Machine Protection

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DESY

CERN Accelerator School on FELs and ERLs — June 9, 2016

Overview

- What & Why?
- Interaction of Beams with Matter
- Damage to Permanent Magnets

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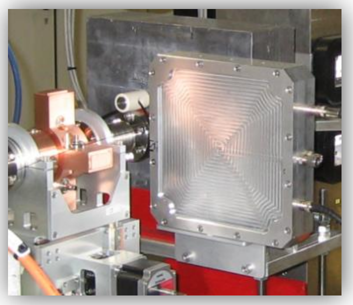
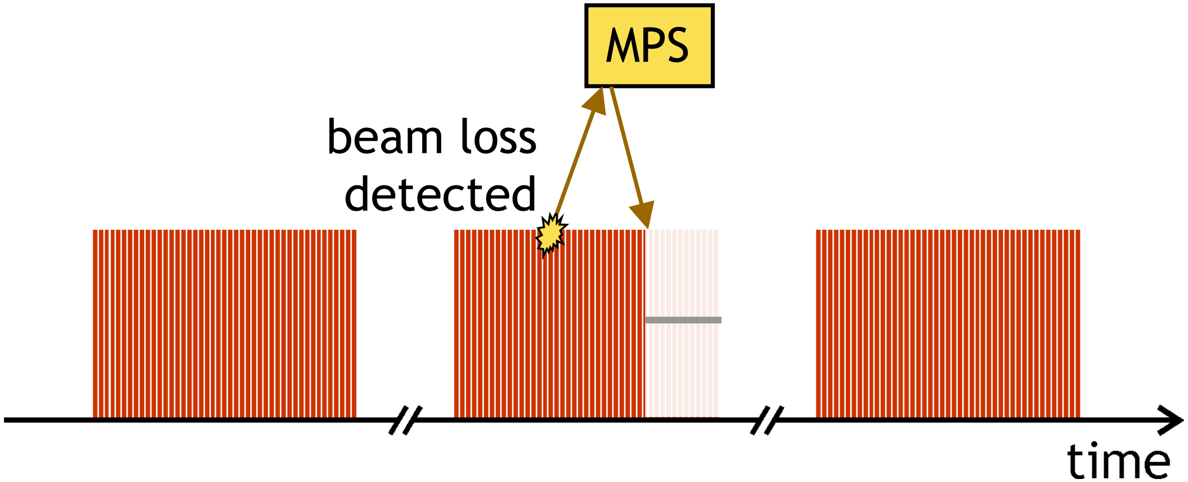
What & Why?

What is Machine Protection?

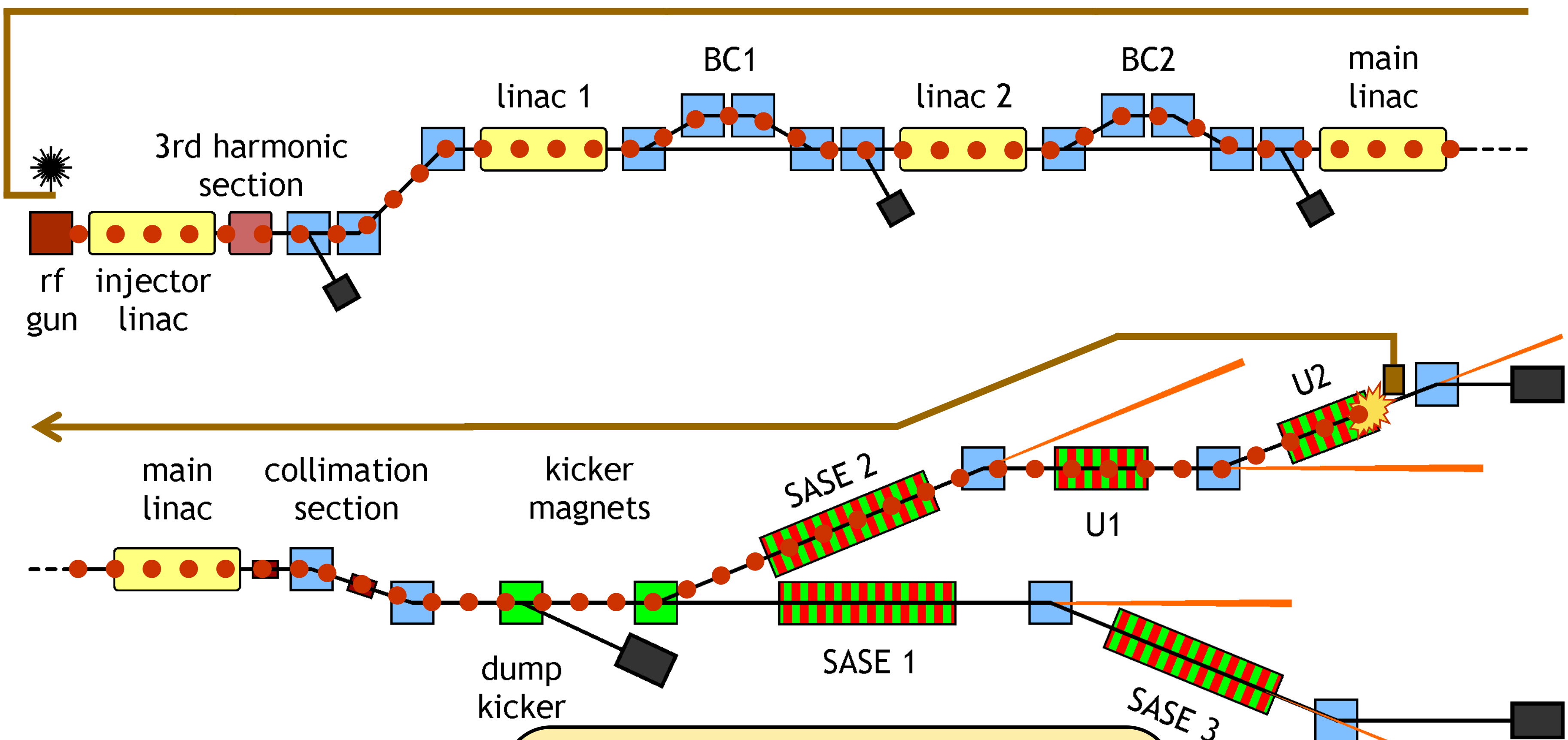
Machine protection is the sum of all measures that protect an accelerator and its infrastructure from the beam.

- Machine Protection System
  - Interlock on components (magnets, screens, ...)
  - Monitoring of the beam (beam loss monitors, charge monitors, BPMs, ...)
  - Mitigation (inform the operator, reduce repetition rate, fire abort kickers, stop beam production immediately, ...)





Case Study: European XFEL (Early Design)



accelerator length: **3 km**
bunch frequency: **4.5 MHz**

45 bunches in the accelerator
68 injected during signal propagation (2/3 c)

113 bunches lost

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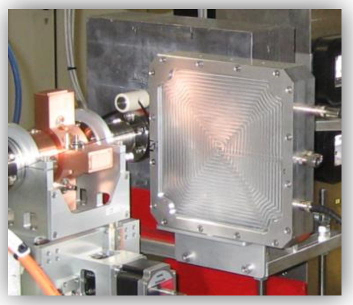
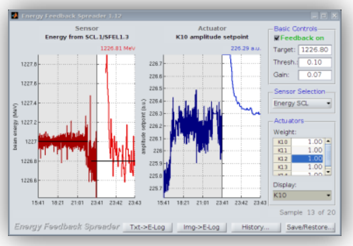


- Collimators, absorbers
- Shielding

- Physics (matching, collective effects, ...)
- Robust systems+software (feedbacks, LLRF, controls, ...)
- Safe procedures (switch on, change beam energy, ramp to full power, ...)



Average Electron Beam Powers


Photo: Michael J. Linden

Normal conducting

• FERMI@Elettra	1.4 GeV	10 Hz	14 W
• SACLA	7 GeV	10–60 Hz	18–140 W
• LCLS	15 GeV	120 Hz	36–360 W

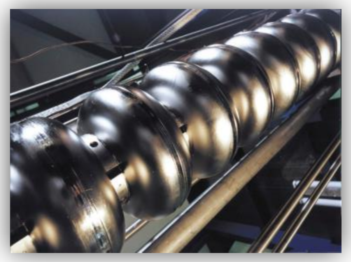
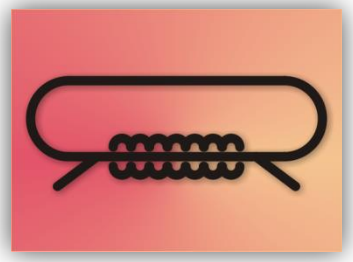


Photo: DESY

Superconducting

• FLASH	1.3 GeV	1–3 MHz pulsed	10 W – 22 kW
• European XFEL	17.5 GeV	4.5 MHz pulsed	>500 kW
• LCLS-II	4 GeV	0.1–1 MHz CW	120 kW



Energy recovery linacs

• NovoFEL	12 MeV	5.6–22 MHz CW	15–60 kW
• Jlab FEL	200 MeV	75 MHz CW	>1 MW
• Future ERLs?	5 GeV	1.3 GHz CW	500 MW

“Power = Energy · Current”


Photo: Michael J. Linden

Normal conducting

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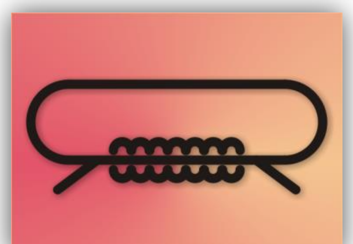
$$\text{average beam power} = \frac{\text{energy}}{\text{charge}} \cdot \frac{\text{charge}}{\text{time}} = \frac{\text{“beam energy”}}{e} \cdot \text{average current} = \frac{\text{“beam energy”}}{e} \cdot \text{repetition rate} \cdot \text{bunch charge}$$



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Hazards

For an accelerator with **P = 1 MW**:

Local loss power (W)	Effects
100 – 1000 10^{-3}	Thermal/mechanical damage
10 – 100	Mechanical failure of flange connections
1 – 100	Activation of components
1 – 100	Radiation damage to electronics, optical components, &c.
1 – 10	Excessive cryogenic load, quenches
0.01 – 0.1 10^{-7}	Demagnetization of permanent magnets


Interaction of Beams with Matter
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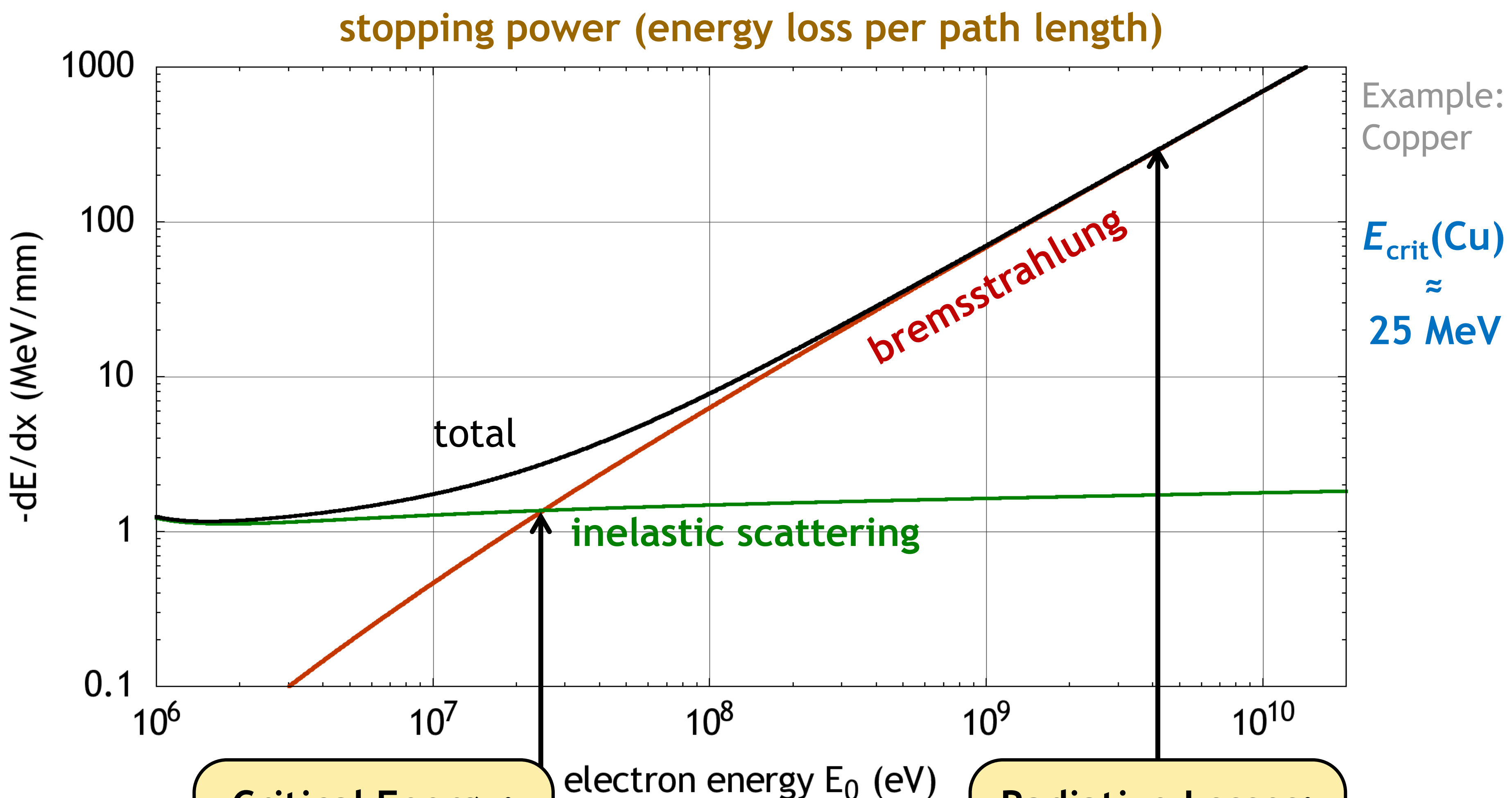
https://commons.wikimedia.org/w/index.php?curid=11085

Energy Loss of Electrons in Matter



Critical Energy:

$$E_{\mathrm{crit}} \approx \frac{800\ \mathrm{MeV}}{Z+1.2}$$

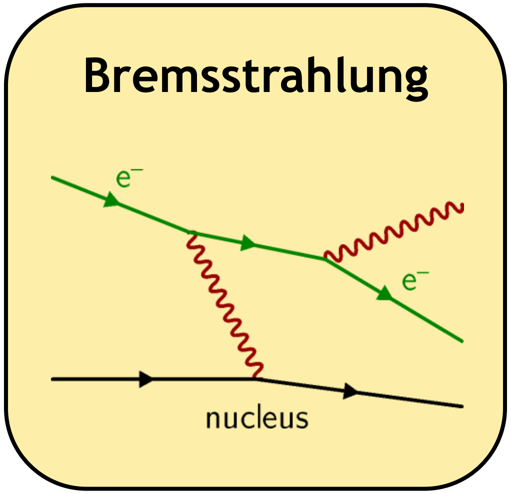
Radiative Losses:

$$\mathrm{d}E/\mathrm{d}x \propto E \cdot \frac{Z^2}{m^2}$$

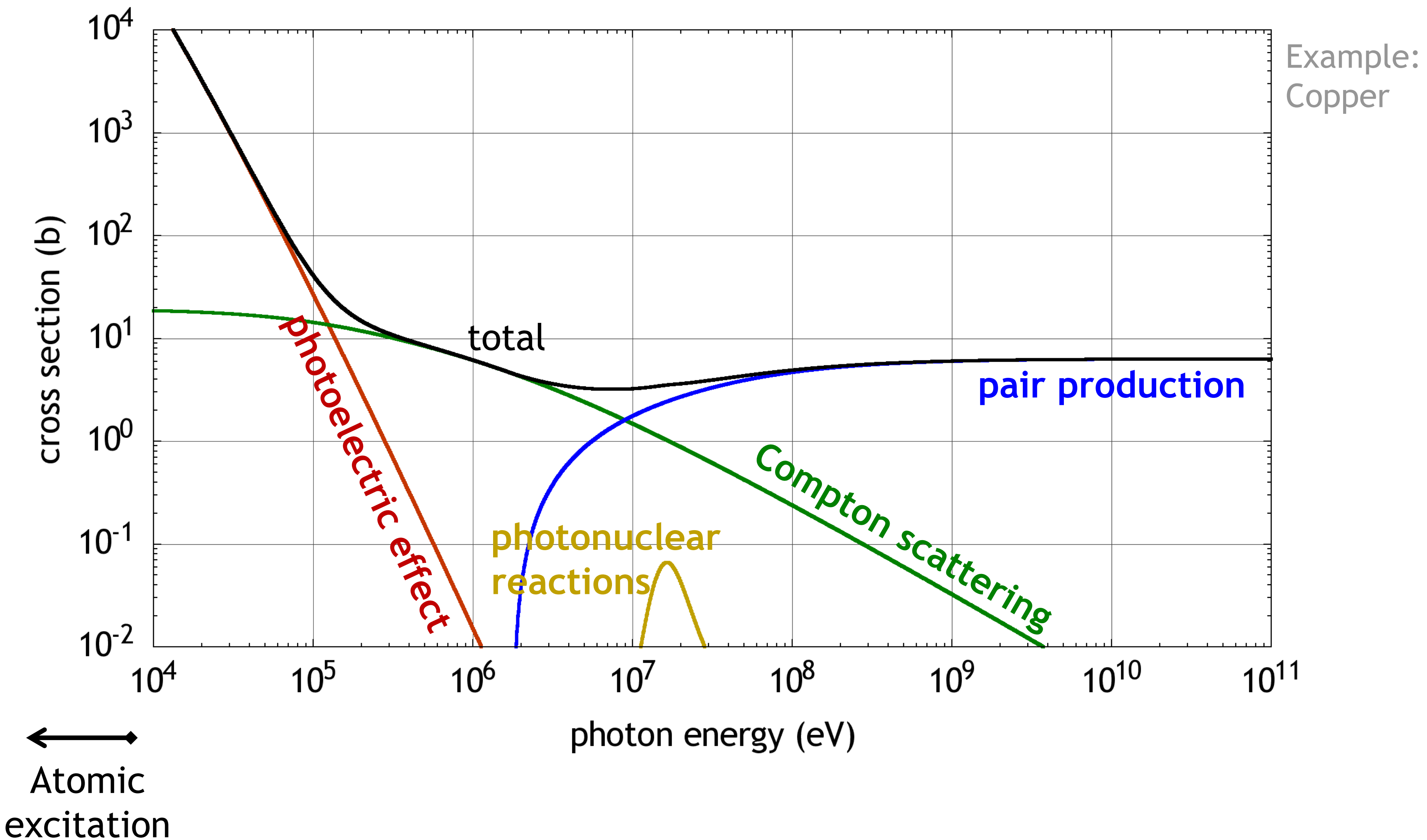
Bremsstrahlung: Radiation Length

- At high energies, the energy loss by bremsstrahlung scales like:
  $\mathrm{d}E/\mathrm{d}x \approx E \cdot const.$
- Therefore, the remaining particle energy can be written as:
  $$E(x) \approx E_0 \exp\left(-\frac{x}{L_{\mathrm{rad}}}\right)$$
- **After one radiation length, the energy of a high energy electron has decreased to 1/e of its initial value.**
- The radiation length is often normalized to a standard density:
  $$X_0 = L_{\mathrm{rad}} \cdot \rho_0$$

	L_{rad} (cm)	X_0 (g/cm²)
Aluminum	8.9	24.01
Titanium	3.56	16.17
Iron	1.76	13.84
Copper	1.43	12.86
Tungsten	0.35	6.76
Lead	0.56	6.37



Photonic Interactions with Matter



Pair Production

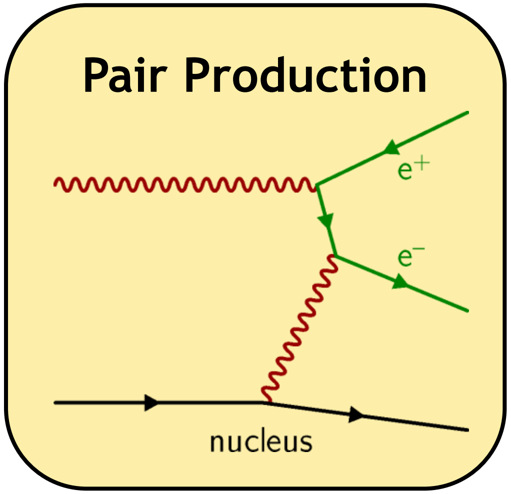
- Minimum energy for pair production:
  $2 \cdot 511$ keV ≈ 1.02 MeV (e^+/e^-)
  $2 \cdot 106$ MeV ≈ 211 MeV (μ^+/μ^-)

- Cross section for muon production is small, but muons are of concern for personnel protection!

- Cross section scales roughly as Z^2: Heavy elements shield well against photon beams

- Mean free photon path at high energies:

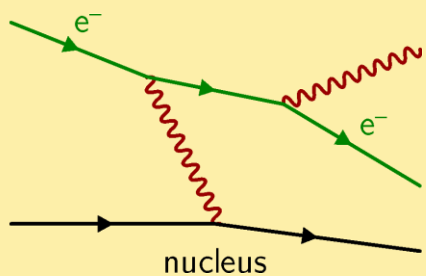
$$L_{\text{pair}} \approx \frac{9}{7} L_{\text{rad}}$$

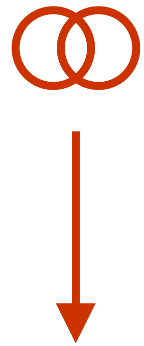


The typical path length a photon can travel in matter until it is consumed in a pair production event is ~30% higher than the radiation length of the material.

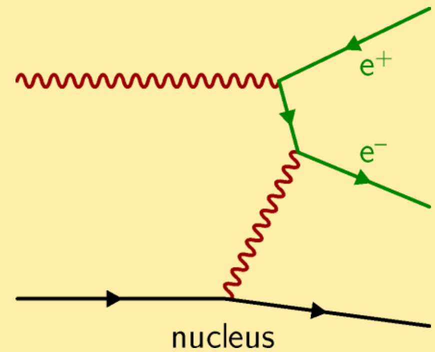
Electromagnetic Cascades

Bremsstrahlung



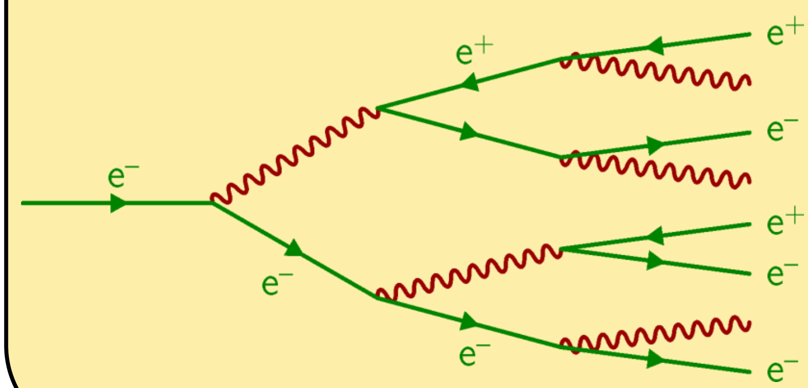


Pair Production



Electromagnetic Shower

one particle of
high energy

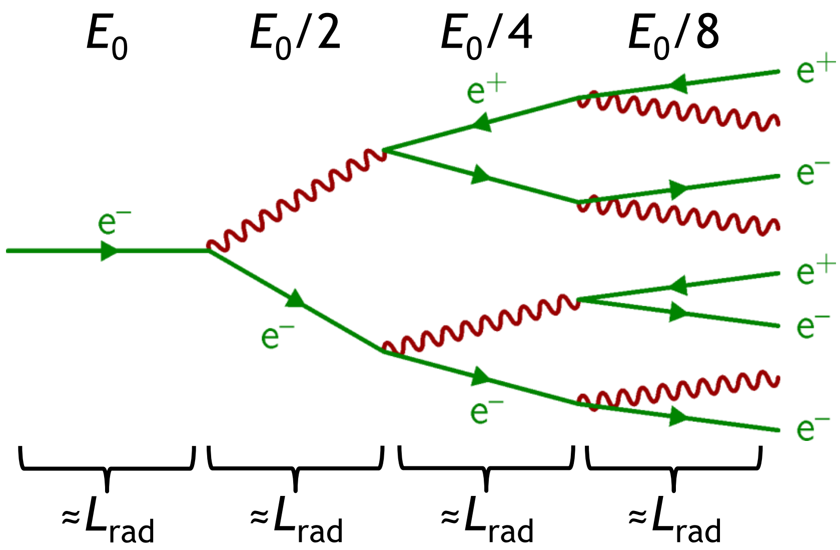


many particles of
lower energy

A *Veeery* Simple Shower Model

Assumptions:

- An electron emits half of its energy as a single photon after L_{rad}.
- A photon is converted to an e^+/e^- pair, each carrying half of its energy, after L_{rad}.
- The shower stops when particle energies drop below the critical energy.



Particle energy after *N* radiation lengths:

$$E(N) = E_0/2^N$$

Number of radiation lengths to reach the critical energy:

$$N_{crit} = \ln(E_0/E_{crit}) \;/\; \ln(2)$$

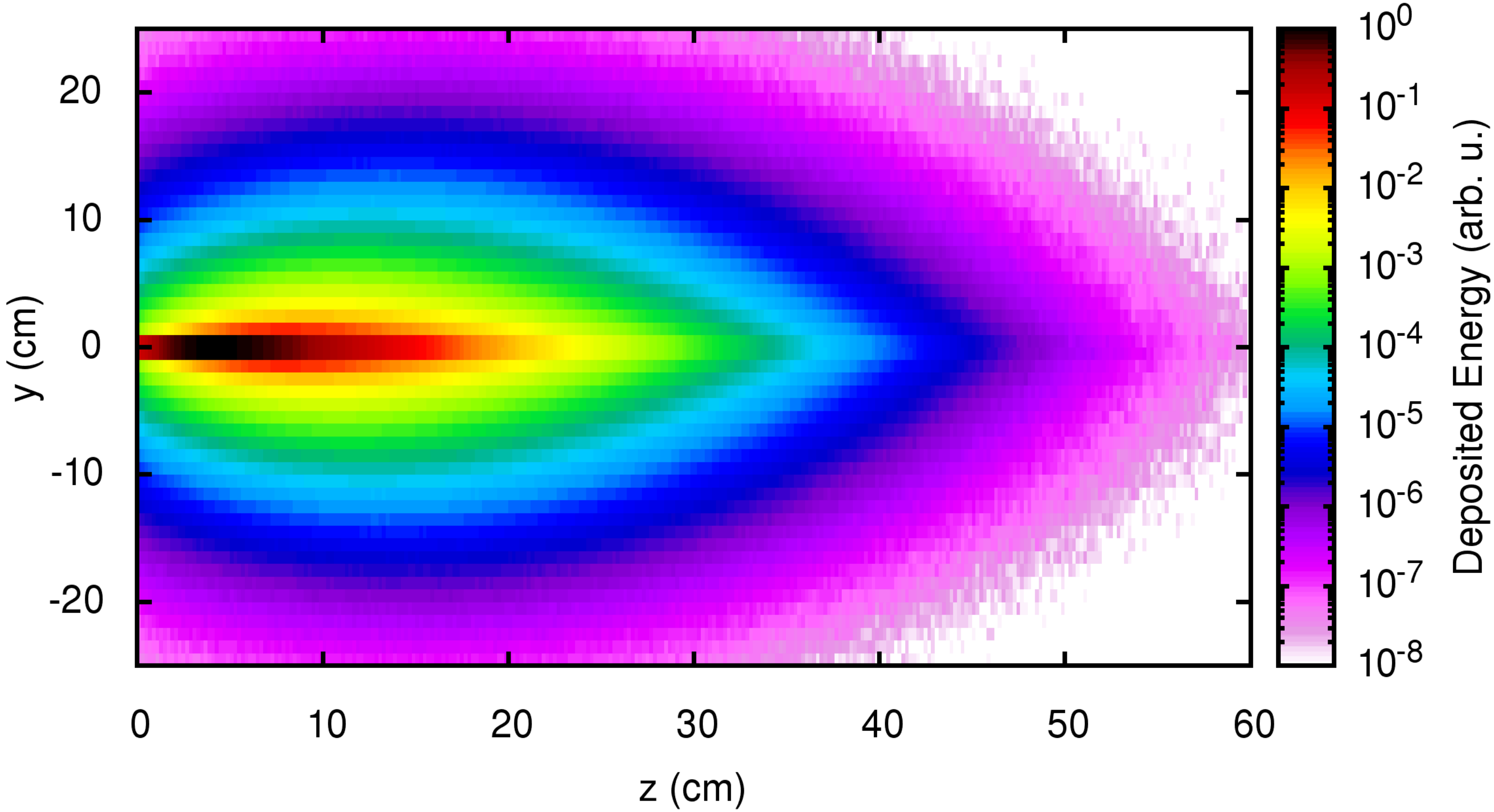
The critical energy is reached after N_{crit} radiation lengths:

$$E_{crit} = E(N_{crit}) = E_0/2^{N_{crit}}$$

This is only a qualitative model!

Better: Monte Carlo (Fluka, Geant, …)

1 GeV Electrons on Copper



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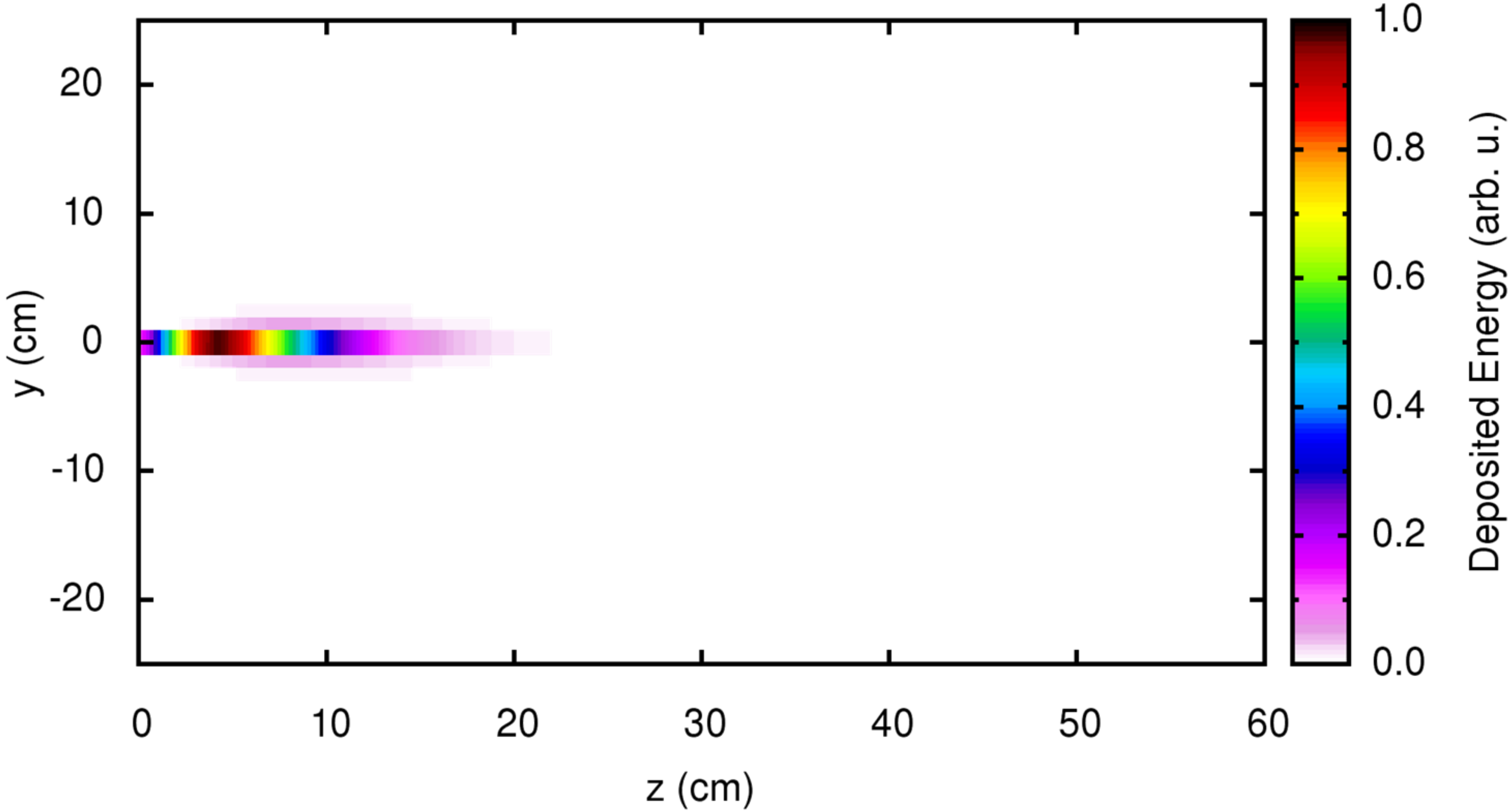
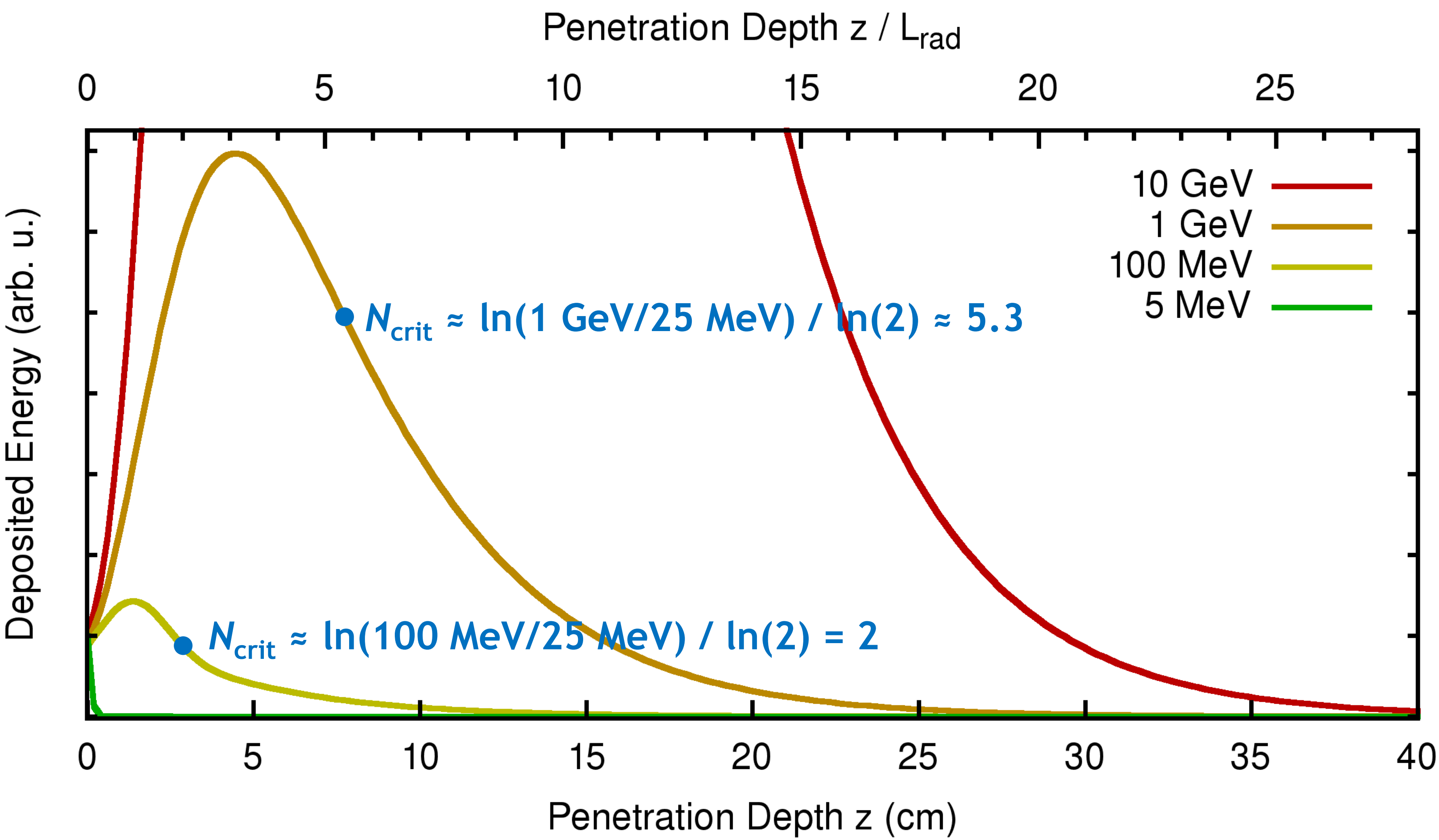
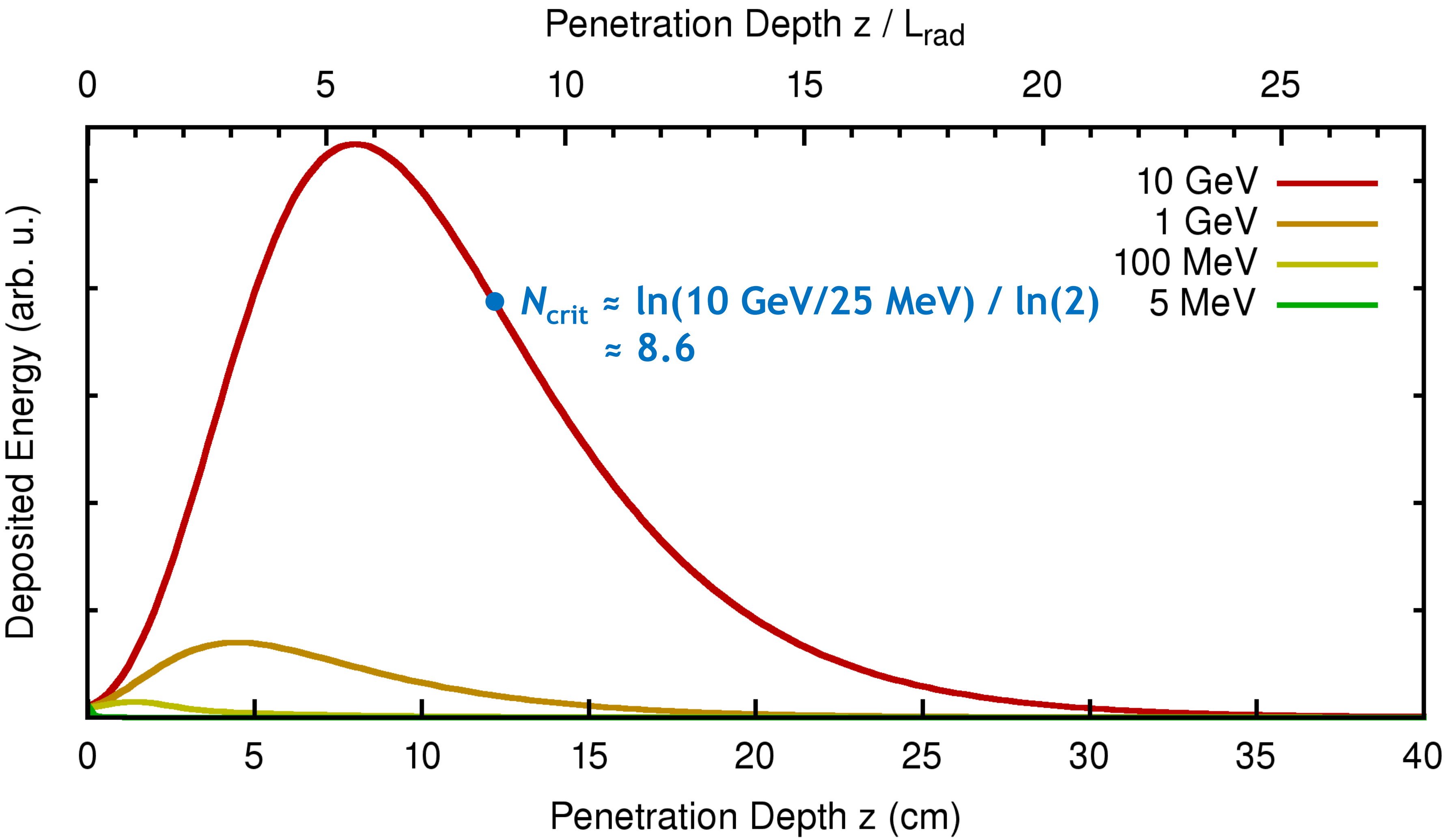


Electron Beam Hitting a Copper Target



Electron Beam Hitting a Copper Target



Damage to Permanent Magnets

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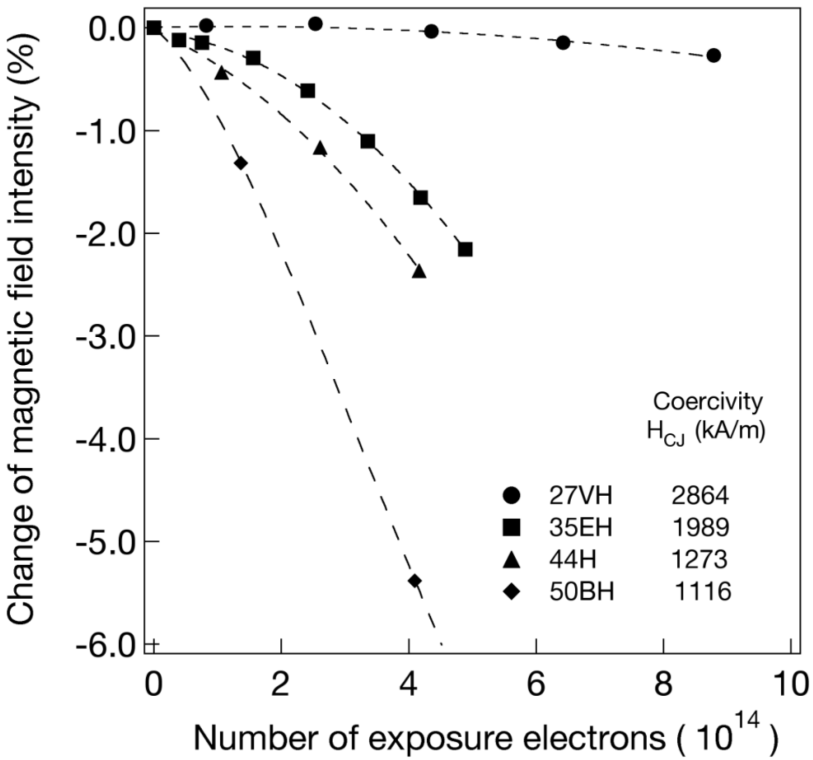
https://commons.wikimedia.org/w/index.php?curid=3971959

Demagnetization of Permanent Magnets

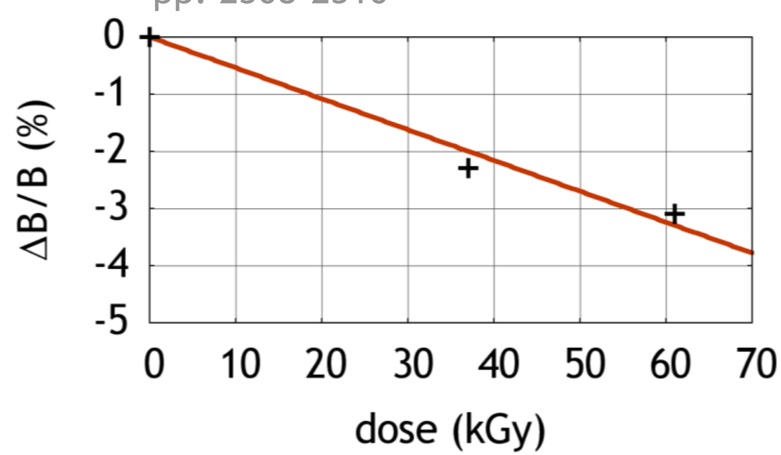


($Nd_2Fe_{14}B$ magnets, 2 GeV electrons)

Teruhiko Bizen – "Brief Review of the Approaches to Elucidate the Mechanism of the Radiation-induced Demagnetization" (ERL workshop 2011, Tsukuba, Japan)

- FELs rely on precision magnetic fields
- Permanent magnets lose magnetic field under irradiation with high energy electron beams
- Various magnetic materials behave differently

Skupin et al., "Undulator demagnetization due to radiation losses at FLASH", Proc. EPAC 2008, pp. 2308–2310

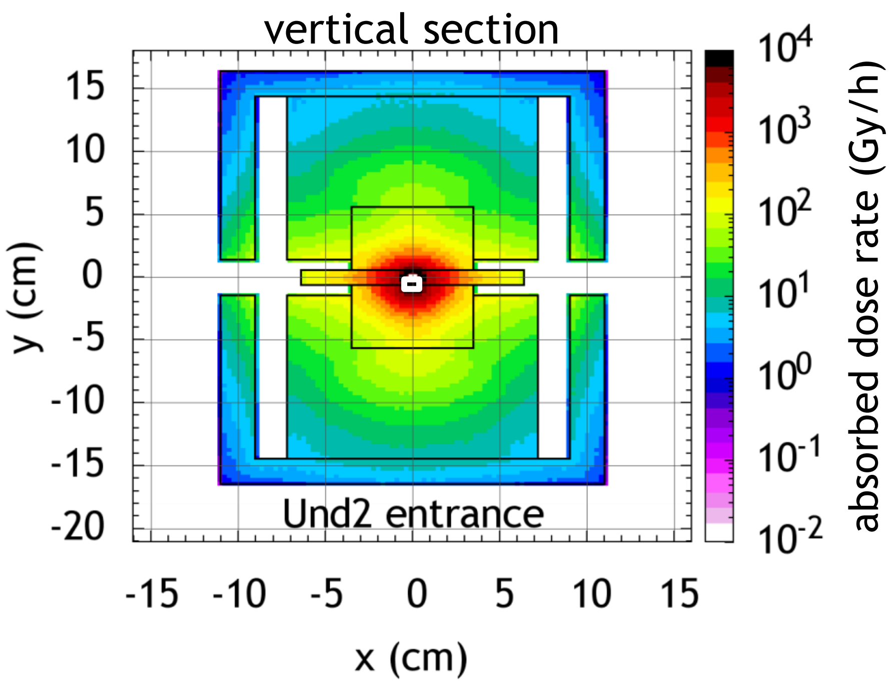


Demagnetization of Permanent Magnets

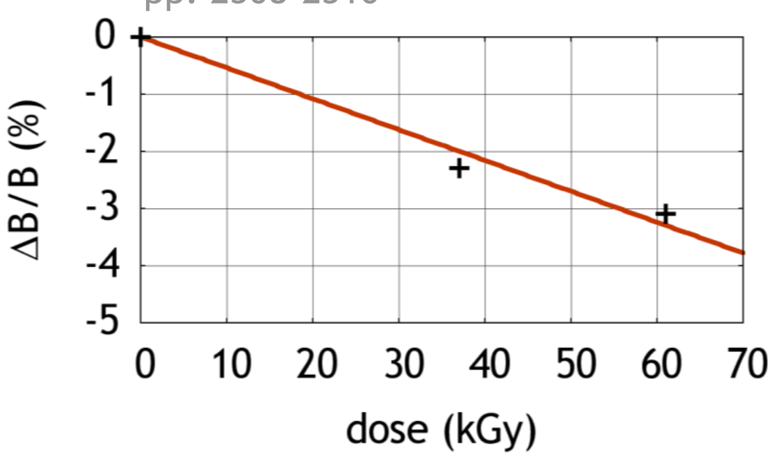
Can demagnetization be compensated by undulator tuning (opening gaps)?

- FELs rely on precision magnetic fields
- Permanent magnets lose magnetic field under irradiation with high energy electron beams
- Various magnetic materials behave differently

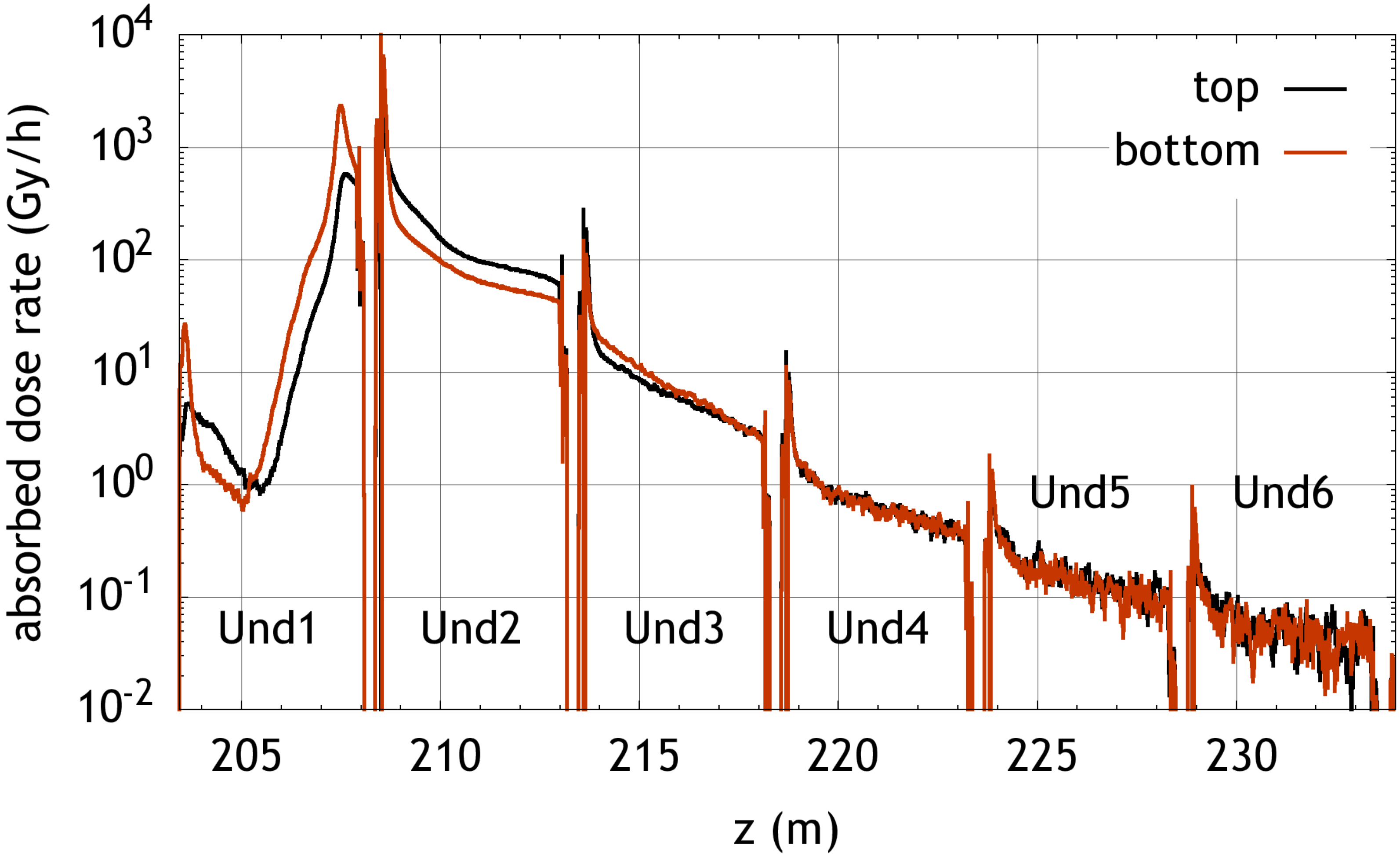
FLUKA beam loss simulation
(FLASH, 1 bunch, 10 Hz)



Skupin et al., "Undulator demagnetization due to radiation losses at FLASH", Proc. EPAC 2008, pp. 2308–2310

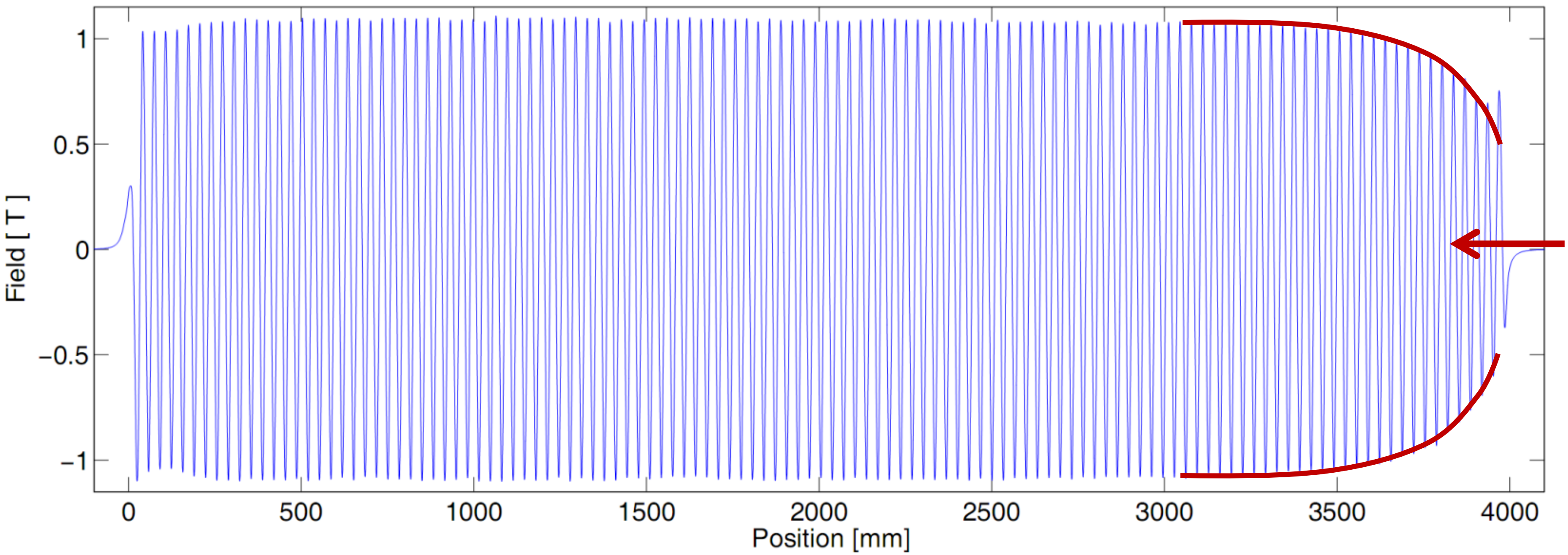


FLASH: Longitudinal Dose Distribution



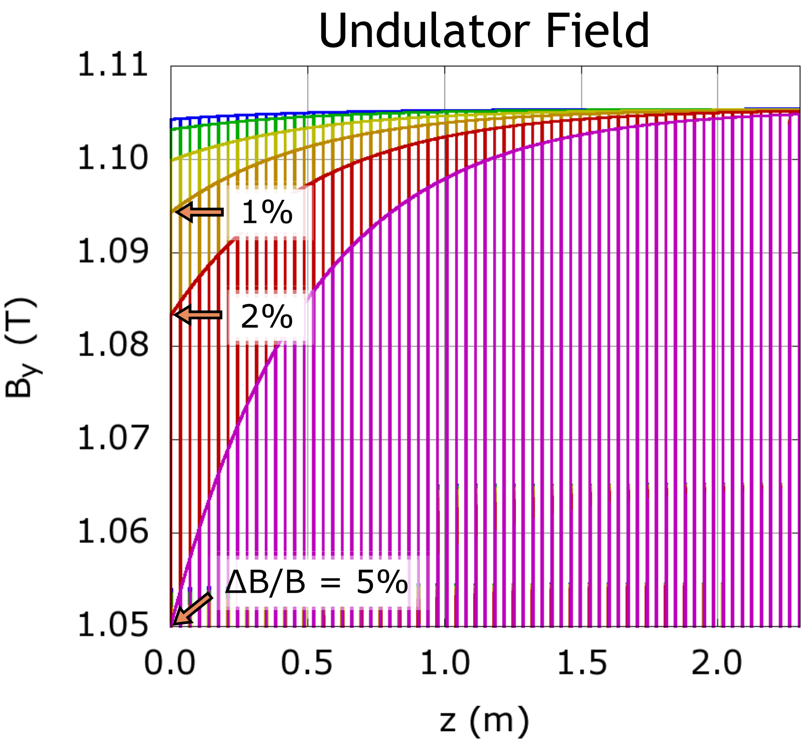
Approximate parameters:
7200 bunches at 1 nC, 10 Hz, ~1 GeV

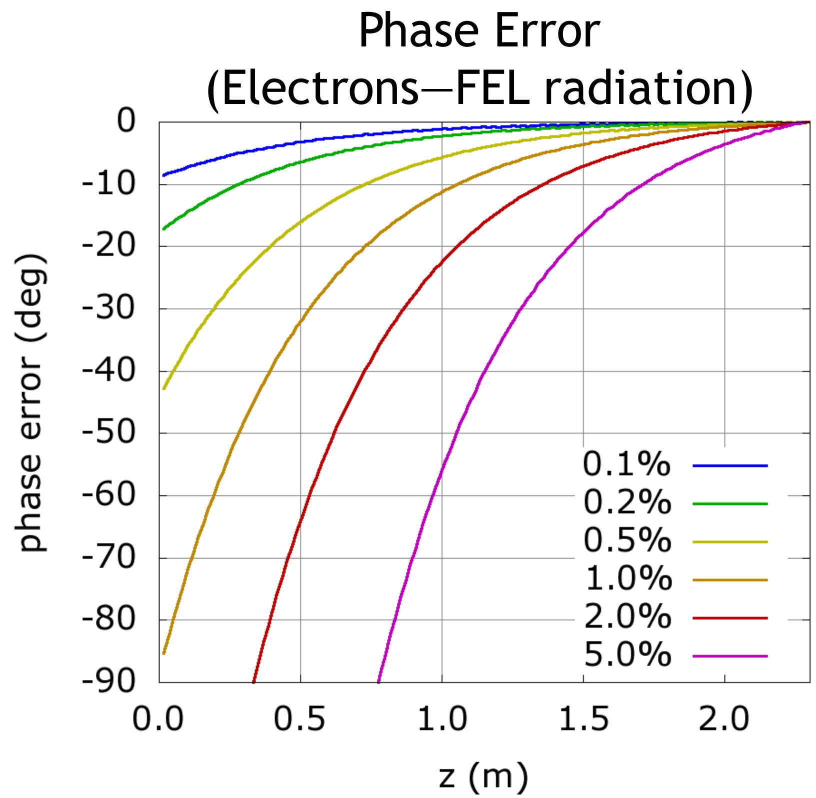
Field Loss of a PETRA-II Undulator



P. Vagin et al., "Commissioning experience with insertion devices at PETRA III", SR2010, Novosibirsk, Russia.

Demagnetization and Phase Error





Example: FERMI@Elettra FEL-2, second stage radiator

66 periods of 3.48 cm

Final Remarks

Final Remarks & References

- Balance:
  - Protect the machine
  - Protect the beam
  - With as little resources as possible
- Variety:
  - Beam dynamics, particle physics, instrumentation, controls, reliability theory, systems design

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The End.
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