FLUKA radiation damage calculations for colliders like the HL-LHC

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in collaboration with

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with valuable inut from

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RESMM'14
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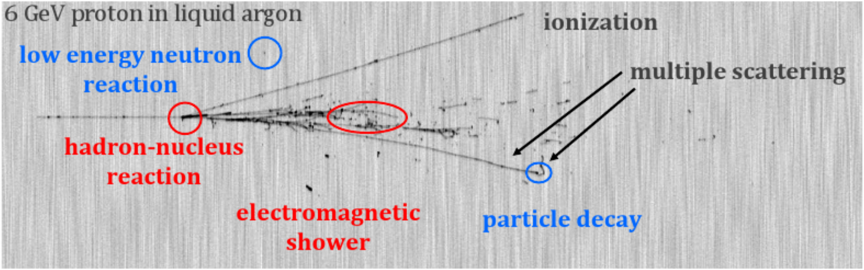
Contents

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

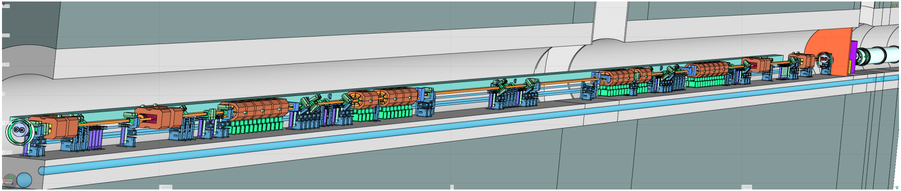
- machine protection
- collimation
- high-luminosity upgrade
- design studies for new devices (absorbers etc.)
- radiation to electronics (R2E project)
- activation studies
- background to experiments
- ...

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
- ...

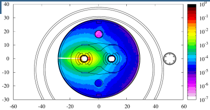
Main focus of this presentation

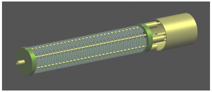
- Dose and DPA calculations for the HL-LHC

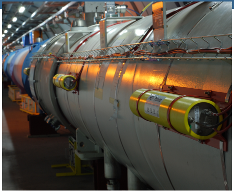


Validation of dose calculations for TeV proton losses (controlled beam loss experiments)

- 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.)

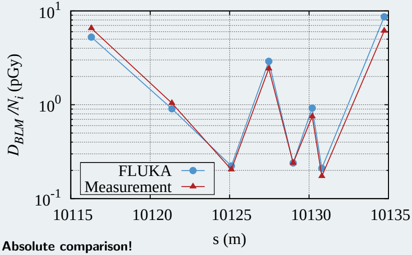






Losses induced by beam wire scanner (p@3.5 TeV)

- 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)

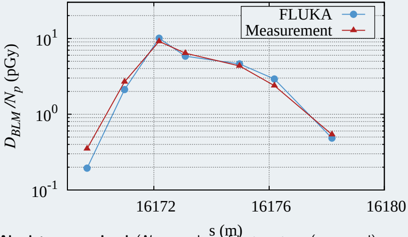


Absolute comparison!

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



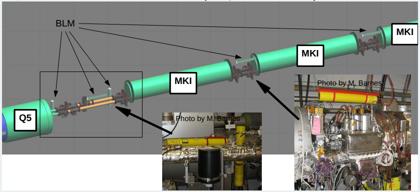
Absolute comparison! (N_p=number of lost protons (measured)

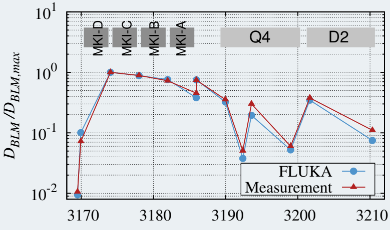
† FLUKA simulations based on MAD-X loss distribution from V. Chetvertkova et al.

Validation of dose calculations for TeV proton losses (operational beam losses)

Losses induced by chamber fragments (p@4 TeV)

- Beam losses due to proton interactions with micrometer-fragments separated from MKI vacuum chambers (caused several beam dumps)
- By analysing BLM pattern, FLUKA studies allowed to determine dust particle locations around MKIs (=injection kickers)



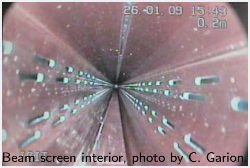


Relative comparison!

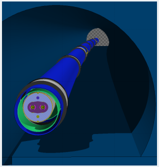
Number of inelastic proton-dust particle interactions not known.

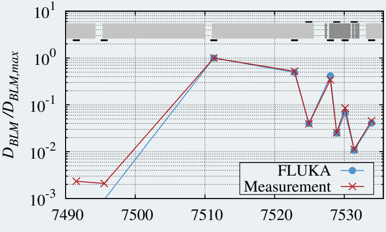
Losses induced by dust particles in arcs (p@4 TeV)

- Proton interactions with dust particles in the LHC arcs (insulation debris etc.)



Beam screen interior, photo by C. Garion.

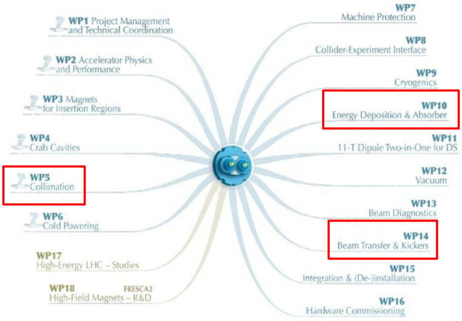




Relative comparison!

Number of inelastic proton-dust particle interactions not known.

Involvement of CERN FLUKA team in collider upgrade/design studies



HL-LHC:

Direct involvement in different Work Packages:

- **WP5** (Collimation)
  TCLs, DS collimators, exp. background etc.
- **WP10** (Energy Deposition & Absorber)
  Joint Studies FLUKA (CERN) and MARS (N. Mokhov, Fermilab)
  IR1/5 triplet, matching section magnets etc.
- **WP14** (Beam Transfer & Kickers)
  injection and extraction absorbers

Close collaboration with many other WPs.

FCC (Future Circular Collider):

Involvement in first design studies (starting right now), e.g. concerning final focus, etc.

FCC
hh ee he

Contents

FLUKA and DPA: a brief recap

- DPA can be induced by all particles produced in the hadronic cascade
- displacement damage related to energy transfers to atomic nuclei (restricted NIEL)
- see also F. Cerutti's talk at RESMM'13 for some more details

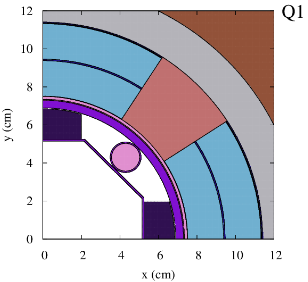
Charged particles (incl. heavy ions)	
During transport	Restricted non-ionizing energy loss (NIEL) calculated along particle step (using Lindhard partition function and energy dependent displacement efficiency $\kappa(T)$)
Particle falls below transport threshold	Nuclear stopping power integrated (using 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.

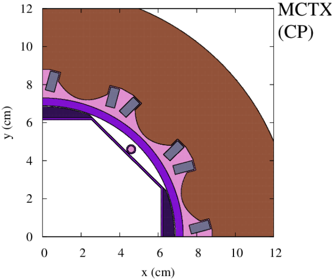
Neutrons	
$\leq$20 MeV[1]	DPA is based on (un)restricted NIEL as provided by NJOY
$>$ 20 MeV	recoils: same as for elastic and inelastic encounters of charged particles

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

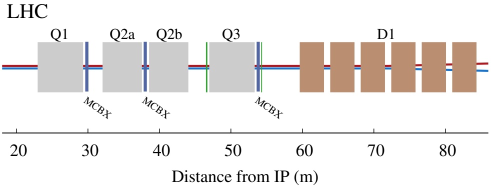
Contents

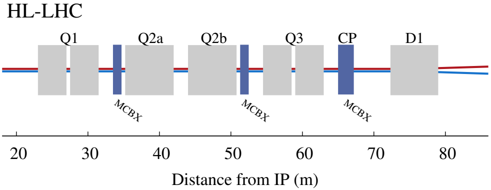
HL-LHC (inner triplet and D1 in IR1/5): FLUKA models and brief recap of layout





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

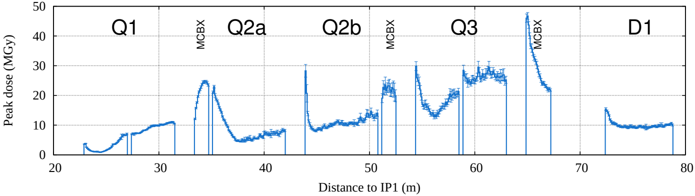


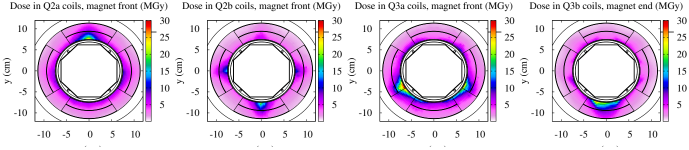


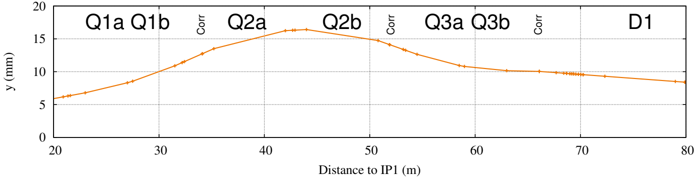
- HL performance goal for proton collisions@IR1/5:
  - instantaneous luminosity of $5\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (= 5 × design luminosity)
  - integrated luminosity of $3000\,\mathrm{fb}^{-1}$ ($250\,\mathrm{fb}^{-1}$ per year)

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

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





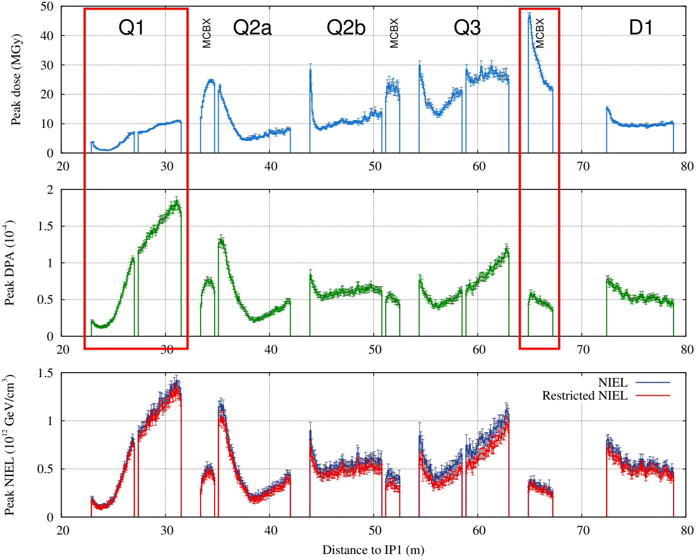


See also N. Mokhov's presentation on MARS results

Optics:	round
β^*	15 cm
$\theta_\times$	590 μrad
$\times$-plane	vertical
$\Delta_\parallel$	1.5 mm

- p–p inelastic cross-section: 85 mb
- collisions simulated by means of DPMJET-III
- details of INERMET (W-alloy) shielding (transverse shape, gaps in interconnects) can change dose values by few 10%

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

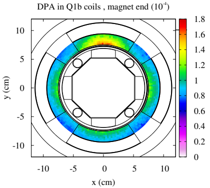


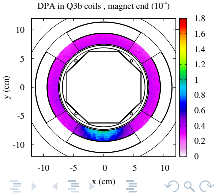
Assumed E_{thr}: 30 eV

Peak dose vs DPA:

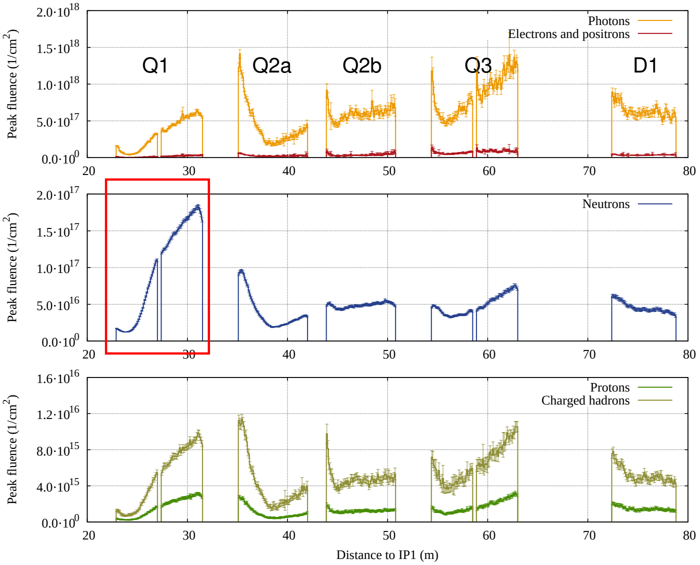
- the latter has its maximum in Q1
- see particle fluences on next page

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





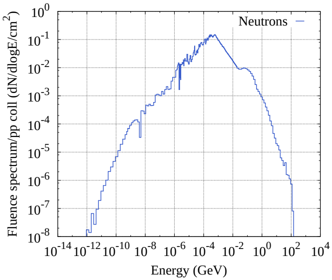
Peak fluences in coils of triplet quadrupoles and D1 (3000 fb^{-1})

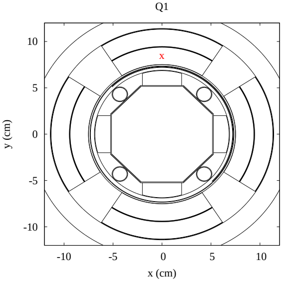


Neutrons in coils:

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

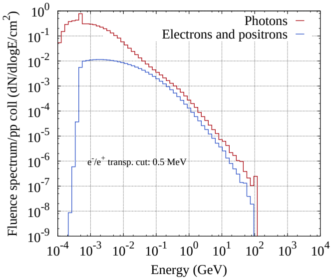
Fluence spectra in Q1 coils

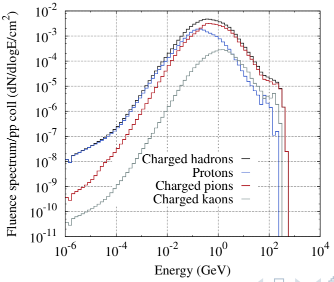




Particle spectra:

- in second Q1 module
- longitudinally and radially averaged over inner cable of upper coils
- expressed per pp collision
- expressed as lethargy



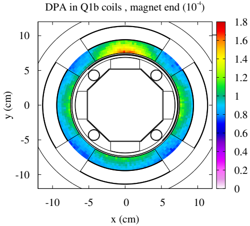


Transp. cut:	
photons	100 keV
e^-/e^+	500 keV
neutrons	10^{-5} eV
ions	0.25 keV/nucl
other	1 keV

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

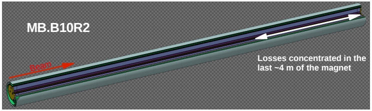
Percentage values rounded; (statistical) error of contributions: few 0.1%

Contents

HL-LHC (DS next to IR2): ion collision debris

- ALICE performance goal for ion operation after 2018 (**Pb@2.76 TeV/u**) [1]:
  - instantaneous luminosity of $6\times10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (= 6 × design luminosity)
  - integrated luminosity of $10\,\mathrm{nb}^{-1}$
- Secondary ion beams due to electromagnetic interactions (see [2] for details):
  - e.g. bound-free pair production (BFPP), with a cross section of $\sim$281 b:

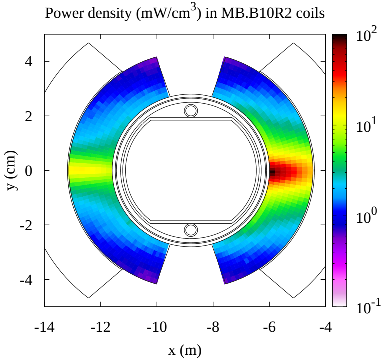
    $${}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \rightarrow {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + e^{+}$$
  - changed magnetic rigidity with respect to primary ion beam
  - localised losses (and heat deposition) in DS magnets next to IR2 due to higher dispersion
- To mitigate risk of quenches, alternative layout with DS collimator + 11T dipoles is under study
  - *not covered in this presentation*

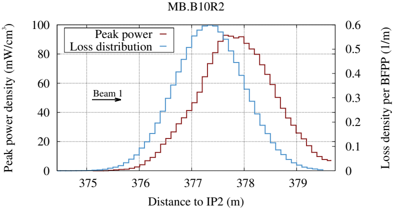


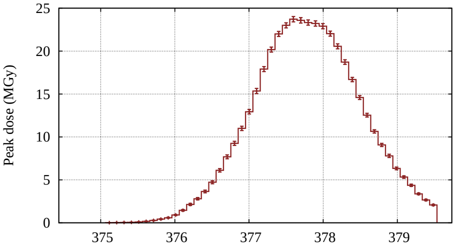
FLUKA simulations are based on SixTrack impact distributions from R. Bruce [2]

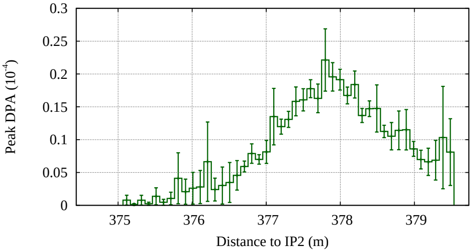
[1] J. Jowett and M. Schaumann, "Dispersion Suppressor Collimators for Heavy-Ion Operation", Collimation Review 2013.
[2] R. Bruce *et al.*, PhysRevSTAB **12**, 071002, 2009.

Peak power density ($6\times10^{27}\,cm^{-2}s^{-1}$), dose and DPA ($10\,nb^{-1}$) in MB.B10R2 coils



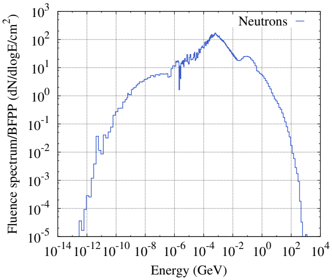


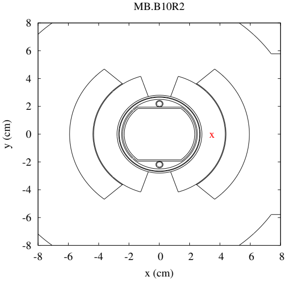




Main DPA contributions from ions (i.e. recoils) and electrons above transport threshold as well as neutrons <20 MeV (same transport cuts used as for IR1 triplet).

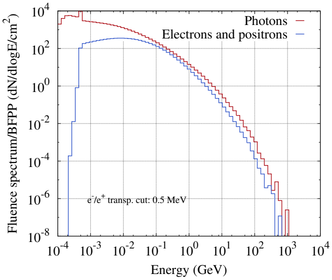
Fluence spectra in MB coils

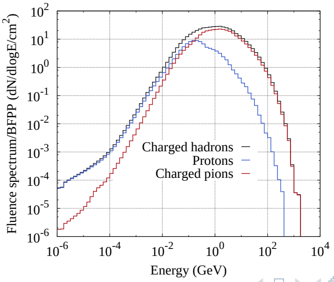




Particle spectra:

- radially averaged over inner cable of most exposed coils
- longitudinally averaged over $\sim$ 180 cm (around peak)
- expressed per bound-free pair production
- expressed as lethargy





Transp. cut:	
photons	100 keV
e^-/e^+	500 keV
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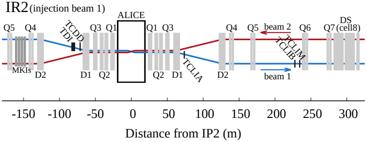
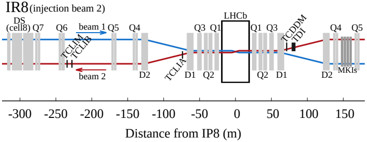
other	1 keV

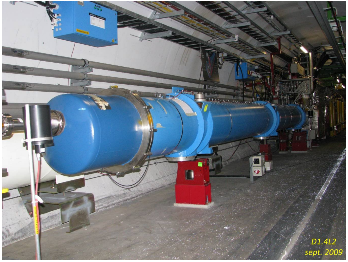
Contents

HL-LHC/LIU (IR2/IR8): fast failures during injection

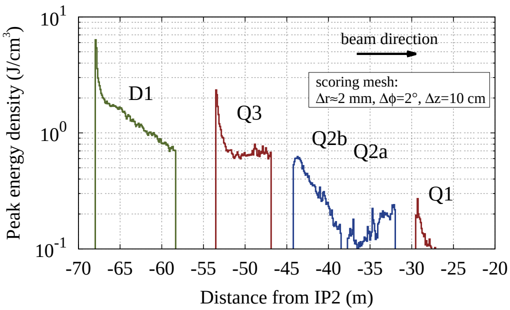
- HL-LHC/LIU injection beam parameters (**p@450 GeV**, 25 nsec, BCMS beams):
  - $\epsilon_n = 1.37\,\mu$m rad
  - $288 \times (2.0\times10^{11}) = 5.8\times10^{13}$ prot. per inj.
    $\rightarrow$ beam brightness significantly higher than for nominal LHC
- Injection kicker (MKI) malfunctions
  - Can lead to fast single-turn failures ($<8\,\mu$sec):
    - Injected beam not kicked (enters machine with vertical angle of 0.85 mrad)
    - Accidental kick of circulating beam
  - Several instances of such failures happened during first years of LHC operation
- Protection of downstream superconducting magnets (D1 and inner triplet):
  - Fast energy dep. in coils, requires adequate protection to stay below damage limit
  - Current system of beam-intercepting decives (TDI+mask, TCLIs) is being redesigned for HL-LHC/LIU upgrade (HL-LHC WP14)



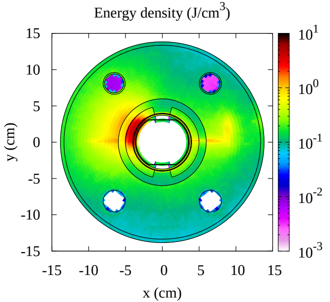




Energy density estimates for previous injection failures



- One of the worst inj. failures in Run I
  - MKI erratic on 28/07/2011
  - 176 circulating bunches deflected with 12.5% of nominal MKI strength
  - most bunches were grazing on TDI
  - D1 and triplet quenched
  - figure left: FLUKA prediction of peak energy density in coils
    - → were safe in the past
    - → failure scenarios to be reevaluated for HL-LHC (higher beam brightness!)



Damage limit for Nb-Ti cables (B. Auchmann, A. Verweij):

- Fast and localized thermal expansion may give rise to thermal shockwave in coils
  - Potentially more damaging than slow heating up to same temperature (due to local shear)
  - Hence, design goal for protection devices:
    - peak temperature in coils due to fast beam losses should be limited to 80 K
    - gives a limiting energy density of 54 J/cm^3 (integration of heat capacity)

Contents

Summary

- HL-LHC proton collision debris impacting on triplet (IR1/5):
  - FLUKA predicts max. DPA of $\sim 1.8\times10^{-4}$ in Q1 coils for $3000\,\mathrm{fb}^{-1}$
  - Dominant contribution due to neutrons <20 MeV (fluence up to 1.8×10^{17} cm^{-2})
  - Compared to the FLUKA model used in the present simulations, some details of shielding and interconnects may be different in eventual design
    $\rightarrow$ however not expected to significantly change DPA predictions
  - Work continues in HL-LHC WP10
- HL-LHC ion collision debris impacting on DS magnets (IR2):
  - Local losses due to secondary beams with changed rigidity
  - Estimated DPA in MB (DS) coils due to BFPP is $\sim 0.2\times10^{-4}$ for $10\,\mathrm{nb}^{-1}$; dose after same integrated lumi is 23 MGy (on to top of this, needs to consider the collision debris from proton operation)
  - DS collimators might be installed, primarily to mitigate risk of magnet quenches; would also significantly reduce dose
- Fast failures during injection (IR2/I8):
  - Protection absorbers for D1 and triplet currently under redesign to cope with significantly higher brightness of HL-LHC/LIU beams (ongoing work in HL-LHC WP14)