BEAM LOSS CONSEQUENCES

Francesco Cerutti

The CERN Accelerator School

on Vacuum for Particle Accelerators

Glumslov, Sweden June 2017

BEAM LOSSES

- *on beam intercepting devices (targets, collimators, dumps, stoppers, stripping foils, …)*
  - *regular*
  - *accidental: smearing failures, injection mis-steering, asynchronous beam dump, top-off*

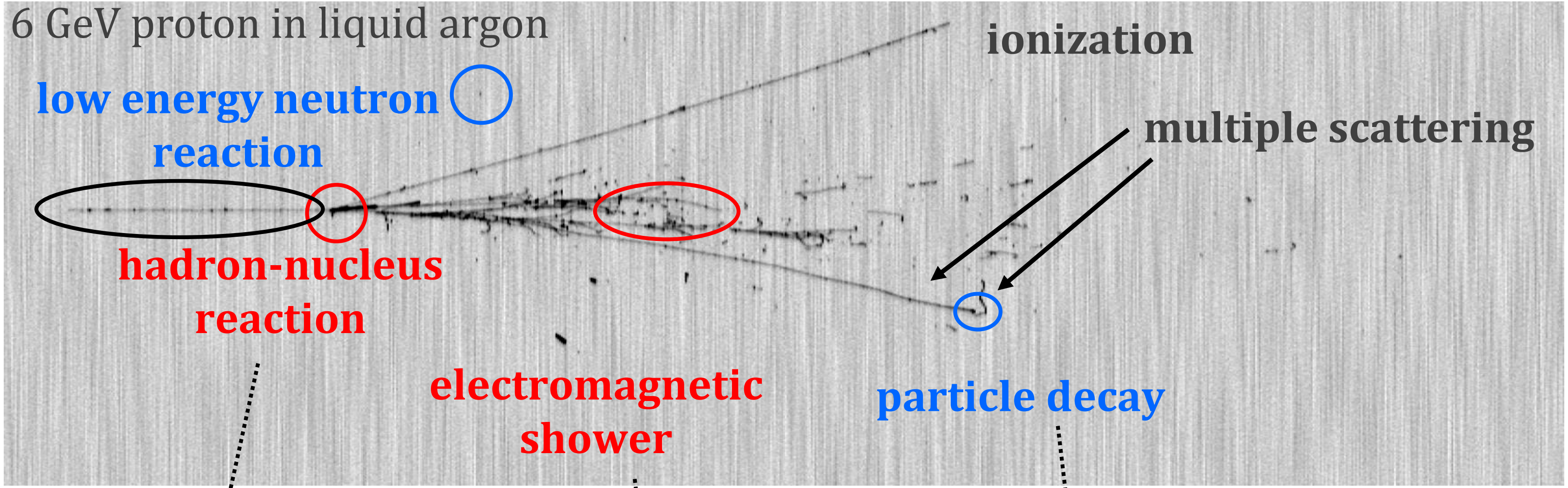
- *diffused*
  - *synchrotron radiation, beam-gas interaction, gas bremsstrahlung*

- *debris from regular collisions at the interaction points*

- *on unexpected obstacles (UFO, ULO, …)*

INTERACTION WITH (ACCELERATOR) MATERIAL:

the microscopic view


6 GeV proton in liquid argon

ionization

low energy neutron reaction

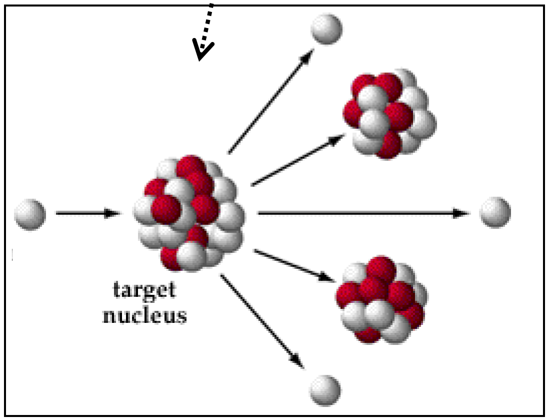
multiple scattering

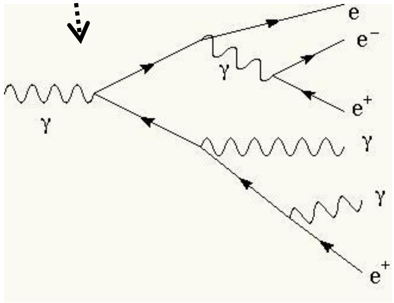
hadron-nucleus reaction

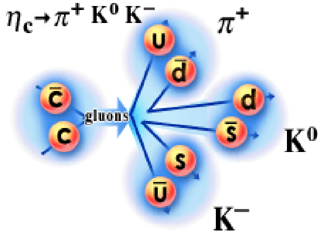
electromagnetic shower

particle decay

interplay of many physical processes described by different theories/models



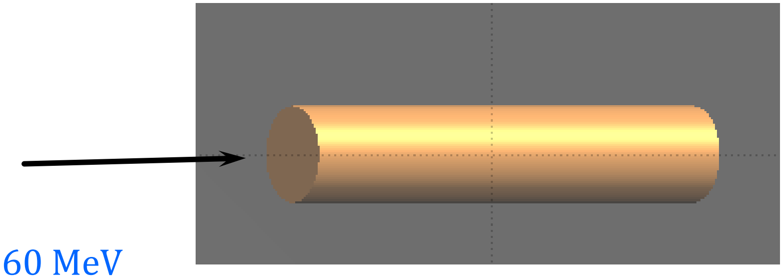




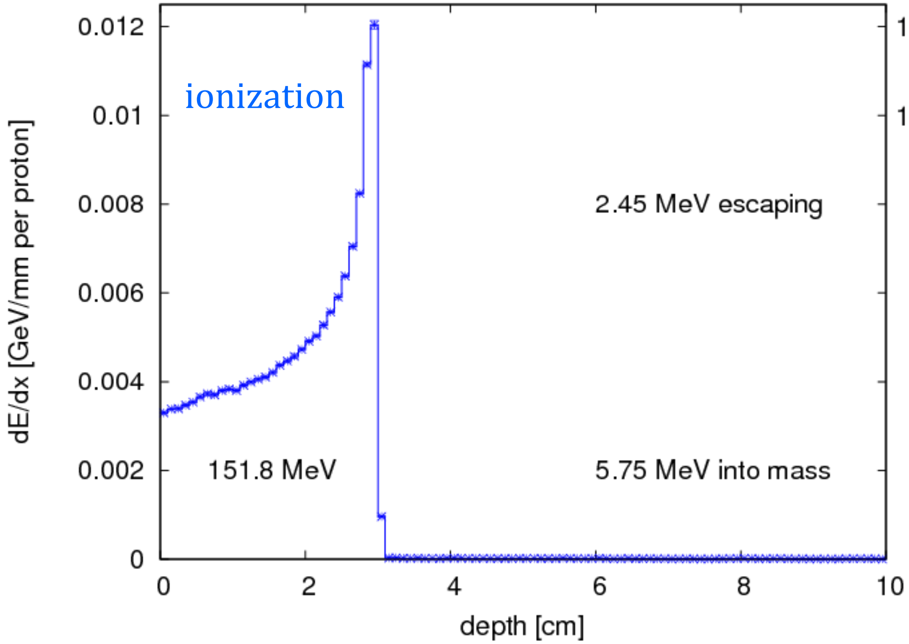
INTERACTION WITH ACCELERATOR MATERIAL:

the macroscopic view

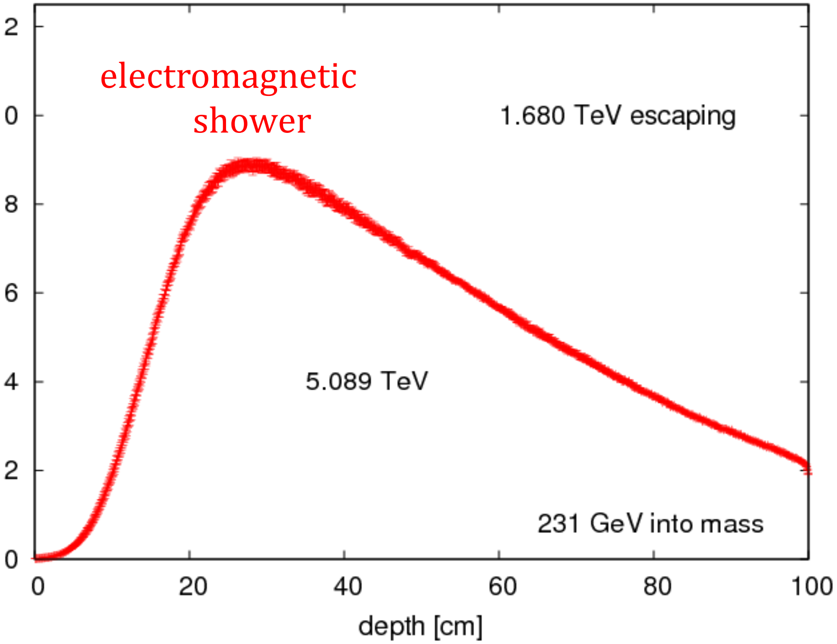
LINAC4 and LHC proton beam on a 1 m long and 10 cm radius copper rod



160 MeV



7 TeV



CONSEQUENCES

	relevant macroscopic quantity
Heating	energy deposition (integral power)
Thermal shock	energy deposition (power density)
Quenching	energy deposition (power density)
Deterioration	energy deposition (dose), particle fluence, DPA
Oxidation, radiolysis, ozone production	energy deposition
Gas production	residual nuclei production
Single event effects in electronic devices	high energy hadron fluence [+ neutron fluence, energy deposition (dose)]
Shielding requirements	particle fluence (*prompt* dose equivalent)
Access limitations, radioactive waste, air activation	*residual* dose rate and activity
Beam Loss Monitors (BLM)	energy deposition
Radiation Monitors (RadMon)	thermal neutron and high energy hadron fluence

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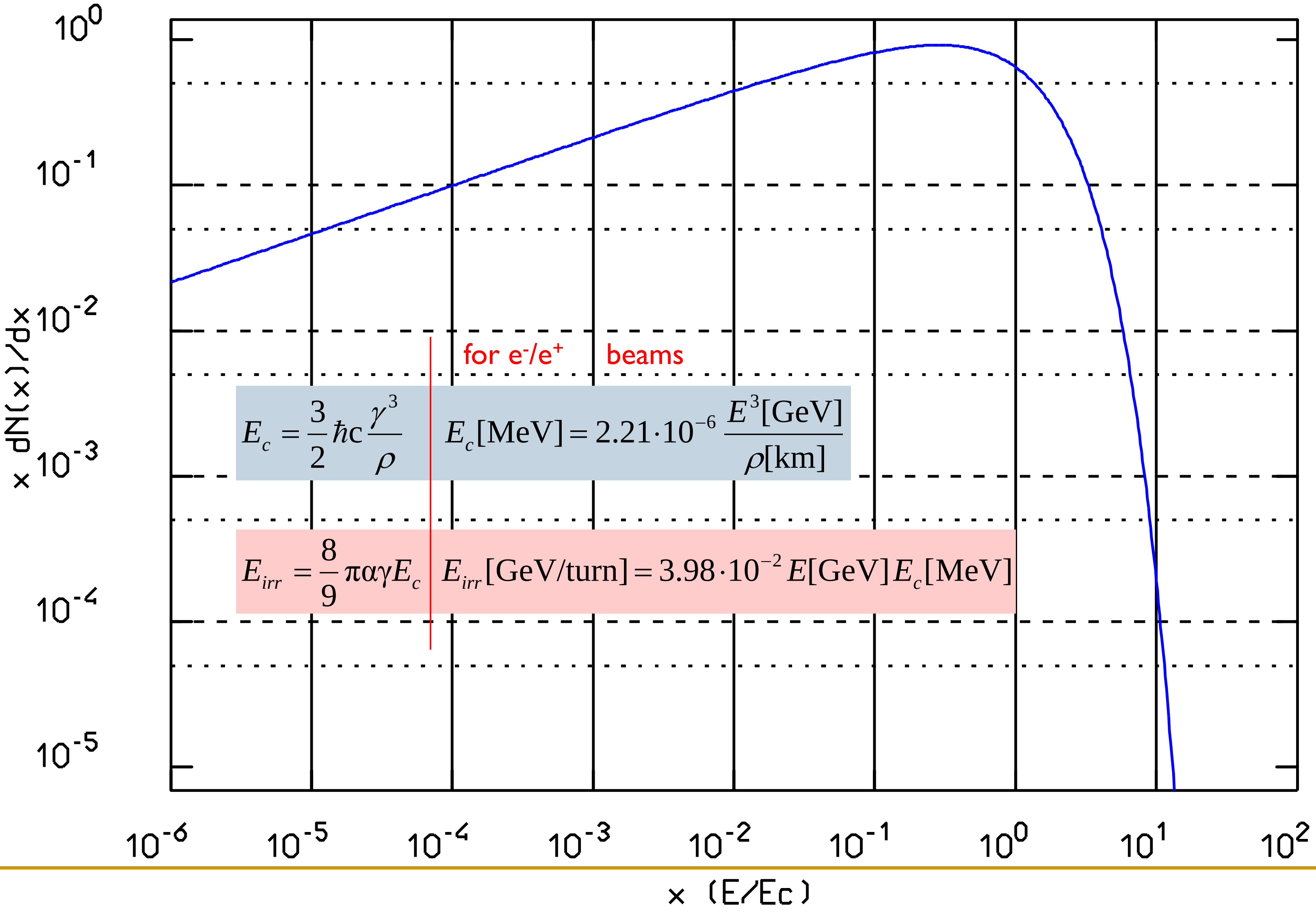
Tumor cell destruction	energy deposition (dose, biological dose)

SYNCHR. RAD. : THE UNIVERSAL SPECTRUM

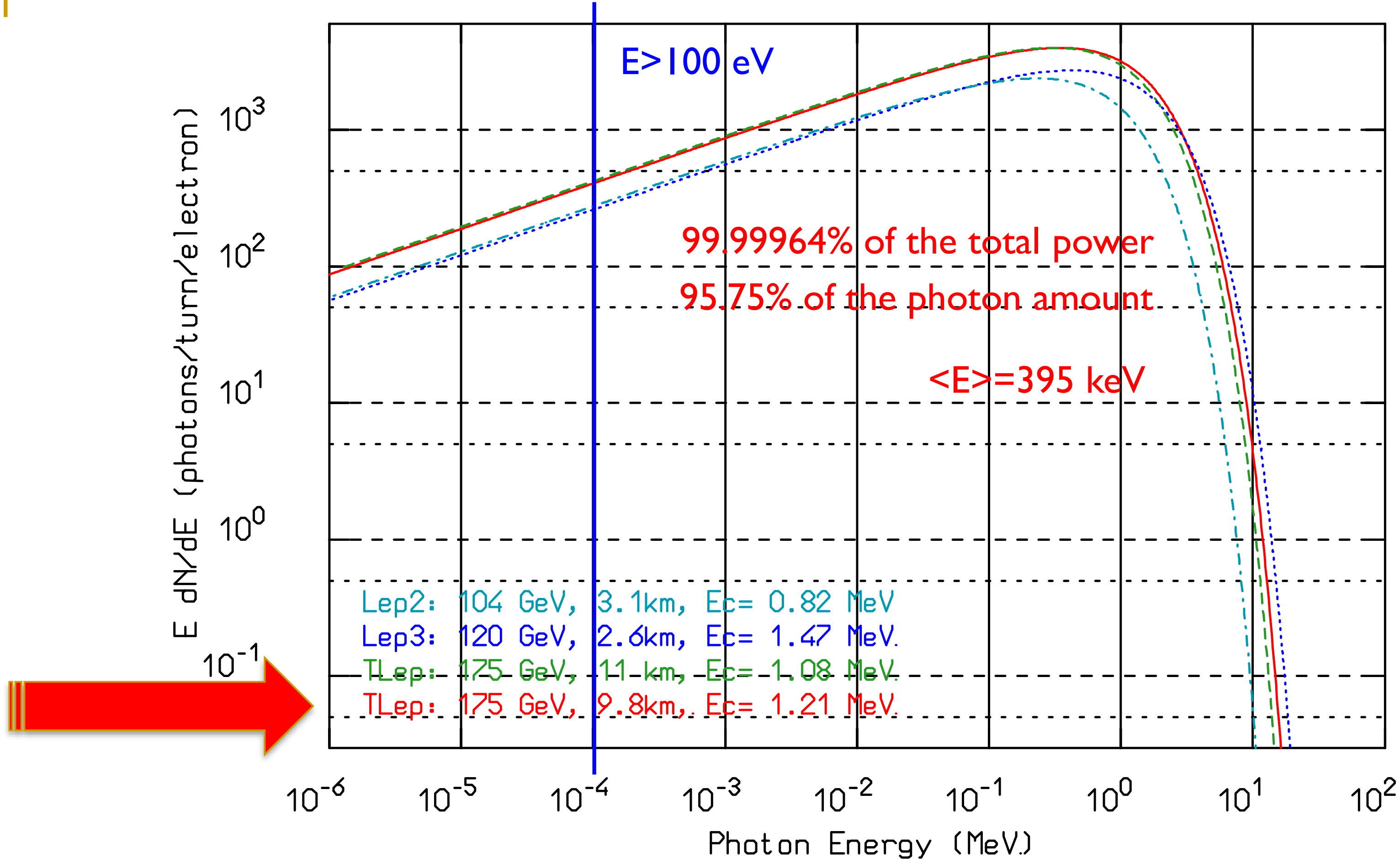


for e^-/e^+ beams

$$E_c = \frac{3}{2}\hbar c\frac{\gamma^3}{\rho} \qquad E_c[\text{MeV}] = 2.21\cdot 10^{-6}\,\frac{E^3[\text{GeV}]}{\rho[\text{km}]}$$

$$E_{irr} = \frac{8}{9}\pi\alpha\gamma E_c \qquad E_{irr}[\text{GeV/turn}] = 3.98\cdot 10^{-2}\,E[\text{GeV}]\,E_c[\text{MeV}]$$

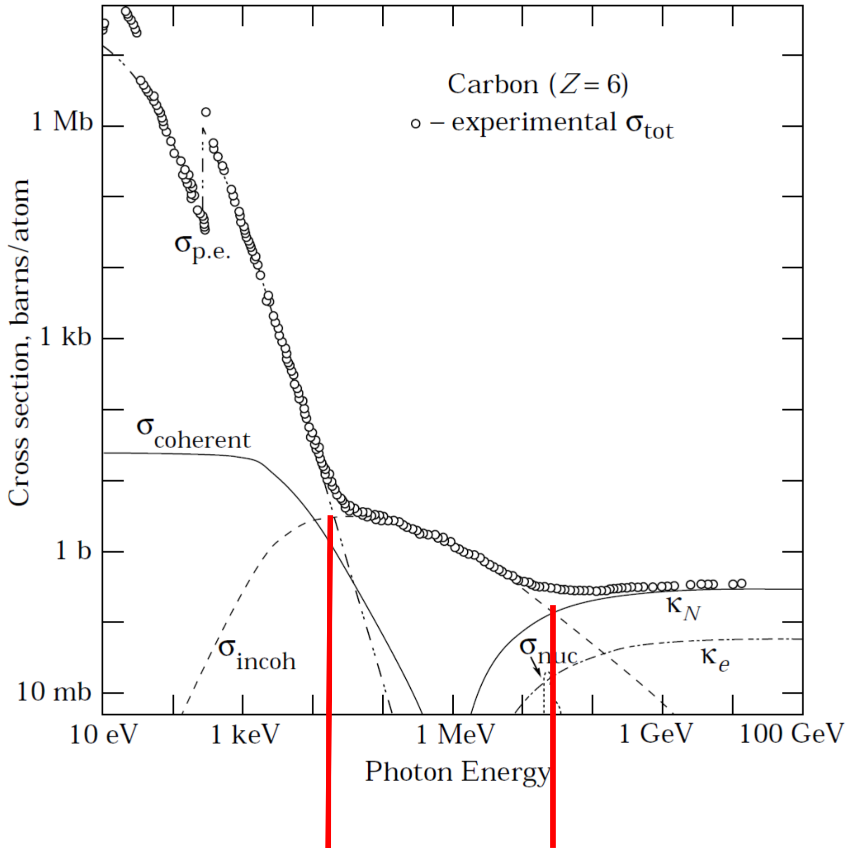
SYNCHR. RAD. : LEPTON RINGS

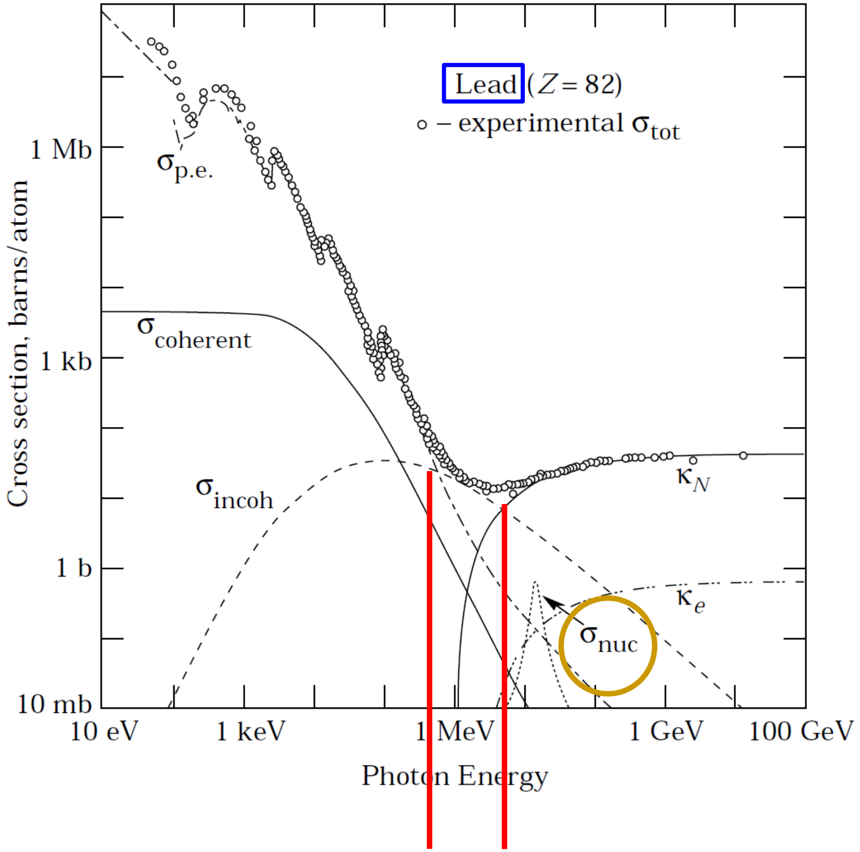


- ΔE= 8.5 GeV/turn (dE/ds=1.375 keV/cm in the dipoles)
- P = 8.5 x I[mA] MW = 8.5 x <u>10mA</u> = 85 MW in the whole accelerator

  (dP/ds= 1.375 x I[mA] W/cm in the dipoles)

PHOTON INTERACTIONS





Photoelectric dominated

Compton dominated

Pair dominated

Photoelectric dominated

Compton dominated

Pair dominated

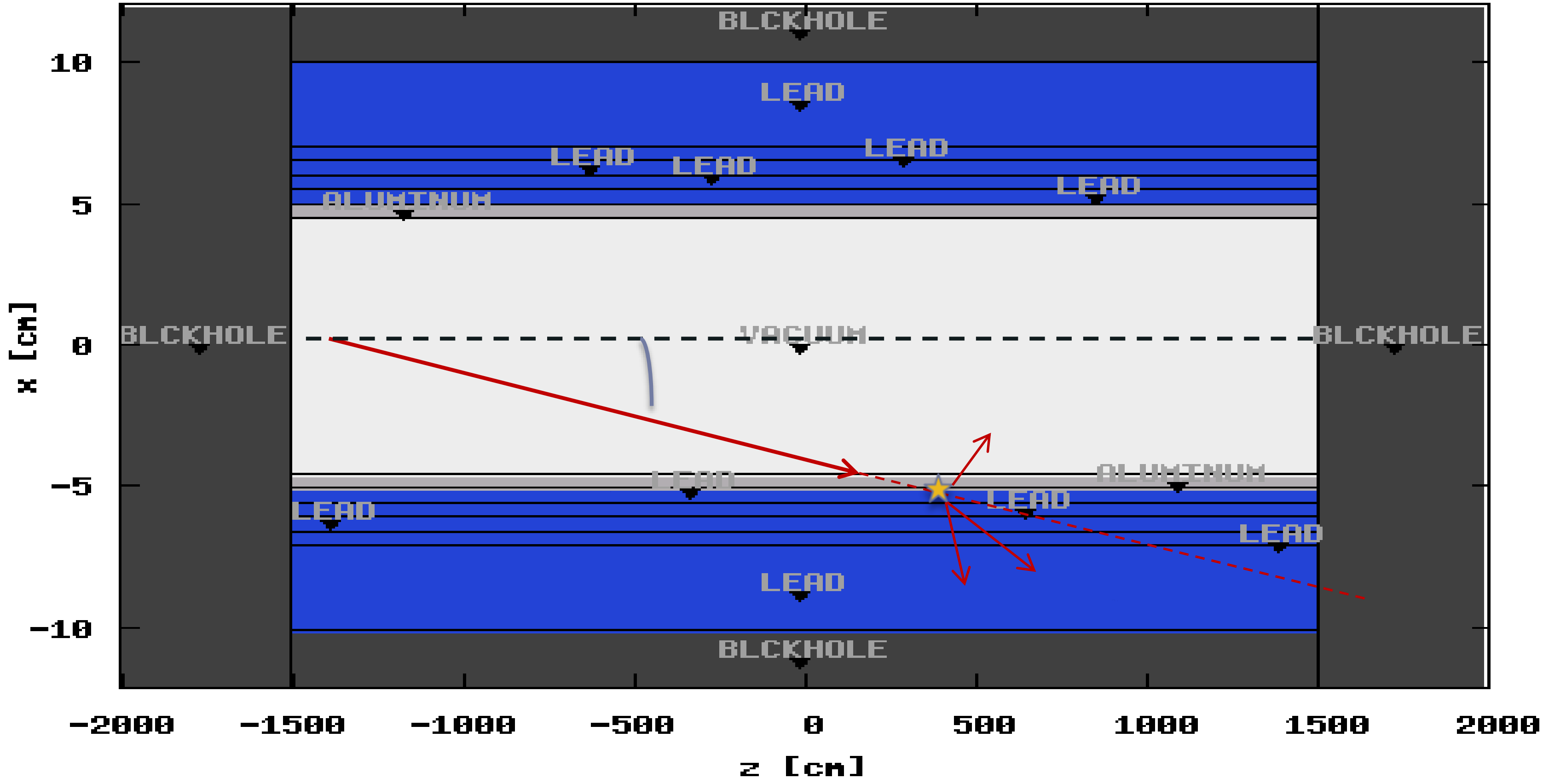
$\Sigma \propto \rho Z^5 / A$ $\Sigma \propto \rho Z / A$ $\Sigma \propto \rho Z^2 / A$

ESCAPING THE VACUUM CHAMBER

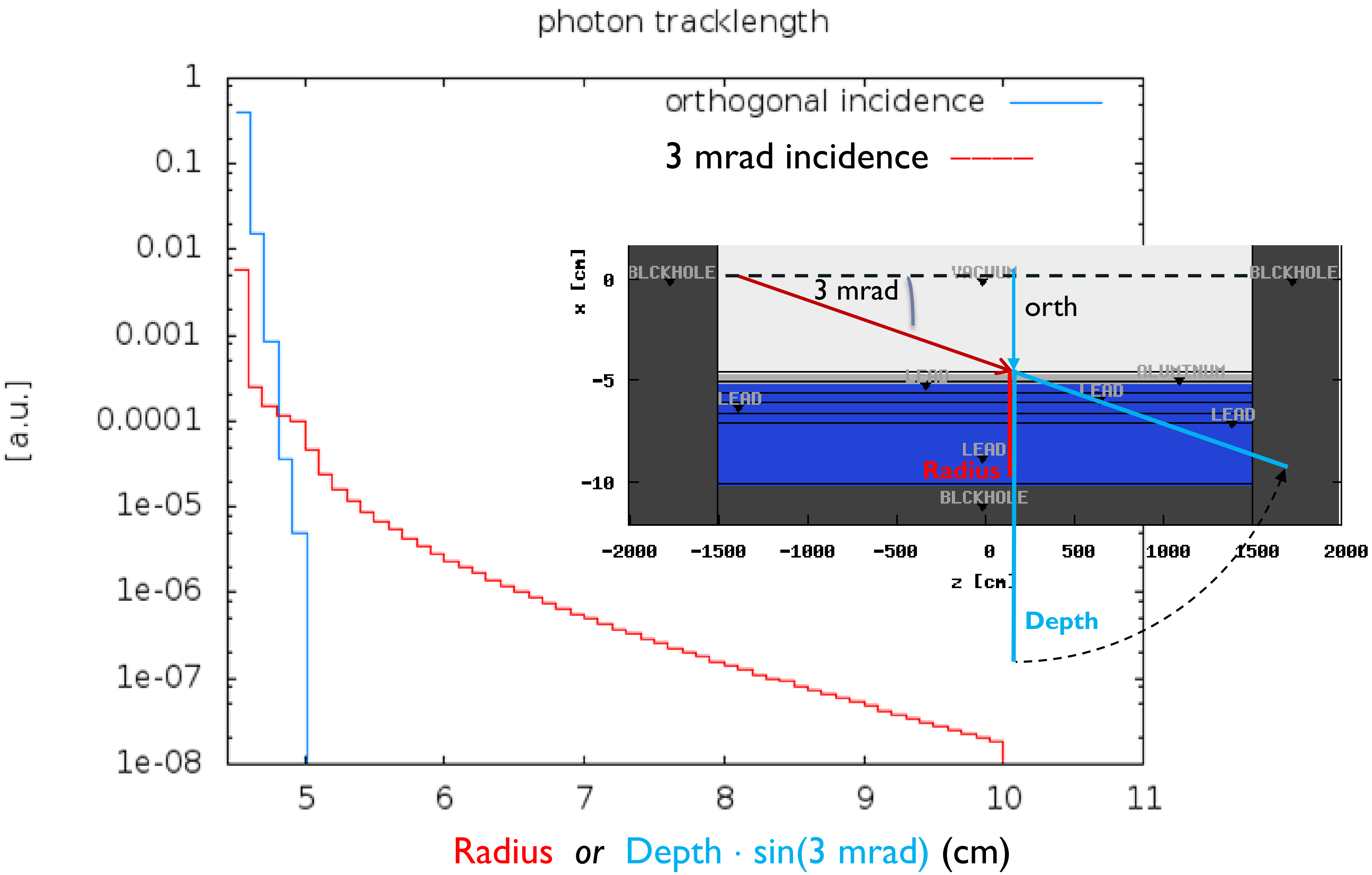
After a Compton interaction
the photon loses "memory" of the initial grazing incidence
because of the much larger scattering angle

9 km radius
E_c = 1.32 MeV

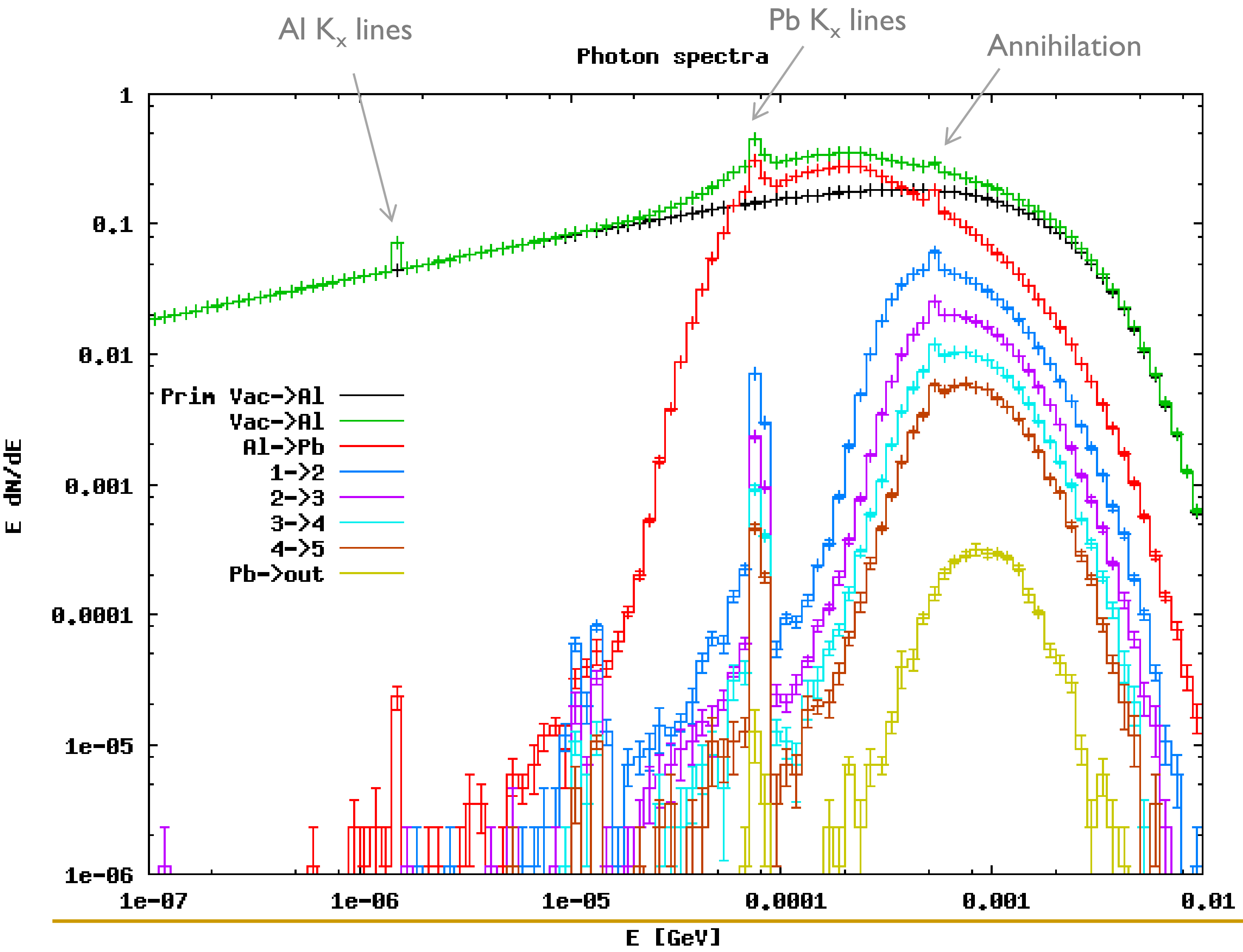
top view



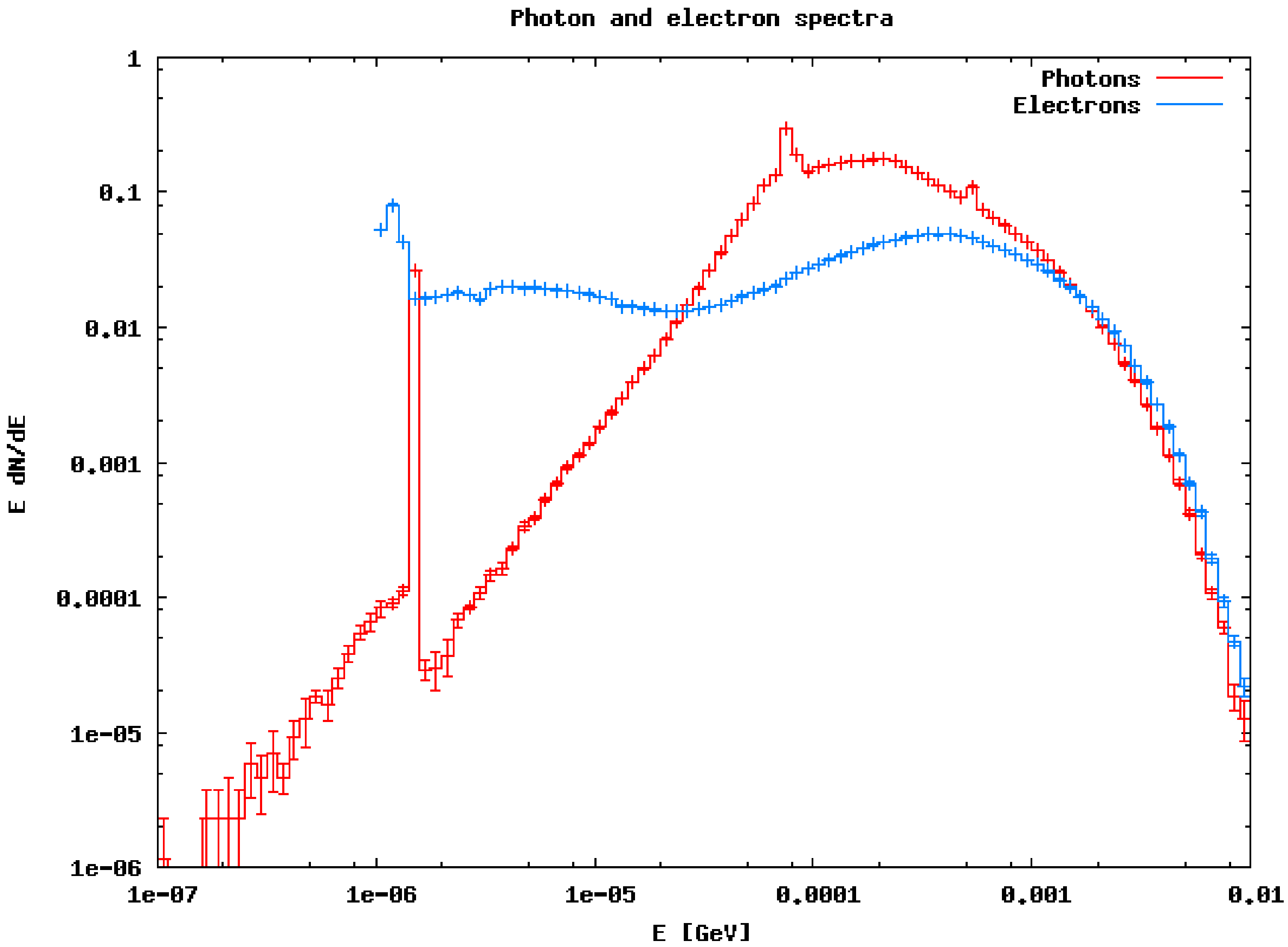
PENETRATION EFFECT



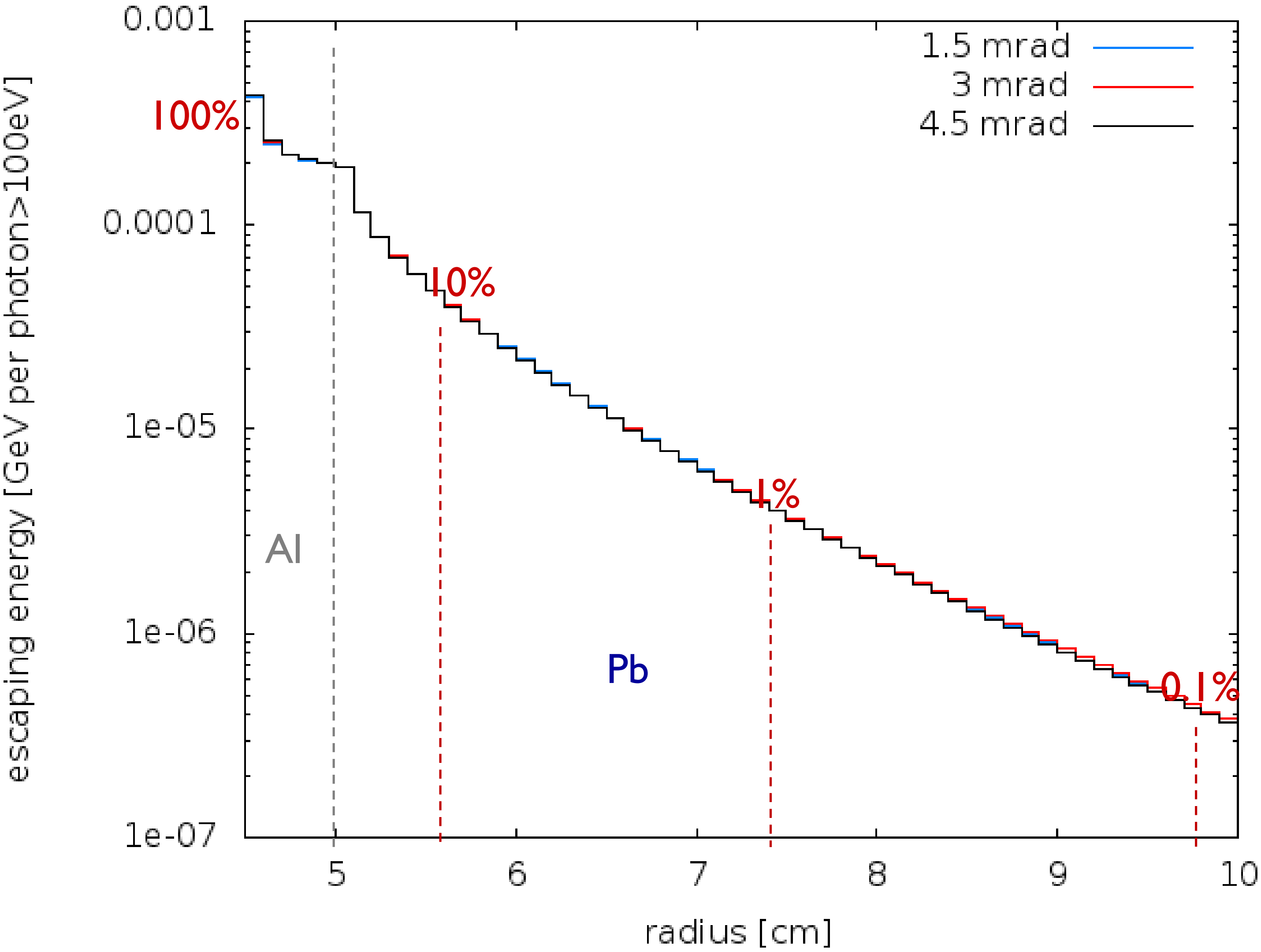
SPECTRUM EVOLUTION



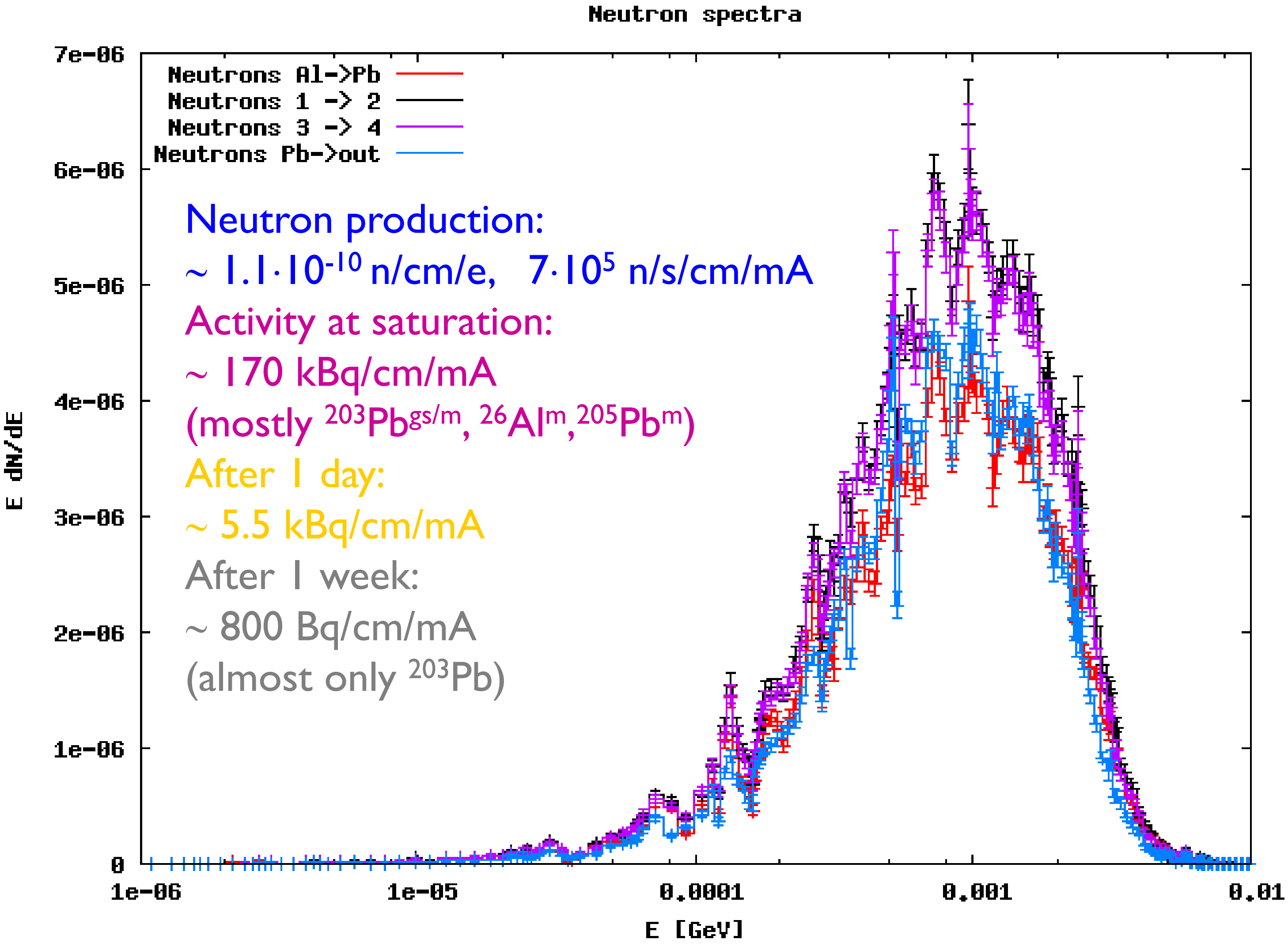
REFLECTION INTO VACUUM



ESCAPING POWER



NEUTRON PRODUCTION AND ACTIVATION



Neutron production:

~ $1.1 \cdot 10^{-10}$ n/cm/e, $7 \cdot 10^{5}$ n/s/cm/mA

Activity at saturation:

~ 170 kBq/cm/mA

(mostly ^{203}Pb$^{gs/m}$, ^{26}Al^{m},^{205}Pb^{m})

After 1 day:

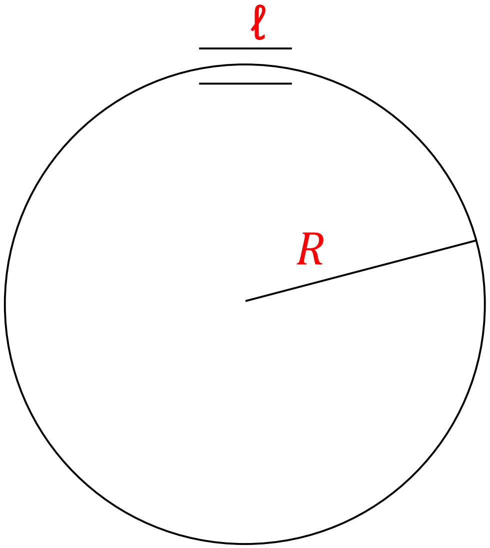
~ 5.5 kBq/cm/mA

After 1 week:

~ 800 Bq/cm/mA

(almost only ^{203}Pb)

SYNCHROTRON RADIATION INTERCEPTION



R accelerator bending radius

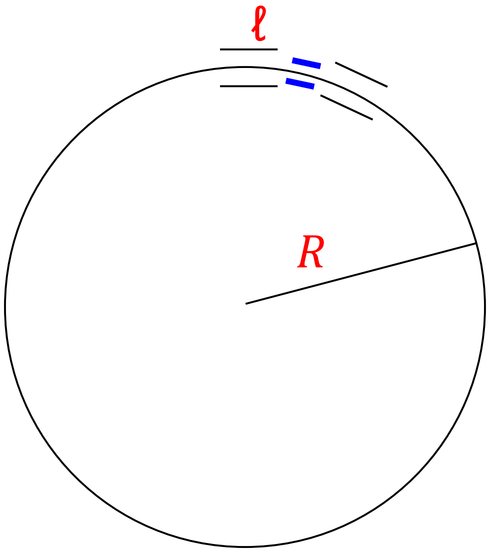
ℓ dipole length

r vacuum chamber radius

inside the same dipole only if $\ell > \sqrt{2\,r\,R}$

for $R = 9$ *km and* $r = 4.5$ *cm* $\ell > 28.5$ *m*

for $R = 3.1$ *km and* $r = 6.5$ *cm (LEP2)* $\ell > 20$ *m*

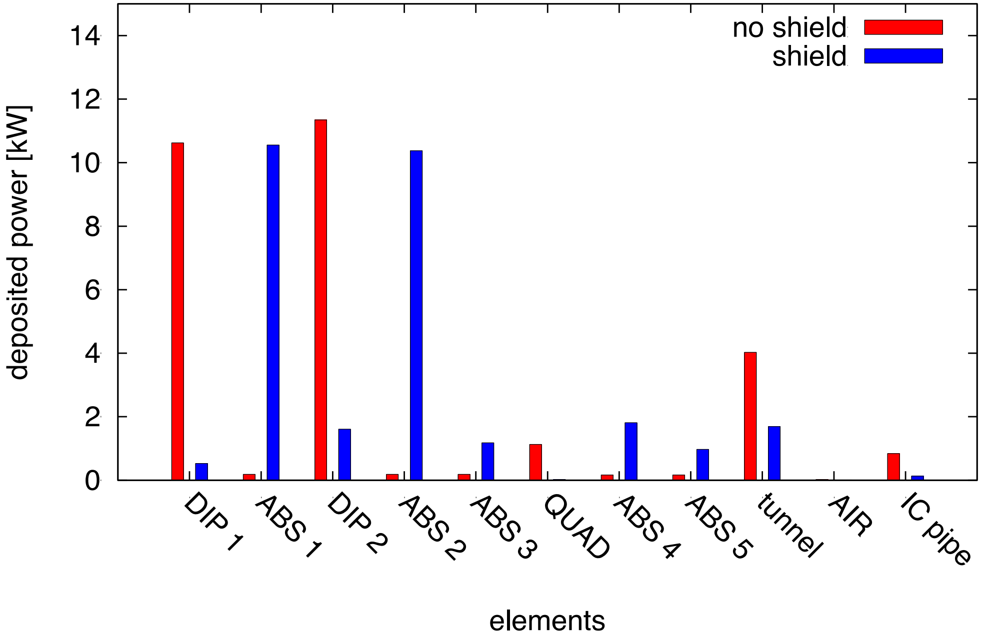


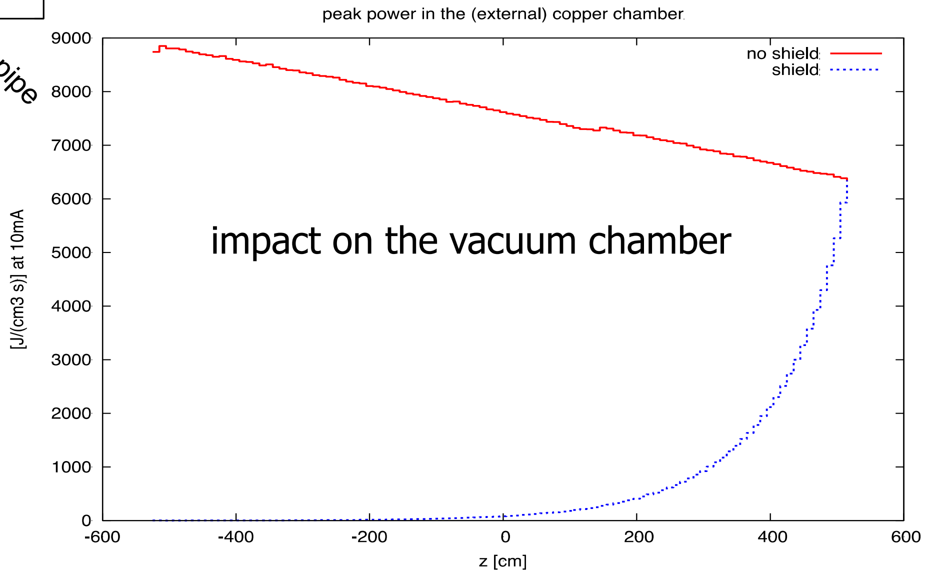
totally escaping for shorter dipoles

shielding in the interconnects ?

CONCENTRATING THE PHOTON ABSORPTION

power sharing

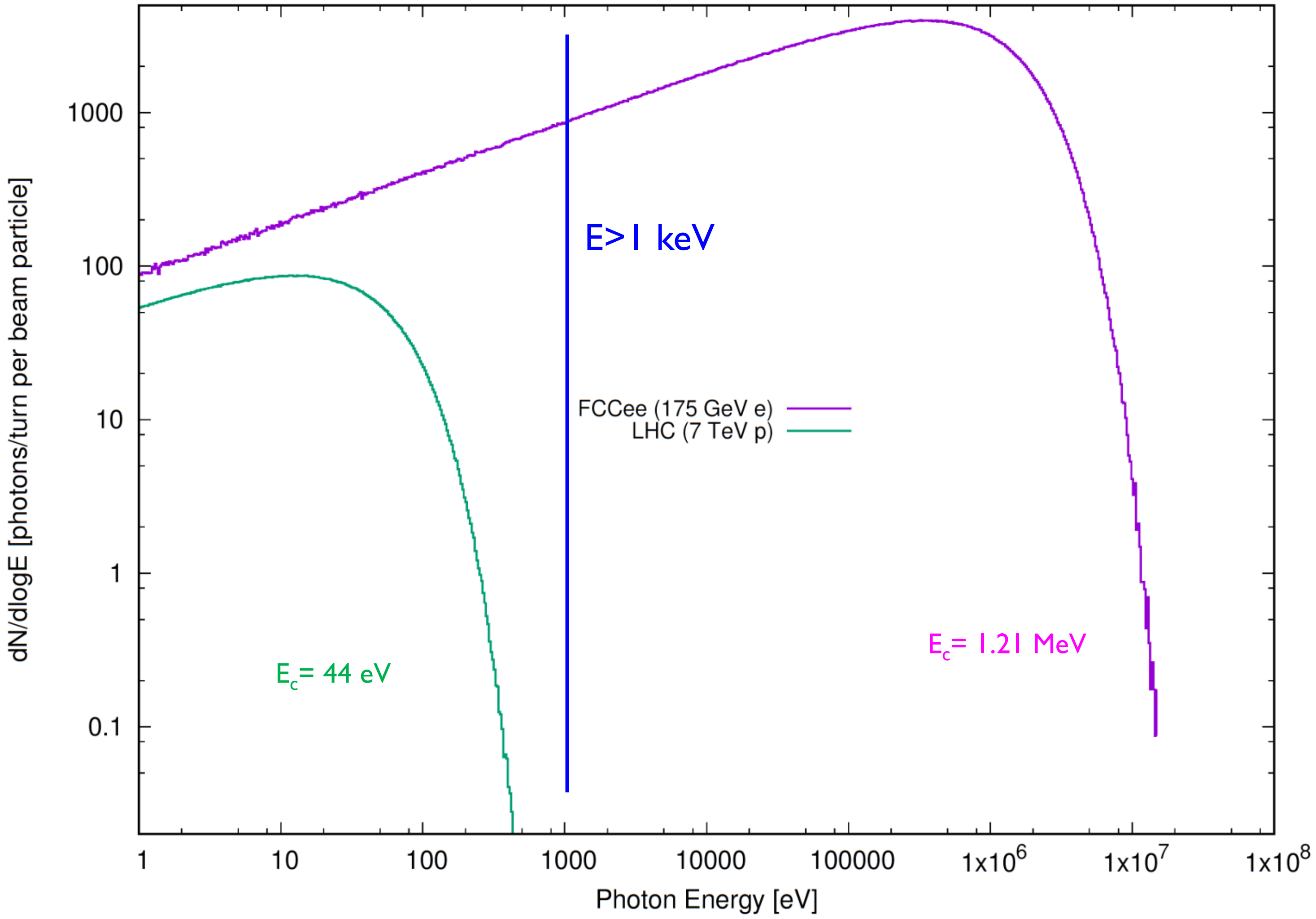




impact on the vacuum chamber

normalized to 10 mA beam current

SYNCHR. RAD. : LEPTON VS HADRON RINGS



BEAM–GAS INTERACTION

- nuclear reaction between the circulating hadron and an atomic nucleus of a gas molecule

σ [m^2] I [s^{-1}] n [m^{-3}] **collision rate** [m^{-1}s^{-1}] 1/(σ [m^2] c [m/s] n [m^{-3}]) **beam lifetime** [s]

LHC (FCChh): 7 (50) TeV **proton** energy σ = *77 (89)* mb 0.58 (0.5) A = 3.6 (3.1) 10^{18} s^{-1} 10^{15} m^{-3} H_2 eq. density

2.8 10^4 m^{-1}s^{-1} **≥ 100 h**

- circulating leptons undergo gas bremsstrahlung, yielding high energy photons,
  ionization, yielding high energy electrons,
  Coulomb scattering, deteriorating beam emittance (up to aperture losses)

NUCLEAR REACTIONS

In general there are two kinds of nuclear reactions:

- **Elastic** interactions are those that **do not change the internal structure** of the projectile/target and **do not produce new particles**. Their effect is to transfer part of the projectile energy to the target (lab system), or equivalently to deflect in opposite directions target and projectile in the Centre-of-Mass system with no change in their energy. There is no threshold for elastic interactions.

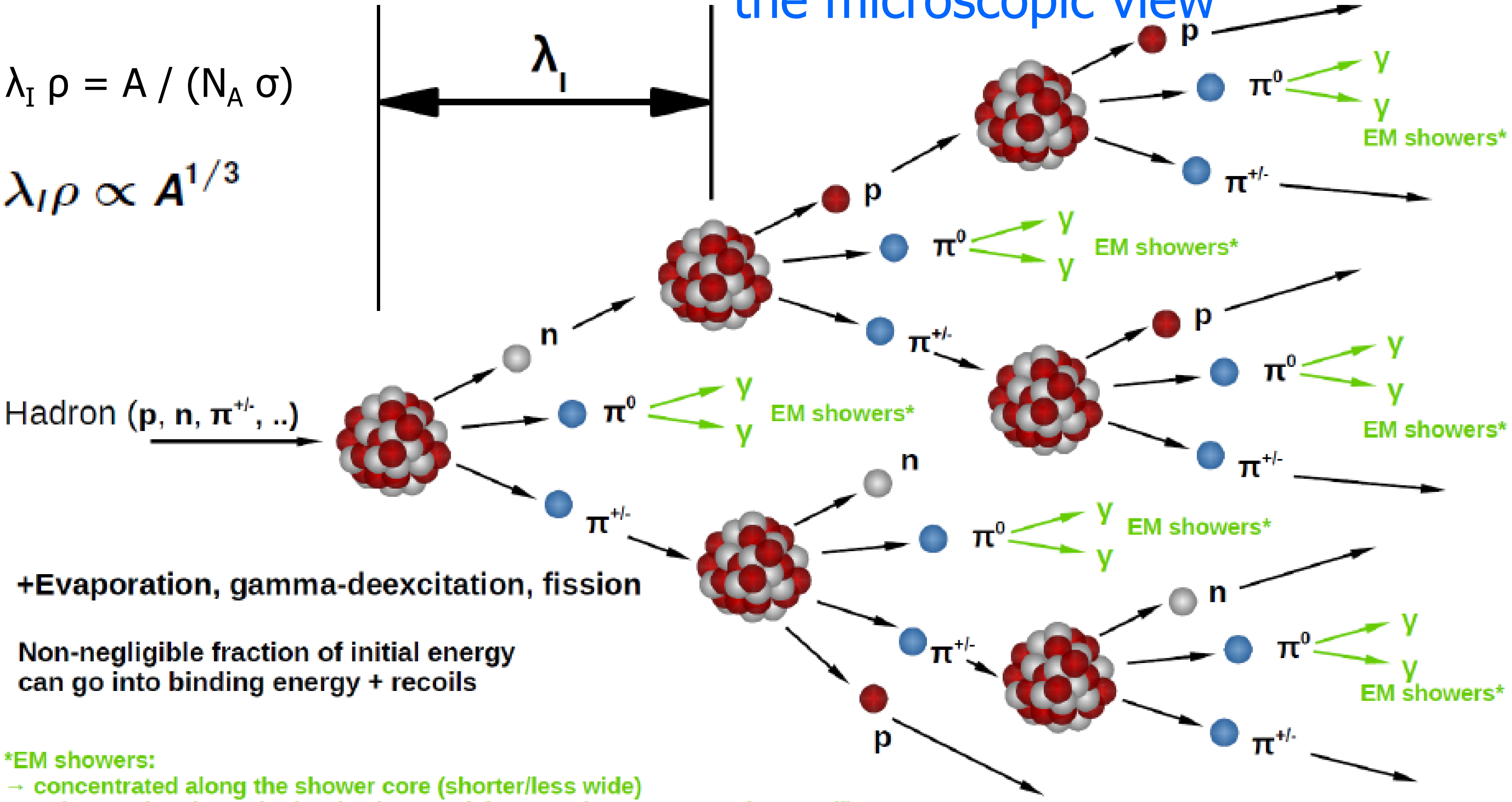
- **Non-elastic** reactions are those where **new particles are produced** and/or the **internal structure** of the projectile/target **is changed** (e.g. exciting a nucleus). A specific non-elastic reaction has usually an energy threshold below which it cannot occur (the exception being neutron capture)

HADRONIC SHOWERS

the microscopic view

$\lambda_I\ \rho = A\ /\ (N_A\ \sigma)$

$\lambda_I \rho \propto A^{1/3}$



+Evaporation, gamma-deexcitation, fission

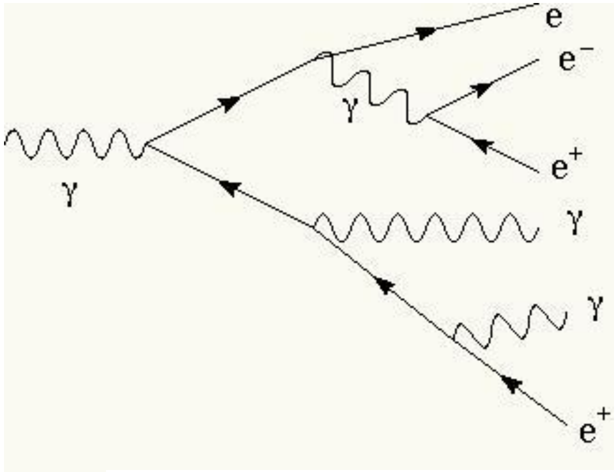
Non-negligible fraction of initial energy can go into binding energy + recoils

*EM showers:
- → concentrated along the shower core (shorter/less wide)
- → ~ do not give rise to hadronic showers (photo-nuclear cross section small)
- → not only π^0 but also other particles like η

roughly continues until particle energy falls below pion production threshold

ELECTROMAGNETIC SHOWERS

the microscopic view



development stops after t_{max} radiation lengths X_0 as energy per particle reaches the critical energy E_c

$$\frac{E_0}{2^{t_{max}}} = E_c$$ hence $$t_{max} \propto \ln\left(\frac{E_0}{E_c}\right)$$

shower depth increases logarithmically with initial energy E_0

radiation length

$$X_0 \rho \simeq \frac{716.4\, g\, cm^{-2}\; A}{Z(Z+1)\log(287/\sqrt{Z})}$$

high energy electrons and photons

$$E_e^{\ell}(x) = E_0\,(1 - \exp(-x/X_0))$$

$$P_{\gamma}^{e^- e^+}(x) = 1 - \exp(-7x/9X_0)$$

Molière radius

$$R_M = X_0 E_s / E_c$$

90% of deposited energy within ~ 1 R_M

$$E_s = 21.2\, MeV$$

$$\boxed{E_c = 800\, MeV/(Z+1.2)}$$

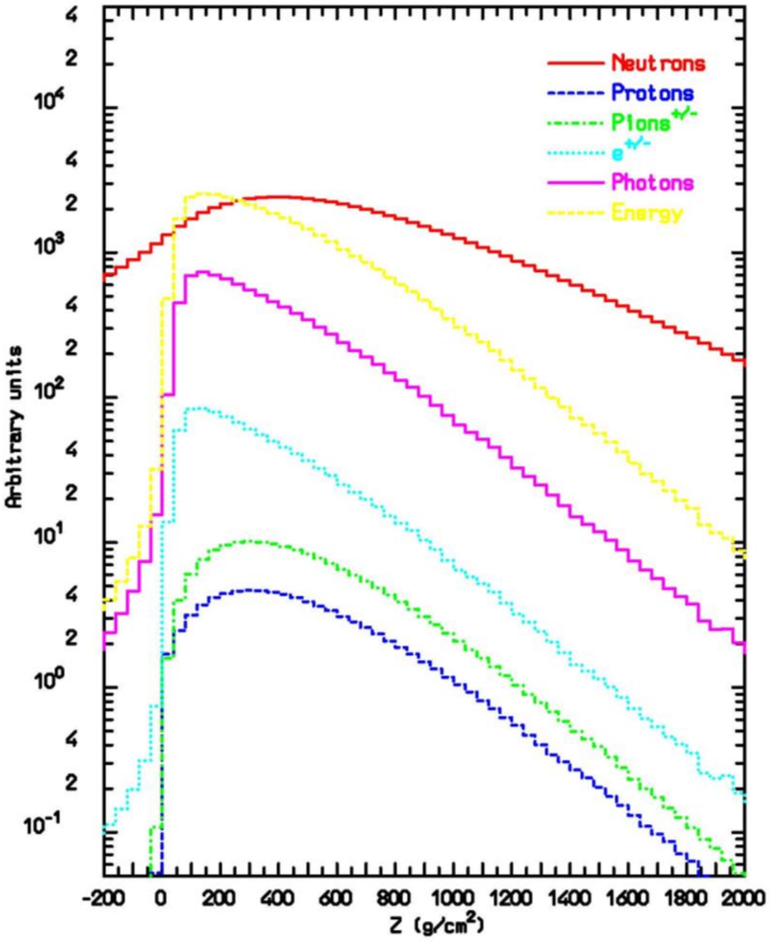
HIGH ENERGY SHOWERS

the macroscopic view

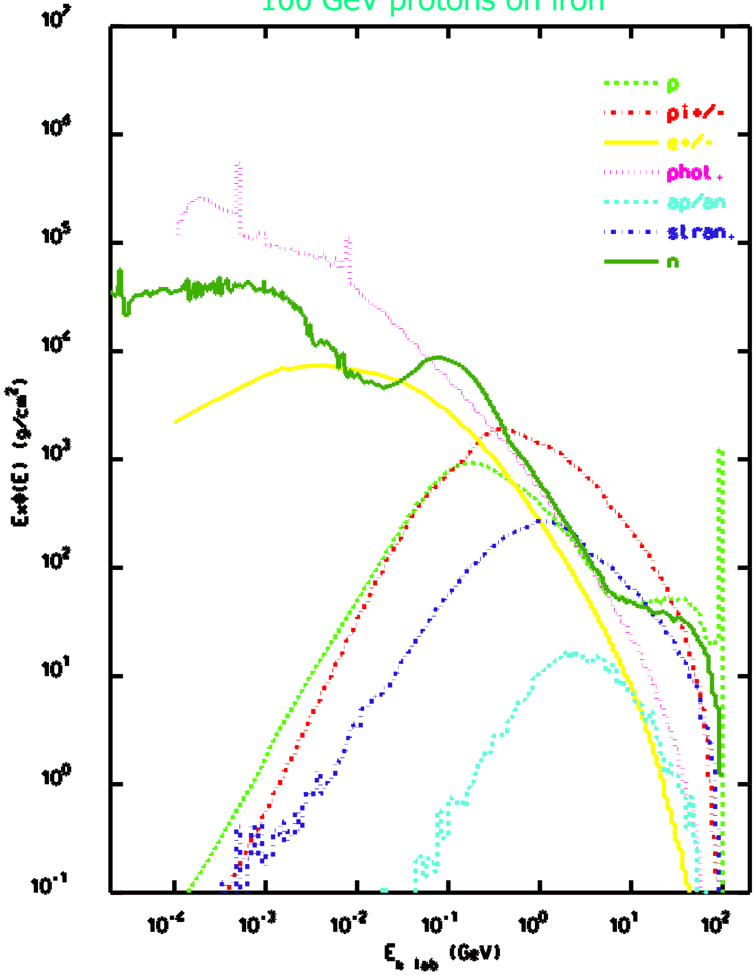
particle fluence and energy deposition profile

volume-averaged particle spectra

100 GeV protons on lead



100 GeV protons on iron



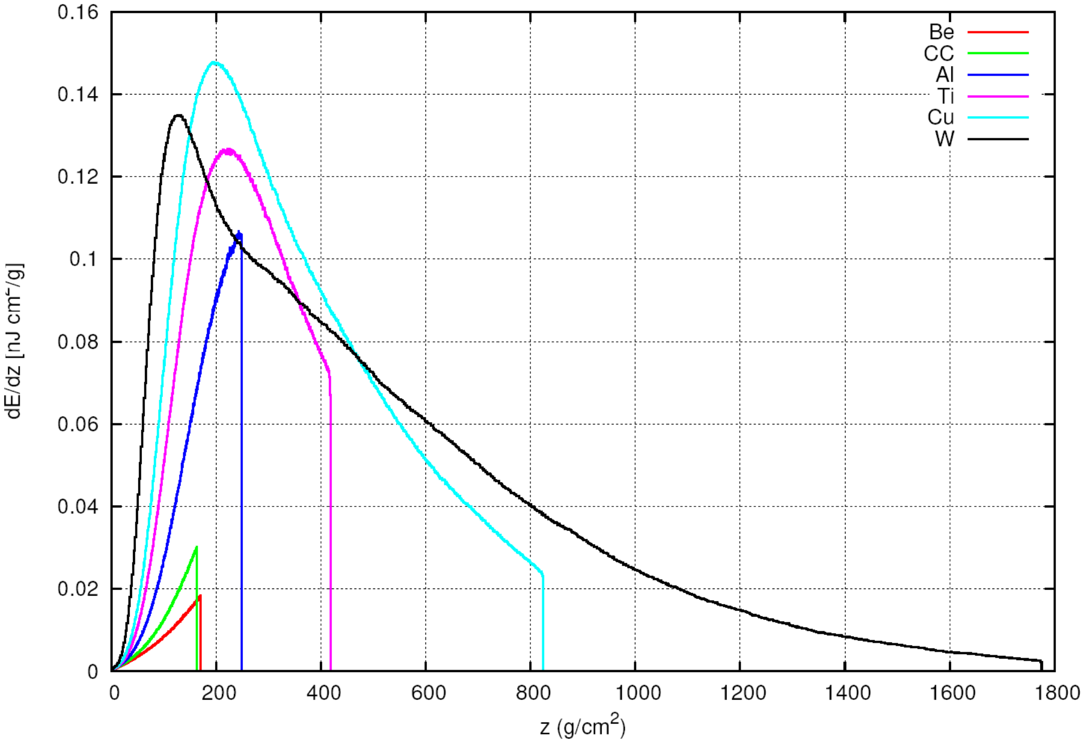
MATERIAL DEPENDENCE

	ρ [g/cm^3]	Z	X_0 [cm]	λ [cm] for 7 TeV p
Be	1.85	4	35.28	37.06
CC	1.77	6	24.12	42.09
Al	2.70	13	8.90	35.35
Ti	4.54	22	3.56	25.04
Fe	7.9	26	1.76	15.1
Cu	8.96	29	1.44	13.86
W	19.3	74	0.35	8.90

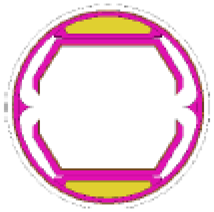
energy deposition transversally integrated

[different from *peak density* profile, which depends on beam size]

for a 7 TeV proton impacting on a 92 cm long jaw



POWER DEPOSITION IN A HADRON COLLIDER ARC



Total Power [W]

Magnet	Cold Mass	Beam Screen
B1	5.31	1.05
B2	6.43	1.41
B3	5.57	1.19
B4	5.62	1.21
B5	6.72	1.49
B6	5.81	1.13
Q1	2.34	0.53
B7	5.05	0.99
B8	6.22	1.36
B9	5.43	1.16
B10	5.46	1.17
B11	6.48	1.43
B12	5.38	1.04
Q2	2.31	0.53

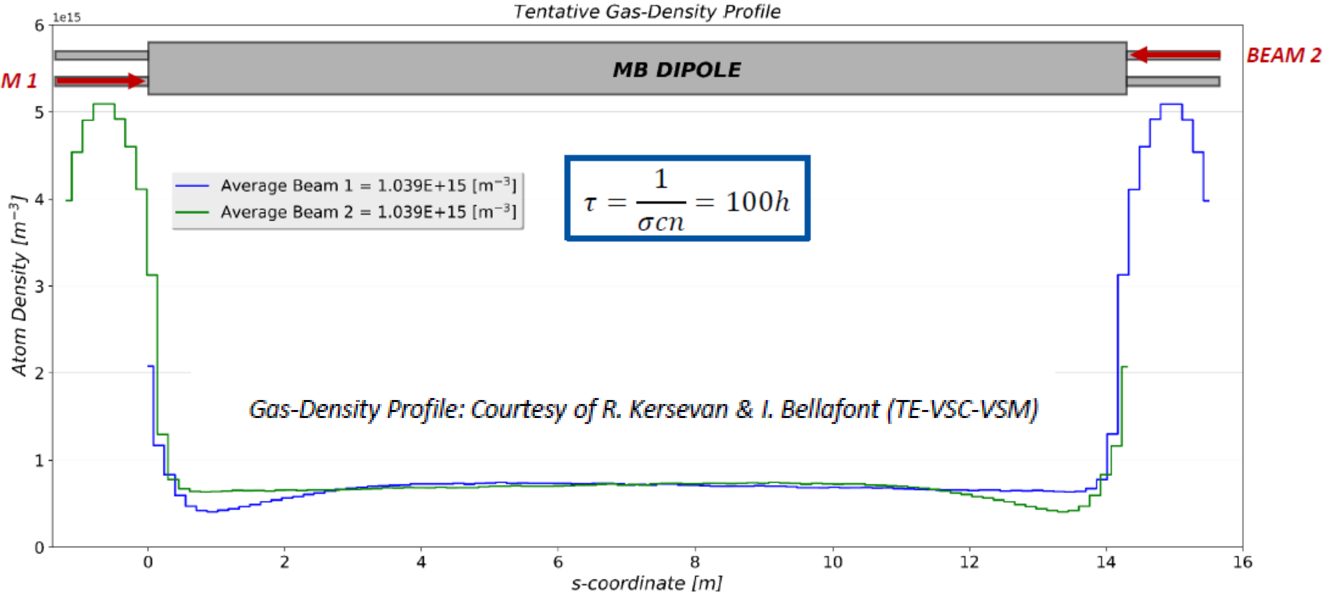
BEAM 1

BEAM 2

Note: Beam 1 & 2 (1.0 A)

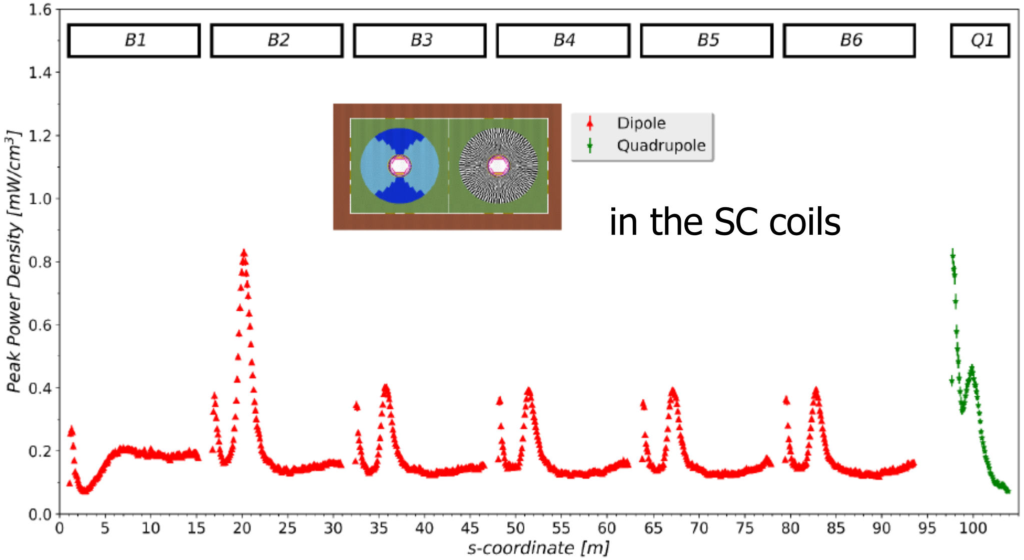
Average power loss per unit arc-cell length:

~466 mW/m



$$\tau = \frac{1}{\sigma c n} = 100h$$

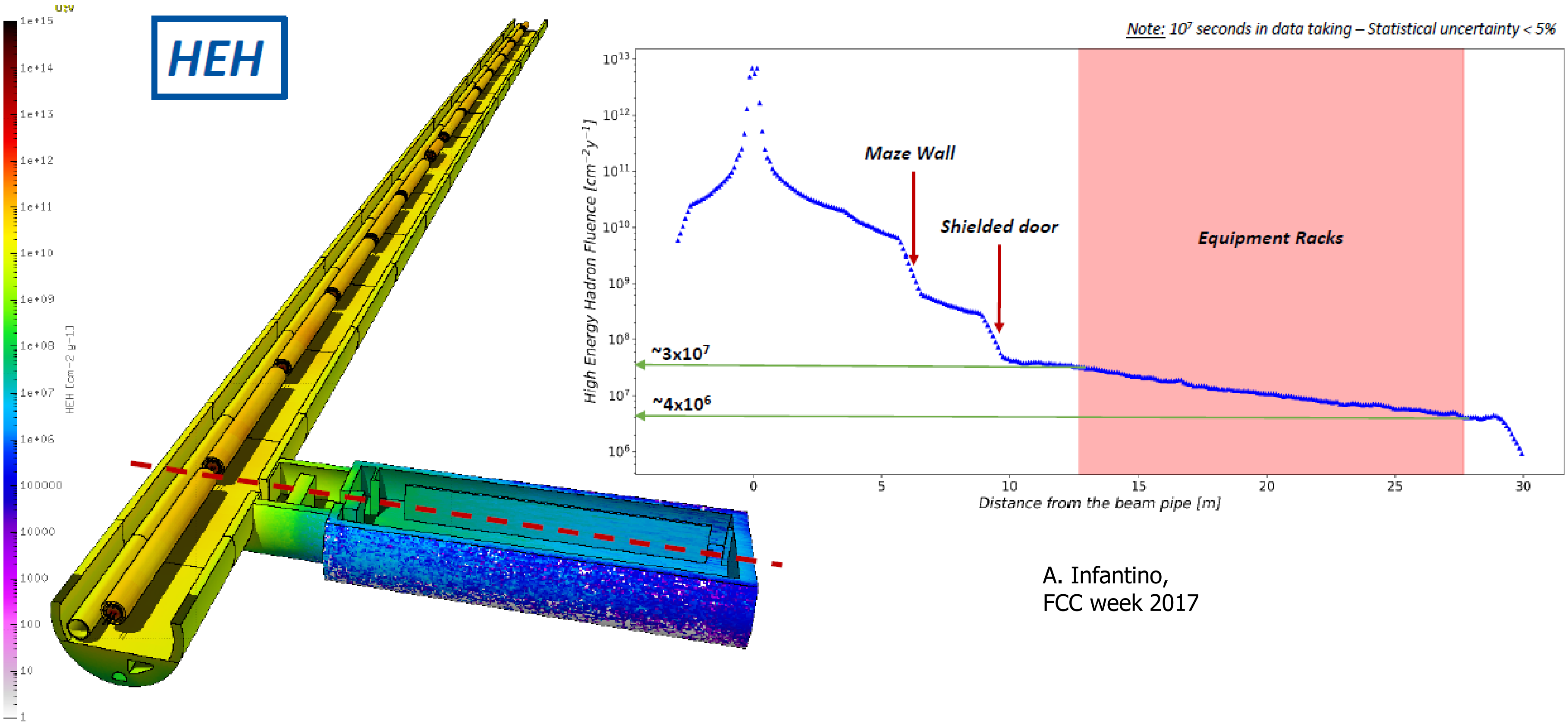
Gas-Density Profile: Courtesy of R. Kersevan & I. Bellafont (TE-VSC-VSM)



in the SC coils

A. Infantino,
FCC week 2017

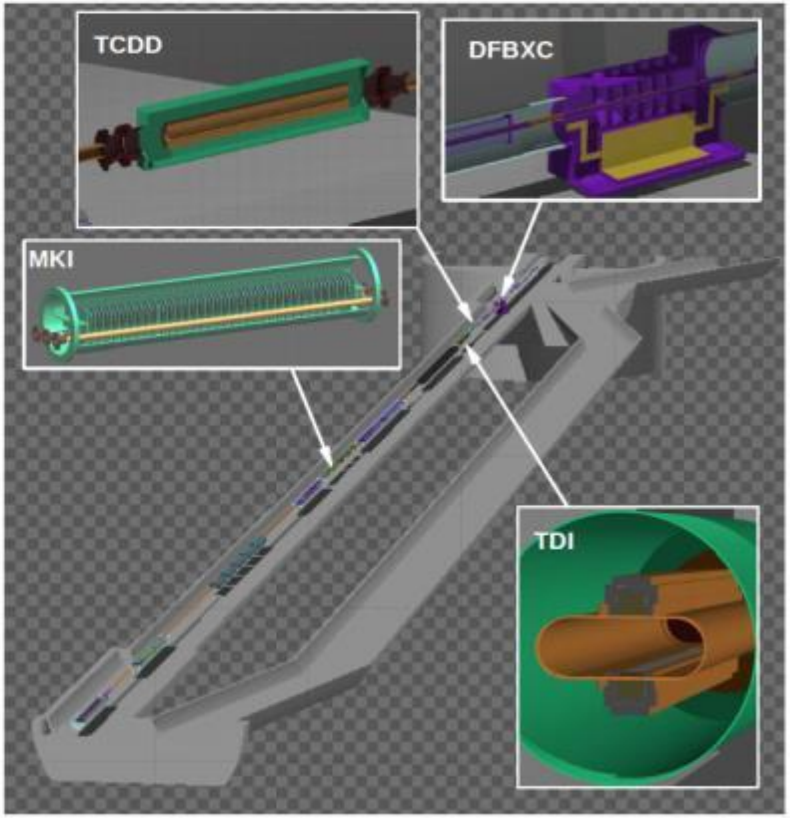
RADIATION LEVELS IN A HADRON COLLIDER ARC



A. Infantino,
FCC week 2017

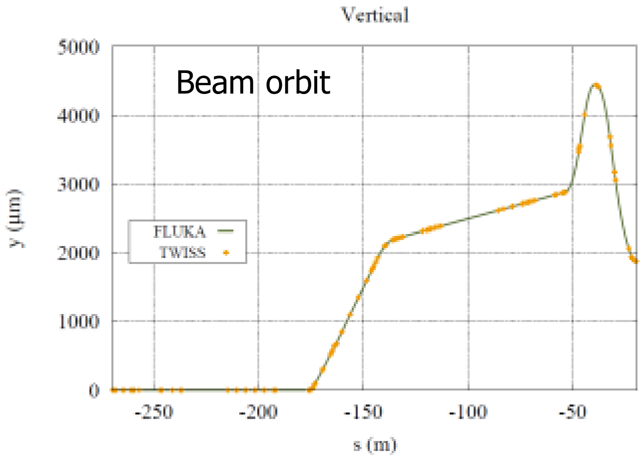
BACKGROUND: ALICE [I]

LHC IR2 Long Straight Section (Left)

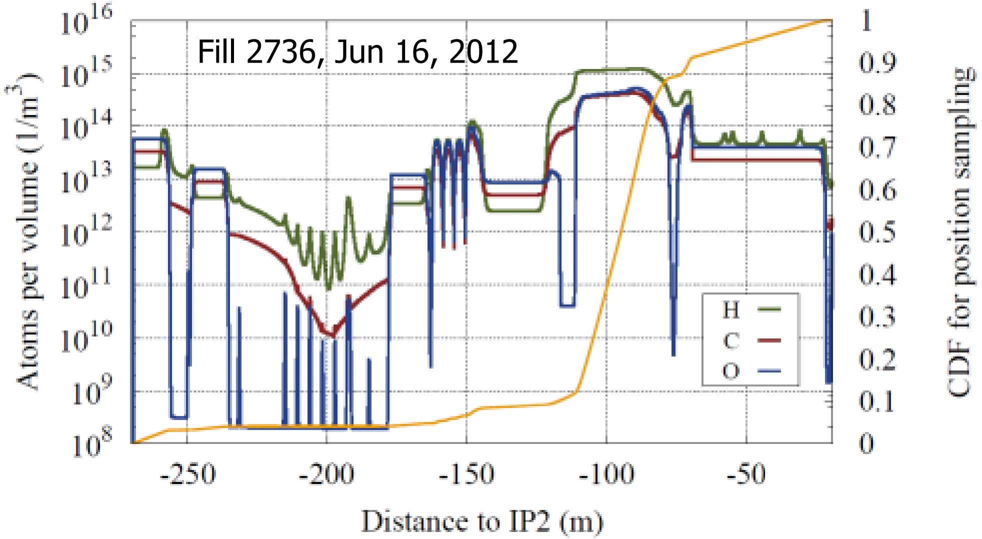


A. Lechner, G. Bregliozzi, E. Leogrande, A. Di Mauro

LHC Background Study Group Meeting, Jan 28th, 2013

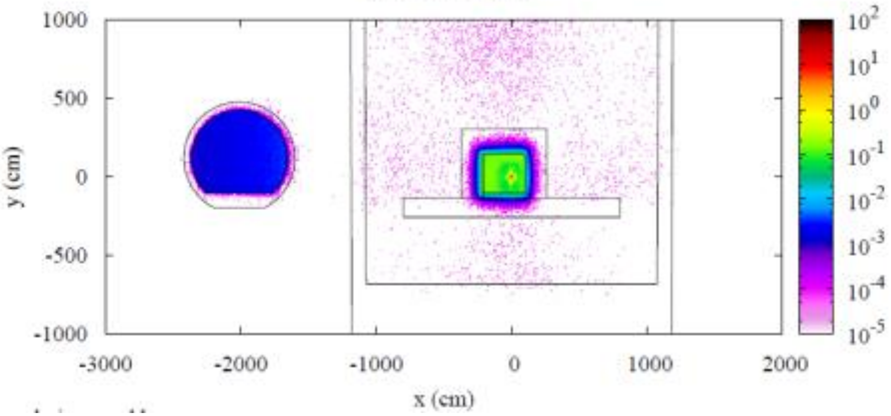


Residual Gas density

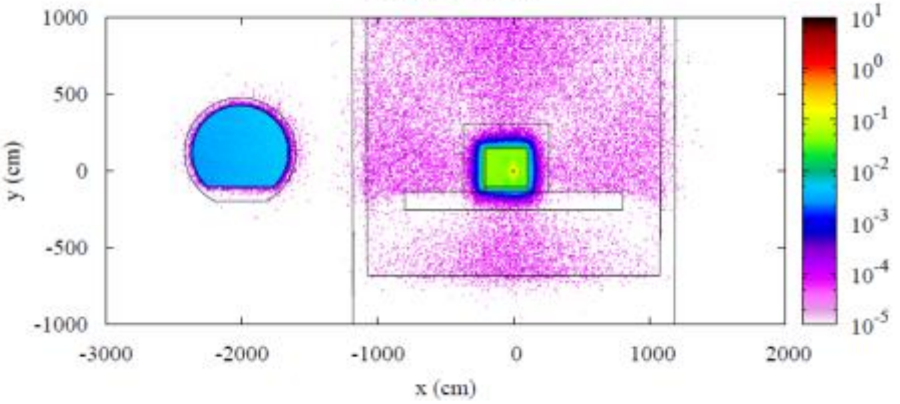


BACKGROUND: ALICE [II]

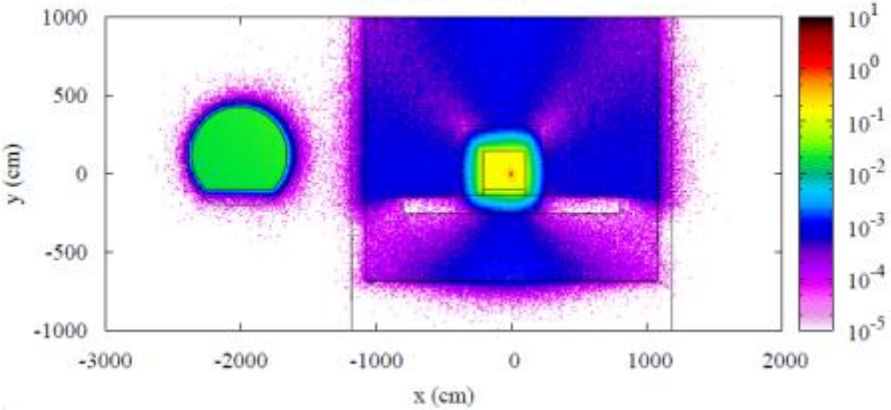
charged pions and kaons



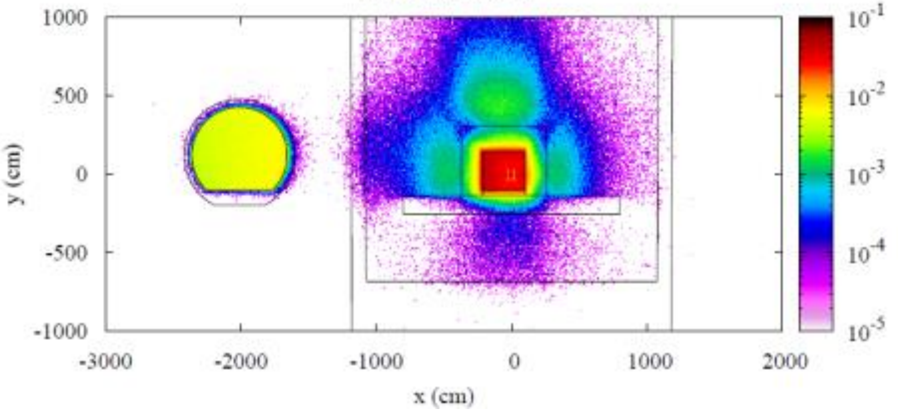
protons



neutrons



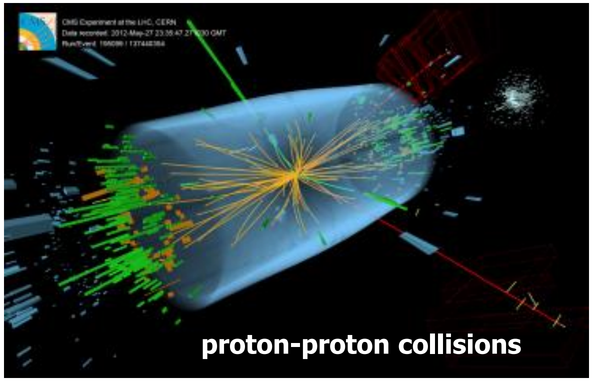
muons

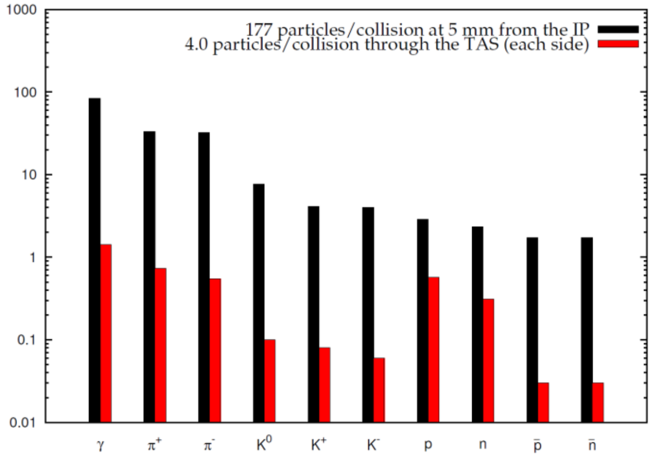


R. Kwee

HL-LHC Annual Meeting 2013

THE **COLLISION DEBRIS**

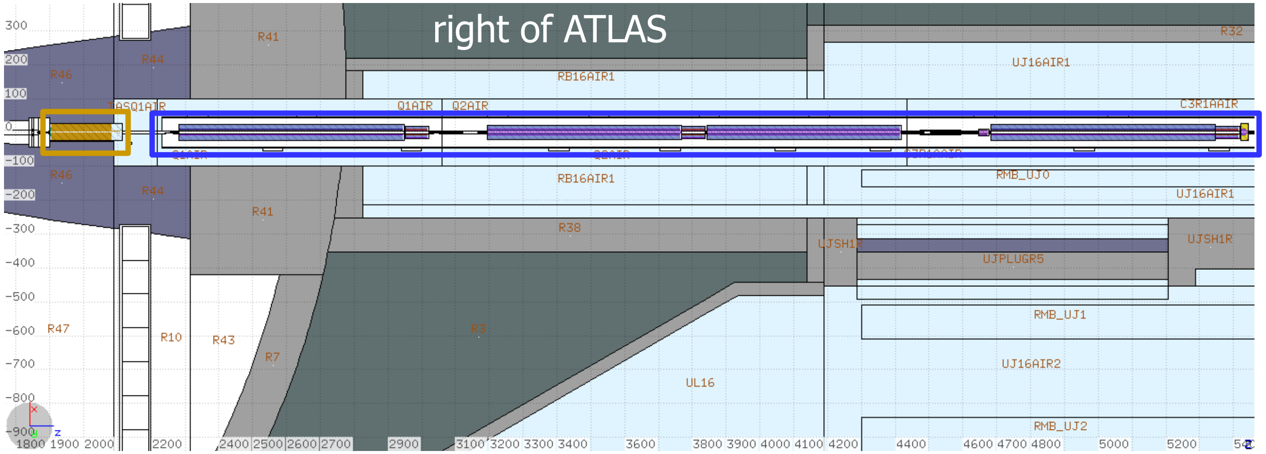




Instantaneous luminosity: 10^{34} cm^{-2} s^{-1}

LHC @ 14 TeV CM

950 W towards each (L&R) side



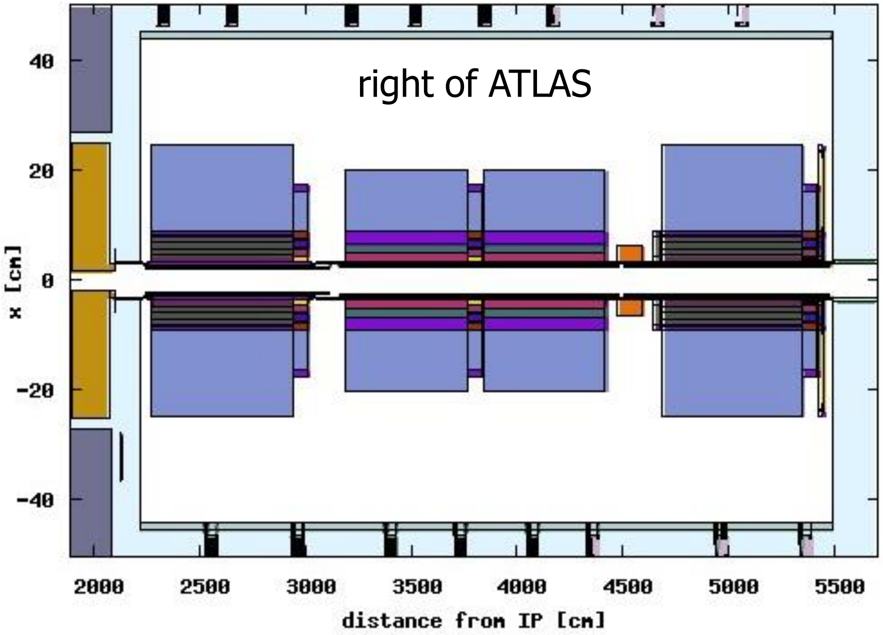
150 W absorbed in the TAS

650 W going through the TAS

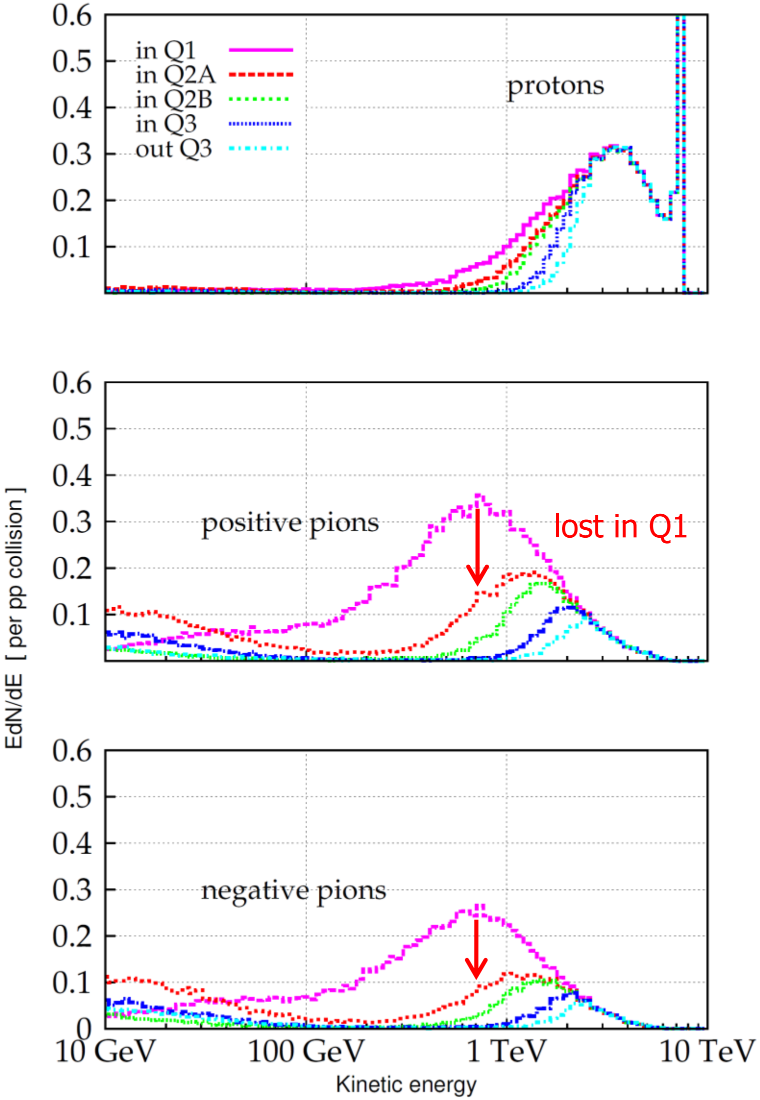
of which

150 W absorbed in the triplet cold magnets

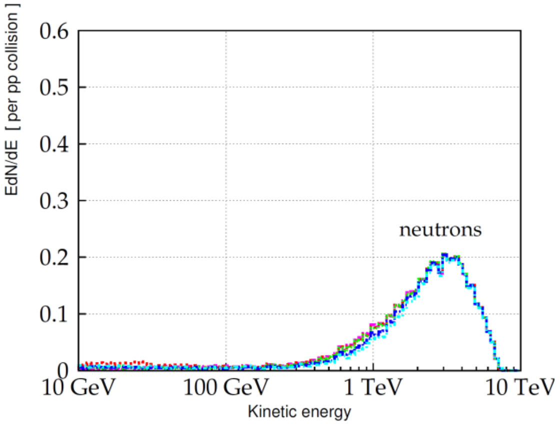
DEBRIS CAPTURE IN THE “TRIPLET”

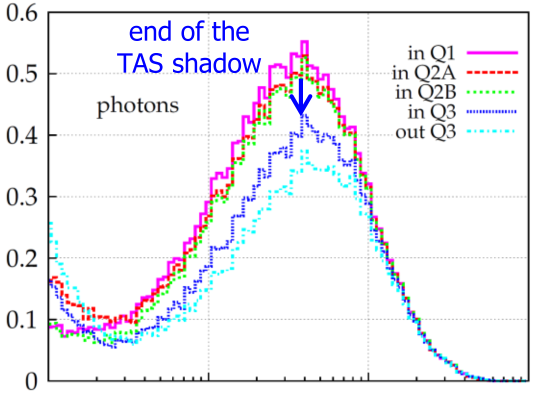


right of ATLAS



lost in Q1

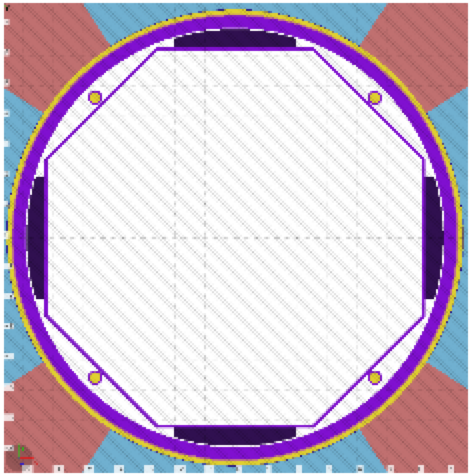


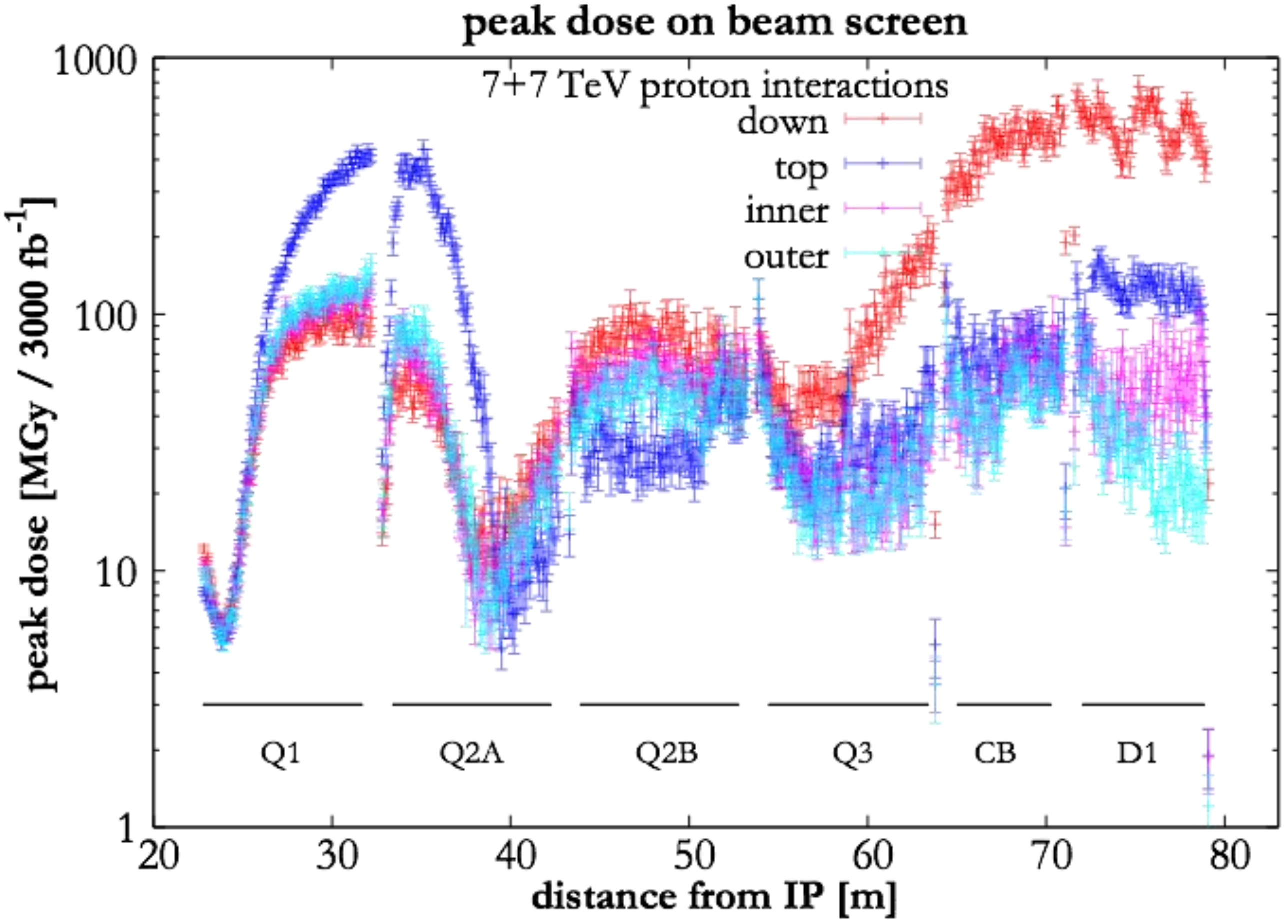


end of the TAS shadow

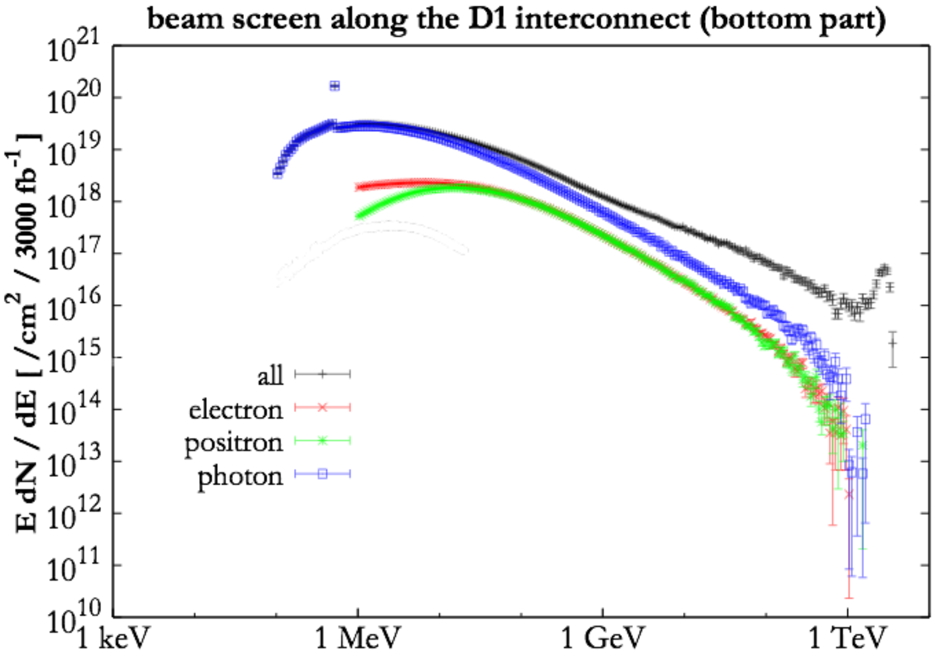
DOSE TO BEAM SCREEN

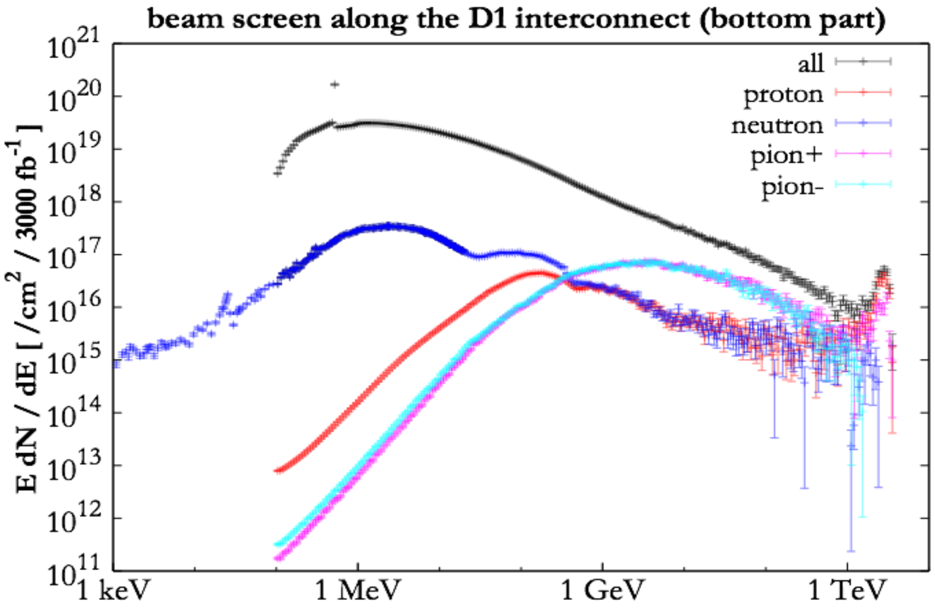
HL-LHC





PARTICLE FIELD

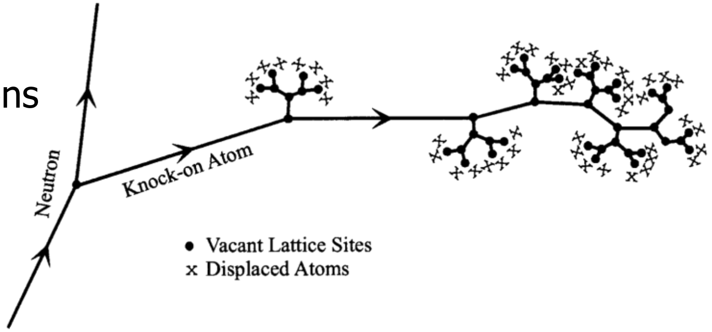




DISPLACEMENTS PER ATOM

It is a “measure” of the amount of radiation damage in inorganic materials

0.3 dpa means that on average 3 atoms out of 10 have been displaced once from their site within the structural lattice



Displacement damage can be induced by all particles

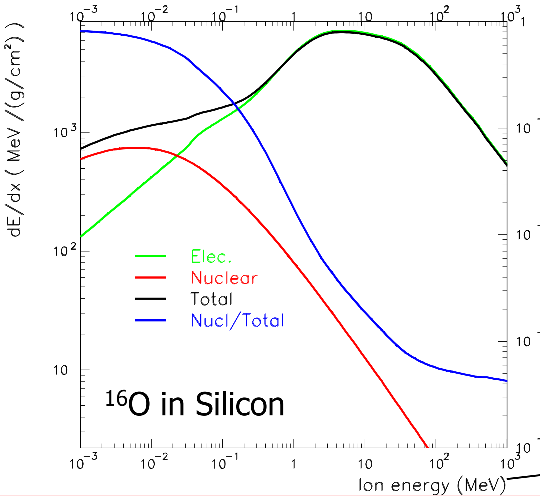
produced in the hadronic cascade, including high energy photons

(through photonuclear reactions).

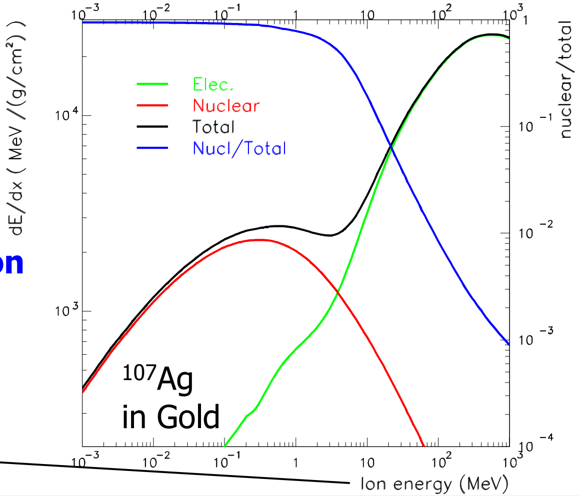
It is directly related to energy transfers to atomic nuclei

i.e. (restricted) NIEL

nuclear stopping power



partition function
$S_n/(S_n+S_e)$



total kinetic

S_n/S is going down with energy and up with charge
→ NIEL/DPA are dominated by low energy heavy recoils!

HYDROGEN AND HELIUM GAS PRODUCTION

Spallation reactions induced by protons, neutrons, pions, … produce a variety of particles including protons (^{1}H), deuterons (^{2}H) , tritons (^{3}H), ^{3}He, and alphas (^{4}He). The least energetic of these products (which are also the most abundant) can stop in the target assembly giving rise to a **hydrogen and helium buildup**.

These gases can lead to grain boundary embrittlement and accelerated swelling.

In the case of the *CNGS target*, for 1.4 10^{20} protons on target one expects about 4 10^{21} H atoms.

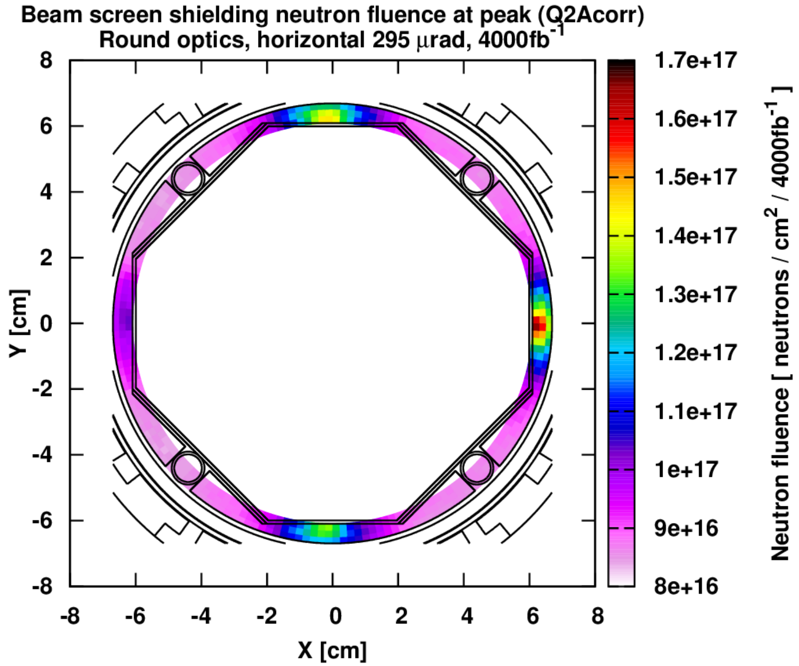
Assuming that all H atoms are desorbed from the target solid structures, this corresponds to ~150 ml of atomic H at atmospheric pressure (75 ml if we assume they combined into molecules).

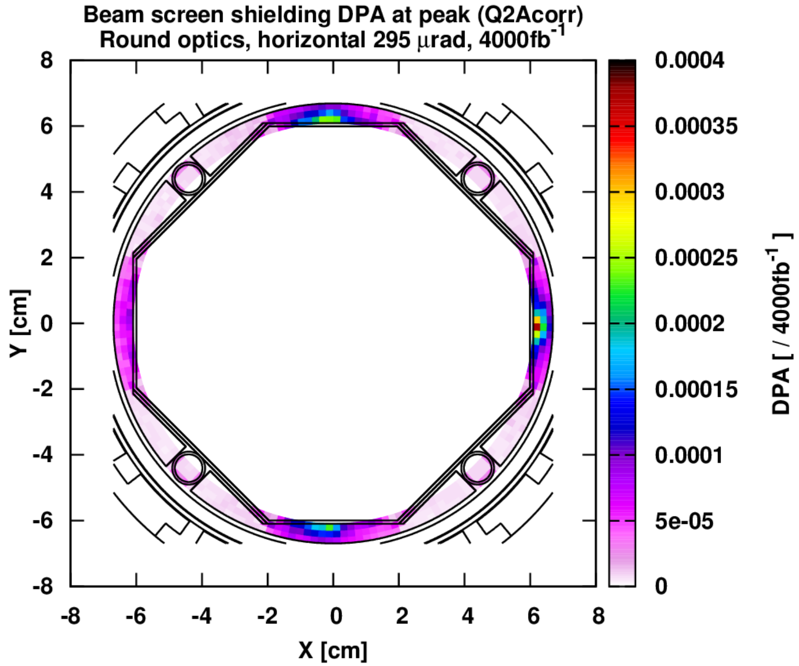
MECHANICAL PROPERTY DEGRADATION

with C. Garion, M. Morrone (TE-VSC), M. Calviani (EN-STI)

In the HL-LHC tungsten absorbers,

a neutron fluence of 10^{17}cm^{-2} and a DPA value of 10^{-4} will be reached over 4ab^{-1}.



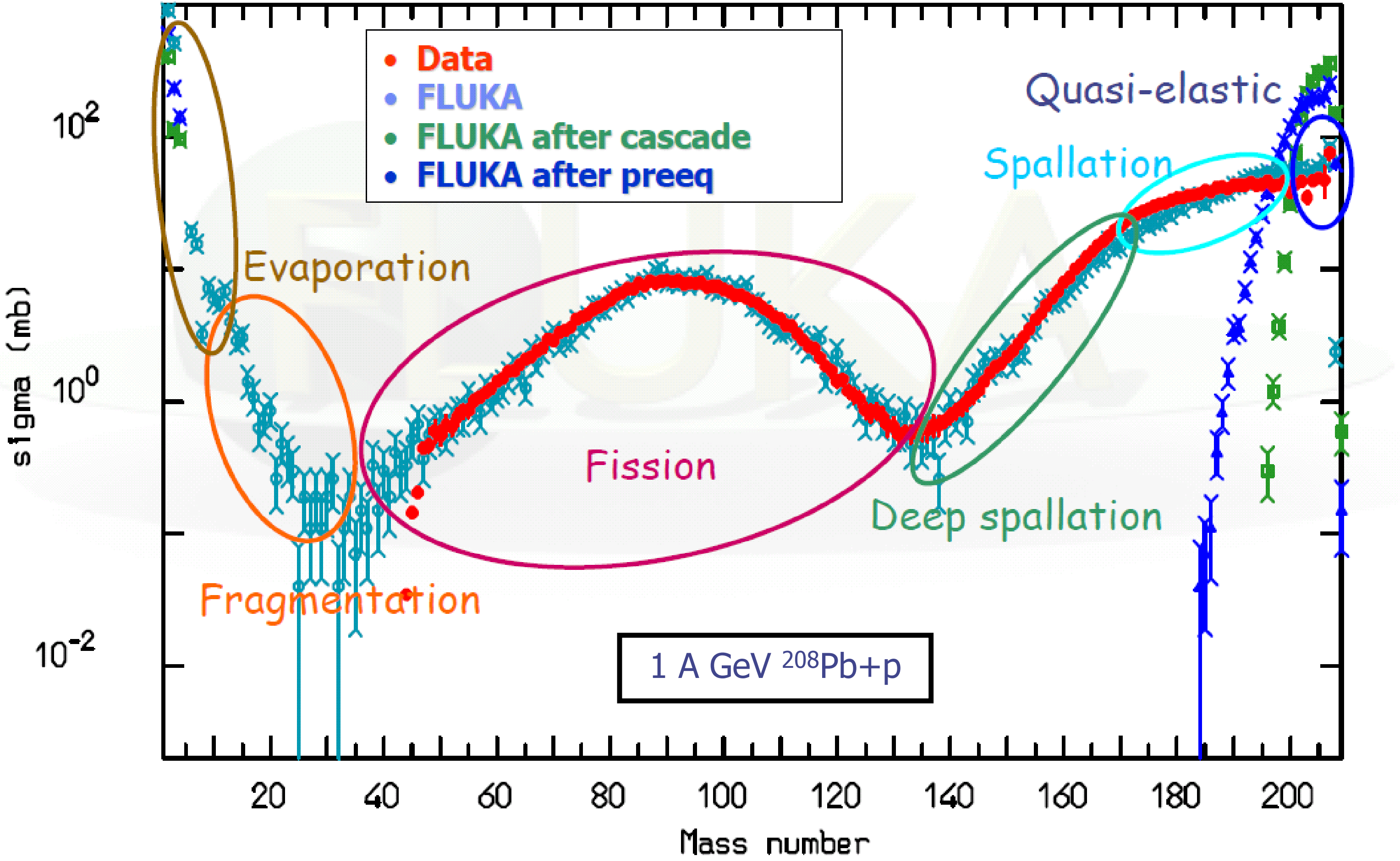


H and He gas production is of the order of 0.01-0.1 ppm.

This is not expected to induce a significant alteration of relevant material properties.

ACTIVATION

A high energy nuclear reaction on a high Z nucleus fills roughly the whole charge and mass intervals of the nuclide chart

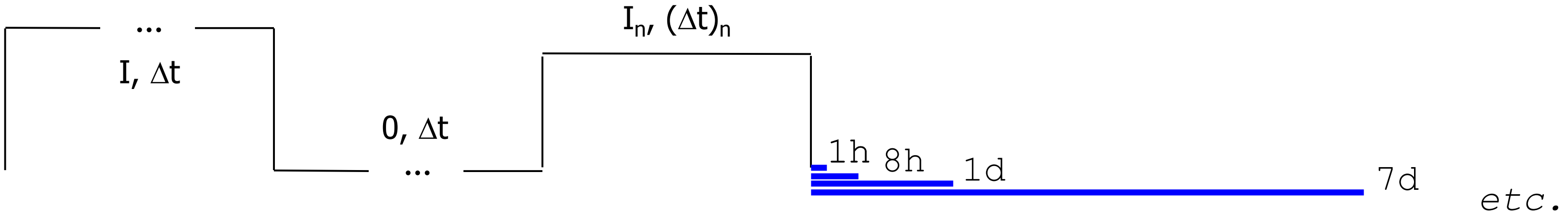


DELAYED RADIATION FROM RADIOACTIVE DECAY

Bateman equations

$$\frac{\mathrm{d}N_n}{\mathrm{d}t} = \underbrace{P_n}_{\text{production rate}} + \underbrace{(b_{n-1,n} \cdot \lambda_{n-1} \cdot N_{n-1})}_{\text{growth by parent decay}} - \underbrace{\lambda_n \cdot N_n}_{\text{decay}}$$

which are solved for a given *irradiation profile* at different *cooling times*



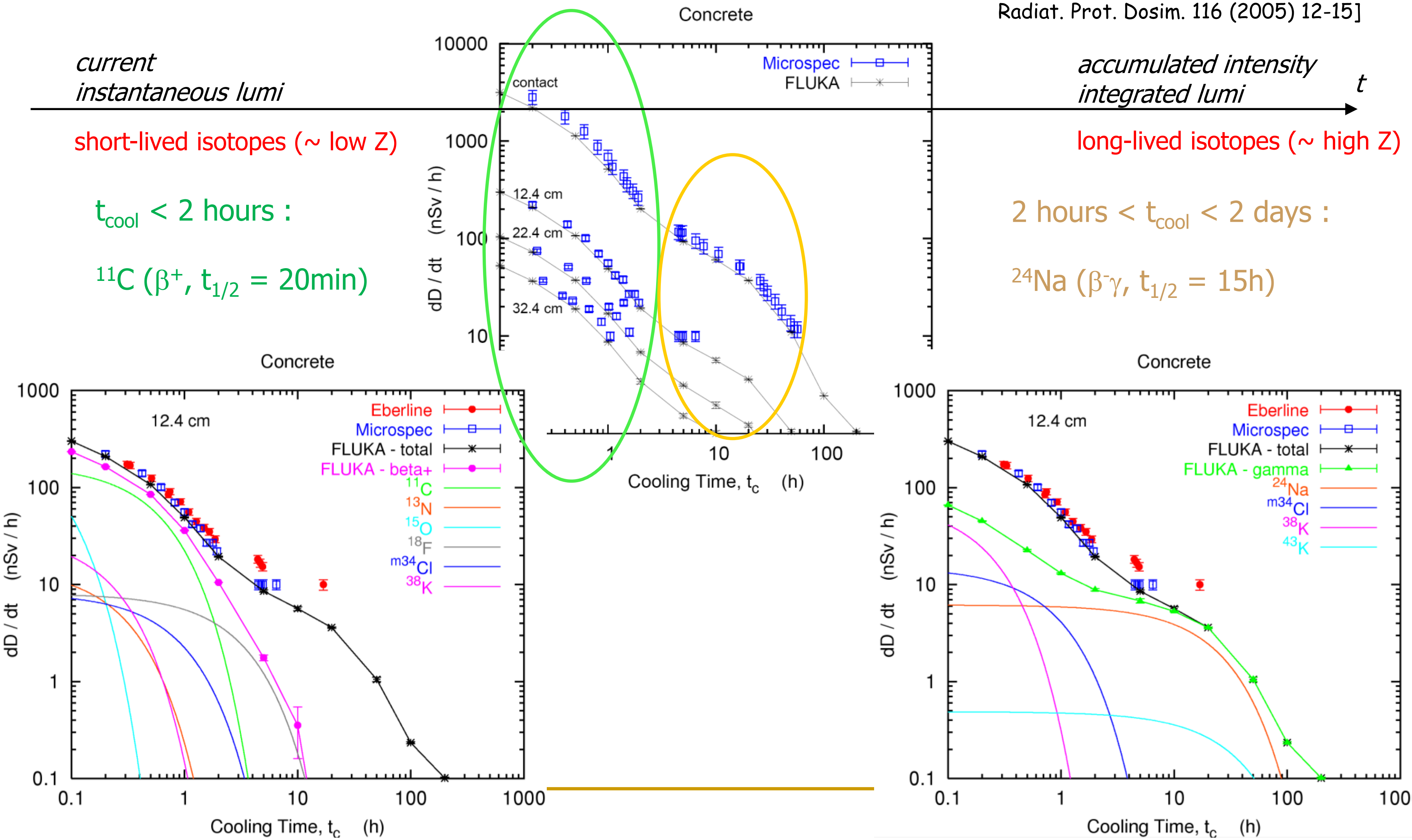
yielding (specific) activities [Bq(/g)] – to be compared to legal <u>exemption limits</u> –

and residual dose rates [uSv/h] by the decay radiation (mainly electromagnetic)

RESIDUAL DOSE RATE EVOLUTION

A benchmarking experiment at CERF: Irradiation of samples of different materials in the stray particle field created by the interaction of a 120 GeV positively charged hadron beam in a copper target

[M. Brugger *et al.*, Radiat. Prot. Dosim. 116 (2005) 12-15]



current
instantaneous lumi

short-lived isotopes (~ low Z)

t_{cool} < 2 hours :

^{11}C (β^+, $t_{1/2}$ = 20min)

accumulated intensity
integrated lumi

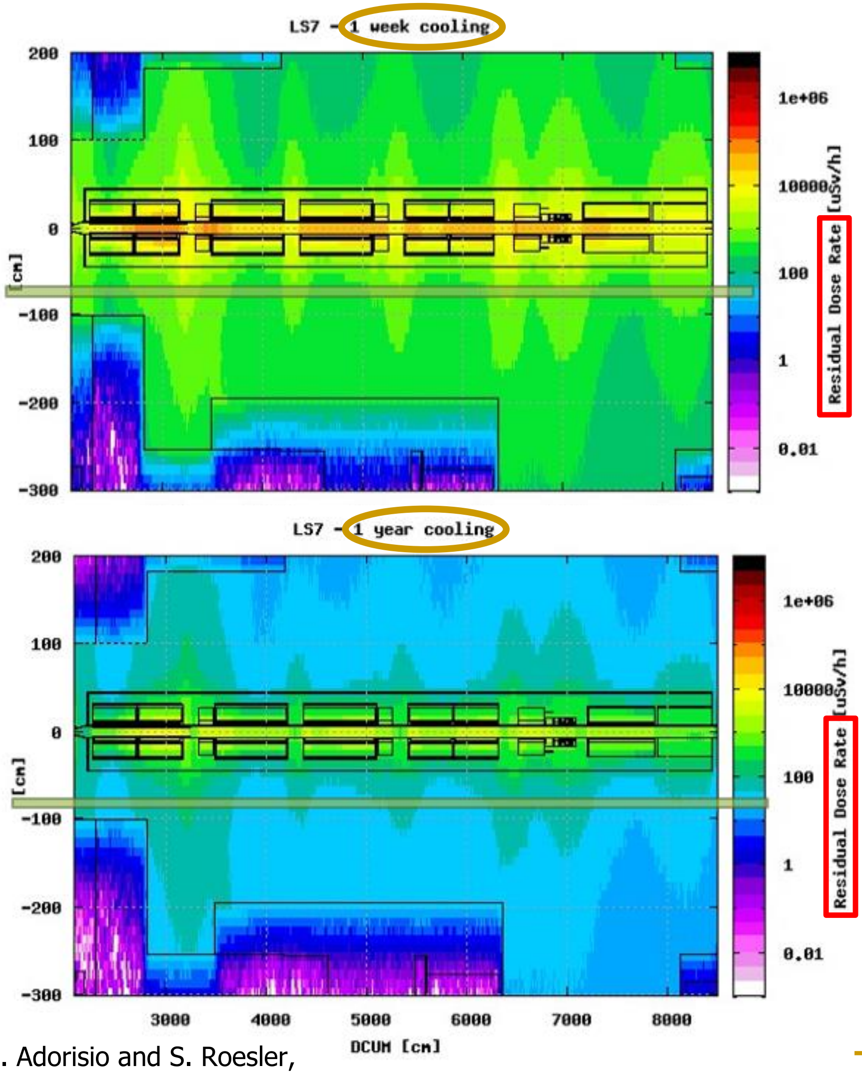
long-lived isotopes (~ high Z)

2 hours < t_{cool} < 2 days :

^{24}Na ($\beta^-\gamma$, $t_{1/2}$ = 15h)

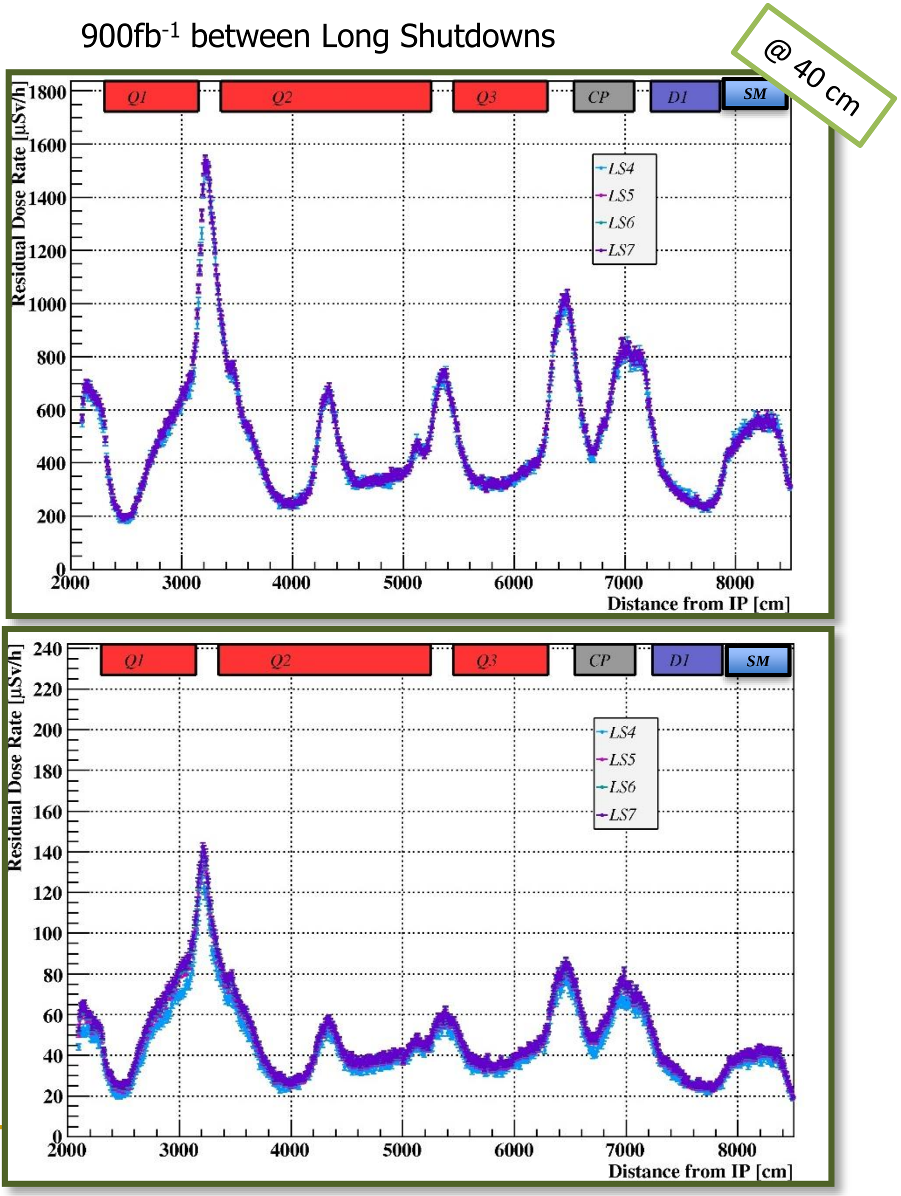
DURING SHUTDOWN

HL-LHC final focus triplet around ATLAS and CMS



[C. Adorisio and S. Roesler, HL-LHC TC, Sep 30, 2014]

900fb^{-1} between Long Shutdowns



INTERVENTION PLAN

valve exchange in the TAS-Q1 region at 22m from the collision point

[work example by C. Garion]

4 months cooling time

[C. Adorisio and S. Roesler, HL-LHC TC, Sep 30, 2014]

team	# person	action	distance from the beam pipe	duration (minutes)	dose per action (μSv)	individual dose (μSv)
T0	2	Valve investigation	400 mm	60	290	145
A	1	Jacket and cabling removal	in contact	30	103	
B	2	Pneumatic system disconnection	400 mm	10	48	427
B	2	Flanges disconnection	in contact	20	138	
B	2	Valve removal	in contact	30	206	
B	2	Valve re-installation	in contact	30	206	
B	2	Flanges reconnection	in contact	30	206	
B	2	Pneumatic system reconnection	400 mm	10	48	
A	1	Jacket and cabling installation	in contact	45	155	258

Collective Dose 1.4 mSv

limit of 6 or 20 mSv/y depending on the worker category
with optimization threshold of 100 uSv/y and design criterion requiring not to surpass 2 mSv per intervention/year

OPTIMIZATION PRINCIPLES

1. Material choice

   - Low activation properties to reduce residual doses and minimize radioactive waste
   - Avoid materials for which no radioactive waste elimination pathway exists (e.g., highly flammable metallic activated waste)
   - Radiation resistant

2. Optimized handling

   - Easy access to components that need manual intervention (e.g., valves, electrical connectors) or complex manipulation (e.g., cables)
   - Provisions for fast installation/maintenance/repair, in particular, around beam loss areas (*e.g.*, plugin systems, quick-connect flanges, remote survey, remote bake-out)
   - Foresee easy dismantling of components

3. Limitation of installed material

   - Install only components that are absolutely necessary, in particular in beam loss areas
   - Reduction of radioactive waste

[C. Adorisio and S. Roesler,
R2E and Availability Workshop,
Oct 16, 2014]

CREDITS

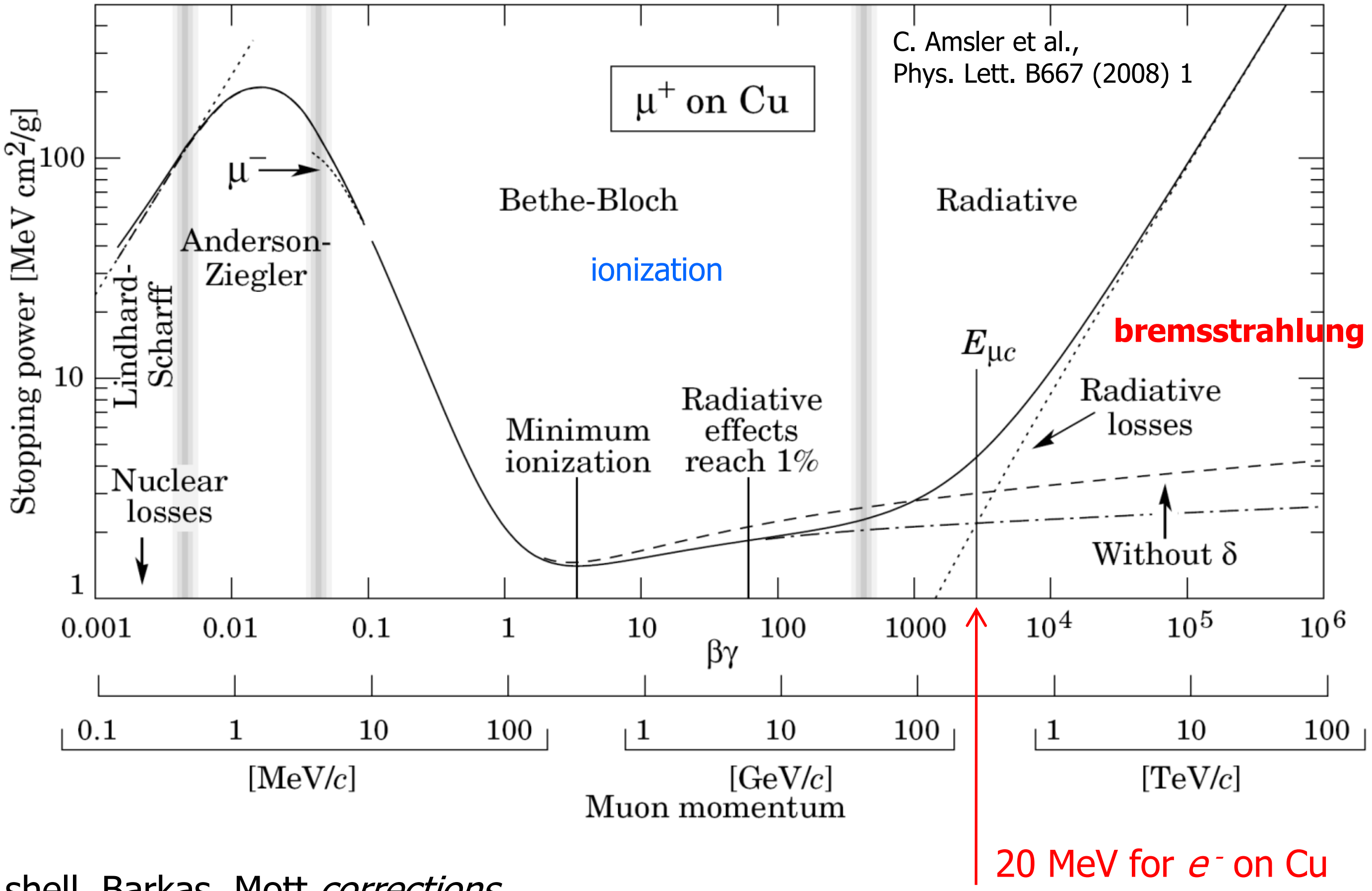
In addition to explicit references, work of and material from

C. Adorisio, I. Besana, M. Brugger, L.S. Esposito, A. Ferrari, A. Infantino, L. Lari,
A. Lechner, A. Mereghetti, S. Roesler, P.R. Sala, A. Tsinganis, V. Vlachoudis

CERN FLUKA TEAM and FLUKA COLLABORATION
CERN VACUUM GROUP, CERN MAGNET GROUP,
and CERN RADIATION PROTECTION TEAM

ENERGY LOSS BASICS [I]

mean energy loss rate



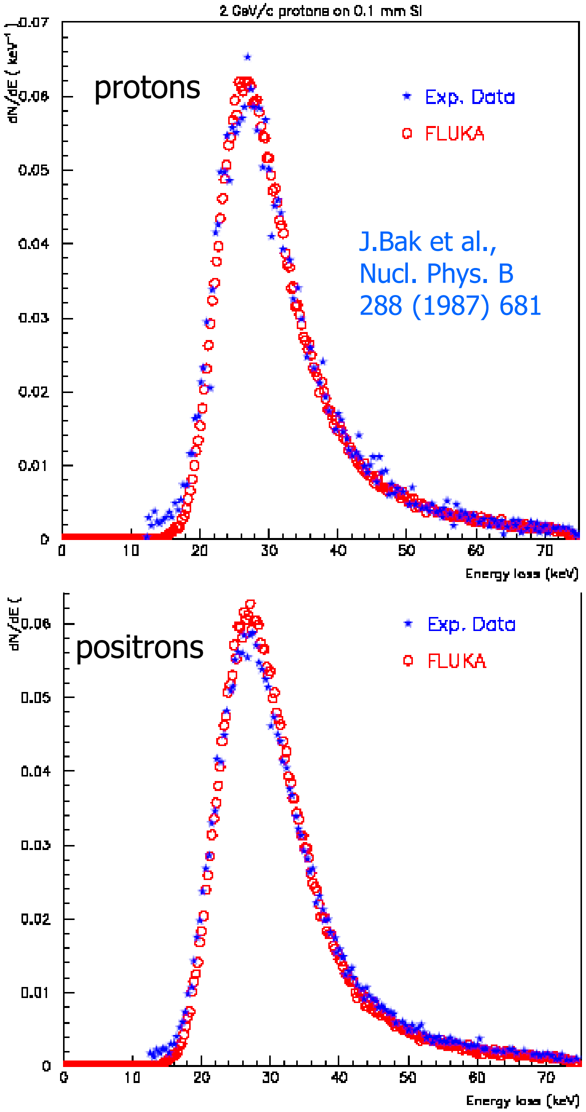
C. Amsler et al., Phys. Lett. B667 (2008) 1

20 MeV for e^- on Cu

- shell, Barkas, Mott *corrections*
- *effective charge* for low energy high Z ions

ENERGY LOSS BASICS [II]

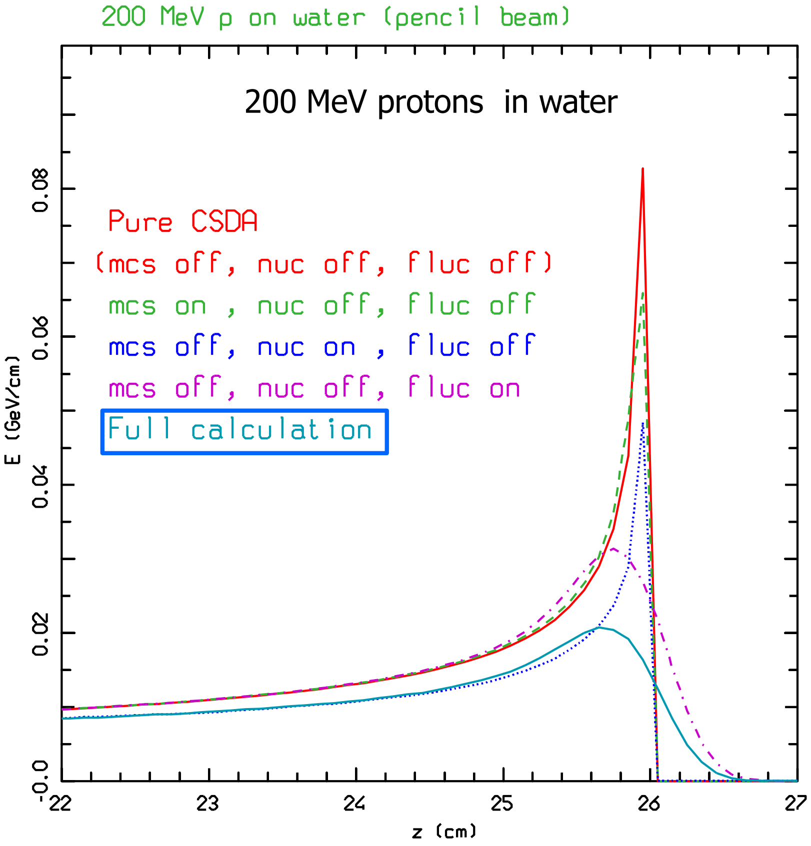
ionization energy loss **fluctuations**



J.Bak et al.,
Nucl. Phys. B
288 (1987) 681

2 GeV/c beams
on 0.1mm Si

energy deposition

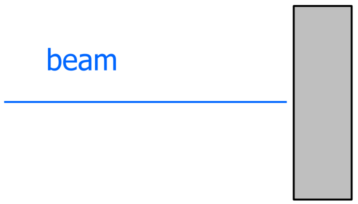


3 MeV PROTON DUMP

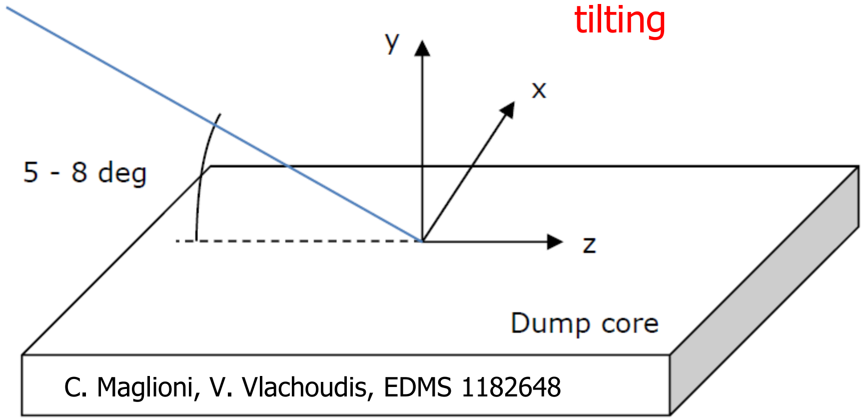
Intensity: 65mA over 100μs

Beam size: 4.5mm $\sigma_x = \sigma_y$

orthogonal impact

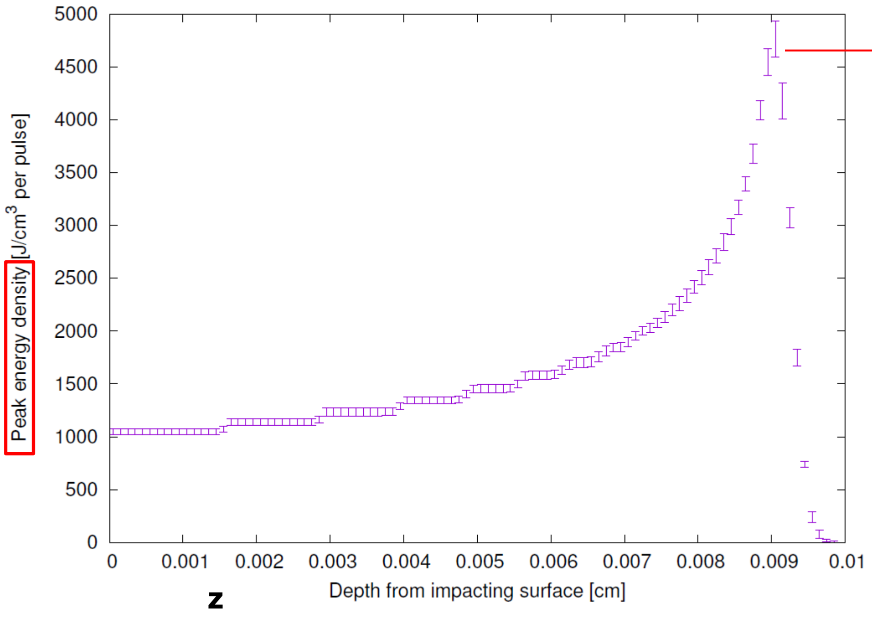


tilting



C. Maglioni, V. Vlachoudis, EDMS 1182648

graphite



85% gain!