BEAM LOSS CONSEQUENCES

Francesco Cerutti

The CERN Accelerator School

on Intensity Limitations in Particle Beams

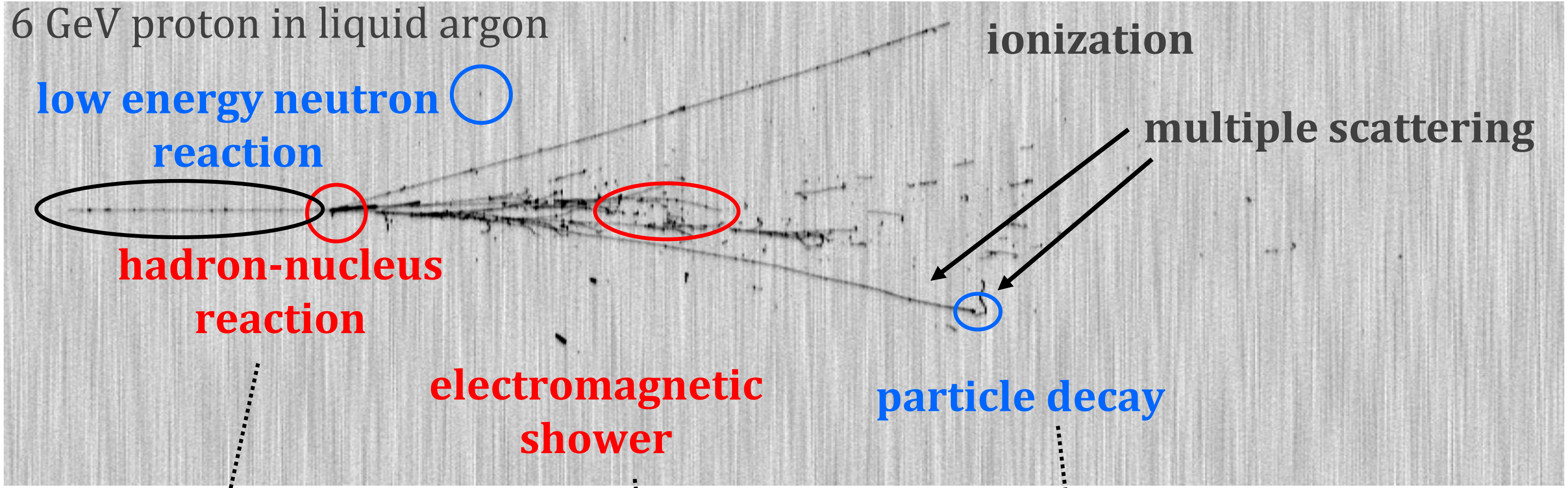
CERN November 2015

BEAM LOSSES

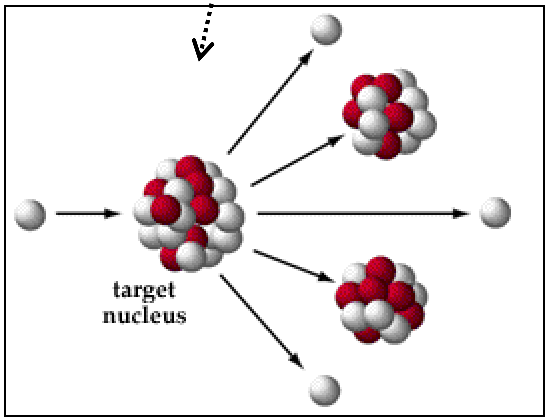
- *on beam intercepting devices (targets, collimators, dumps, stoppers, stripping foils, …)*
  - *regular*
  - *accidental: smearing failures, injection mis-steering, asynchronous beam dump, top-off*
- *diffused*
  - *synchrotron radiation, beam-gas interaction, gas bremsstrahlung*
- *debris from regular collisions at the interaction points*
- *on unexpected obstacles (UFO, ULO, …)*

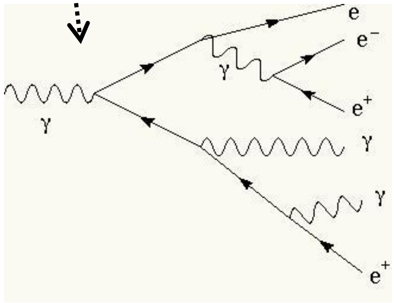
INTERACTION WITH (ACCELERATOR) MATERIAL:

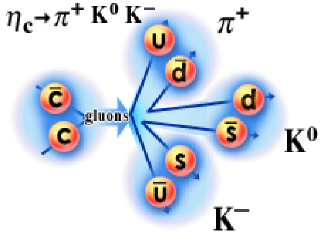
the microscopic view



interplay of many physical processes described by different theories/models



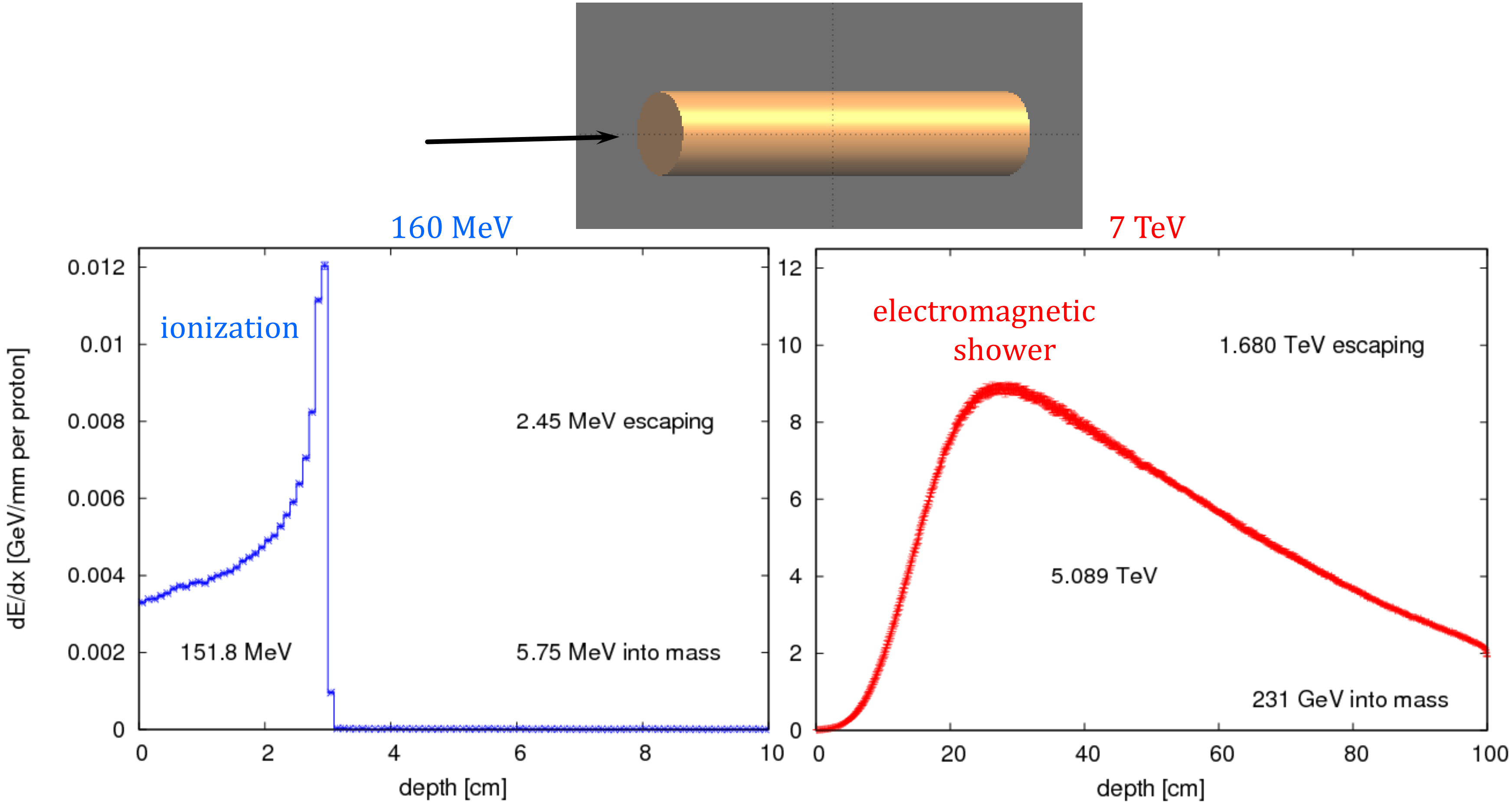




INTERACTION WITH ACCELERATOR MATERIAL:

the macroscopic view

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



CONSEQUENCES

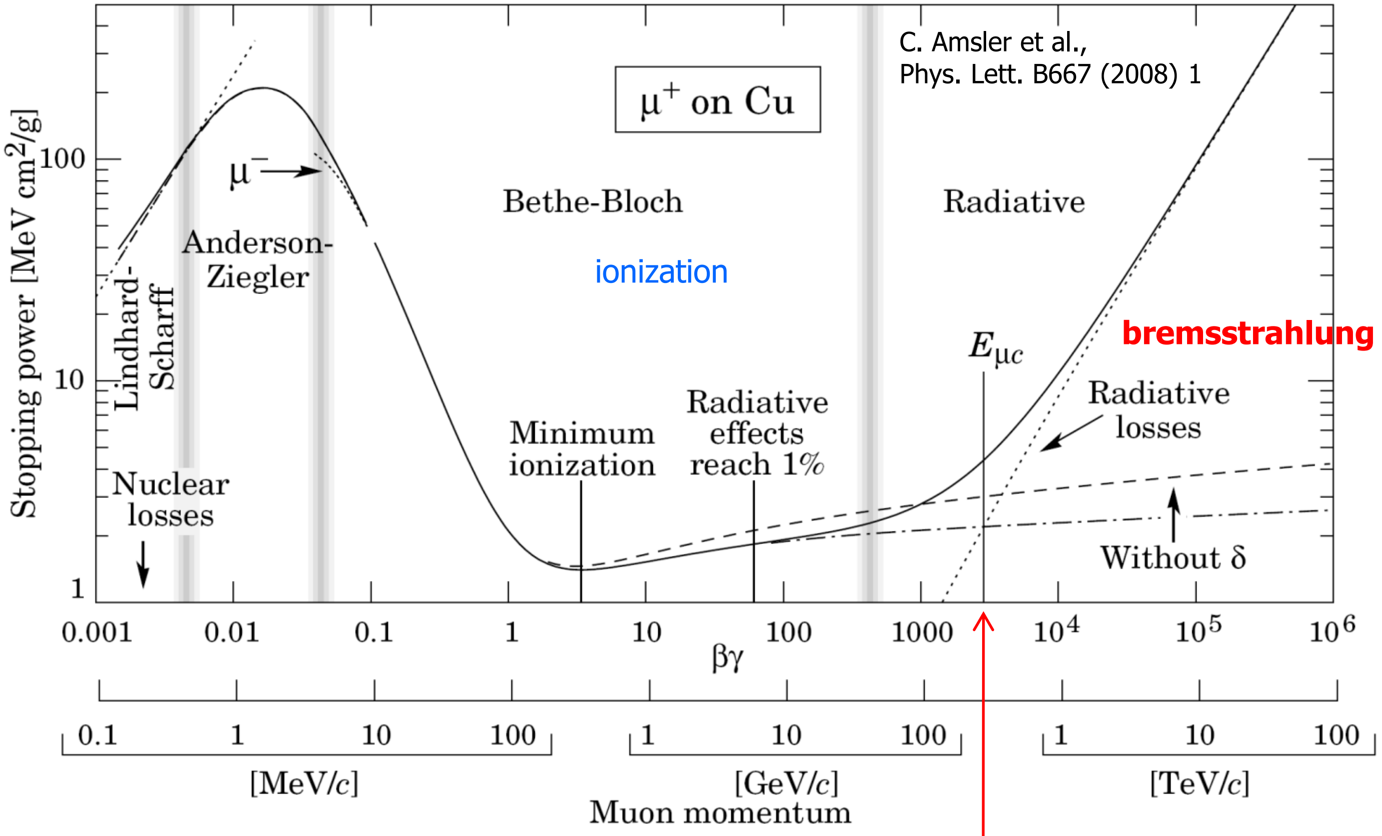
	relevant macroscopic quantity
Heating	energy deposition (integral power)
Thermal shock	energy deposition (power density)
Quenching	energy deposition (power density)
Deterioration	energy deposition (dose), particle fluence, DPA
Oxidation, radiolysis, ozone production	energy deposition
Gas production	residual 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

Tumor cell destruction	energy deposition (dose, biological dose)

ENERGY LOSS BASICS [I]

mean energy loss rate



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

ionization

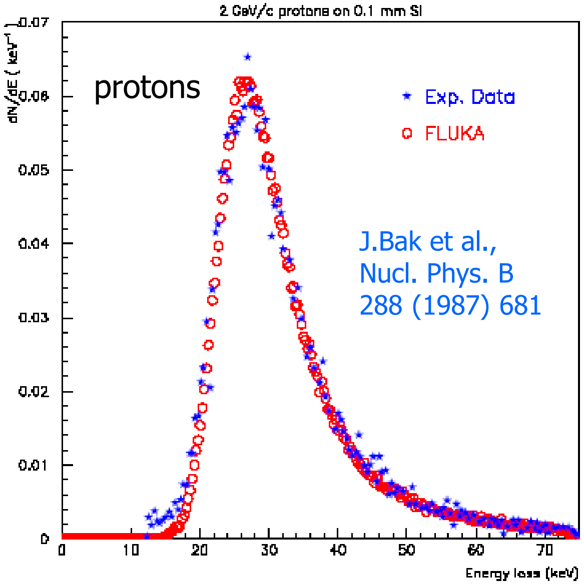
bremsstrahlung

20 MeV for e^- on Cu

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

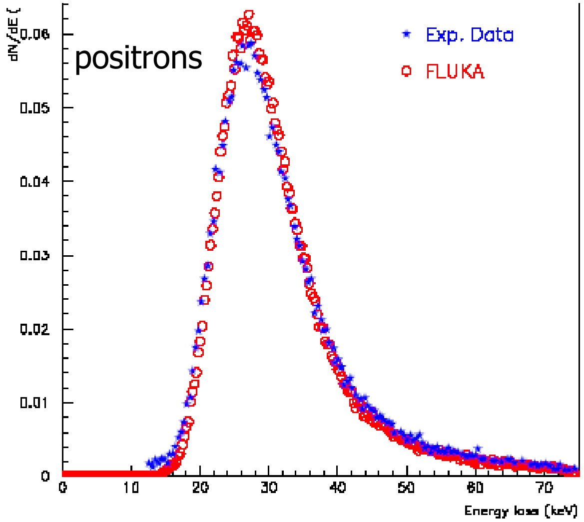
ENERGY LOSS BASICS [II]

ionization energy loss **fluctuations**

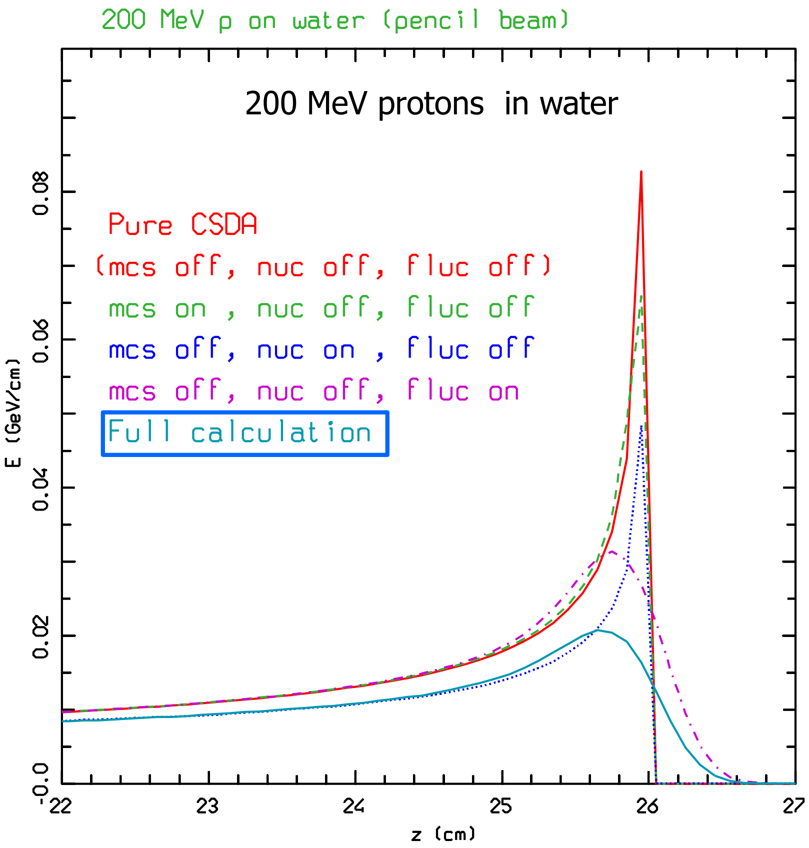


J.Bak et al., Nucl. Phys. B 288 (1987) 681

2 GeV/c beams
on 0.1mm Si



energy deposition

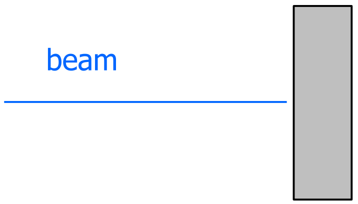


3 MeV PROTON DUMP

Intensity: 65mA over 100μs

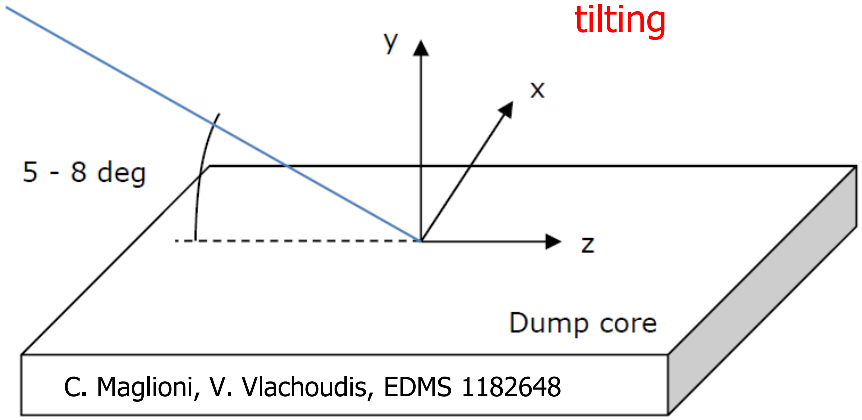
Beam size: 4.5mm $\sigma_x = \sigma_y$

orthogonal impact

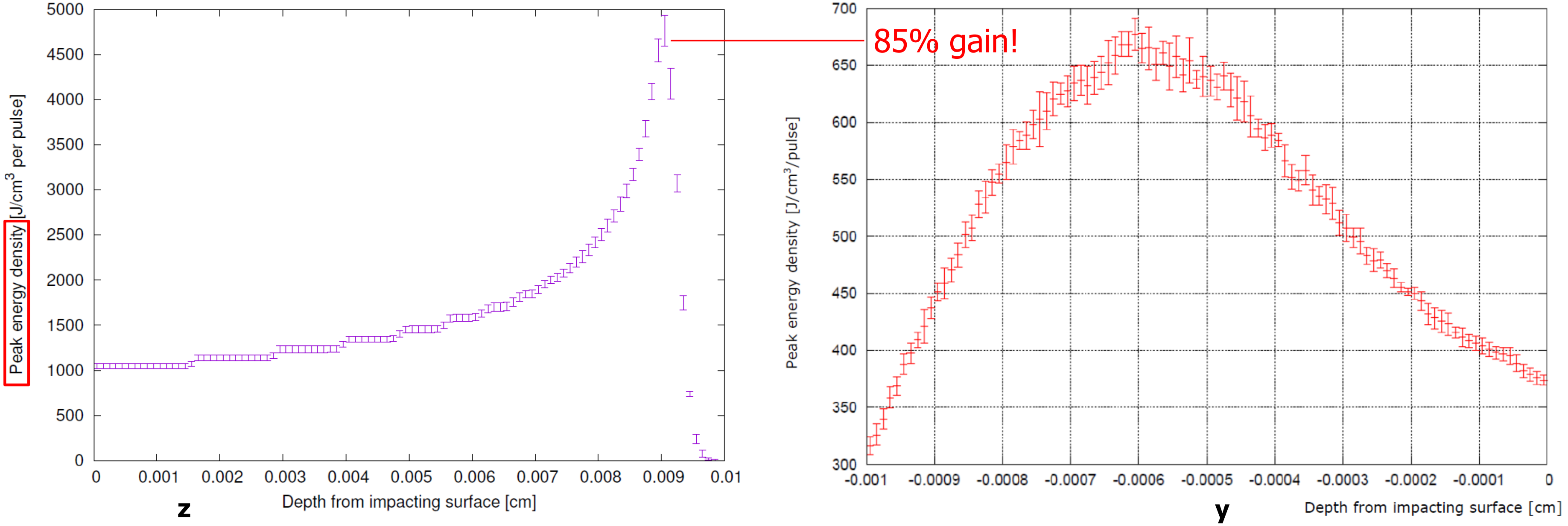


graphite

tilting



C. Maglioni, V. Vlachoudis, EDMS 1182648



85% gain!

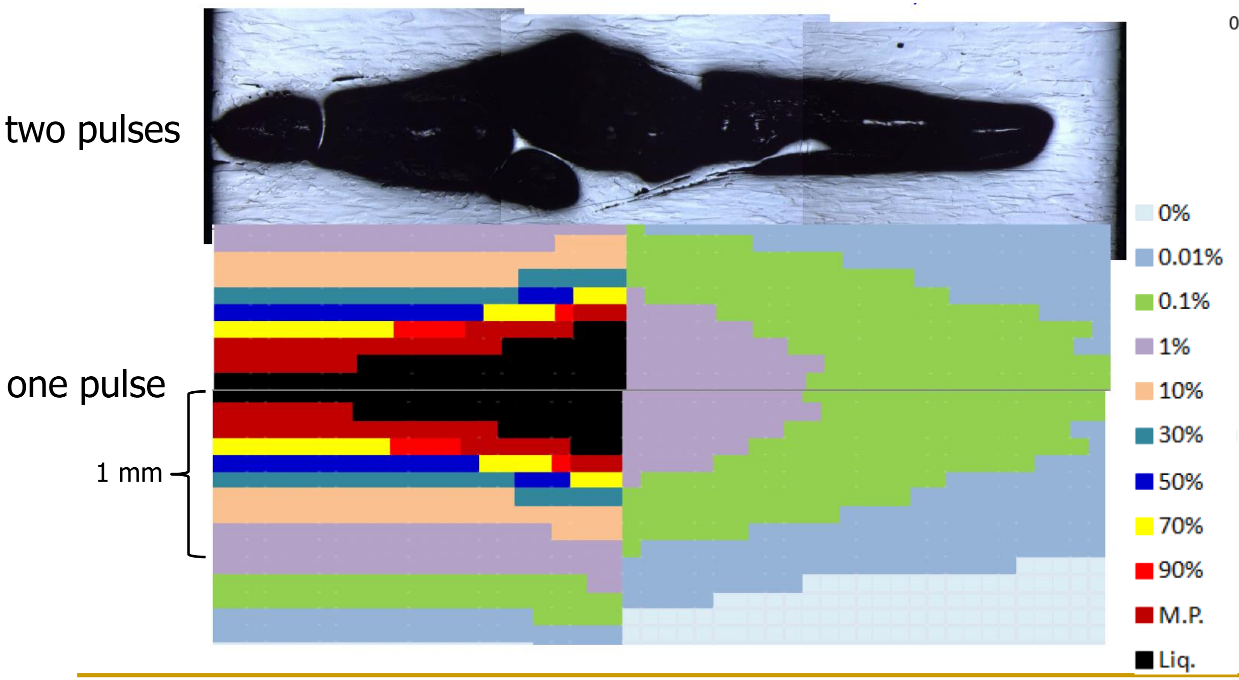
HIGH Z ION BEAMS
350 MeV/n ^{238}U

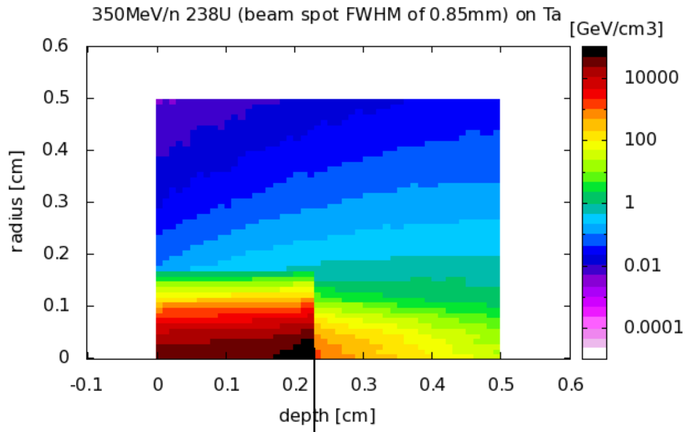
Intensity: 2.4 10^9 ions per pulse

Beam size: 0.85 mm FWHM

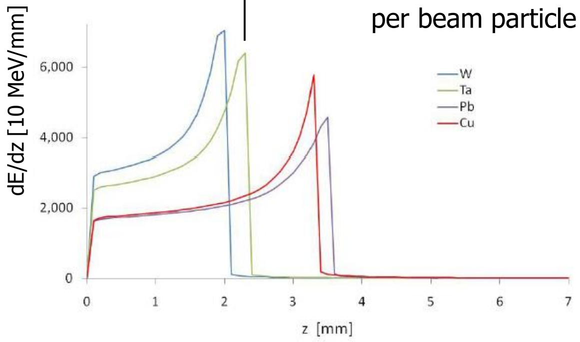
tantalum target

GSI S-334 experiment (courtesy of J. Lettry)



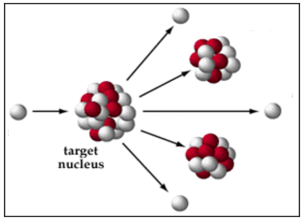


per beam particle



HIGH ENERGY PROTON BEAMS

Beam particles cannot come to rest
and are lost by nuclear non-elastic interaction …



inelastic scattering length

beam protons

$$\lambda\rho = \frac{A}{\sigma_R N_A} \qquad \sigma_R \simeq \pi r_0^2 A^{2/3} \qquad P^{in}(x) = 1 - \exp(-x/\lambda)$$

multiple Coulomb scattering

beam protons

$$\theta_0 = \frac{13.6\,MeV}{\beta cp}\, z\sqrt{x/X_0}\,[1 + 0.038\log(x/X_0)]$$

Gaussian width (for small deflection angles)

	ρ [g/cm^3]	Z	X_0 [cm]	λ [cm]
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

… generating neutral pions whose decay
initiates electromagnetic showers

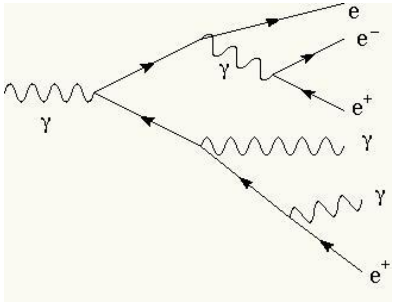
radiation length

high energy electrons and photons

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

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

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



Molière radius

electromagnetic showers

$$R_M = X_0 E_s/E_c$$

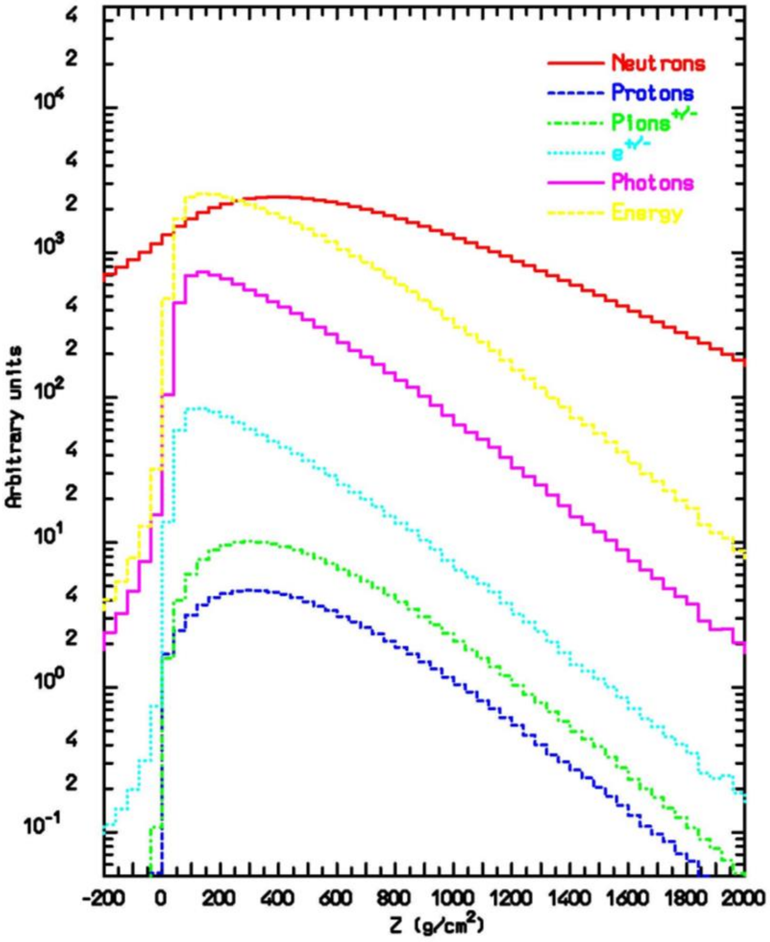
$$E_s = 21.2\,MeV$$

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

HADRONIC AND ELECTROMAGNETIC SHOWERS

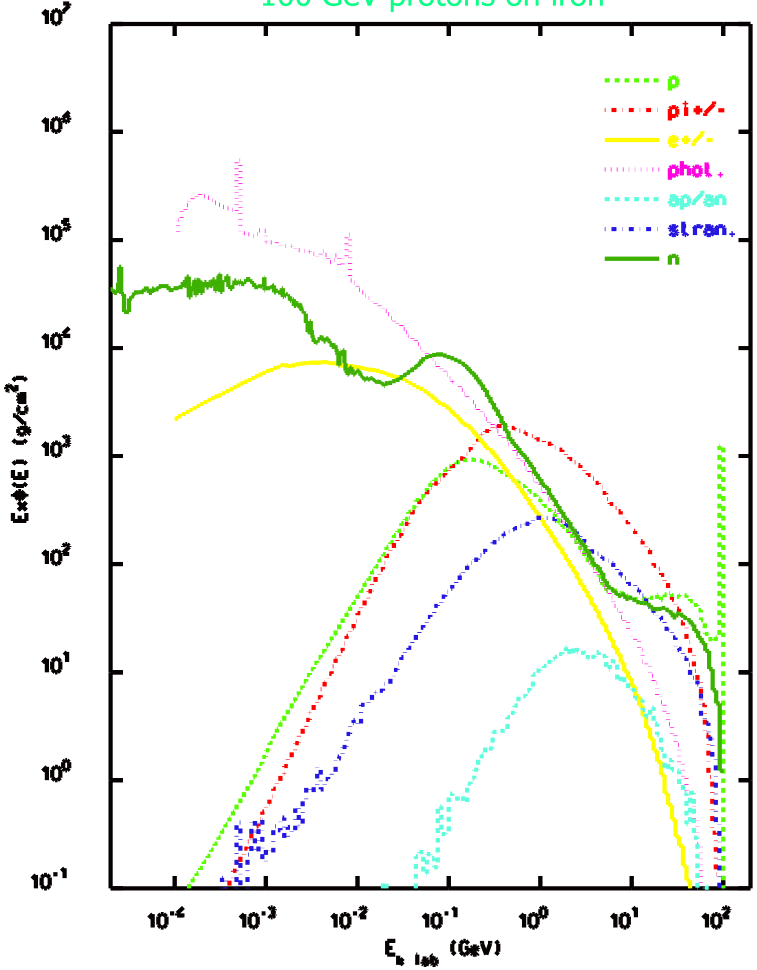
particle fluence and energy deposition development

100 GeV protons on lead



space-averaged particle spectra

100 GeV protons on iron

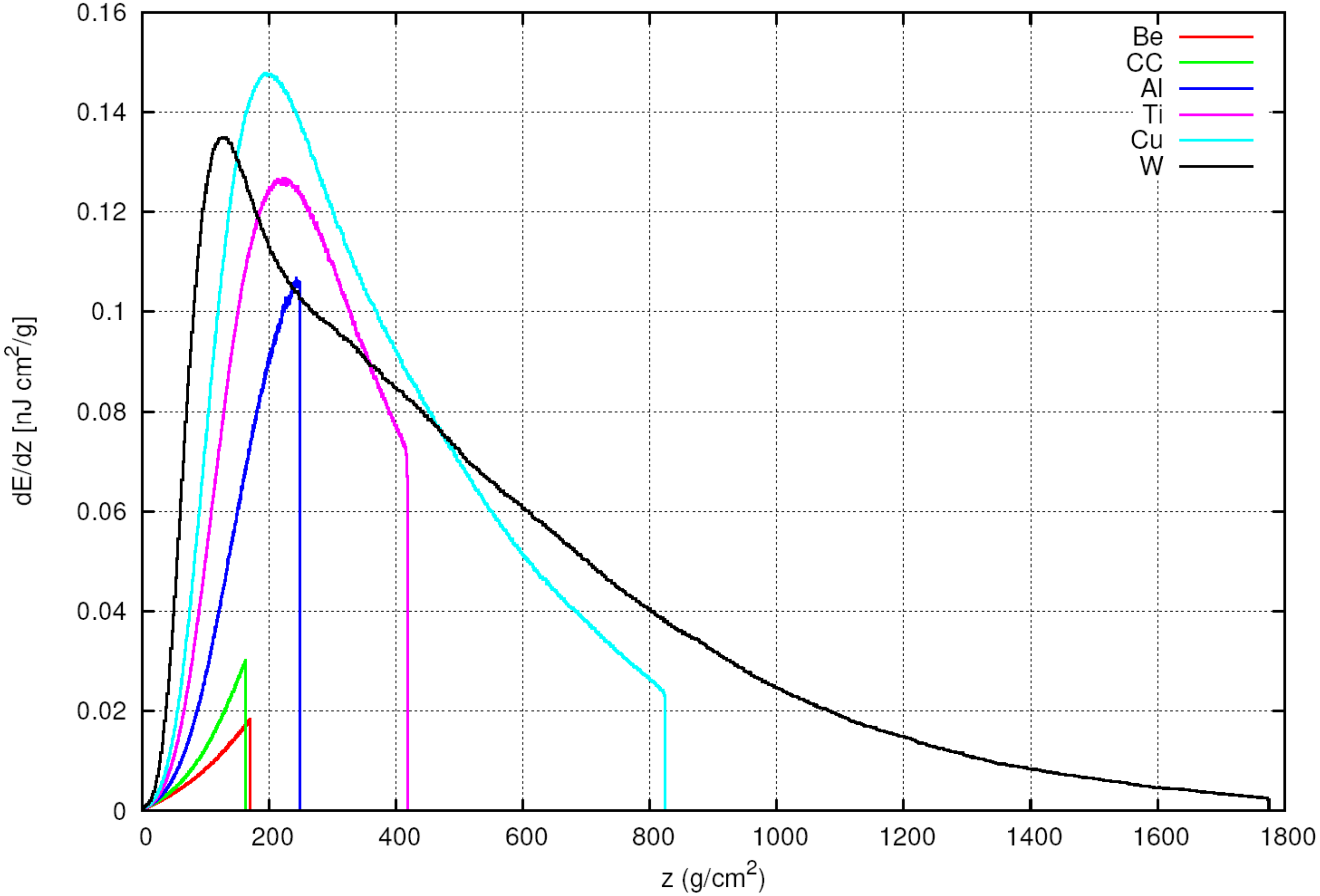


ENERGY DEPOSITION

transversally integrated

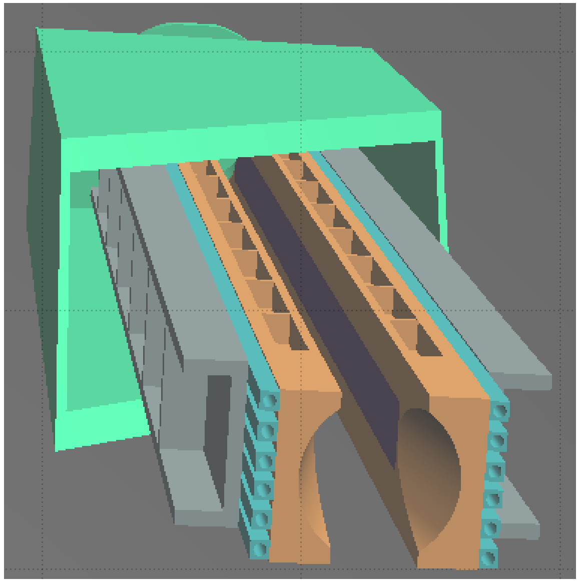
[different from *peak density* profile, which depends on beam size]

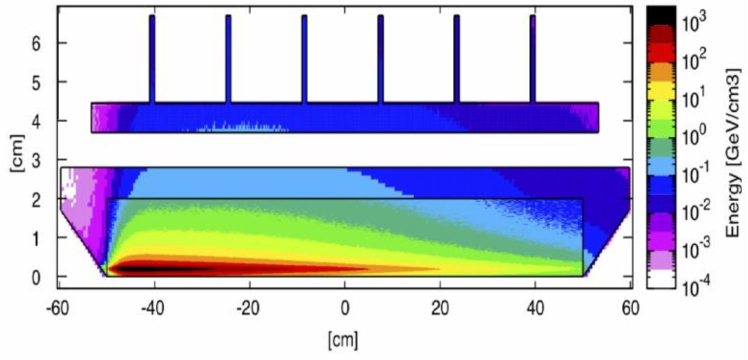
for a 7 TeV proton impacting on a 92 cm long jaw



5 TeV PROTON BUNCH ON TERTIARY COLLIMATOR [I]

__Intensity__: 1.3 10^{11} p *__Beam size__*: 1.75 μm rad norm. emittance (0.3 mm σ_x and 0.19 mm σ_y)



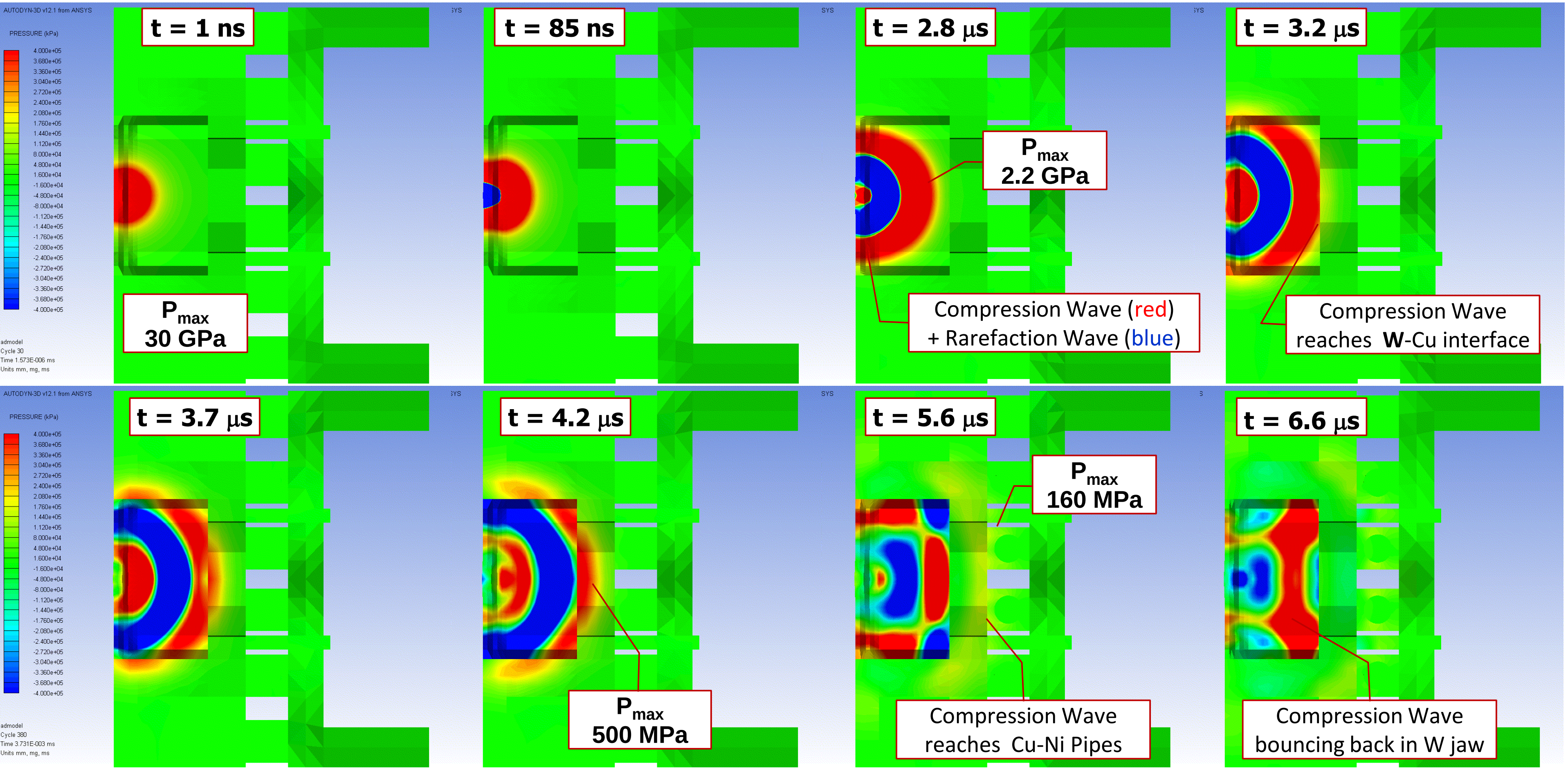


5 TeV PROTON BUNCH ON TERTIARY COLLIMATOR [I]

Intensity: 1.3 10^{11} p *Beam size*: 1.75 μm rad norm. emittance (0.3 mm σ_x and 0.19 mm σ_y)

shock wave propagation

courtesy of A. Bertarelli and his team



t = 1 ns

P_{max} 30 GPa

t = 85 ns

$t = 2.8\ \mu s$

P_{max} 2.2 GPa

Compression Wave (red) + Rarefaction Wave (blue)

$t = 3.2\ \mu s$

Compression Wave reaches **W**-Cu interface

$t = 3.7\ \mu s$

$t = 4.2\ \mu s$

P_{max} 500 MPa

$t = 5.6\ \mu s$

P_{max} 160 MPa

Compression Wave reaches Cu-Ni Pipes

$t = 6.6\ \mu s$

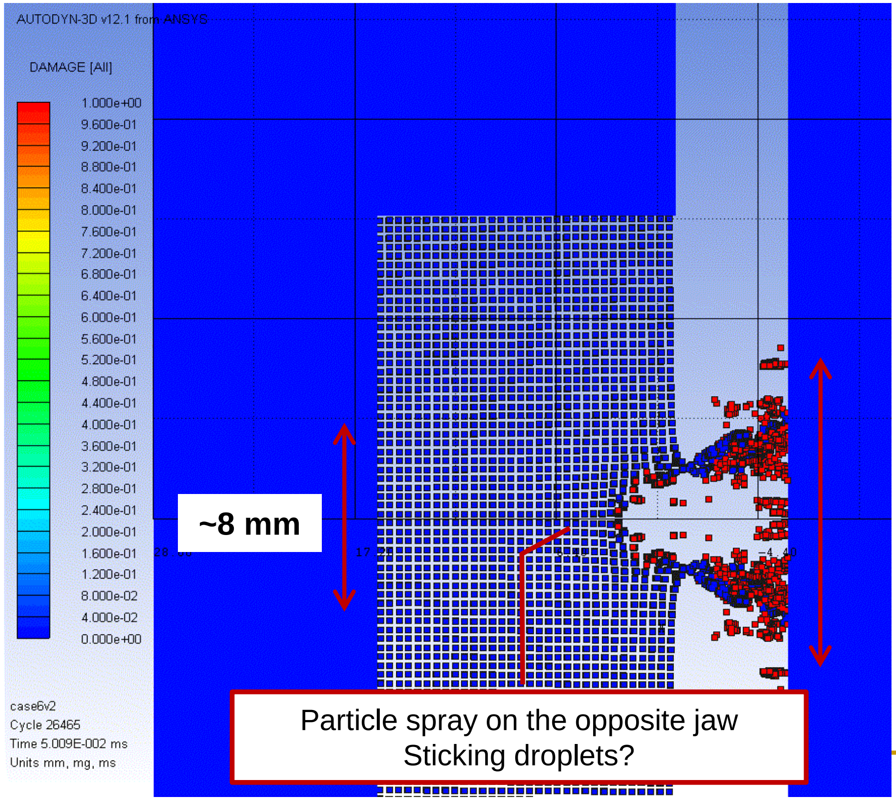
Compression Wave bouncing back in W jaw

5 TeV PROTON BUNCH ON TERTIARY COLLIMATOR [III]

Intensity: 1.3 10^{11} p

Beam size: 1.75 μm rad norm. emittance
(0.3 mm σ_x and 0.19 mm σ_y)

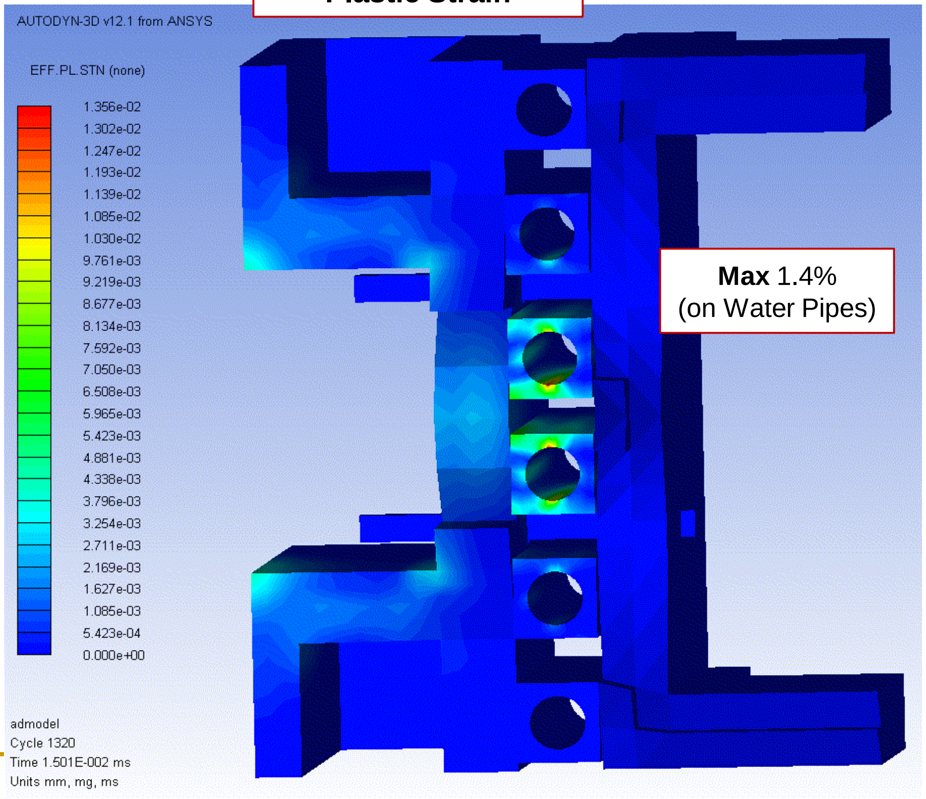
courtesy of A. Bertarelli and his team



~8 mm

Particle spray on the opposite jaw
Sticking droplets?

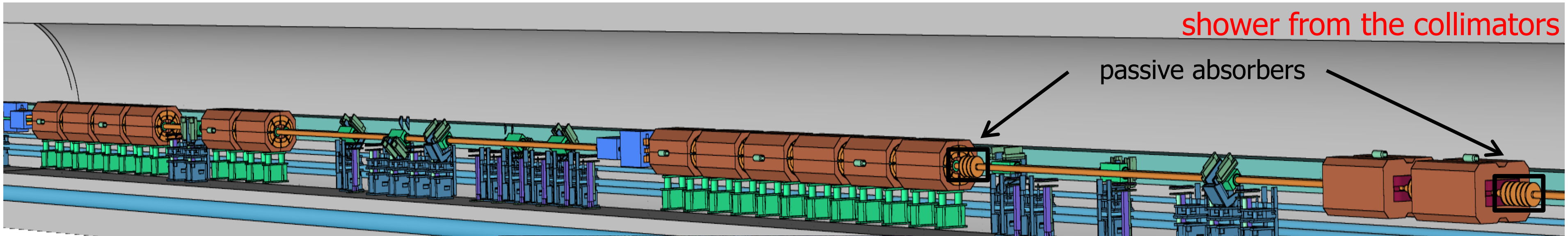
Plastic Strain



Max 1.4%
(on Water Pipes)

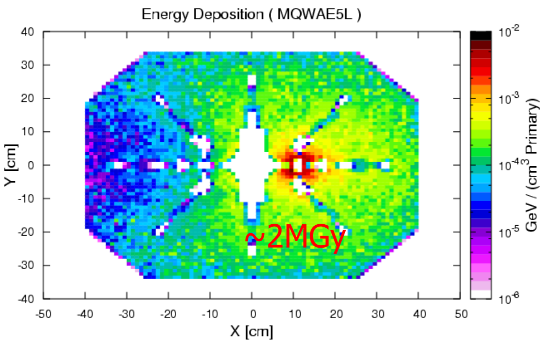
6.5 TeV PROTON BEAM REGULAR CLEANING

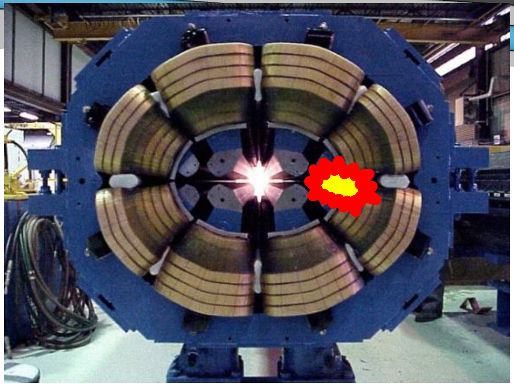
Cumulated losses: 1.15 10^{16} p per year on the betatron cleaning insertion collimators



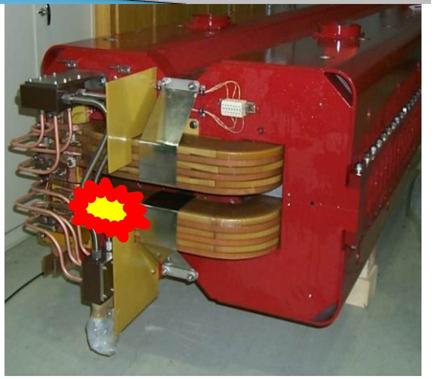
shower from the collimators

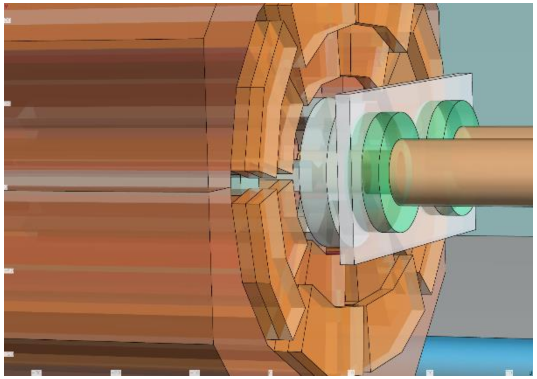
passive absorbers



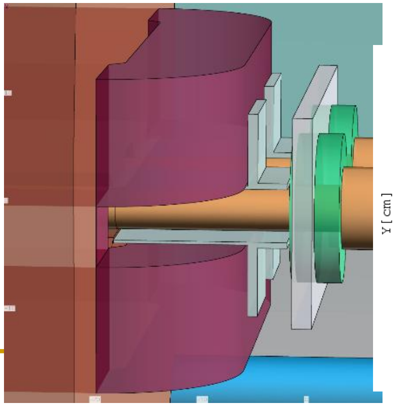


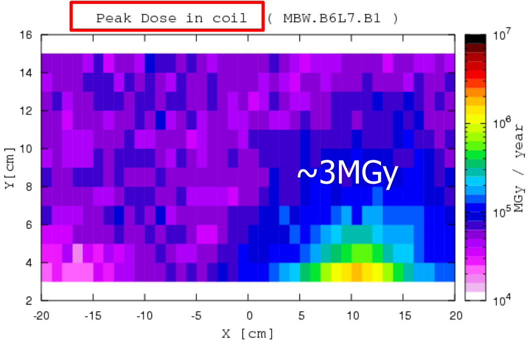
warm magnets



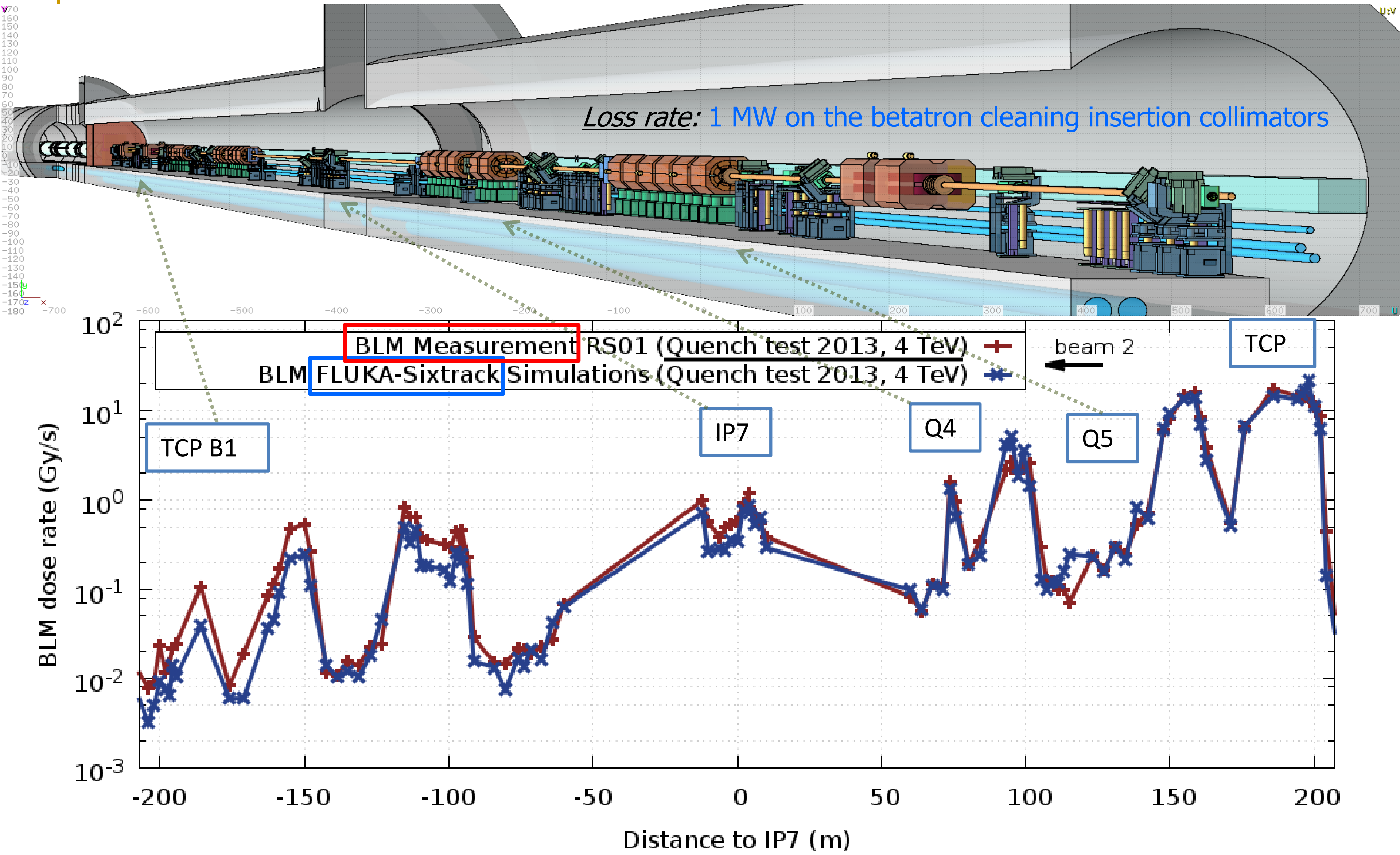


additional factor 3
peak dose reduction
provided by tungsten masks



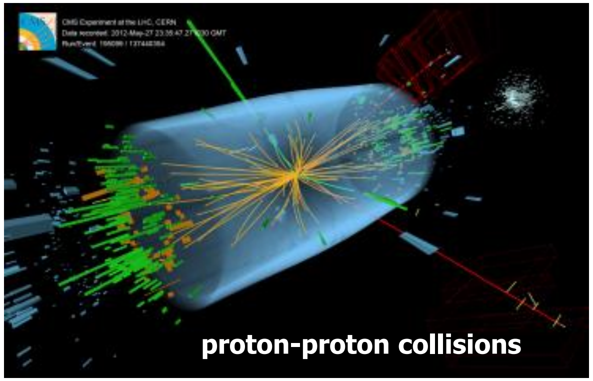


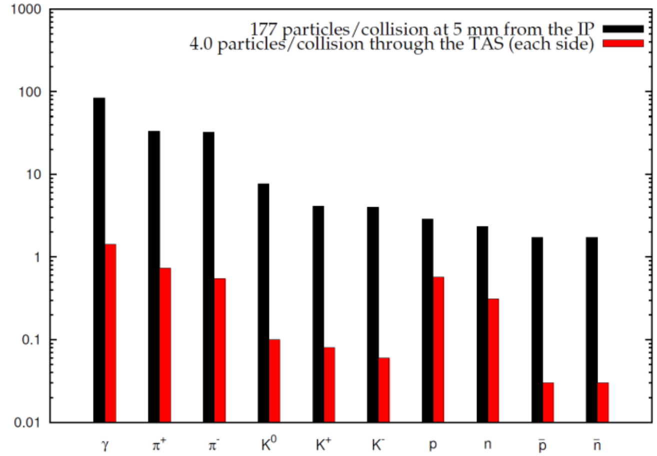
LOSS PATTERN MEASUREMENT AND PREDICTION



Loss rate: 1 MW on the betatron cleaning insertion collimators

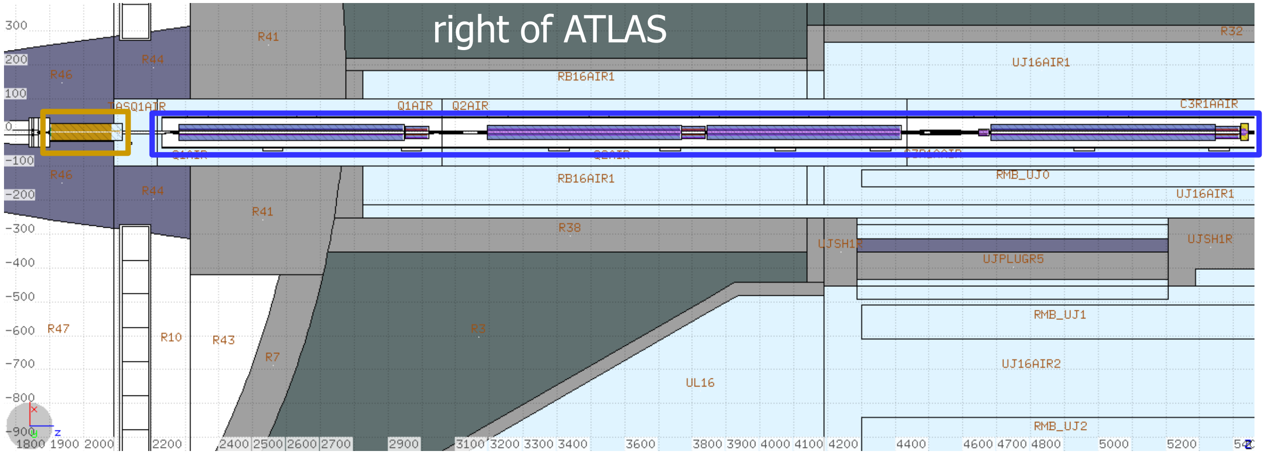
THE LHC 14 TeV CoM COLLISION DEBRIS





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

950 W towards each (L&R) side



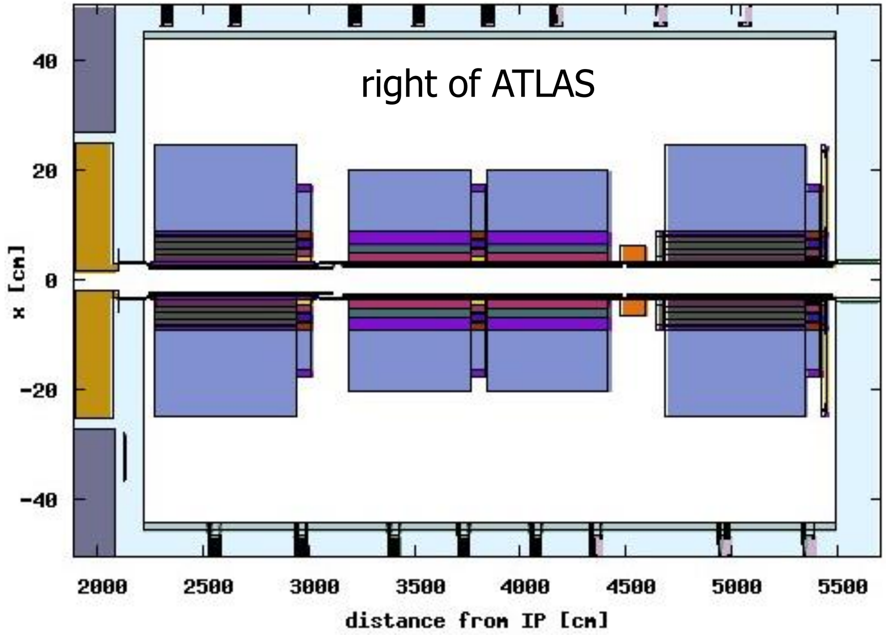
150 W absorbed in the TAS

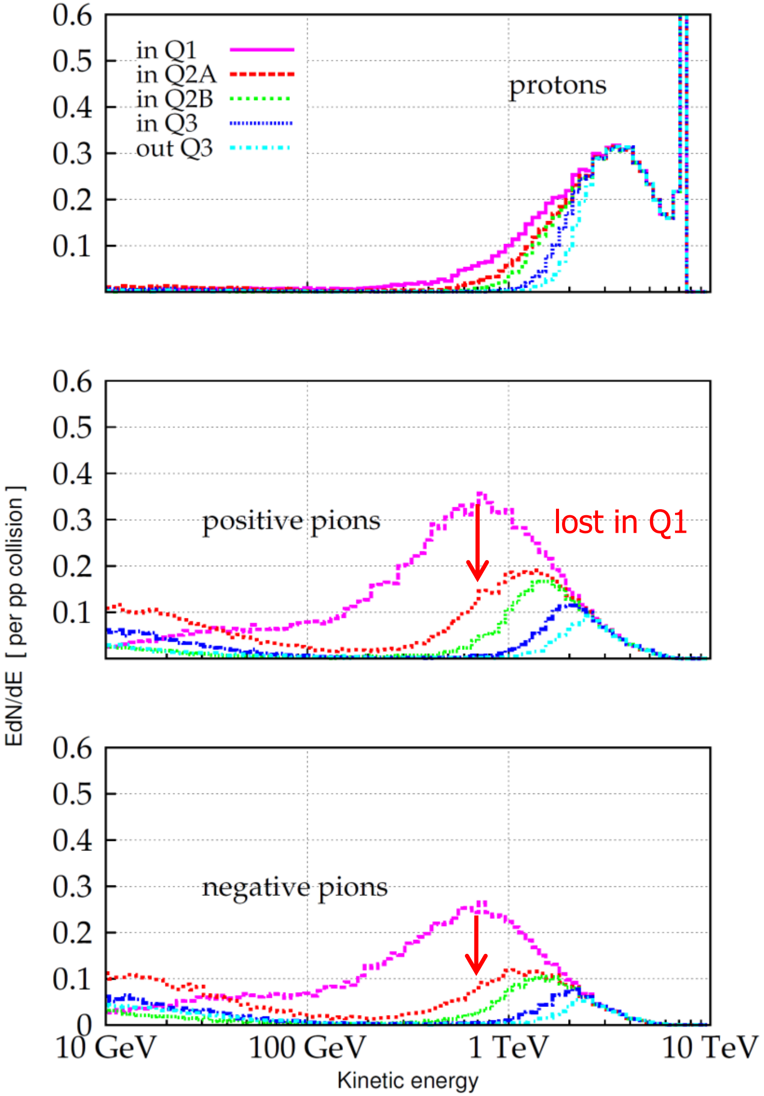
650 W going through the TAS

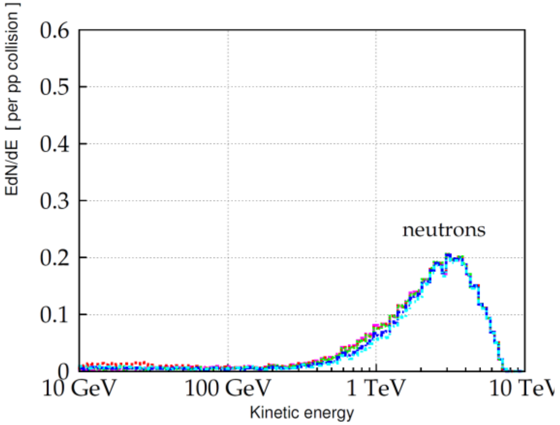
of which

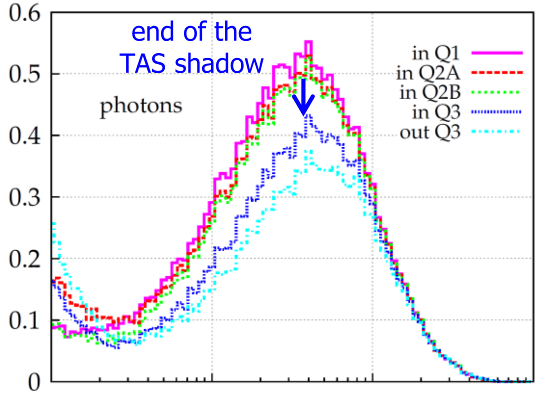
150 W absorbed in the triplet cold magnets

DEBRIS CAPTURE IN THE "TRIPLET"

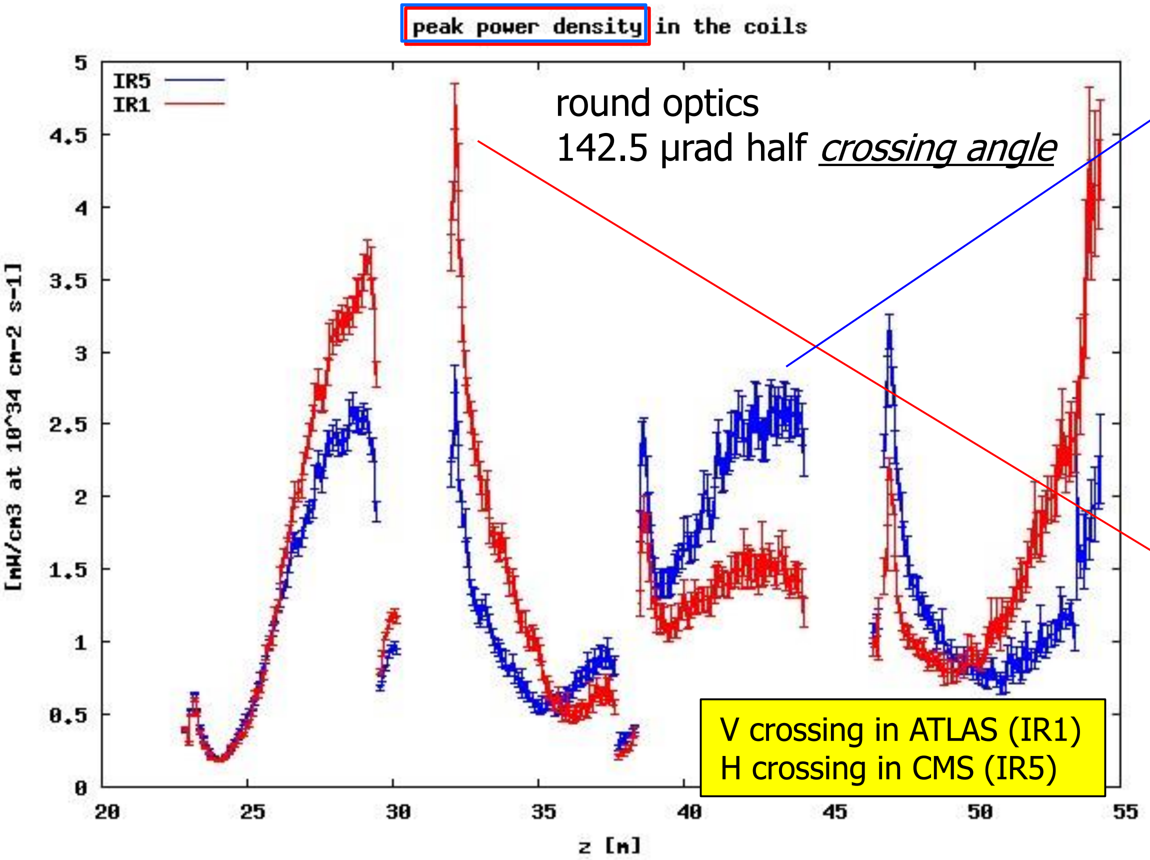






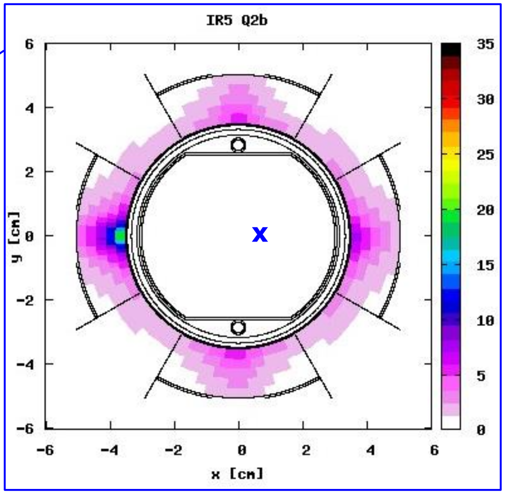


MARGIN TO QUENCH

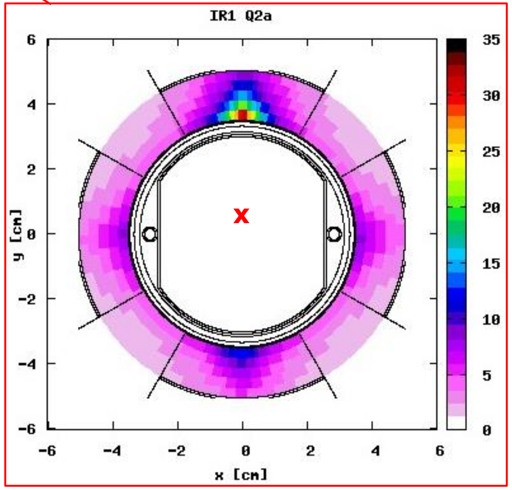


round optics
142.5 μrad half *crossing angle*

V crossing in ATLAS (IR1)
H crossing in CMS (IR5)



peak dose [MGy] after 300 fb^{-1}, relevant for triplet (i.e. coil insulator) lifetime



- different behavior reflecting the crossing plane variation for the same magnetic configuration of the triplet (FDF in the horizontal plane for positively charged particles coming from the IP)
- IR1 triplet (Q2a) reaches the design limit at nominal luminosity

DISPLACEMENTS PER ATOM

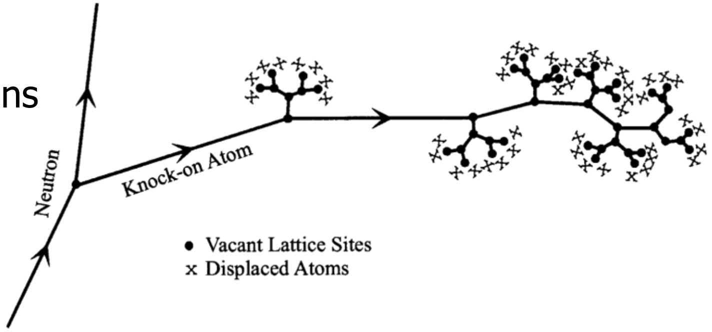
It is a “measure” of the amount of radiation damage in inorganic materials

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

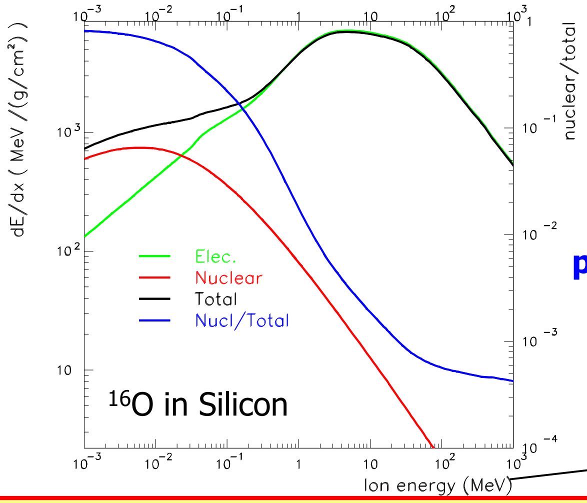
Displacement damage can be induced by all particles produced in the hadronic cascade, including high energy photons (through photonuclear reactions).

It is directly related to energy transfers to atomic nuclei

i.e. (restricted) NIEL

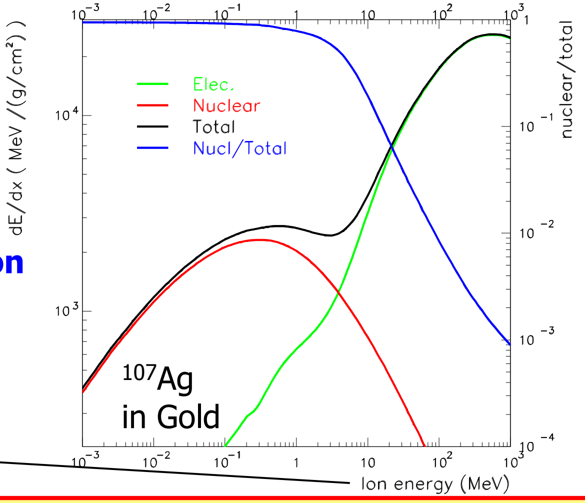


nuclear stopping power



partition function

$S_n/(S_n+S_e)$

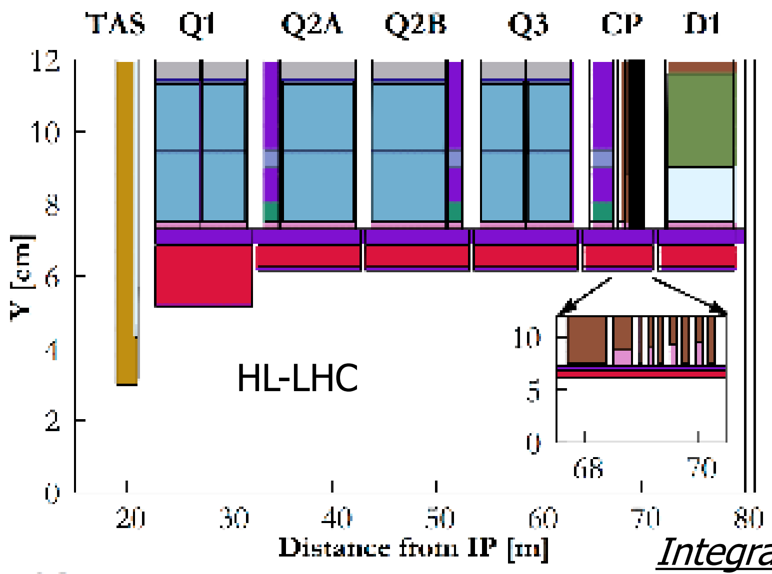


total kinetic

S_n/S is going down with energy and up with charge

→ NIEL/DPA are dominated by low energy heavy recoils!

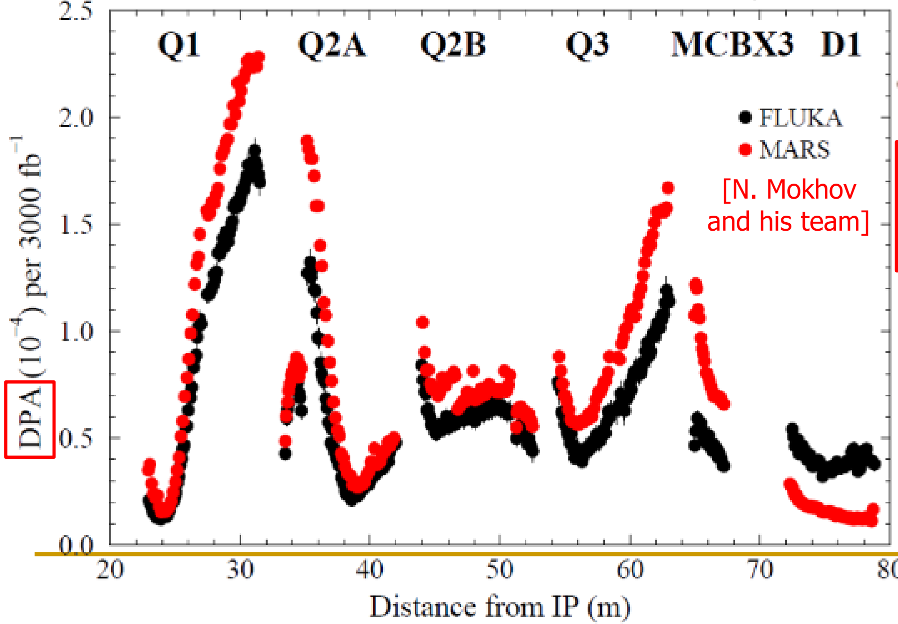
SUPERCONDUCTOR DEGRADATION



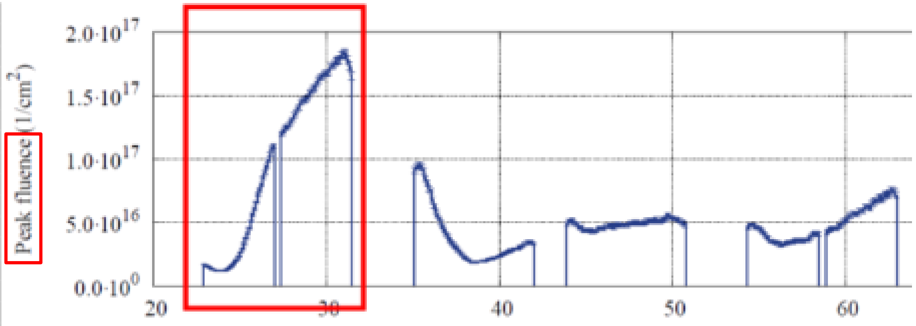
Nb_3Sn coils

tracklength fraction [%]	
photons	88
electrons/positrons	7
neutrons	4
pions	0.45
protons	0.15

Integrated luminosity: 3000 fb^{-1}



[N. Mokhov and his team]



dominant contribution to DPA
from recoils by low energy (<20 MeV) neutrons

HYDROGEN AND HELIUM GAS PRODUCTION

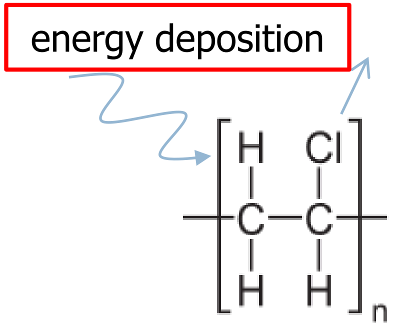
Spallation reactions induced by protons, neutrons, pions, … produce a variety of particles including protons (^{1}H), deuterons (^{2}H) , tritons (^{3}H), ^{3}He, and alphas (^{4}He). The least energetic of these products (which are also the most abundant) can stop in the target assembly giving rise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

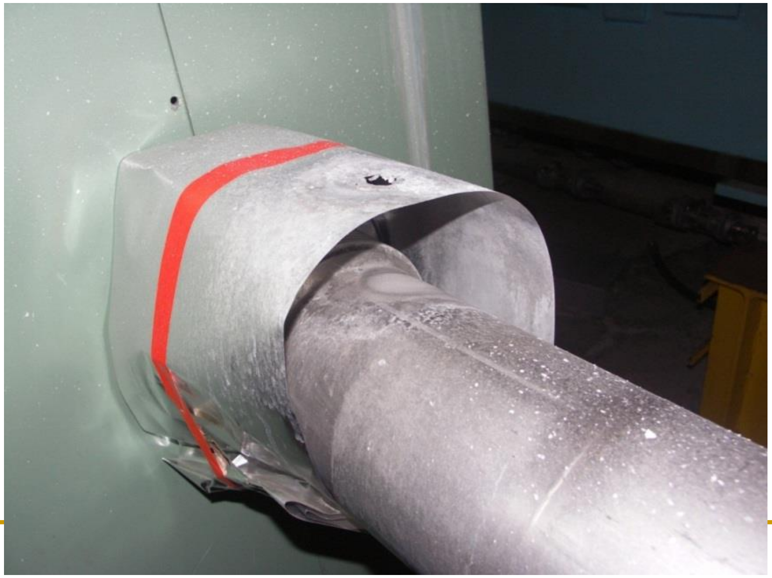
REDOX

Ionising radiation creates radicals chemically active


energy deposition

PVC dehydrochlorination by X and γ-rays

Cl^- ions react with water droplets and create a very corrosive environment



Ball bearings exposed to hadronic showers in air

OZONE PRODUCTION

$$C_{O_3} = \frac{C_{o_2} G P_{eV} \tau}{N_{Av}\left(\frac{\rho_{Air} V}{A_{Air}}\right)}\left(1-\mathrm{e}^{-\frac{t}{\tau}}\right) \qquad \tau = (\alpha + 1/\tau_{vent})^{-1} \quad \alpha = 2.3\cdot 10^{-4}\,[\mathrm{s}^{-1}] \quad O_3 \text{ dissociation constant}$$

conversion factor

$$C_{O_2} = 0.232 \quad \boxed{G = 0.06 - 0.074\ \ [\mathrm{O_3/eV}]} \quad N_{Av}\frac{\rho_{Air}}{A_{Air}} @\, NTP = 2.50\cdot 10^{19}\,[\mathrm{molecules/cm^3}]$$

$$\boxed{P_{eV}\,[\mathrm{eV/s}] = 6.24\cdot 10^{18}\,P[\mathrm{W}]} \qquad \dot{r} = \frac{1}{\tau_{vent}}[\text{air renewal/s}]$$

deposited power

$$C_{O_3}[\mathrm{ppm}] = 9.28\cdot 10^{-15}\,G[\mathrm{eV}^{-1}]\,\frac{P_{eV}\,[\mathrm{eV/s}]\,\tau[s]}{V[\mathrm{cm^3}]}\left(1-\mathrm{e}^{-\frac{t}{\tau}}\right)$$

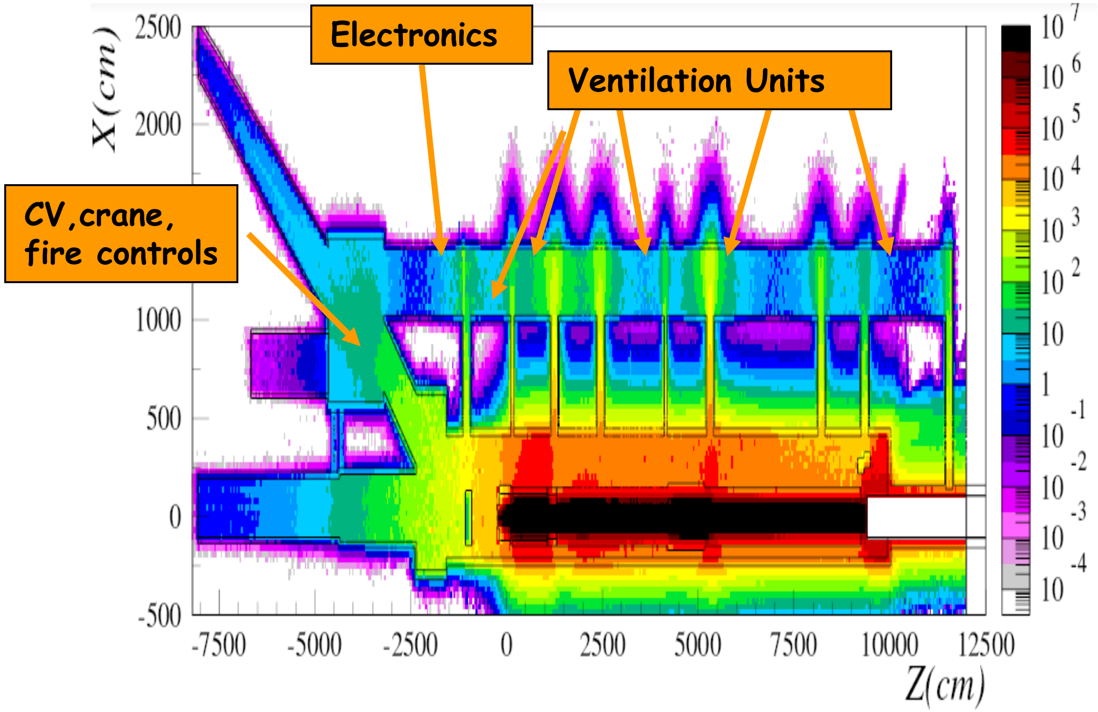
[NCRP Report 51, LEP Note 379]

under the assumption of no O_3 *decomposition*
(yielding in the τ expression a neglected term kP_{eV}/V with k decomposition constant equal to 1.4 10^{-16} cm^3/eV)

ELECTRONICS FAILURES [I]

CNGS 2007 physics run, 8 10^{17} protons on target delivered (≈2% of a nominal CNGS year)

Gy per 4.5 10^{19} p.o.t.



Predicted *dose* levels

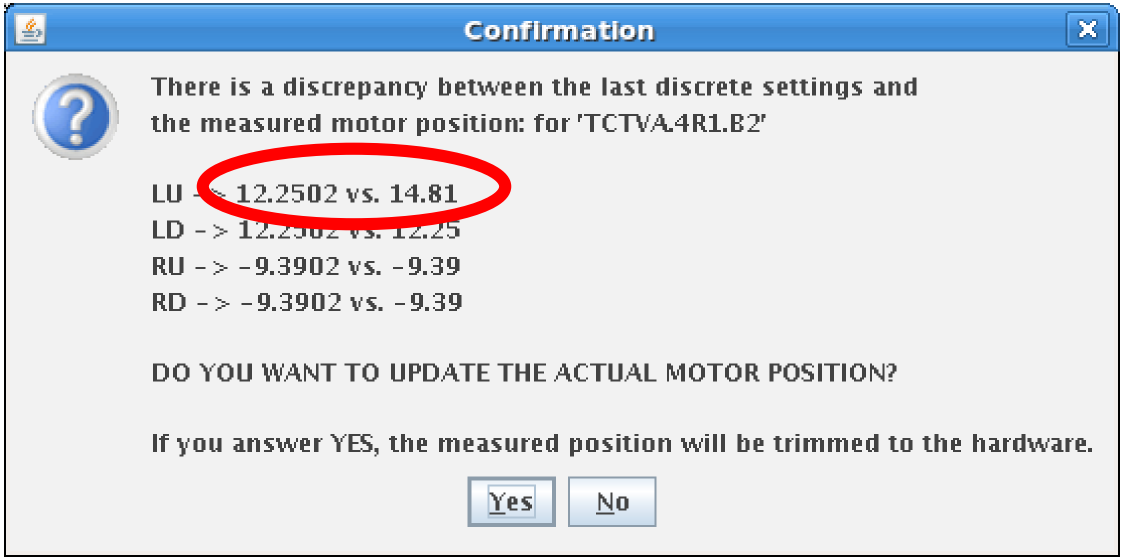
[in agreement with measurements]

Single event upsets in ventilation electronics caused

ventilation control failure and interruption of communication

ELECTRONICS FAILURES [II]

collimator controls



There is a discrepancy between the last discrete settings and the measured motor position: for 'TCTVA.4R1.B2'

LU -> 12.2502 vs. 14.81
LD -> 12.2502 vs. 12.25
RU -> -9.3902 vs. -9.39
RD -> -9.3902 vs. -9.39

DO YOU WANT TO UPDATE THE ACTUAL MOTOR POSITION?

If you answer YES, the measured position will be trimmed to the hardware.

	position	register															
resolver	12.250	4900		0	1	0	0	1	1	0	0	1	0	0	1	0	0
counter	14.810	5924		0	1	0	1	1	1	0	0	1	0	0	1	0	0

MAIN RADIATION EFFECTS ON ELECTRONICS

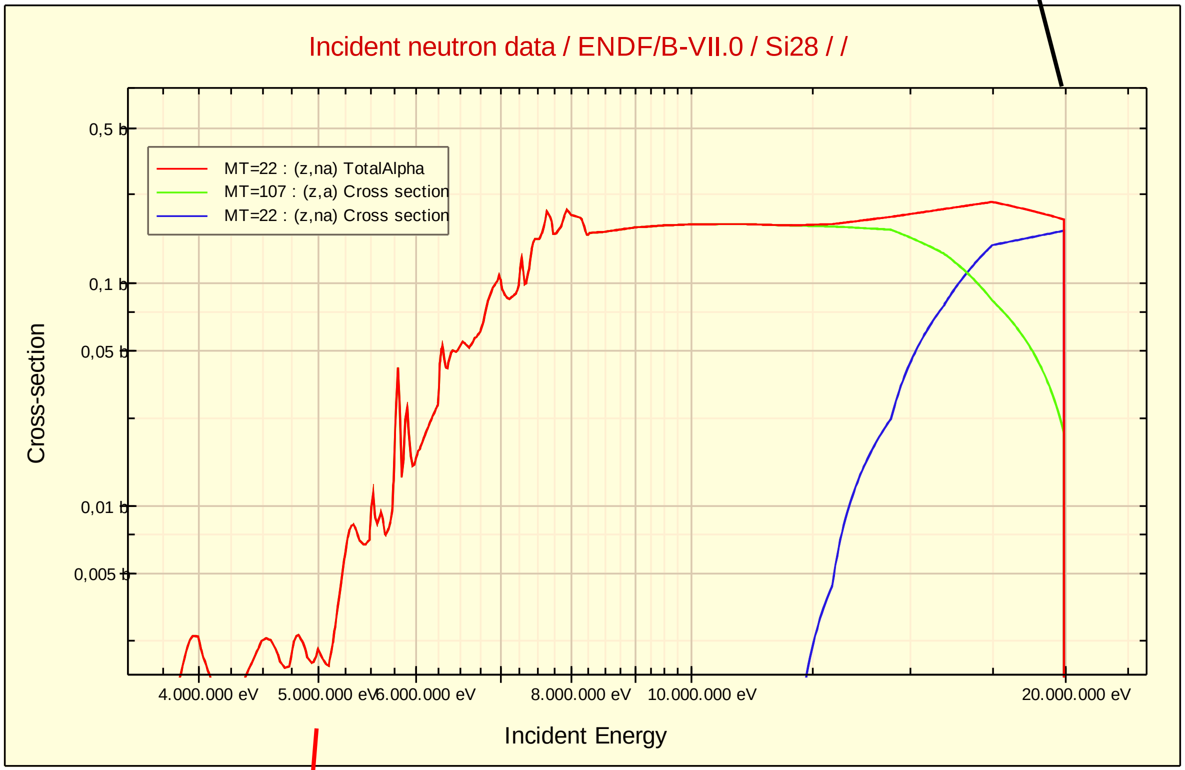
			relevant physical quantity the effect is scaling with
Single Event effects (Random in time)	***Single Event Upset (SEU)***	Memory bit flip (soft error) Temporary functional failure	High energy hadron fluence [cm^{-2}] (but also thermal neutrons!)
	Single Event Latchup (SEL)	Abnormal high current state Permanent/destructive if not protected	High energy hadron fluence [cm^{-2}]
Cumulative effects (Long term)	***Total Ionizing Dose (TID)***	Charge build-up in oxide Threshold shift & increased leakage current Ultimately destructive	Ionizing dose [Gy]
	Displacement damage	Atomic displacements Degradation over time Ultimately destructive	Silicon 1 MeV-equivalent neutron fluence [cm^{-2}] {NIEL -> DPA}

HOW HIGH ENERGY HADRONS?

plus

^{28}Si(n,xα) cross section

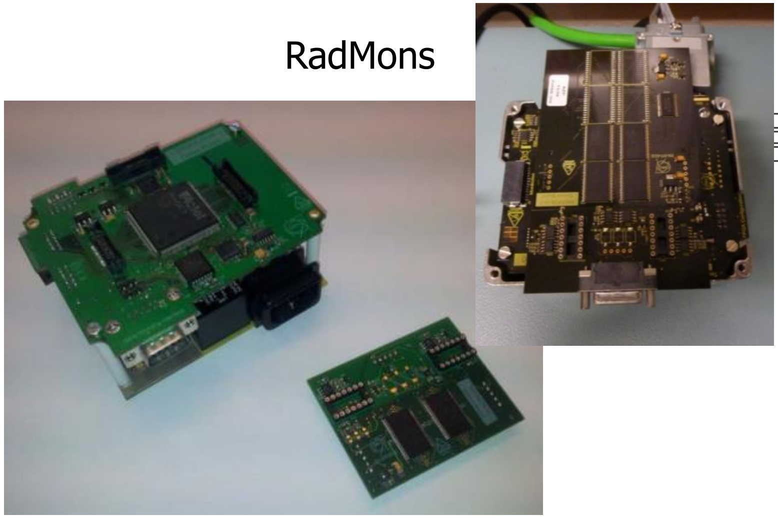
>20 MeV

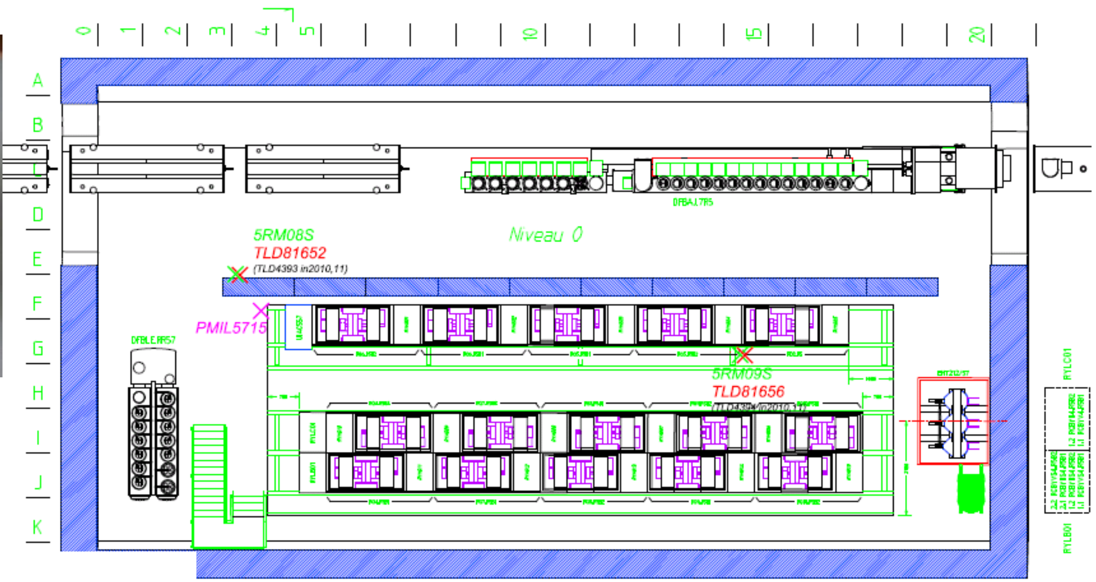


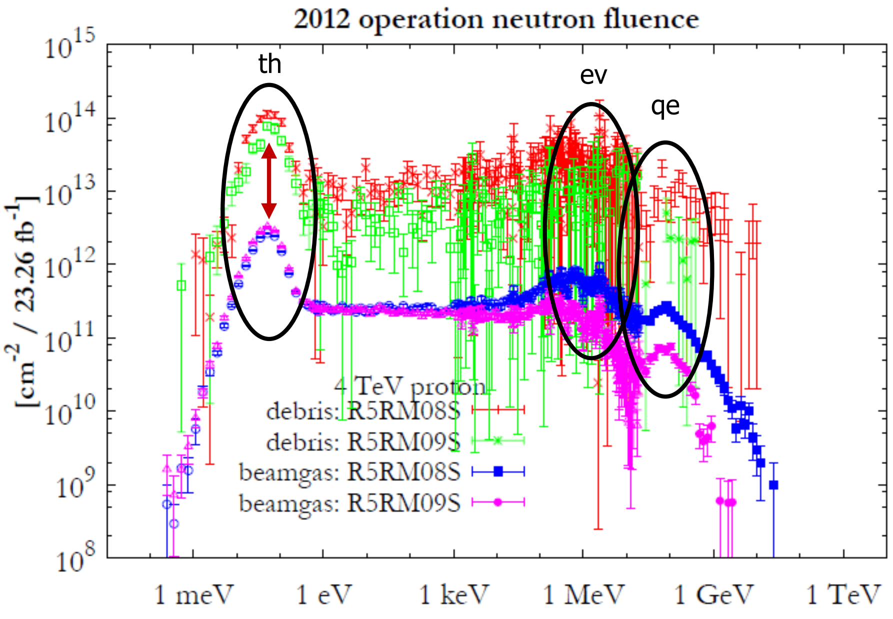
5 MeV

MONITORING AND BENCHMARKING

RadMons



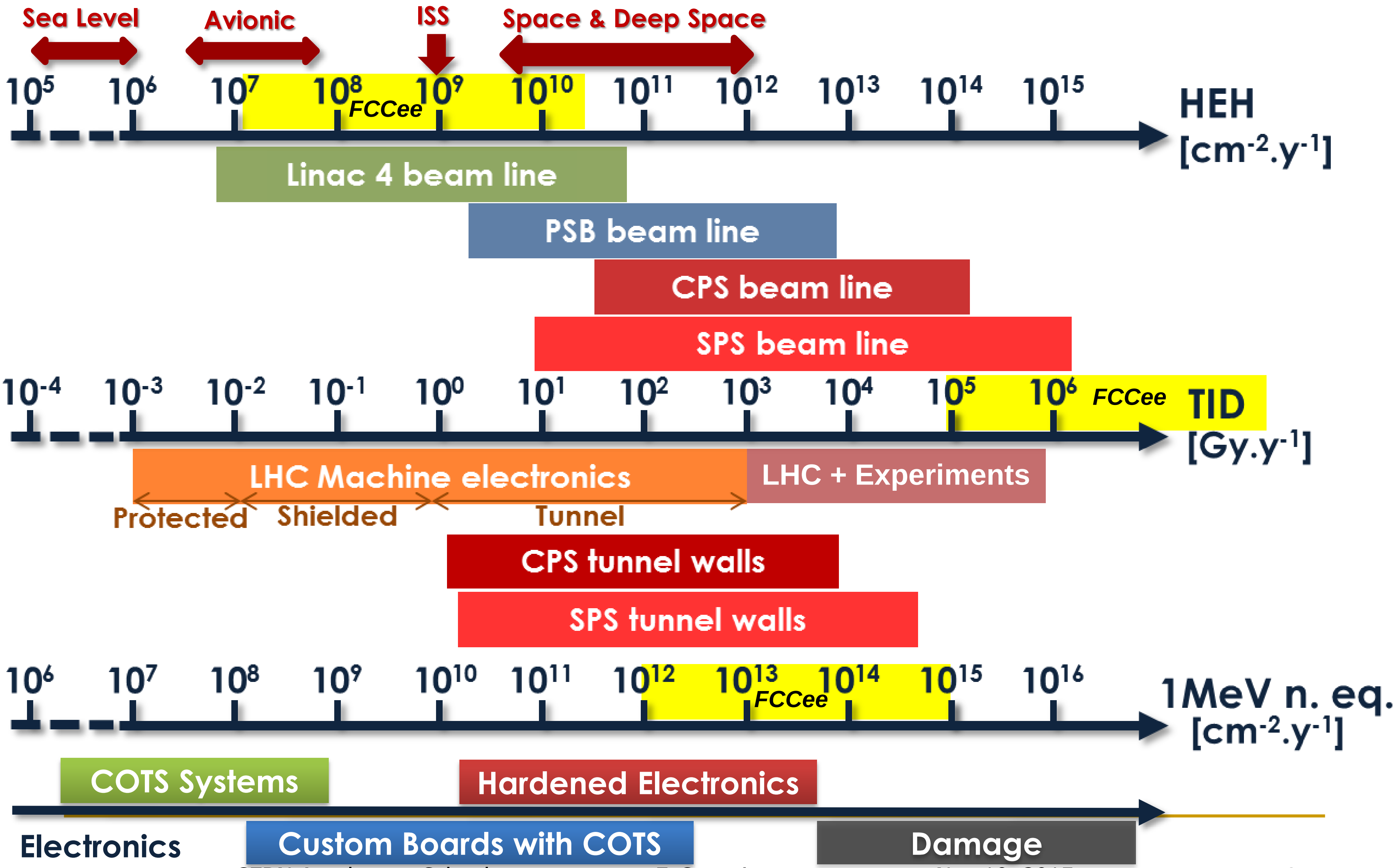




$F_{H>20MeV}$ [cm^{-2}] (L_{2012})	5RM08S	5RM09S
FLUKA	6.1 10^8	3.0 10^7
DATA	4.56 10^8 (256 upsets)	4.32 10^7 (25 upsets)

Agreement within 30%

RADIATION LEVELS



Sea Level

Avionic

ISS

Space & Deep Space

10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15}

FCCee

HEH $[cm^{-2}.y^{-1}]$

Linac 4 beam line

PSB beam line

CPS beam line

SPS beam line

10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}

FCCee

TID $[Gy.y^{-1}]$

LHC Machine electronics

LHC + Experiments

Protected

Shielded

Tunnel

CPS tunnel walls

SPS tunnel walls

10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16}

FCCee

1MeV n. eq. $[cm^{-2}.y^{-1}]$

COTS Systems

Hardened Electronics

Electronics

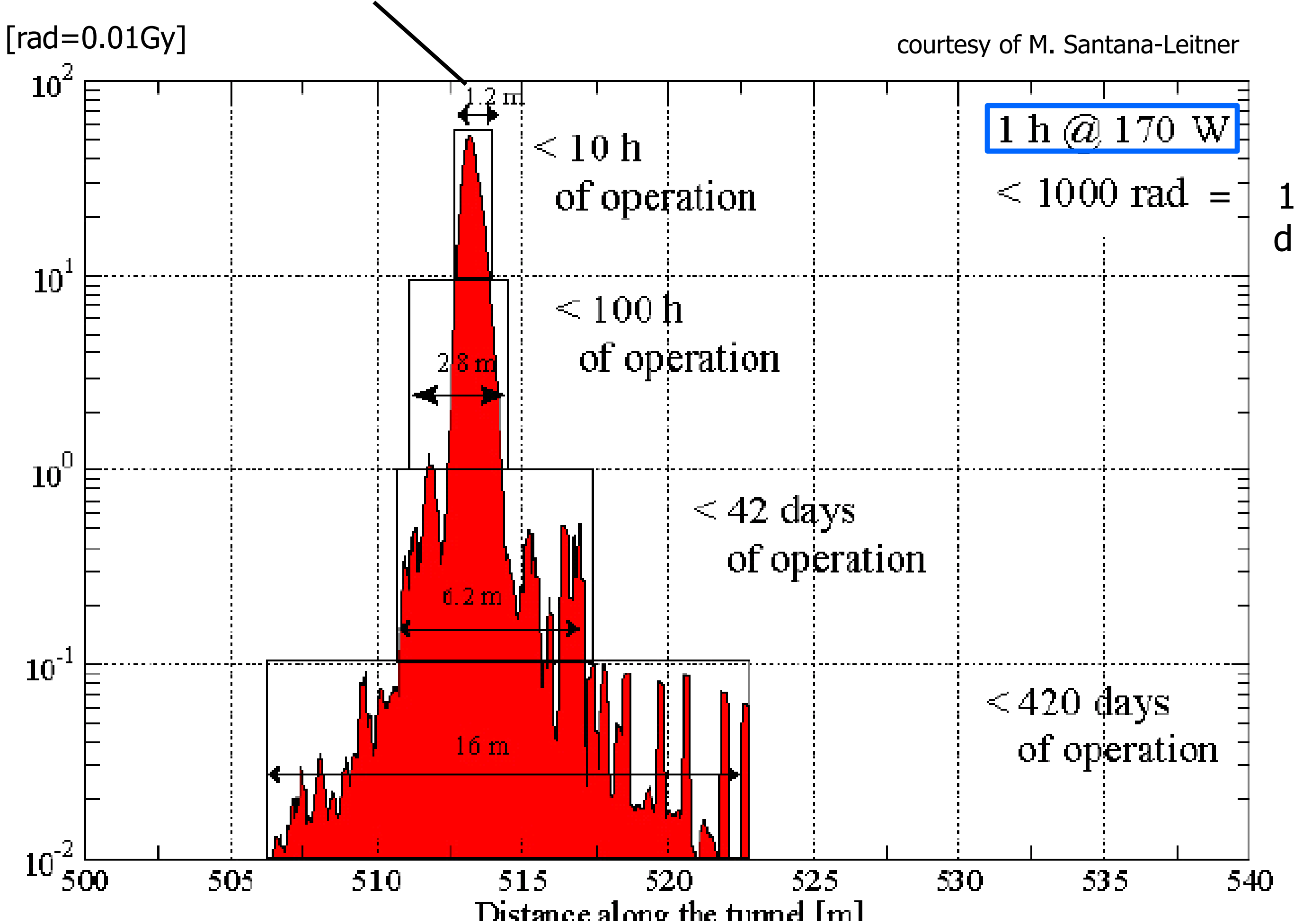
Custom Boards with COTS

Damage

17 GeV ELECTRON BEAM ENVIRONMENT

dump of the ***L**inear **C**oherent **L**ight **S**ource* @ SLAC

courtesy of M. Santana-Leitner



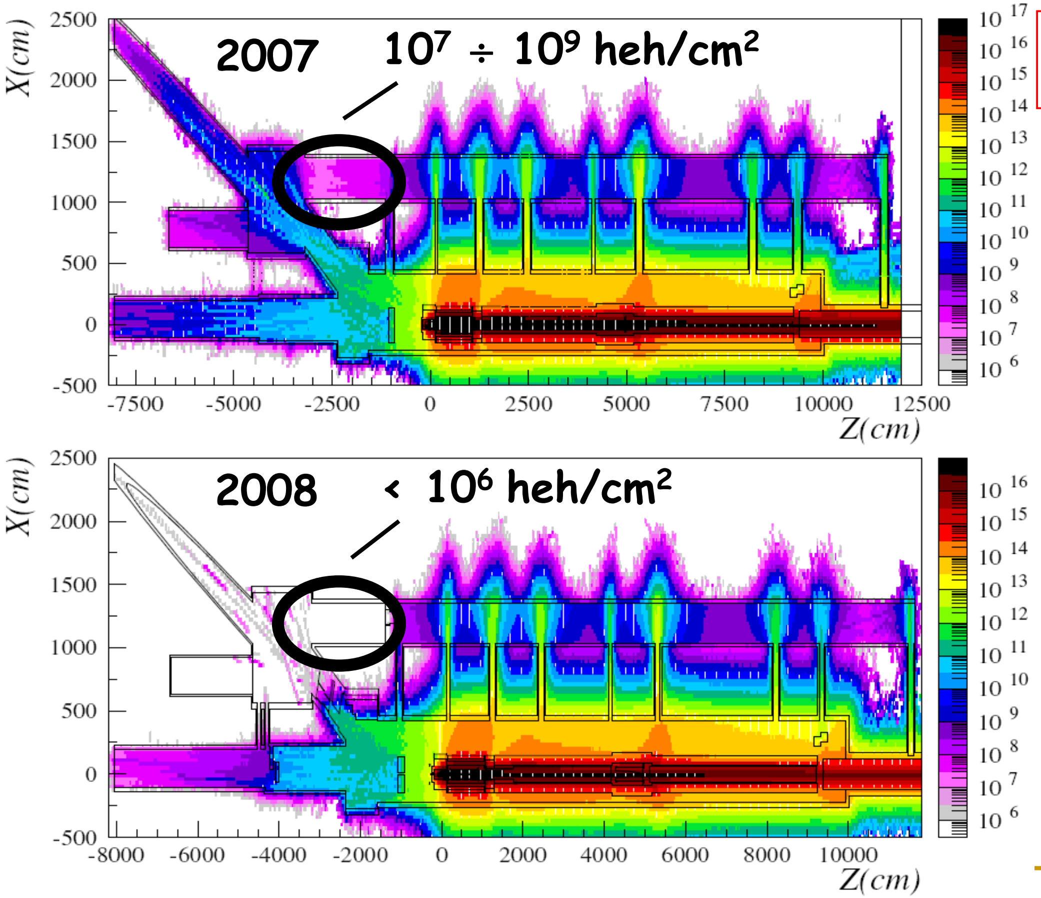
10 Gy
dose limit

role of **photoneutrons**!

MITIGATION/PREVENTION STRATEGY

identify forbidden regions

→ relocate   design shielding   → install radiation resistant equipment



high energy hadron fluence per nominal CNGS year

CNGS radiation issues solved
during shutdown 2007-2008

FACILITY SHIELDING DESIGN

For **radiation protection** purposes, depending on the aspects to be considered,

particle fluence in a given location is transformed into *effective dose* or *ambient dose equivalent* (Sv)

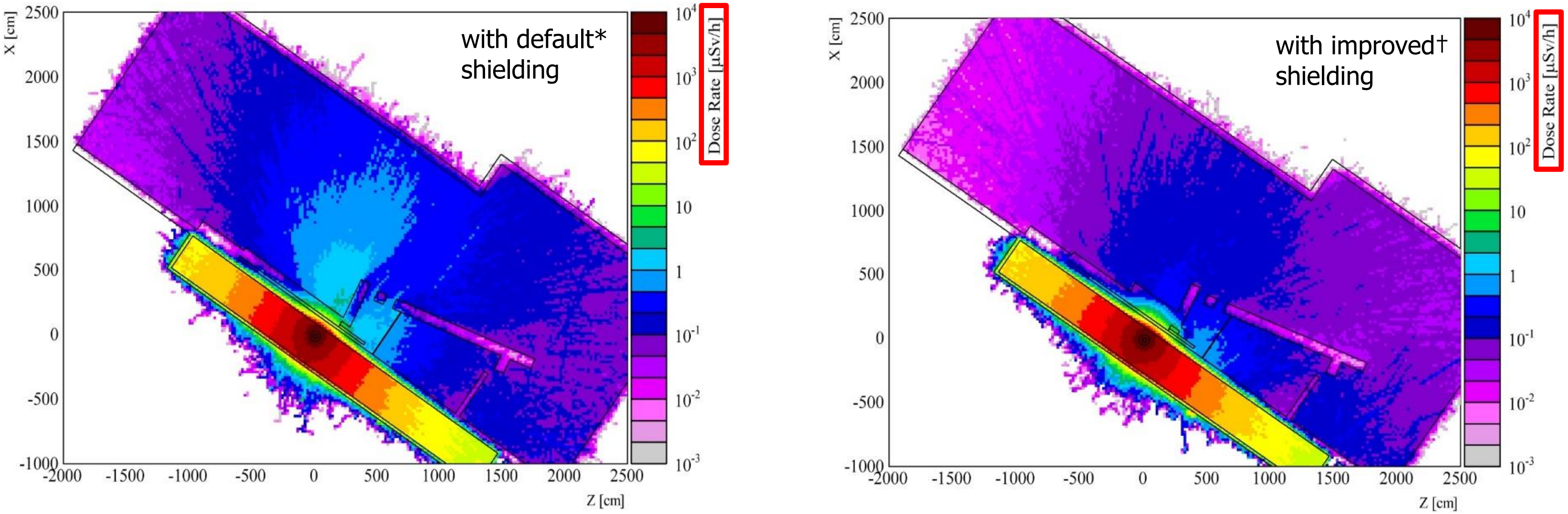
through the use of respective sets of conversion coefficients, which are a function of particle type and energy.

Prompt dose equivalent outside a radiation facility, reflecting the relevant radiation level in a public space during normal or accidental operation of the facility, is the quantity to minimize below acceptable limits.

top view of the ISR tunnel on the side of the *n_TOF EAR-2 vertical beam line*
(for neutrons from 1.6 10^{12} Hz 20 GeV/c protons on lead)

I. Bergström, V. Vlachoudis, J. Vollaire

0.5 μSv/h classification limit

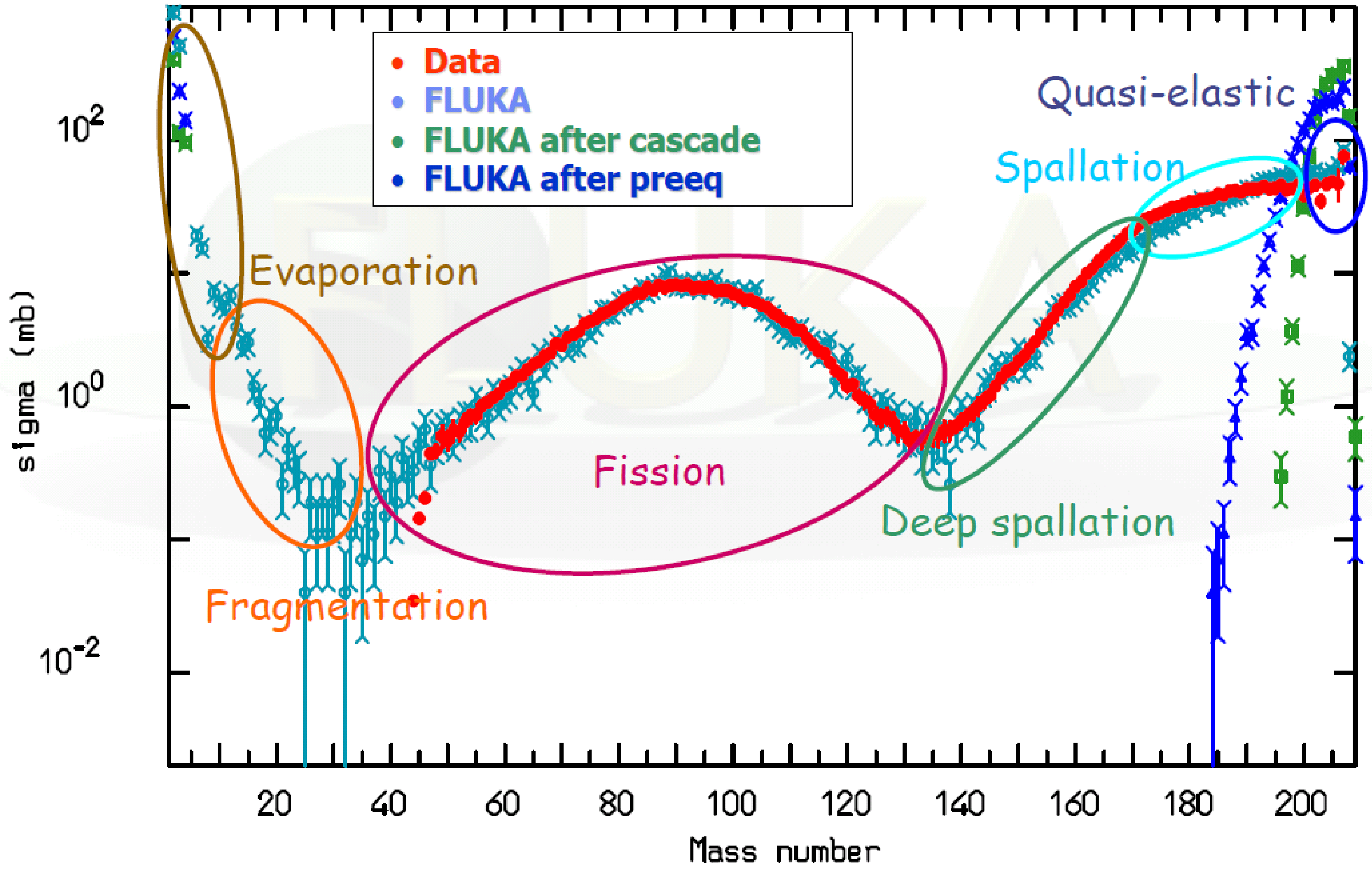


* 80 cm thick 2m high concrete block

† triple concrete volume + two iron plates

ACTIVATION

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



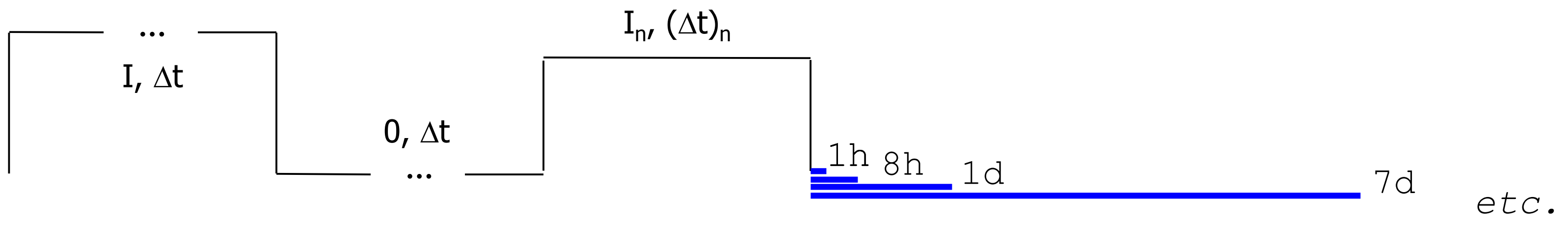
DELAYED RADIATION FROM RADIOACTIVE DECAY

Bateman equations

$$\frac{\mathrm{d}N_n}{\mathrm{d}t} = P_n + (b_{n-1,n} \cdot \lambda_{n-1} \cdot N_{n-1}) - \lambda_n \cdot N_n$$

production rate | growth by parent decay | decay

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

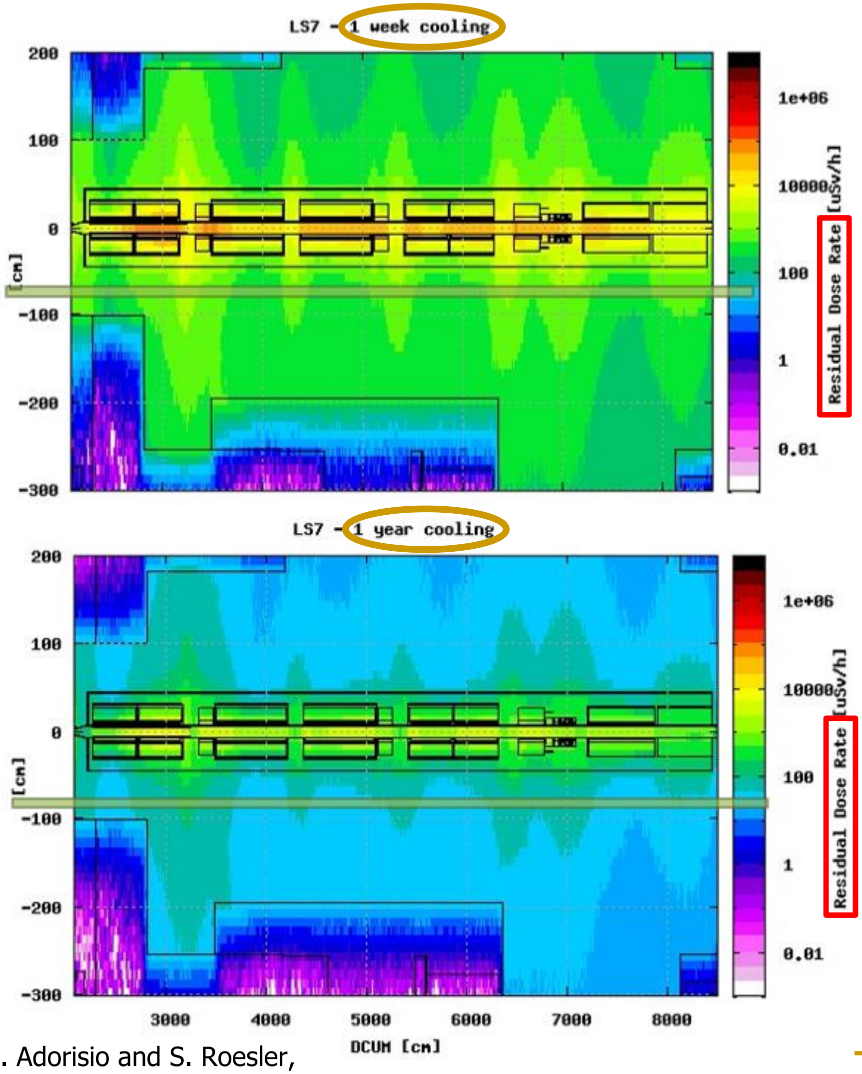


yielding (specific) activities [Bq(/g)] – to be compared to legal exemption limits –

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

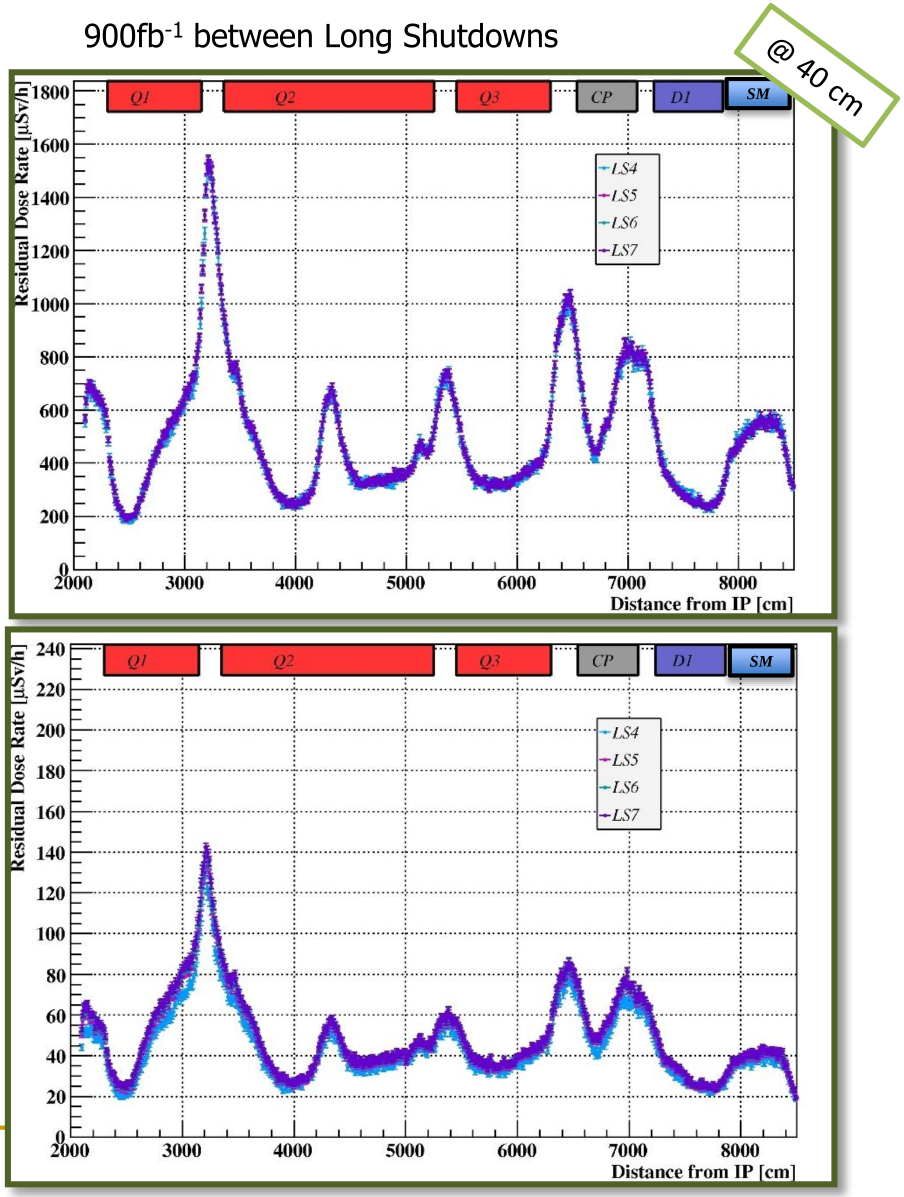
DURING SHUTDOWN

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



AIR ACTIVATION

The activity of an air radioisotope (^{7}Be, ^{11}C, ^{13}N, ^{15}O, ^{38}Cl, ^{39}Cl, etc.) in the irradiation area at the end of the irradiation period T is

$$A_T = A_S \left(1 - \exp\left(-(\lambda + m_{on})T\right)\right)$$

where m_{on} is the relative air exchange rate during irradiation, i.e. the fraction of the air volume renewed per unit time

and A_S is the saturation activity

$$A_S = \frac{V\lambda}{\lambda + m_{on}} \sum_{P,T,j} \phi_P(E_j)\sigma_{P,T}(E_j)N_T\,(\Delta E)_{j,P}$$

irradiated air volume

differential fluence rate of (hadron) particles (P=p,n,$\pi^{\pm}$)

production cross section

air atom density (T=^{12}C,^{14}N,^{16}O,^{40}Ar)

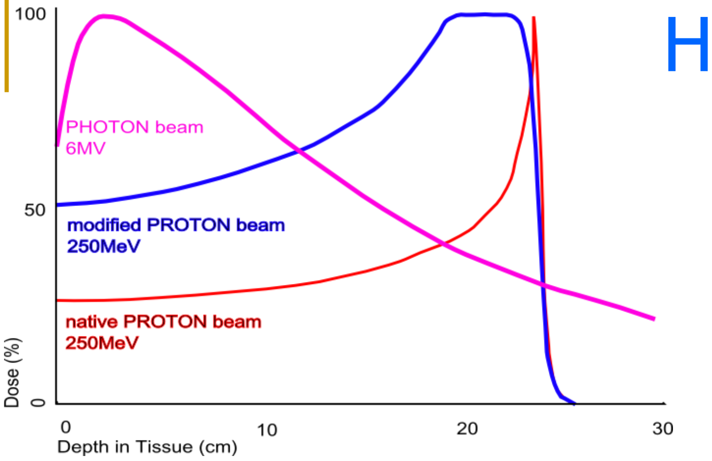
Amount of *activity released into atmosphere all along the irradiation period*
(t_{on} is the time taken by the air flux to reach the release point from the irradiated area)

$$A_{on} = m_{on} A_S \left(T - \frac{1 - \exp\left(-(\lambda + m_{on})T\right)}{\lambda + m_{on}}\right) \exp\left(-\lambda\, t_{on}\right)$$

Amount of *activity released into atmosphere after the end of the irradiation*
(m_{off} and t_{off} as m_{on} and t_{on} but referring to the shutdown period)

$$A_{off} = A_T \frac{m_{off}}{\lambda + m_{off}} \exp\left(-\lambda\, t_{off}\right)$$

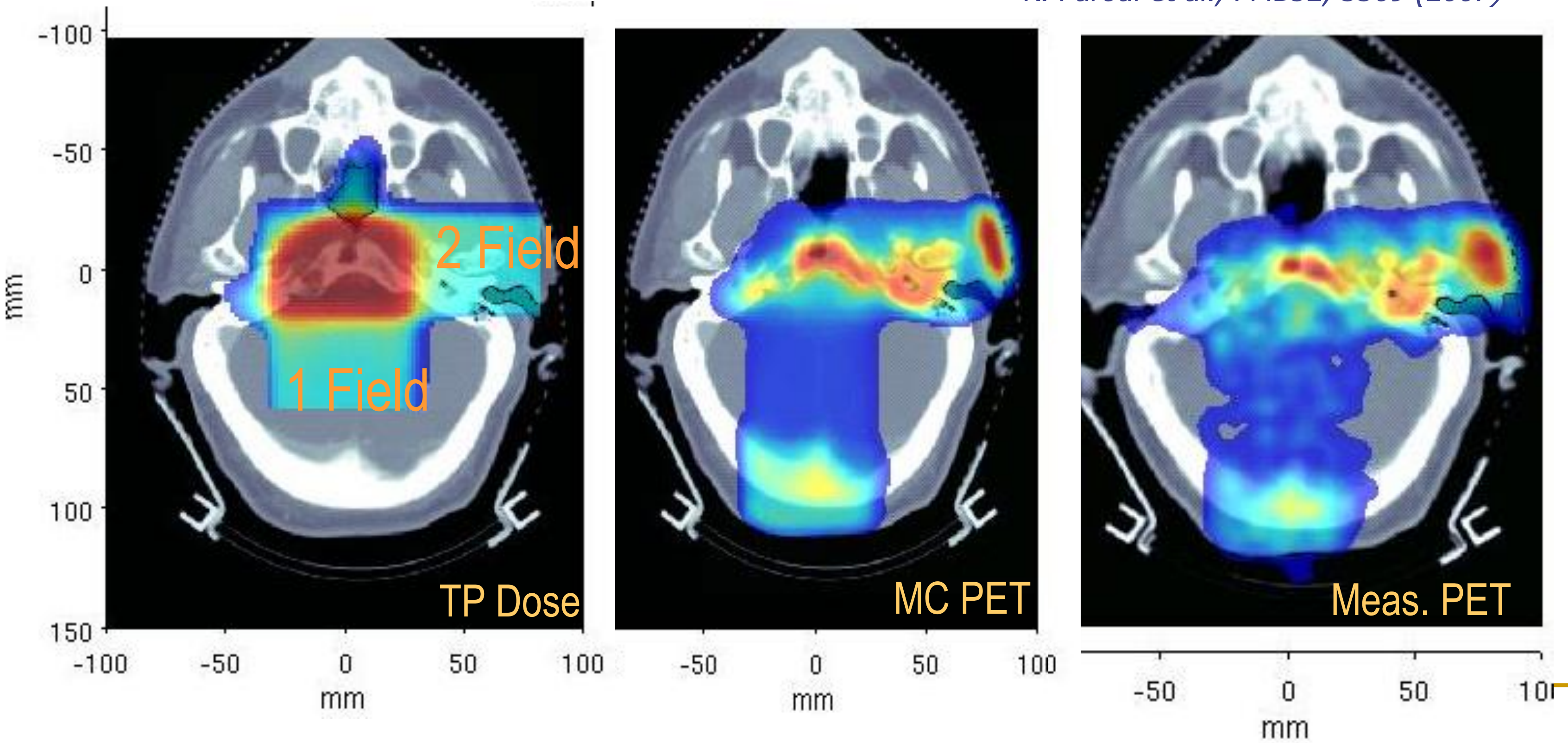
HUMAN MATTERS



not just damage

proton therapy (tumor cell destruction)

K. Parodi et al., PMB52, 3369 (2007)



CREDITS

In addition to explicit references, work of and material from

I. Besana, V. Boccone, M. Brugger, L.S. Esposito, A. Ferrari,
A. Lechner, R. Losito, A. Mereghetti, N. Mokhov, S. Roesler,
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