DPA calculations with FLUKA

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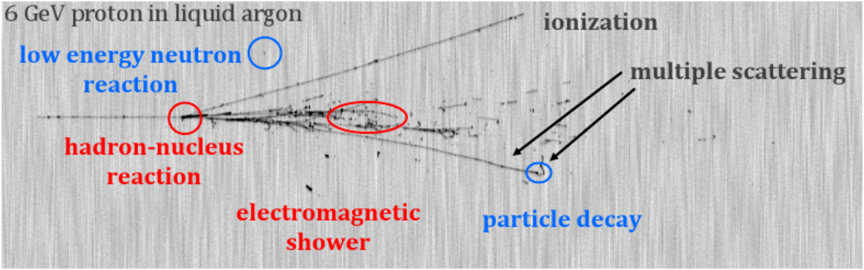
Radiation transport in matter ... stochastic in nature

FLUKA



- Hadron-nucleus interactions
- Nucleus-Nucleus interactions
- Electron interactions
- Photon interactions
- Muon interactions (inc. photonuclear)
- Neutrino interactions
- Decay
- Low energy neutrons

- Ionization
- Multiple scattering
- Combinatorial geometry
- Voxel geometry
- Magnetic field
- Analogue or biased
- On-line buildup and evolution of induced radioactivity and dose

LHC beam-machine interaction studies: from beam losses to secondary shower description

FLUKA is regularly used at CERN to perform LHC beam-machine interaction simulations in the context of

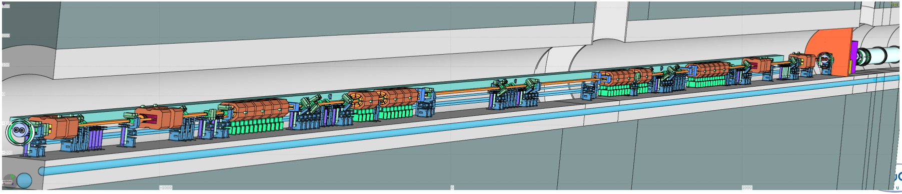
- machine protection
- collimation
- BLM threshold settings
- high-luminosity upgrade
- design studies for new devices (absorbers etc.)
- radiation to electronics (R2E project)
- activation studies
- background to experiments
- ...

Types of LHC beam losses simulated with FLUKA – both, normal and accidental ...

- luminosity production in experiments
- halo collimation
- injection and extraction failures
- residual gas in vacuum chamber
- dust particles falling into beam
- ...

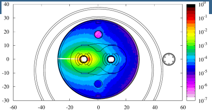
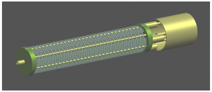
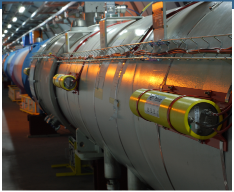
Main focus of this presentation

- DPA calculations with FLUKA (incl. examples)



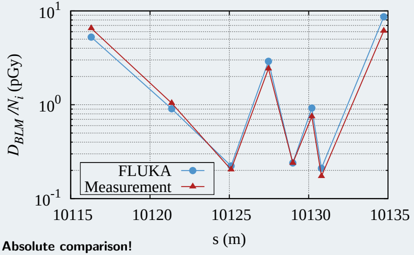
Validation of dose calculations for TeV proton losses (controlled beam loss experiments)

- FLUKA is based, as far as possible, on well bench-marked microscopic models
- However, first years of LHC operation also allowed to validate FLUKA dose predictions against Beam Loss Monitors (BLMs) measurements
- BLMs measure dose from secondary showers in machine elements (magnets, collimators, etc.)
- Several thousand BLMs are installed around the ring (ICs, filled with N_2 gas, about 1500 cm^2 active vol.)

Losses induced by beam wire scanner (p@3.5 TeV)

- Quench test **2010** in LHC IR4 (M. Sapinski et al.)
- Wire scans: showers due to collision products registered in BLMs installed on downstream magnets (∼35 from wire scanner)

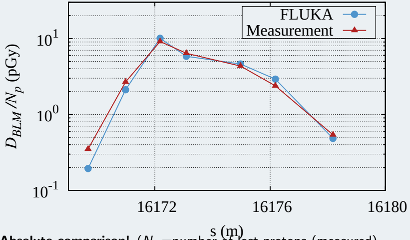


Absolute comparison!

N_i=number of inelastic proton-wire interactions (derived analytically)

Direct losses on MQ beam screen† (p@4 TeV)

- Quench test **2013** in arc sector 56 (A. Priebe et al.)
- Proton losses on beam screen (over ∼1.5 m) by means of orbit bump/beam excitation, dose measured by BLMs outside of MQ cryostat



Absolute comparison! (N_p=number of lost protons (measured)

† FLUKA simulations based on MAD-X loss distribution from V. Chetvertkova et al.

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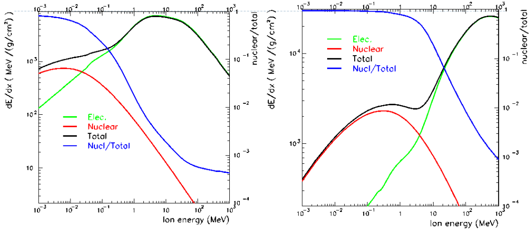
FLUKA and DPA in a nutshell

- DPA can be induced by all particles produced in the hadronic cascade
- displacement damage related to energy transfers to atomic nuclei

Charged particles (incl. heavy ions)	
During transport	DPA based on non-ionizing energy loss (NIEL) along particle step (restricted above damage threshold E_{th}), using Lindhard partition function $\zeta(T)$ and energy dependent displacement efficiency $\kappa(T)$

$$N(E) = \int_{E_{th}}^{\gamma E} \left[\xi_r(T, E_{th}) \left(\frac{d\sigma}{dT} \right)_E \int_{E_{th}}^{\gamma' T} \kappa(T') \xi_r(T', E_{th}) T' \left(\frac{d\sigma}{dT'} \right)_T dT' \right] dT$$



Figures: stopping powers for oxygen ions in silicon (left), silver ions in gold(right)

FLUKA and DPA in a nutshell

continued from previous page:

Charged particles (incl. heavy ions)	
Particle falls below transport threshold	Nuclear stopping power integrated (using Lindhard partition function)
Elastic and inelastic encounters	Recoils and secondary charged particles explicitly produced if their energy lies above transport threshold (i.e. they become a projectile), otherwise they are treated as below threhold.

Neutrons	
$\leq$20 MeV[1]	DPA is based on (un)restricted NIEL as provided by NJOY
$>$ 20 MeV	recoils: same as for elastic and inelastic encounters of charged particles

[1] For $\leq$20 MeV neutron transport, FLUKA uses multi-group approach (group-to-group scattering probabilities from NJOY).

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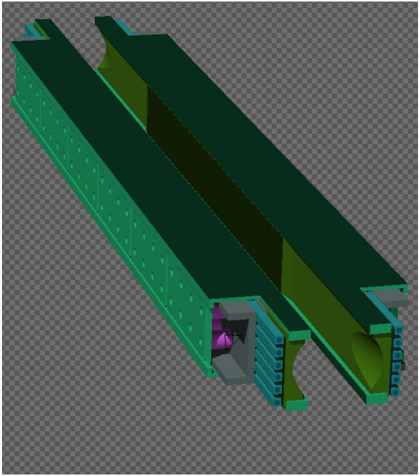
Estimating DPA in LHC primary collimators (made of AC150)

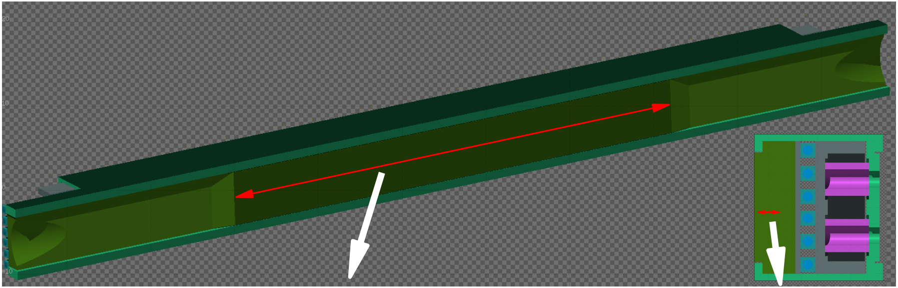


- Two step simulation:
  - Spatial distribution of inelastic proton-nucleus collisions in collimators is derived by means of multi-turn tracking simulations (using FLUKA-Sixtrack coupling, in collaboration with LHC collimation team)
  - Starting from this loss distribution, the DPA distribution is calculated in detailed (low-cut) FLUKA shower calculations in jaw of TCP.C6L7
- Note:
  - By starting from the spatial distribution of inelastic collisions, we neglect the DPA contribution of primary protons before the collision

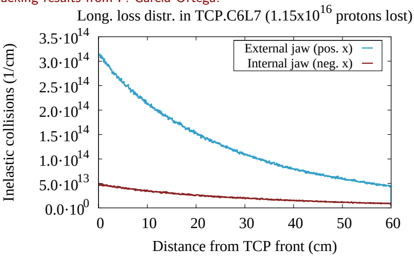
- Assumptions for DPA calculations:
  - beam energy of 7 TeV
  - horizontal losses only
  - annual beam losses of 1.15×10^{16} protons

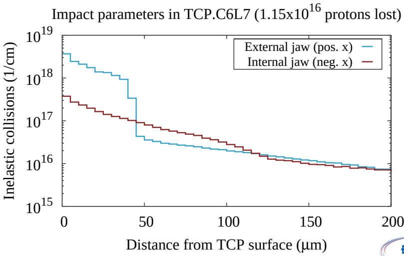
  → corresponding to 40 fb^{-1} in 2012
  → one needs to apply approximately a factor 100 to get an estimate for HL-LHC lumi goal (4000 fb^{-1})

Spatial distribution of inelastic proton collisions in the horizontal TCP



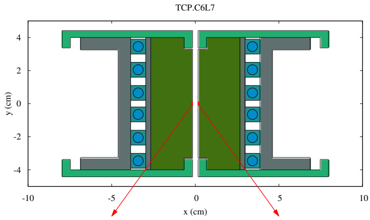
Tracking results from P. Garcia Ortega.

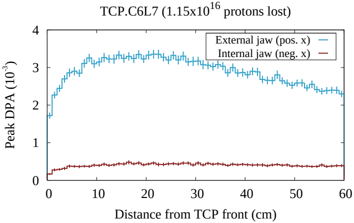


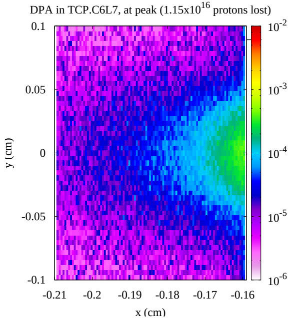


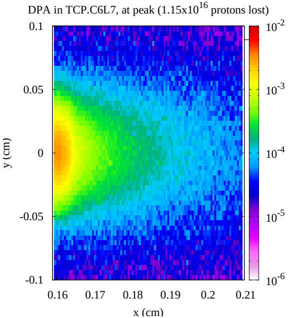
→ tracking simulations show unequal sharing of losses between TCP.C6L7 jaws (∼6:1)

DPA in TCP jaws (1.15×10^{16} protons lost) – preliminary results









Assumed E_{thr} (AC150): 35 eV

Max. DPA: $\sim 3\times10^{-3}$

Transp. thre.	
photons	100 keV
e^-/e^+	500 keV
neutrons	10^{-5} eV
ions	0.25 keV/nucl
other	1 keV

Anatomy of DPA predictions in TCP jaw – preliminary results

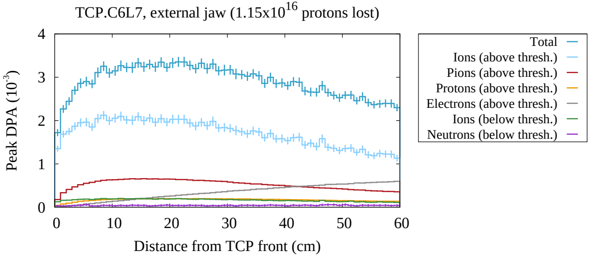


Table below : contributions to peak DPA at a depth of ∼15 cm (for the TCP jaw with higher proton losses)

Peak DPA contribution:	Type of contribution:
62%	Ions above transport threshold (>250 eV/nuc) → explicitly generated recoils
20%	Pions above transport threshold (>1 keV)
5-6%	Protons above transport threshold (>1 keV)
5-6%	Ions below transport threshold (<250 eV/nuc) → non-transported recoils
6-7%	Electrons above transport threshold (>500 keV)
<0.5%	Others

Percentage values rounded; (statistical) error of contributions: ∼1%

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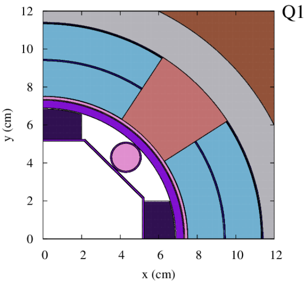
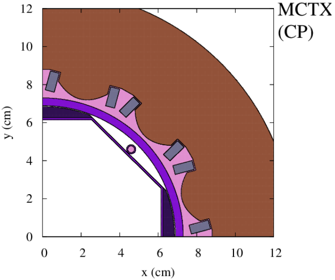
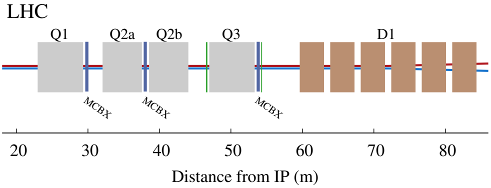
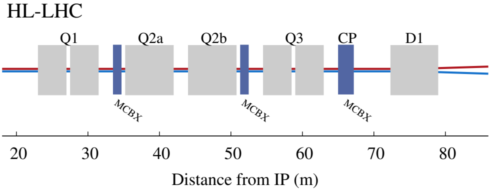
HL-LHC (inner triplet and D1 in IR1/5): FLUKA models and brief recap of layout





FLUKA model by L. Esposito (HL-LHC WP10)

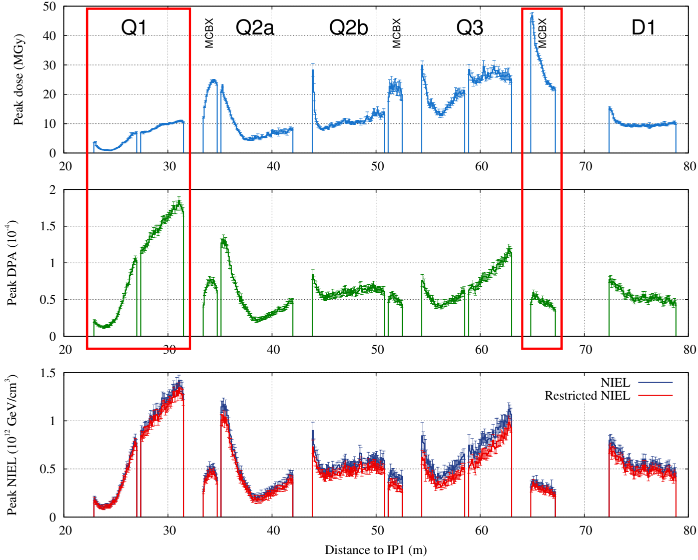




- HL performance goal for proton collisions@IR1/5:
  - instantaneous luminosity of 5×10^{34} $cm^{-2}s^{-1}$ (= 5 × design luminosity)
  - integrated luminosity of $3000\,fb^{-1}$ ($250\,fb^{-1}$ per year)

HL-LHC: Q1,Q2,Q3 → Nb_3Sn; D1, MCBX → NbTi

Peak DPA and NIEL in coils of triplet quadrupoles, correctors and D1 (3000 fb^{-1})

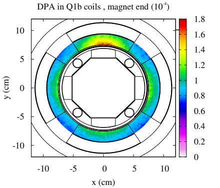


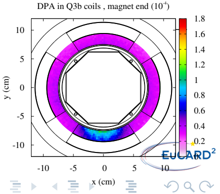
Assumed E_{thr}: 30 eV

Peak dose vs DPA:

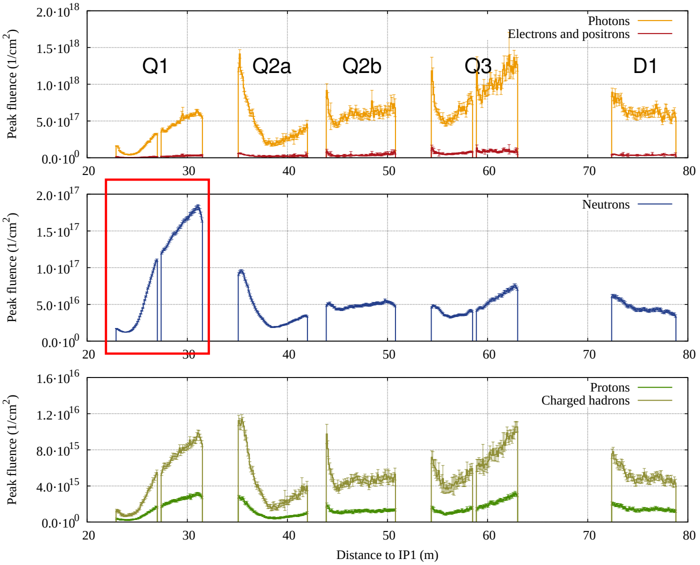
- the latter has its maximum in Q1
- see particle fluences on next page

Max. DPA: $\sim 1.8 \times 10^{-4}$





Peak fluences in coils of triplet quadrupoles and D1 (3000 fb^{-1})



Neutrons in coils:

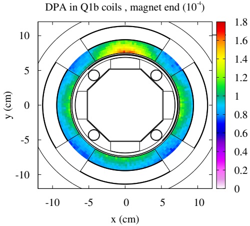
- max. fluence: 1.8×10^{17} cm^{-2}
- correlation peak neutron fluence – peak DPA
- see anatomy of DPA calculations in next page

Transp. cut:	
photons	100 keV
e^-/e^+	500 keV
neutrons	10^{-5} eV
ions	0.25 keV/nucl
other	1 keV

Anatomy of DPA predictions in Q1

Contributions to DPA maximum in Q1:

- Dominated by low-energy neutrons (for which FLUKA relies on NJOY-based values for DPA)



Peak DPA contribution:	Type of contribution:
70.7%	Neutrons <20 MeV (NJOY)
24.4%	Ions above transport threshold (>250 eV/nucleon) → explicitly generated recoils (from neutron, proton, etc. interactions)
1.7%	Protons above transport threshold (>1 keV)
1.6%	Ions below transport threshold (<250 eV/nucleon) → non-transported recoils
1.0%	Electrons above transport threshold (>500 keV)
0.6%	Pions above transport threshold (>1 keV)
<0.1%	Others

Percentage values rounded; (statistical) error of contributions: few 0.1%

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Summary

- FLUKA offers a powerful way to calculate DPA for beam losses as encountered in the LHC operational environment or during beam tests
  - In particular, allows to take into account the contribution of different particle types, including all particles produced in the particle shower development
- DPA estimates for horizontal primary collimator (preliminary):
  - Simulation predicts a peak DPA of 3×10^{-3} for $\sim$40 fm^{-1} aka 1×10^{16} protons lost (or $\sim$0.3 for $\sim$4000 fm^{-1})
  - Predominant contribution comes from recoils
  - However, present calculations still neglect contribution of primary protons before they have an inelastic interaction
- DPA estimates for HL-LHC proton collision debris impacting on triplet magnets (IR1/5):
  - FLUKA predicts max. DPA of $\sim1.8\times10^{-4}$ in Q1 coils for 3000 fm^{-1}
  - Dominant contribution due to neutrons $<$20 MeV (fluence up to 1.8×10^{17} cm^{-2})