Accelerator Technology Challenges (Part 3) :

Accelerator **operation** and design challenges (1/2)

Francesc Salvat Pujol

With precious input from many CERN colleagues
Special thanks to A. Lechner!

The Accelerator Technology Challenges lecture block

1 - Superconducting magnets

Monday, 8 July

11:35 → 12:30 **Magnet Superconductivity 1/2**
Speaker: Susana Izquierdo Bermudez (CERN)
2407_SusanaIzquier... | 2407_SusanaIzquier... | Recording | Video preview

Tuesday, 9 July

10:25 → 11:20 **Magnet Superconductivity 2/2**
Speaker: Susana Izquierdo Bermudez (CERN)
2407_SusanaIzquier... | 2407_SusanaIzquier...

2 –Superconducting RF cavities

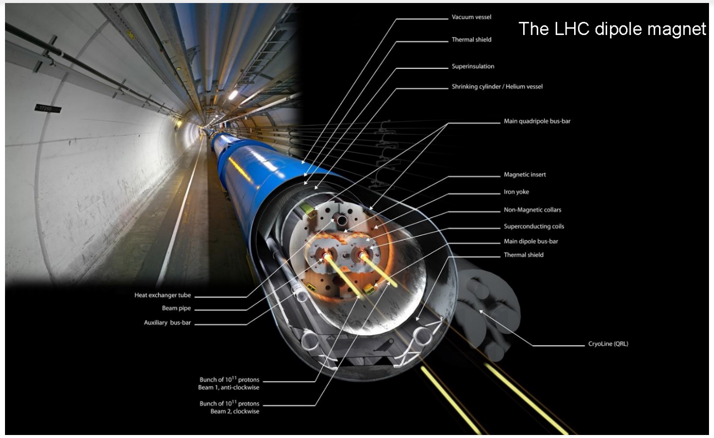
Monday, 22 July

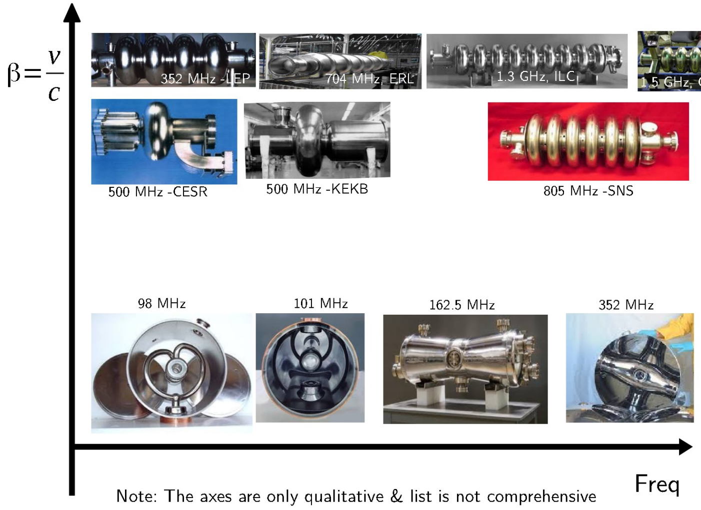
09:15 → 10:10 **Radio Frequency Superconductivity 1/2**
Speaker: Akira Miyazaki (Uppsala University (SE))
AkiraMiyazaki_CER... | AkiraMiyazaki_CER...

Tuesday, 23 July

10:25 → 11:20 **Radio Frequency Superconductivity 2/2**
Speakers: Akira Miyazaki (Uppsala University (SE
AkiraMiyazaki_CER... | AkiraMiyazaki_CER...

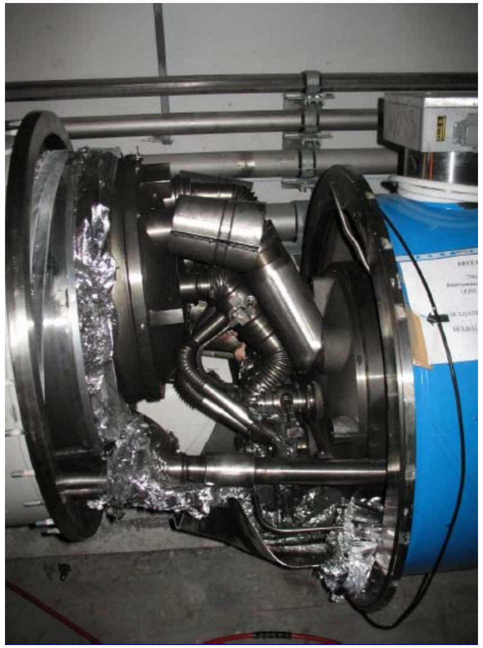
3- Operational and design challenges





2008 incident at the LHC

- Sep 10, 2008: p circulate through the LHC
- Sep 19, 2008: **incident** during dipole commissioning:
  - Current was being ramped up to produce 6.5 T field
  - **Shortcircuit** in interconnect between quadrupole (white/left) and dipole (blue/right) due to a welding issue
  - Electrical arc (**spark**) developed, which punctured the cryogenic He enclosure
  - He at high T and P -> He **gas expanded** with exposive force. 6 tonnes of He leaked.
  - Magnets (weighing tonnes!) displaced
  - **Damage to ~50 superconducting magnets, as well as their anchor mounting to concrete floor, and vacuum pipe contamination**
  - 14 months delay in LHC operation schedule until all affected magnets were repaired
  - LHC had to be run at lower energy than nominal until all magnet interconnects were upgraded by 2013



Refs: Nov 2008 DG slides. A detailed account. Press release.

Accelerator operation and design challenges

- The 2008 incident, while a nuisance, was not the end of LHC

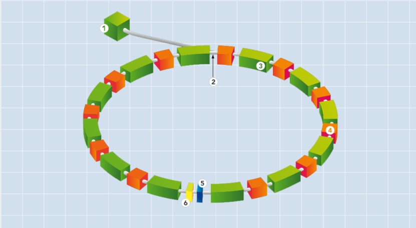
- 1st take-home message:

  Accelerator operation is ridden with technical challenges

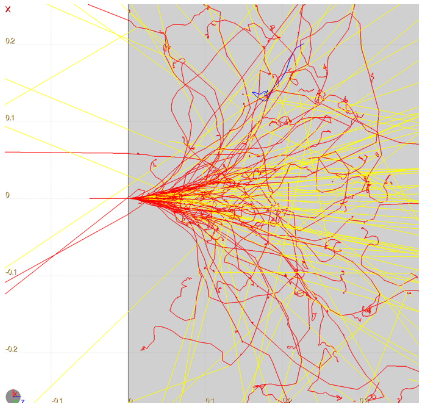
- Without wandering into the realm of incidents, in today's lecture we will focus on a series of **daily challenges** posed by particles lost from the beam and impacting somewhere in the machine (**beam losses**)

Outline of the material ahead

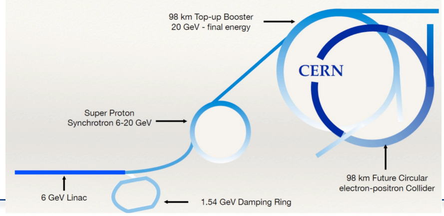
- Particle accelerator recap:
  - Basic **building blocks**
  - **Operational cycle** of a particle accelerator



- A qualitative discussion of **beam losses,** their causes, their effects, and their implications for the **operation** of particle accelerators (today)



- Basic generalities of **hadronic and EM particle showers**
- Numerical simulation tools (Monte Carlo method)
- Application to the **design** of particle accelerators (tomorrow)



Recap: building blocks and basic operational cycle of a particle accelerator

Introduction to particle accelerators and beam dynamics

Many more details in these lectures from a couple weeks ago, which you may revisit:

10:25 → 11:20 **Accelerators and Beam Dynamics 1/3**
Speaker: Foteini Asvesta (CERN)
introAccelerators_s... introAccelerators_s...

MONDAY, 8 JULY

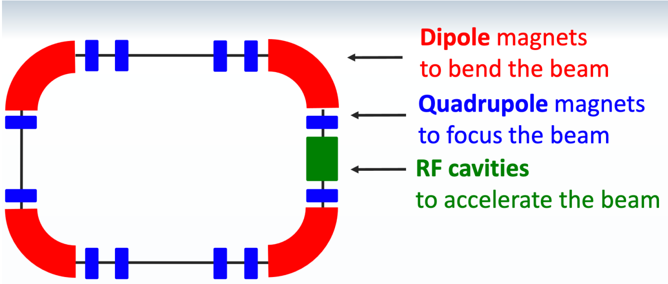
09:15 → 10:10 **Accelerators and Beam Dynamics 2/3**
Speaker: Foteini Asvesta (CERN)
introAccelerators_s... introAccelerators_s...

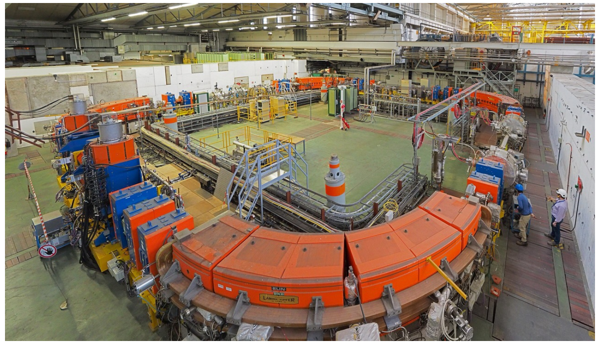
TUESDAY, 9 JULY

10:25 → 11:20 **Accelerators and Beam Dynamics 3/3**
Speaker: Foteini Asvesta (CERN)
introAccelerators_s... introAccelerators_s...

WEDNESDAY, 10 JULY

For today, we'll just need a very basic schematic:

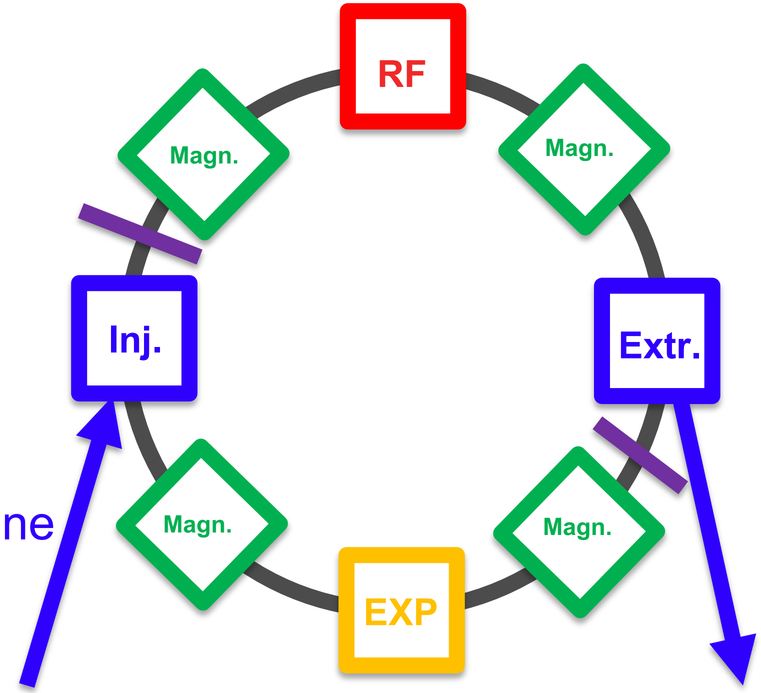




E.g. LEIR – which you may actually visit while at CERN!

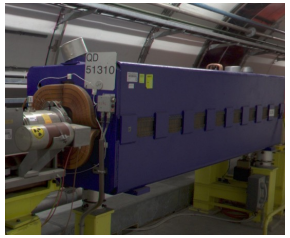
Schematic of a particle accelerator (synchrotron)

- Particle **injection system**
- **Magnets** (bending dipole, focusing quadrupoles, …)
- Radiofrequency (**RF**) cavities: accelerate particles
- **Collimation**
- **Vacuum system**
- **Experiment**
- Particle **extraction system:** B or E field
- **Synchronization -> typical operational cycle**

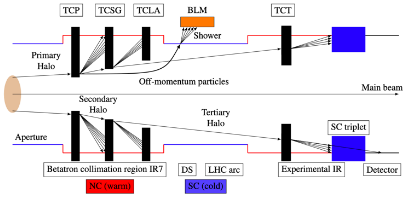


- Transfer line
- Previous accelerator or source
- Next accelerator
- Target/experiment
- Beam dump


SPS dipole

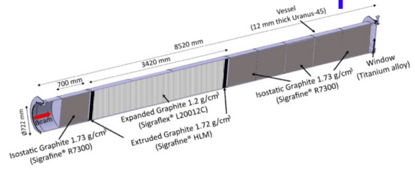

SPS quadrupole


LHC RF cavities

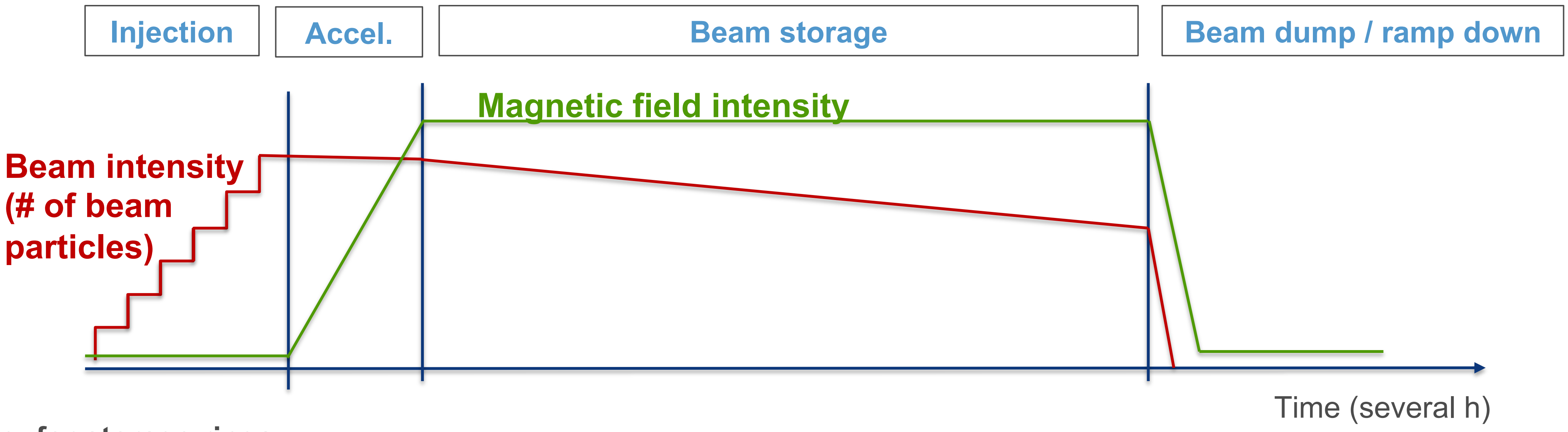


LHC collimation


SPS internal beam dump

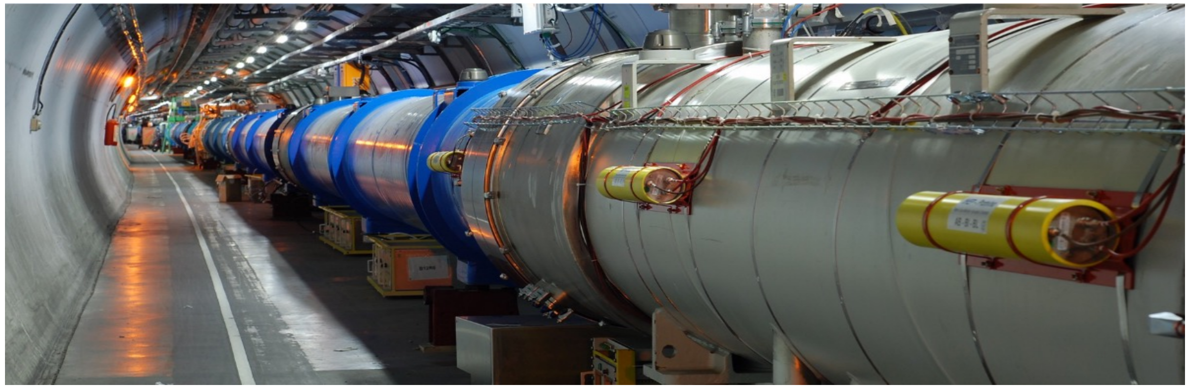

LHC beam dump

Schematic operational cycle of a particle accelerator (synchrotron)



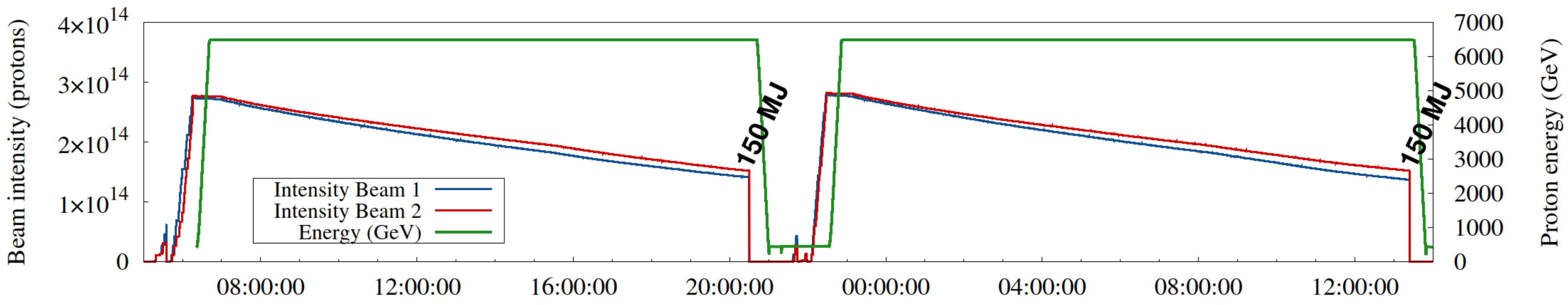
E.g. for storage rings:

- Beam circulating for many h
- Multiple particle injection to fill the ring
- Acceleration: energy increase, B also ramped up to keep particles in circulating beam orbit
- Beam is then stored for hours, serving experiments
- Beam quality degrades (desired collisions, undesired beam losses): eventual beam dump, ramp down magnets

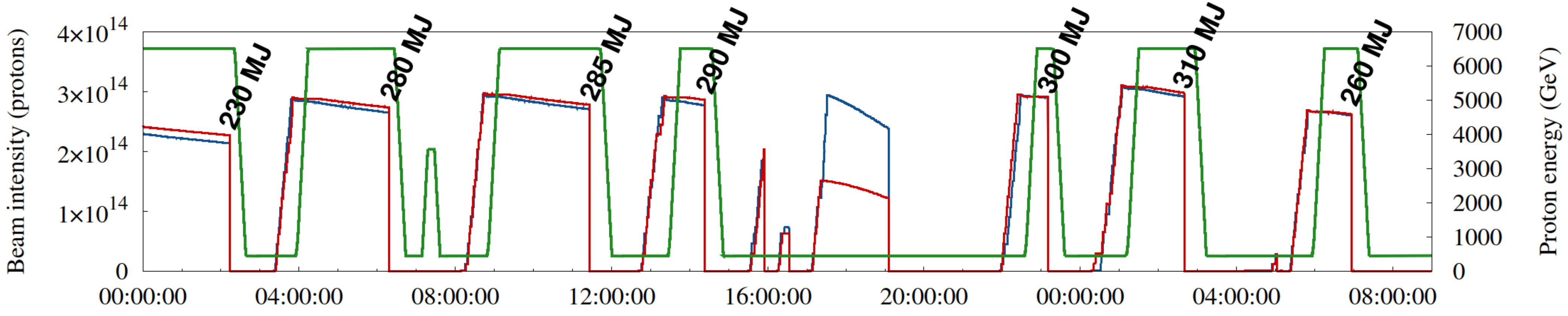


LHC cycles: https://op-webtools.web.cern.ch/vistar/vistars.php

- On good days: successful injection, successful E ramp-up, beam serves exp ~12h



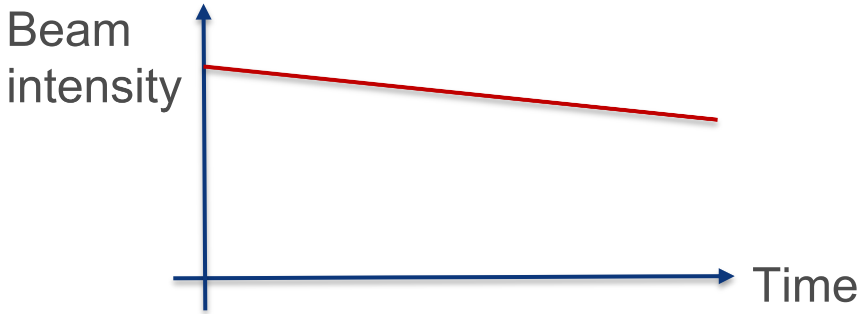
- On bad days: injection failure, dumps after just a few h, etc.

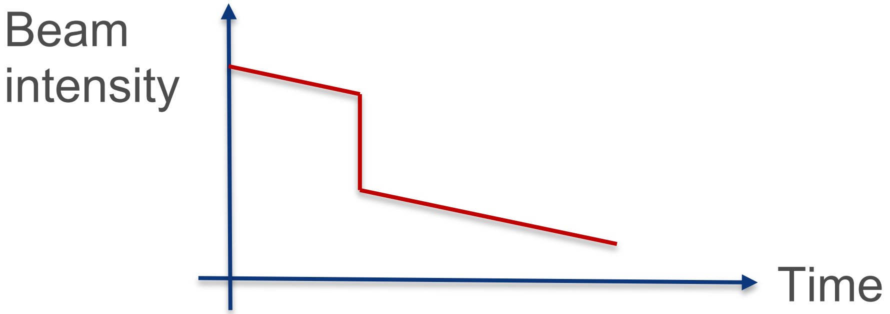


Ref: A. Lechner, “Beam-induced energy deposition on dump block assembly”, TDE autopsy technical review, 2021.
(Several figures from this talk used also below)

Coming up

- Processes that contribute to:
  - The **monotonic regular loss** of beam intensity
  - The **fast/sudden beam losses** and subsequent beam dumps
- But first: are beam losses such a big deal?





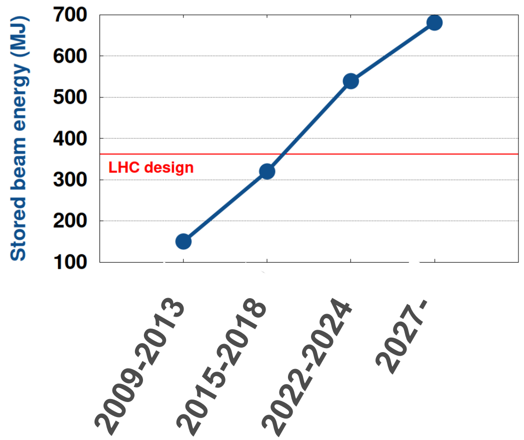
Energy stored in the LHC beam

- Energy of p beam*: $O(10^2\ \mathrm{MJ})$
  *See additional slides

- Equivalent to that of a 400 tonne train at ~140 km/h

- Losing even a fraction of this energy poses challenges

- Beam losses cannot be left unattended



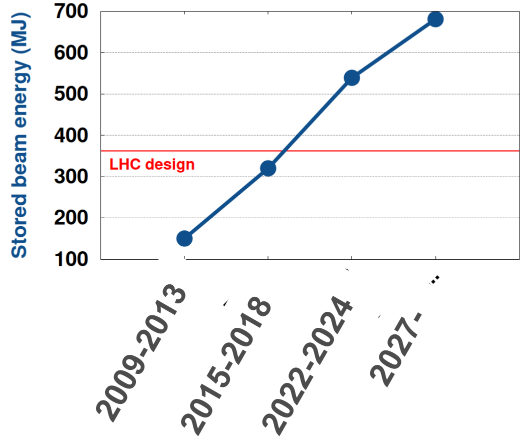
(A. Lechner)

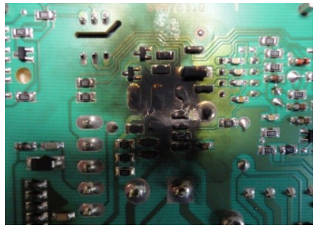
(Wikipedia)

Beam losses

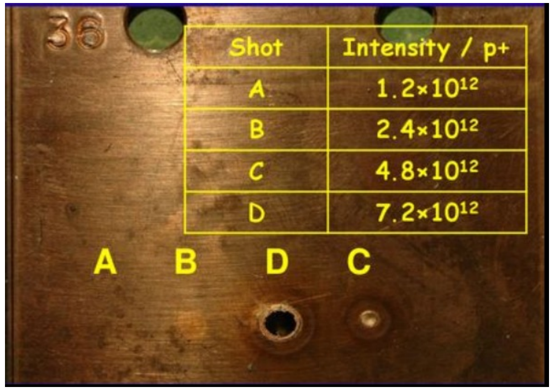
An introduction to beam losses

- Energy stored in circulating p beam @LHC: **O(100) MJ**
- Considerable challenge for accelerator **operation, equipment, and personnel** in case even a fraction of the beam is lost in the accelerator (**beam losses**):
  - **Malfunction** of accelerator systems → **Operation has to be stopped** until affected system is back in service (no collisions, no DAQ for exp.)
  - E.g. Superconducting (SC) magnets brought out of SC state **(quench)**
  - **Macroscopic effects on materials:** heating, melting, evaporation, embrittlement
  - **Microscopic/structural damage** affecting lifetime of accelerator equipment
  - Especially important: radiation-induced **errors in electronics**
  - **Activation** -> delays operator access for maintenance
- Consequences range from temporary absence of beam to an extended shutdown of the accelerator





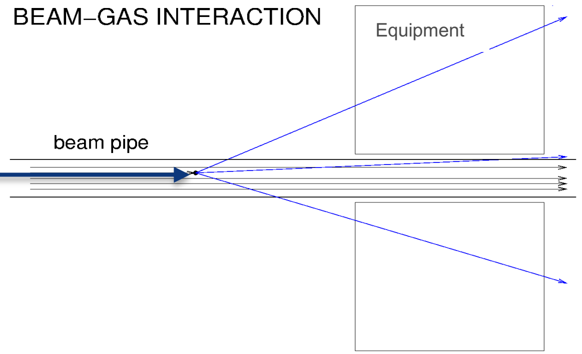
450 GeV p on Cu



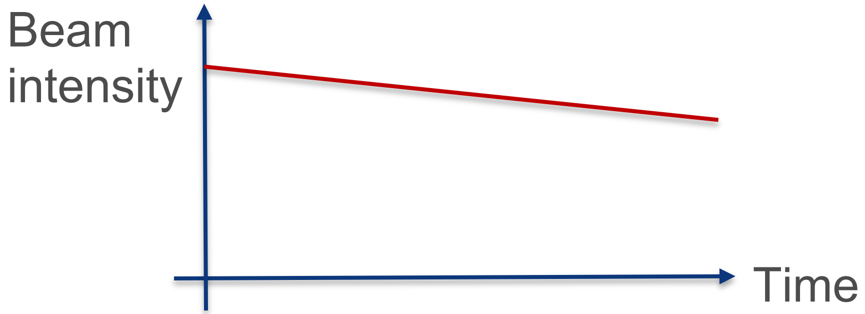
Beam losses pose **challenges** to the **operation** of particle accelerators and are a main concern in their **design**

Regular vs. accidental beam losses

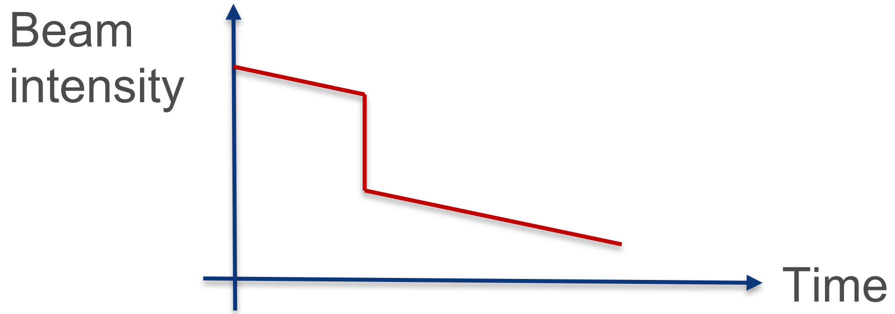
- **A beam particle is lost for a variety of reasons:**
  - ❌ It is in the wrong orbit and ends up traversing the vacuum chamber
  - ❌ It impinges on a beam intercepting device (e.g. absorber) -> shower
  - ❌ It undergoes a collision with e.g. residual gas in the beam pipe (at ultra-high vacuum)
  - ❌ It undergoes unintended collision with unidentified falling object (UFO), e.g. dust
  - ✅ It undergoes an intended collision at an interaction point



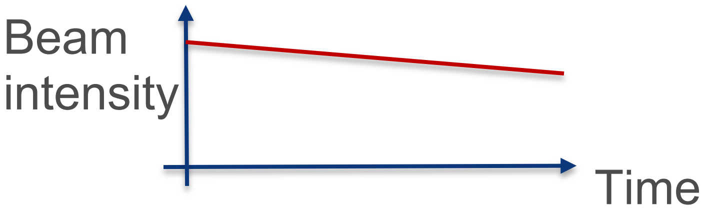
- **Regular** beam losses:
  - Generally unavoidable, continuous, every cycle
  - Slow (~minutes/hours)
  - O(10%) intensity drop / cycle



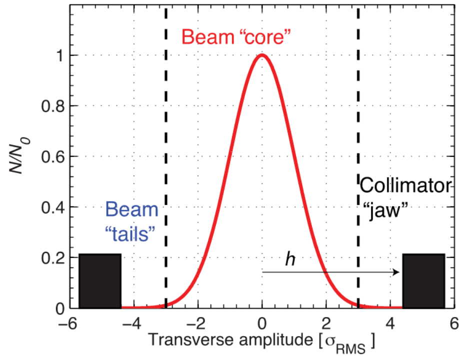
- **Accidental** beam losses:
  - Occasional, not every cycle
  - Sudden / fast (ns-ms)
  - Potentially large intensity loss

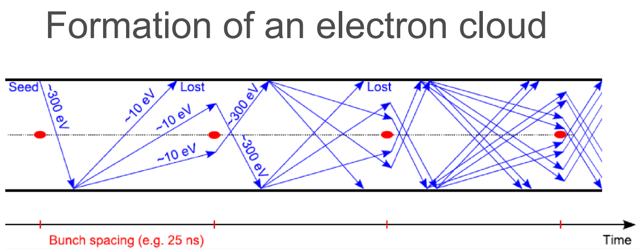


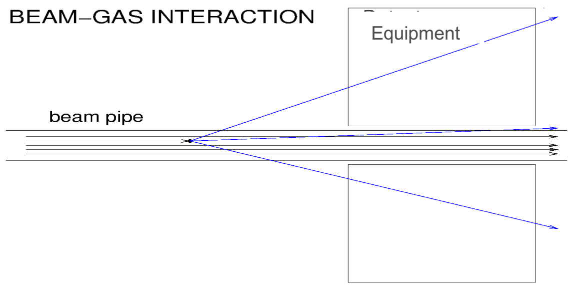
Regular beam losses

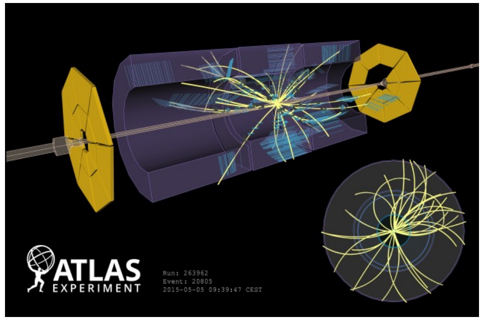


- **Halo** (tail in spatial profile) of beam can be lost on machine aperture due to various effects which transfer particles from the core to the halo region of the beam profile, e.g.:
  - Magnetic field errors, RF noise, interaction between beam particles, e- clouds, etc
- **Direct losses:**
  - Elastic collision with residual gas
  - Nuclear inelastic collision with residual gas
  - (Intended!) collisions
- **Operational variations:**
  - Beam orbit drifts due to optics changes in the cycle
  - Changes in the tune
  - …



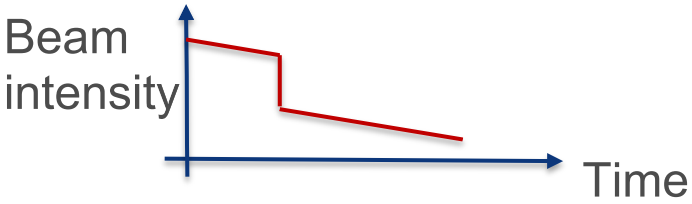




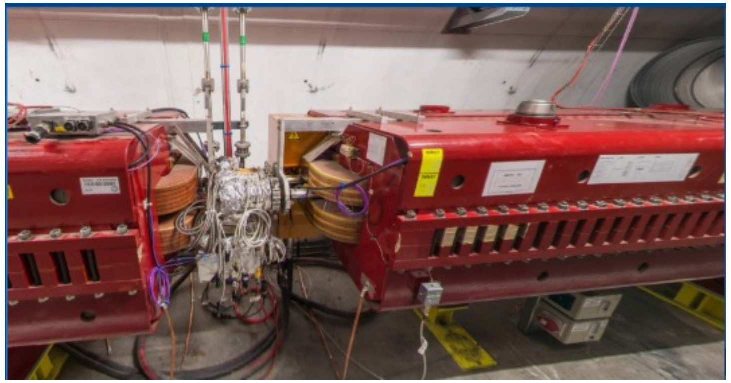


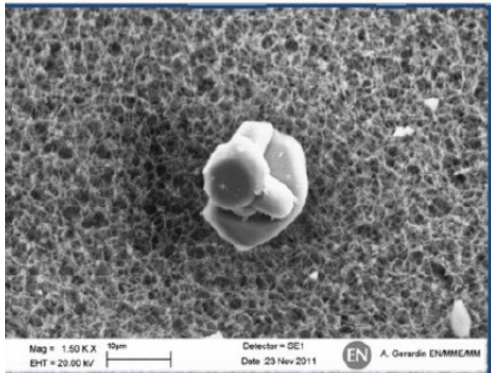
Accounted for in design phase to reduce impact on **equipment**, **personnel**, and **operation**

Accidental beam losses



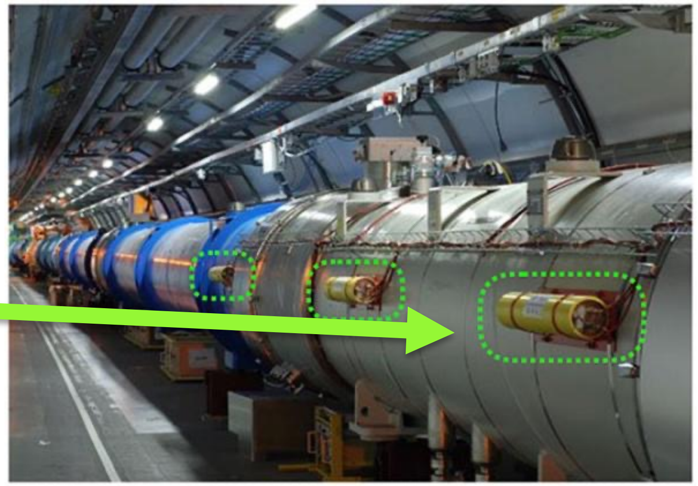
- Typical causes:
  - Malfunction of accelerator equipment
    - E.g. power converter for a magnet fails, wrong kick applied, beam mis-steered, eventually lost.
  - Operational mistake (human / software error)
  - Unidentified falling objects (UFOs), ~micrometer-sized dust particles in beam path (negatively charged, which are attracted to the beam and scatter it away)
  - …
- Beam has typically to be refilled: operational loss O(h)



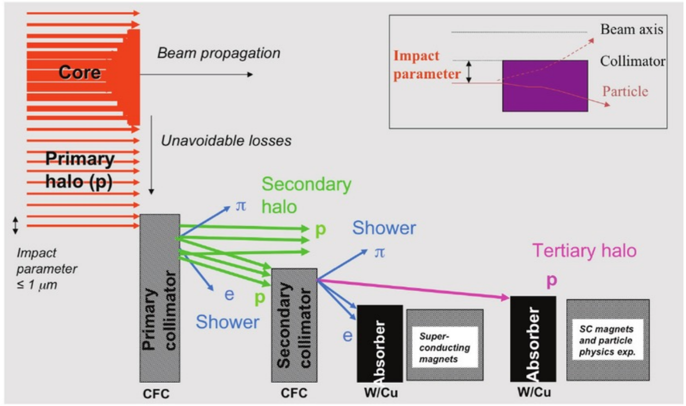


Protection / monitoring of accidental beam losses

- **Active** protection
  - Constant monitoring of beam and equipment parameters (e.g. beam current, position, profile…), beam-loss monitor signal, magnet current, etc.
  - O(10^5) parameters constantly being monitored within safety range. If any of them gets out of hand, beam is extracted on the beam dump.



- **Passive** protection
  - There can be losses for which the scheme above is not fast enough
  - Collimation system



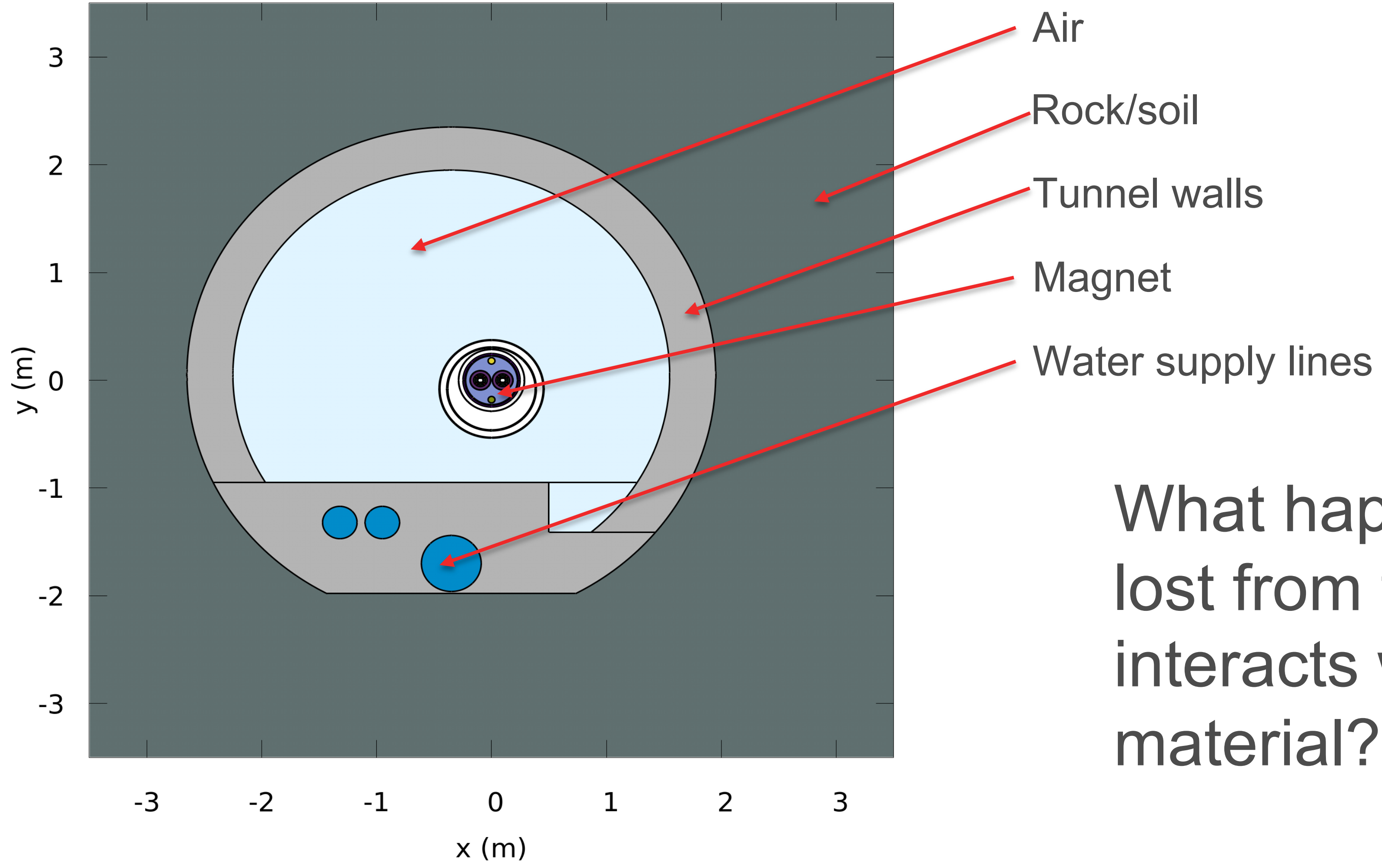
Ref: S. Redaelli *et al., HL-LHC Technical design report, Chapter 5, Collimation System*
http://cds.cern.ch/record/2750434/files/1159-Article%20Text-4918-1-10-20201218.pdf

Thus far: general description of beam losses and their operational implications

Next: what happens when an energetic particle lost from the beam impinges on a material?

Basic radiation-matter interaction mechanisms at play in order to understand/predict/mitigate macroscopic effects of beam losses on materials

Example: tunnel cross section for a 450 GeV p accelerator



What happens when a p is lost from the beam and interacts with the surrounding material?

→

Radiation shower set up by a **single** 450 GeV proton loss

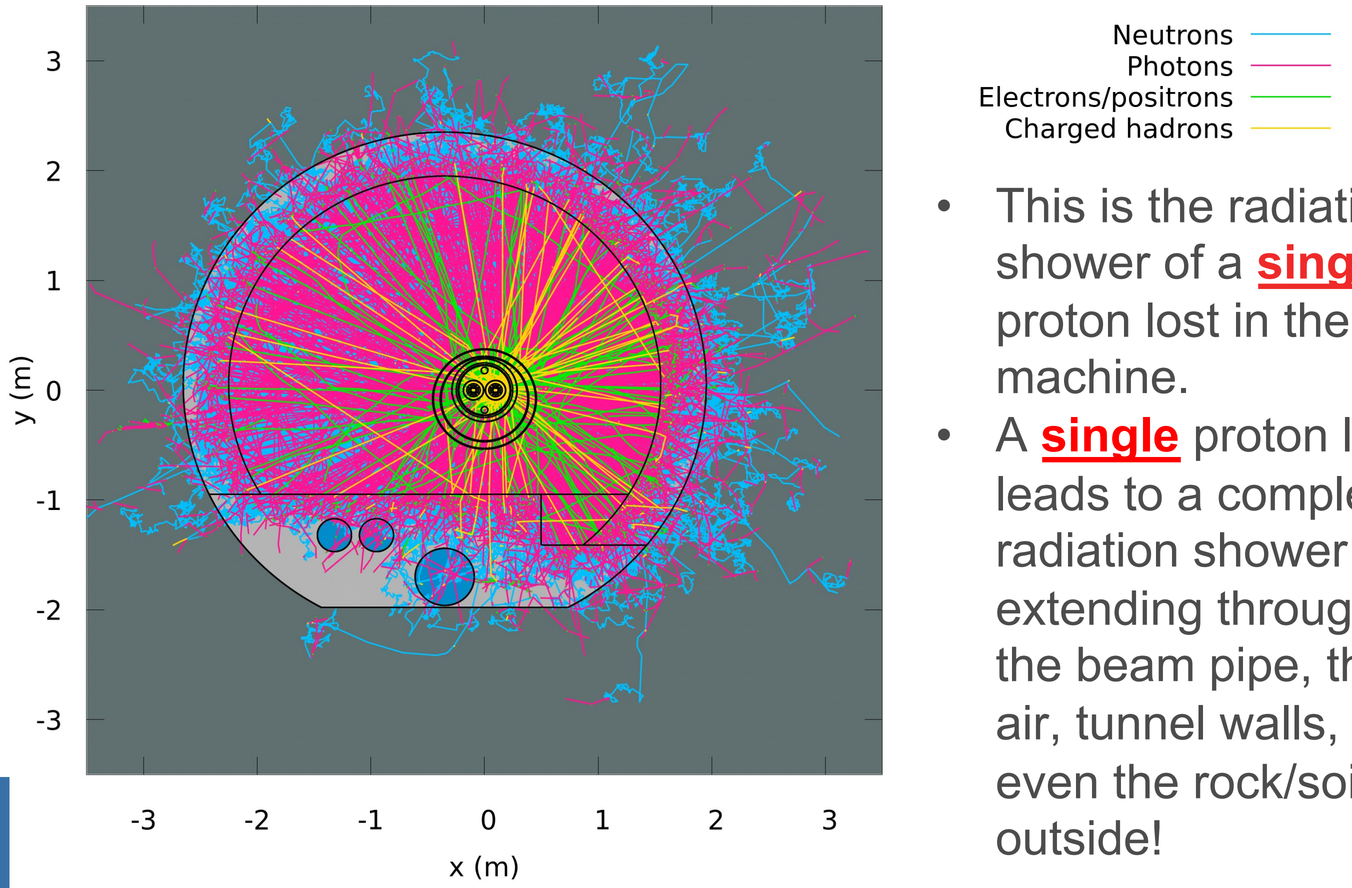
- Go-to tool to assess these kind of questions:
  Monte Carlo simulation of radiation transport
  (more on this tomorrow!)

- Basic idea: define radiation source, material geometry, interaction physics, and simulate full radiation showers

Particle showers shown in this and further slides have been simulated with

FLUKA

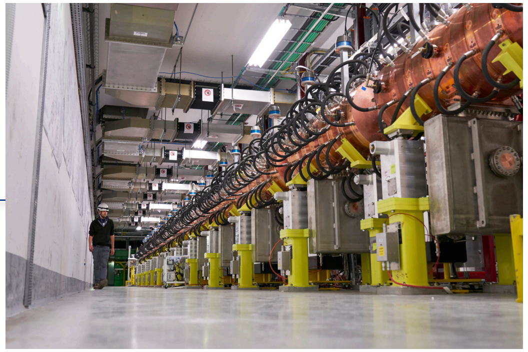
https://fluka.cern



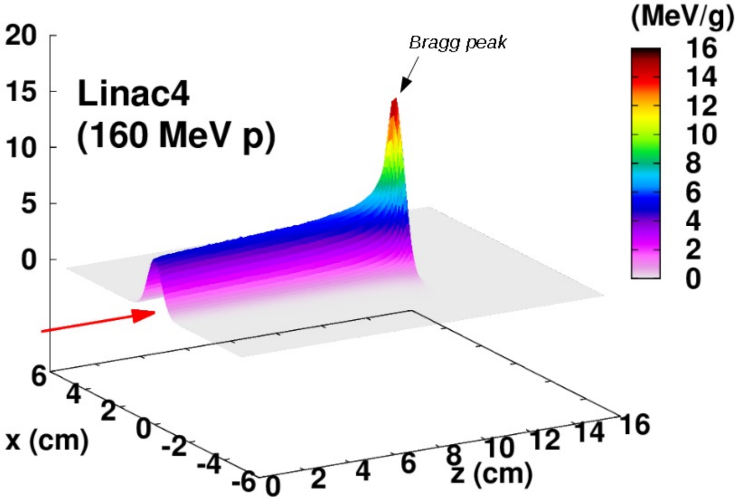
- This is the radiation shower of a **single** proton lost in the machine.
- A **single** proton loss leads to a complex radiation shower extending throughout the beam pipe, the air, tunnel walls, and even the rock/soil outside!

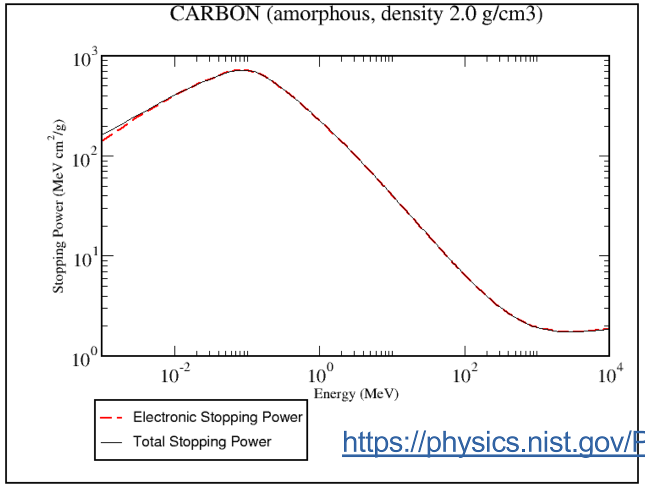
All sorts of complications: energy deposition (magnet quench!), possible damage of electronics, material activation, etc.

LINAC4 protons onto a graphite block



- Radiation-matter interactions vary: lepton vs hadron, low/high E, low/high Z material…
- Energy (per unit mass) by **160 MeV protons** from LINAC4 onto a graphite block.





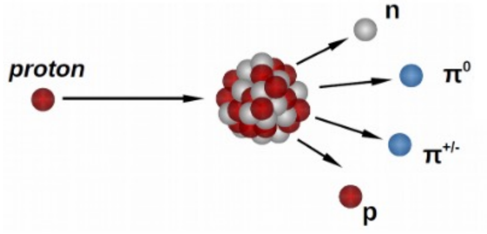
https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

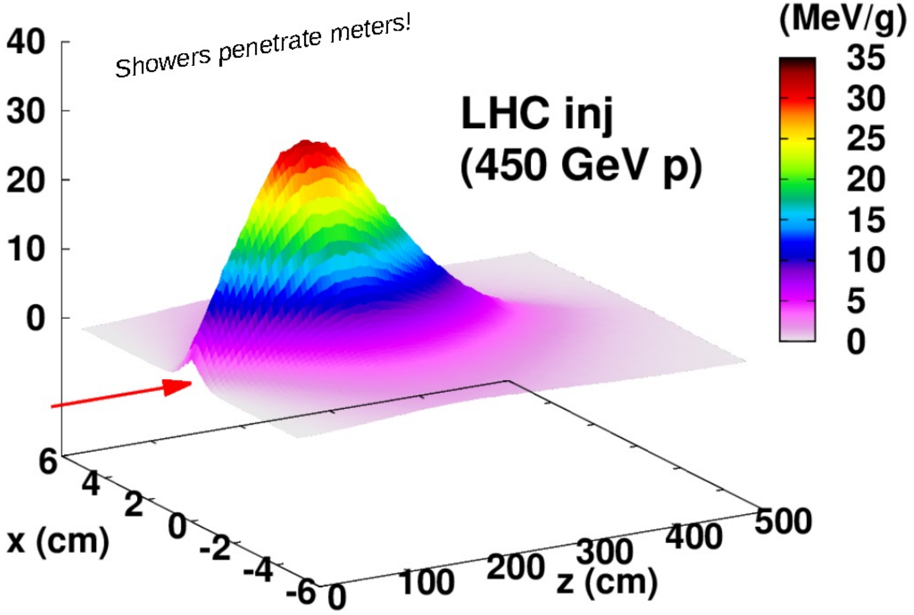
- Energy deposition driven by **ionization** losses (collisions with target e-).
- Energy loss rate increases drastically at low energies (i.e. at the end of p range), hence the ***Bragg peak*** *(interesting for **medical applications**, see Manuela Cirilli's talks!)*
- There is also elastic scattering (on target atoms): progressive spread (x) as a function of z
- Few protons will undergo nuclear reactions: secondary n and light fragments produced, giving a low dose tail
- Incidentally, you see that ~10 cm of graphite are needed to effectively stop the beam

SPS protons onto a graphite block

- Very different situation at at higher energies, e.g. for 450 GeV p on graphite
- Dominant mechanism: copious **hadron-nucleus inelastic interactions, about once every few 10s of cm**
- Plenty of secondaries are produced: n, p, pions, etc.
- Complex radiation shower extending beyond the lower-energy example
- About 4 m of graphite are now needed to effectively stop the beam (!)
- Let's take a closer look at how such a radiation shower builds up

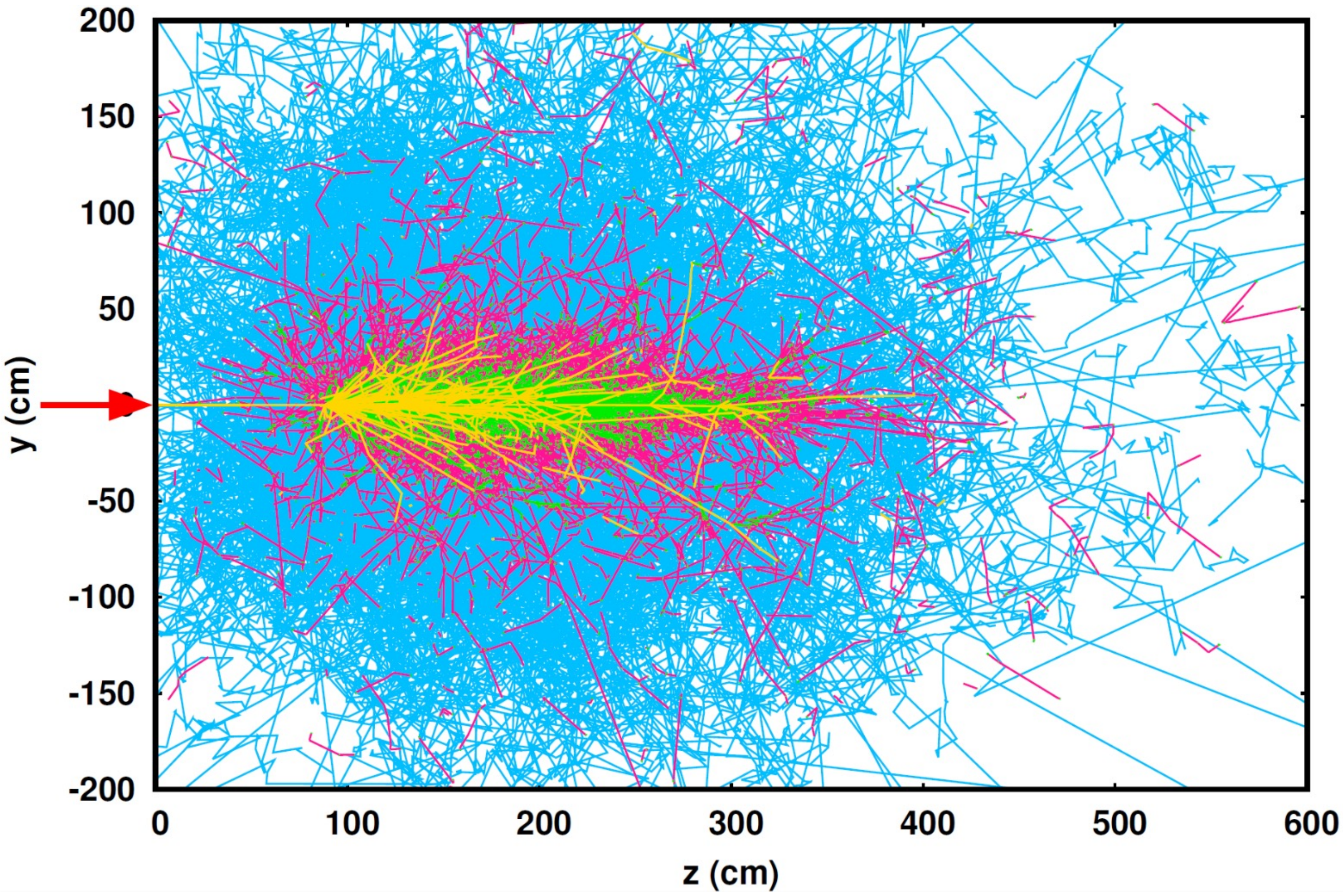
Hadron-nucleus interaction



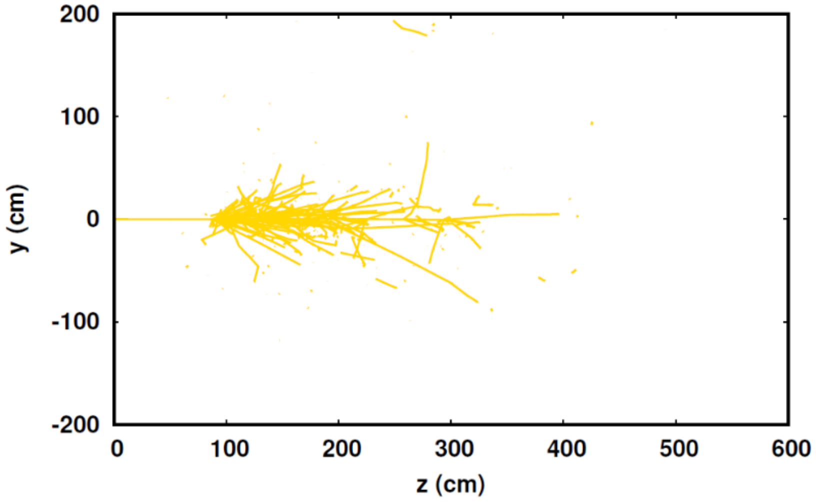


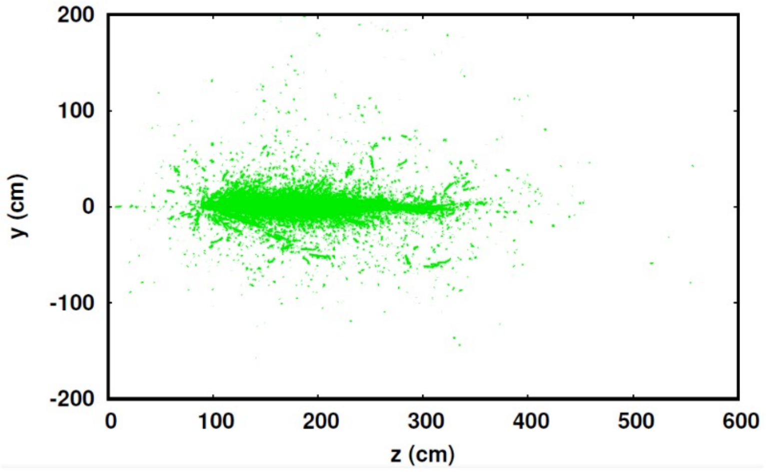
Interactions of a **single** 450-GeV p, this time on Al

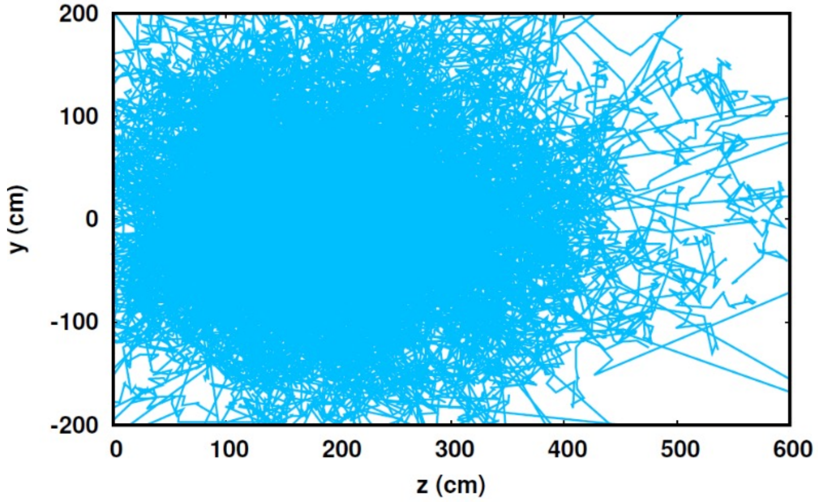
- Radiation shower simulated (with FLUKA)
- All segments you see represent particle tracks from the complex shower set up by a SINGLE 450 GeV p in Al
- Let's now try to guess which kind of particles produce which tracks in this shower

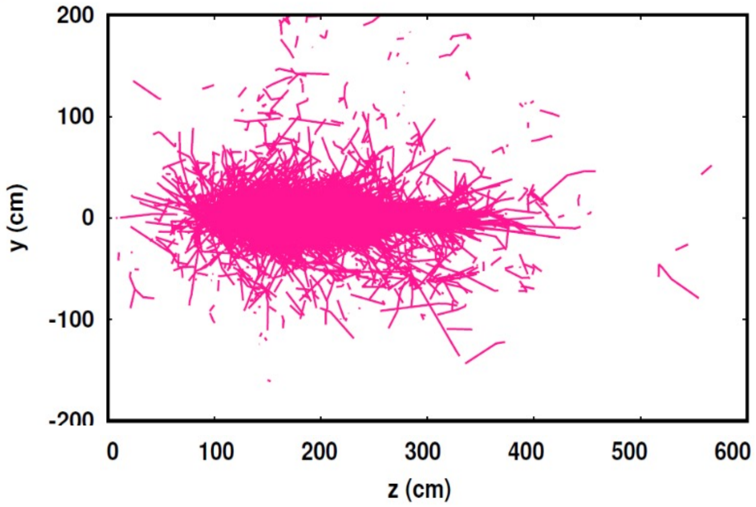


Care to guess who is who?



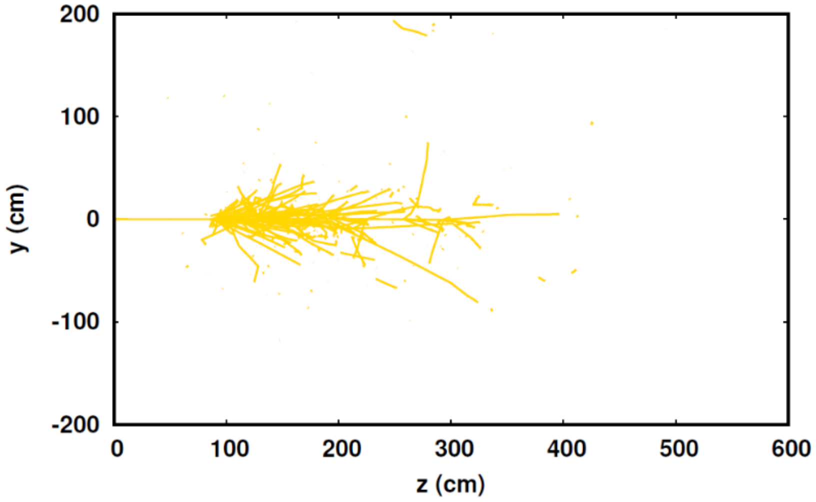


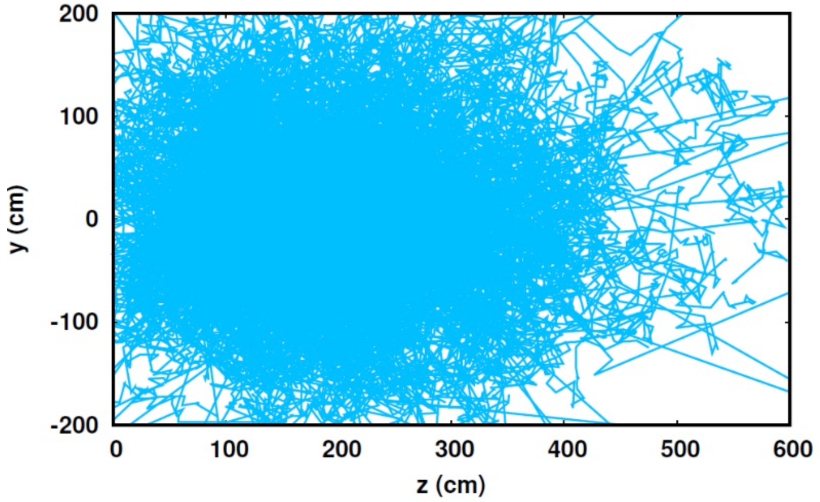




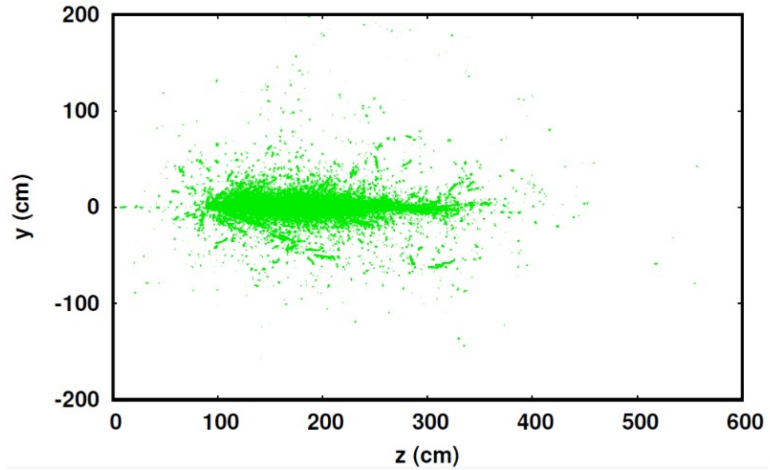
- Electrons/Positrons
- Photons
- Neutrons
- Charged hadrons

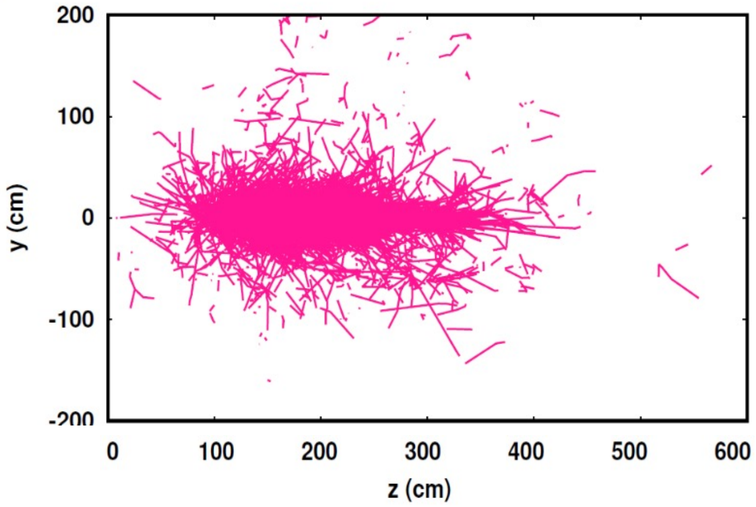
Care to guess who is who?   HINTS





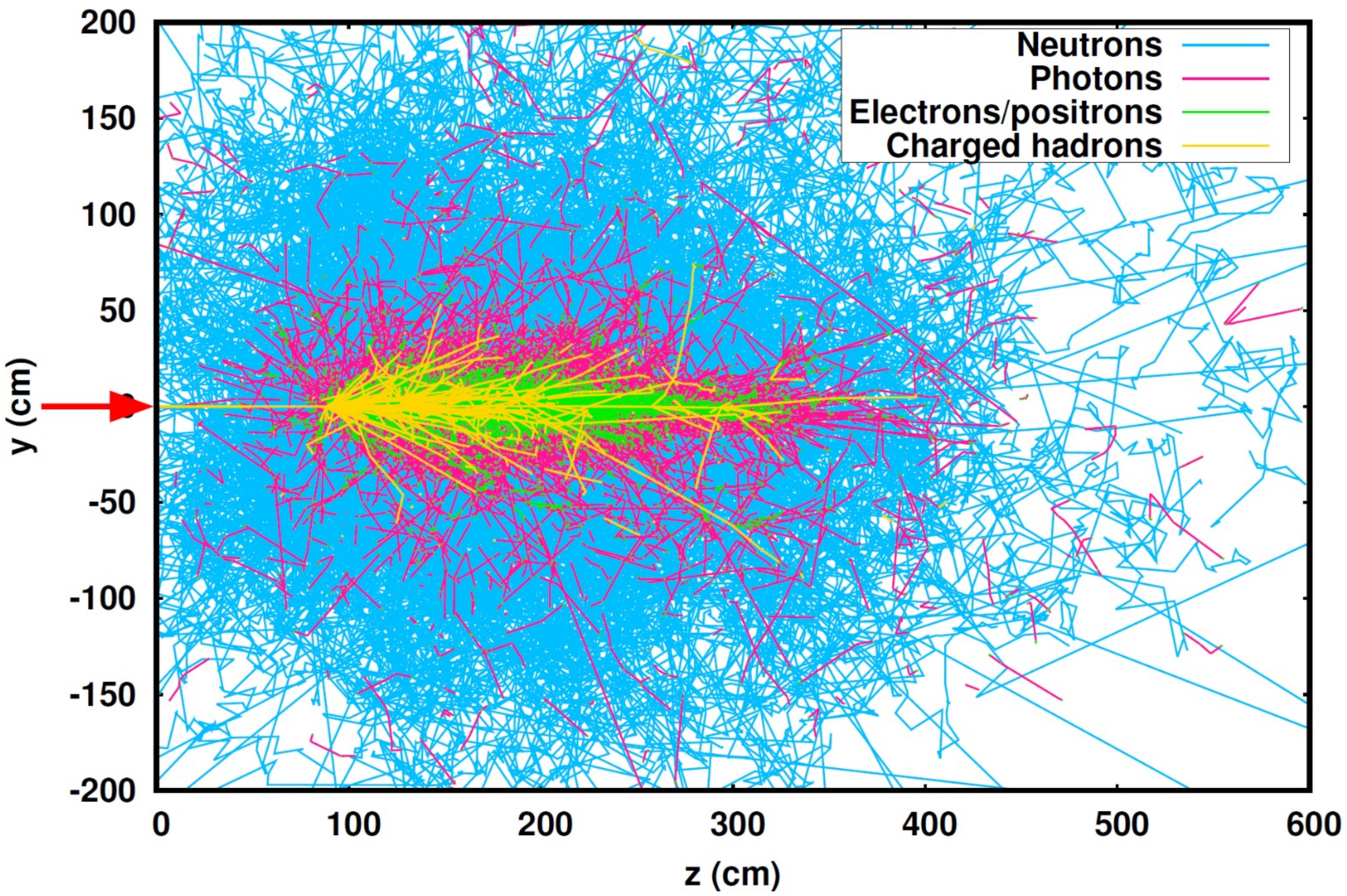
- Neutrons have no charge (they make it far from the beam)
- Charged hadrons: the proton is one itself!
- Photons make it a bit farther than e+-
- By elimination: e+- (much shorter range)





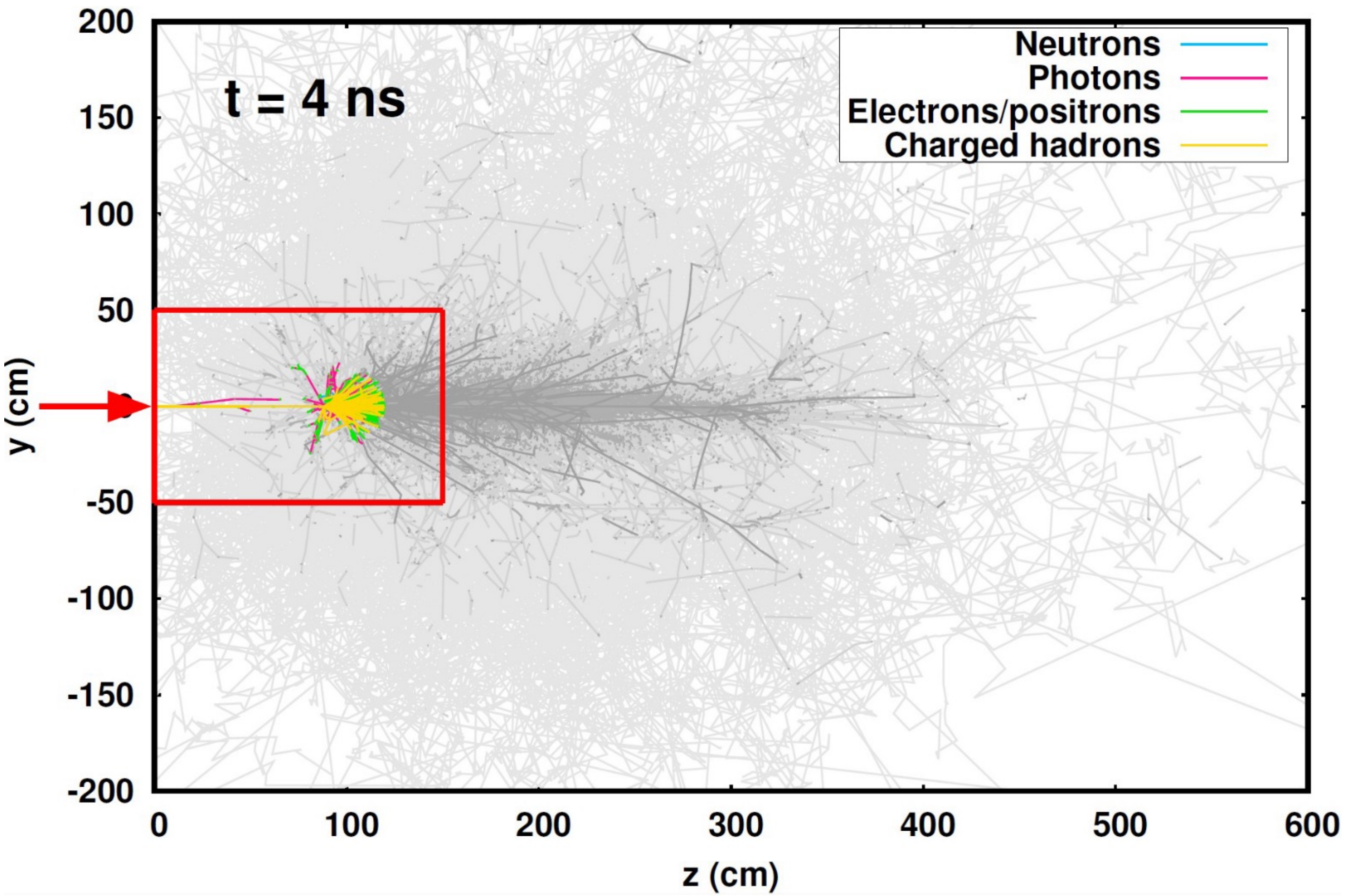
Radiation shower set up by a **single** 450-GeV p impinging on Al

- Great, but how is this shower produced?
- What are the basic interaction mechanisms governing it?
- Let's take a somewhat deeper look!



The shower until the first nuclear reaction

- We freeze frame **4 ns** after the beam penetrates the graphite block
- Let's zoom in to the red area

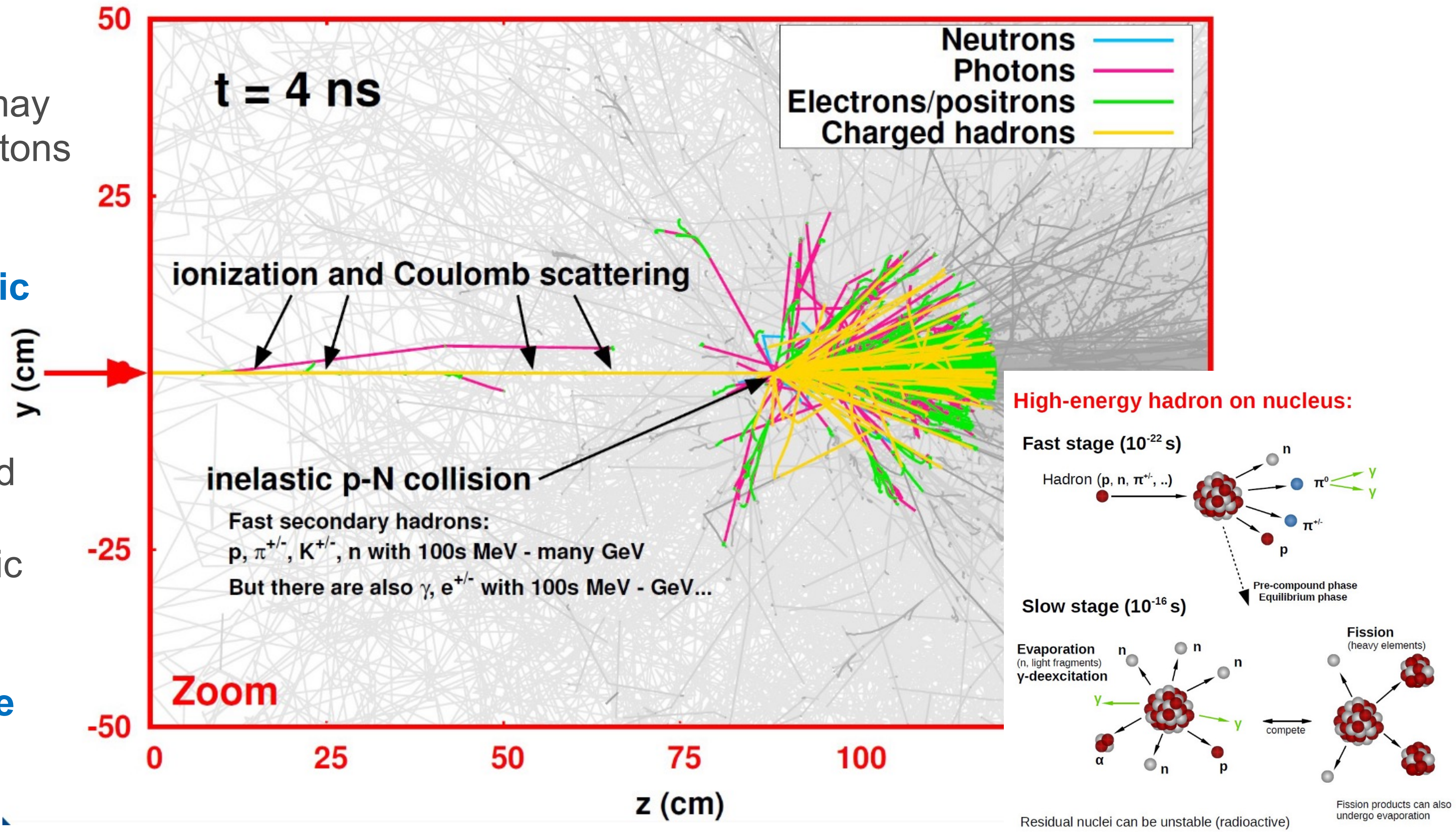


Aftermath of the first nuclear inelastic interaction

- **First few 10s of cm**:
  - Collisions with target e-
  - If e- are energetic, they may emit Bremsstrahlung photons
  - Proton is not impressed

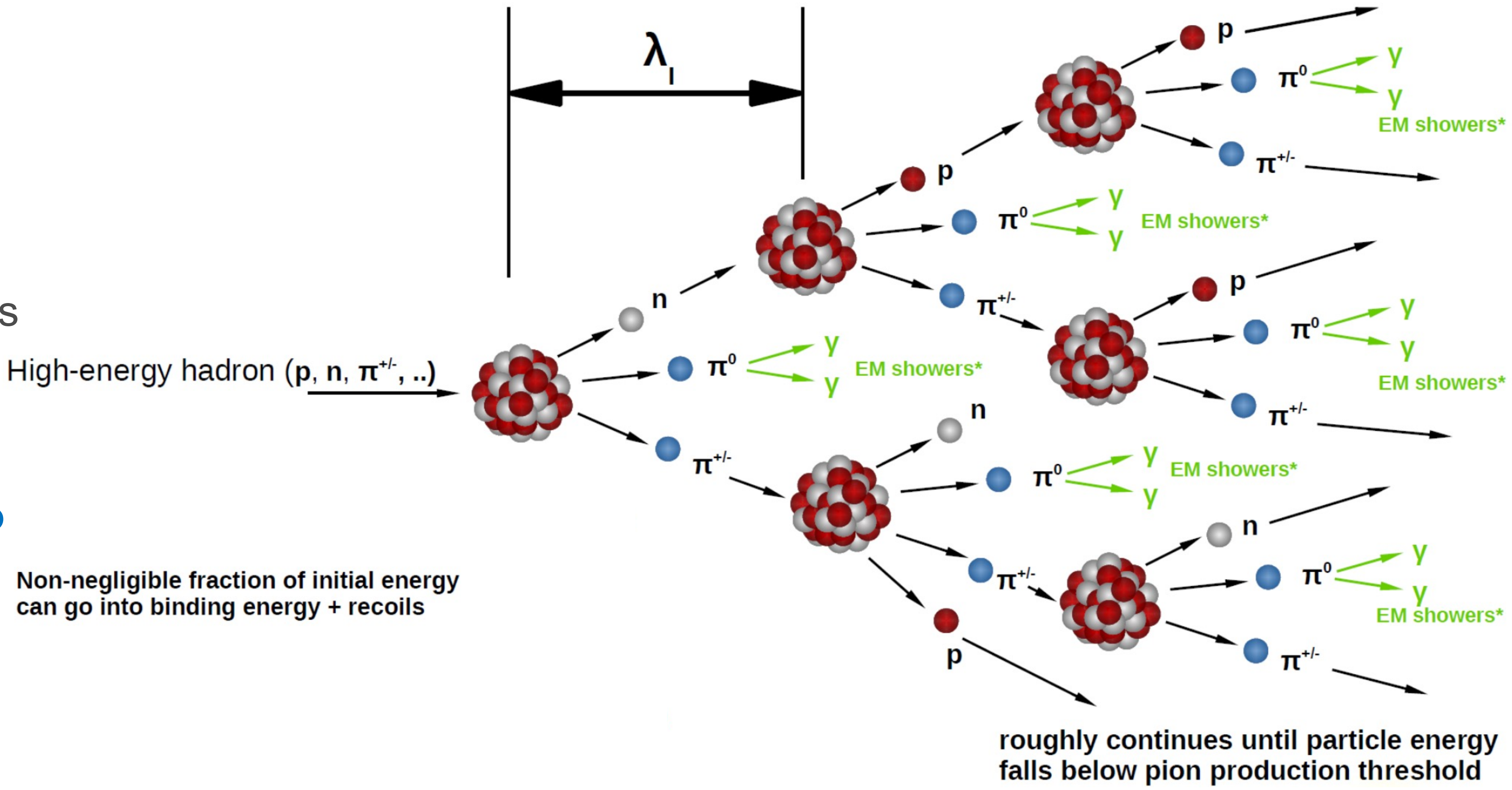
- **At ~85 cm, something drastic happens, i.e. a nuclear reaction:**
  - Fast stage: multiple secondaries (hadrons and photons) mostly fwd
  - Slow stage: more isotropic emission

- **Already ~100 particles in the shower!**



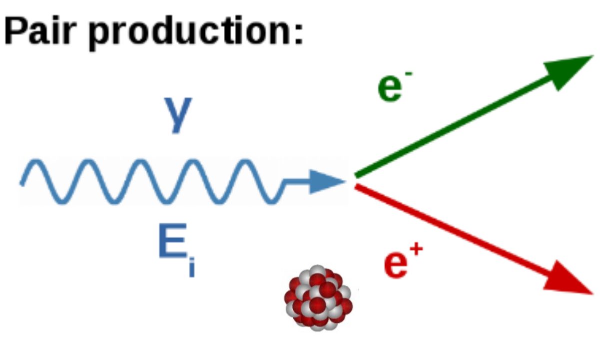
Hadronic shower development

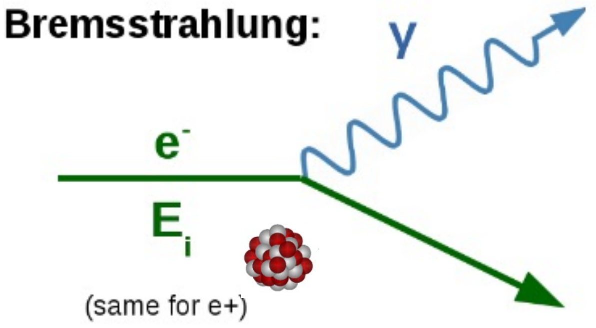
- Secondary hadrons reinteract with a similar mean free path
- This leads to a **geometric increase** in the number of hadrons in the shower!
- Some of the produced hadrons are unstable and may decay, e.g. pion0 -> 2 gammas
- **Hadronic showers couple to electromagnetic showers**
- Along hadronic shower, residual nuclei are produced, possibly radioactive

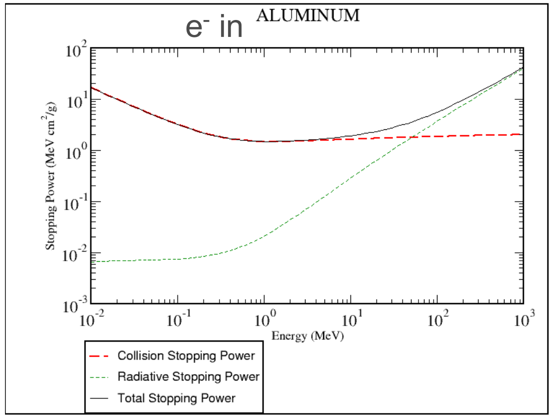


Electromagnetic shower development

- Relevant interaction mechanisms (at high E):

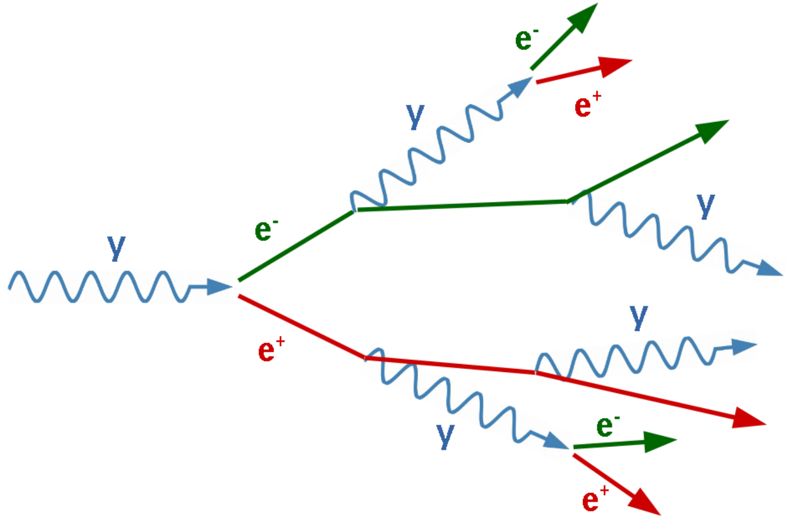






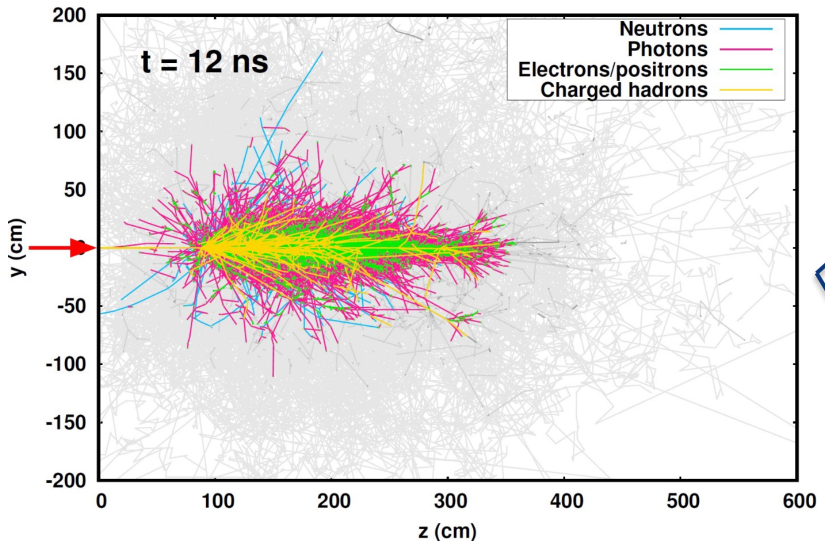
https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

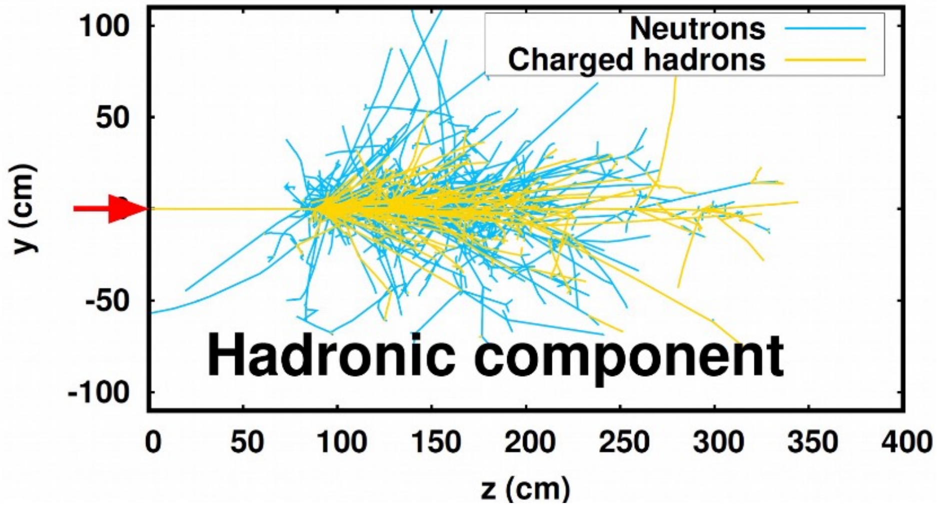
- Electrons/positrons lose energy via radiative (Bremsstrahlung emission) or non-radiative (elastic scattering on target e-) collisions
- EM shower development: fewer secondaries (~2), but EM interactions have much shorter MFPs, so one still ends up with a large number of secondaries.
- Incidentally, EM showers may couple to hadronic showers (**photonuclear interactions), but cross section is low,** so the feedback into the hadronic shower is modest.

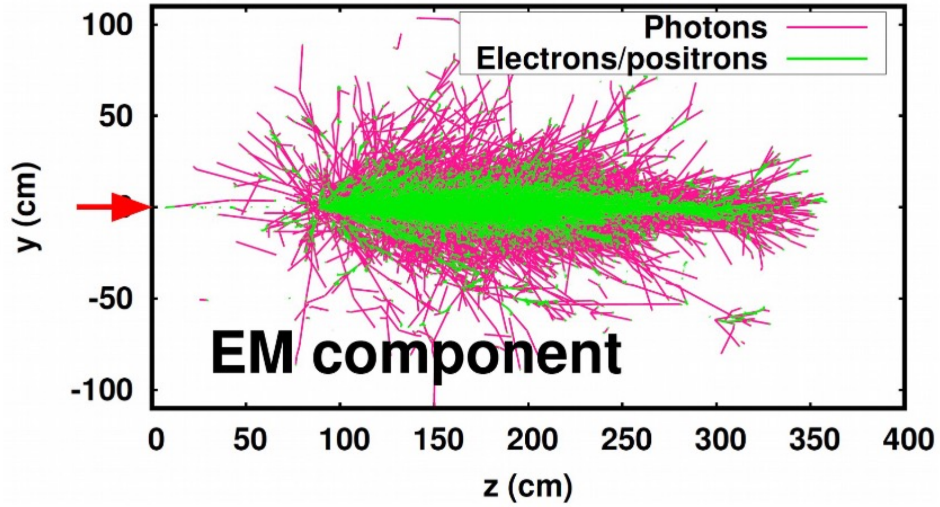


Back to our p in Al

- We now freeze frame **12 ns** after the beam penetrates the graphite block







- A complex shower is developing:
  - Hadronic: p, n, pions, other hadrons
  - Electromagnetic: photons, e-, e+

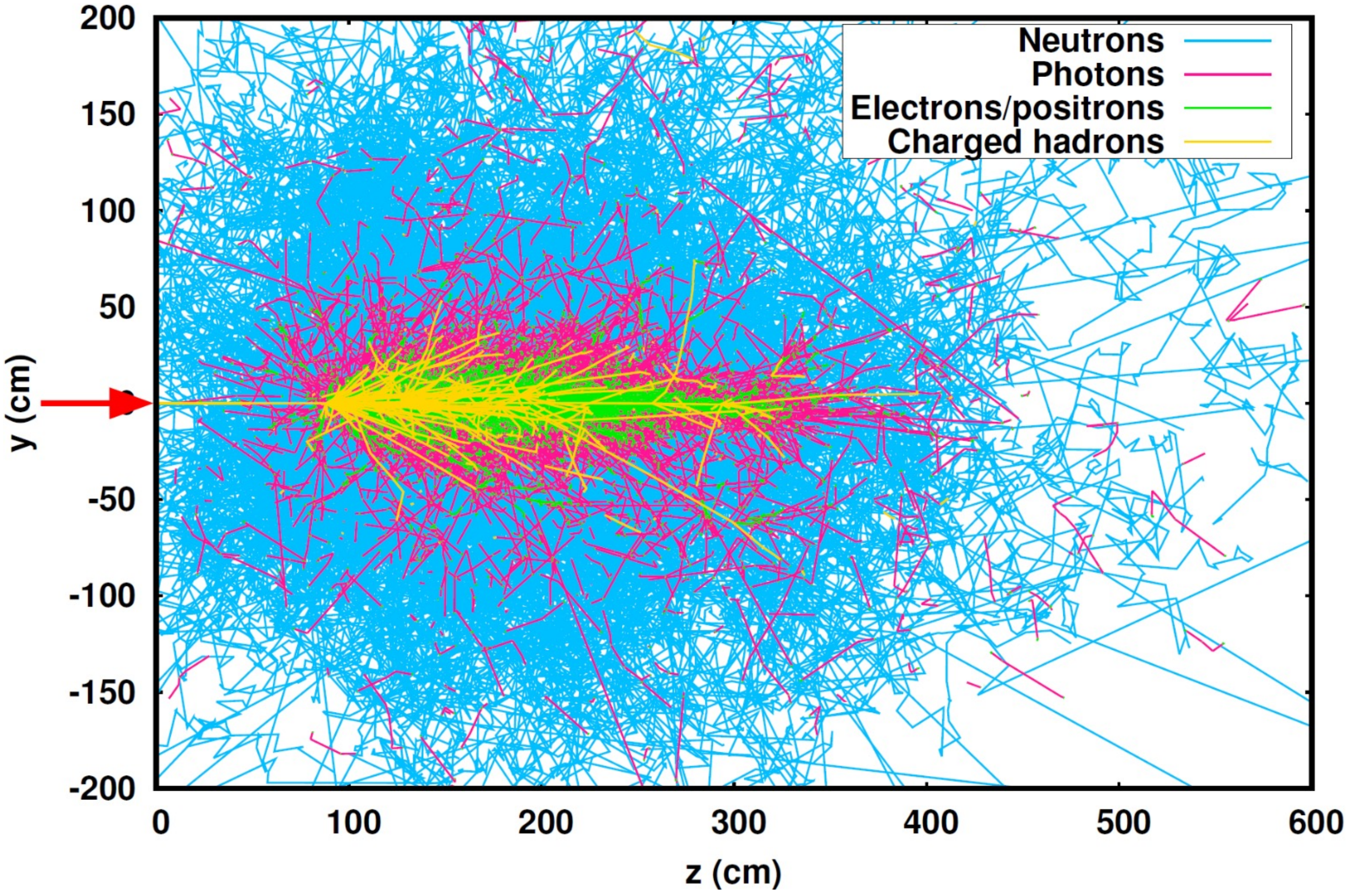
- Let's now advance the clock!

Snapshot of the radiation shower at longer times

- We now freeze frame **20 ms** (not ns, but ms!) after the beam penetrates the graphite block

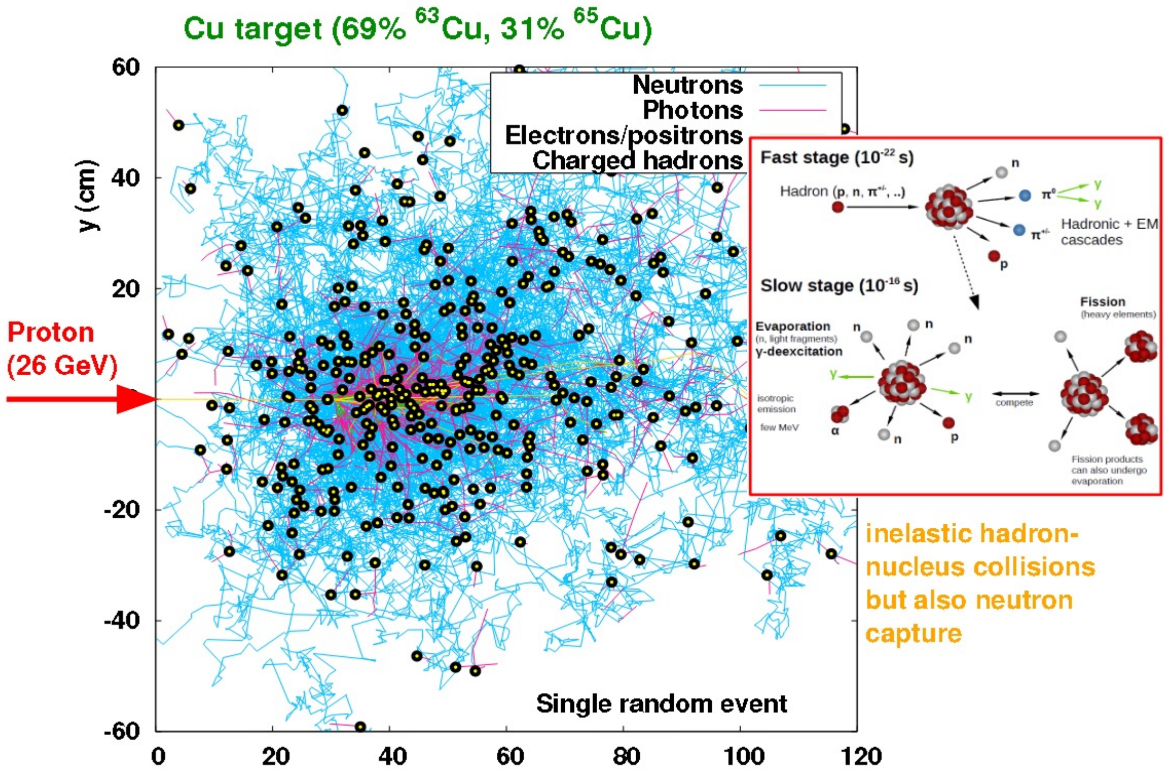
- There is now an bundance of **neutron** tracks:
    - No charge
    - Not subject to ionization
    - They can travel longer paths
    - They interact with nuclei (bouncing off elastically, or via nuclear reactions)
    - At low energies, capture: (n,gamma).

- A few more details will follow in tomorrow's lecture

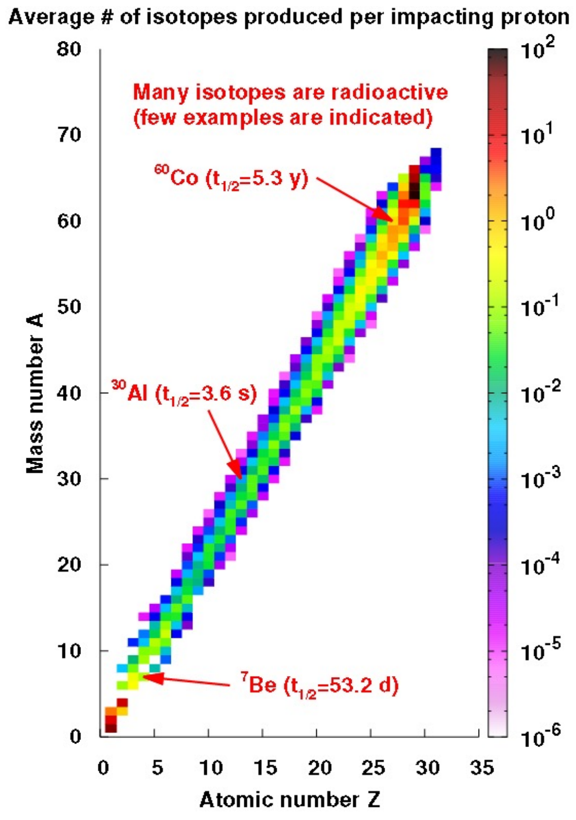


One last aspect: production of radioactive nuclei

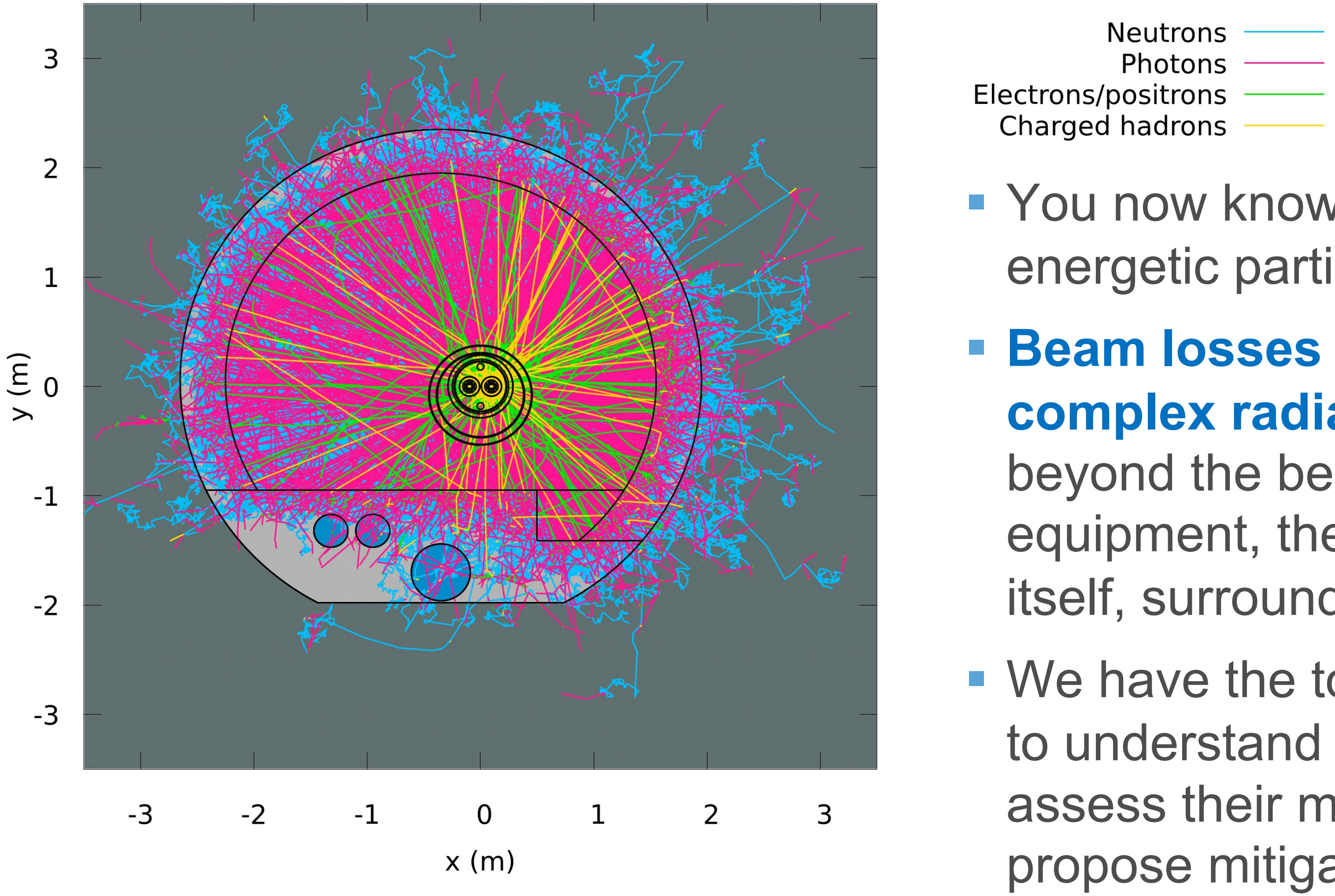
- At the end of a hadron-nucleus interaction, a **residual nucleus** (of a possibly different A and Z) is produced.
- E.g., for 26 GeV protons in Cu, here you can see all the residual nuclei produced
- And to the right you see them resolved by A and Z
- Some of them are unstable, leading to the **emission of radiation at a delayed time**



circle = location where a radioisotope was produced



Recap: radiation shower set up by a **single** 450 GeV proton loss

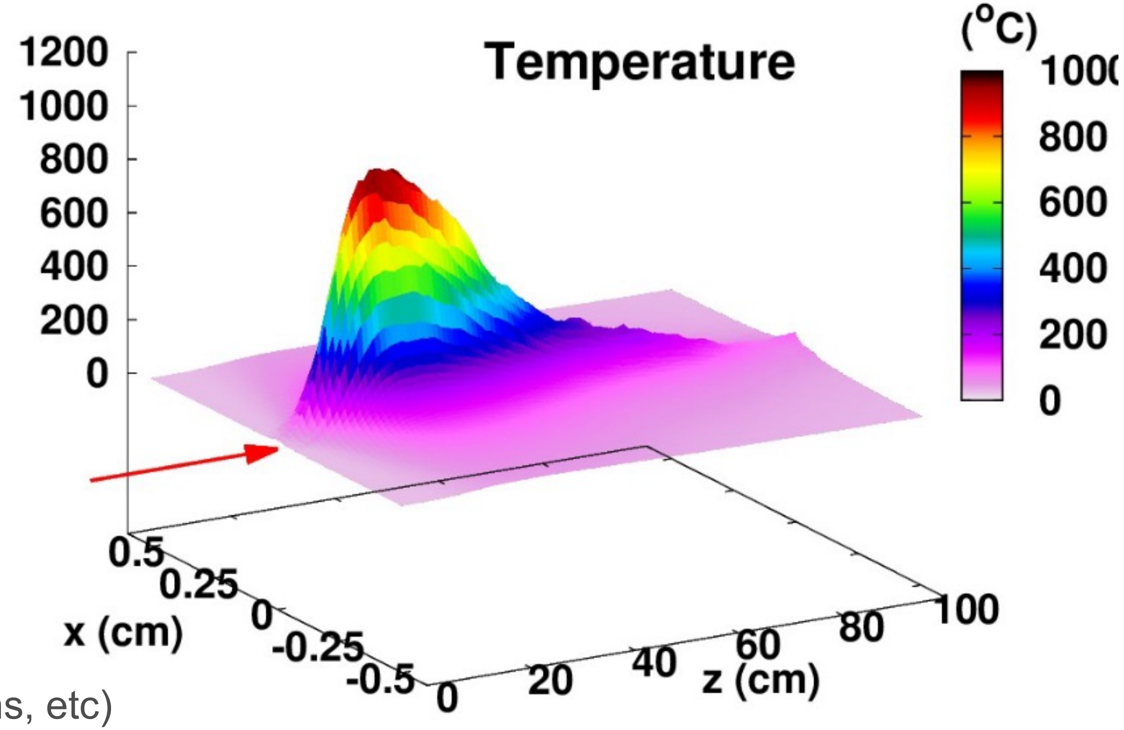


- You now know what happens when energetic particles interact with matter.
- **Beam losses in an accelerator generate complex radiation showers**, extending well beyond the beam pipe, affecting nearby equipment, the air in the tunnel, the tunnel itself, surrounding soil, etc
- We have the tools at hand (MC simulation) to understand them at microscopic level, assess their macroscopic effects, and to propose mitigation strategies (engineering)

Macroscopic effects of beam-matter interaction

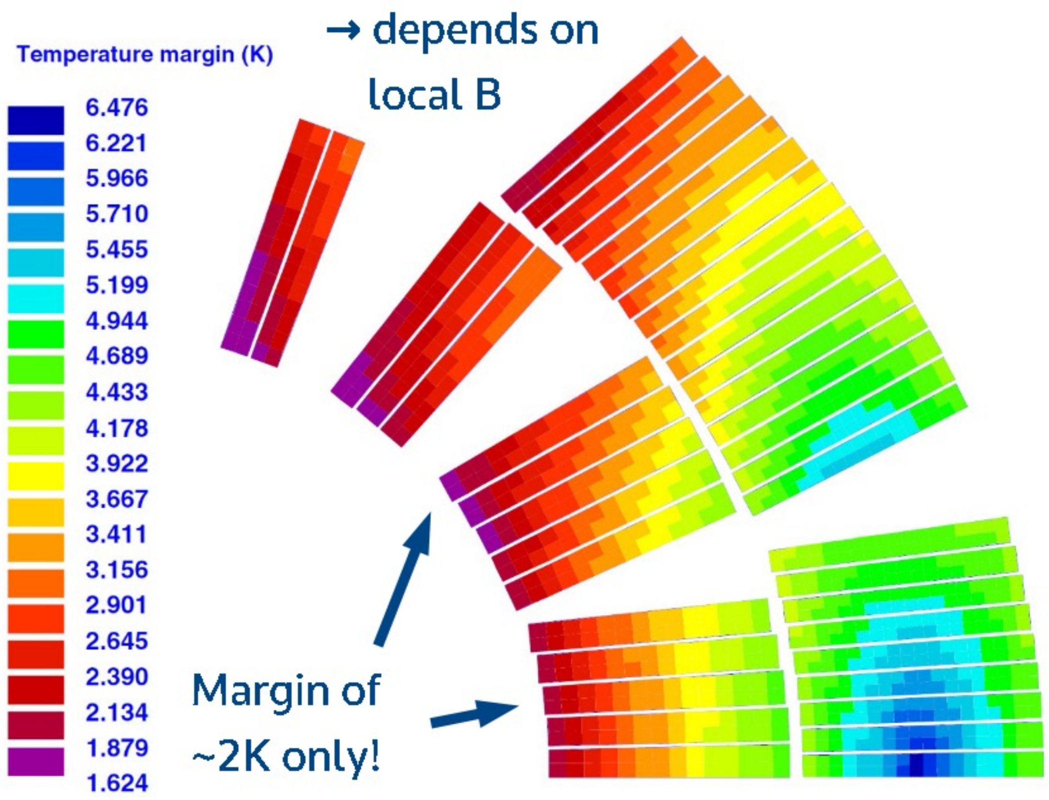
Material heating

- When an energetic p impacts on a material, hadronic and EM shower develops
- Collisions on target atoms/nuclei → local energy deposition leading to atomic/molecular/lattice vibrations
- **The material heats up**
- **Energy deposition profiles** from e.g. MC simulations can be used to assess temperature profile
- Consider a single nominal LHC p bunch impinging on Cu:
  - 1.15e11 protons, 7 TeV
  - 0.3 mm x 0.3 mm spot size
- Here is the temperature profile on Cu, with peak values around 1000°C
- Cu melts at 1085°C (!)
- Main consequences (next slides):
  - Loss of SC in magnets
  - Material damage (melting, plastic deformation, phase transitions, etc)



Heating - Quenches of superconducting magnets

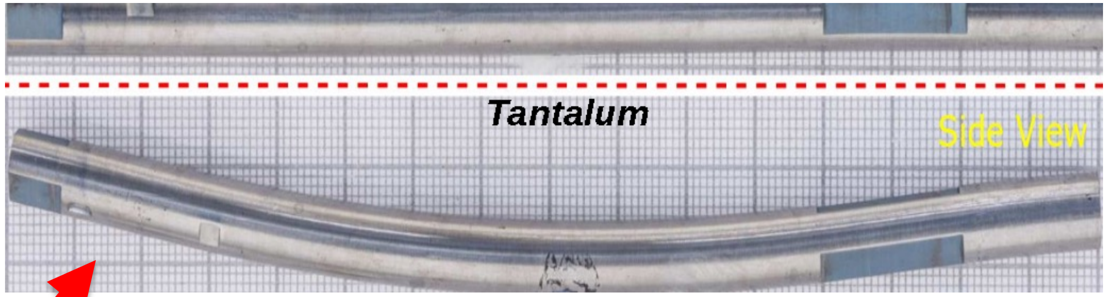
- Maximum temperature increase that LHC dipole coils can sustain without losing SC state:

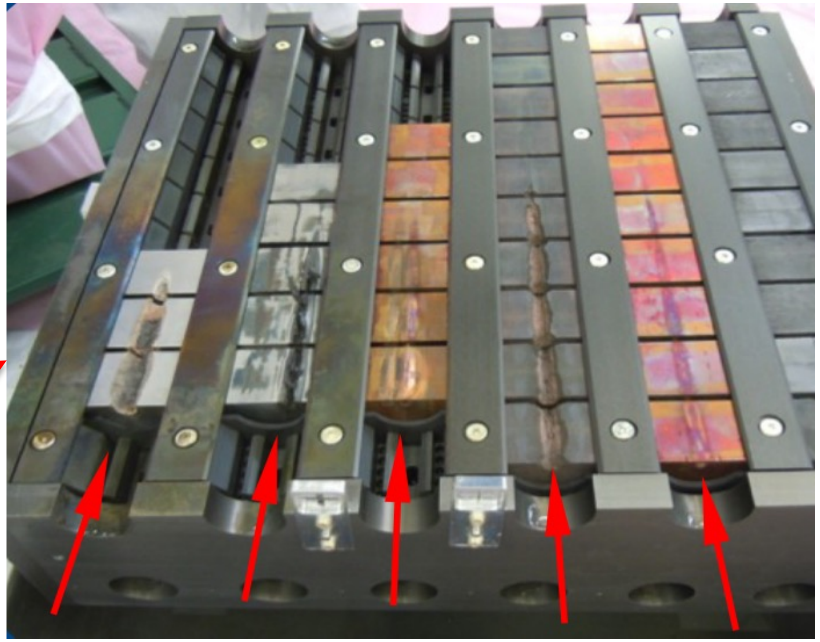


- There are regions where the margin is a mere increase of 2 K
- At 6.5 TeV, an instantaneous energy deposition of O(**mJ/cm^3**) can lead to a quench
- Suffices to lose ~ 1 in 10^7 p from the beam in order to quench (!)
- ~1/2 day to recover (cryogenics)
- Systems are in place to protect SC magnets (see superconductivity lecture)

Heating - Energy depositions O(0.1-1 kJ/cm^3)

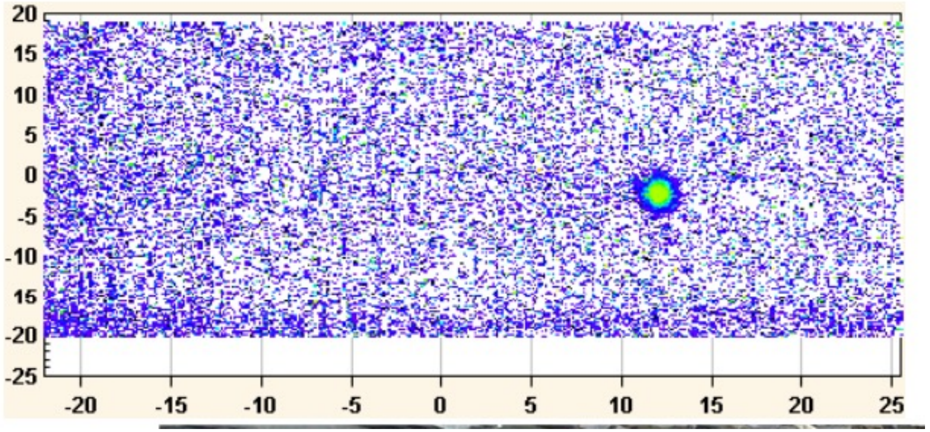
- Orders of magnitude larger than what is needed to induce a quench
- Tests in HiRadMat (450 GeV p from SPS for material response under intense irradiation)
- E.g.:
  - Thermal stresses in Ta rod, exceeding plastic limit, leading to a permanent deformation
  - Melting, evaporation, explosions, sputtering in a series of metals

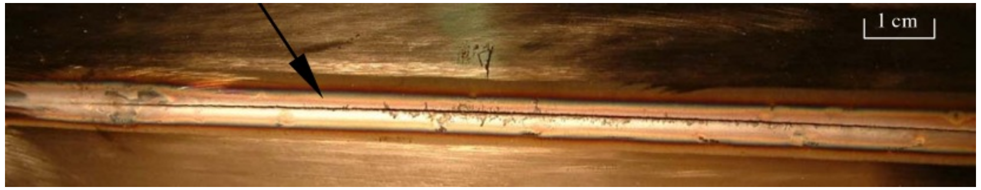


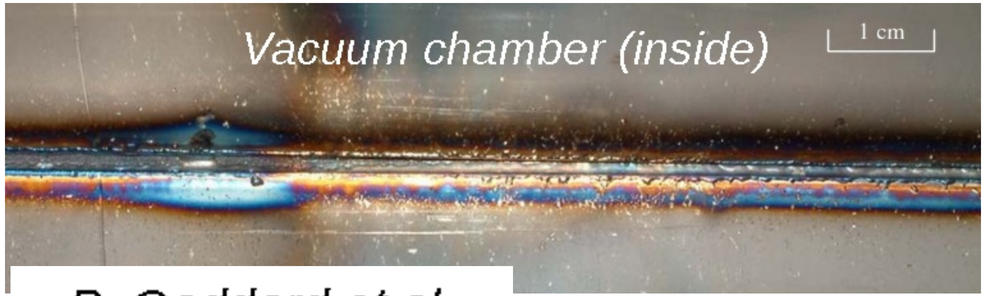


Heating – Historical example from SPS (2004)

- LHC not operational at that time.
- SPS was being used (among other) to test collimator materials for the LHC
- Incident during extraction of SPS beam (450 GeV p, 2.5 MJ/beam)
- Fault on extraction magnet
- Wrong trajectory
- Impact on vacuum chamber
- It ripped open. Gash of ~ 25 cm
- Vacuum leak, operation stop, magnet replacement
- **Weeks to repair damage**
- **Good example for importance of active/passive protection (slide 19)**



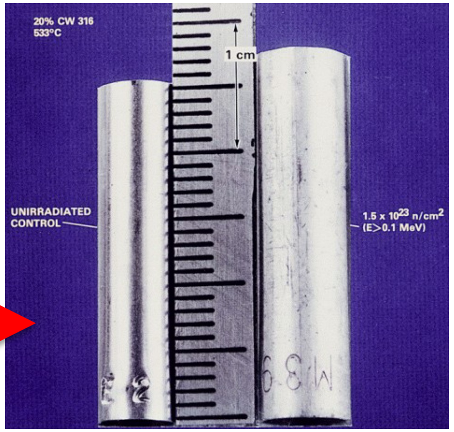


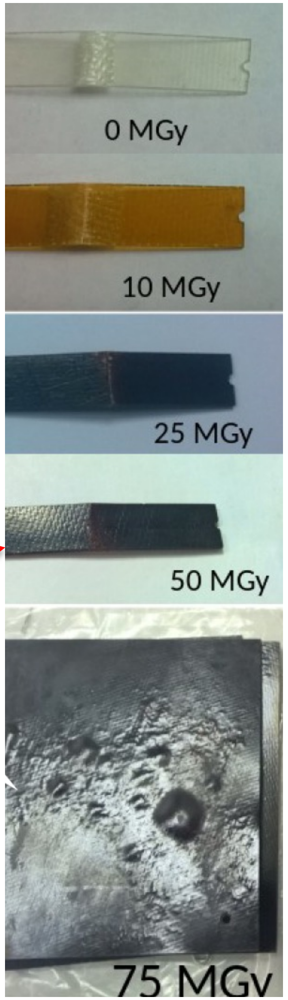


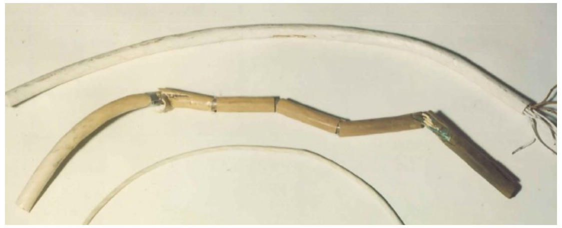
B. Goddard et al.
AB-Note-2005-014 BT

Structural defects

- Radiation showers -> collisions with target atoms -> recoil -> lattice displacements:
  - May make materials more brittle/fragile
  - Example: stainless steel rod exposed to n: atomic displacements -> formation of voids -> material swelled from to 2.5 cm to 2.7 cm length
  - Changes in mechanical/thermal/electronic properties
- Ionization (besides heating) affects chemical bonds
  - Relevant for organic materials (plastics, polymers…)
  - Cable / magnet coil insulation
  - E.g. insulator degradation after exposure to progressively higher doses. At 10 MGy (change of colors) while up to 75 MGy bubbles formed. Structure compromised. If this happens in the coils of a magnet, shortcircuits may occur between coils, one has to replace them. Implying again downtime in the accelerator

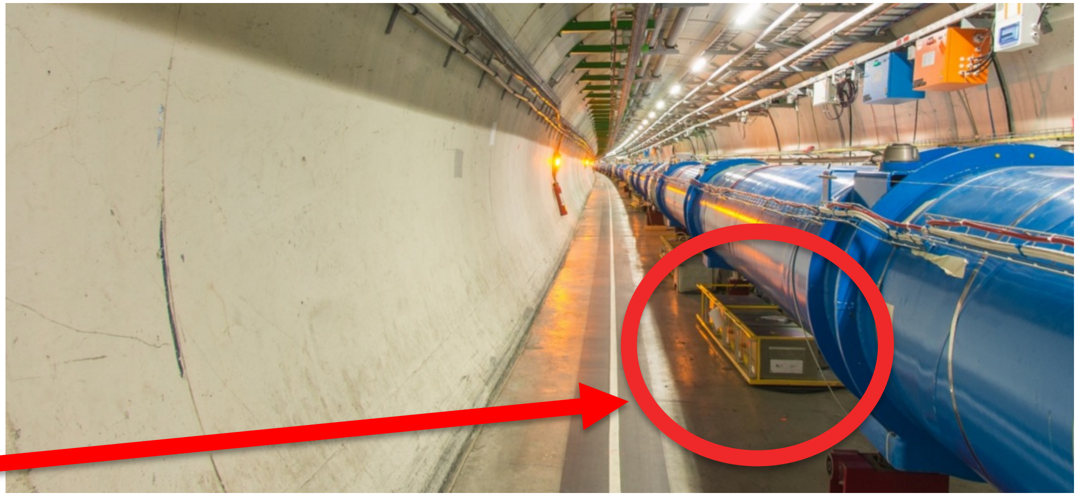






Last macroscopic effect today: single-event effects in electronics

- A single particle causes a disturbance in a circuit, e.g. a bit flip in a RAM memory -> data corruption -> malfunction of electronic component
- They are a concern for
  - Satellites in orbit (outages!)
  - Accelerators (electronics racks for vacuum, detectors, control systems, etc)
- Soft errors (recoverable):
  - Single-event upset, multiple bit upset, etc
- Hard errors (unrecoverable):
  - Single-event burnout



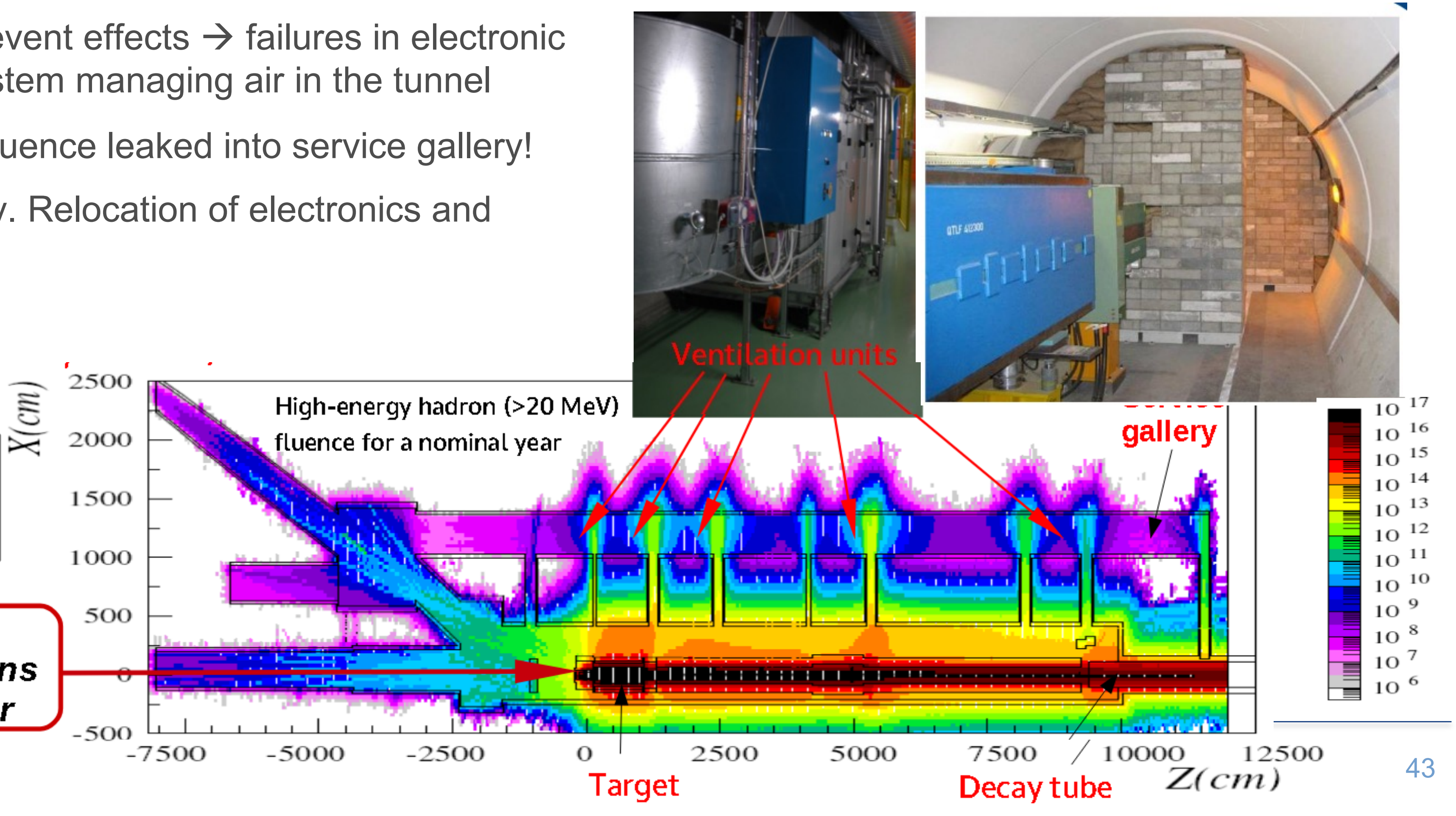
Electronics racks in LHC tunnel

Single-event effects example: CNGS (2000-2012)

- Energetic protons on target, producing pions, and kaons, decaying in a decay tube, mostly into muons and neutrinos
- Stopping block downstream to stop charged particles, muons stopped after ~1 km of rock.
- Neutrinos remain. Idea: study neutrino oscillations several 100 km away at the Gran Sasso (GNGS) lab in Italy
- Early runs: plenty of single-event effects → failures in electronic controllers for ventilation system managing air in the tunnel
- Why? High-energy hadron fluence leaked into service gallery!
- Premature stop of the facility. Relocation of electronics and improvement of shielding

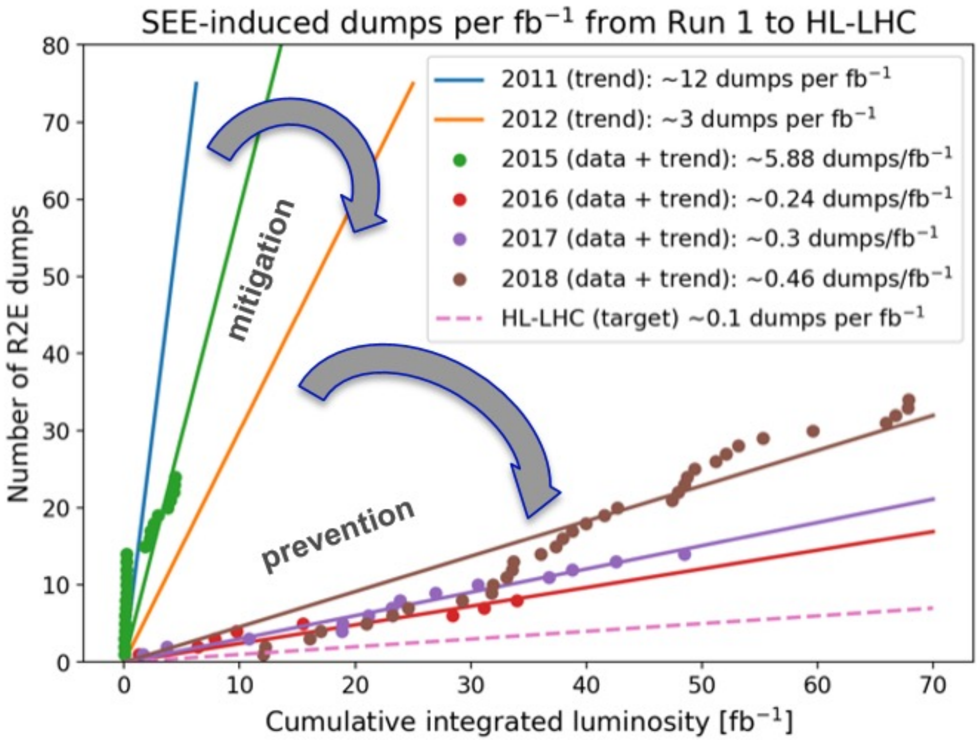
With material from:
E. Gschwendtner,
I. Efthymipoulos, M. Brugger,
A. Ferrari, L. Sarchiapone

400 GeV
4.5×10^{19} protons
on target/year



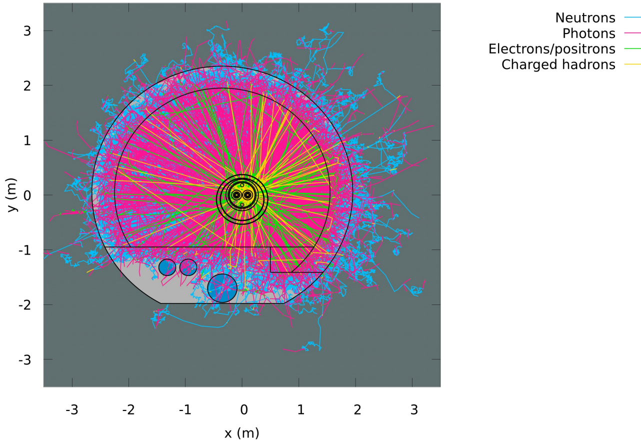
Radiation to electronics (R2E) @CERN

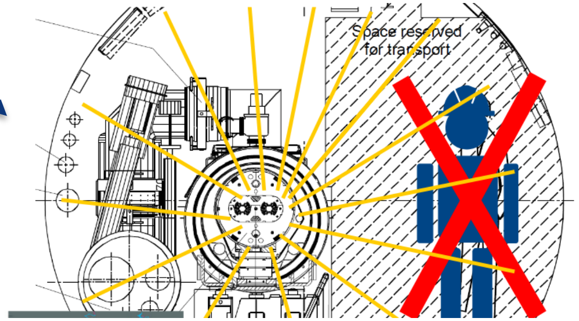
- R2E is the CERN activity in charge of ensuring that radiation effects on electronic components and systems across the CERN infrastructure do not negatively impact the availability and performance of the accelerator complex
- Propose mitigation strategies
- https://r2e.web.cern.ch/
- R2E Annual Meeting (2022): https://indico.cern.ch/event/1116677

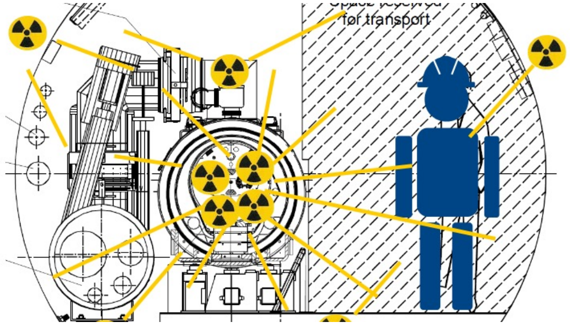


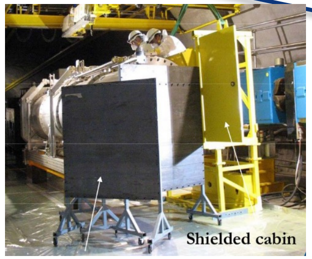
Last beam loss effect for today: activation

- Beam loss -> radiation shower, leading to **prompt** radiation field: p, n, $\pi^{\pm}$, K,…, γ,$e^{\pm}$, $e^{\pm}$, $\mu^{\pm}$, etc.
- Tunnel subject to an intense radiation field. Nobody allowed in tunnel if beam is on.
- Nuclear inelastic interaction -> residual nucleus (may be radioactive!)
- Residual nuclei: **delayed** emission of γ, $e^{\pm}$. Even when beam is off (!). Gradually decreases with time. Whole unit at CERN for these assessments: HSE-RP
- As a measure to reduce dose to personnel, robots!









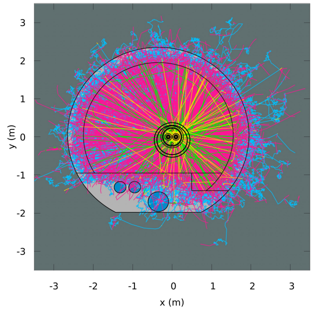
Robots at CERN: https://www.youtube.com/watch?v=wiO65xck9cM

Summary

Main topics introduced in today's lecture

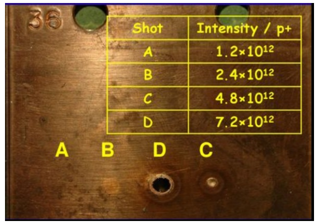
- We've become aware of **beam losses**

- **Operational** implications of beam losses: system malfunction, superconducting magnet quenches, etc

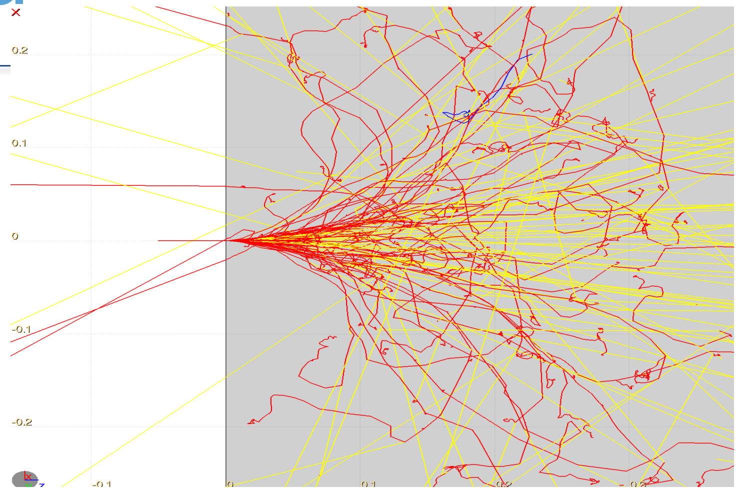


- **Microscopic description** of radiation-matter interaction:
  - Hadronic and electromagnetic shower formation

- **Macroscopic effects** of beam losses on materials:
  - Heating (magnet quenching, material deformation/evaporation, etc)
  - Displacement damage: defects in material structure
  - Single-event effects
  - Activation



Sneak peek of tomorrow's lecture menu



- A bit more on radiation-matter interaction
- Monte Carlo simulation of radiation transport
- MC applications to overcome design challenges for prospective particle accelerators (FCCee, Muon Collider)

Thanks for your attention

I hope you found this interesting!

To keep up with latest LHC performances

- Yearly LHC Performance Workshop, traditionally held in Chamonix.
- 23 February, 2023 - Summary from the latest edition by ATS director:
  - https://home.cern/news/opinion/accelerators/news-chamonix-workshop
- “Firstly, the **inner triplet quadrupoles and associated corrector magnets situated on either side of ATLAS and CMS take a serious hit from luminosity debris coming from the interaction point**. The associated radiation levels anticipated for Run 3 could eventually compromise their performance. The LHC Triplet Task Force has analysed the impact of radiation on equipment lifetime in the LHC inner triplet regions and proposed a number of mitigation measures, some of which will be deployed immediately to minimise the local integrated radiation dose. Additional measures and supporting activities are under study.”

To keep up with latest LHC performances

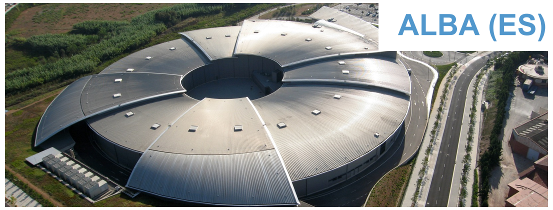
- “Secondly, **electron cloud is an issue in the LHC** and, when operating with high bunch currents, the associated heat load deposited on the beam screens in the main dipoles pushes the cryogenics system to the limits. Following the long shutdowns, the situation appears to be degrading locally in some sectors, and the effects have become a potential intensity limitation for the HL-LHC era. The complex surface chemistry involved appears to be understood, and a variety of mitigation measures are being considered.”

LHC Operations workshop (Evian)

- https://indico.cern.ch/event/1077835/timetable/
- Talk on UFOs by A. Lechner:
  https://indico.cern.ch/event/1077835/contributions/4602794/attachments/2352808/4014155/2021_11_25_ufosrun3.pdf
- e-cloud talk by L. Mether:
  https://indico.cern.ch/event/1077835/contributions/4533371/attachments/2353050/4014646/Evian_2021_ecloud.pdf
  - Mitigation strategy: beam scrubbing (running under intense e-cloud effect seemse to inhibit the effect itself!)
  - Less important at collision energy (higher magnetic rigidity)

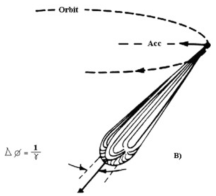
A (necessarily incomplete) overview of particle accelerators

ALBA (ES)



MAX IV (SE)

NSLS (USA)

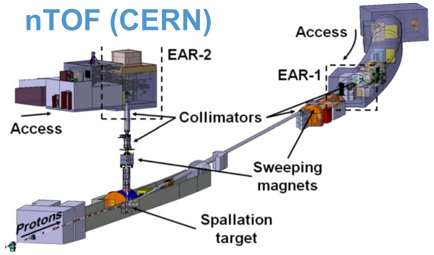


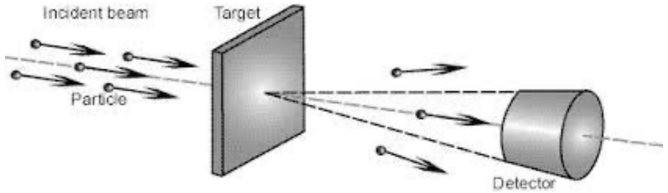
Synchrotron light sources:

- **Circulating** e- beam, O(1 GeV)
- Synchrotron radiation emission

ESS (SE)

nTOF (CERN)

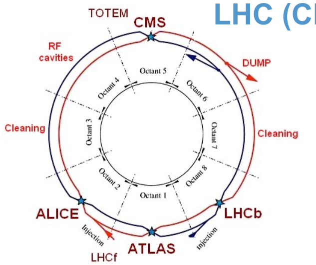




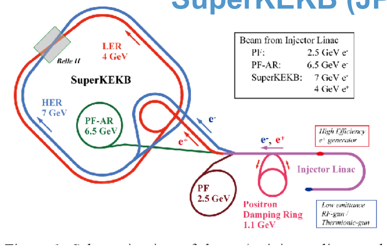
Fixed target experiments:

- Incident **beam on a target** to produce secondary particles/beams
- E.g. neutron spallation source:
  - Proton beam O(1 GeV)
  - Flux of secondary particles, e.g. n

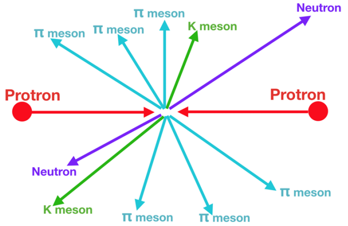
LHC (CERN)



SuperKEKB (JP)



RHIC (USA)



Particle colliders:

- **Circulating** beams
- ~Head-on high-energy particle collisions
- Probe inner structure of matter

Engineering and fundamental physics:

- Accelerator and cosmic ray physics
- Particle physics R+D
- Interaction cross section measurements
- …

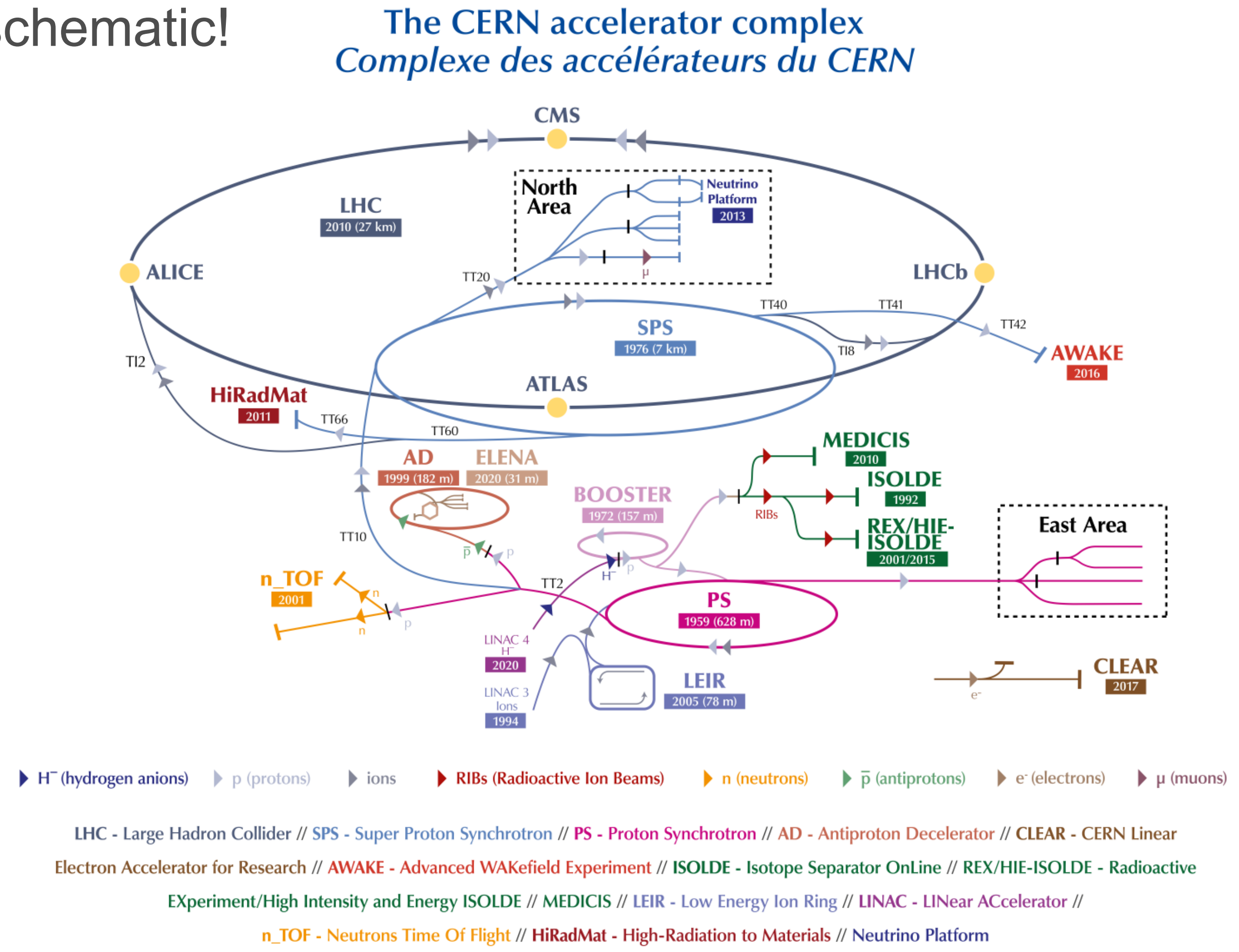
Applications

- Material science: crystallography, magnetism, …
- Medical imaging and radiotherapy
- Airport security, food sterilization,
- ...

See lecture by Michaela Schaumann: Particle accelerators and Beam Dynamics, (1/3)

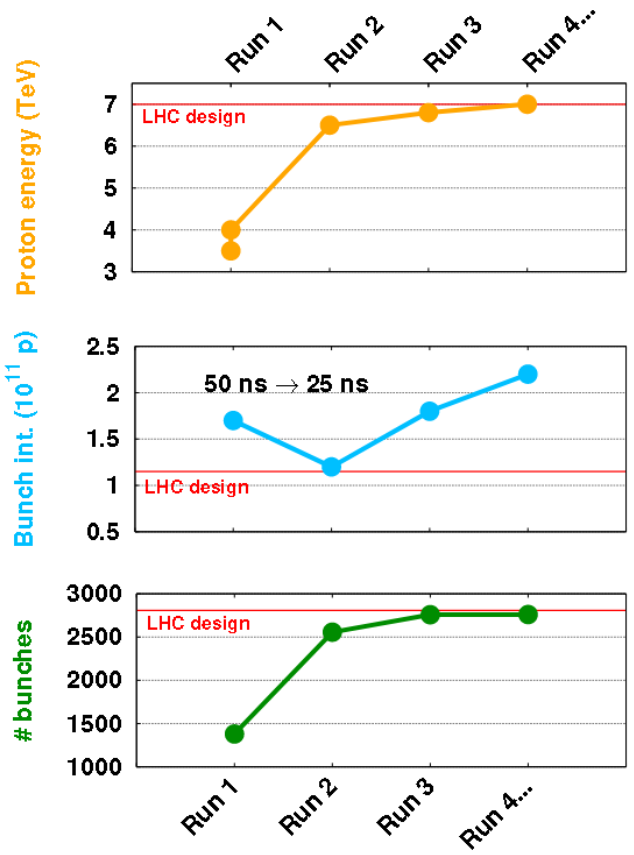
CERN's accelerator complex

- One more occasion to rejoice at this schematic!
- *Chain* of particle accelerators
  - From H_2 bottle to TeV p-p collisions
- Fixed-target experiments:
  - nTOF
  - ISOLDE
  - North and East Area lines
  - …
- (Nearly) head-on collisions:
  - ALICE
  - ATLAS
  - CMS
  - LHCb
  - …

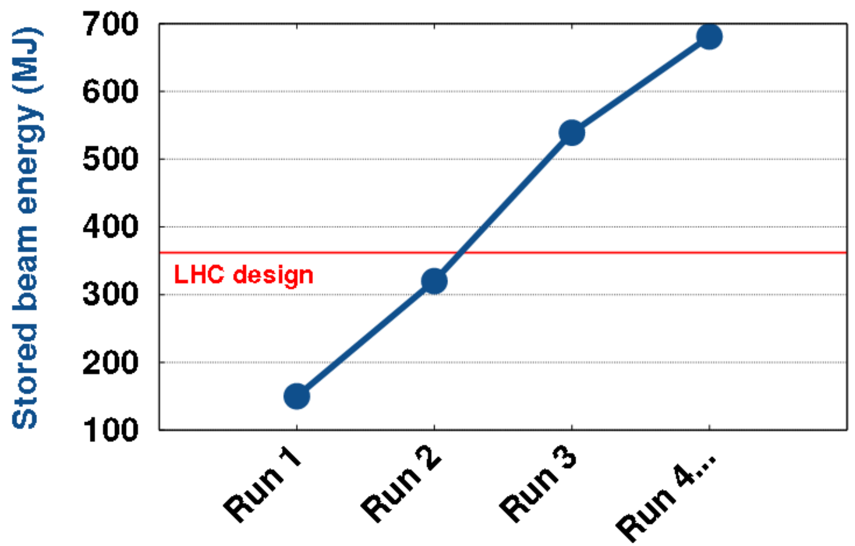


LHC proton beam parameter evolution since 2009

Run 1: *2009 - 2013* **Run 2:** *2015 - 2018* **Run 3:** 2022 - 2024 **Run 4 (HL)...:** 2027-



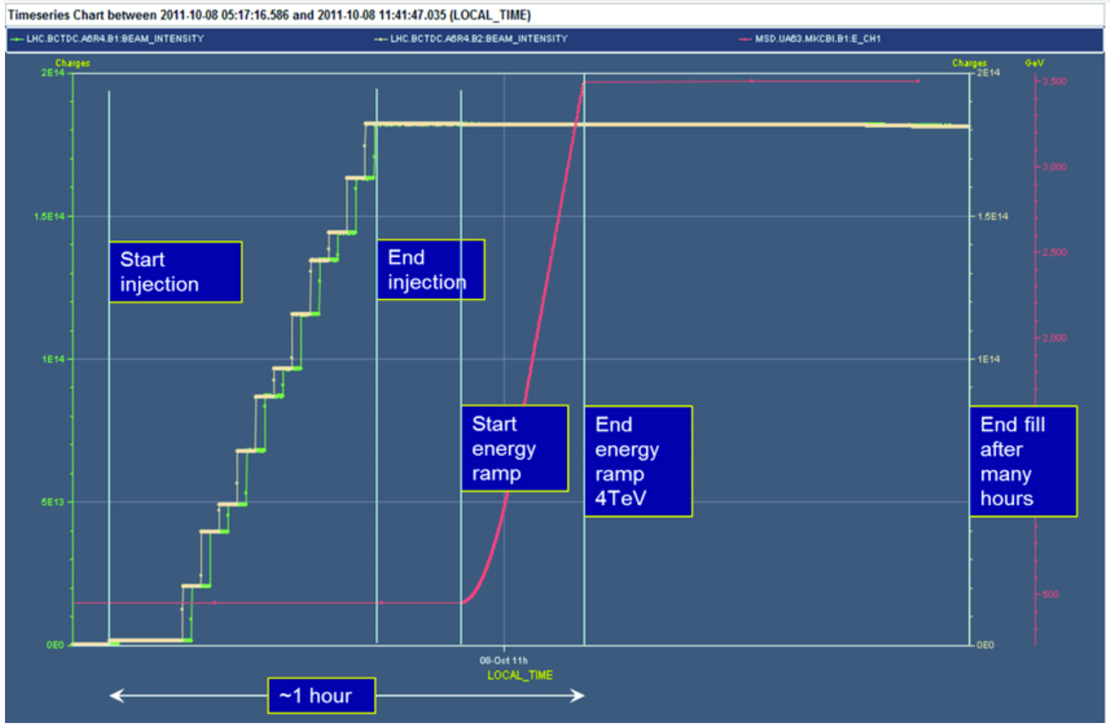
Stored beam energy =
proton energy × bunch intensity × # bunches

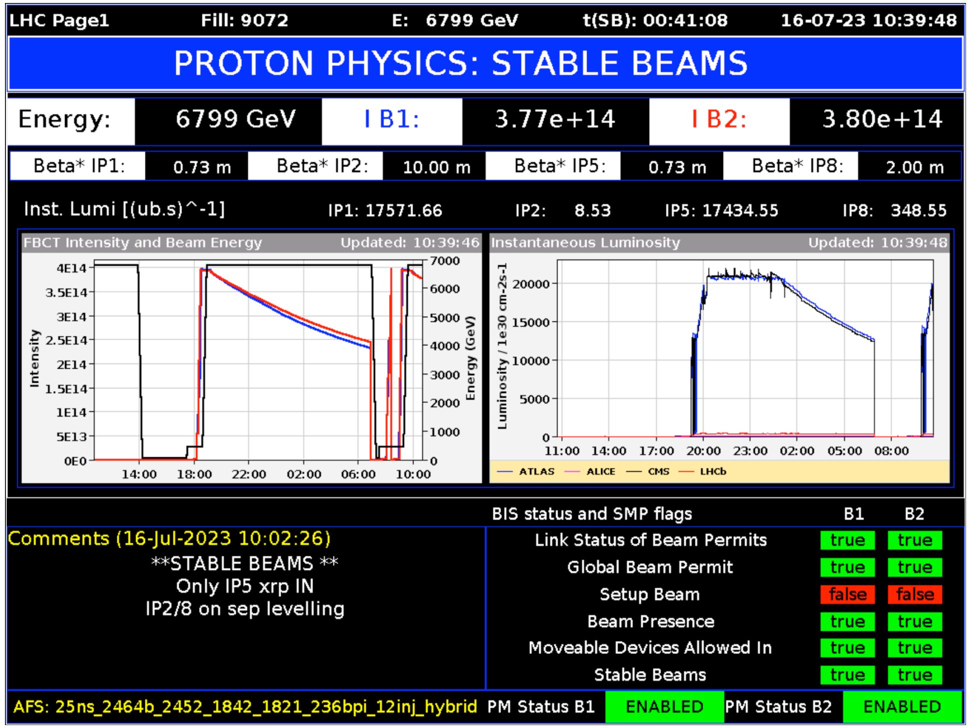


Heavy ion operation not discussed in this talk (load on dump is less)

A. Lechner

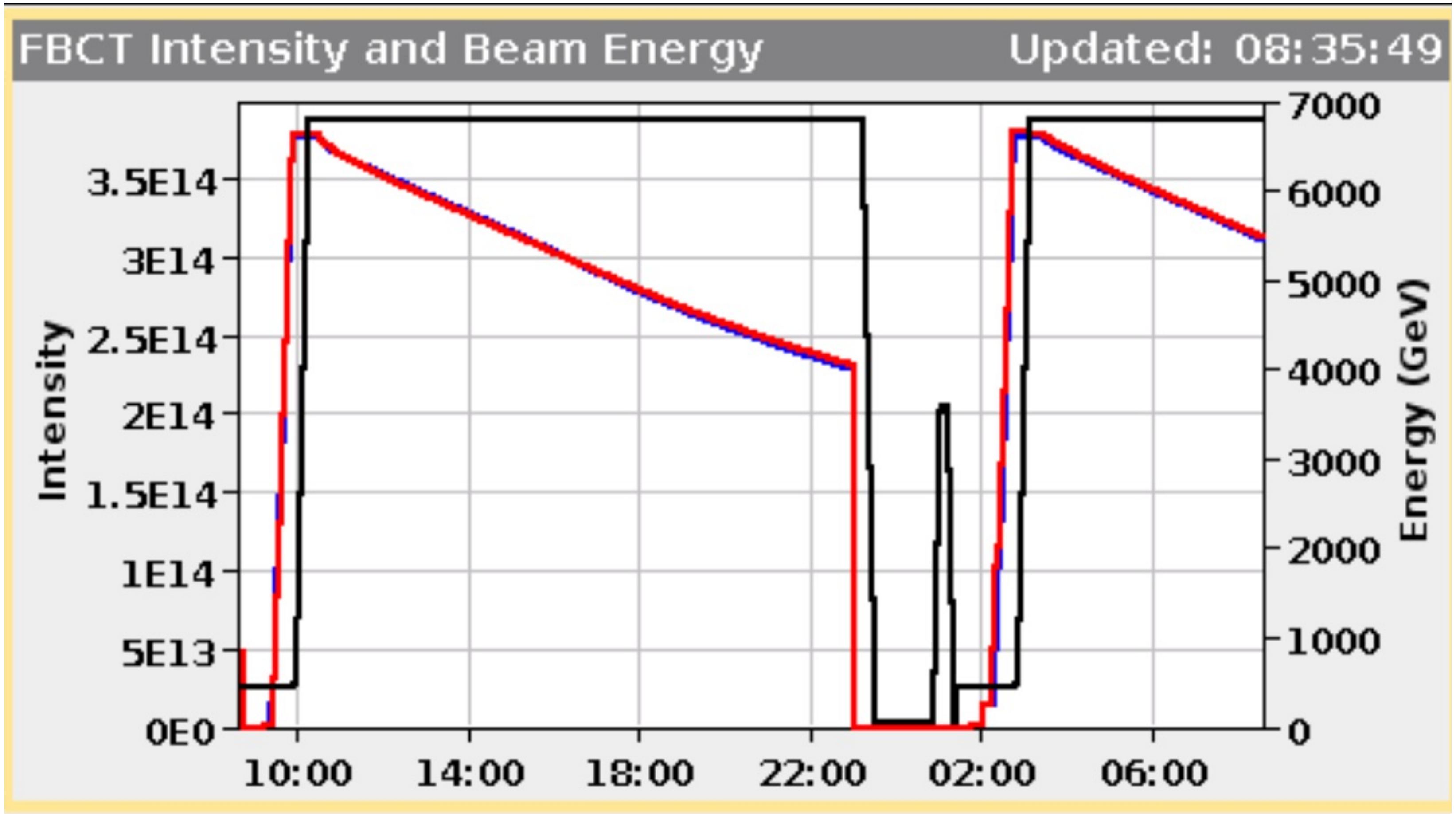
E.g. LHC operational cycle



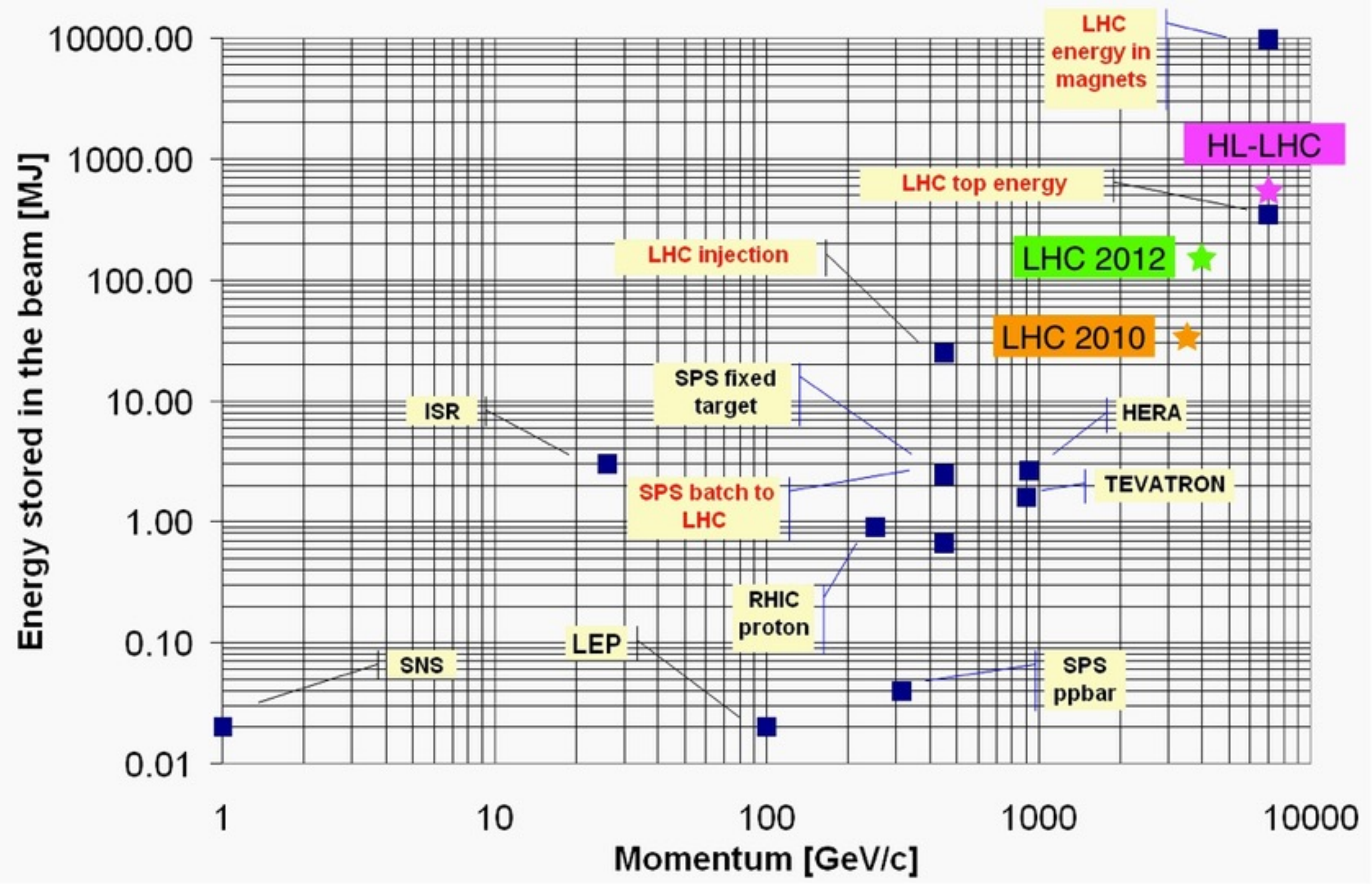


[1] M.S. Camillocci, LHC Nominal cycle
https://indico.cern.ch/event/434129/contributions/1917195/attachments/1205096/1765722/Nominal_cycle.pdf
[2] Machine Protection and Interlock Systems for Circular Machines - Example for LHC
https://e-publishing.cern.ch/index.php/CYR/article/view/239/181

[3] Live: https://op-webtools.web.cern.ch/vistar/vistars.php **(see e.g. LHC Page 1, SPS Page 1)**


FBCT Intensity and Beam Energy
Updated: 08:35:49
Intensity
3.5E14
3E14
2.5E14
2E14
1.5E14
1E14
5E13
0E0
7000
6000
5000
4000
3000
2000
1000
0
Energy (GeV)
10:00
14:00
18:00
22:00
02:00
06:00

Atlas of energy stored per beam in various accelerators around the world



LHC Operation schedule

Longer term LHC schedule

In January 2022, the schedule was updated with long shutdown 3 (LS3) to start in 2026 and to last for 3 years. HL-LHC operations now foreseen out to end 2041.

Last update: April 2023