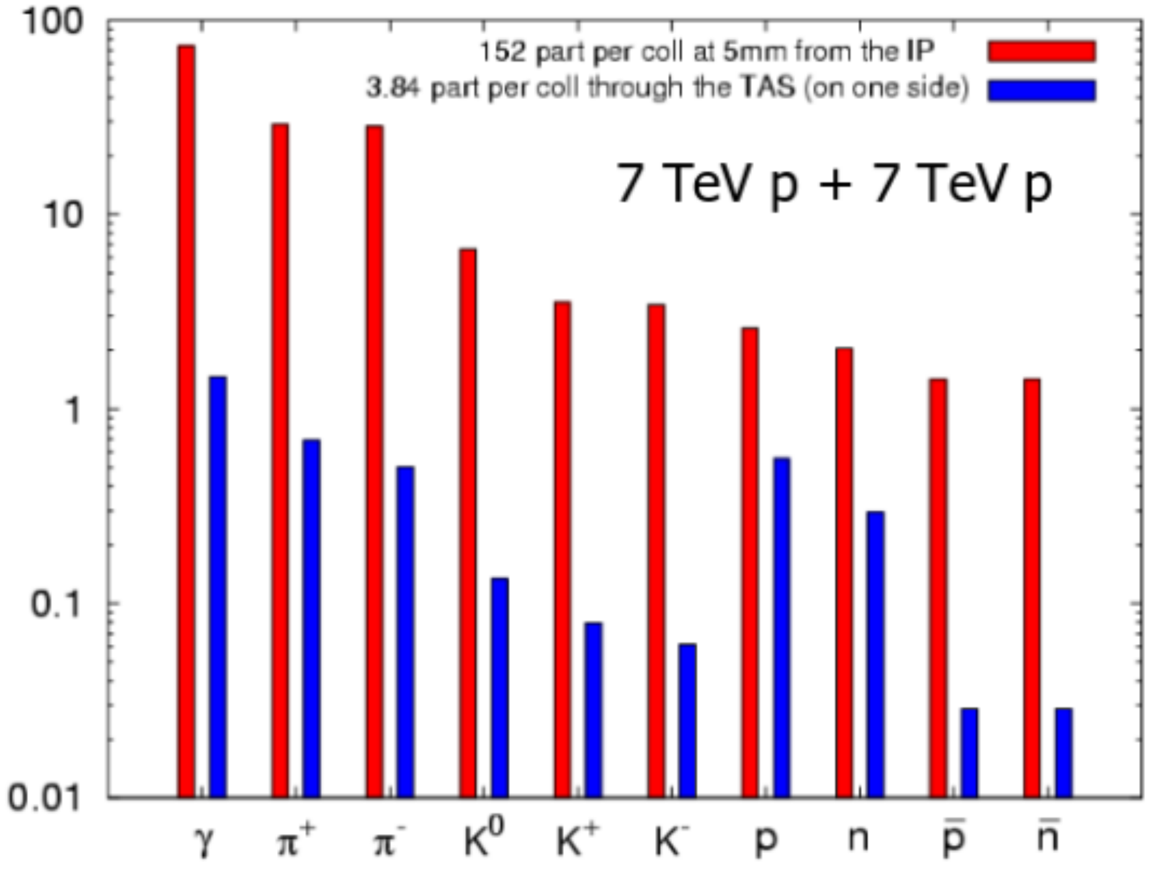
- Interesting particles are much rarer: 1e-10 probability for producing a Higgs boson (hence need for ever higher luminosities – HL-LHC!)

- 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

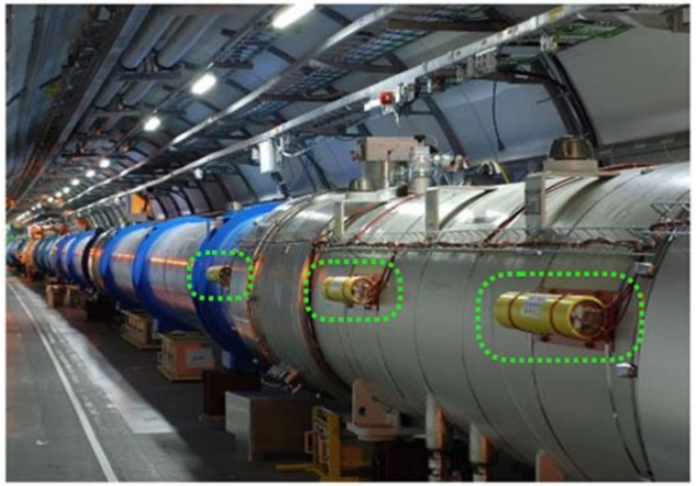
but:

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)

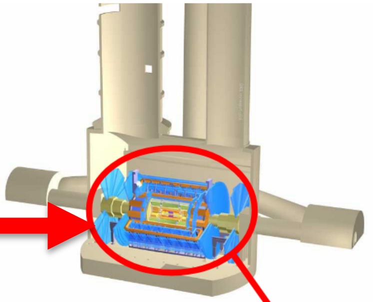


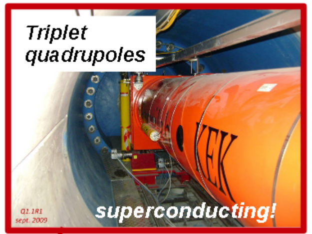
Beam loss monitor: ionization chambers (they measure dose rate in a given time window)

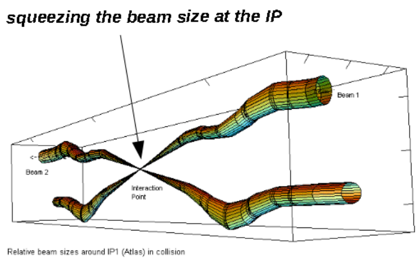
There are a few thousand of them along the LHC.

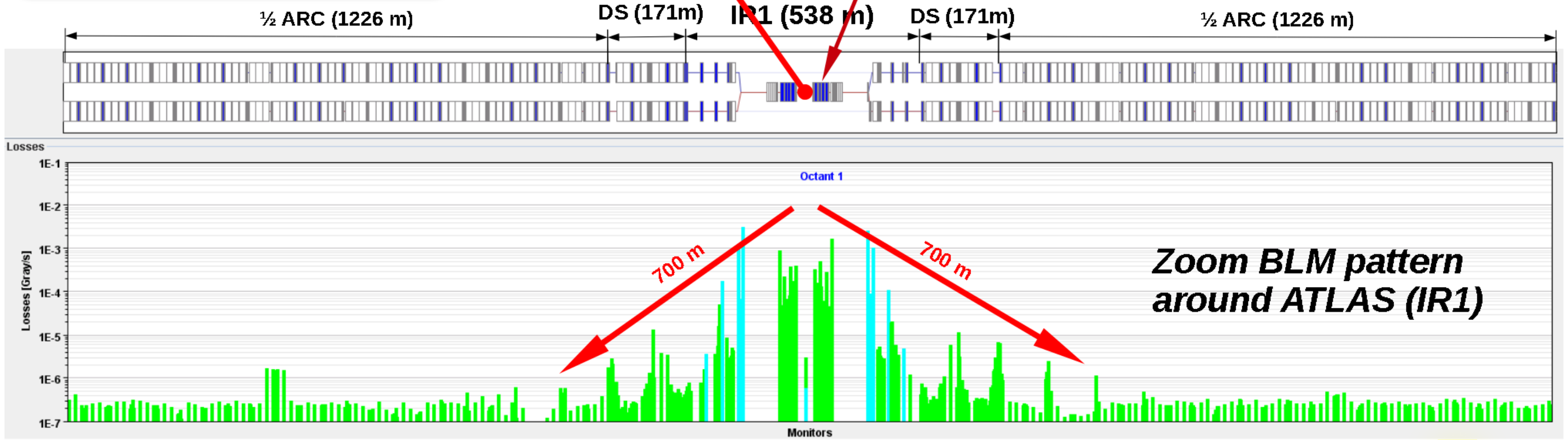
If BLM signal(s) go above threshold, this may lead to an extraction of the beam (dump)

Signal from BLMs ~1.5 km downstream either side of the **ATLAS IP**







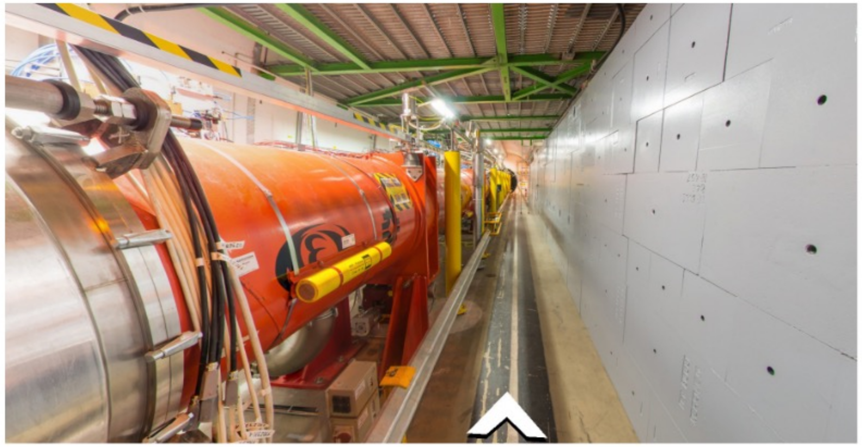


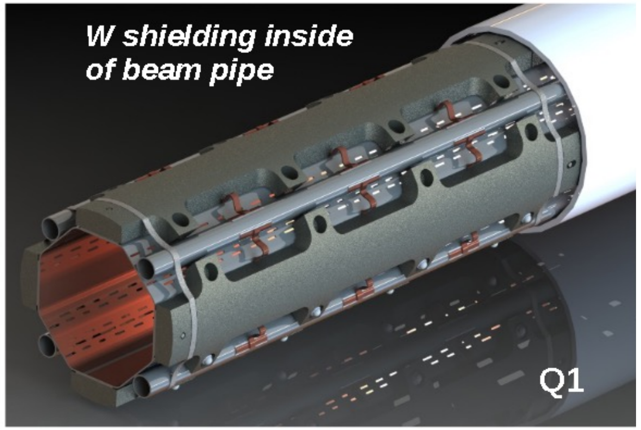
Collision debris from the interaction point can be seen 700 m downstream at either side

Most delicate equipment nearby: inner triplet quadrupoles (they squeeze the colliding beams into the interaction point). These are **superconducting magnets(!)**

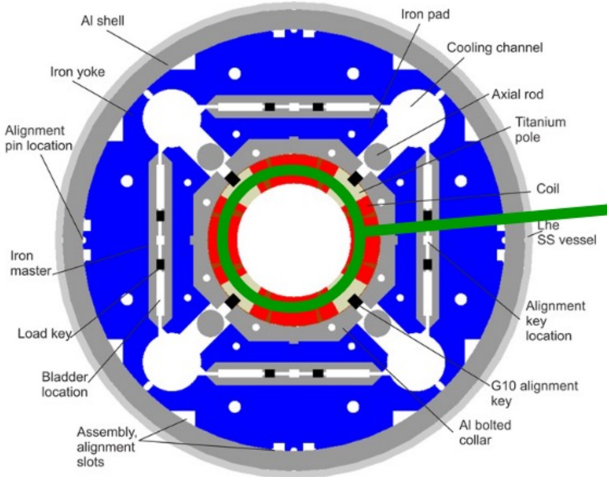
Inner triplet W shielding for HL-LHC

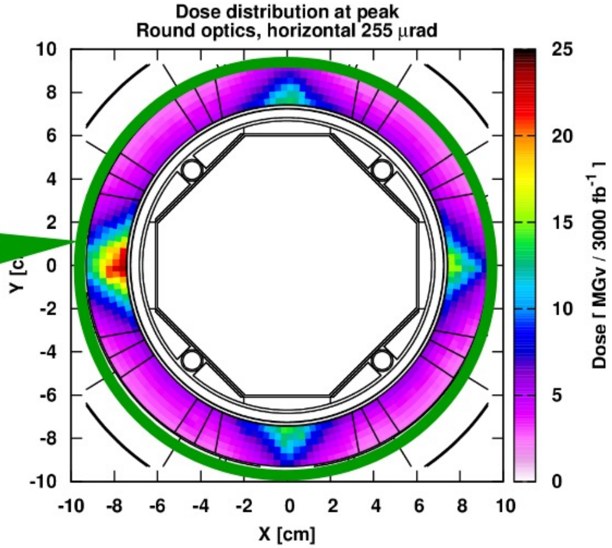
- Inner triplets are **exposed to energetic charged hadrons** leaking from IP, now impacting on the magnet
- These are strong magnets: they capture charged particles
- **Without protection: immediate quench of the magnet**
- In view of increased luminosity (HL-LHC), it was suggested to **insert W inserts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





HL-LHC upgrade:



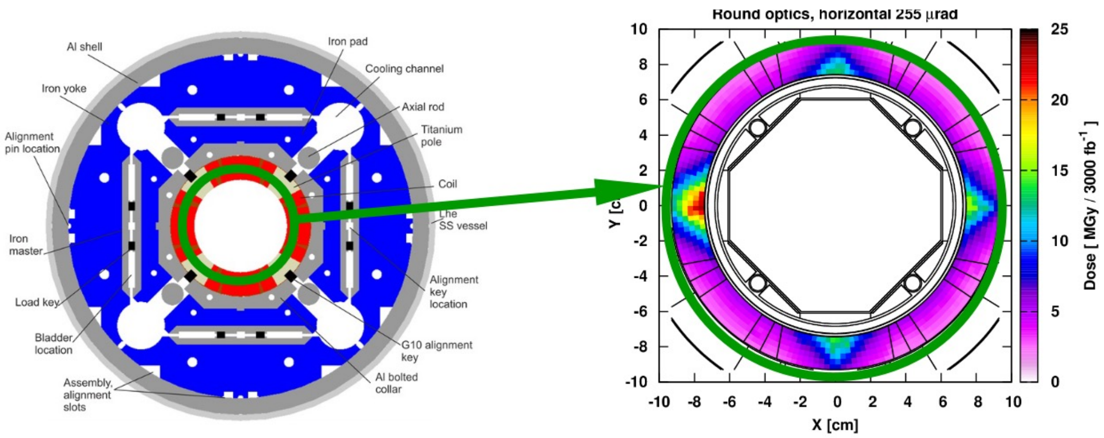


A. Tsinganis, F. Cerutti

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
- Maximum value: **20-25 MGy**.
- 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.



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

Dose < 30 MGy

A. Tsinganis, F. Cerutti

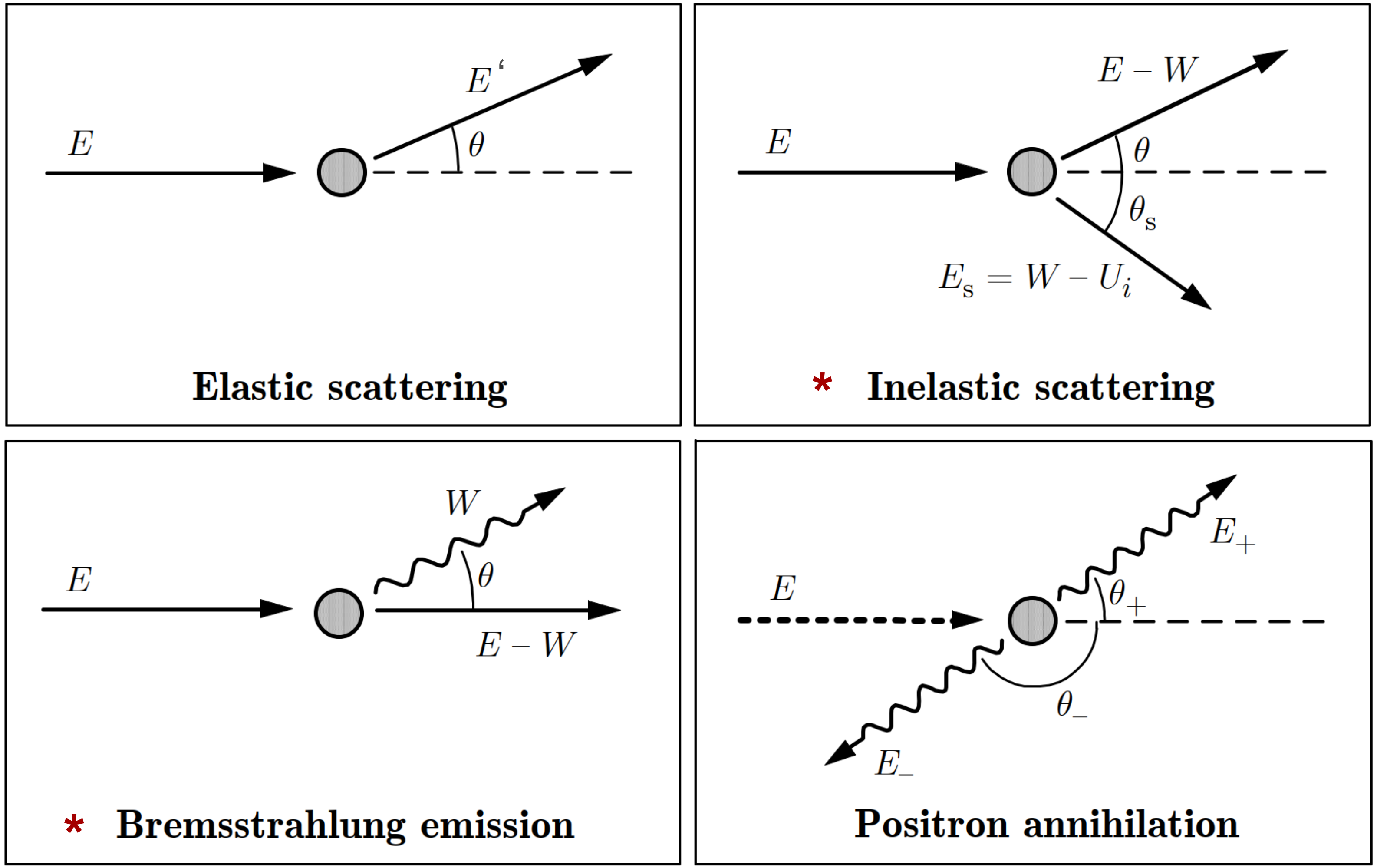
Beam loss / radiation source → MC simulation → Mitigation strategy

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



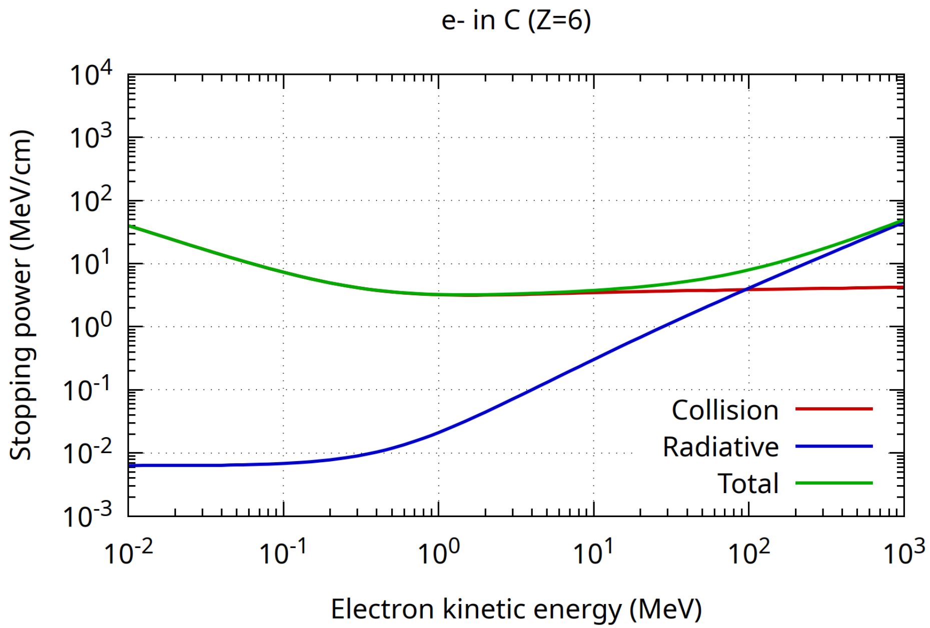
***Synchrotron radiation** emission in B fields!

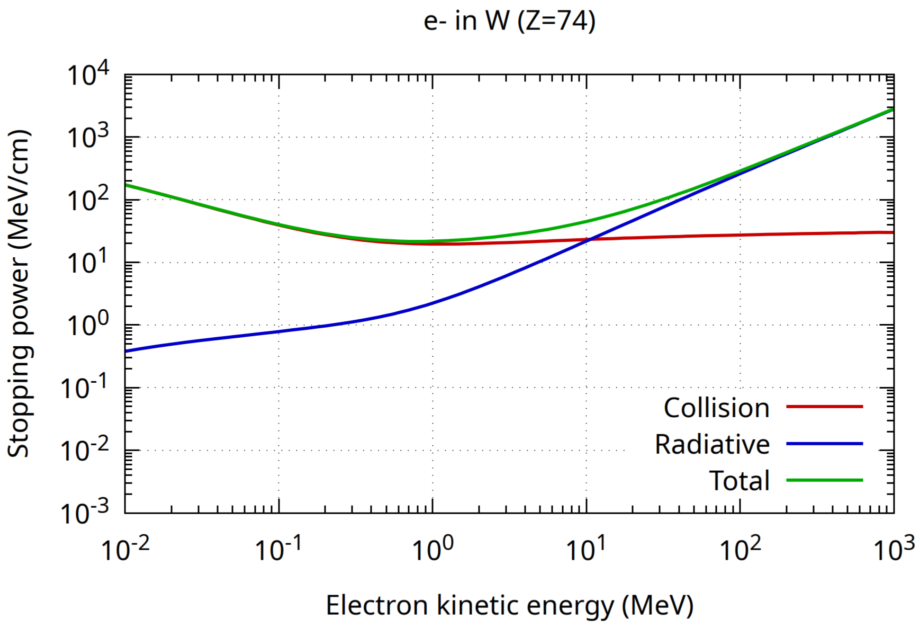
***most relevant mechanisms for the examples below**

Figures: PENELOPE manual (NEA 2018)

Energy loss / slowing down of e+-: stopping power

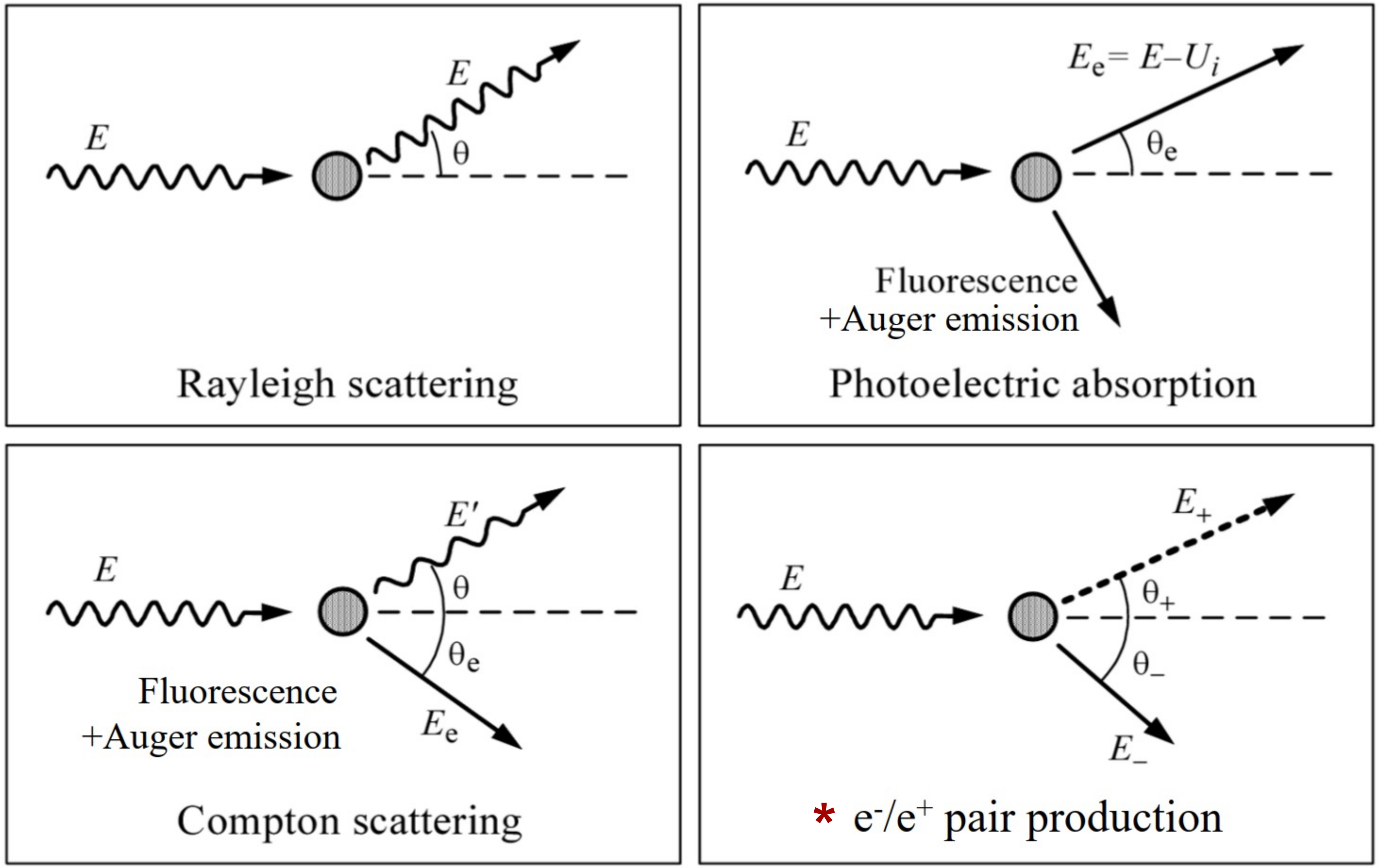
- Stopping power: average energy loss per unit path length
- At high energies: **Bremsstrahlung emission** dominates
- At low energies: Ionization losses dominate





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

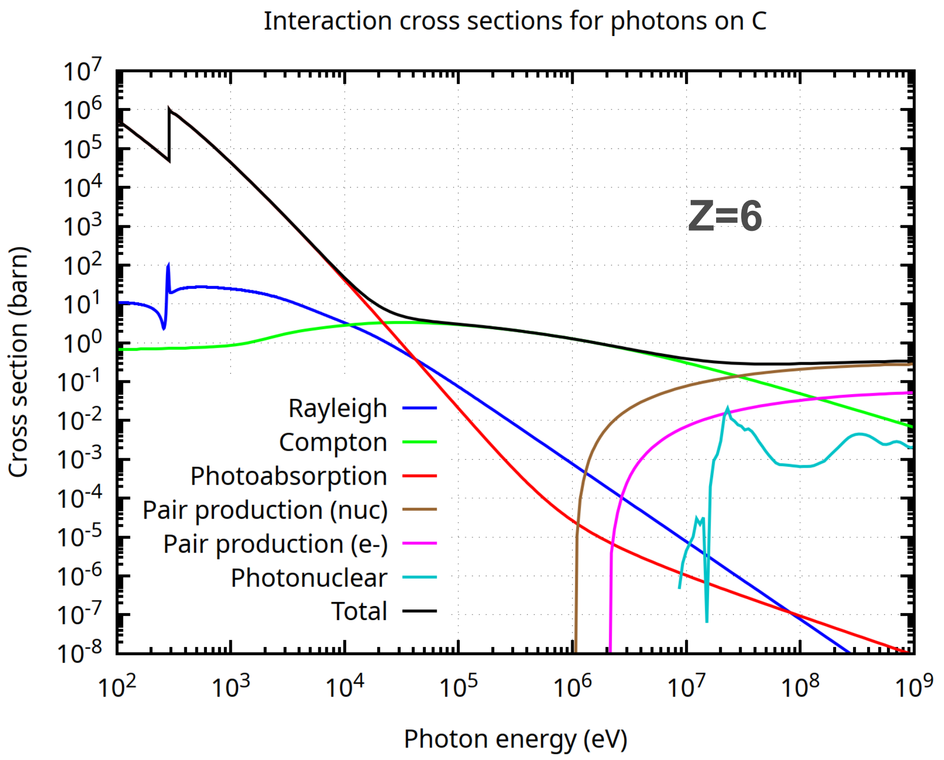
Most relevant interaction mechanisms of photons

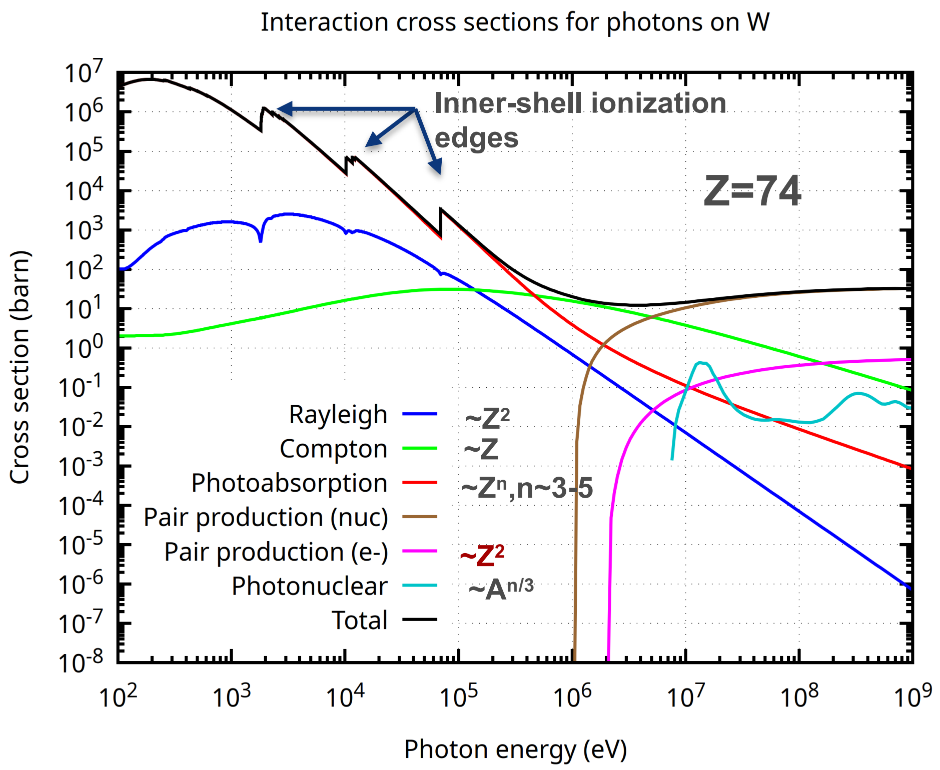


- Photonuclear reactions:
  - (γ,n), (γ,2n),…
- μ± pair production

***most relevant mechanisms for the examples below**

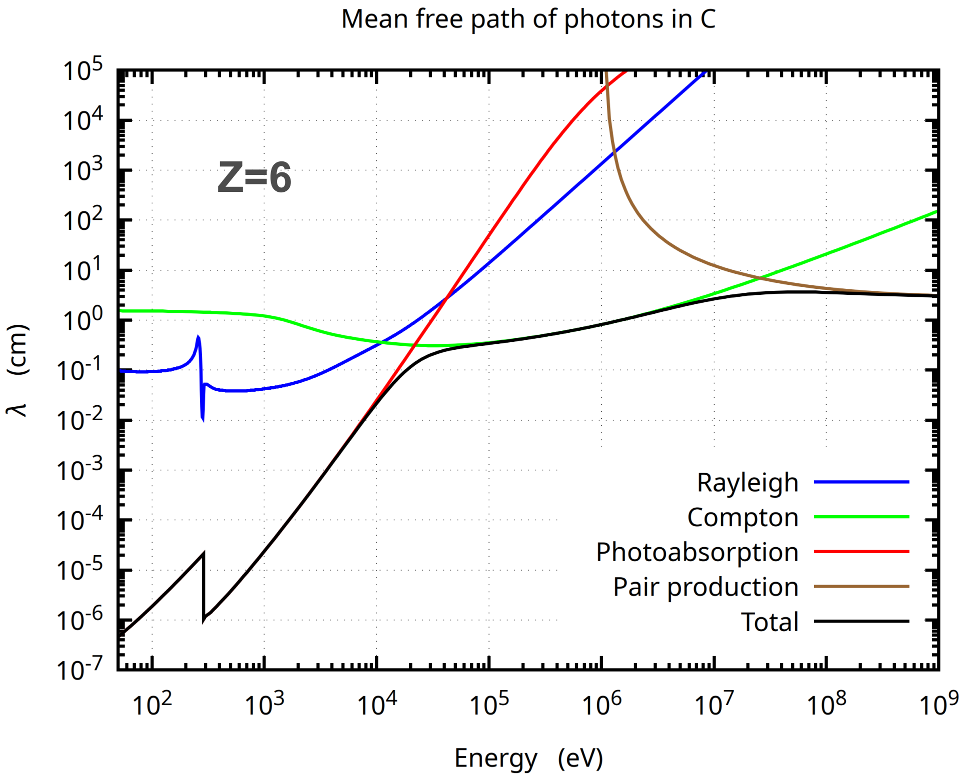
Photon interaction cross sections

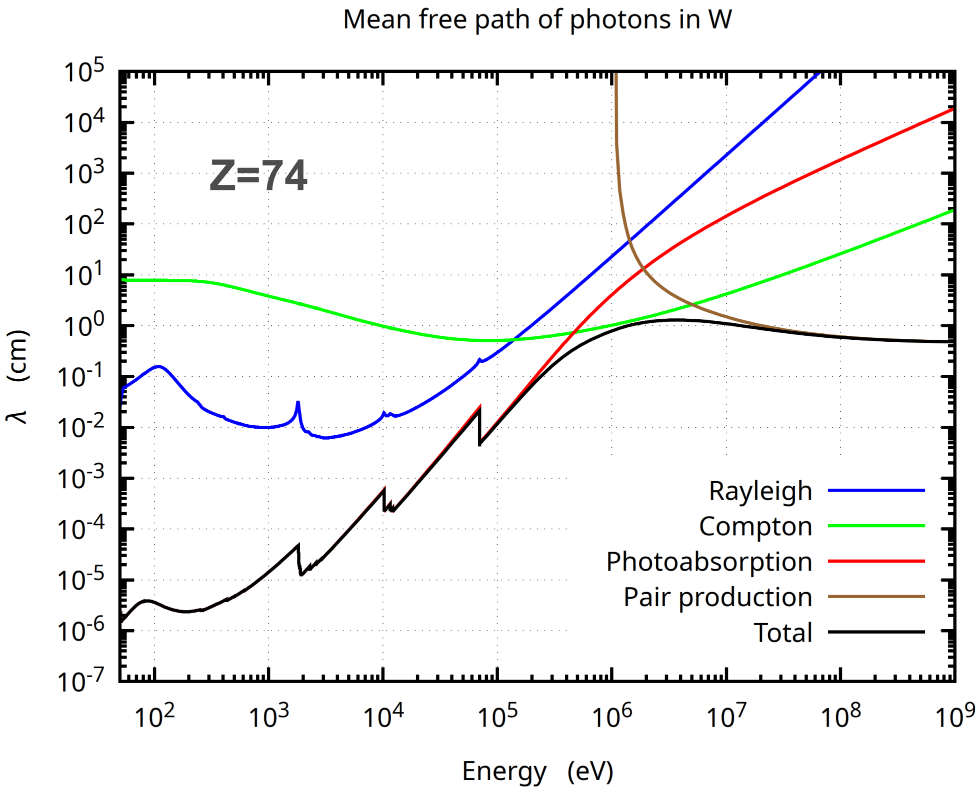




- Photoelectric effect dominates at low energies (signatures from various ionization edges)
- Compton dominates at intermediate energies
- **Pair production is what matters at high energies**
- Photonuclear cross section is rather low

Photon mean free paths (same info, now in terms of avg interaction length)





- MFP for e^-/e^+ pair production:
  - **C: O(1 cm)**
  - **W: O(1 mm)**

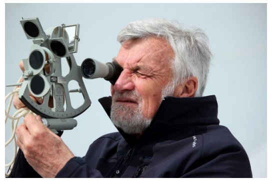
In anticipation of an example below: if one wishes to produce e+ from energetic photons, the larger the Z of the target material, the better!

After this brief interlude on e-/e+ and photon interactions, we go back to the leitmotiv of this lecture:

Beam loss / radiation source → MC simulation → Mitigation strategy

…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.
  3. Development and exploitation of laser/plasma acceleration techniques.
  4. **Studies and development towards future bright muon beams and muon colliders.**
  5. Advancement and exploitation of energy-recovery linear accelerator technology

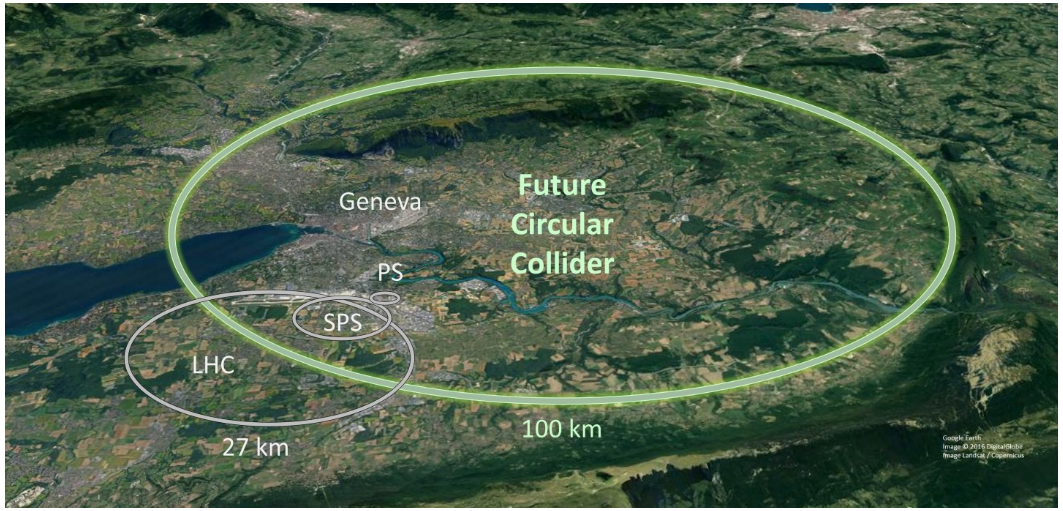
In view of FCC

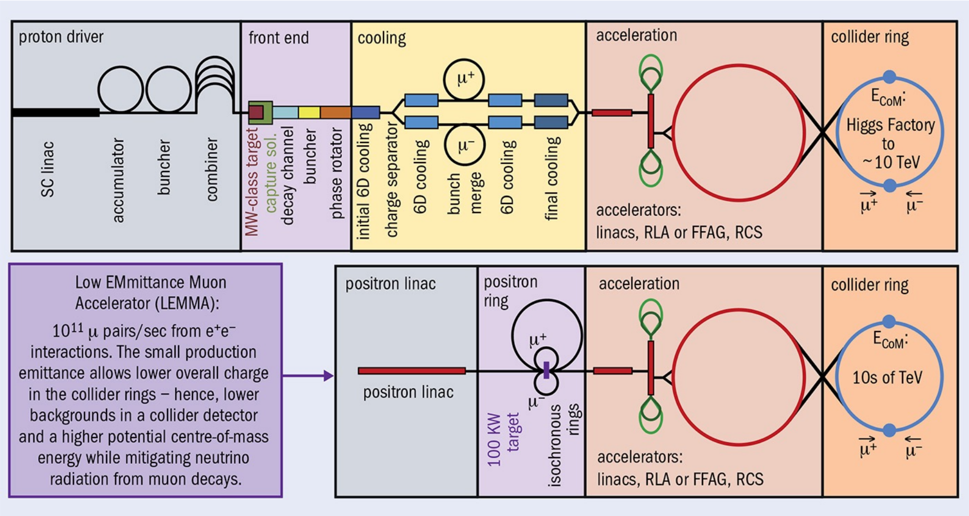
- We shall now close this lecture series with two examples: one on FCC, one on muon collider

Ref: https://e-publishing.cern.ch/index.php/CYRM/issue/view/146

Future colliders

- For today's lecture we jut need to recall two big ongoing projects:





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

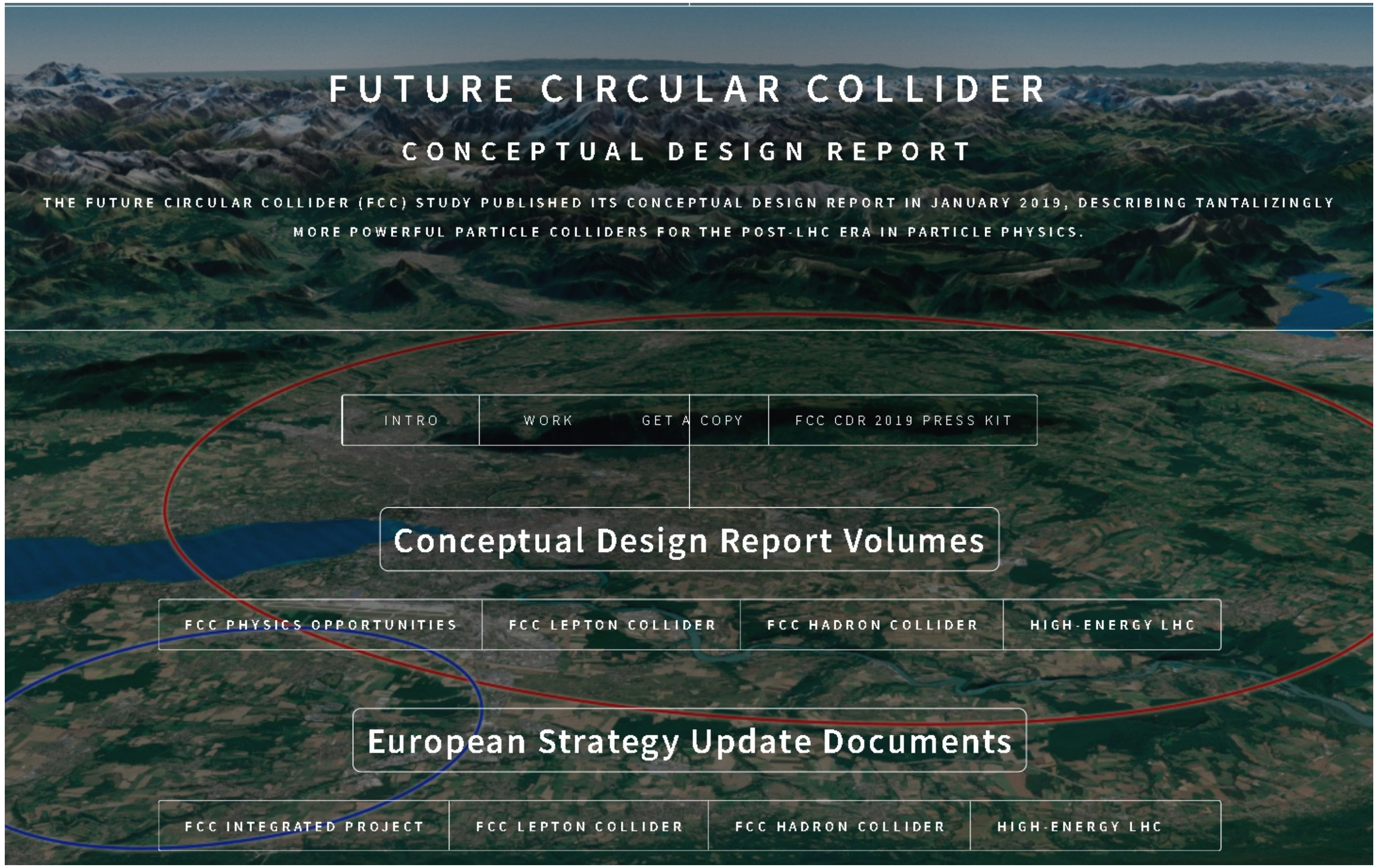
More details, machine specs, aims, etc., see B. Dalena's lectures on Mon, Jul 10 and Tue, Jul 11: "Future High-Energy Collider Projects (1 and 2)"

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)

Eur. Phys. J. Special Topics **228**, 261–623 (2019)

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

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Regular Article

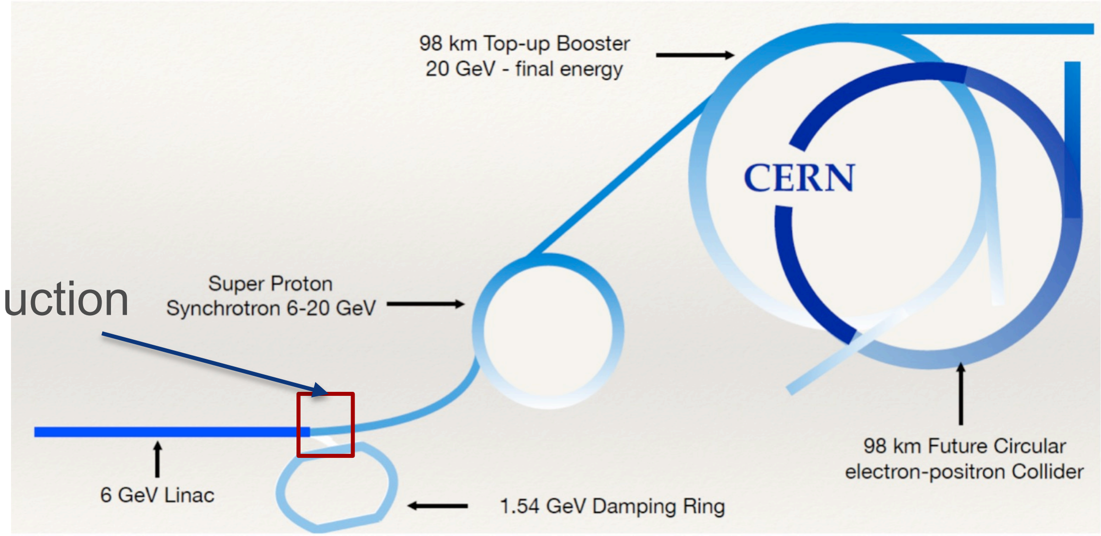
FCC-ee: The Lepton Collider

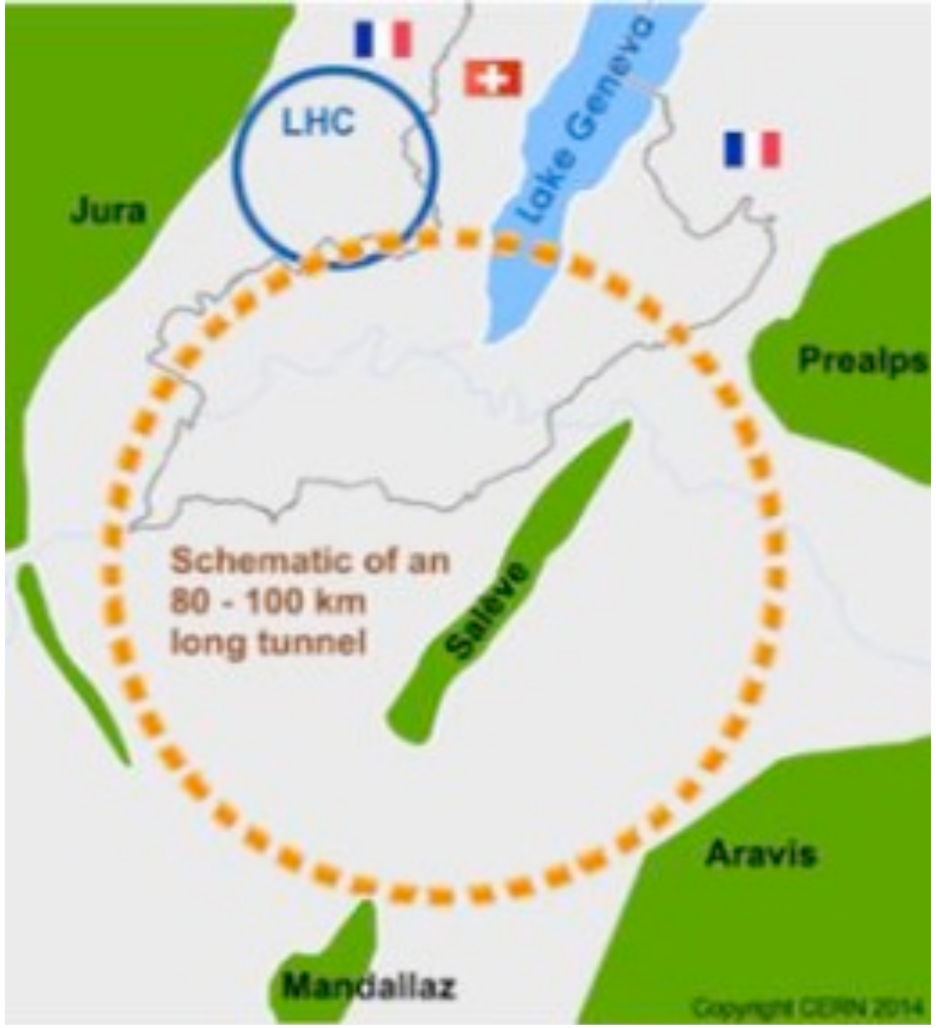
Future Circular Collider Conceptual Design Report Volume 2

FCC ee: electron positron collider

- ~91 km tunnel enclosing the Saleve
- 6 GeV e^- on heavy target → 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

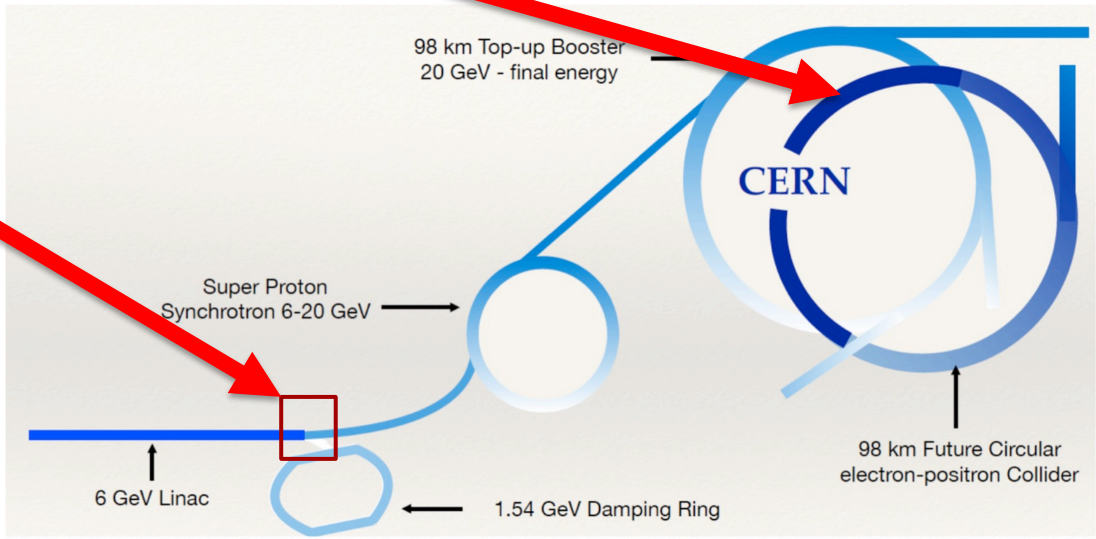
e⁺ production target





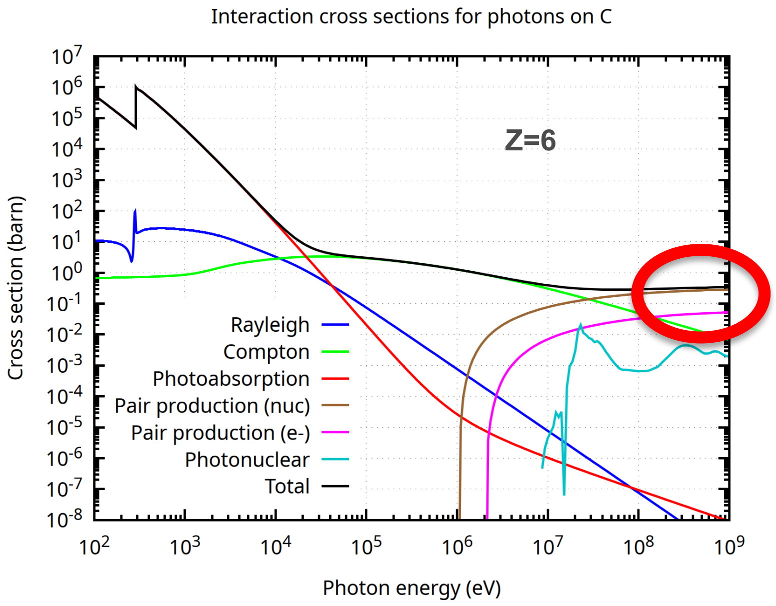
Aspects we will focus on

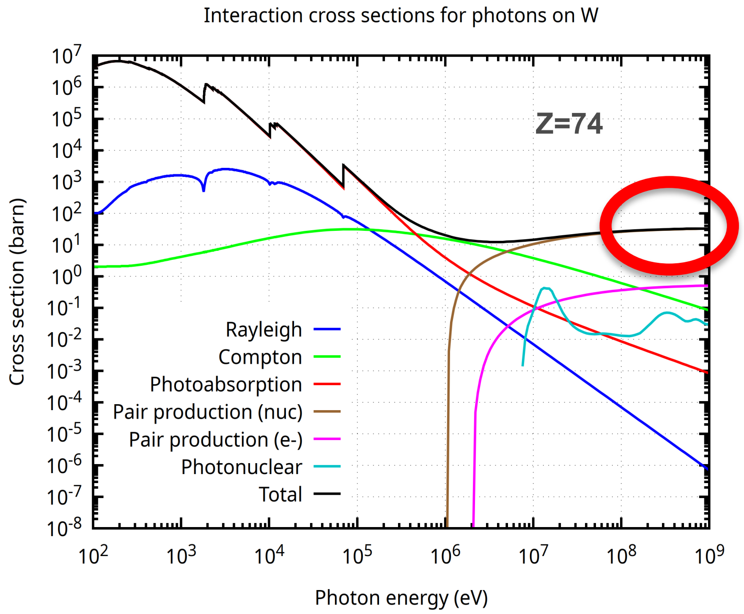
- Emission of synchrotron radiation on the arc of the collider
- Positron production target

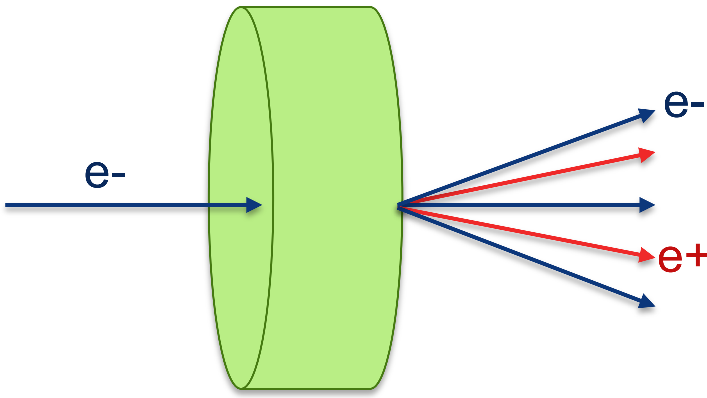


FCCee positron production target

- 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

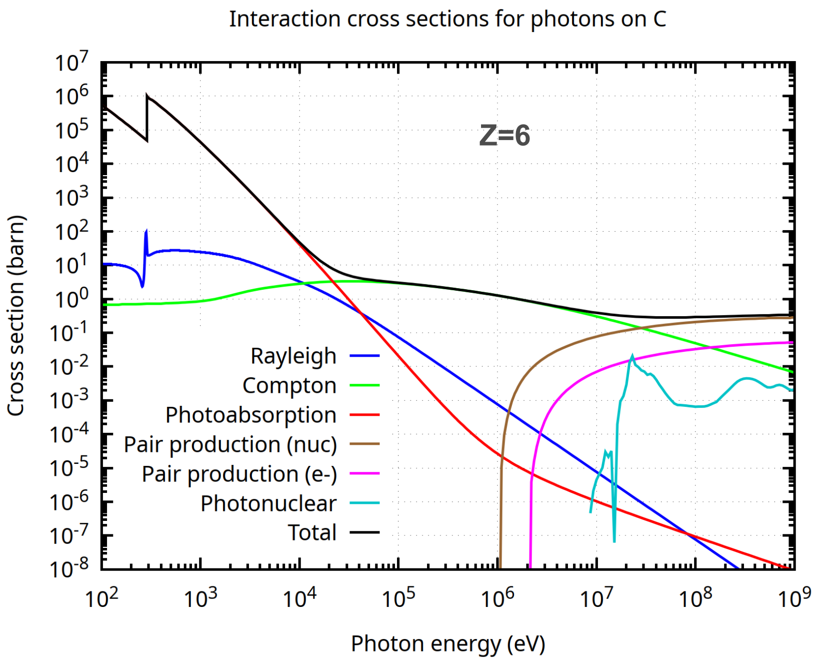


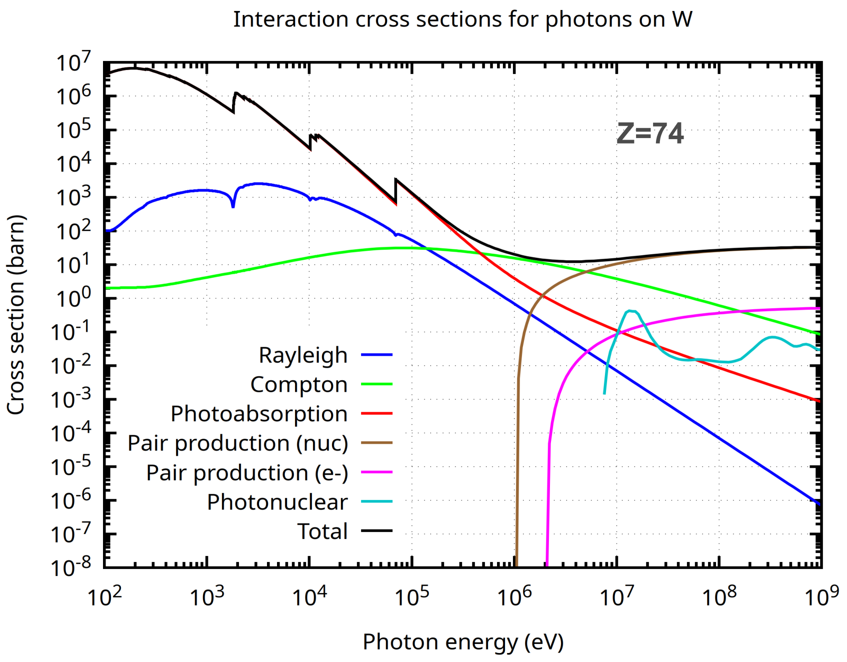


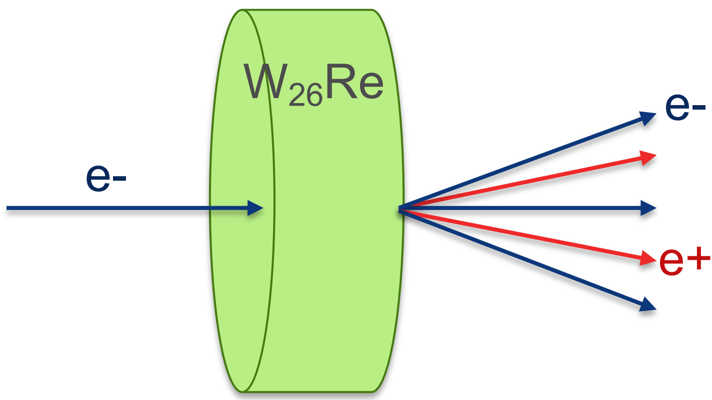


- **Given GeV photons, would you take C or W for the e+ production target?**

FCCee positron production target material

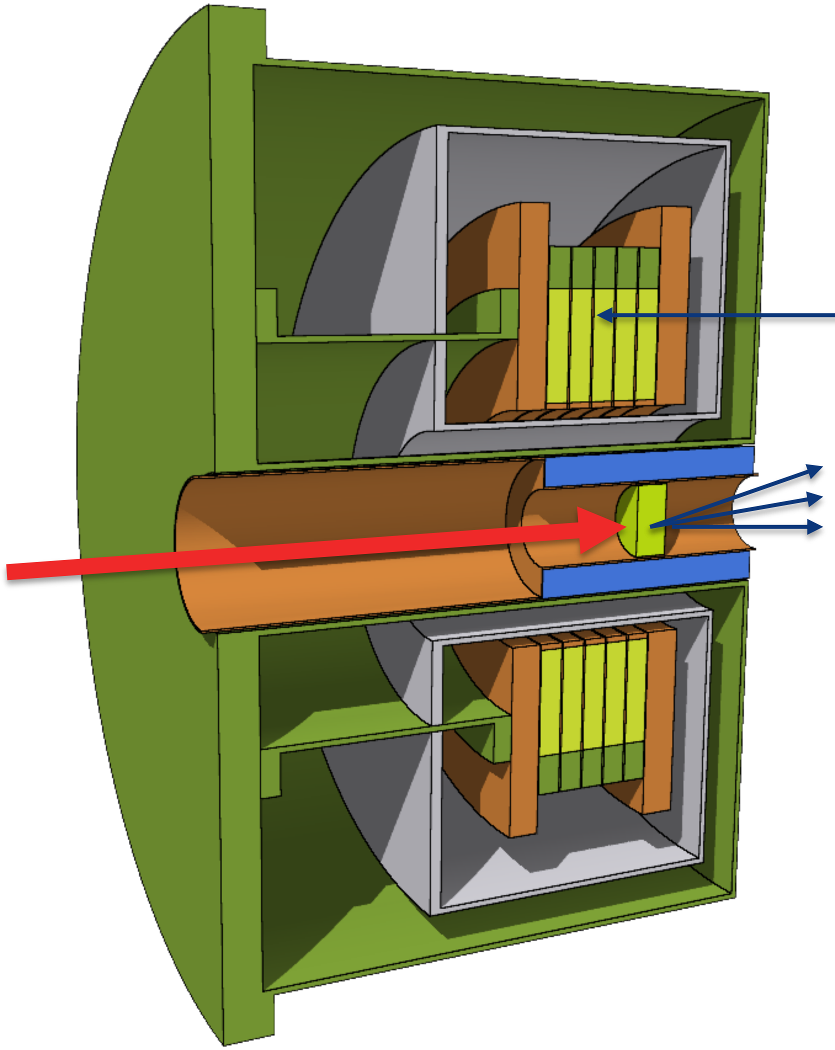






- You want bremsstrahlung photons to generate e-/e+ pairs as copiously as possible
- So indeed, you'd take W (**highest pair-production cross section, by almost an order of magnitude**)
- Turns out not to be far from the actual design, made of a W alloy

A more realistic schematic of the e^+ production target

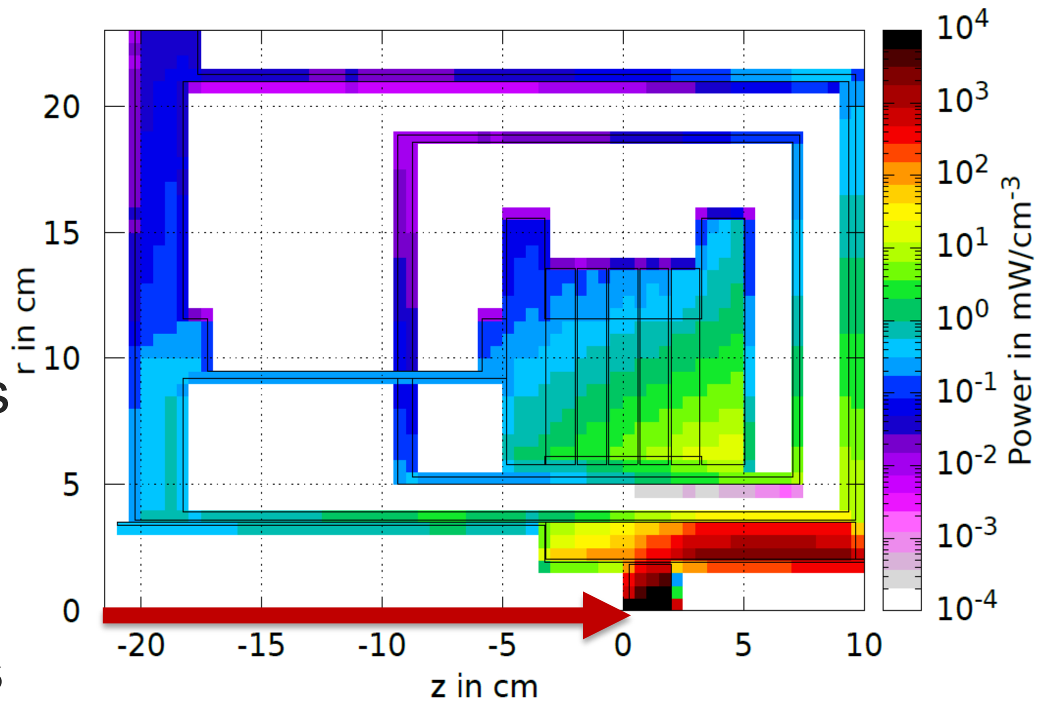


- **Electron beam** impinging on the target
- Once e+ are emitted, one needs to focus them (intense B field needed)
- For this there are SC magnet coils. Not conventional, but high-Tc superconductors (operating at liquid nitrogen temperature instead of liquid He temperature)
- Advantage: a higher power 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?**

Short-term radiation effects (magnet quenches)

- 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 mW/cm³**
- This is within the quench limit for bending dipoles in the LHC (**15-20 mW/cm³**). 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)

Power density on the HTS coils



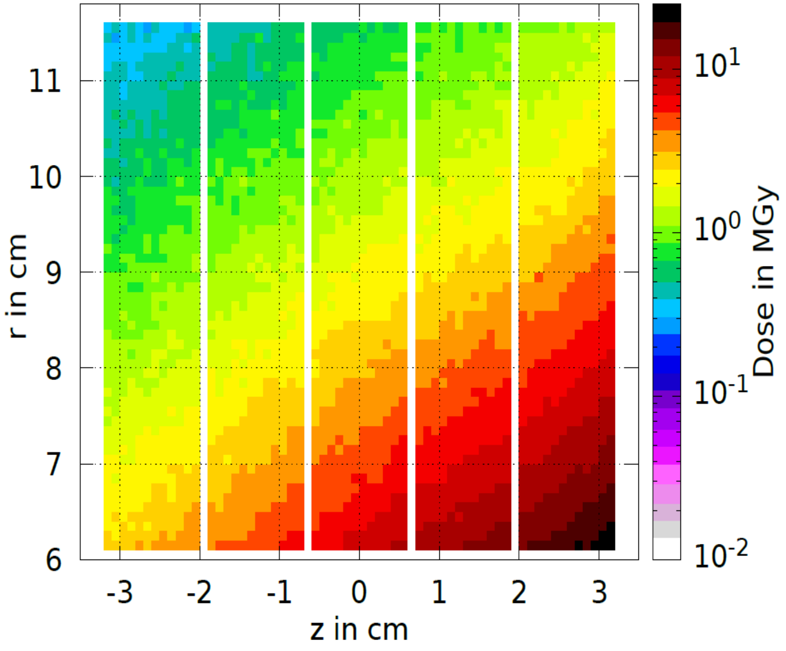
Thanks to B. Humann for kindly making this material available!

Long-term radiation effects (HTS coil insulator breakdown)

- 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 →
- **<u>For conventional SC</u>**, 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

FLUKA

Dose per year



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Next challenging source of radiation: SR emission of e- in collider arc

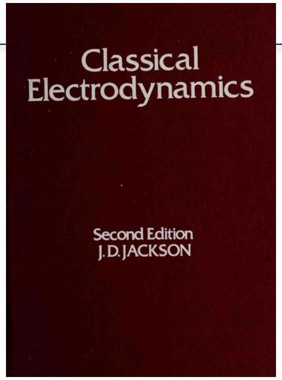
- Remember your classical electrodynamics lectures?
- Accelerated charged particles radiate.
- In presence of acceleration normal to v, charged particles emit synchrotron radiation (SR)
- Strongly peaked around v, 1/gamma spread
- Radiated power:

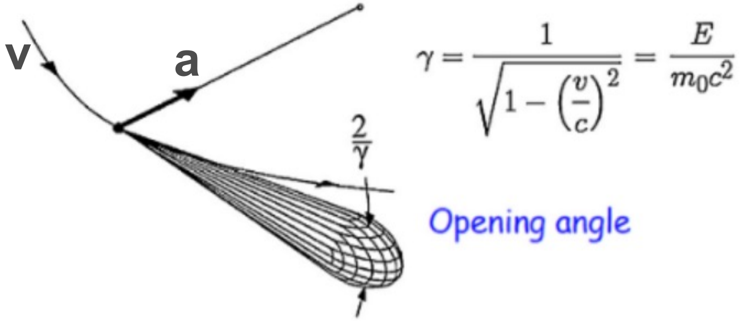
$$P = \frac{2}{3}\frac{e^2 c}{4\pi\epsilon_0}\frac{\beta^4\gamma^4}{\rho^2}$$

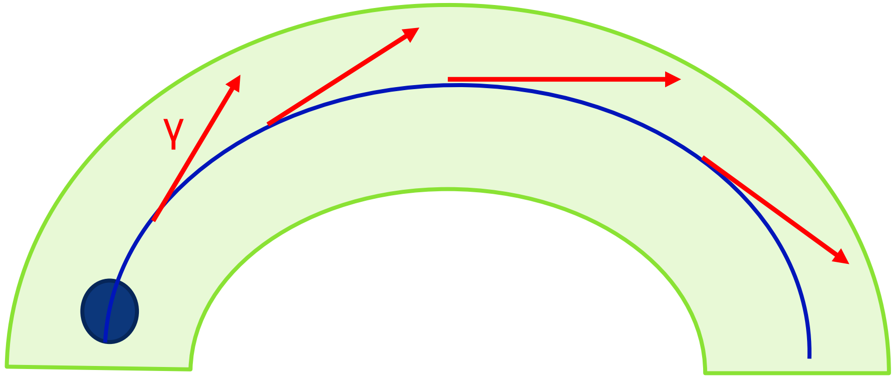
(bending radius)

- Putting in ~numbers for e- in FCCee orbit:
  - Radius ρ=10.76 km, E=182.5 GeV
  - Energy radiated by e⁻ per turn in FCCee: **9.2 GeV**

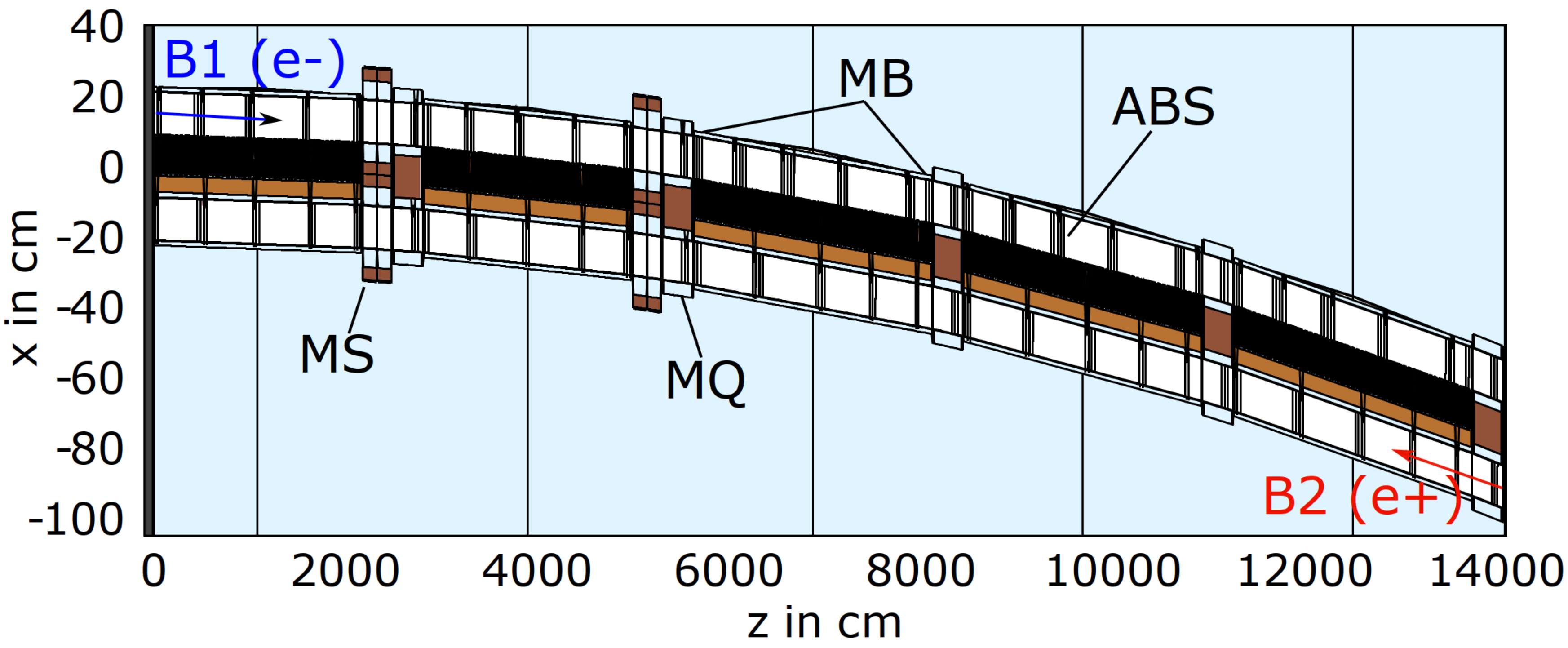
SR is a major source of radiation in lepton machines like FCC-ee







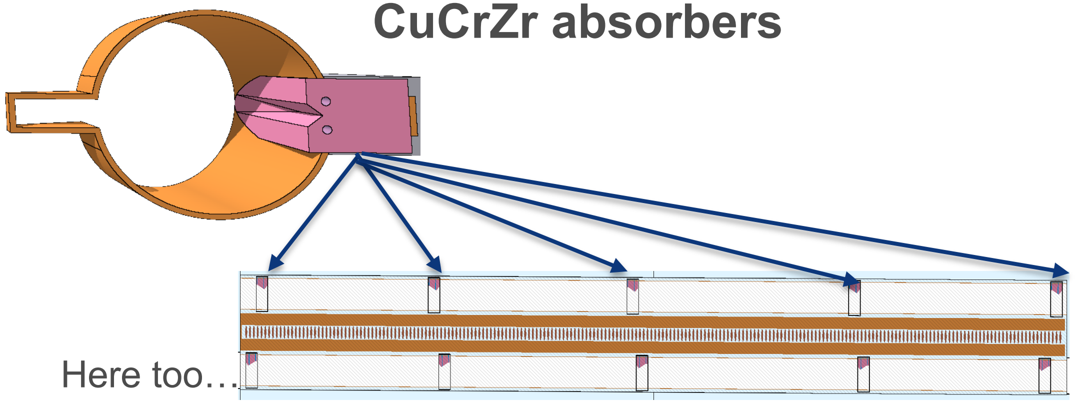
Representative arc cell for FCCee

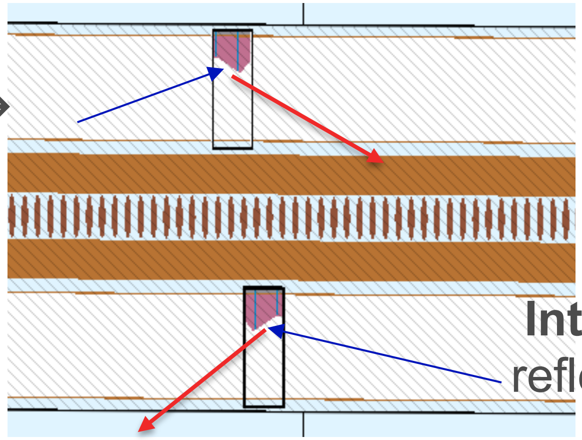


- Length: ~140 m
- Comprising:
  - dipoles (MB),
  - quadrupoles (MQ),
  - sextupoles (MS)
- Circulating e- beam (B1) and e+ beam (B2)
- Central problem: **copious emission of synchrotron radiation**
- How does one protect equipment?

Absorbers

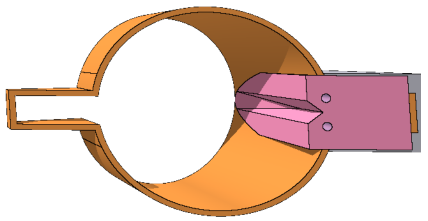
- A series of **absorbers** is placed along the beam pipe
- SR emission in the external beam pipe is intercepted
  - Secondaries emitted back into the chamber (some may impact on magnets!)
- SR emission in the internal beam pipe is intercepted:
  - Secondaries emitted back into the tunnel
- Questions:
  - **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?**





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!)



FLUKA

	Copper
ABS	131 kW
MB	23.4 kW
MQ	2.6 kW
MS	0.09 kW
Tunnel	9.5 kW
Total	**167 kW**

(Power radiated by SR by the 2 circulating beams in the 140-m long arc cell)

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.

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*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:

11:35 AM → 12:30 PM **Future High Energy Collider Projects 1/2** MONDAY, JULY 10

Speakers: Barbara Dalena (CEA-Irfu & Université Paris-Saclay (FR)), Barbara Dalena (Univ. + INFN)

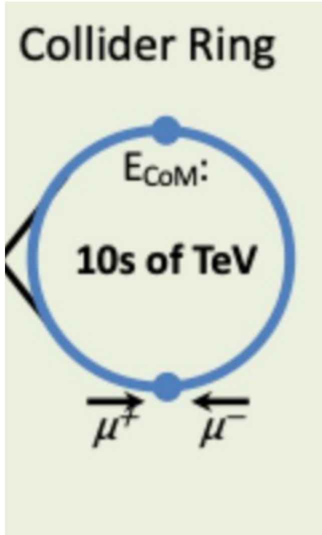
bdalena_FCP_Sum... | bdalena_FCP_Sum...

9:15 AM → 10:10 AM **Future High Energy Collider Projects 2/2** TUESDAY, JULY 11

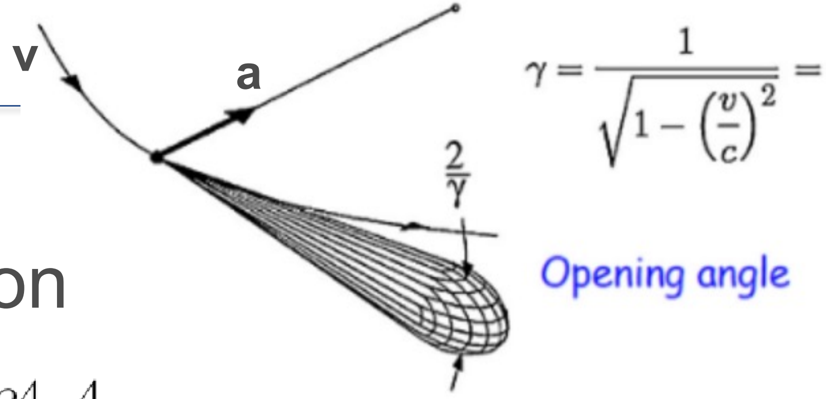
Speakers: Barbara Dalena (CEA-Irfu & Université Paris-Saclay (FR)), Barbara Dalena (Univ. + INFN)

bdalena_FCP_Sum... | bdalena_FCP_Sum... | Future High Energy ... | qr_Future High Ener...

- More details: https://muoncollider.web.cern.ch/node/25
- **For our purposes: muon beams in a circular collider with 10 TeV CM energy**

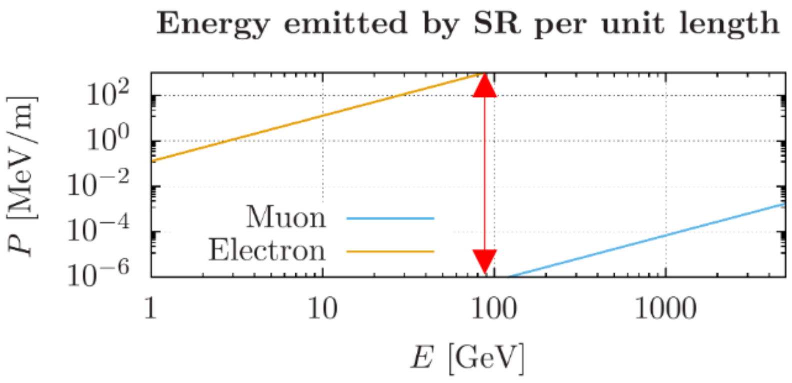


Synchrotron radiation



$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{E}{m_0 c^2}$$

- As recalled in earlier slides, charged particles in a magnetic field emit synchrotron radiation (SR):
- Radiated power goes like $1/m^4$: $P = \frac{2}{3}\frac{e^2 c}{4\pi\epsilon_0}\frac{\beta^4\gamma^4}{\rho^2}$
- 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 (!)**

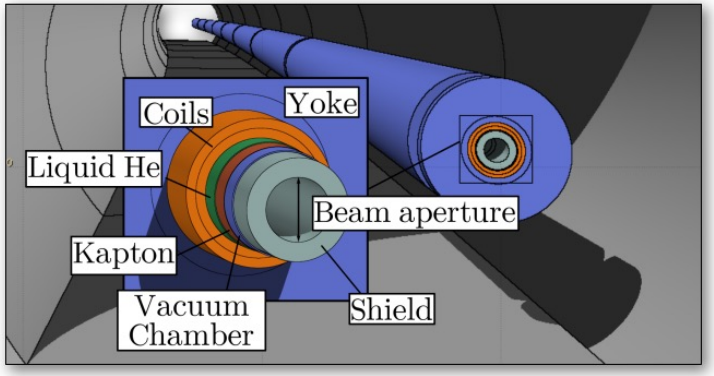


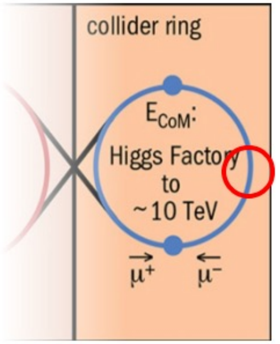
$$\mu^- \to e^- \, \bar{\nu}_e \, \nu_\mu$$

$$\mu^+ \to e^+ \, \nu_e \, \bar{\nu}_\mu$$

Effect of decay-e-+ SR on SC coils

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

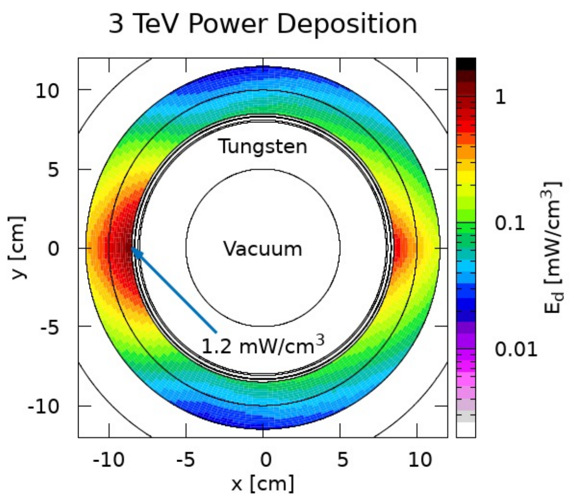


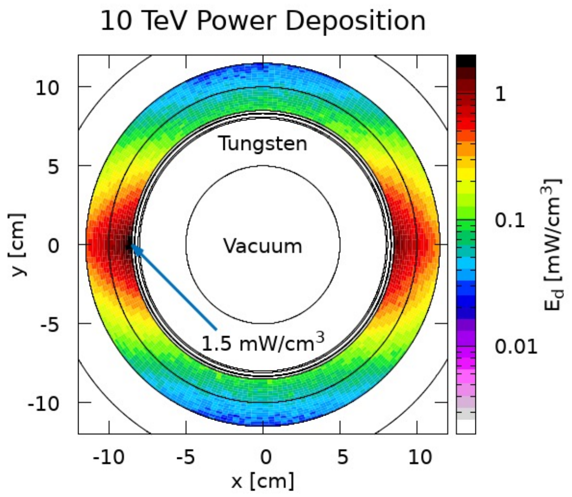


- Short term effects:
  - **What's the power load on the superconducting coils? Are we within the quench limit?**
- Long term effects:
  - **Dose delivered to SC coil insulators (organic materials) after 10 years?**
  - **What about displacement damage in the SC coils? What is the DPA after 10 years?**

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/cm^3**
  - Well below typical **15-20 mW/cm^3** 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!

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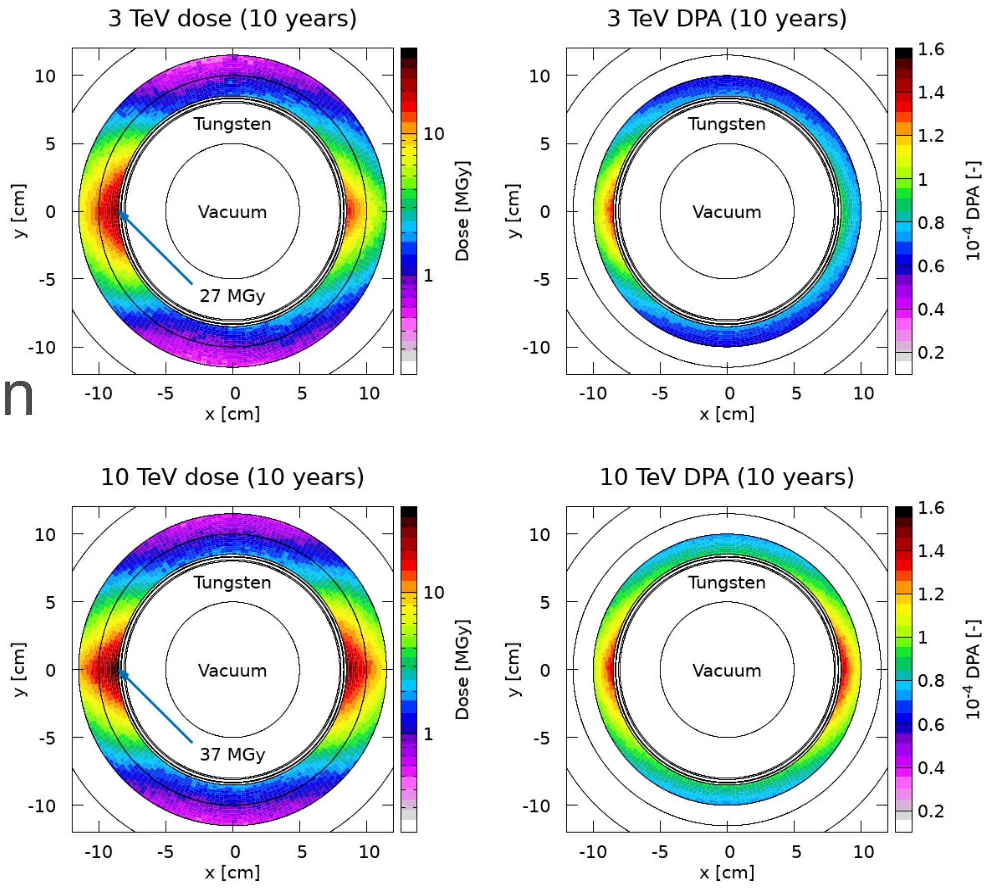
- Displacement damage:
  - DPA ~ 1e-4
  - Ref: Nb_3Sn critical temperature degrades after 1e-3 DPAs.

✓



Summary

Summary and key points

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

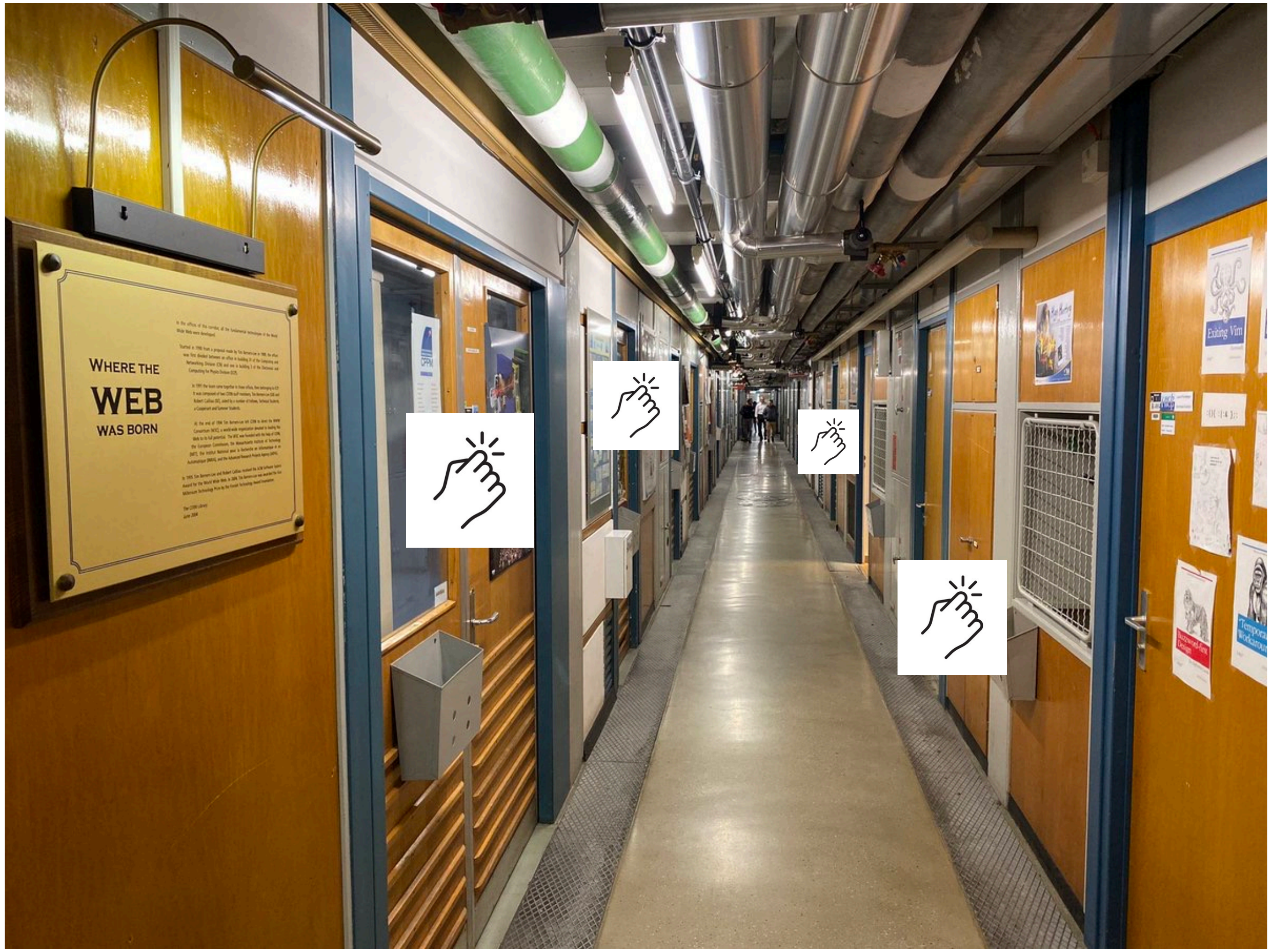
- **Monte Carlo** method as powerful tool to assess the effect of beam losses and other sources of radiation in the design/operation of particle accelerators
  - Quantities relevant for short-term effects (power deposition)
  - Quantities relevant for long-term effects (dose and displacements per atom)

- 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 interest 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

	$\sqrt{s}$=3 TeV	$\sqrt{s}$=10 TeV
Beam energy	1.5 TeV	5 TeV
Bunch intensity	2.2×10^{12}	1.8×10^{12}
Number of bunches	1	1
Injection frequency	5 Hz	5 Hz
Circumference	4.5 km	10 km
Arc dipole strength	7 T	10.4 T