BEAM MATERIAL INTERACTION, HEATING & ACTIVATION [second module]

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Joint International Accelerator School

on Beam Loss and Accelerator Protection

Newport Beach November 2014

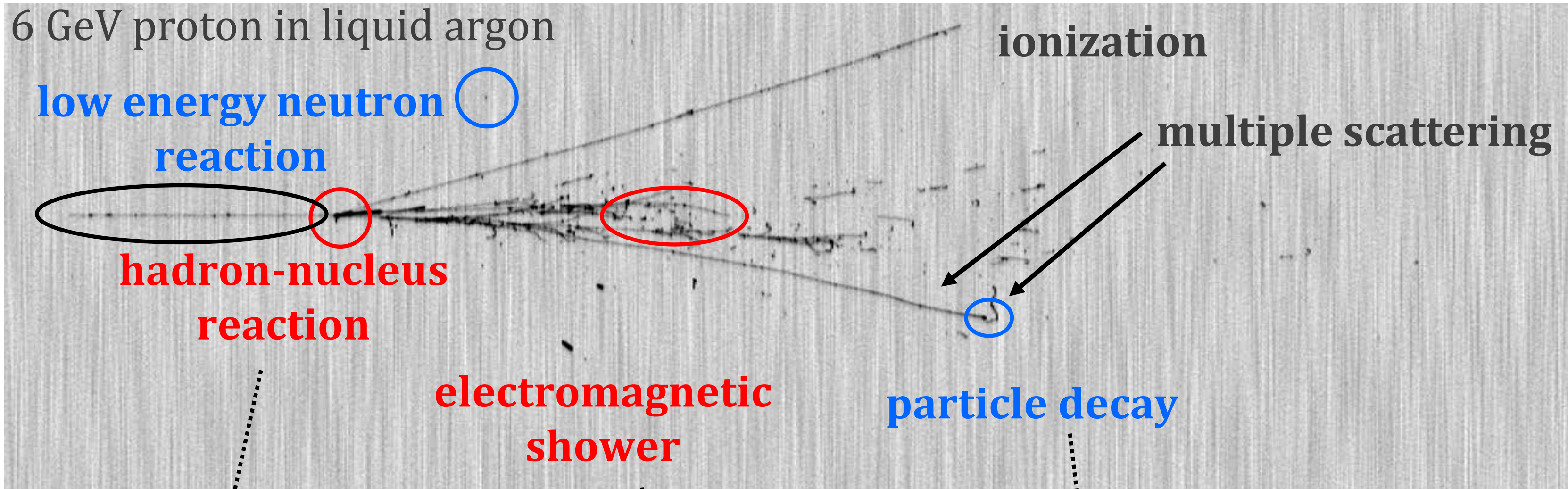
OUTLINE

- *Beam-material interaction: Nuclear reactions*

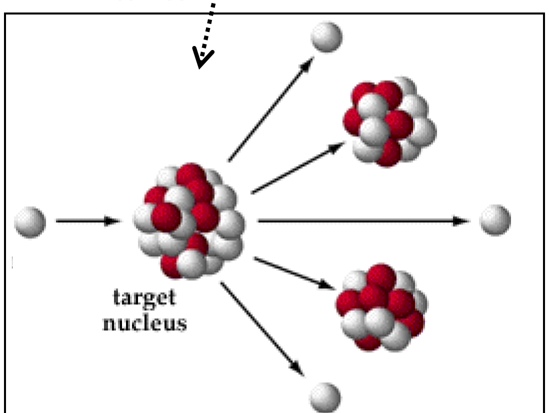
- Radiation to Electronics
- Shielding
- Activation

- Accelerator geometry modeling
- Input from beam tracking

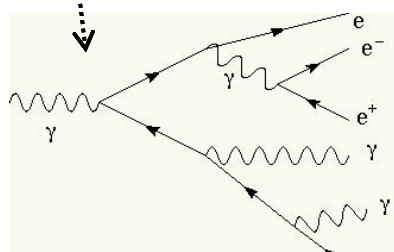
THE MICROSCOPIC VIEW



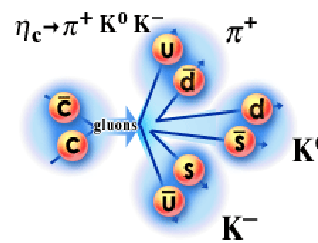
$$\lambda\rho = \frac{A}{\sigma_R N_A} \qquad \sigma_R \simeq \pi r_0^2 A^{2/3}$$



interplay of many physical processes described by different theories/models



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



NUCLEAR REACTIONS

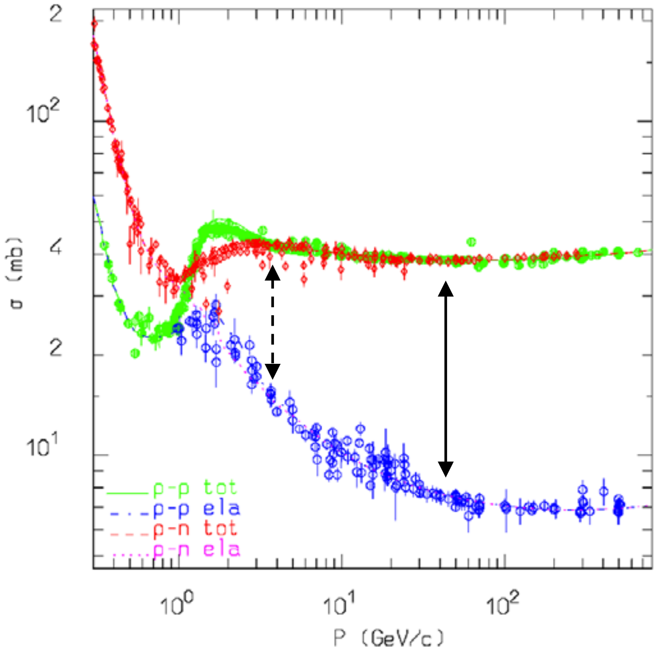
In general there are two kinds of nuclear reactions:

- **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)

NON-ELASTIC HADRON-NUCLEON REACTIONS

In order to understand Hadron-Nucleus (hA) nuclear reactions, one has to understand first Hadron-Nucleon (hN) reactions, since nuclei are made up by protons and neutrons.

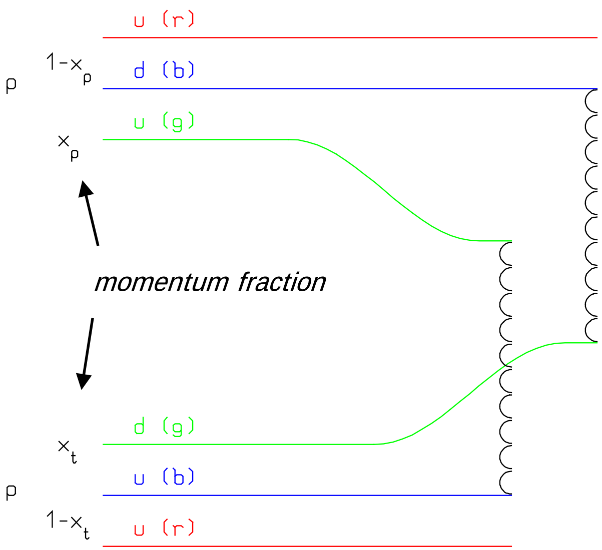


Intermediate Energies

All reactions proceed through an intermediate state containing at least one resonance (dominance of the $\Delta(1232)$ resonance and of the N* resonances)

$N_1 + N_2 \rightarrow N_1' + N_2' + \pi$ threshold around 290 MeV, important above 700 MeV

$\pi + N \rightarrow \pi' + \pi'' + N'$ opens at 170 MeV



High Energies: Dual Parton Model/Quark Gluon String Model etc

Interacting strings (quarks held together by the gluon-gluon interaction into the form of a string). Each of the two hadrons splits into 2 colored partons $\rightarrow$ combination into 2 colorless chains $\rightarrow$ 2 back-to-back jets.

Each jet is then hadronized into physical hadrons.

NON-ELASTIC HADRON-NUCLEUS REACTIONS

Target nucleus description (density, Fermi motion, etc)

↓

Glauber-Gribov cascade with formation zone

↓

Generalized IntraNuclear cascade

↓

Preequilibrium stage
with current excitation energy and exciton configuration
(including all nucleons below 30-100 MeV.
All non-nucleons are emitted/decayed)

↓

Evaporation/Fragmentation/Fission model

γ de-excitation

t (s)

10^{-23}

10^{-22}

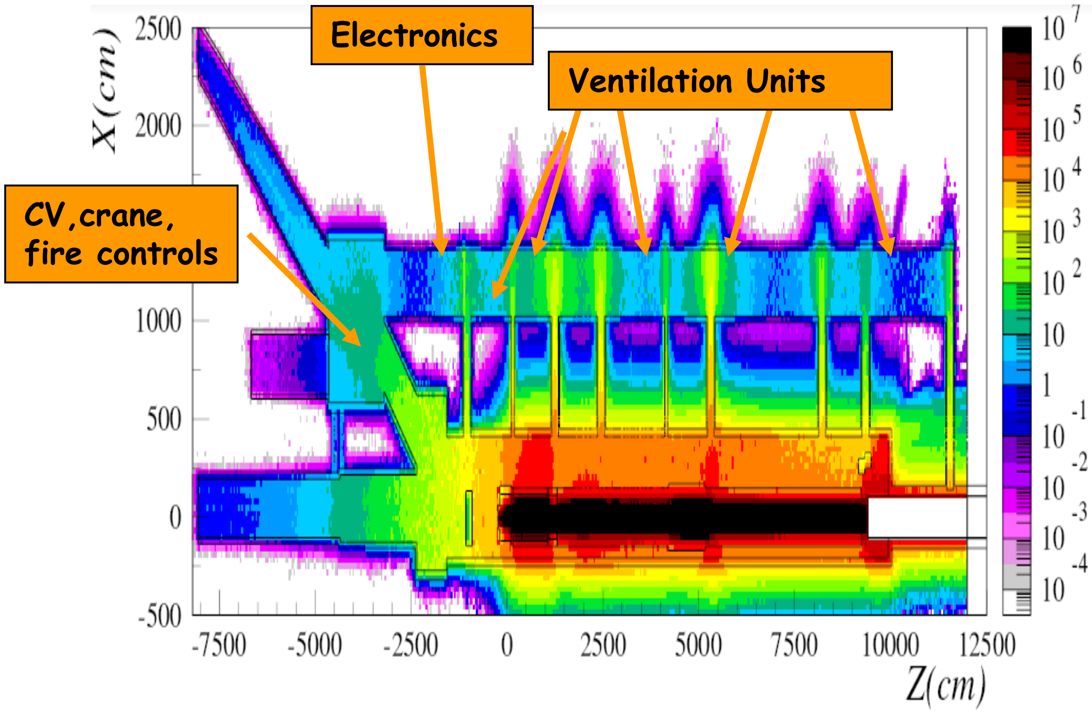
10^{-20}

10^{-16}

ELECTRONICS FAILURE [I]

CNGS 2007 physics run, 8 10^{17} p.o.t. delivered (≈2% of a nominal CNGS year)

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



Predicted *dose* levels

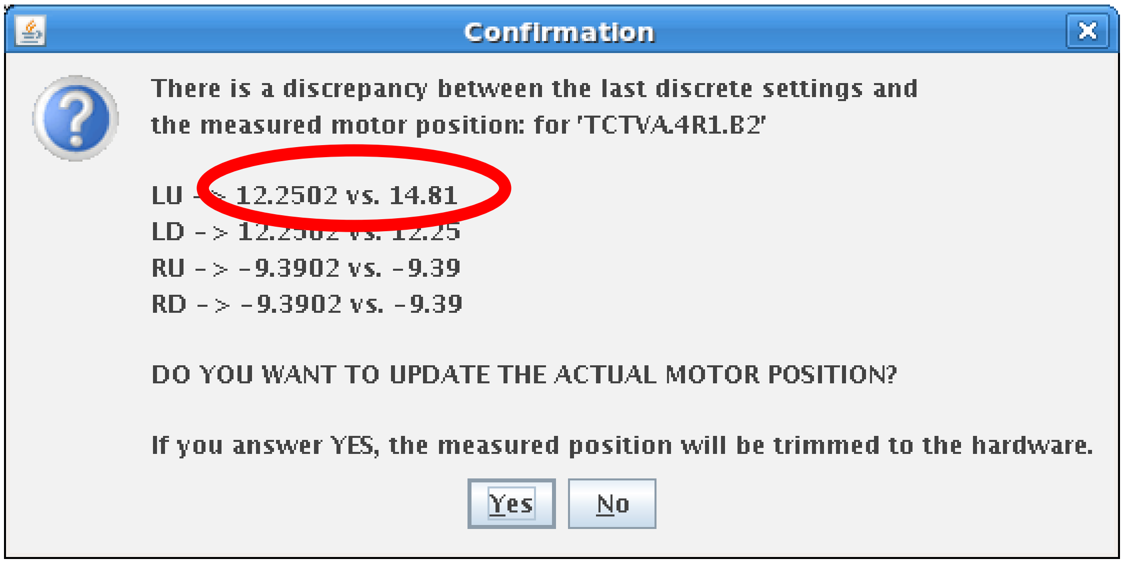
in agreement with measurements

Single event upsets in ventilation electronics caused

ventilation control failure and interruption of communication

ELECTRONICS FAILURE [II]

collimator controls

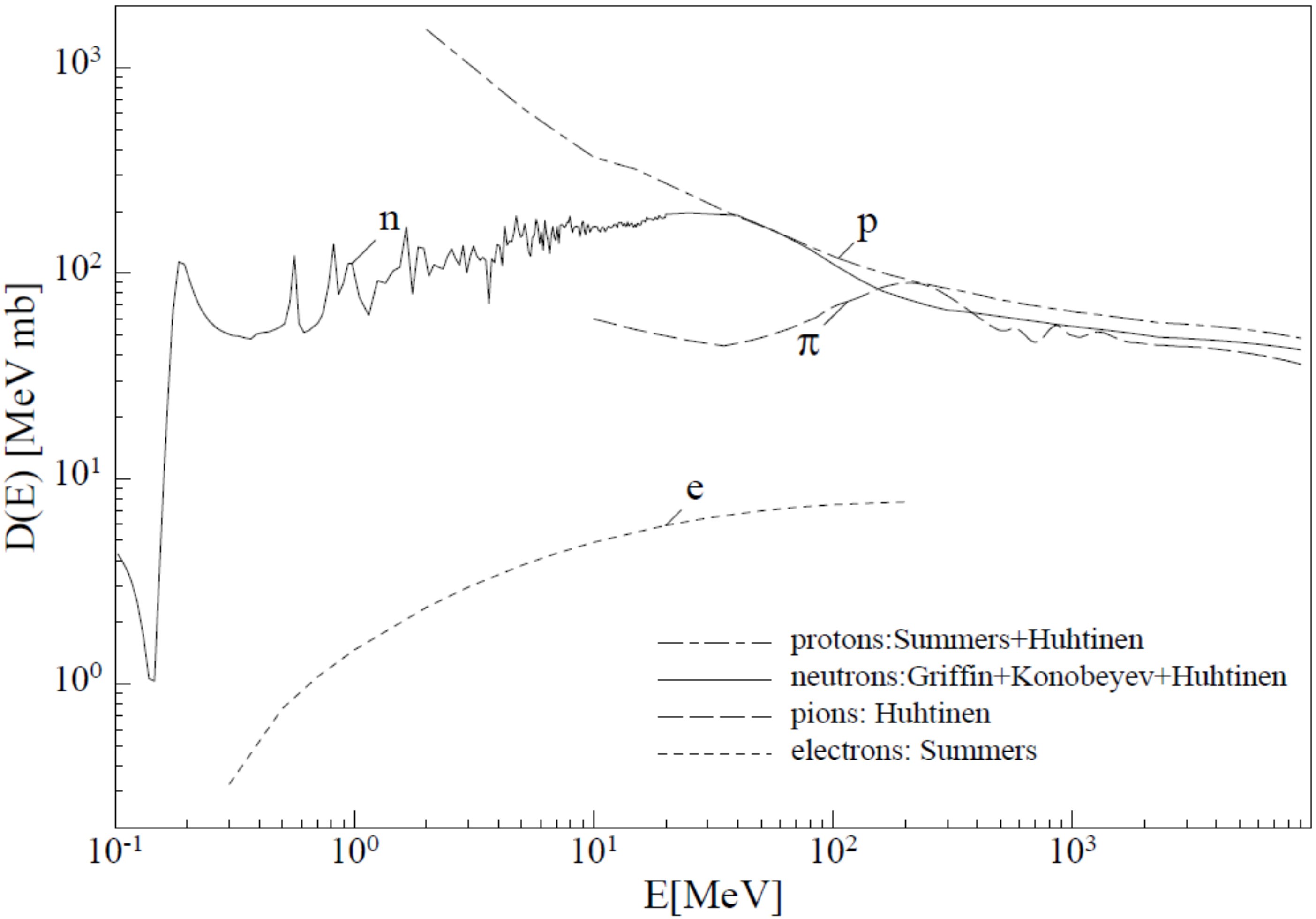


	position	register															
resolver	12.250	4900		0	1	0	0	1	1	0	0	1	0	0	1	0	0
counter	14.810	5924		0	1	0	1	1	1	0	0	1	0	0	1	0	0

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}

CONVERSION FACTORS FOR SILICON 1MeV-EQUIVALENT NEUTRON FLUENCE

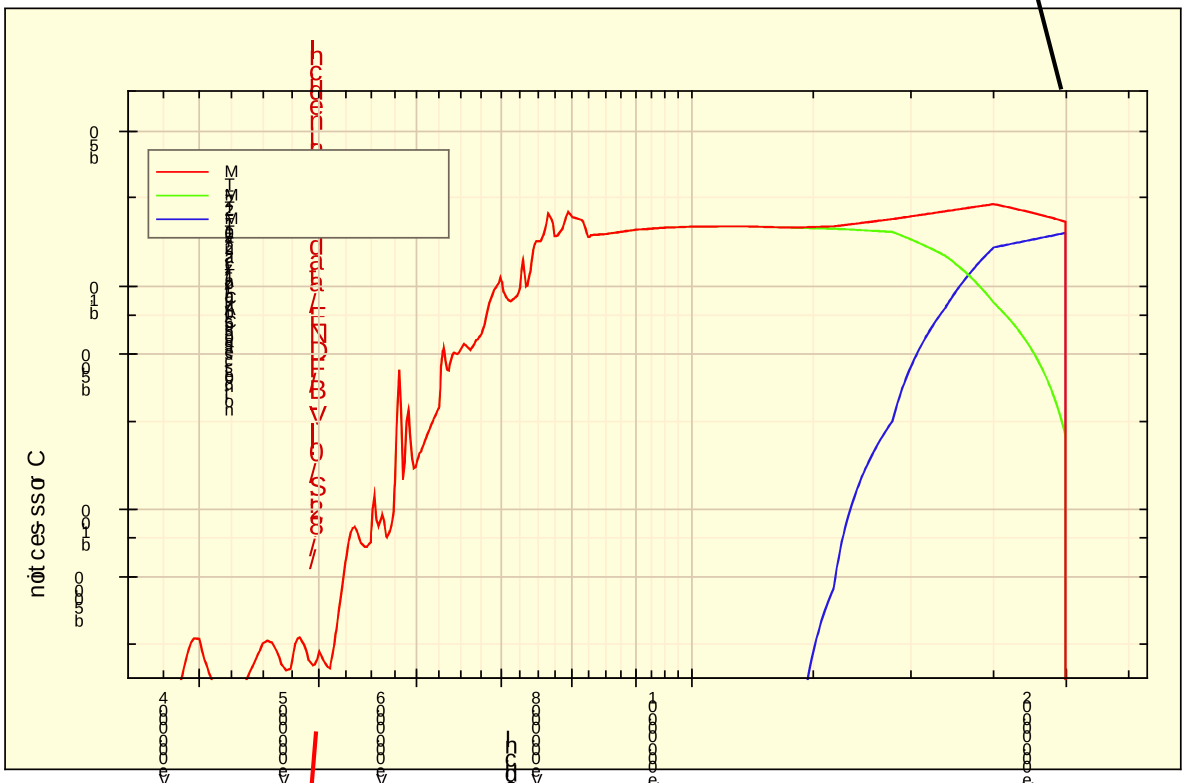


HOW HIGH ENERGY HADRONS?

>20 MeV

plus

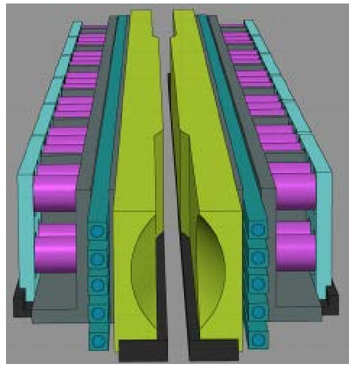
^{28}Si(n,xα) cross section



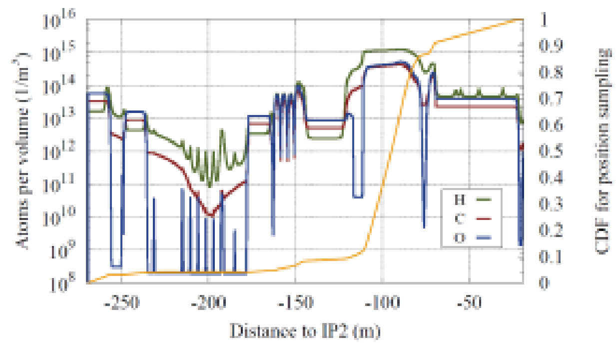
5 MeV

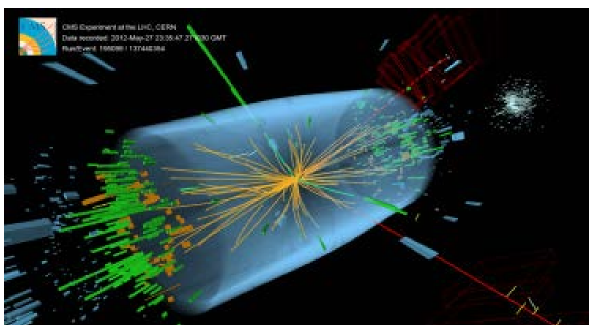
RADIATION SOURCES

beam impact on protection devices (collimators, dumps)

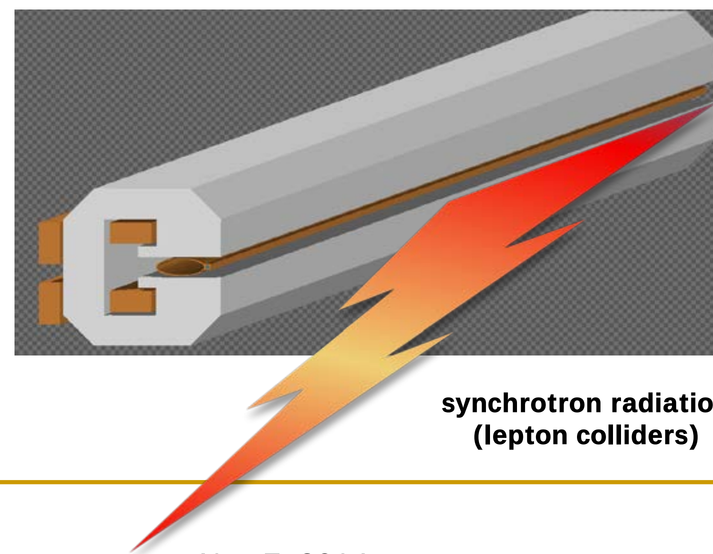


beam interaction with residual gas



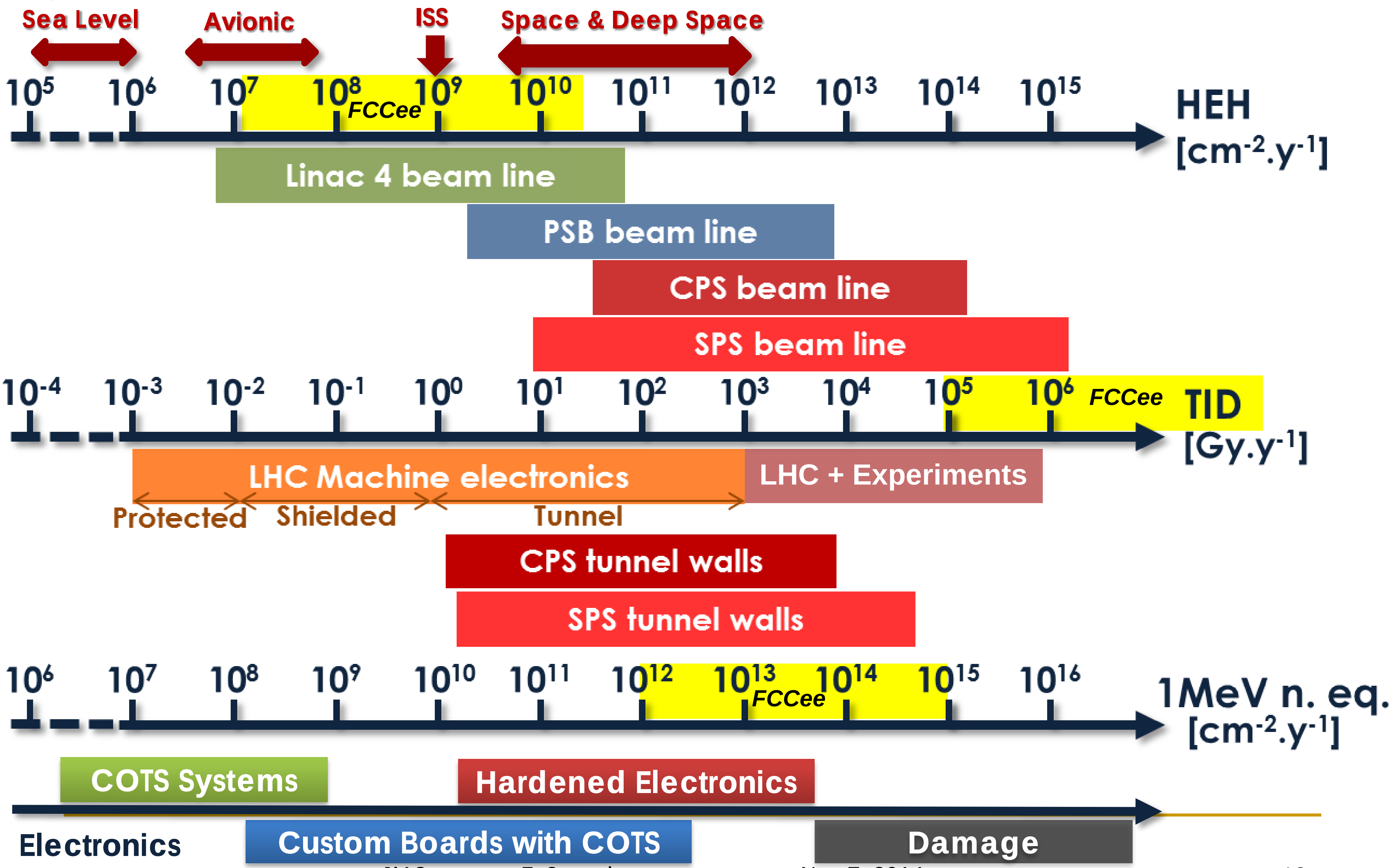


beam-beam collisions



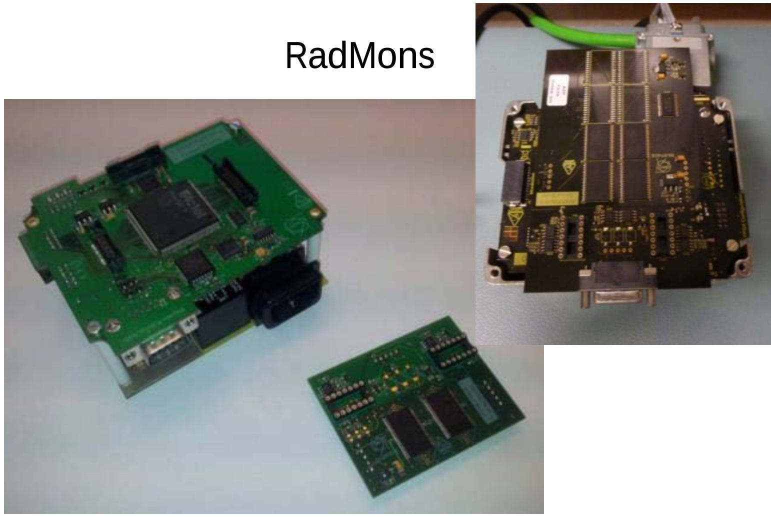
synchrotron radiation (lepton colliders)

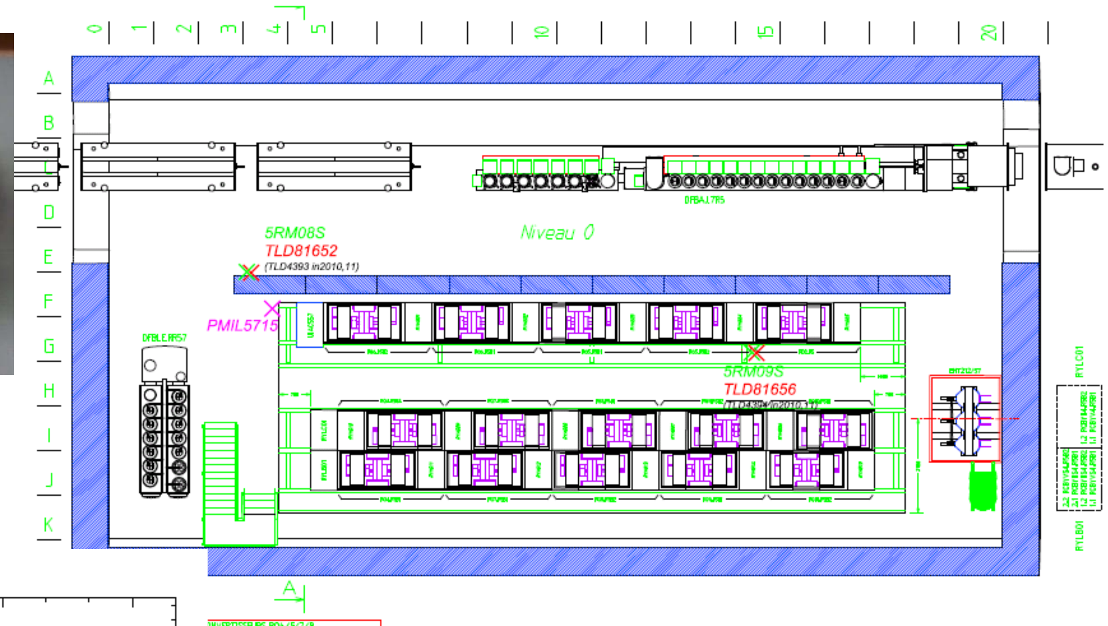
RADIATION LEVELS

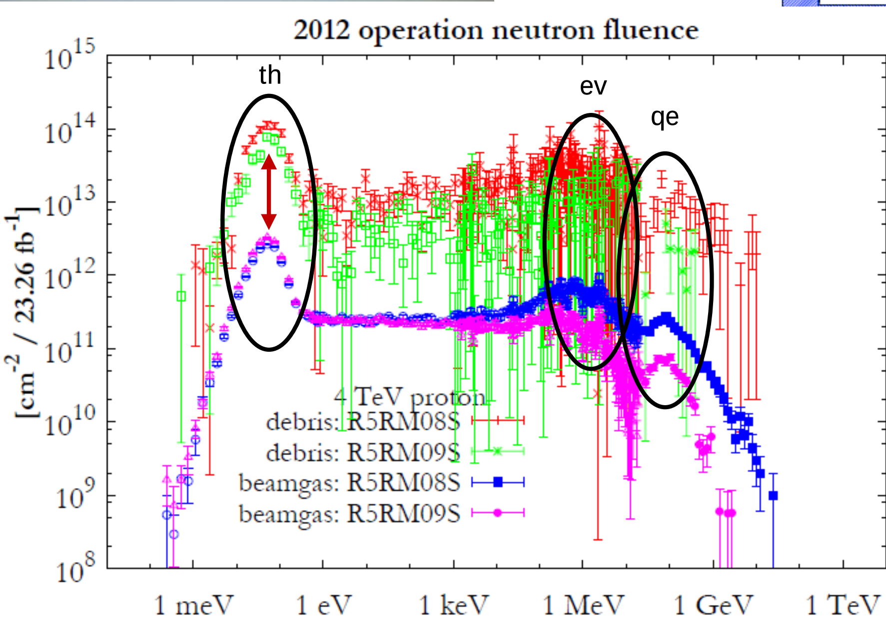


MONITORING AND BENCHMARKING

RadMons







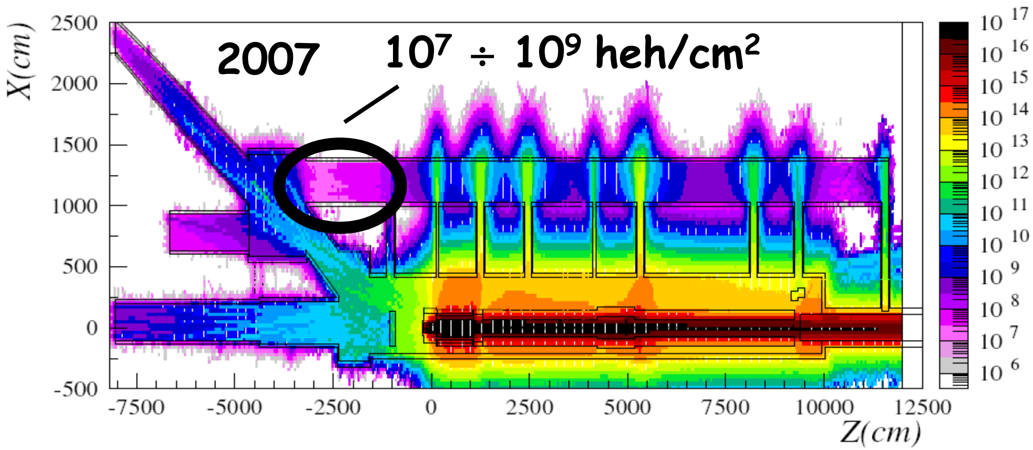
$F_{H>20MeV}$ [cm^{-2}] (L_{2012})	5RM08S	5RM09S
FLUKA	6.1 10^8	3.0 10^7
DATA	4.56 10^8 (256 upsets)	4.32 10^7 (25 upsets)

Agreement within 30%

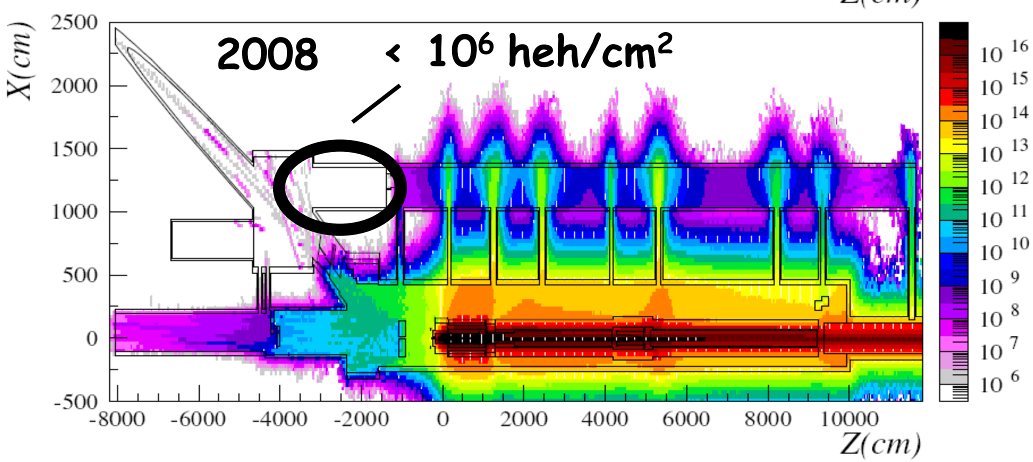
MITIGATION/PREVENTION STRATEGY

→ 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

HADRON (NEUTRON) ATTENUATION

high energy

“disappearing” by <u>non-elastic reactions</u>

$$\lambda\rho = \frac{A}{\sigma_R N_A} \qquad \sigma_R \simeq \pi r_0^2 A^{2/3} \qquad \boxed{\Sigma \propto \rho / A^{1/3}}$$

through dense (and cheap) materials

iron

low energy neutrons

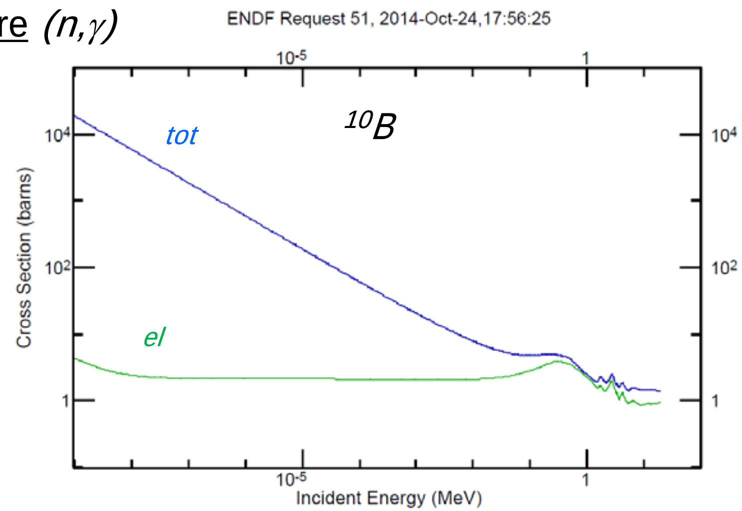
slowed down by <u>elastic scattering</u>

$$T_{rec} \approx 2E_{kin\ n}\left(1-\cos\theta^*\right)\frac{m_n M_{A,Z}}{(m_n + M_{A,Z})^2}$$

through hydrogen-rich materials

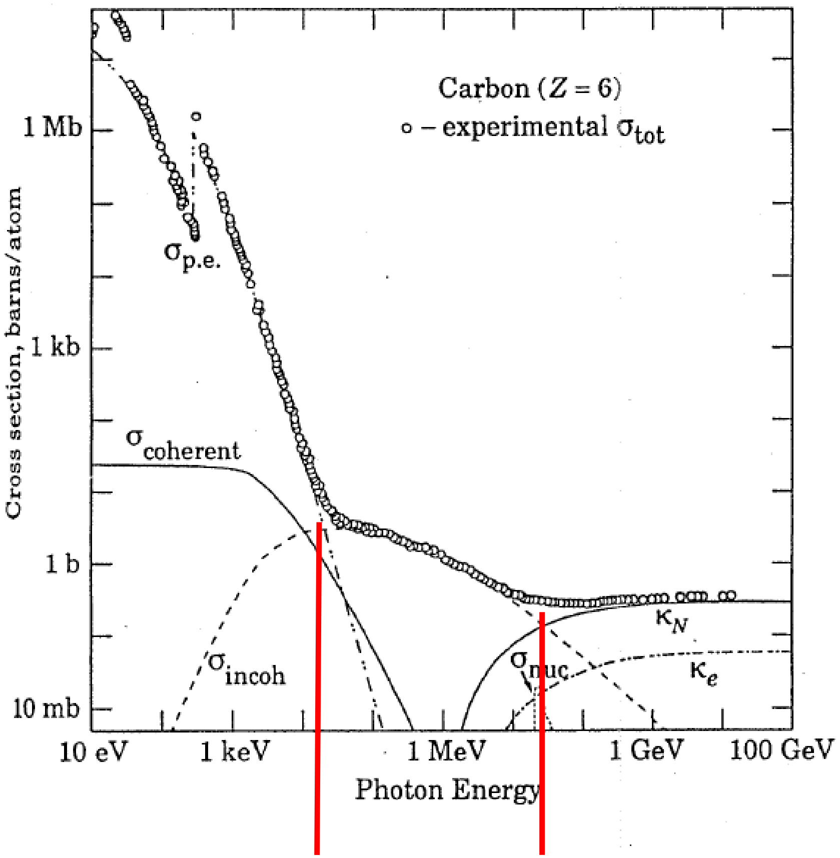
and once *thermalized*

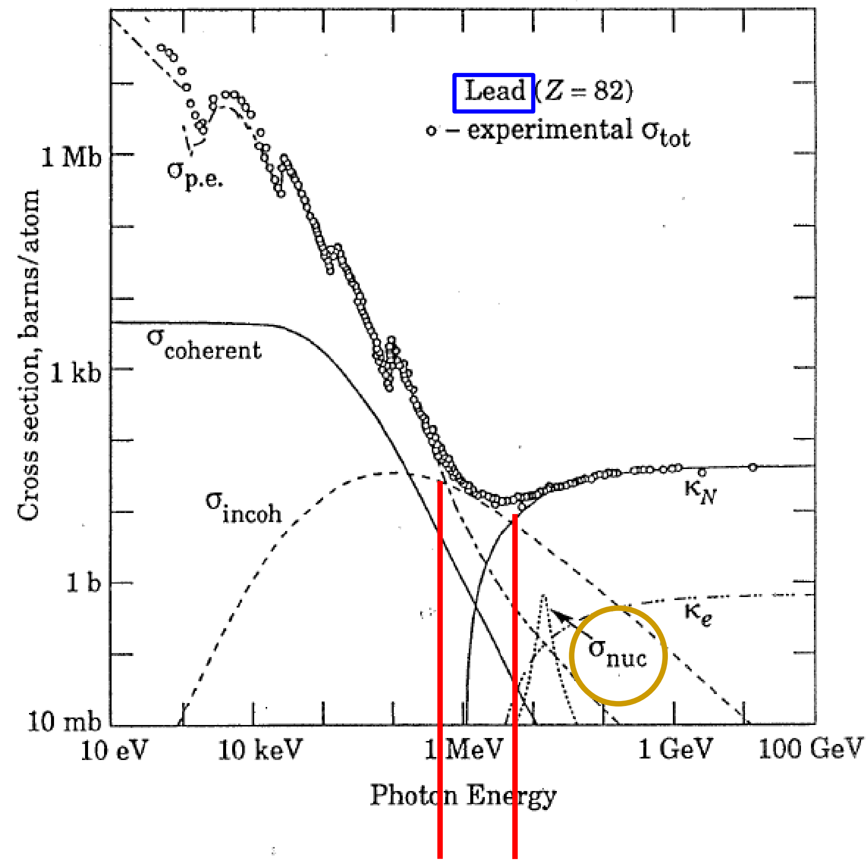
absorbed by <u>radiative capture</u> *(n,γ)*



borated polyethylene

PHOTON ATTENUATION





Photoelectric dominated | Compton dominated | Pair dominated

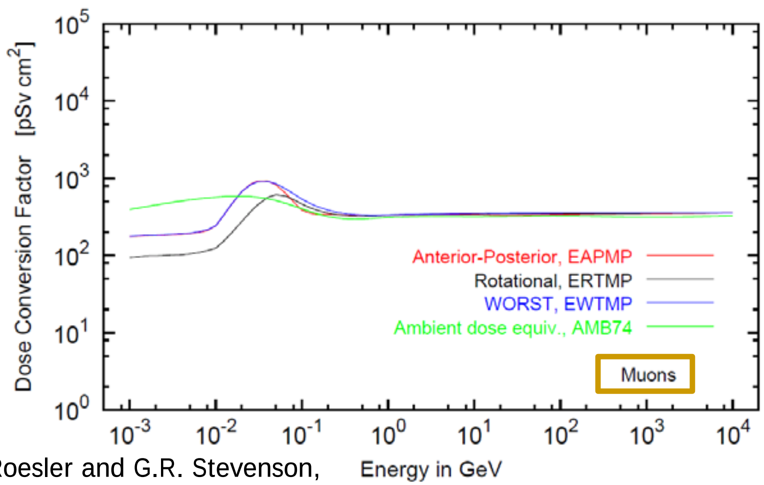
Photoelectric dominated | Compton dominated | Pair dominated

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

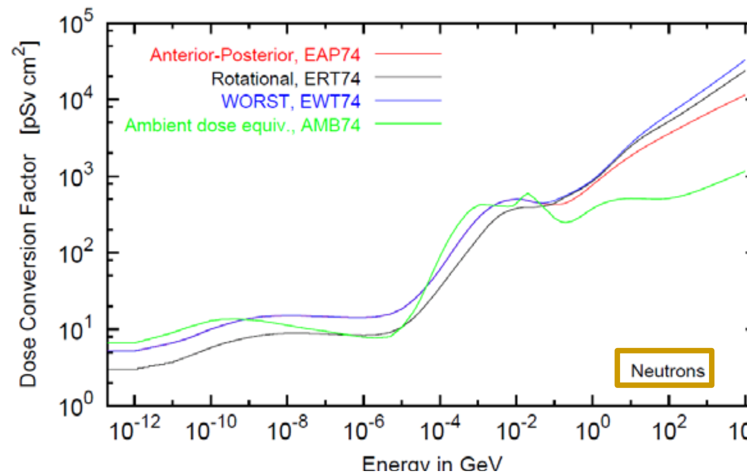
DOSE EQUIVALENT

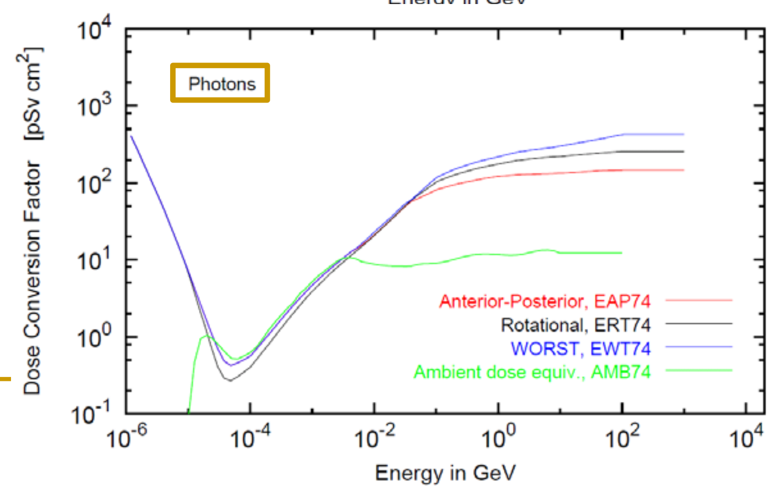
Particle fluence [cm^{-2}] yields ***effective dose*** and ***ambient dose equivalent H*(10)*** [uSv] which can be calculated through respective sets of conversion coefficients [pSv cm^2], which are a function of the particle type and energy.

The effective dose is the sum of the weighted equivalent doses in all tissues and organs of the human body: $E = \sum_T w_T H_T$
being the equivalent dose the sum of the weighted average absorbed doses from all radiation types: $H_T = \sum_R w_R D_{T,R}$
It depends on the irradiation geometry.



[S. Roesler and G.R. Stevenson, CERN-SC-2006-070-P-TN]





<u>Prompt dose equivalent</u> is a quantity to minimize as the shielding of a facility is designed, in order to allow its integration in the environment
(e.g. at CERN limit of 300 uSv/y
with optimization (ALARA) threshold of 10 uSv/y)

SHIELDING DESIGN

Accidents

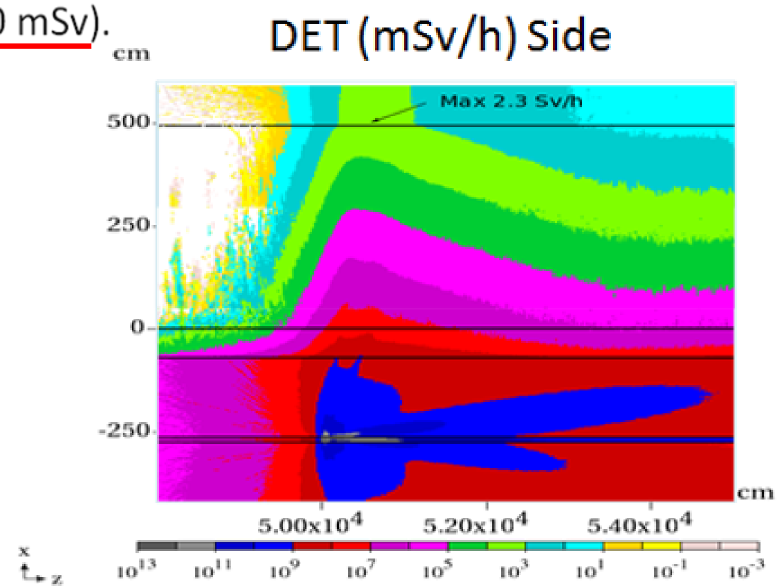
[L. Tchelidze]

- Point full beam loss is considered (5 MW):

- “Sullivan” – 0.31 Sv/h maximum total dose equivalent rate outside of berm.
- With 30 MJ anticipated beam spill limit -> ~ 0.5 mSv (limit is 20 mSv)
- With 600 MJ DBA beam spill limit - > ~ 10 mSv (limit is 50 mSv).

Design Basis Accident

- MARS results:
  - 5 MW of 2 GeV proton beam lost in a single point, upwards.
  - 2.3 Sv/h max dose rate.
  - 30 MJ -> 3.8 mSv (under the limit)
  - 600 MJ -> 77 mSv (above the limit)



ACTIVATION [I]

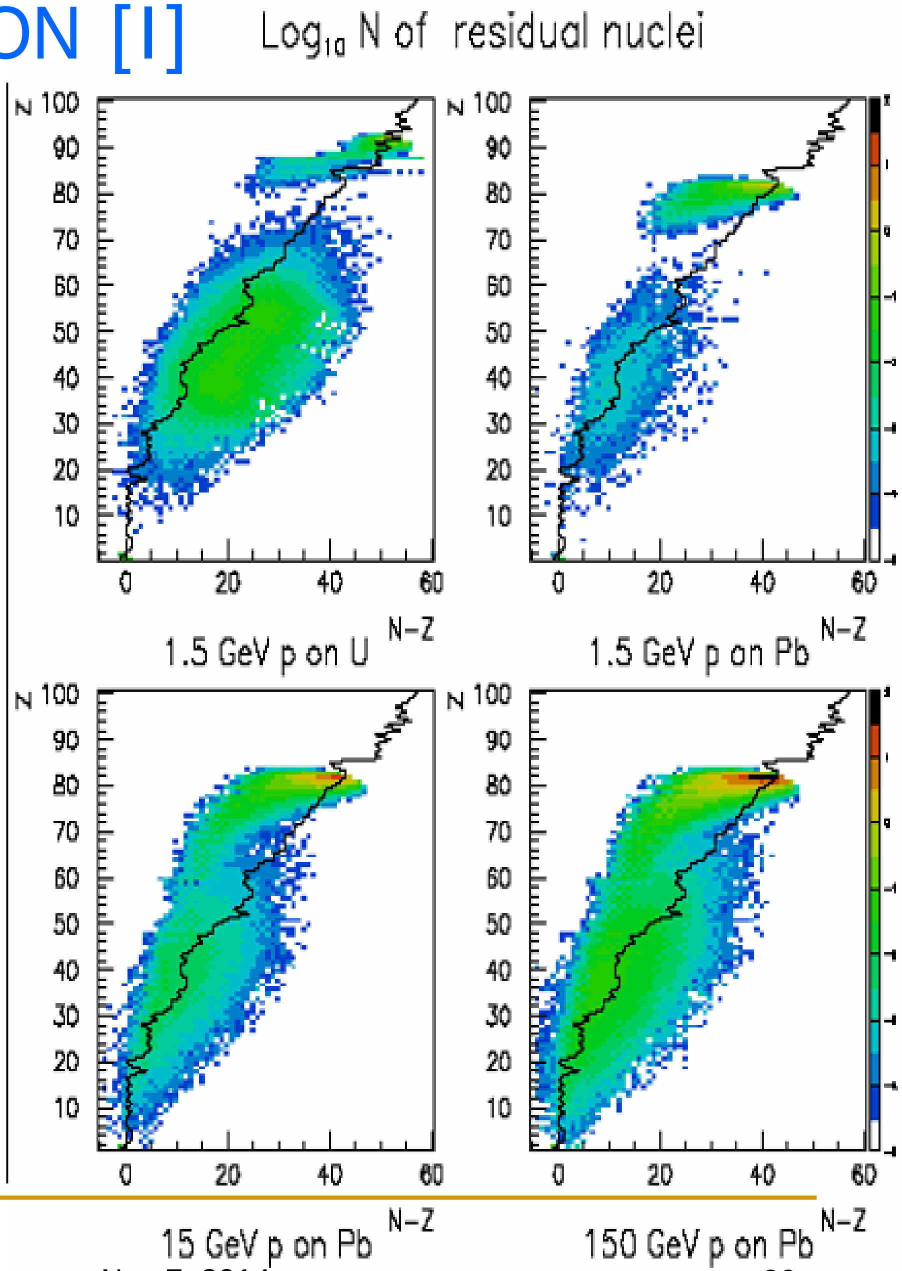
The production of residuals is the result of the last step of the nuclear reaction, thus it is influenced by all the previous stages. However, the production of specific isotopes may be influenced by fine nuclear structure effects which have little or no impact on the emitted particle spectra.

After many collisions and possibly particle emissions, the residual nucleus is left in a **highly excited equilibrated state**. De-excitation can be described by **statistical models** which resemble the **evaporation** of “droplets”, actually **low energy particles (p, n, d, t, ^{3}He, alphas…)** from a “boiling soup” characterized by a “nuclear temperature”.

The process is terminated when all available energy is spent $\rightarrow$ the leftover nucleus, possibly radioactive, is now “cold”, with **typical recoil energies** of ~ **MeV**.

For heavy nuclei the excitation energy can be large enough to allow breaking into two major chunks (**fission**).

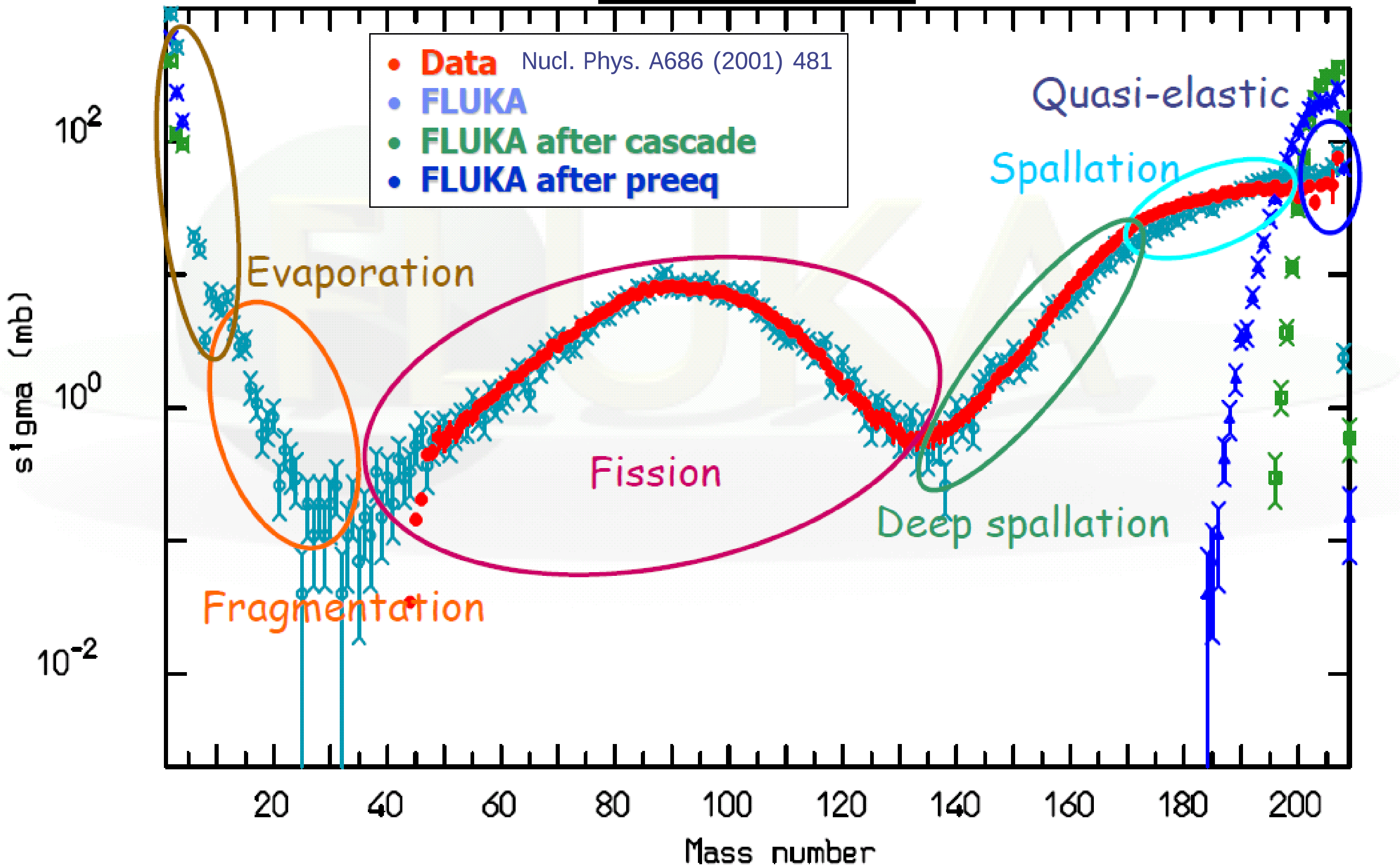
Since only neutrons have no barrier to overcome, **neutron emission is strongly favored**.



ACTIVATION [II]

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

1 A GeV ^{208}Pb+p



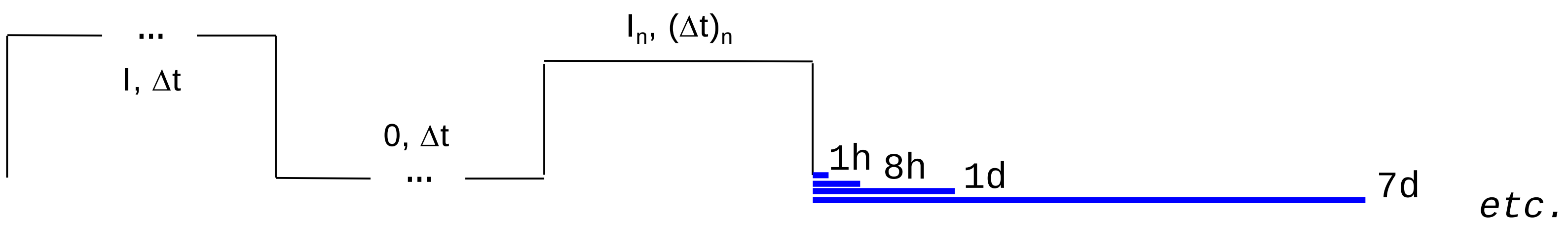
RADIOACTIVE DECAY

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*



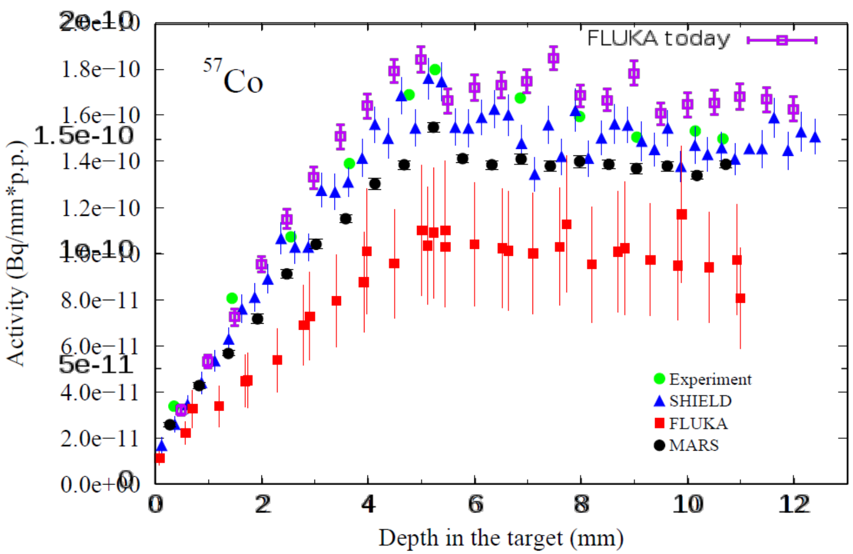
yielding (specific) activities [Bq(/g)] – to be compared to legal <u>exemption limits</u> –

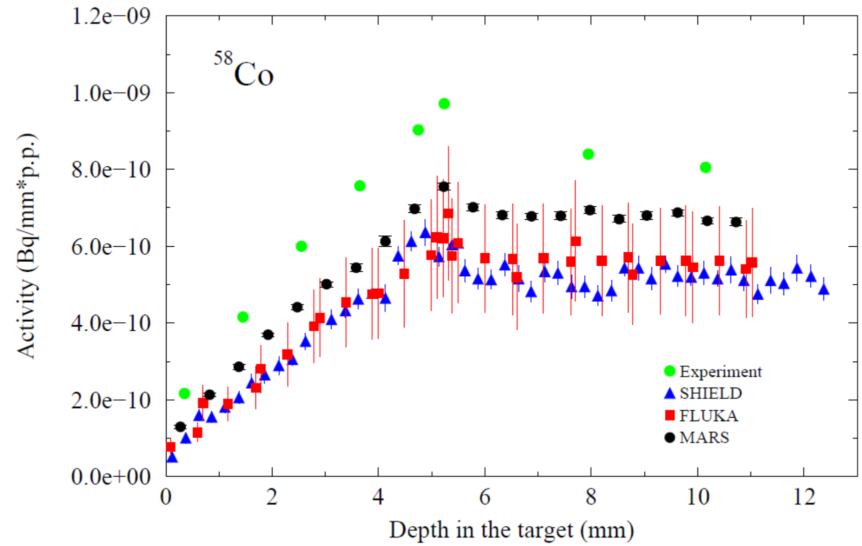
and residual dose rates [uSv/h] by the decay radiation (mainly electromagnetic)

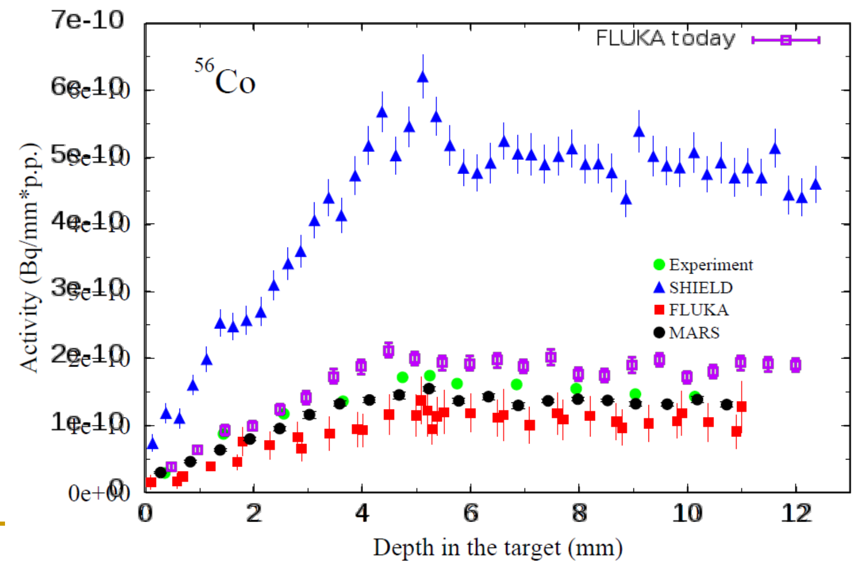
ACTIVITY BENCHMARKING

500 MeV/n ^{238}U beam on Cu

[E. Mustafin *et al.*, EPAC 2006, TUPLS141, 1834]

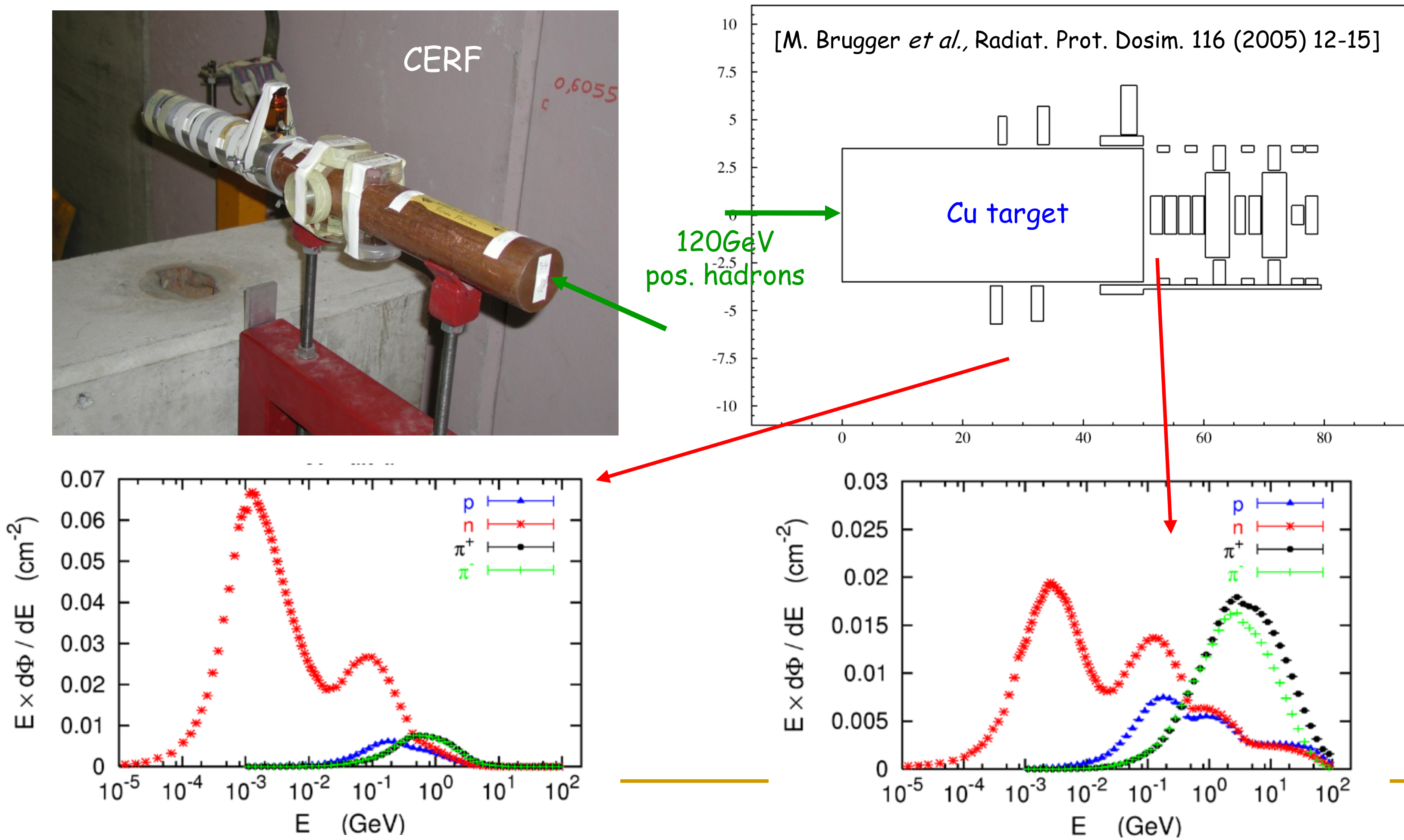






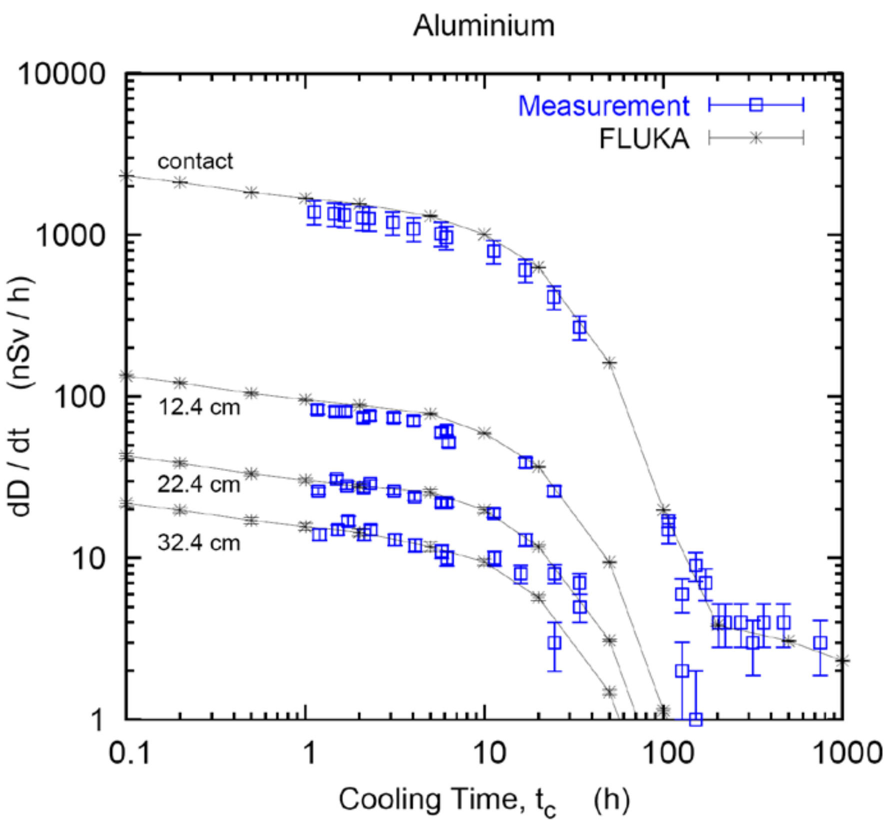
RESIDUAL DOSE RATES:
A BENCHMARKING EXPERIMENT

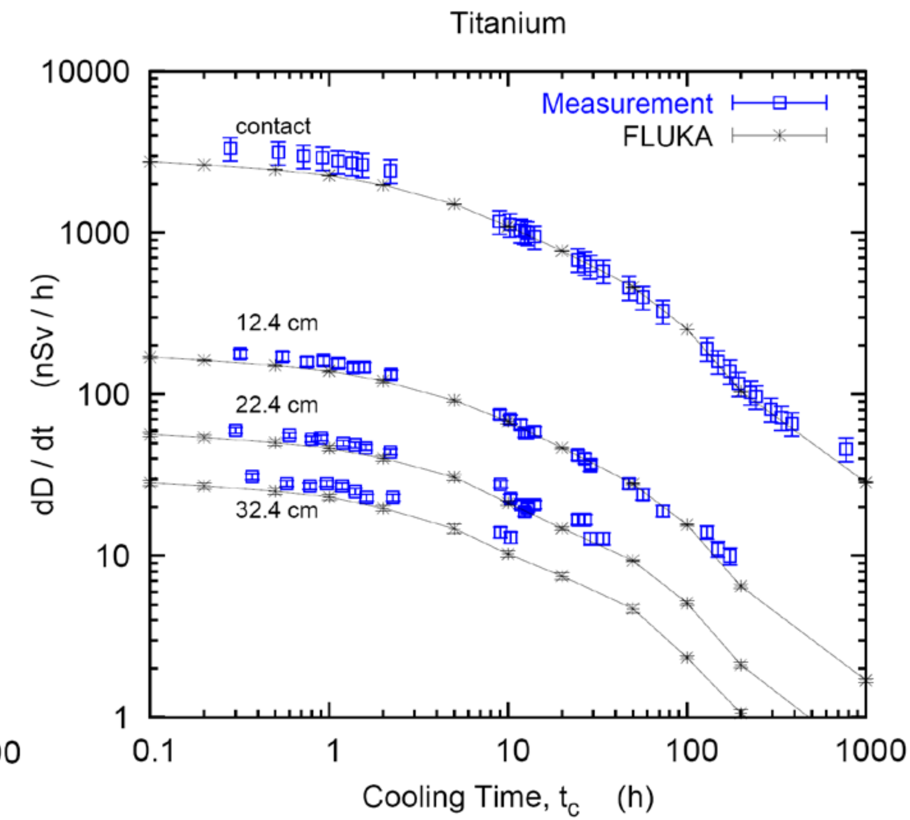
Irradiation of samples of different materials to the stray radiation field created by the interaction of a 120 GeV positively charged hadron beam in a copper target



RESIDUAL DOSE RATES: MEASUREMENTS AND SIMULATIONS [I]

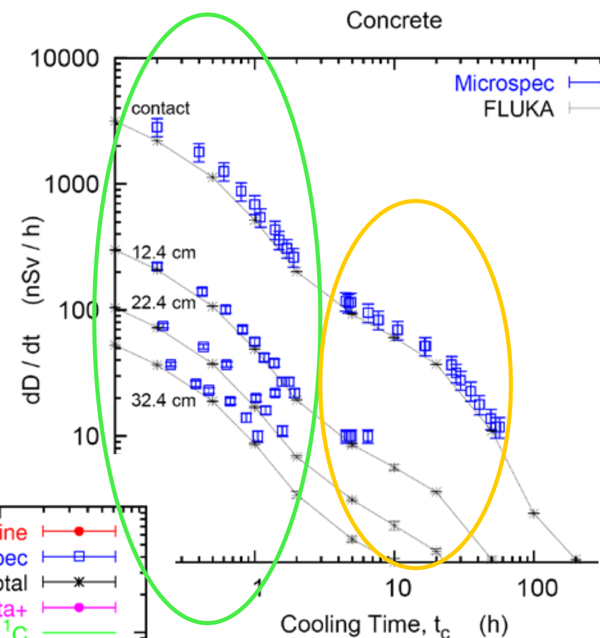
Dose rate as function of cooling time for different distances between sample and detector





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

RESIDUAL DOSE RATES: MEASUREMENTS AND SIMULATIONS [II]

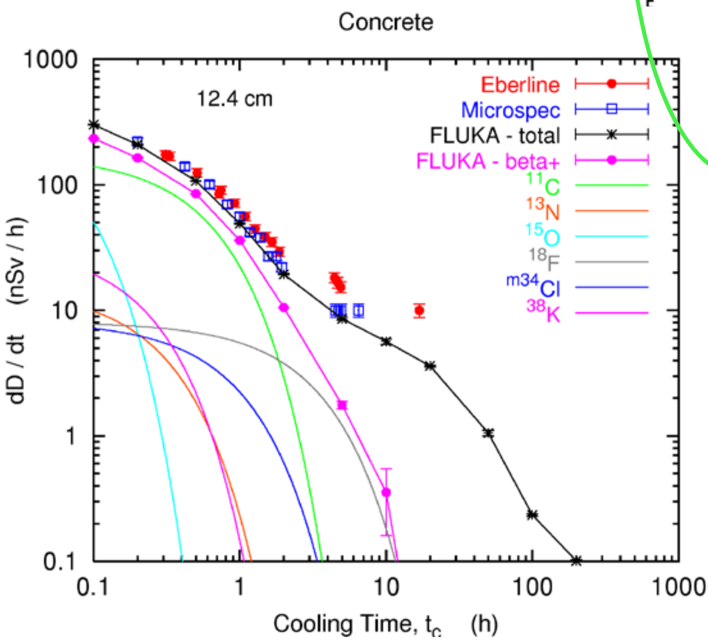


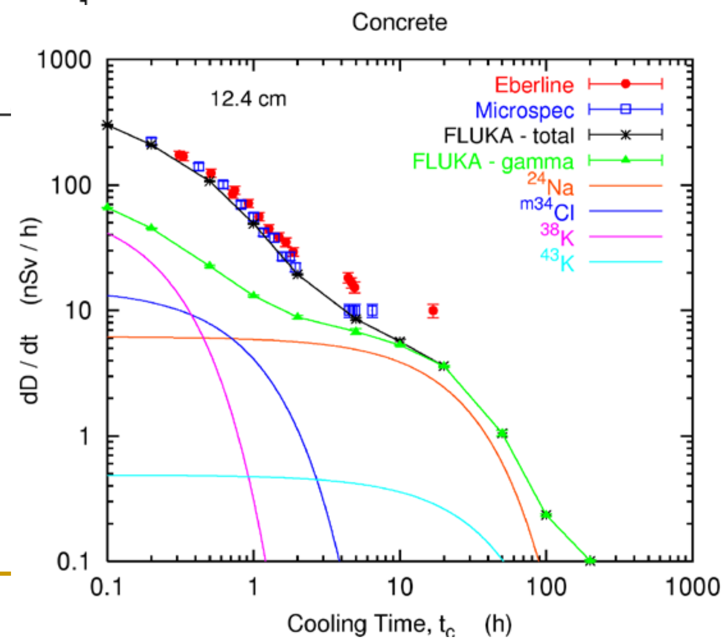
t_{cool} < 2 hours :

^{11}C (β^+, $t_{1/2}$ = 20min)

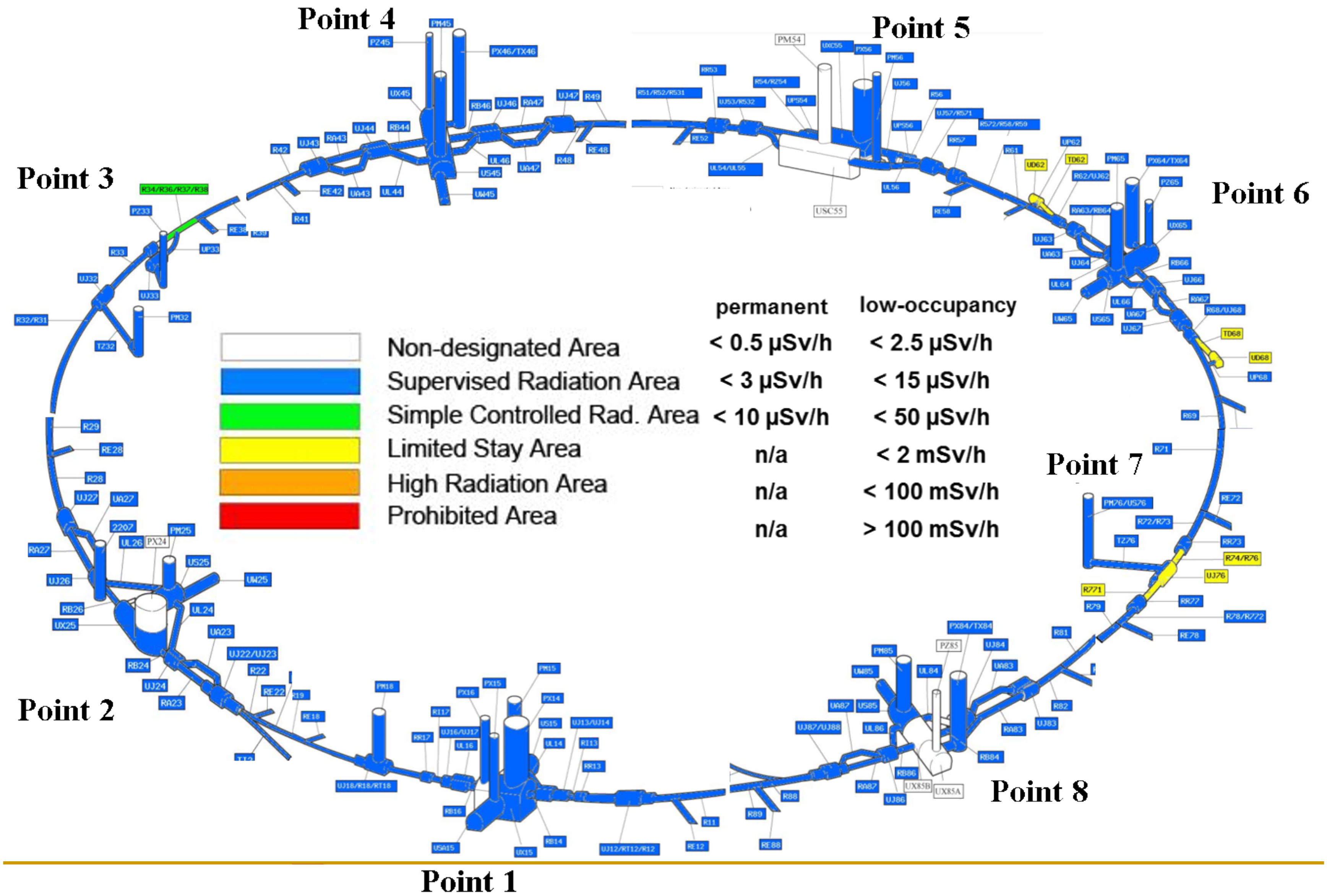
2 hours < t_{cool} < 2 days :

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





LHC RADIOLOGICAL CLASSIFICATION DURING LS1



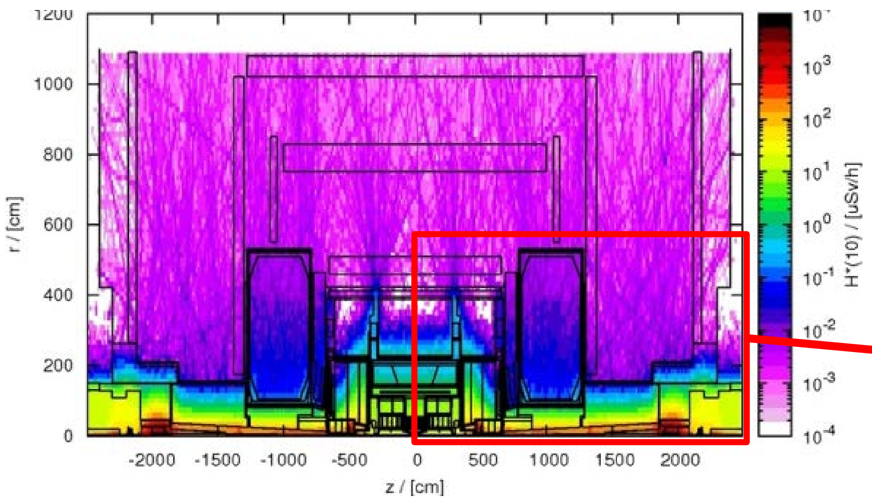
	permanent	low-occupancy
Non-designated Area	< 0.5 μSv/h	< 2.5 μSv/h
Supervised Radiation Area	< 3 μSv/h	< 15 μSv/h
Simple Controlled Rad. Area	< 10 μSv/h	< 50 μSv/h
Limited Stay Area	n/a	< 2 mSv/h
High Radiation Area	n/a	< 100 mSv/h
Prohibited Area	n/a	> 100 mSv/h

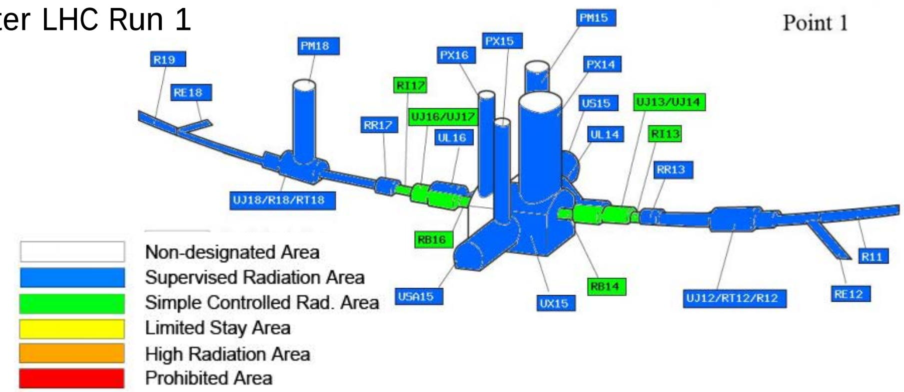
RESIDUAL DOSE RATE MAPS [I]

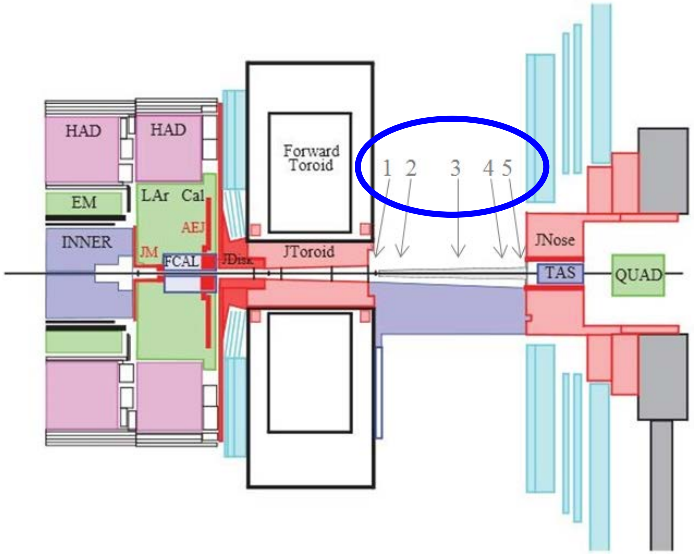
ATLAS cavern

after LHC Run 1

1 week cooling







Location	Measurement [µSv/h]	FLUKA [µSv/h]
1	19	13 (±0.3)
2	10	13 (±0.3)
3	7.2	10 (±0.2)
4	47	46 (± 0.5)
5	42	72 (± 0.5)

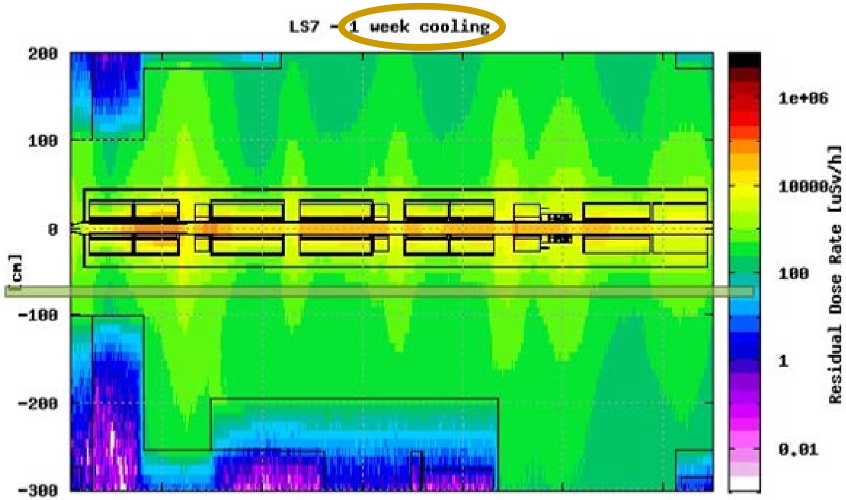
[C. Urscheler et al.]

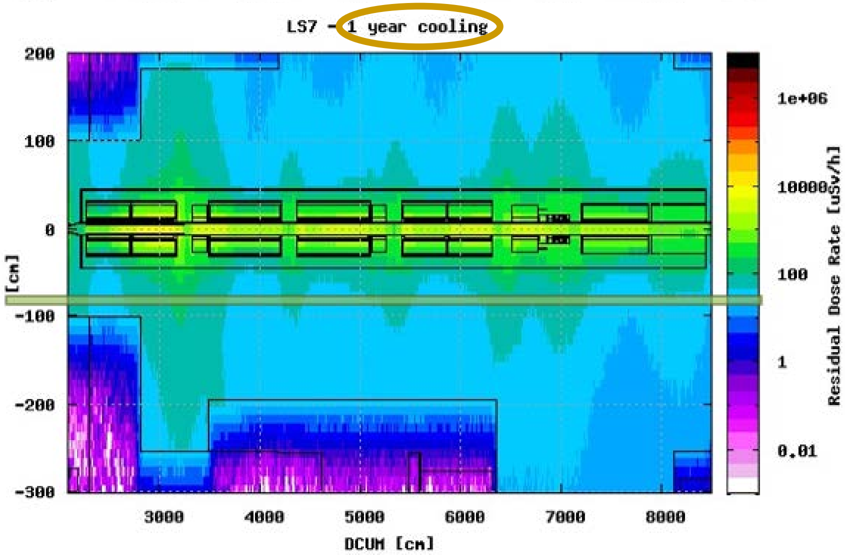
RESIDUAL DOSE RATE MAPS [II]

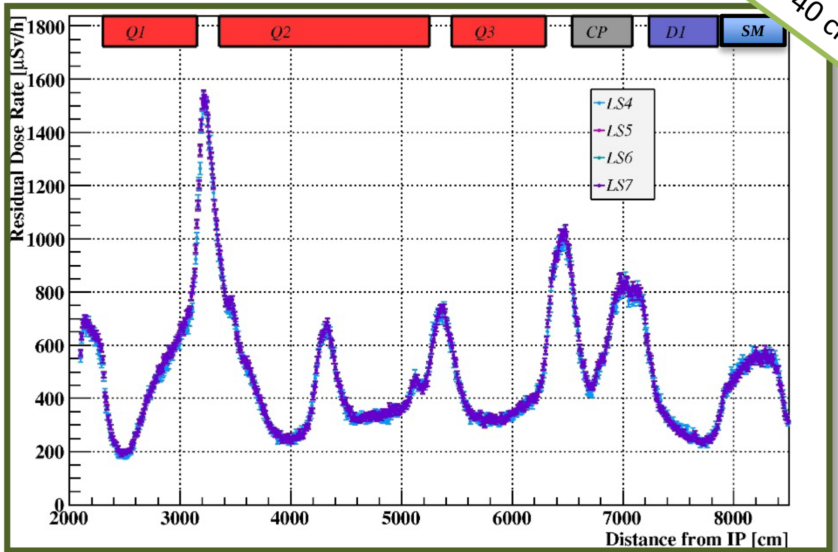
HL-LHC final focus triplet around ATLAS and CMS

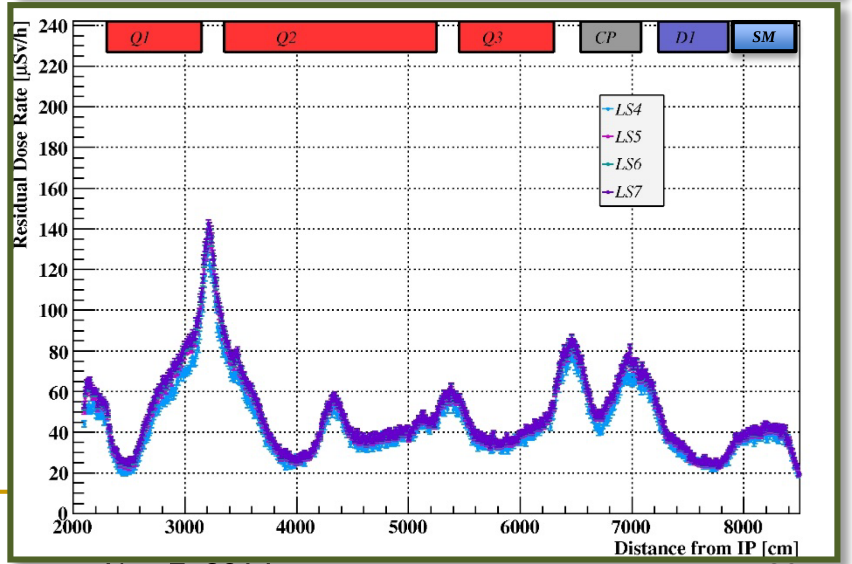
900fb^{-1} between Long Shutdowns

@ 40 cm









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

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]

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

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

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)

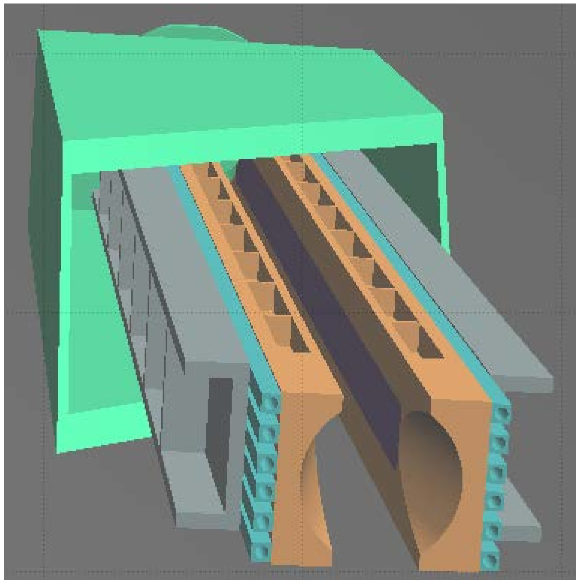
$$A_{on} = m_{on}A_S\left(T - \frac{1 - \exp\left(-(\lambda + m_{on})T\right)}{\lambda + m_{on}}\right)\exp\left(-\lambda\, t_{on}\right)$$

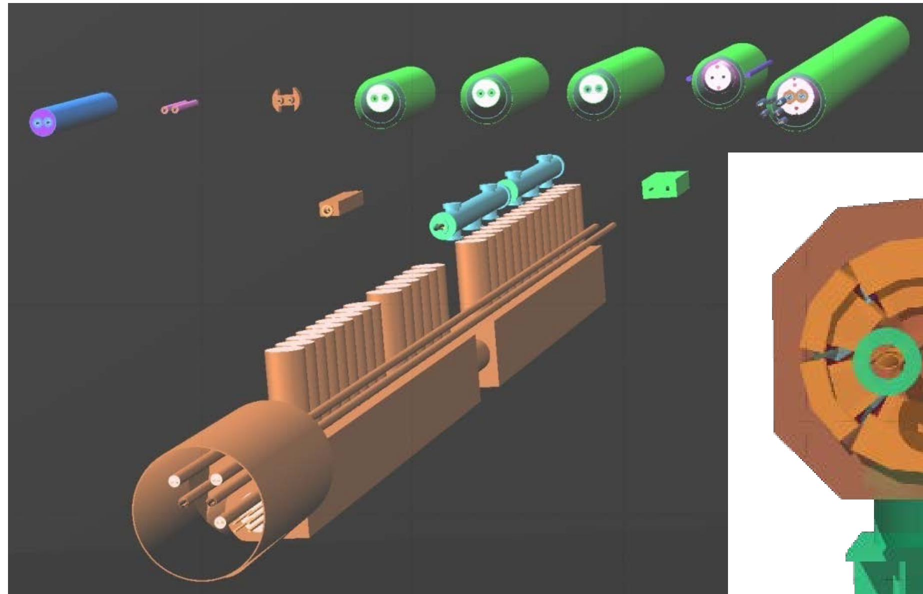
Amount of *activity released into atmosphere after the end of the irradiation* (m_{off} and t_{off} as m_{on} and t_{on} but referring to the shutdown period)

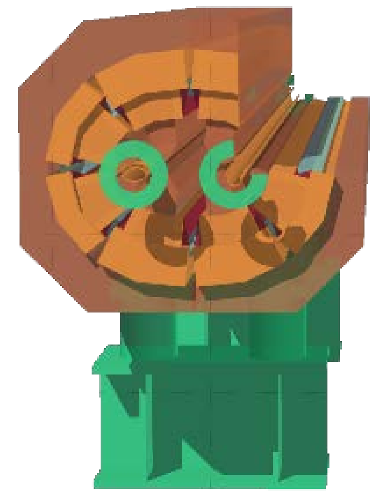
$$A_{off} = A_T\frac{m_{off}}{\lambda + m_{off}}\exp\left(-\lambda\, t_{off}\right)$$

GEOMETRY MODELING

NEED FOR DETAILED MODELS OF ACCELERATOR COMPONENTS WITH ASSOCIATED SCORING



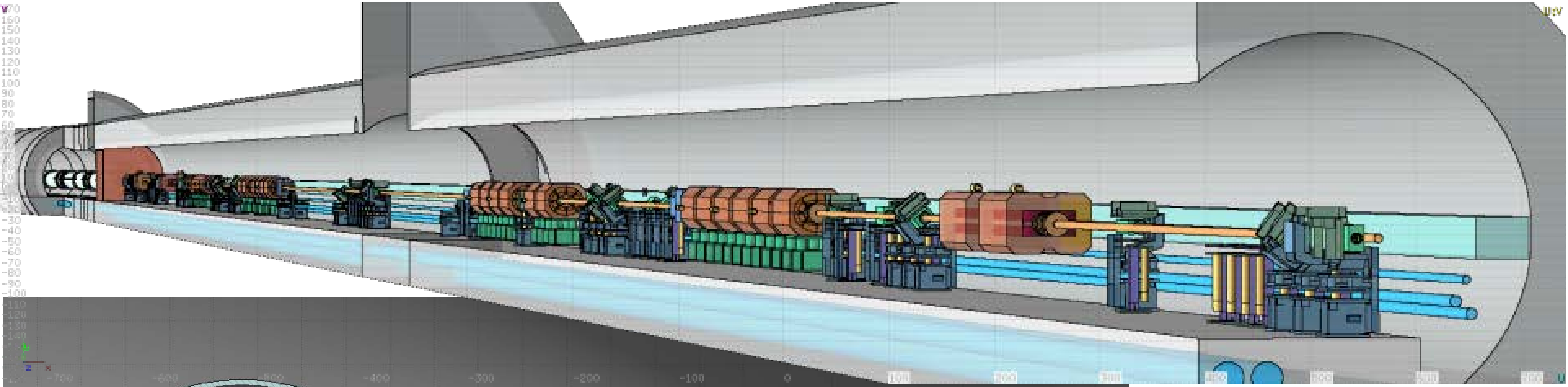


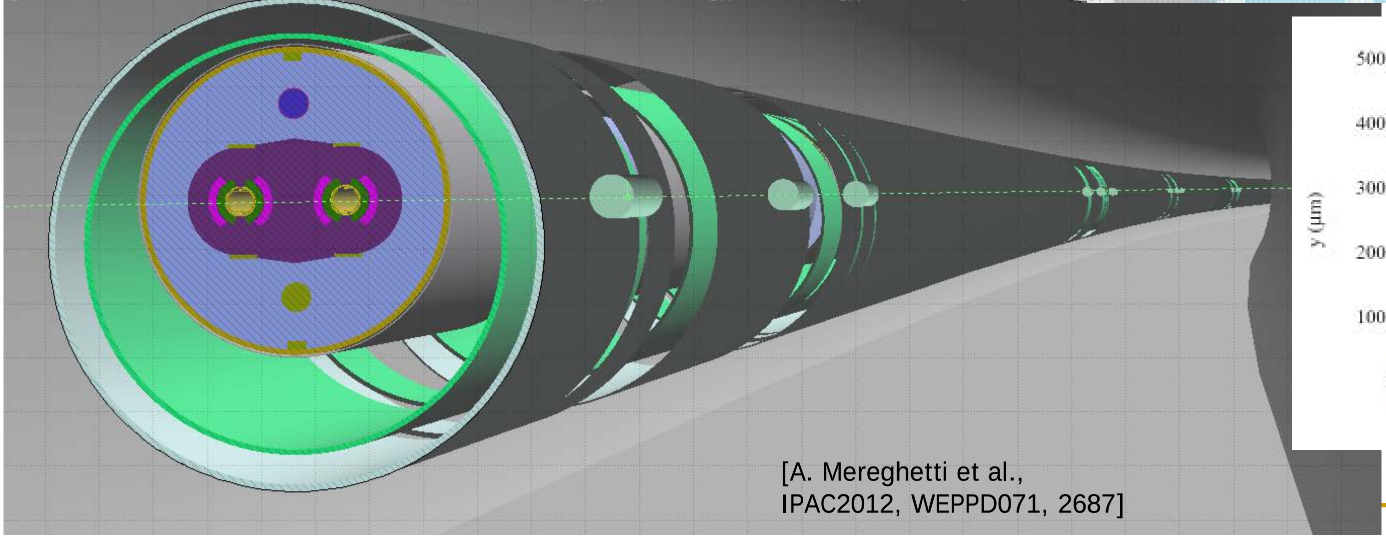


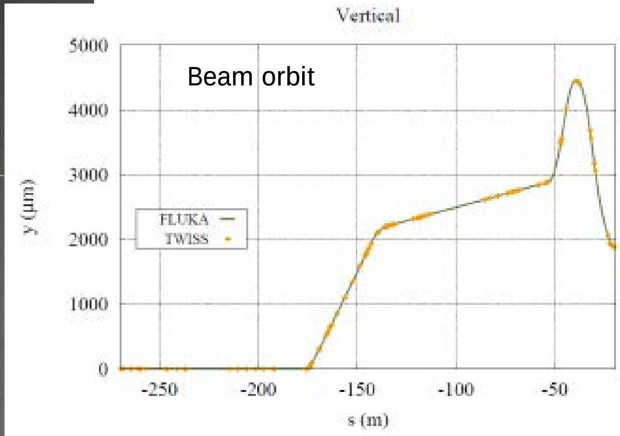
ELEMENT SEQUENCE AND RESPECTIVE MAGNETIC STRENGTHS
IN THE MACHINE OPTICS (TWISS) FILES

THE LINE BUILDER

Profiting from roto-translation directives and replication (lattice) capabilities,
the AUTOMATIC CONSTRUCTION OF COMPLEX BEAM LINES,
including collimator settings and element displacement (BLMs), is achievable





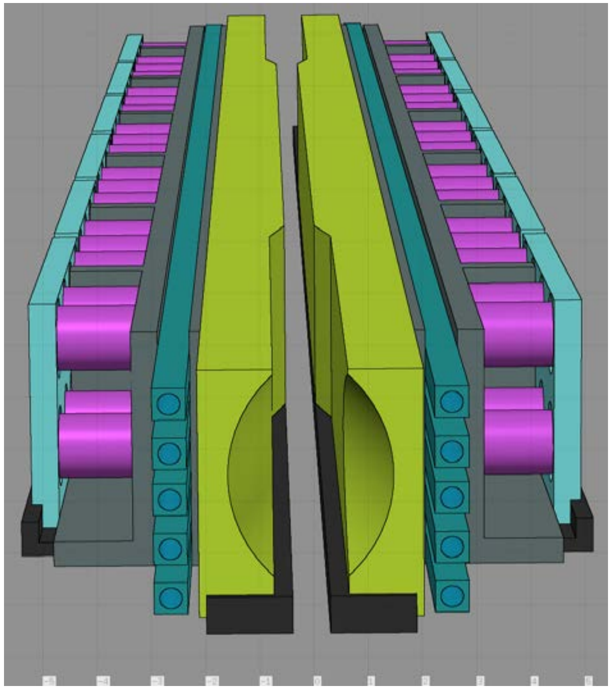


[A. Mereghetti et al.,
IPAC2012, WEPPD071, 2687]

INPUT FROM BEAM (HALO) TRACKING

Machine protection calculations lie in a multi-disciplinary field, where particle dynamics in accelerators and radiation-matter interaction play together.

Energy deposition, particle fluence, monitor signals ... are simulated by shower Monte Carlo codes but imply *multi-turn tracking in accelerator rings* which requires dedicated codes. On the other hand, the latter ones are faced with the problem of *particle scattering in beam intercepting devices* (like collimators).

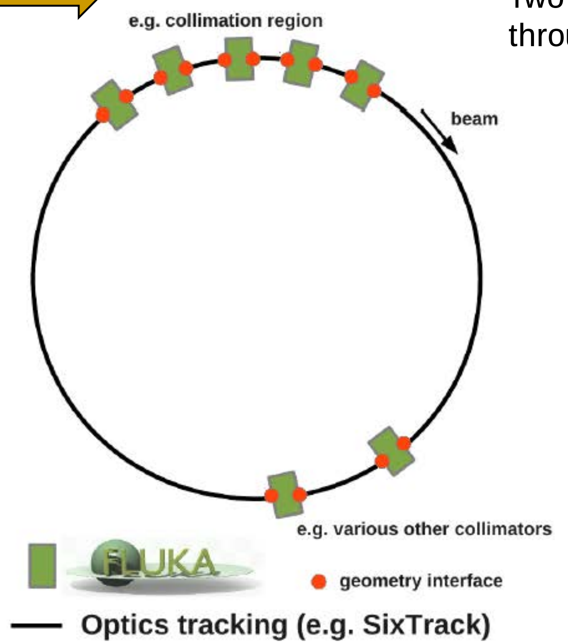


The interface regularly goes through static loss files

giving the spatial distribution of non-elastic interactions - which cannot be handled by tracking codes - inside the jaw material, together with the direction and energy of the beam particle being lost

COUPLING TOOLS

On-line coupling is becoming also available, allowing to avoid possibly critical simplifications (approximate interaction modules in tracking codes and vice versa).



Two codes running at the same time and talking to each other through a network port, by which particles are exchanged at run-time

- *Primary particles are transported turn by turn by* SixTrack *throughout the lattice.*
- *When they reach a labelled element, they are transferred to* FLUKA *for transport in its 3D geometry and for simulating the interaction with accelerator components.*
- *At the end of the* FLUKA *insert, marked as a geometry interface, particles are sent back to* SixTrack.

[P.G. Ortega, P. Hermes et al., LHC Collimation Working Group, Oct 6, 2014]

Proceedings of IPAC2013, Shanghai, China WEPEA064

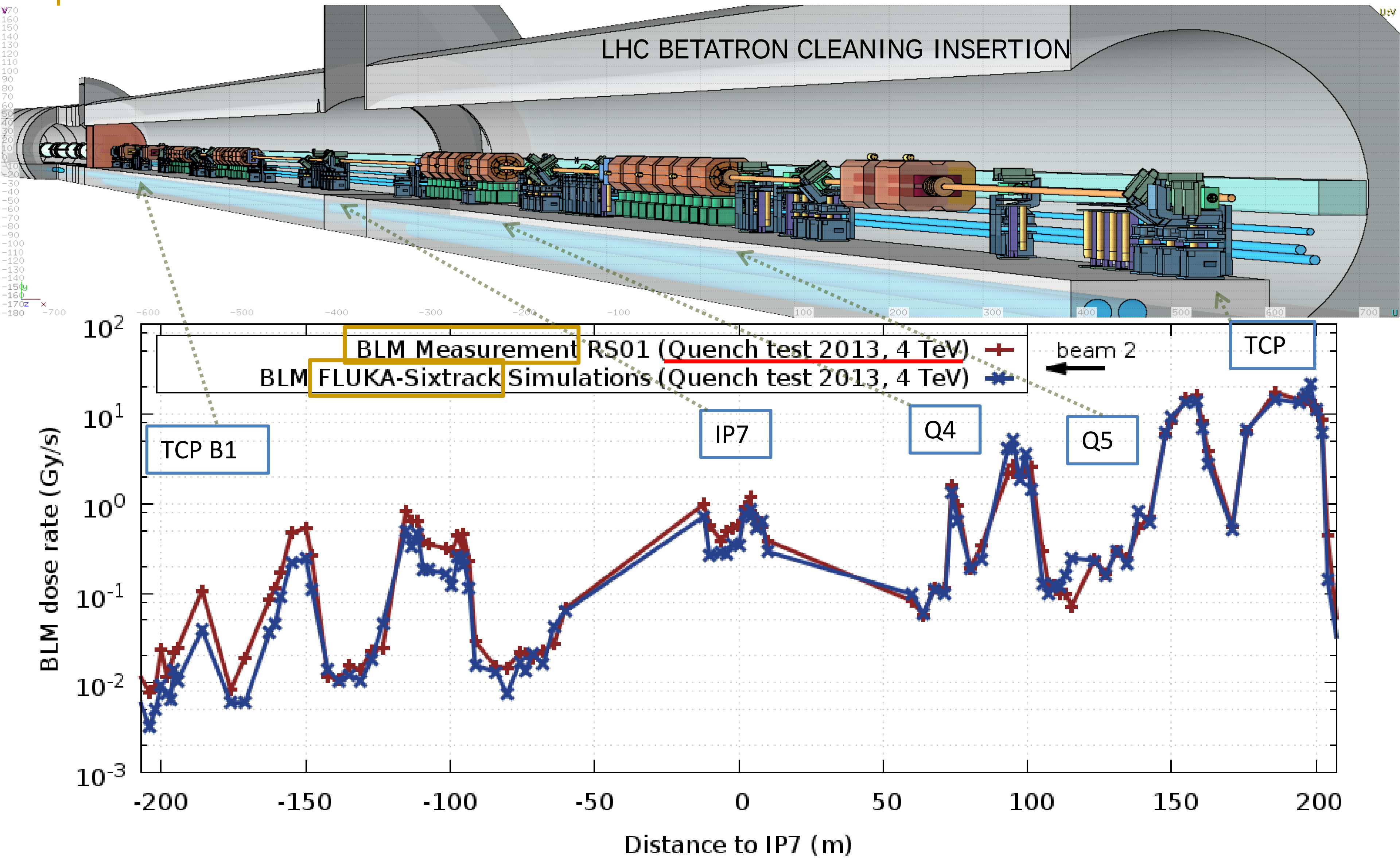
SIXTRACK-FLUKA ACTIVE COUPLING FOR THE UPGRADE OF THE SPS SCRAPERS

A. Mereghetti*, CERN, Geneva, Switzerland, and UMAN, Manchester, UK,
F. Cerutti, R. De Maria, B. Goddard, V. Kain, M. Meddahi, O. Mete, Y. Papaphilippou,
D. Sinuela Pastor, V. Vlachoudis, CERN, Geneva, Switzerland
R. B. Appleby, UMAN, Manchester, UK

MMBLB
MARS and MAD

Beam Delivery Simulation (BDSIM)
Geant4 and C++ particle tracking code

SIMULATION CHAIN VALIDATION



CREDITS

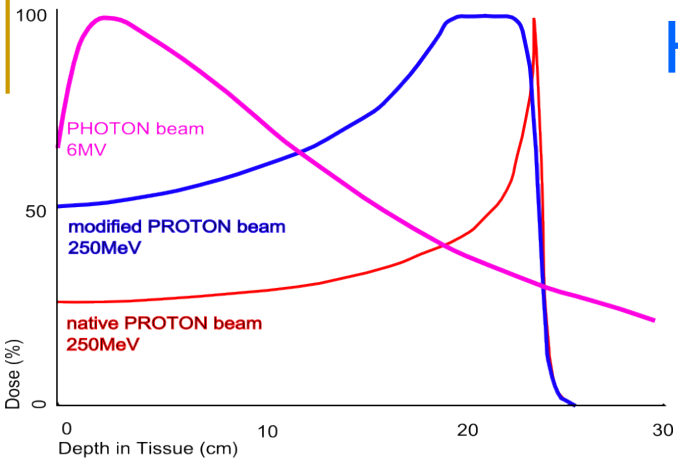
In addition to explicit references, work of and materials from

M. Brugger, L.S. Esposito, A. Ferrari, A. Lechner, R. Losito,

A. Mereghetti, S. Roesler, E. Skordis, P.R. Sala, L. Sarchiapone, V. Vlachoudis

CERN FLUKA TEAM and FLUKA COLLABORATION

CERN COLLIMATION TEAM and CERN RADIATION PROTECTION TEAM



HUMAN MATTERS

not just damage

proton therapy (tumor cell destruction)

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