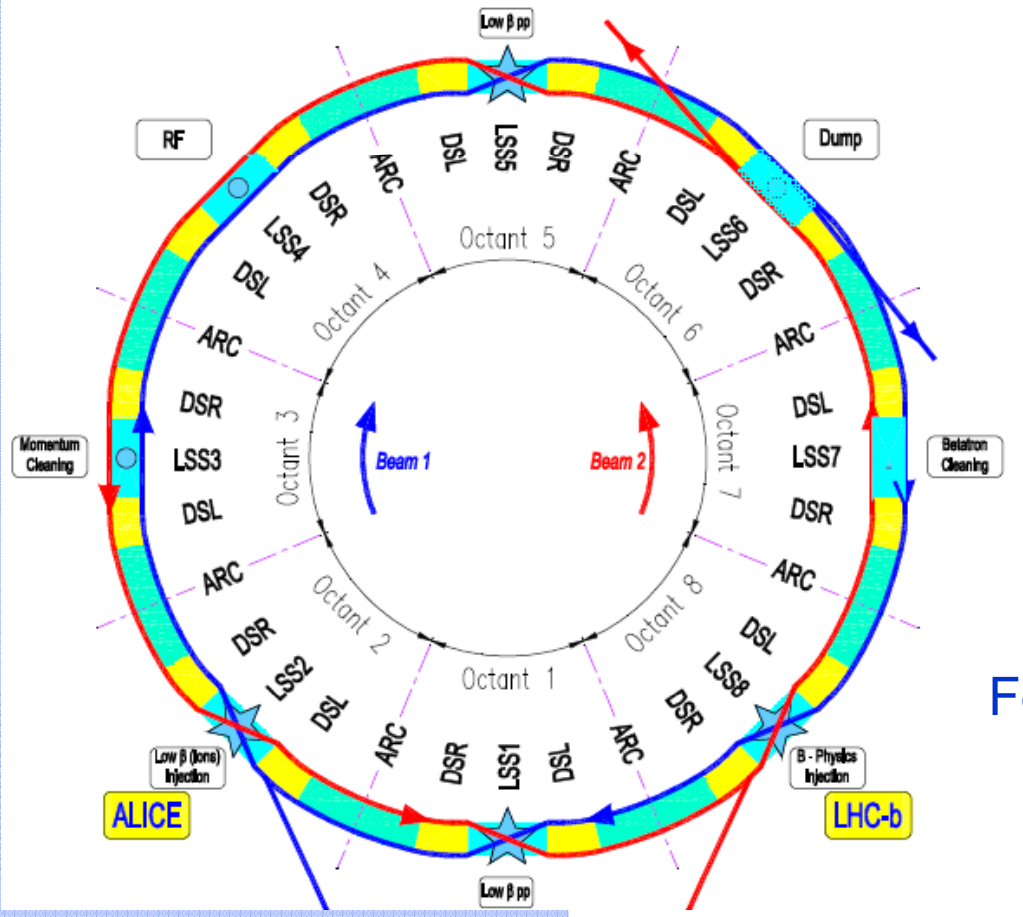
# Beam induced losses

Elena Wildner,
CERN

# Contents

- Direct and indirect beams
- Particle zoology
- Interaction with matter
- Examples from machine
  - Interaction region
  - Absorbers for decayed beam

# Impinging particles I



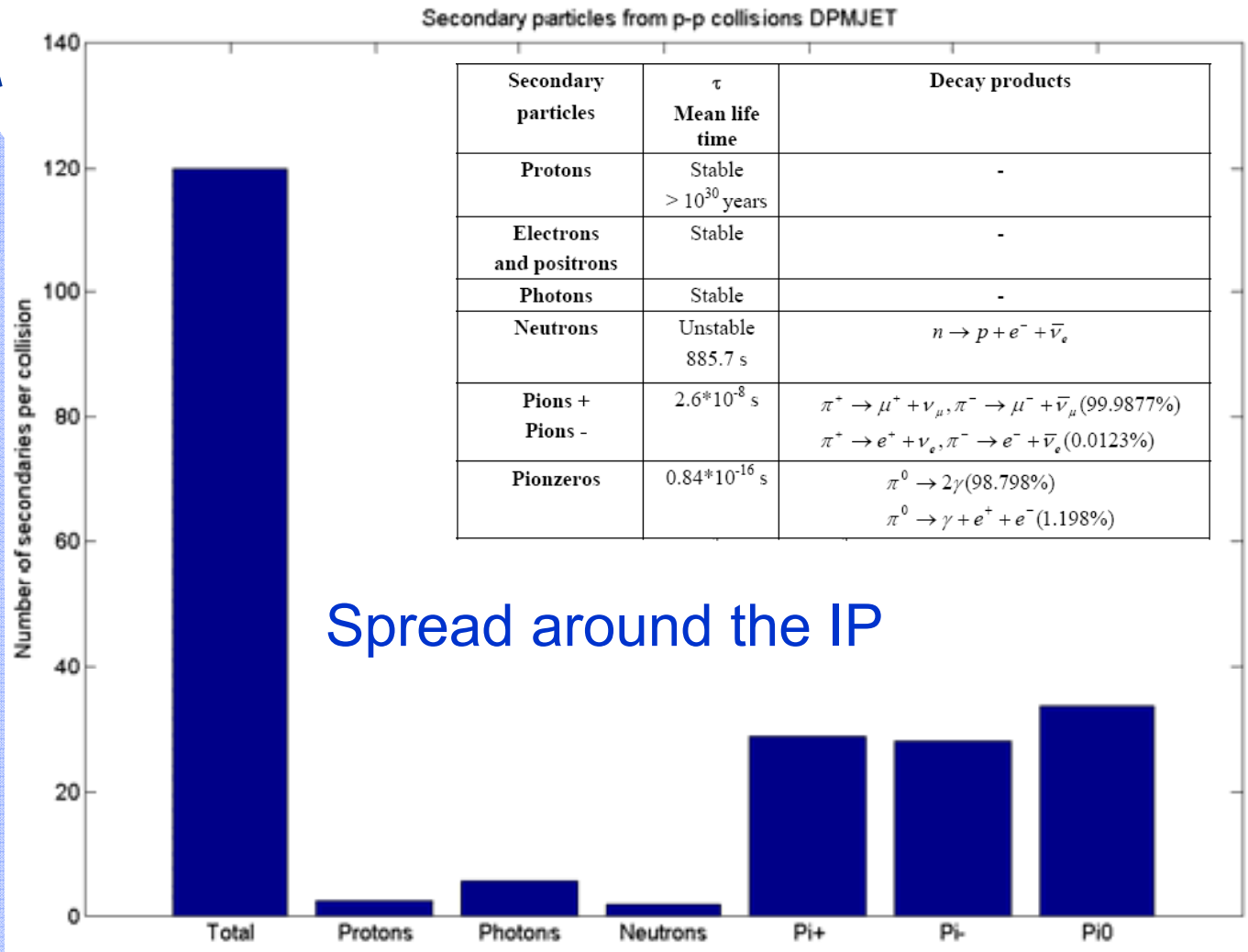

- Collisions
- Dumping
- Beam Halo
- Mishaps

Foreseen regions in the machine

# Impinging particles II

- Collisions — Creation of particle debris → interaction with matter Eventgenerators (DPMJET...)
- Dumping
- Beam Halo — Interaction with matter
- Mishaps

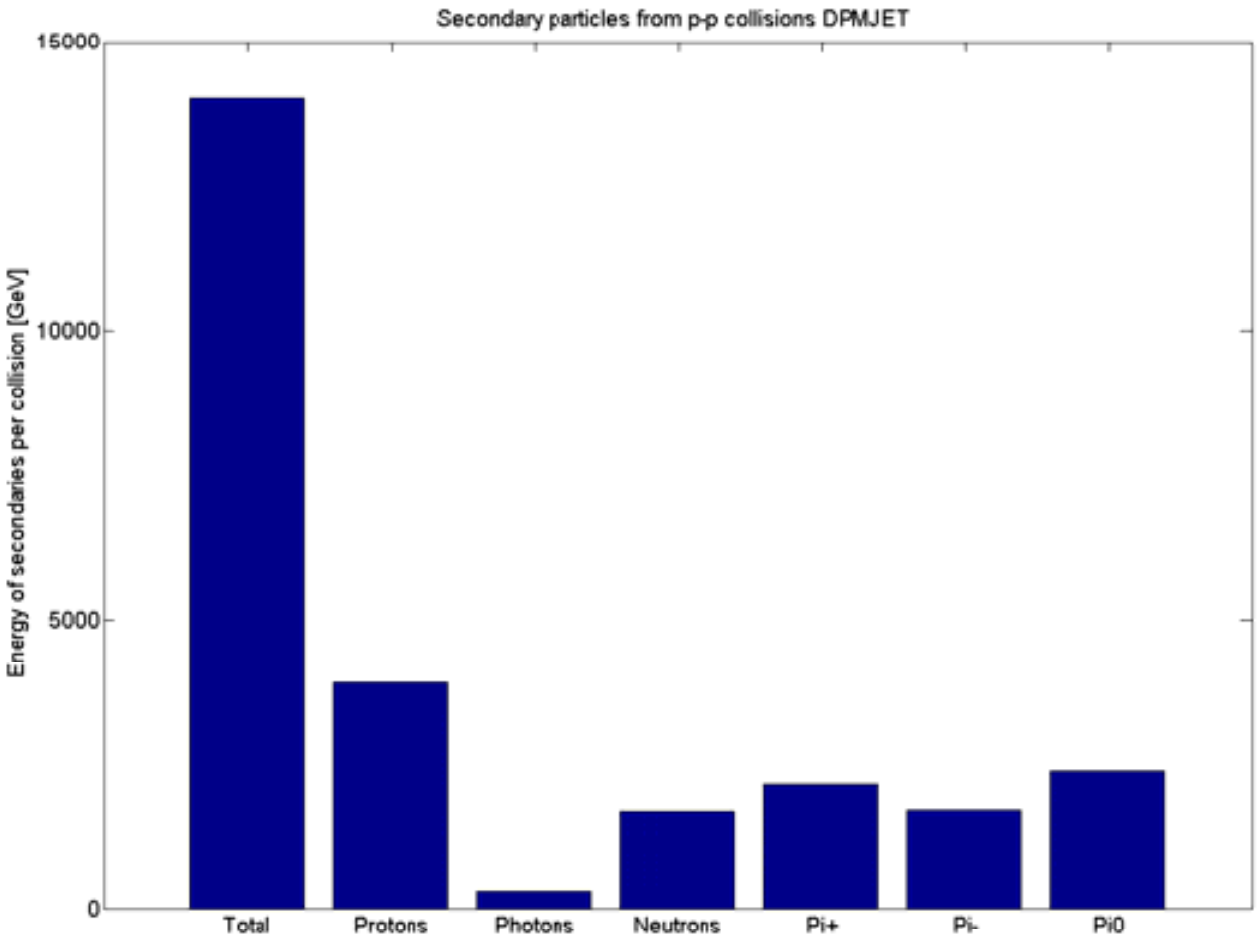
# Secondaries from p-p collisions



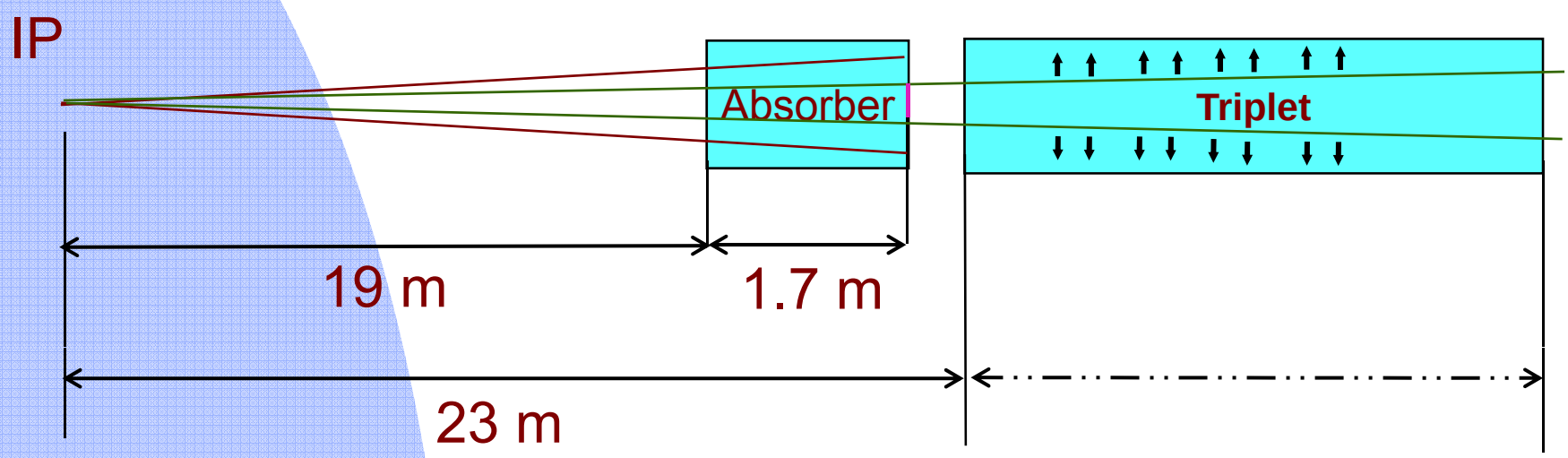

| Secondary particles | $\tau$ Mean life time | Decay products |
|---|---|---|
| Protons | Stable $> 10^{30}$ years | - |
| Electrons and positrons | Stable | - |
| Photons | Stable | - |
| Neutrons | Unstable 885.7 s | $n \rightarrow p + e^- + \bar{\nu}_e$ |
| Pions + Pions - | $2.6*10^{-8}$ s | $\pi^+ \rightarrow \mu^+ + \nu_\mu, \pi^- \rightarrow \mu^- + \bar{\nu}_\mu (99.9877\%)$ <br> $\pi^+ \rightarrow e^+ + \nu_e, \pi^- \rightarrow e^- + \bar{\nu}_e (0.0123\%)$ |
| Pionzeros | $0.84*10^{-16}$ s | $\pi^0 \rightarrow 2\gamma (98.798\%)$ <br> $\pi^0 \rightarrow \gamma + e^+ + e^- (1.198\%)$ |

Spread around the IP

# Energies of secondaries in p-p collisions



# The “debris-cone”

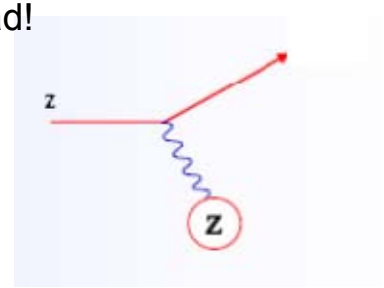


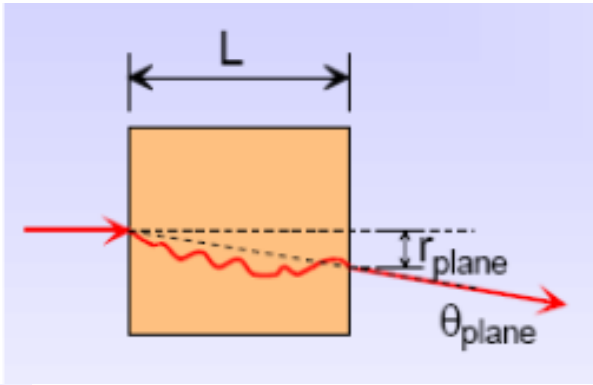
# Interactions

- charged particles < = > e, p, nuclei, charged pions
  - multiple scattering
  - ionisation energy loss
  - Bremsstrahlung
- photons
- hadrons
- neutral particles

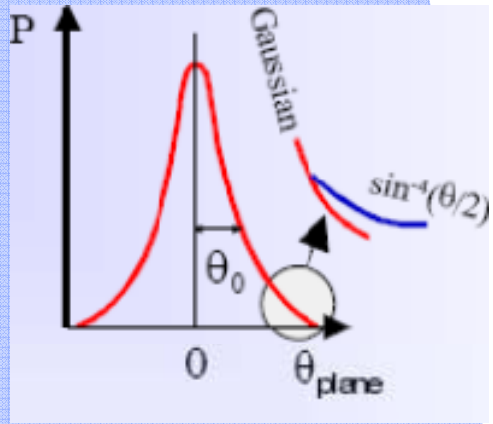
# Multiple scattering

Nucleus heavy, not much energy loss, but spread!



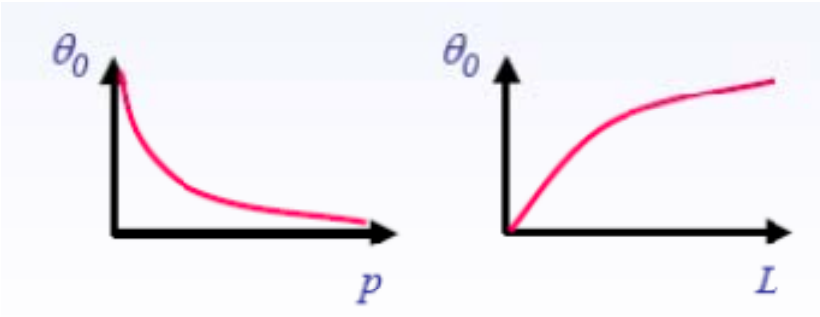




$$\frac{d\sigma}{d\Omega} = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4\theta/2}$$ Rutherford formula




$$\theta_0 \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$$

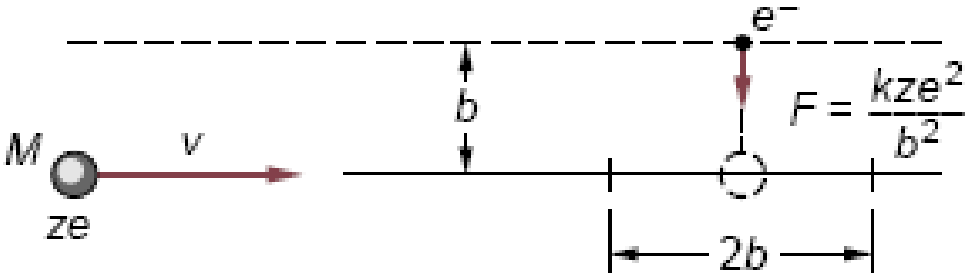
Radiation length



# Energy loss of impinging particle

- may lead to ionization
- many electrons in medium gives many encounters
- energy loss for the particle above some keV can be treated as continuous
- below some keV
  - processes related to heat
  - individual encounters important
- after some “range” the particle comes to a stop
  - for electrons large statistical variations, for heavy projectiles only a few % variation (straggling)

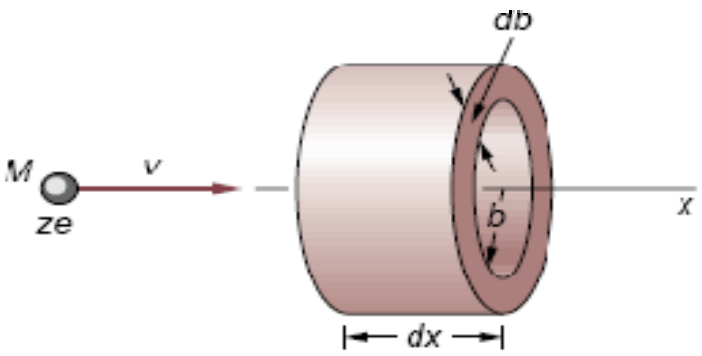
# Energy loss of charged particle: collision with one electron




$$p \approx Ft = \frac{kze^2}{b^2}\frac{2b}{v} = \frac{2kze^2}{bv}$$

$$K_e = \frac{p^2}{2m_e} = \frac{2k^2z^2e^4}{m_e v^2 b^2}$$

# Energy loss of charged particle: collision with many electrons




Volume of shell is $2\pi b\, db\, dx$
Number in shell is $n 2\pi b\, db\, dx$

**Z the atomic number,**
**A the atomic weight,**
**NA Avogadro's Number**
**ρ the mass density**

**Z (NA/A)ρ 2πb db dx electrons in the shell**

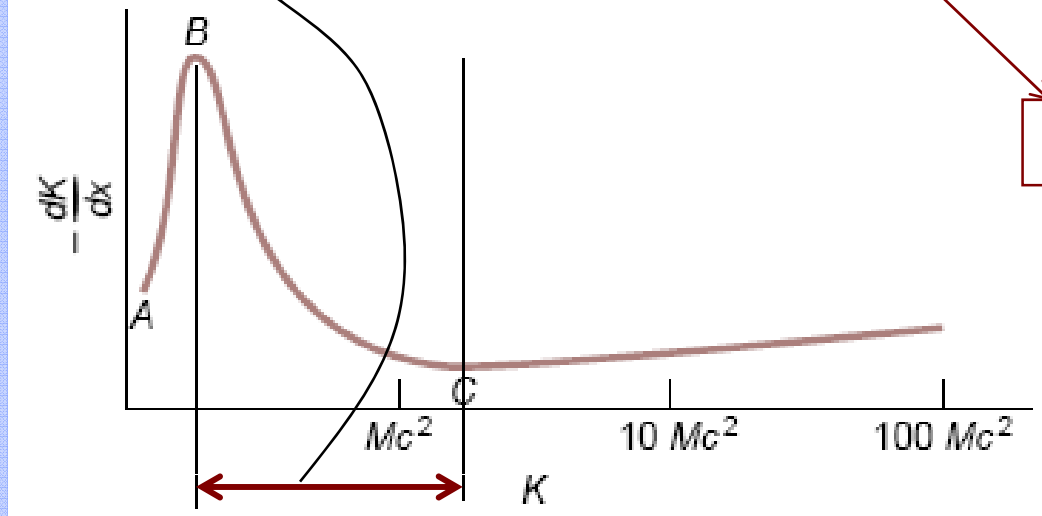
$$-dK = \frac{2k^2 z^2 e^4}{m_e v^2 b^2} Z \frac{N_A}{A} 2\pi b \rho\, db\, dx$$

# Energy loss with energy

$$-dK = \frac{2k^2z^2e^4}{m_e v^2 b^2} Z \frac{N_A}{A} 2\pi b\rho \, db \, dx$$

$$-\frac{dK}{dx} = \frac{4\pi k^2 z^2 e^4 (Z/A) N_A \rho}{m_e v^2} L \qquad L = \ln\left(\frac{b_{max}}{b_{min}}\right)$$

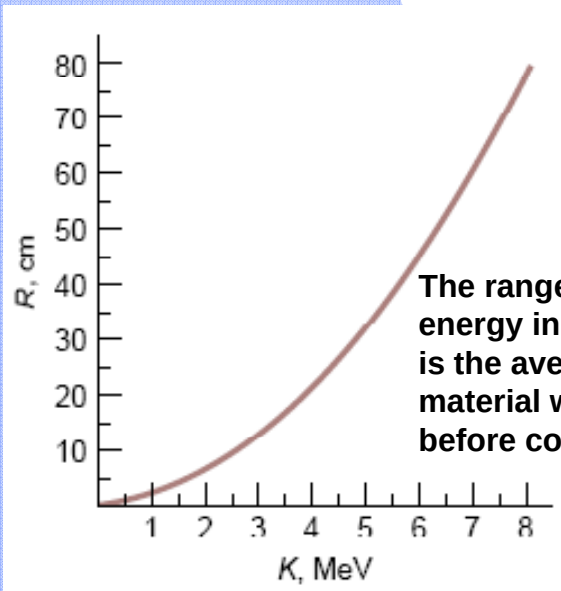
**~ density!!!**



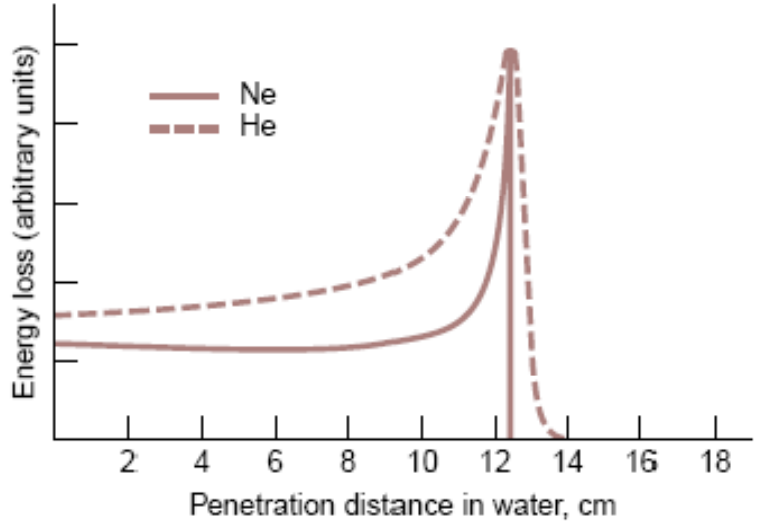
# Range and Stopping power

- **The range and the stopping power:**
  - **type of particle**
  - **on its (initial) energy**
  - **the material which it passes**

*$l=\rho x$ g/cm$^3$*
*dK/dl similar for different materials*




**The range of a particle of given energy in an absorbing material is the average thickness of material which it traverses before coming to rest**




Energy loss very large at low energy for heavy particles: **Bragg peak**

# High energy electrons and TeV muons

Coulomb field of nuclei: radiation of real photons, Bremsstrahlung

For electrons: $$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln\frac{183}{Z^{1/3}}$$

$$\boxed{-\frac{dE}{dx} = \frac{E}{X_0}} \longrightarrow E = E_0\, e^{-x/X_0}$$

$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

radiation length [g/cm$^2$]

(divide by specific density to get $X_0$ in cm)

Radiation length:
mean distance over which a high-energy electron loses all but 1/e of its energy by bremsstrahlung, and 7/9 of the mean free path for pair production by a high-energy photon. It is also the appropriate scale length for describing high-energy electromagnetic cascades

# Critical energy

- **Critical energy $E_c$**

$$\left.\frac{dE}{dx}(E_c)\right|_{Brems} = \left.\frac{dE}{dx}(E_c)\right|_{ion}$$

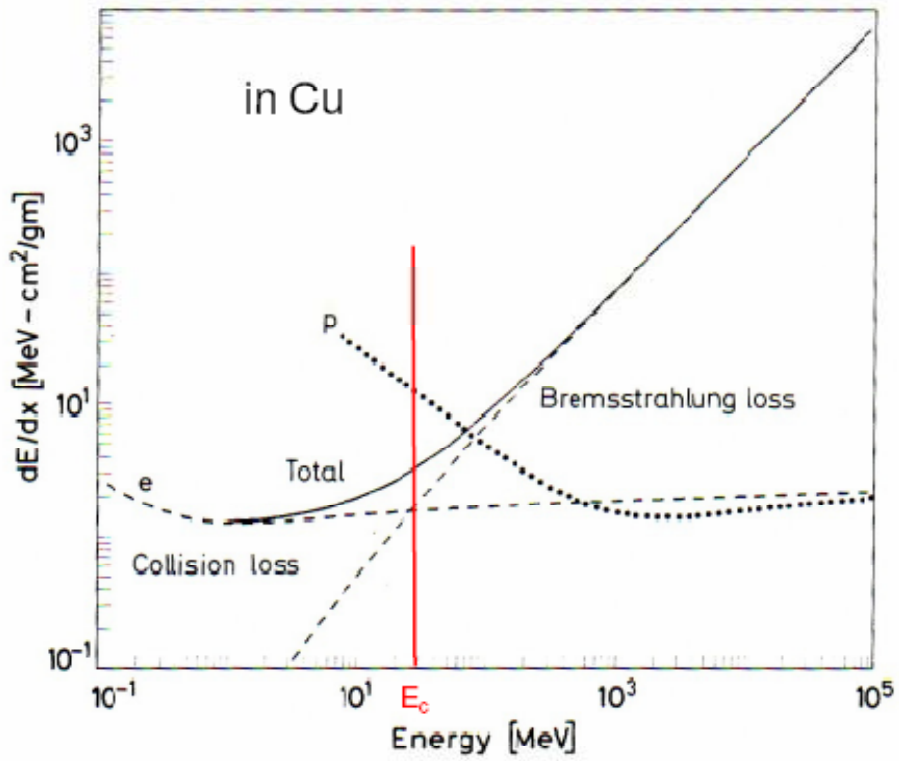
For electrons one finds approximately:

$$E_c^{solid+liq} = \frac{610MeV}{Z+1.24} \qquad E_c^{gas} = \frac{710MeV}{Z+1.24}$$

$E_c(e^-)$ in Cu(Z=29) = 20 MeV

For muons $E_c \approx E_c^{elec}\left(\frac{m_\mu}{m_e}\right)^2$

$E_c(\mu)$ in Cu $\approx$ 1 TeV




Unlike electrons, muons in multi-GeV range can traverse thick layers of dense matter.

# Neutrons

- Interaction via magnetic moments of electrons
  - No transfer of kinetic energy to electrons
- Scattering by nuclear potentials
- Capture
- Energies larger than the thermal energy (kT)*: elastic and inelastic scattering
- Neutrons only scatter a few times before they are lost from the “beam”.
- Exponential decrease of intensity

* thermal energy comes form the movement of atoms and molecules in matter. It is a form of kinetic energy produced from the random movements of those molecules (0.01 eV).

# Neutrons

Neutron removed from “beam” at first scattering:
probability is proportional to the number of neutrons in beam and the path distance.

$$-dN = \sigma I(nAdx) = \sigma nNdx$$

| | |
|---|---|
| $\sigma$ | Cross section for scattering and absorption |
| $I$ | Intensity of neutron beam |
| $R = \sigma I$ | Removed from beam |
| $A$ | Area of beam |
| $n$ | Nuclei per unit volume |
| $nAdx$ | Nuclei encountered in distance dx |
| $N = IA$ | Neutrons per unit time in beam |

$$N = N_0 e^{-\sigma nx}$$

$$I = I_0 e^{-\sigma nx}$$

$$1/2 N_0 = N_0 e^{-\sigma n x_{1/2}}$$

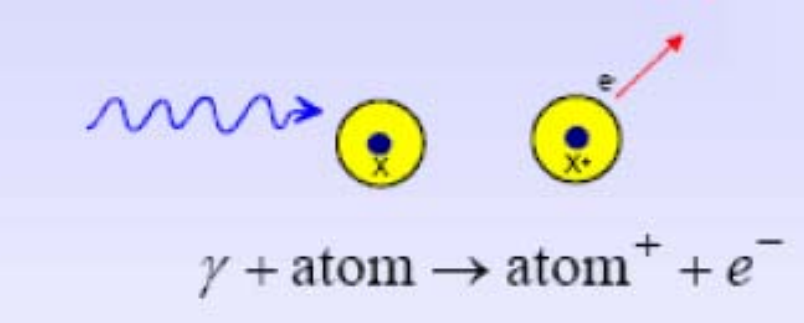
$$e^{-\sigma n x_{1/2}} = 2$$

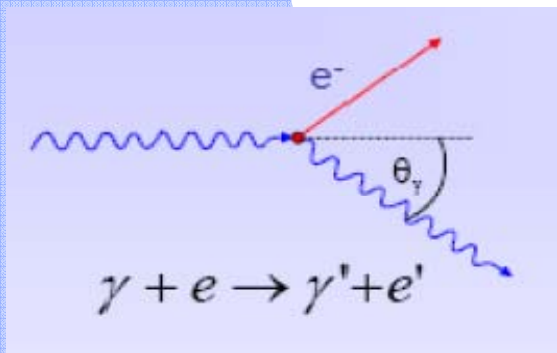
$$x_{1/2} = \frac{\ln 2}{\sigma n}$$

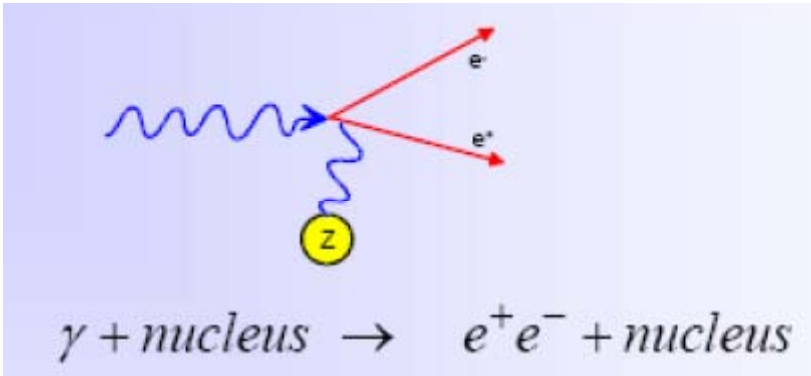
Half penetration distance: number of neutrons 1/2

# Photons, interactions

- Interaction with electrons
  - photoelectric effect (~$Z^4$ or ~$Z^5$)
  - Compton Scattering (~Z)
  - pair production (~$Z^{2)}$



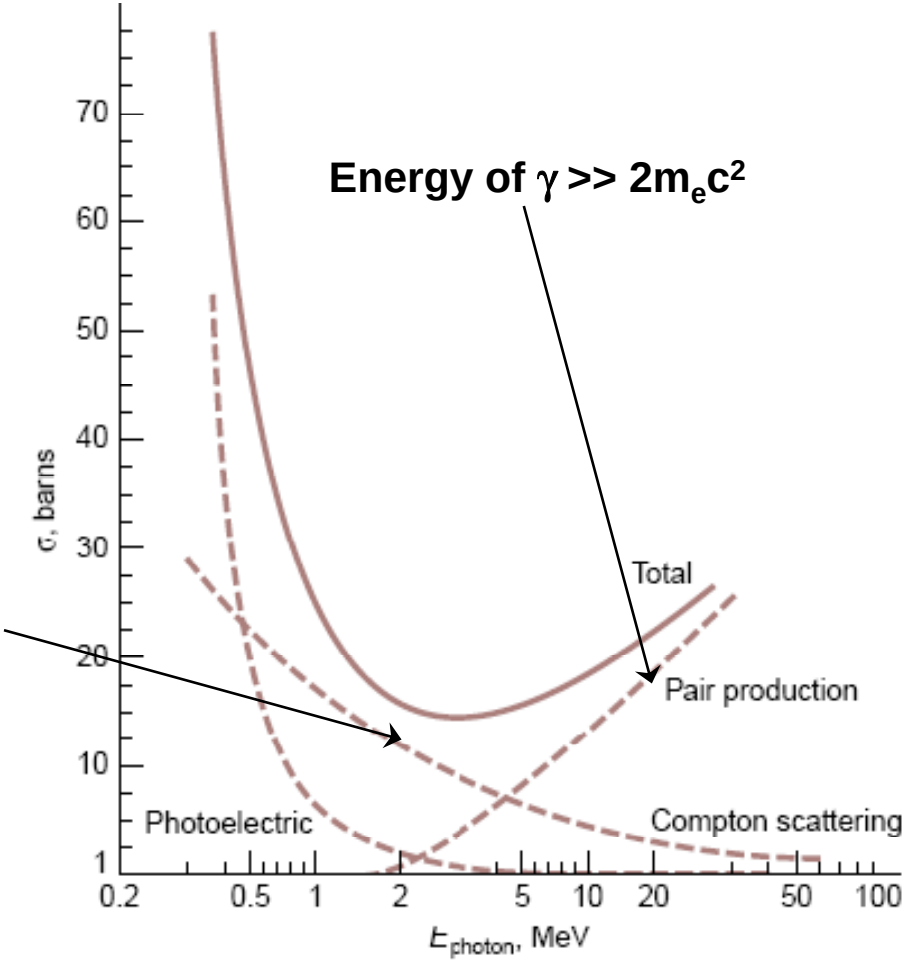



# Photons

**Energy of $\gamma$ >> $2m_ec^2$**

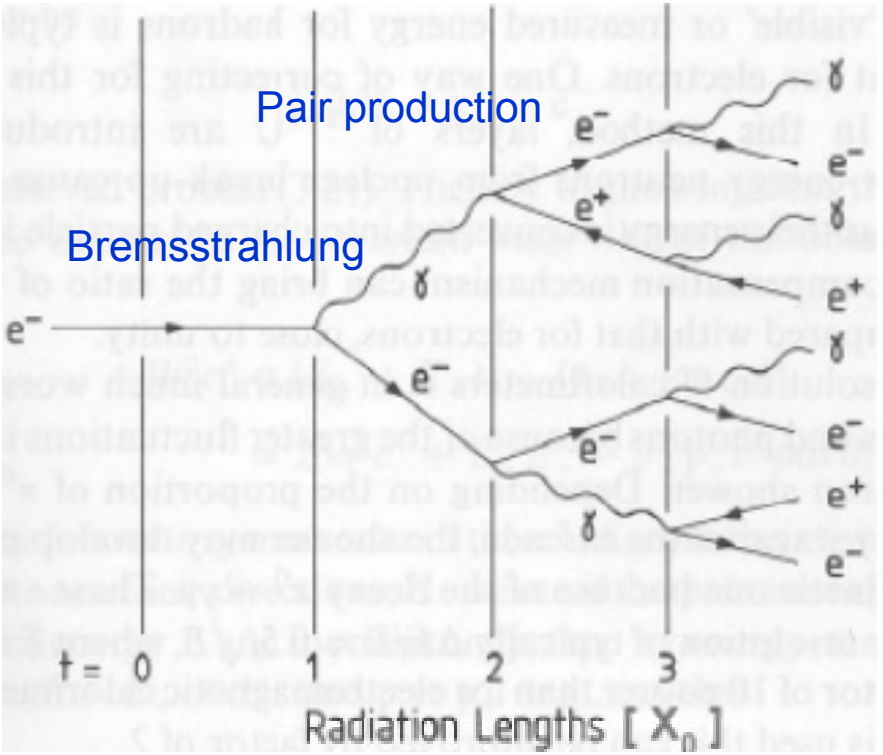
**Energy of $\gamma$ >> binding energy of electrons (a few keV)**



# Electromagnetic showers

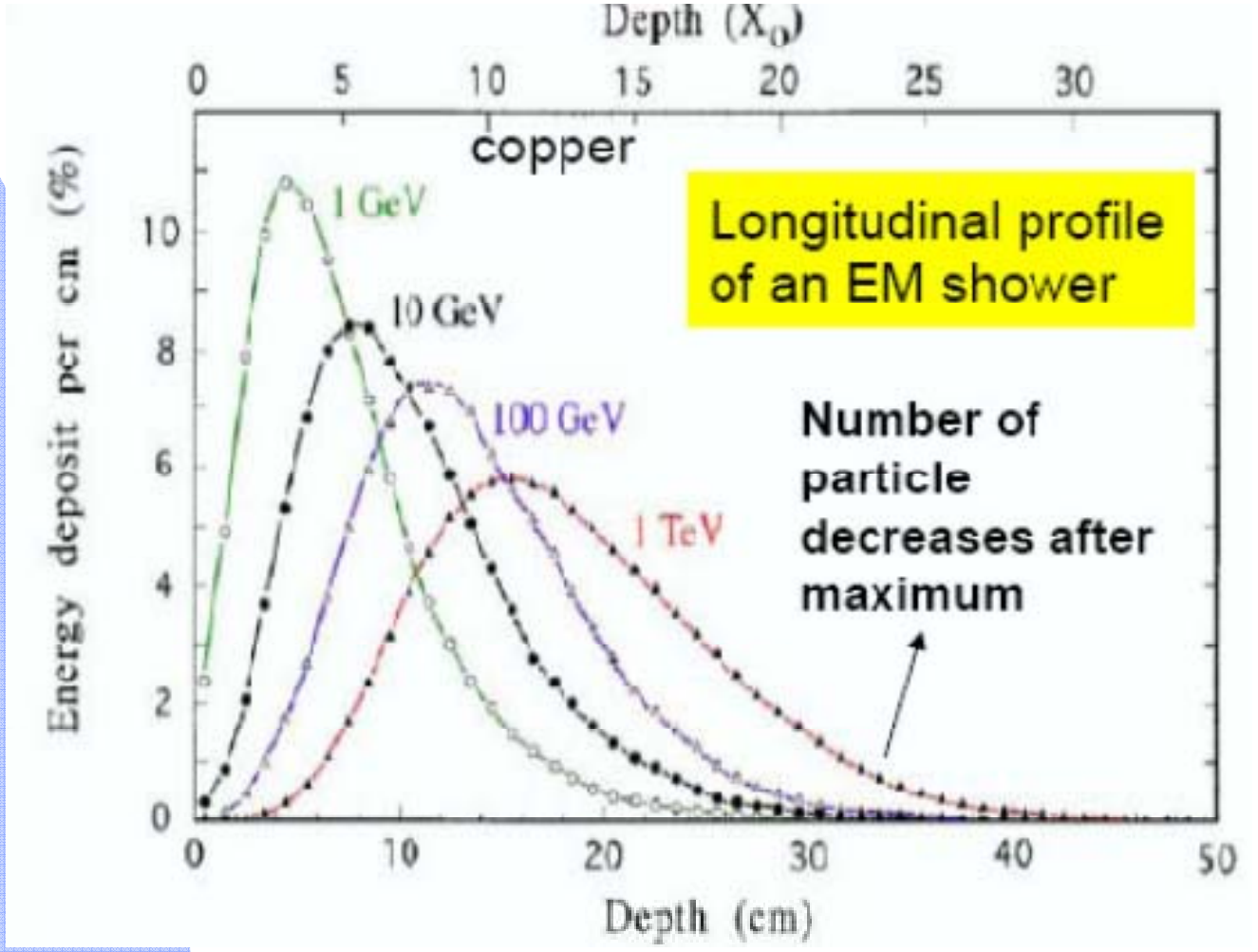
***Radiation length*** [g/cm$^2$]:

It is both the mean distance over which a high-energy electron loses all but 1/e of its energy by bremsstrahlung, and 7/9 of the mean free path for pair production by a high-energy photon



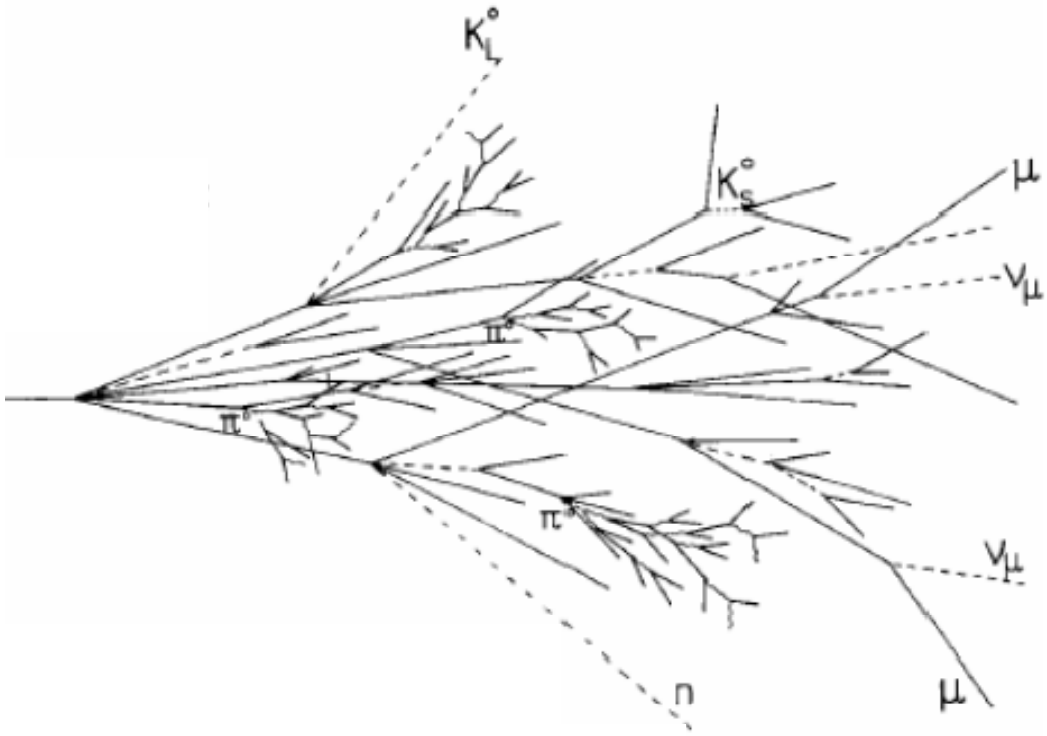

Photoelectric effect

# Electromagnetic showers

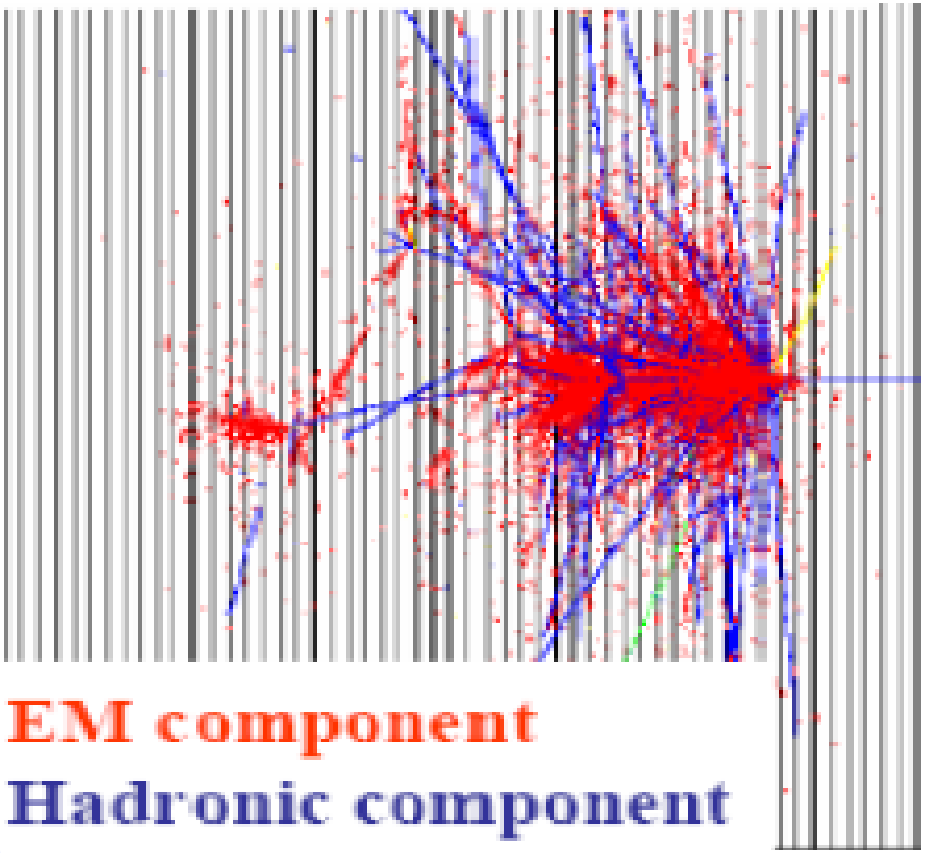


# Hadronic showers

- More complex than em showers
- Stops when energies small enough (ionization) or absorption in nuclear process
- Spread more laterally than em showers



# Hadronic showers




Energy deposition by

# Heat

- Energy sufficiently low not to involve further transport of particles
- Kinetic energy may displace atoms permanently
- Creation of lattice vibration, phonons, heat
- The tracking code stops the tracking and gives the remaining kinetic energy deposited in the scoring bin

# Simulation codes

- Fluka
  - "FLUKA: a multi-particle transport code", A. Fasso`, A. Ferrari, J. Ranft, and P.R. Sala, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773
- Geant
  - Nuclear Instruments and Methods in Physics Research A 506 (2003) 250-303, and IEEE Transactions on Nuclear Science 53 No. 1 (2006) 270-278.
- Mars
  - Mokhov, N. V. **The MARS** code **system** user's **guide**. Fermilab-FN-628, Fermi National Accelerator Laboratory (1995).

# Heat deposition model details

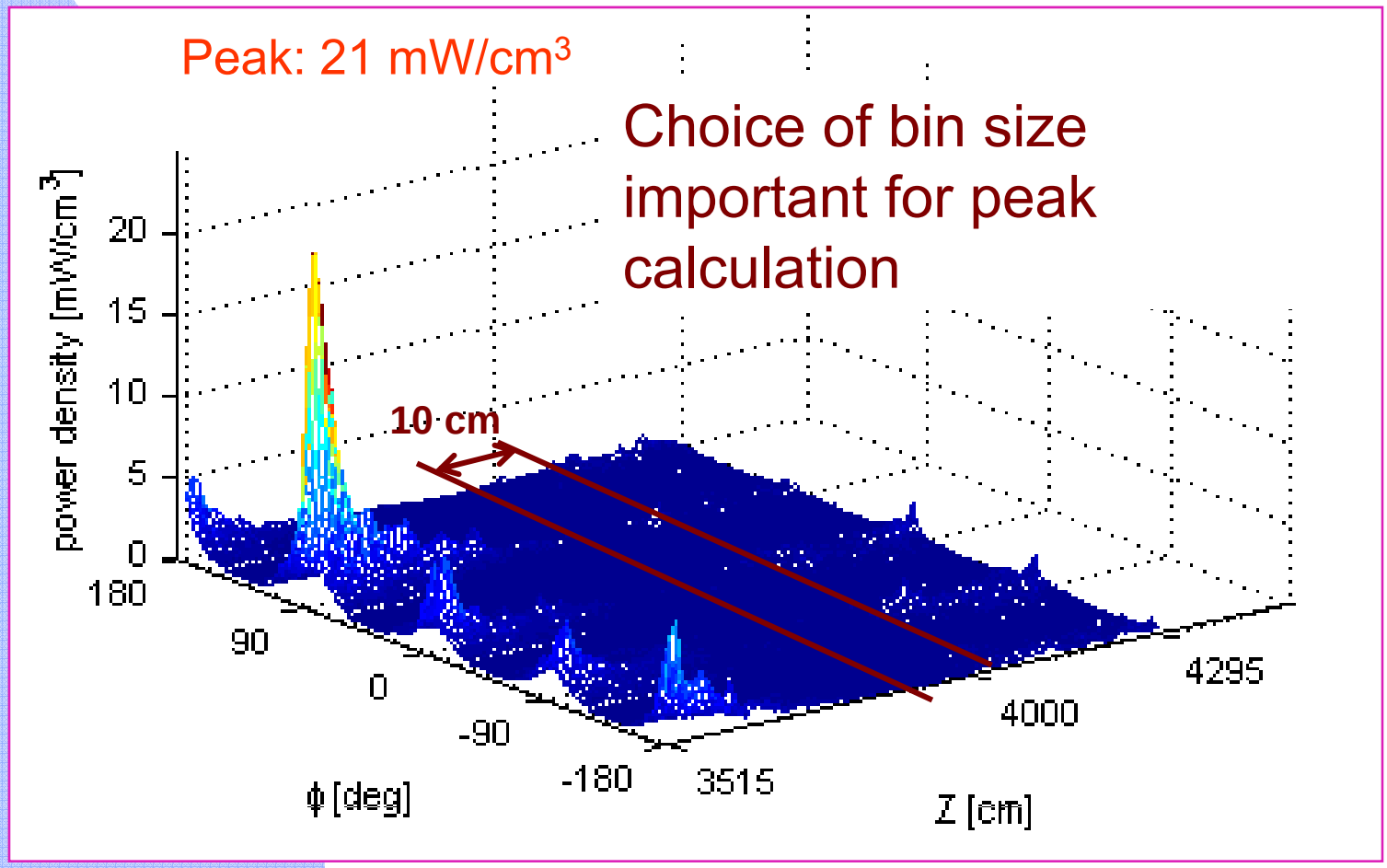
- Small regions
  - Low statistics
  - Special treatment in model if sensitive material (epoxy, silicon…)
- Processing time
  - Cutoffs and bias
- Statistics
  - Each model is run with normally 5 independent seeds
  - Statistics for each bin has to be made
  - Correlation between bins

# Results, what we consider

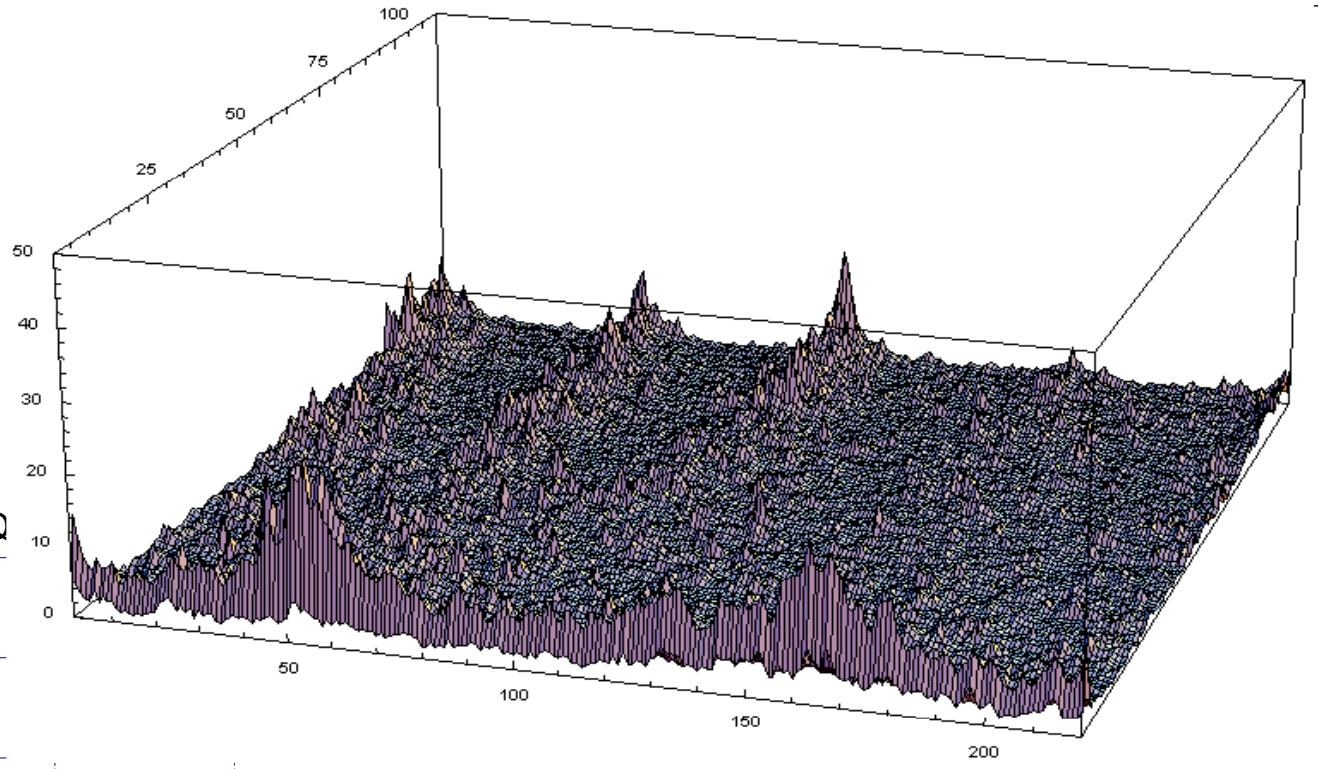
- Cable
  - We make the binning for the scoring so that it corresponds to a maximum volume of equilibrium for the heat transport (cable transverse size, with a length of around 10 cm, ***value to be confirmed***)
- Total power deposited in the magnets
  - Important to know the volume of the magnet (the model has to be realistic)
- The power deposited per meter of magnet

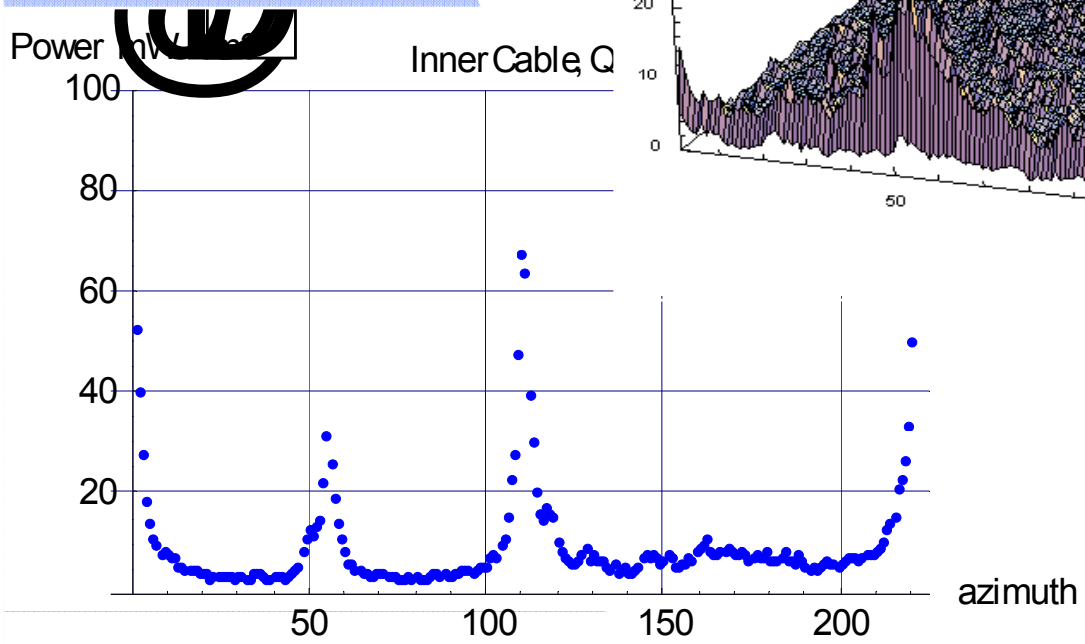
**N.B. For the *total* energy deposited we need a ”realistic” design of the magnet**

# One cable: power deposition



# Statistical variations

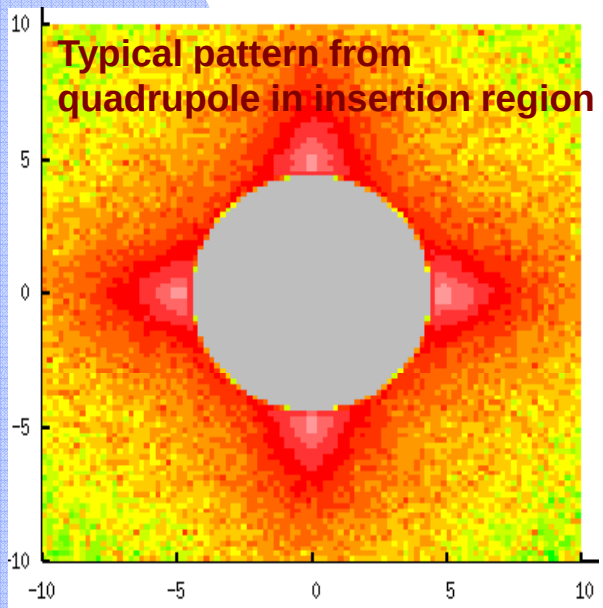


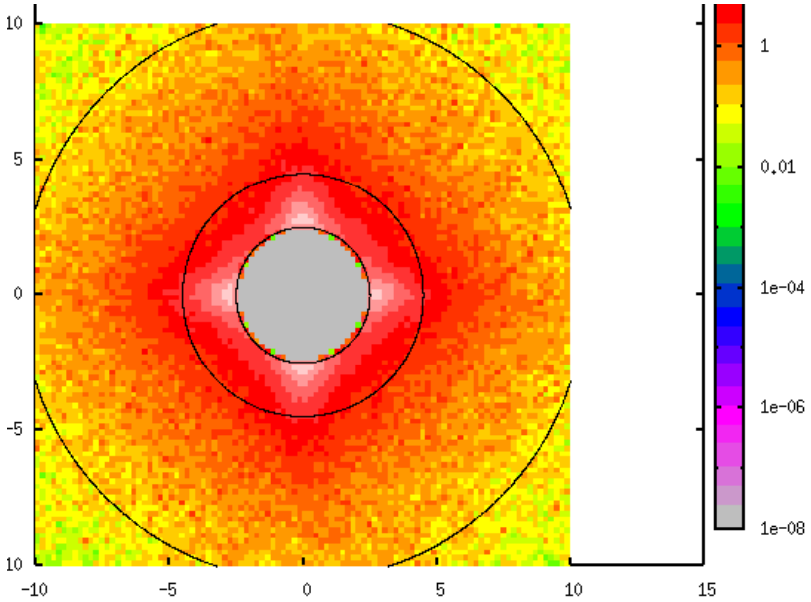



# How to make it work : Liner

**Material choice and thickness should be optimized!**
**In this example it is taken as stainless steel 2 cm thick.**

**No crossing angle in this example.**
**This case was calculated for L = 1.0 $10^{35}$ $cm^{-2}$ $s^{-1}$**

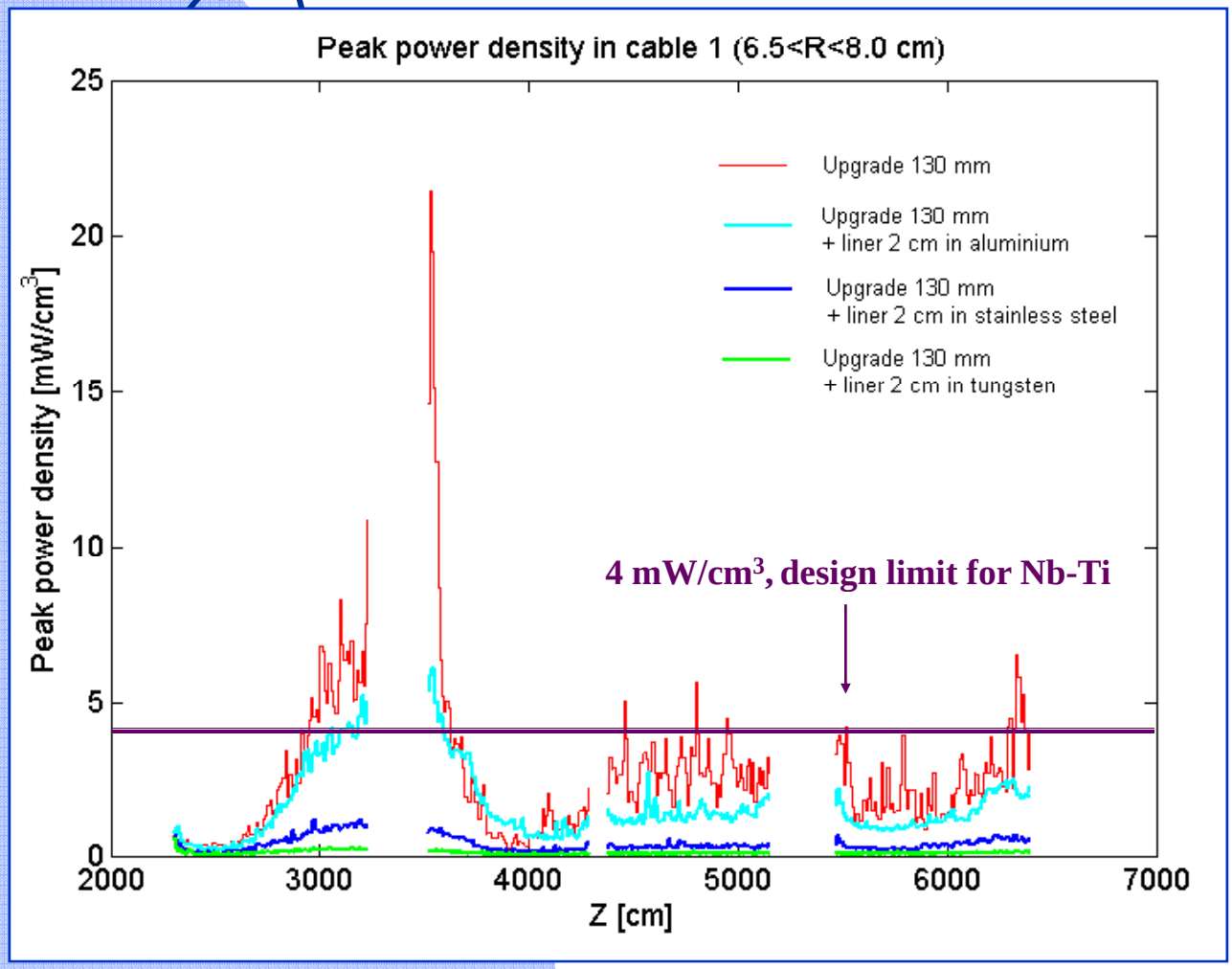



**Example from previous study:**

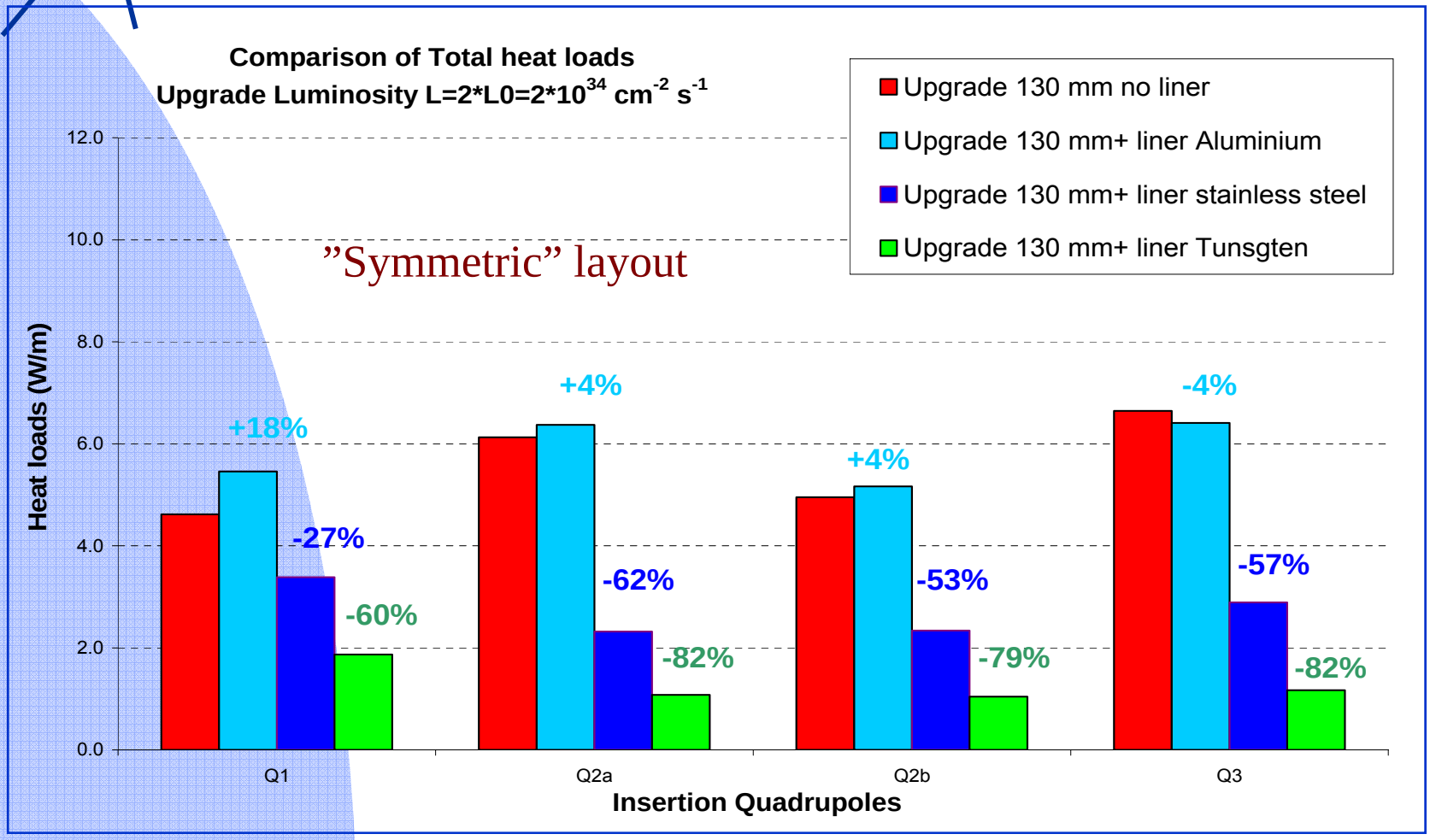
**Elena Wildner: "Heat deposition and backscattering for one of the configurations of the IR for LHC upgrade",**
**Internal Note CERN/AT/MCS/ Mars 2007**

# Peaks, with liner



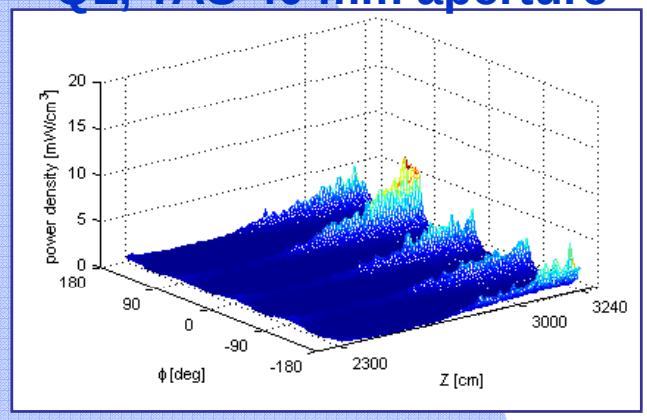

- **2 cm Liner**
- in **Aluminium**
  - -71% decrease of the peak
  - 21.5 mW/cm$^3$ to 6.1 mW/cm$^3$
- in **Stainless steel**
  - -95% decrease of the peak
  - 21.5 mW/cm$^3$ to 1.1 mW/cm$^3$
- in **Tunsgten**
  - -99% decrease of the peak
  - 21.5 mW/cm$^3$ to 0.2 mW/cm$^3$

# Total, with liner

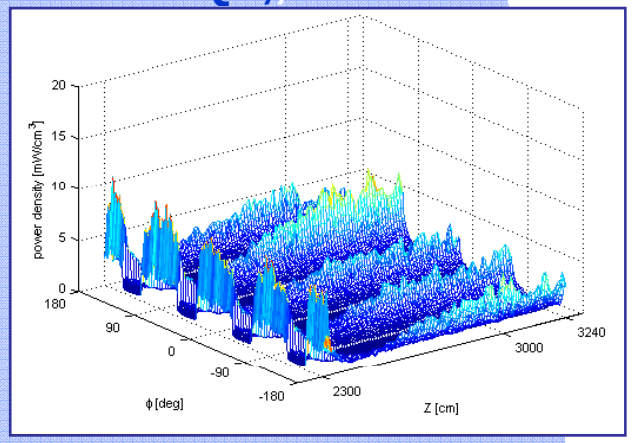


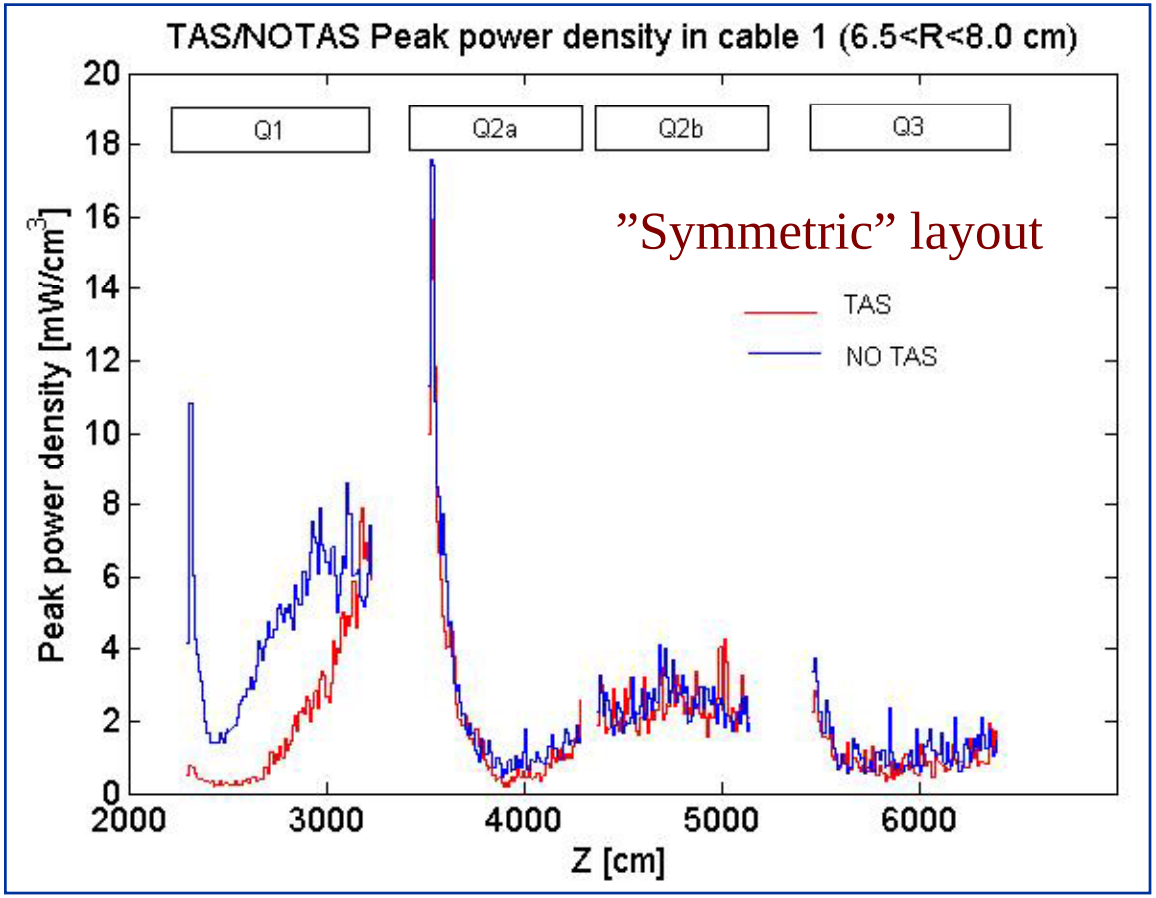
# TAS/ noTAS

**Q1, TAS 40 mm aperture**

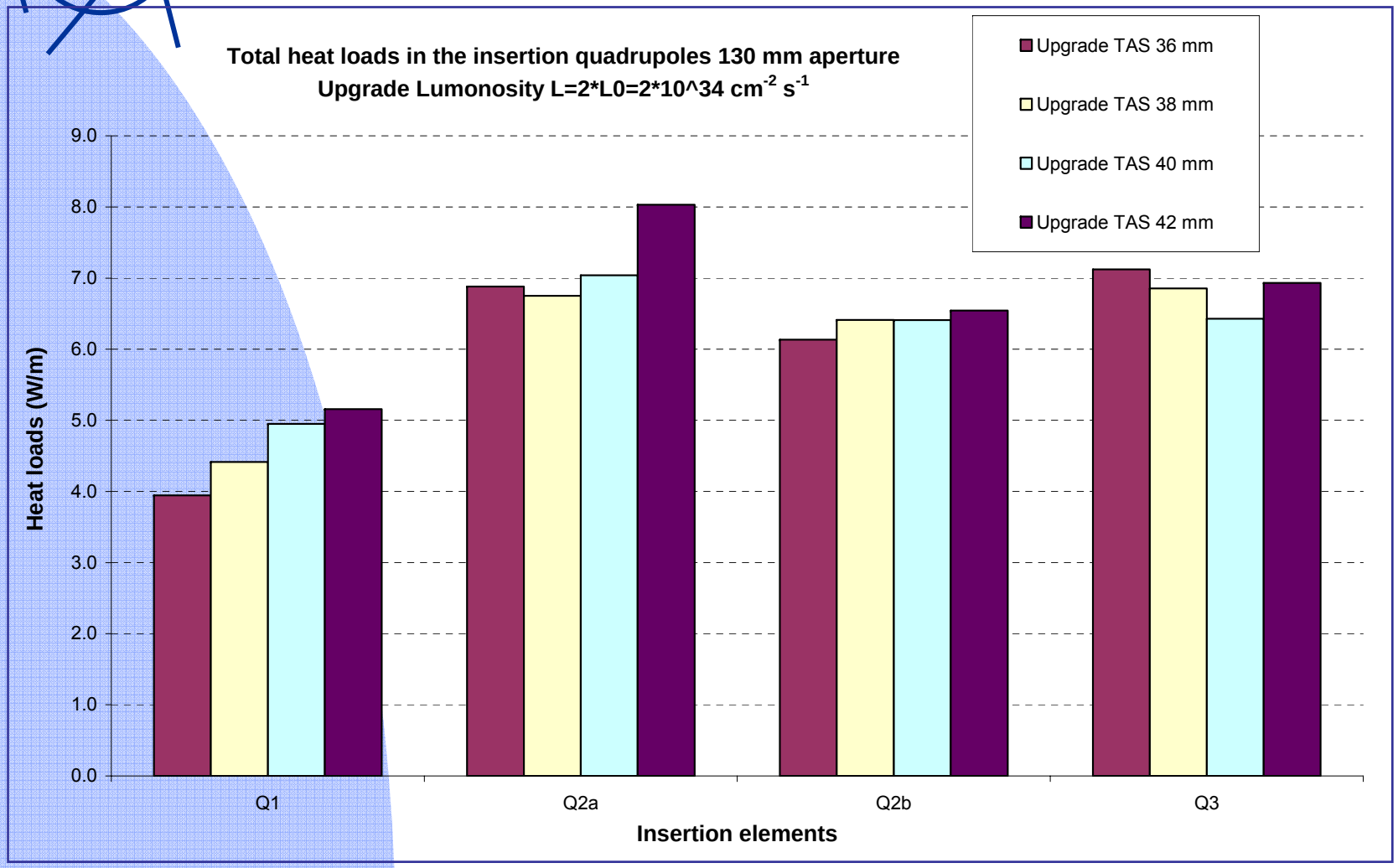



**Q1,, no TAS**

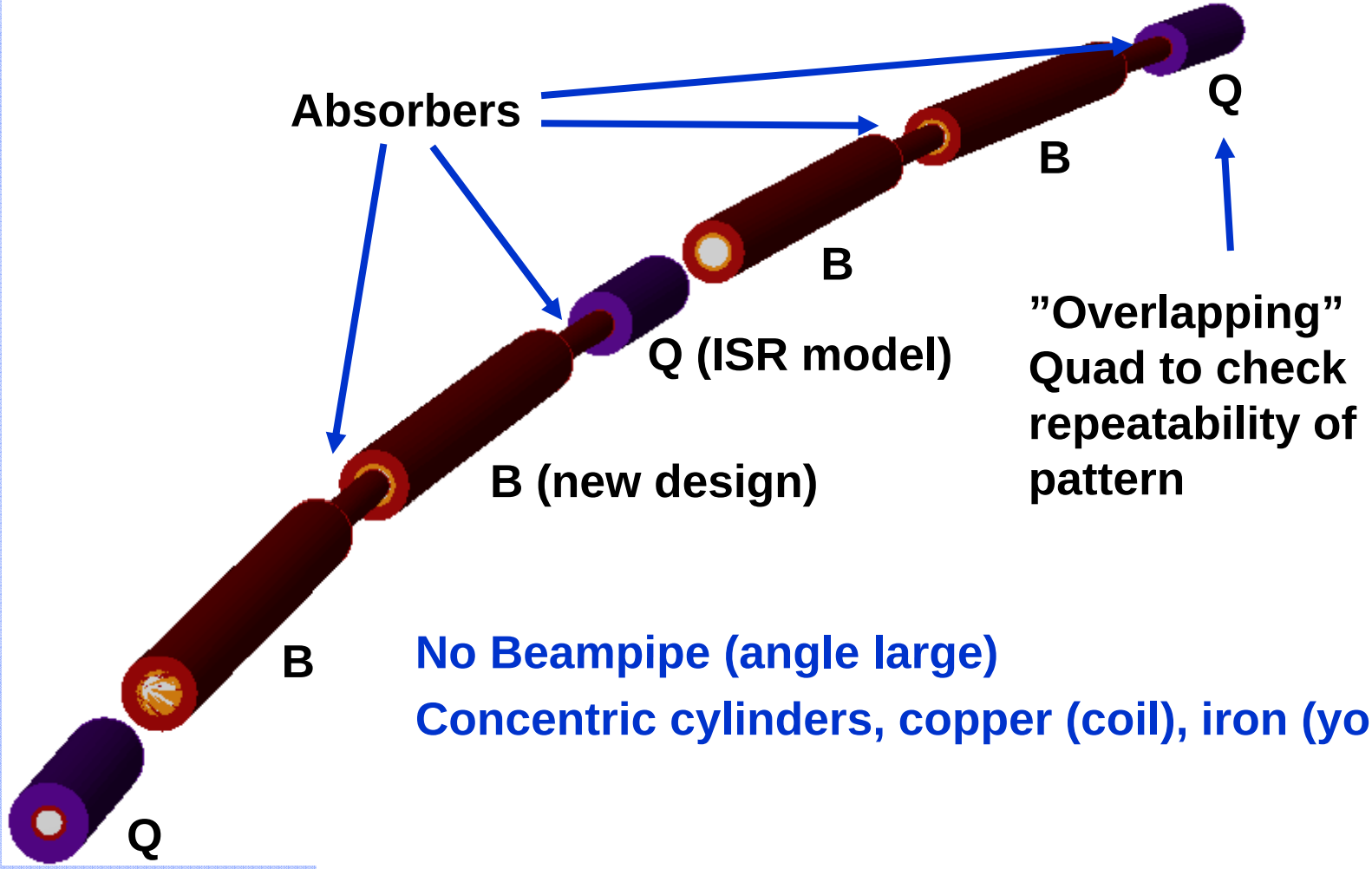


# Variation of TAS aperture



# Heat deposition model: one arc of an accelerator

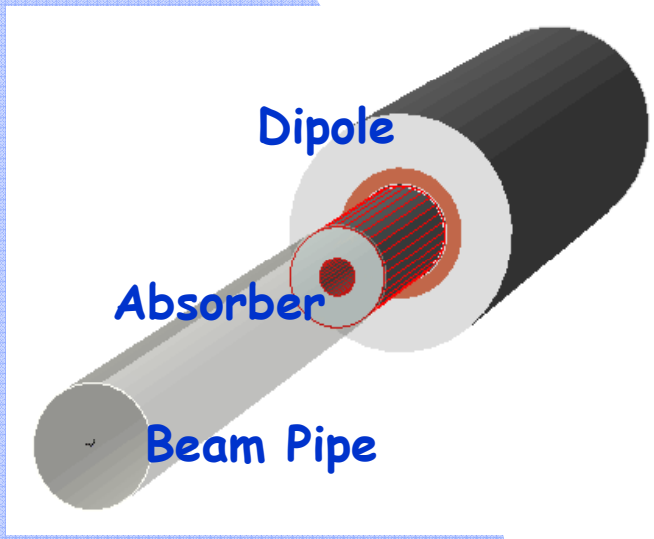



”Overlapping” Quad to check repeatability of pattern

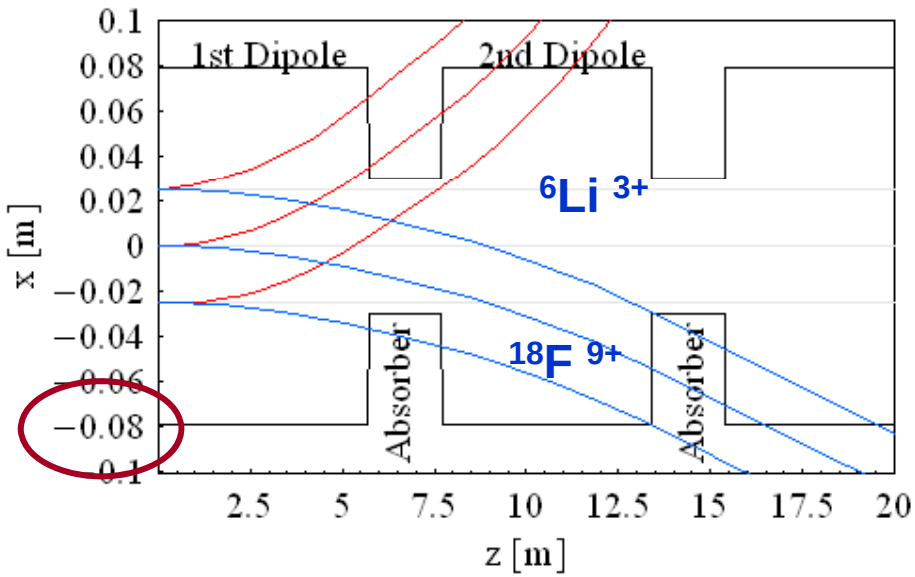
No Beampipe (angle large)

Concentric cylinders, copper (coil), iron (yoke)

# Simple model of magnet




Field always very important for heat deposition:
described either by field map or analytically

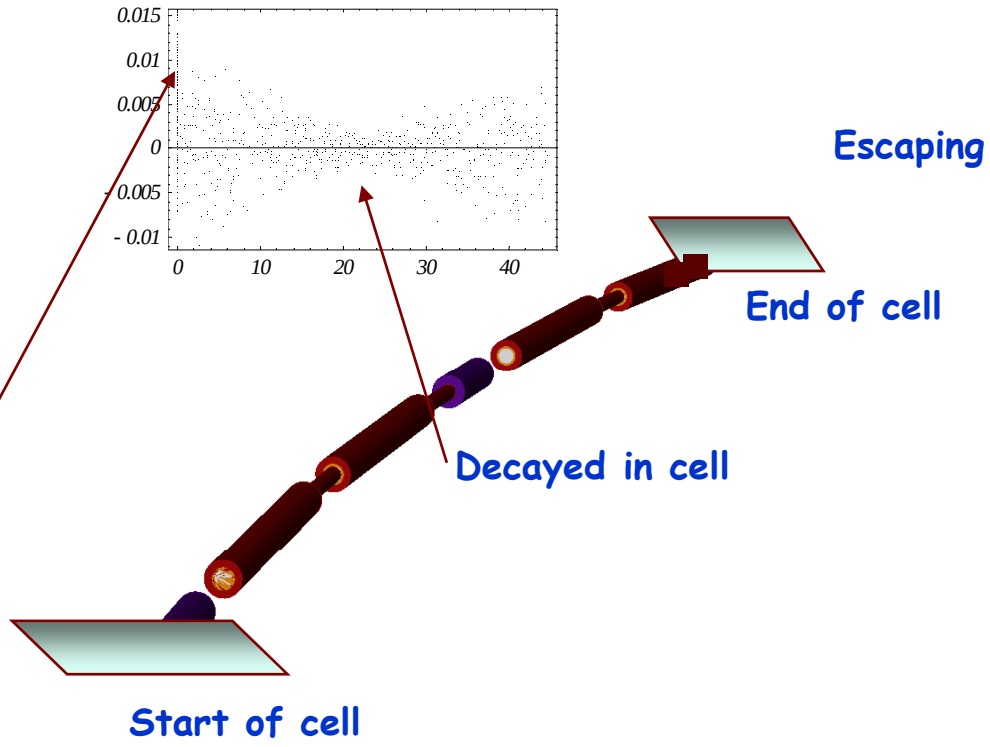


# Particle generation and treatment Beamcode and FLUKA together

1. Beamcode tracks 6Li and 18F particle ***decaying in the ring*** up to cell entry

2. beamcode gives coordinates and momentum vectors of particles ***just decayed*** in cell

3. Particles ***escaping the vacuum pipe*** are treated by Fluka



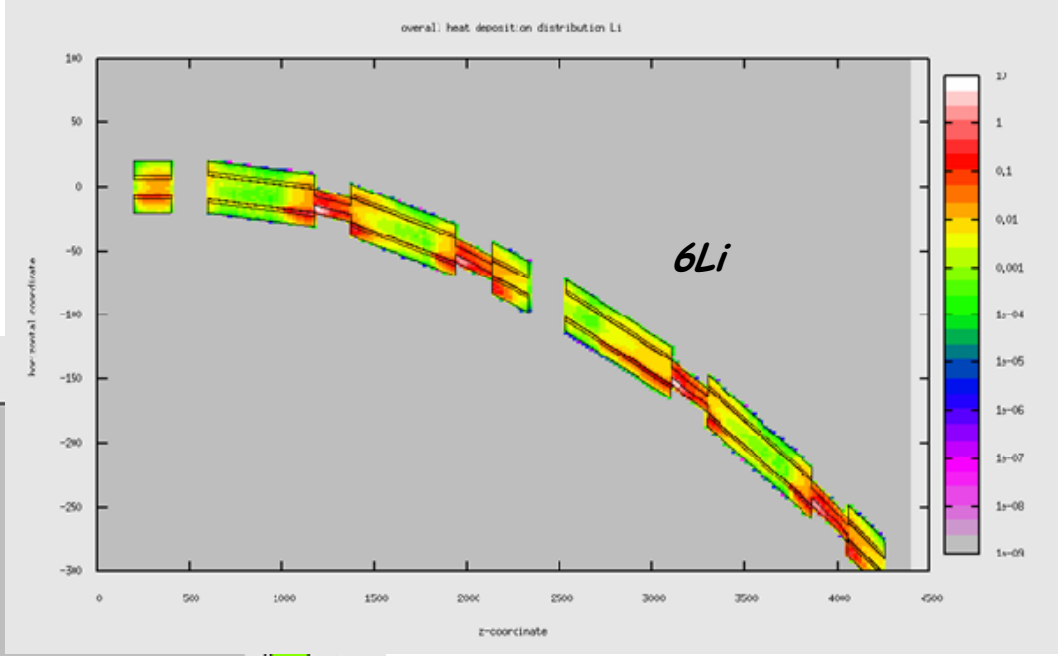

**Decayed in machine with absorbers inserted in the beamcode**

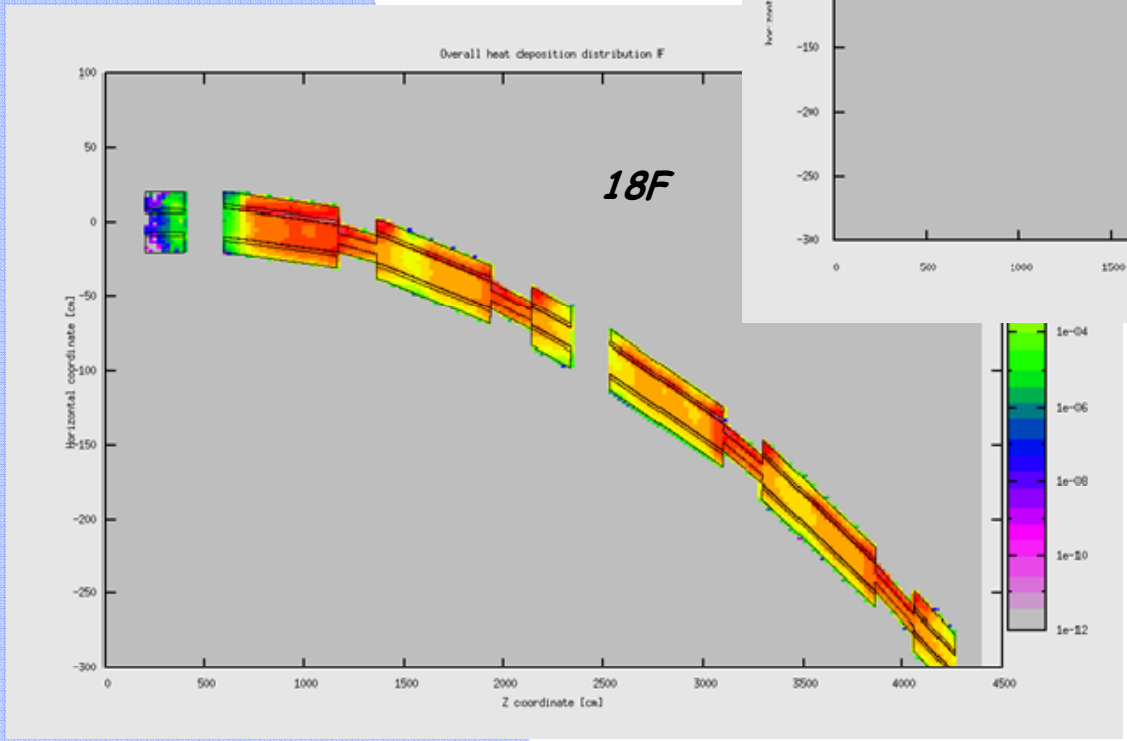
# Example: Overall Power Deposition

**Normalized to a decay rate in cell:**

**He: 5.37 $10^9$ decays/s**

**Ne: 1.99 $10^9$ decays/s**




**Compare to technical limits (10W/m)**

- **not exceeding for either ion**

# Courtesy

More: Interaction of particles and matter
http://www.whfreeman.com/modphysics/PDF/12-2c.pdf