Beam Losses and Collision Debris Studies in Europe

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EN-STI-EET on behalf of the FLUKA team

Acknowledgements:
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W. Riegler, R. Tomas, D. Schulte, E. Todesco

Outline

- Introduction:
  - Radiation sources

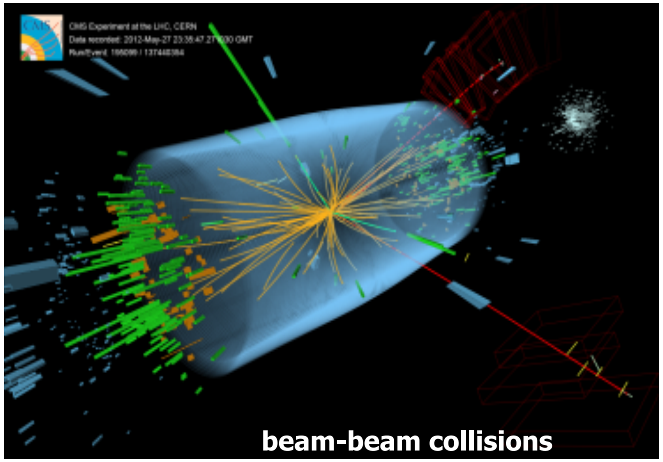
- Validation studies at the LHC:
  - Comparison between simulation results and BLM measurements

- **First results on expectations at the FCC:**
  - Collision debris particles
    - impact on the inner triplet: ruling factors and solution strategies
  - Beam-gas interaction
    - impact on the arc cell

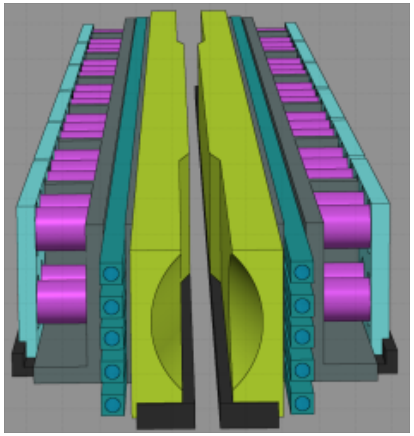
- Next steps:
  - Radiation in the cavern
    - levels at the inner detectors
    - shielding to protect from the machine background
  - Beam intercepting devices

Radiation sources

- Collision debris particles
  - energy deposition in the superconducting magnet coils of the insertion region
    - 100 TeV p-p collisions @ $\mathcal{L} = 5\ 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$: 45 kW towards each (L&R) side
    - $\mathcal{L} = 2\ 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$: 175 kW towards each (L&R) side
  - back-scattering induced background on detectors

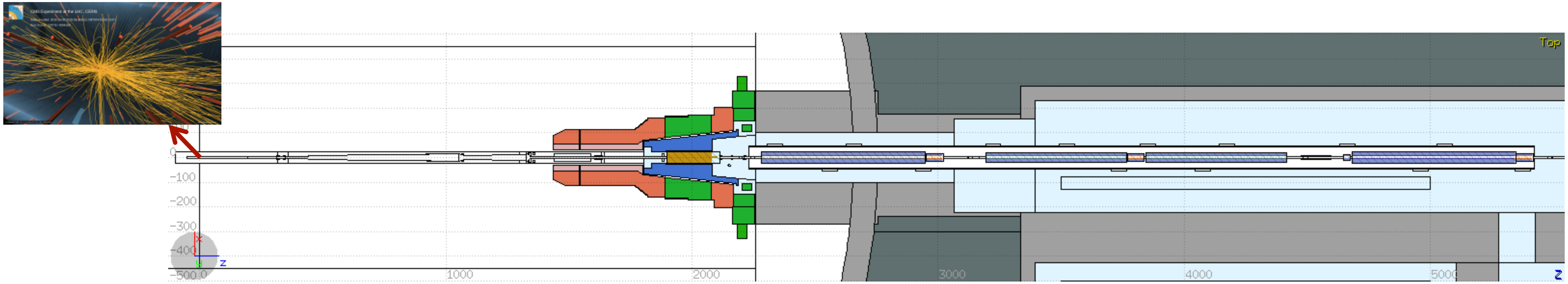


beam-beam collisions

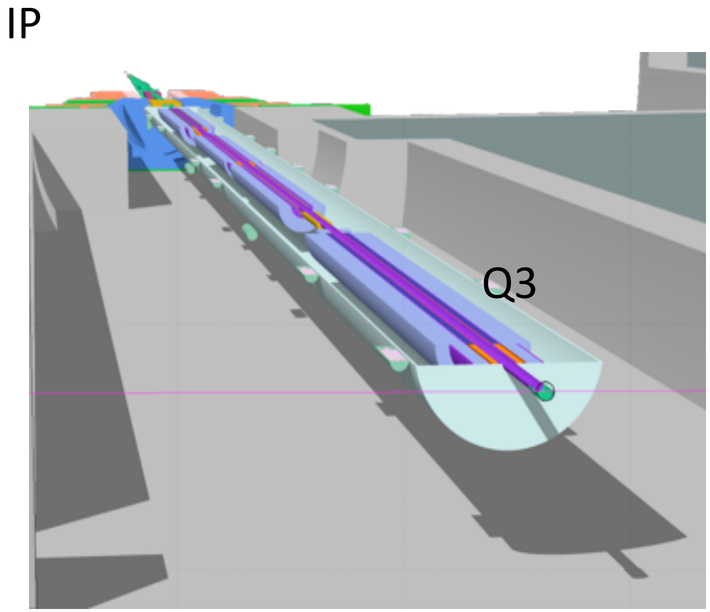


- Beam impact on intercepting devices
  - load on devices
  - essential to evaluate the impact of the shower, developed from the collimation system, on the downstream elements
  - impact on detectors of the tertiary beam halo generated in the collimation system
- Beam interaction with residual gas (or unexpected obstacles)
  - important with respect to vacuum/intensity limits
    - FCC: the copious flux of synchrotron radiation photons will also generate a not negligible amount of gas
  - load on detectors from "close-by" beam gas interactions

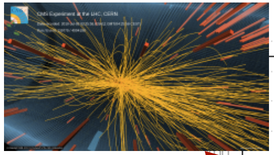
FLUKA validation: collision debris

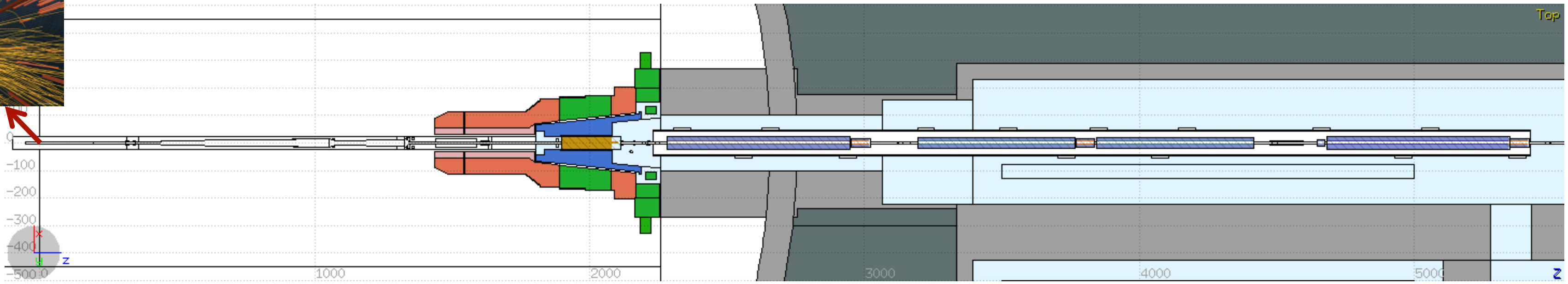


p-p collisions at 7 TeV centre-of-mass energy
@CMS

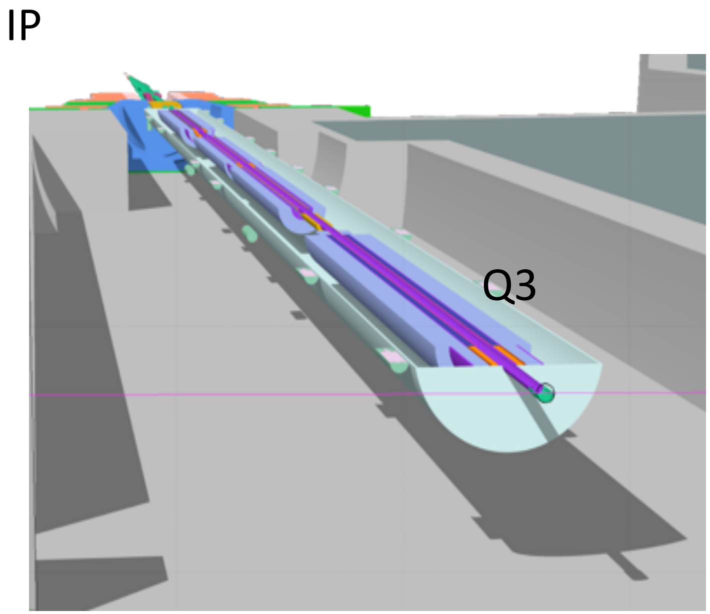


FLUKA validation: collision debris

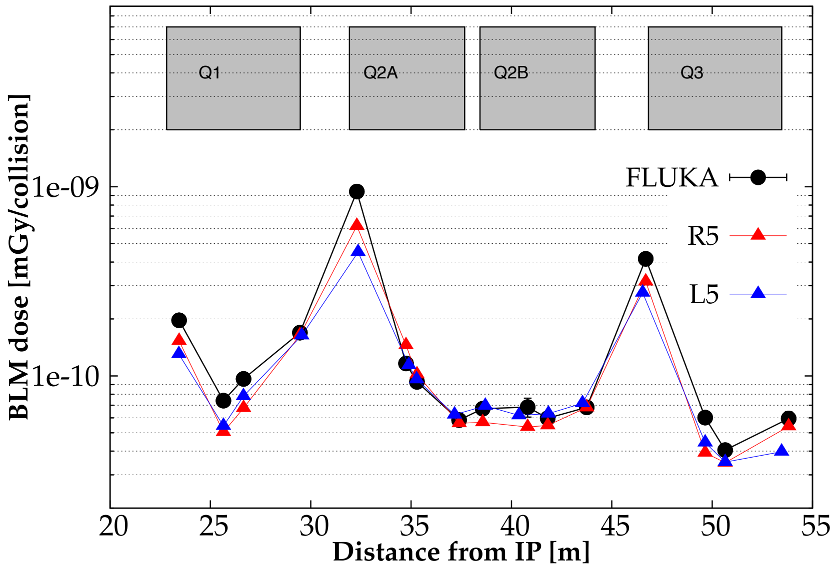




p-p collisions at 7 TeV centre-of-mass energy @CMS

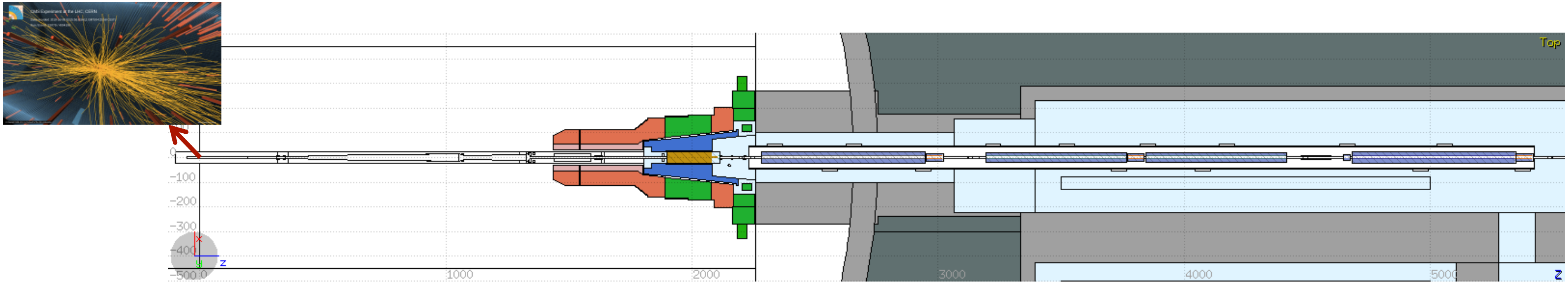


BLM pattern along IR5 triplet (2011)

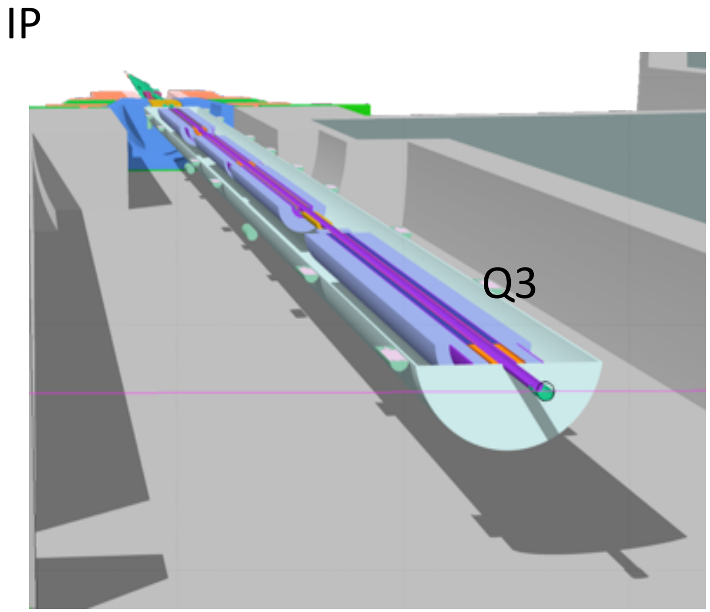


BLM dose per collision, assuming CMS luminosity measurement and 73.5 mb proton-proton cross section (from TOTEM)

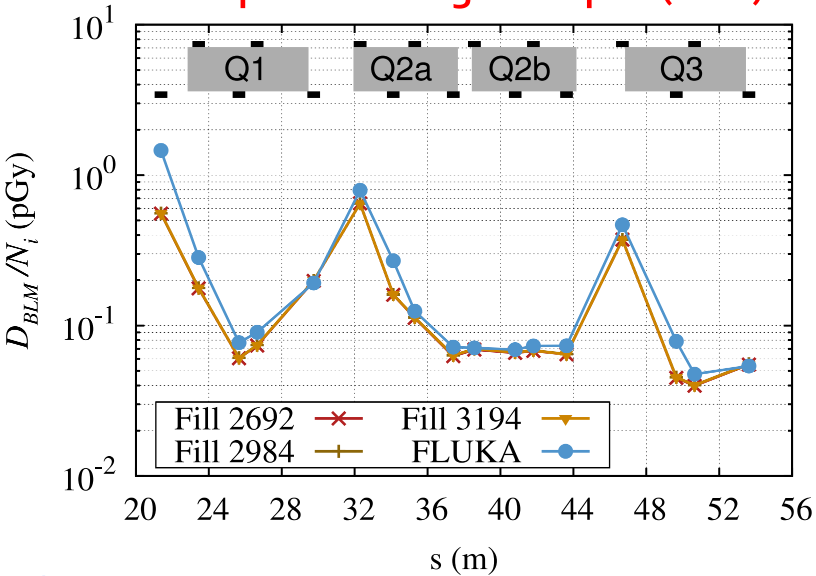
FLUKA validation: collision debris



p-p collisions at 8 TeV centre-of-mass energy @ATLAS



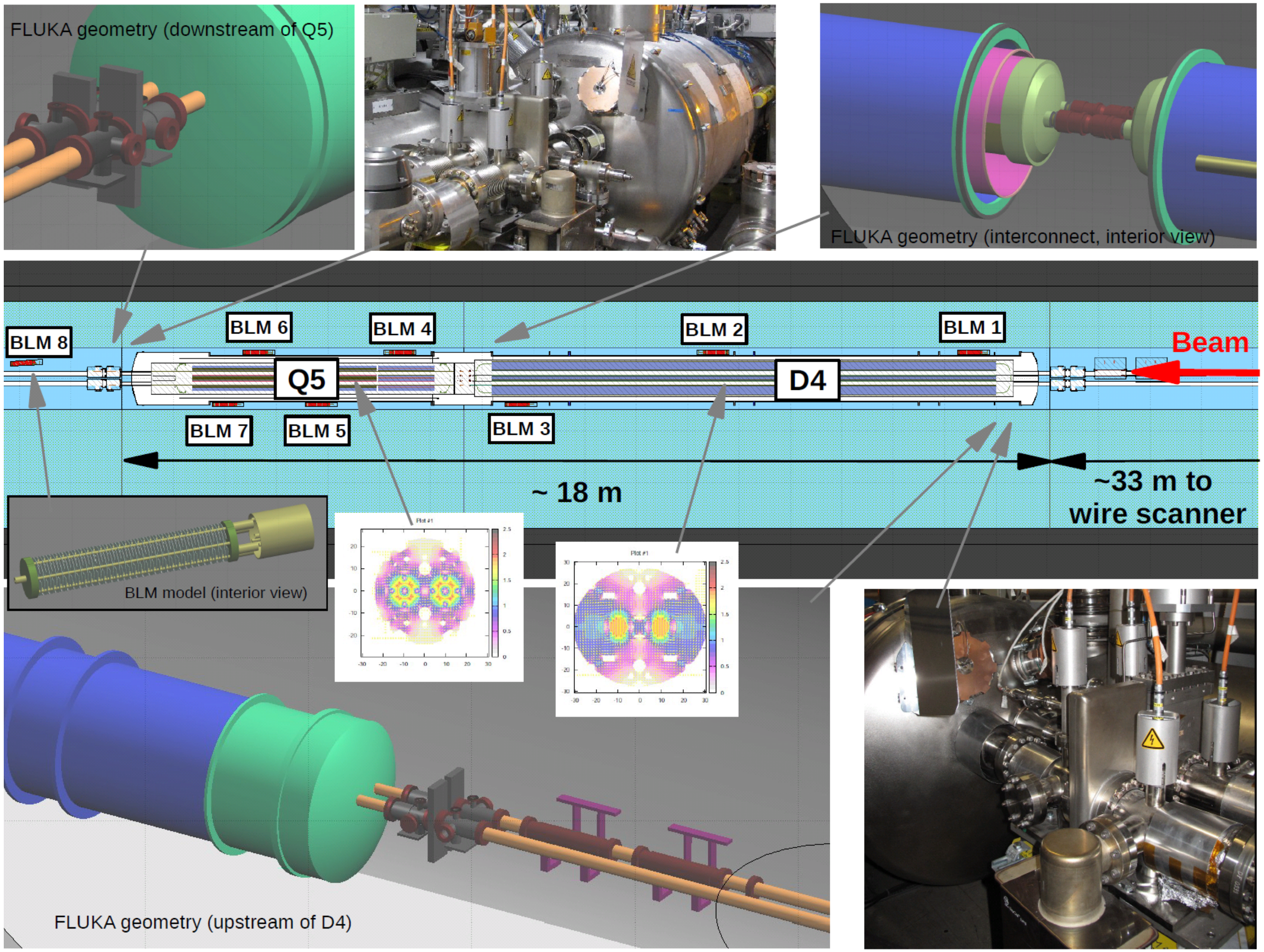
BLM pattern along IR1 triplet (2012)



BLM dose per collision, assuming ATLAS luminosity measurement and 74.7 mb proton-proton cross section (from TOTEM)

FLUKA validation: Losses Induced by Wire Scanner

Wire Scanner test, performed on 2010 Nov 1, on the left of **P4** at 3.5TeV



Controlled benchmarking conditions

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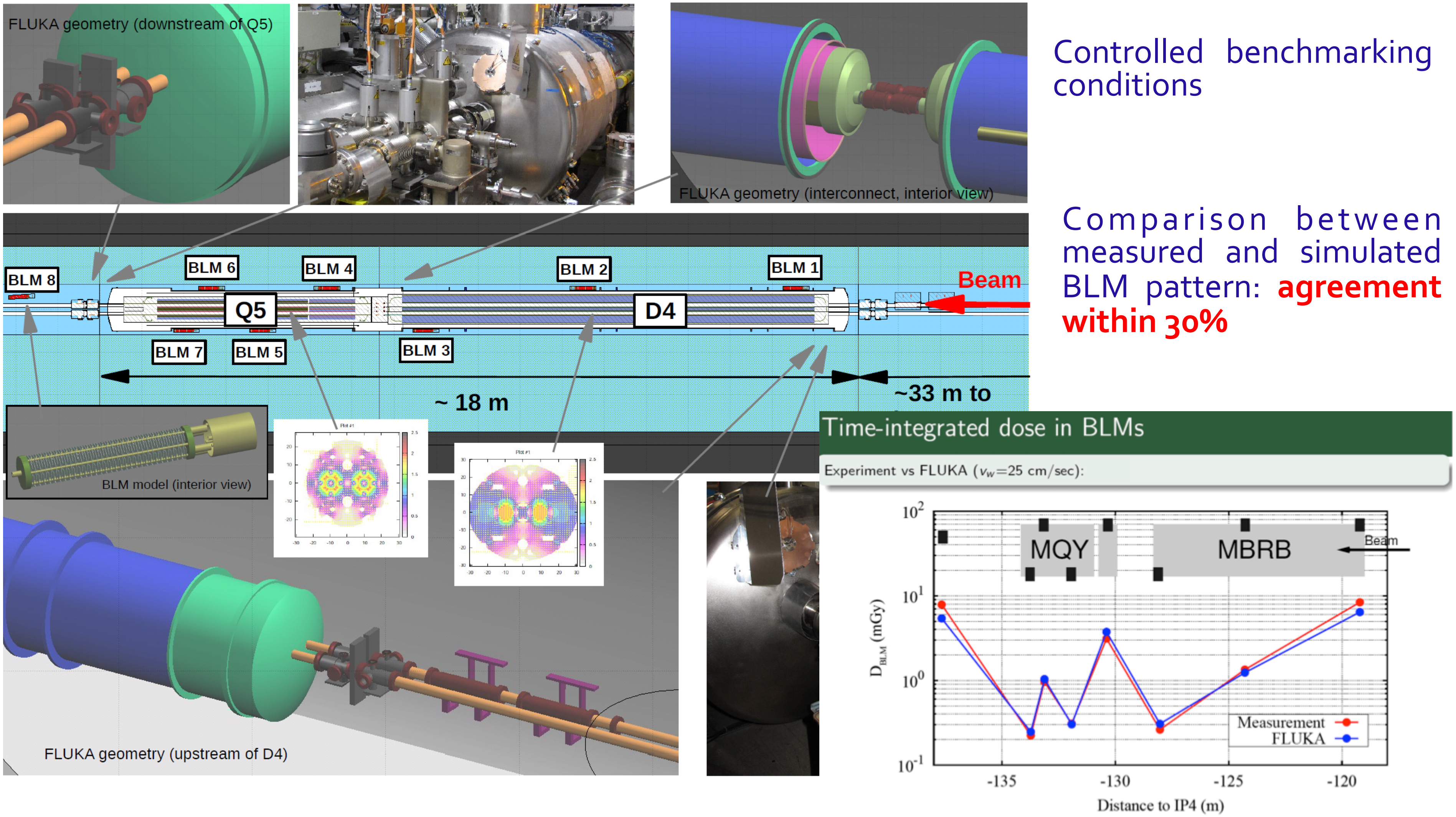


Time-integrated dose in BLMs

Experiment vs FLUKA (v_w=25 cm/sec):

Controlled benchmarking conditions

Comparison between measured and simulated BLM pattern: **agreement within 30%**

Collision debris particles

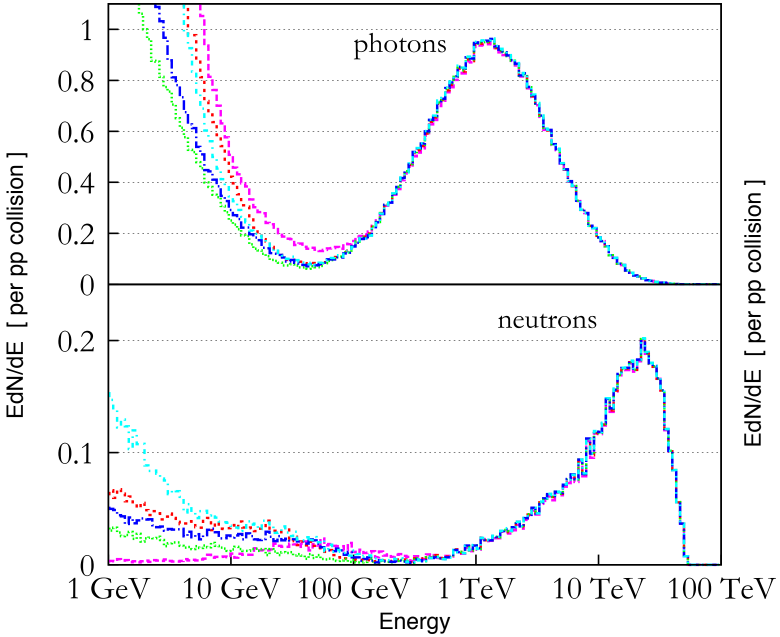
Which particles in the collision debris? Mainly photons, pions, protons and neutrons

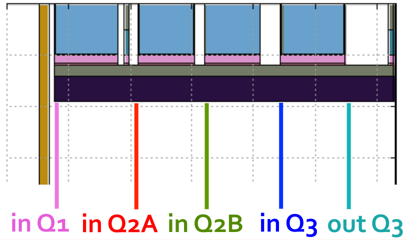
Charged particles are captured by the triplet magnetic field.

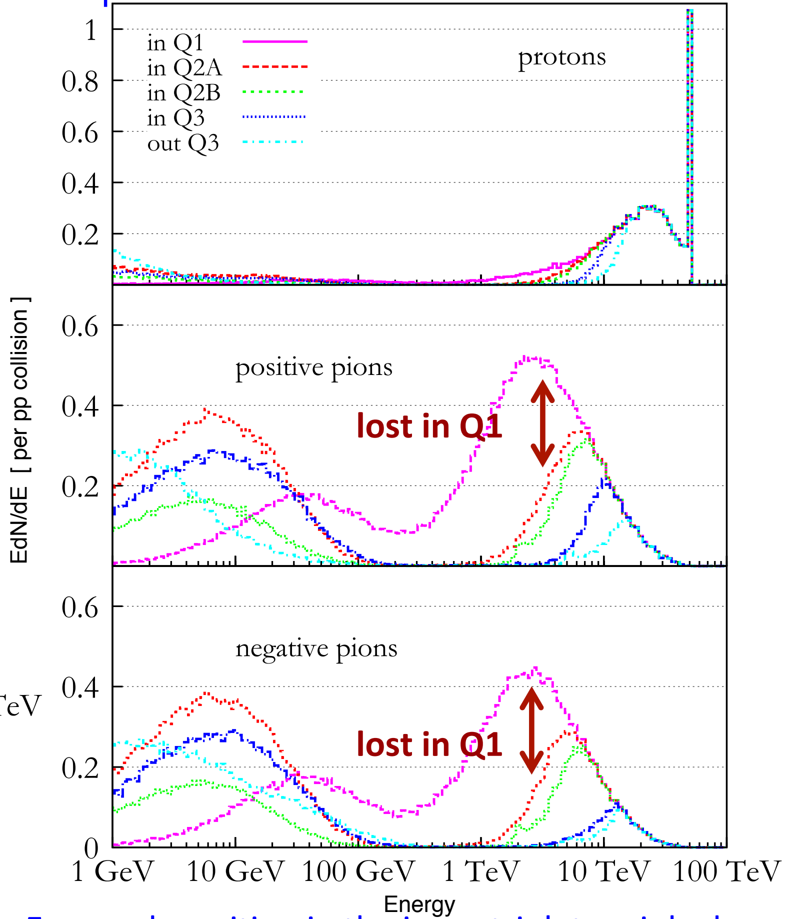
Neutral particles basically don't hit the triplet, because of the shadow effect of the TAS.

FCC-hh: 100 TeV proton-proton collisions

Collision debris particles spectra in the vacuum chamber along the inner triplet







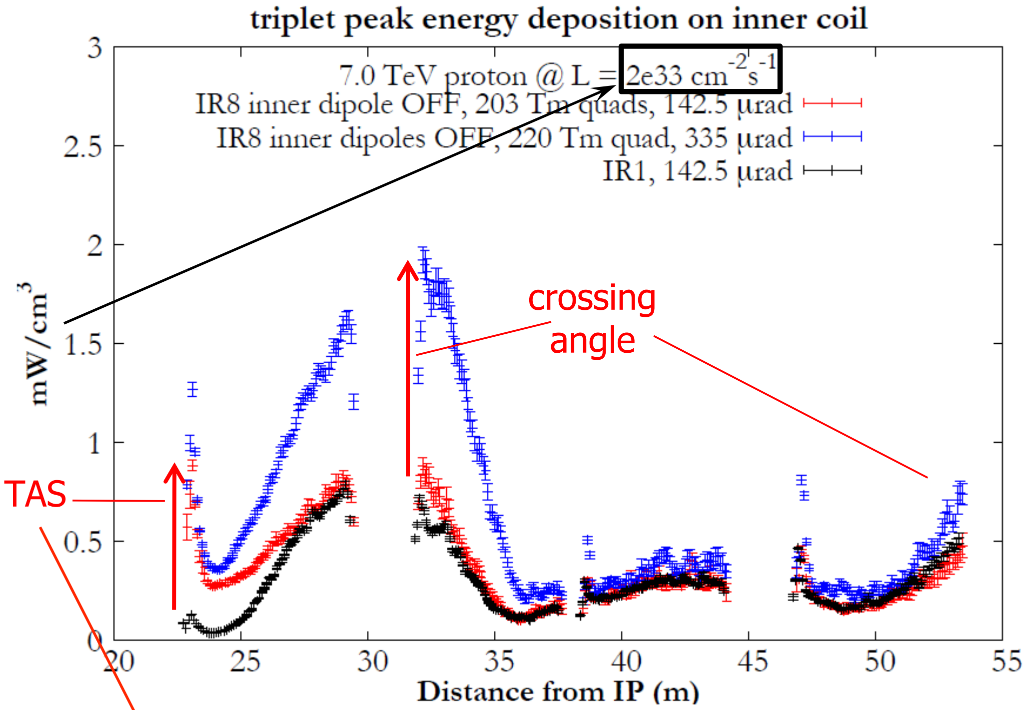
Energy deposition in the inner triplet mainly due to charged pions, which develop EM showers

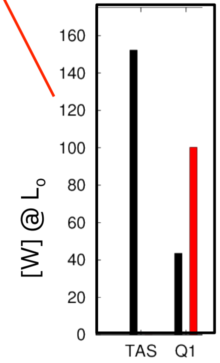
Energy deposition ruling factors

The energy deposition is influenced by different factors:

- TAS presence
- value of the crossing angle
- crossing plane with respect to the triplet configuration
    - for FDDF triplet configuration in the h-plane, vertical crossing is more challenging than horizontal one
- shielding (magnets and interconnects)
- inner triplet aperture, gradient and length, and L*

LHC





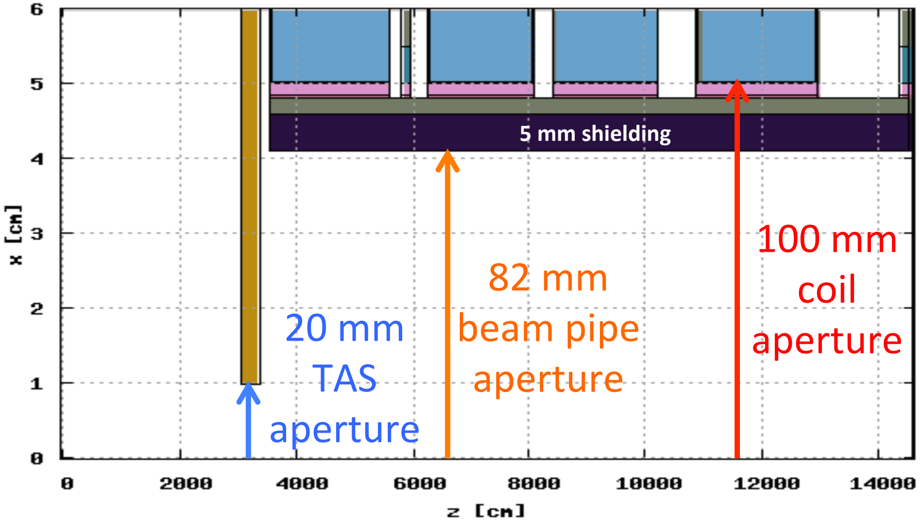
cryogenic load: the TAS absence redoubles (+130%) the Q1 load

FCC: preliminary layout

Case study:

- 100 TeV proton collisions, non-elastic cross section of 108 mbarn, $\mathcal{L}=5 \times 10^{34}$ cm^{-2} s^{-1} and $\mathcal{L}_{int} = 3000$ fb^{-1}
- vertical crossing, 70 μrad half crossing angle
- L* = 36 m, 110 m long triplet including TAS
- quadrupole gradients: 189 T/m (Q2) – 220 T/m (Q1)

R. Tomas and R. Martin



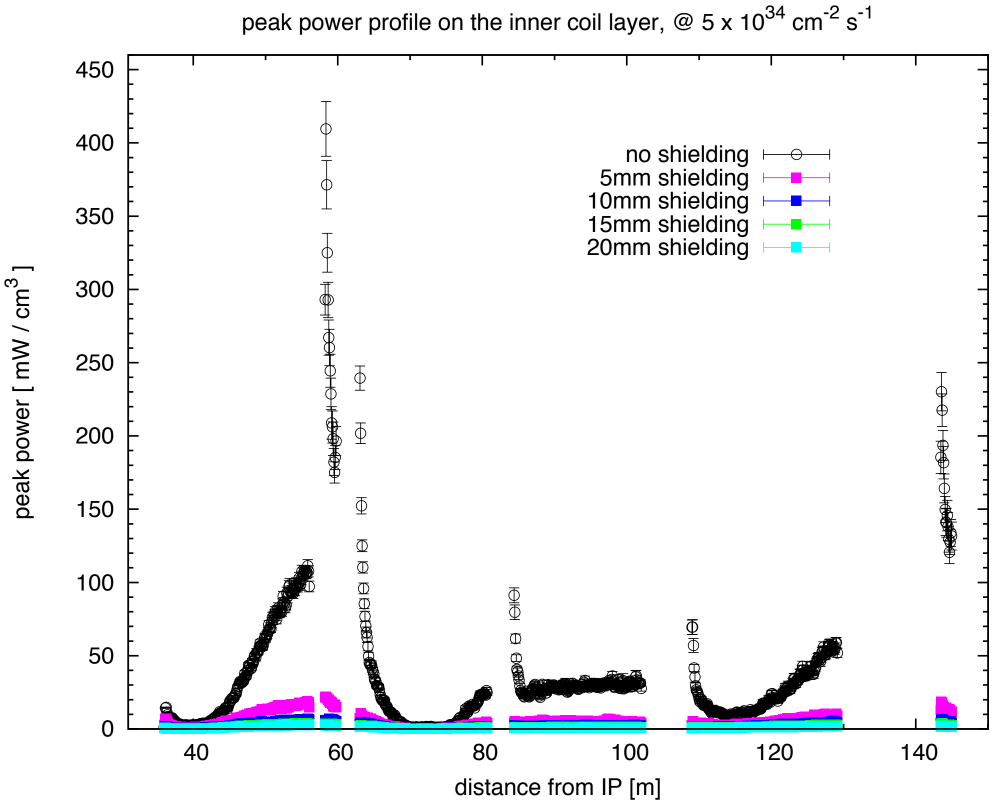
- coil aperture: 100 mm
  - 92 mm beam pipe aperture without shielding
- TAS aperture of 20 mm
- simplified hypothesis for the shielding: continuous shielding of INERMET (tungsten) in both the magnets and the interconnects: 5/10/15/20 mm thick shielding

Power

	TAS	Q1	C1	Q2a	Q2b	Q3	C2
Length [m]	3	20.53	1.6	18.03	18.03	20.53	1.6
Power [kW]	6.96(*)	1.6	0.46	0.84	2.0	1.9	0.59

(*)overestimated, since no beam pipe has been modeled before TAS

- Total power:
  - no shielding
- Peak power density:
  - without shielding:
    - peak power density almost two orders of magnitude higher than for LHC
    - one order of magnitude higher than considered quench limit
  - effect of the shielding:
    - even with only 5 mm of shielding, the peak power density is reduced by about an order of magnitude and it is <30 mWcm^{-3}
      - estimated Nb3Sn quench limit: 40 mWcm^{-3}



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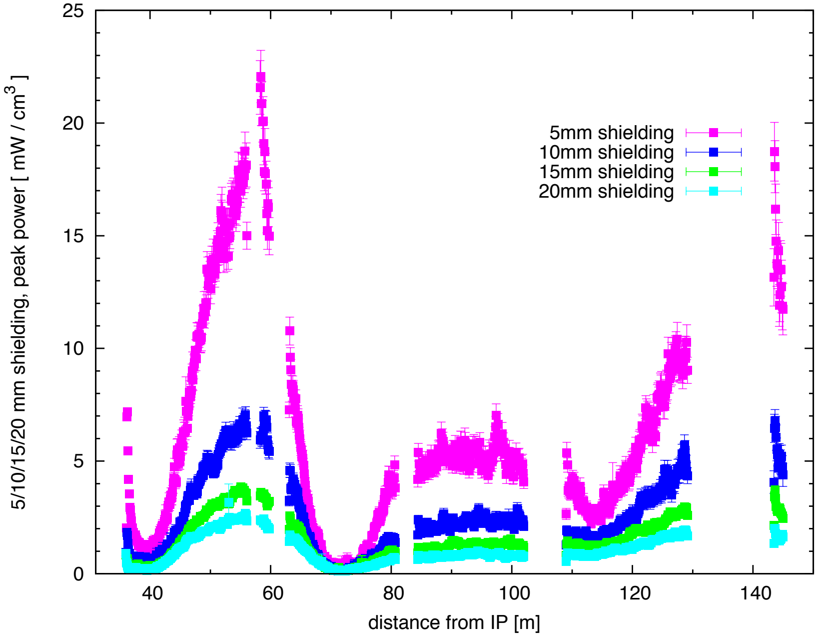
- ☐ Total power:
  - ○ no shielding
- ☐ Peak power density:
  - ○ 15 mm thick shielding: peak power density <5 mWcm^{-3}
  - ○ target of ultimate instantaneous luminosity (2 10^{35} cm^{-2}s^{-1}) seems to be on reach

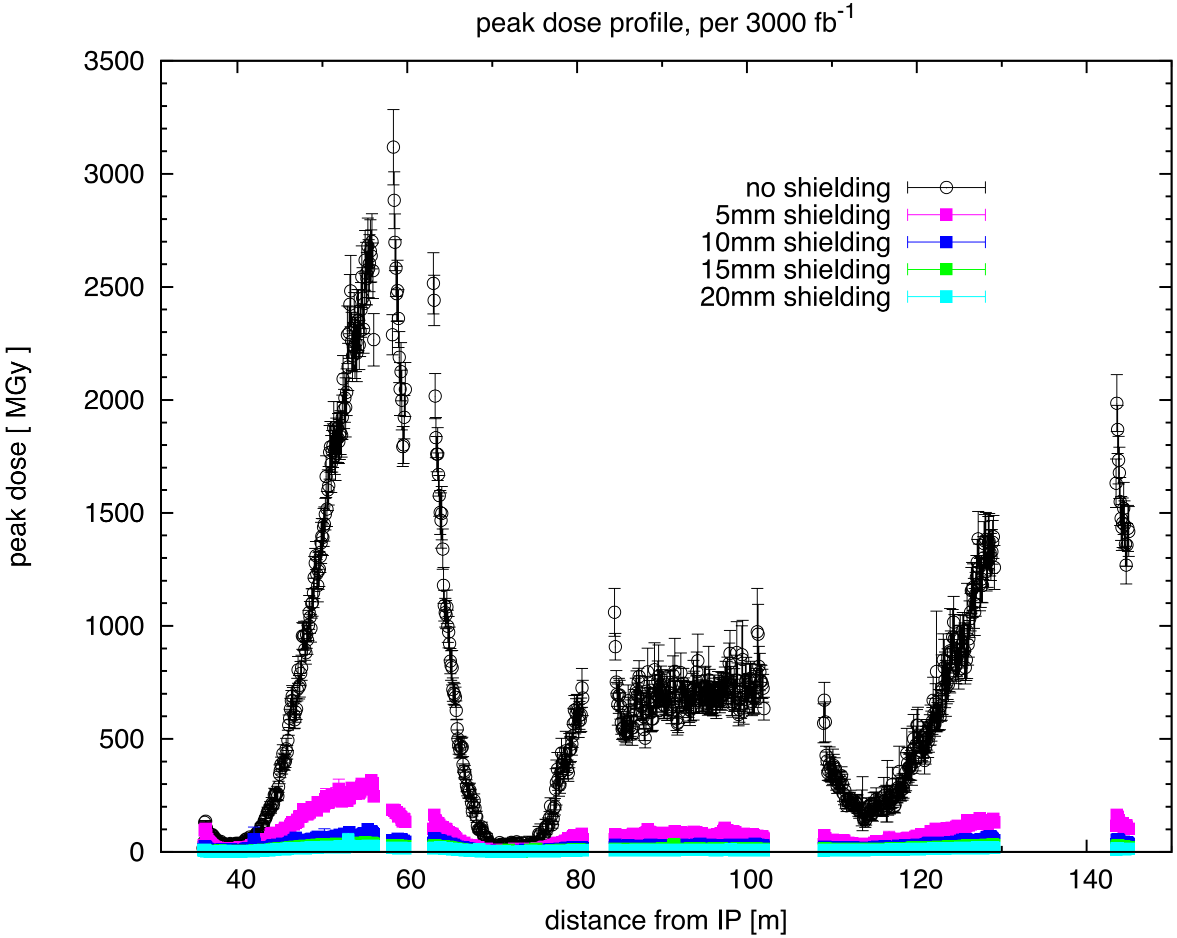
peak power profile on the inner coil layer, @ 5 x 10^{34} cm^{-2} s^{-1}



Power [kW], 15 mm thick shielding		
	Cold mass	Shielding
Q1	0.5	1.6
C1	0.1	0.2
Q2a	0.2	0.6
Q2b	0.4	1.3
Q3	0.5	1.7
C2	0.04	0.16
Interconnects		2.5

Peak dose

- Without shielding:
  - peak dose is almost two orders of magnitude higher than for LHC
  - two orders of magnitude higher than the acceptable dose (30 MGy)
- Effect of the shielding:
  - even with only 5 mm of shielding, the peak dose is reduced by an order of magnitude



Peak dose

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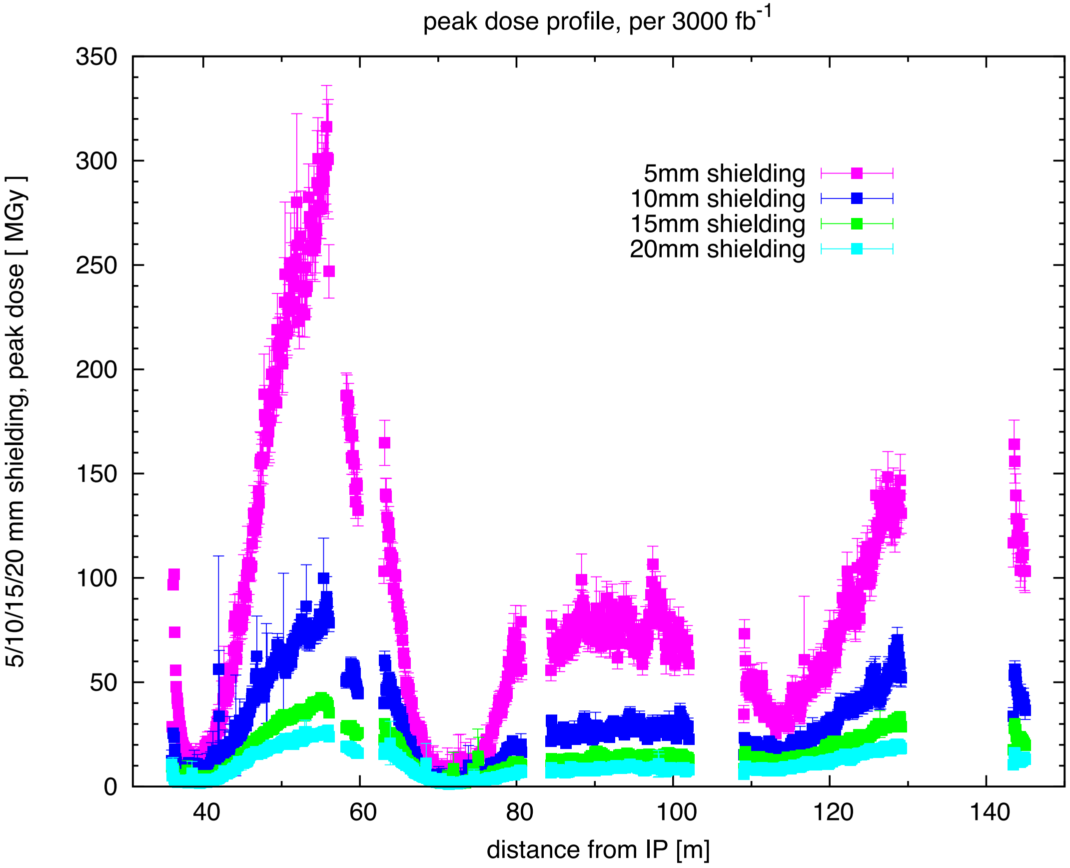
  - peak dose is almost two orders of magnitude higher than for LHC
  - two orders of magnitude higher than the acceptable dose (30 MGy)

- Effect of the shielding:

Shielding [mm]	Acceptable $\mathcal{L}_{int}$ (fb^{-1})	Time
5	300	
10	1000	
15	2000	
20	3000	Run I

  - the target of 30,000 fb^{-1} integrated luminosity still implies other strategies.

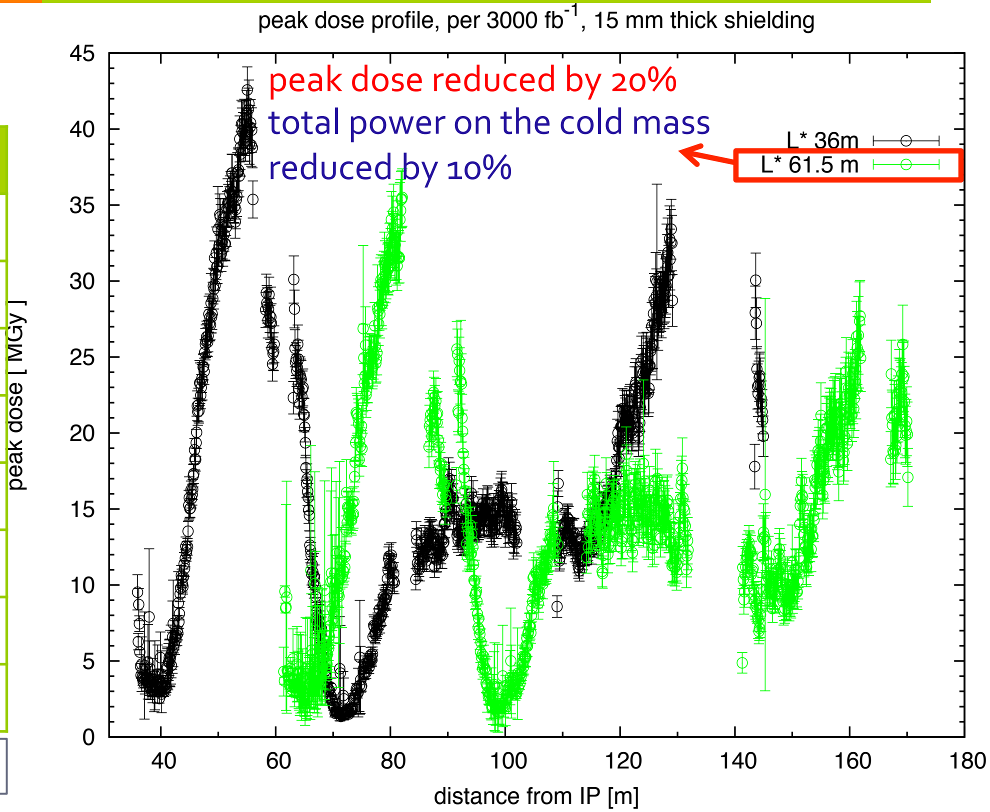


L* = 61.5 m

- Second layout with L* of 61.5 m:

L* [m]	36	61.5	Effect
crossing plane	vertical	vertical	
half crossing angle [μrad]	70	85	↑
coil aperture [mm]	100	140	↓
maximum gradient [Tm^{-1}]	220	184	↓
TAS aperture [mm]	20	35	
Q1/Q3 length [m]	20.0	20.54	
Q2 length [m]	17.5	17.58	
corrector length [m]	1.5	3	

R. Tomas and R. Martin

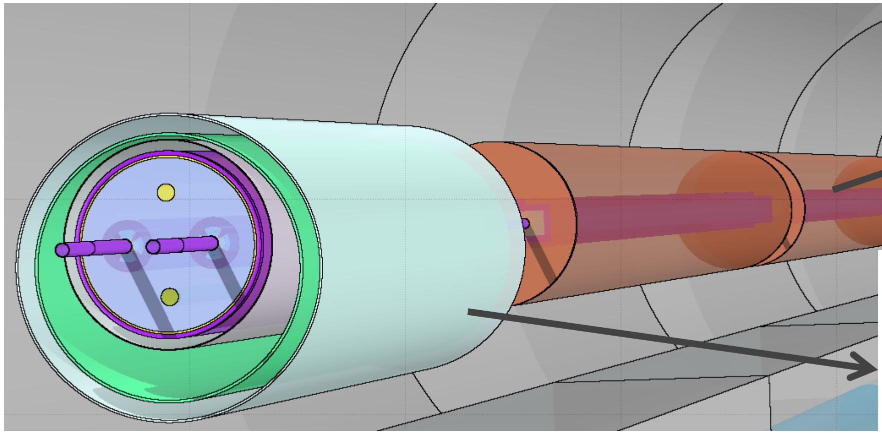


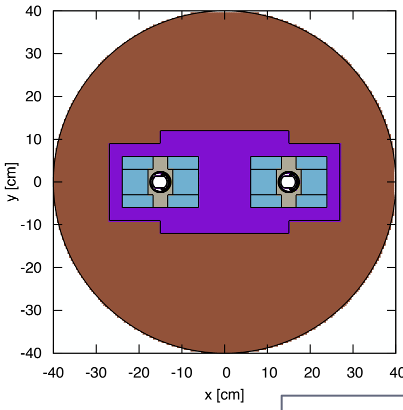
peak dose reduced by 20%
total power on the cold mass reduced by 10%

- Remark: these are two preliminary options
  - work ongoing in close collaboration with the optics team to define the best layout for the triplet
  - the shielding has been considered as continuous:
    - optimistic approximation: the shielding in reality has some interruptions → this will be modeled in a more advanced phase

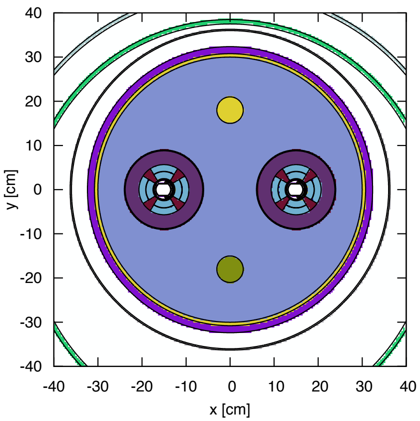
FCC: Beam Gas Interaction I

- ❑ Cell of 210 m: 12 dipoles and 2 quadrupoles

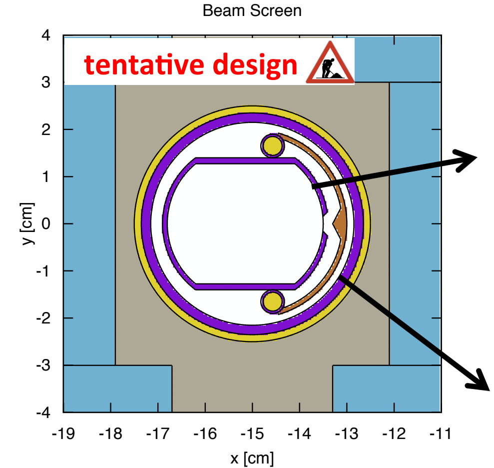




E. Todesco



- ❑ Composite and asymmetric beam screen design:



R. Kersevan

LHC-like concept with a continuous slot to catch at a larger distance the primary synchrotron radiation photons

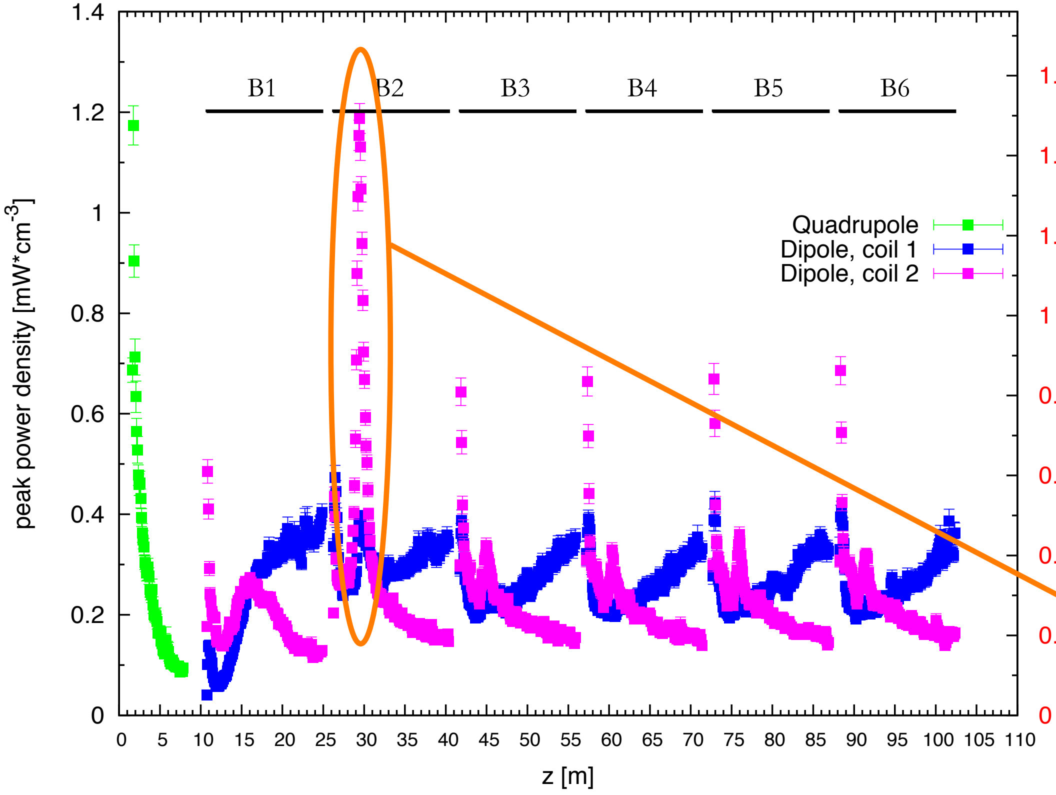
“external” absorber

- ❑ Magnets:
  - ○ 14.2 m long dipoles with a field of 15.8 T
  - ○ 6.3 m long quadrupoles with a gradient of 362 Tm^{-1}

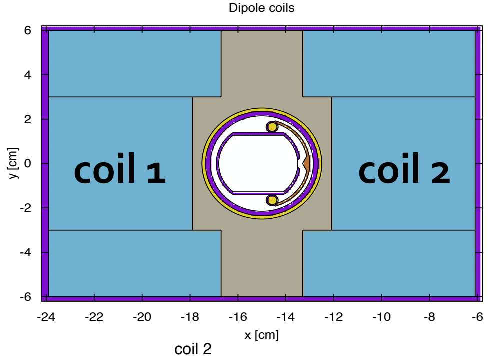
R. Alemany Fernandez, B. Holzer

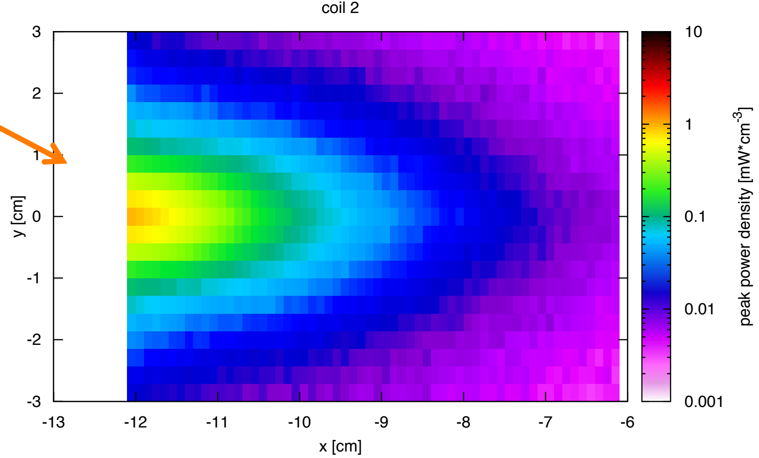
- ❑ Gas considered for the simulation: H_2, 10^{15} m^{-3}

FCC: Beam Gas Interaction II



power normalization 0.5 A beam current
dose normalization: one year (10^7 s)



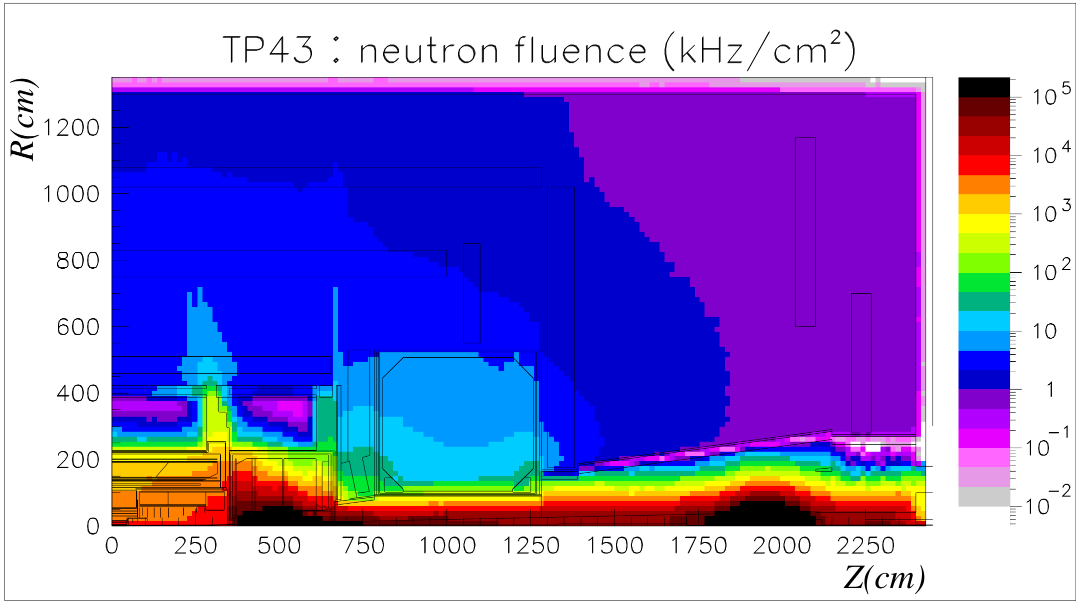


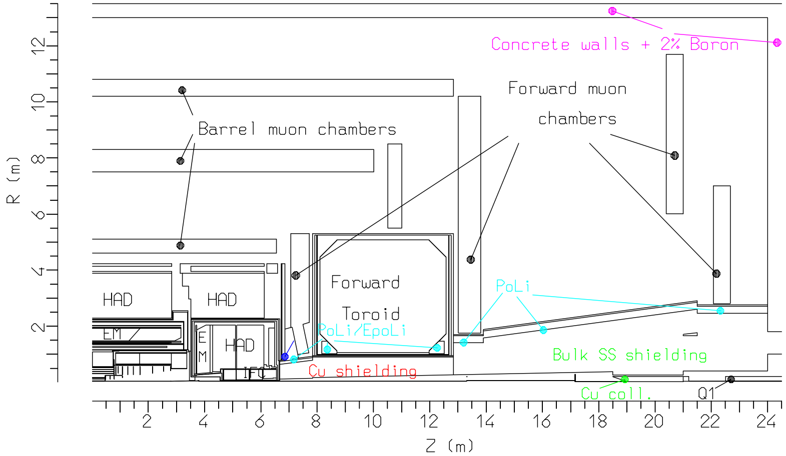
Magnets[*]	Total power [W]	
	Cold mass	Beam Screen
Quadrupole	1.1	0.15
Dipole	3.4	0.3

(*) the magnets with the higher load are shown in the table

Detector Protection: Shielding in the Cavern

- Simulation of energy deposit in the beam-pipe, the detector and cavern in general are a key ingredient for the detector layout:
  - shielding design to protect the detector from particles coming from the TAS and the triplet
- Simulation done for the ATLAS detector construction → design of a shielding around the TAS



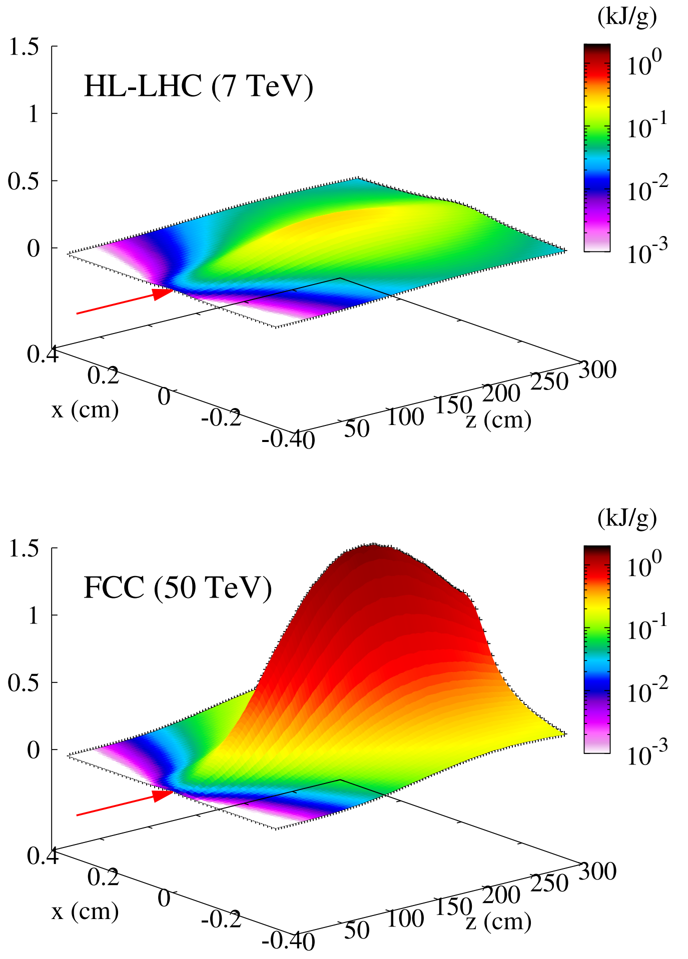


- Collaboration already started to produce similar results for the FCC

Beam intercepting devices

- Load on protection devices during halo cleaning, dump and mis-injection …
- Shower to close-by machine element
- Impact of the leakage to the cold section
    - Anton Lechner's talk today:

      http://indico.cern.ch/event/340703/session/95/contribution/54



Figures: Energy density in 3 m-long Graphite (1.83 g/cm^3) for one nominal proton bunch ($\sigma = 400 \mu m$), comparing HL-LHC (top) and FCC (bottom).

Conclusions

- The study activity is based on several years work and on the robust experience acquired during LHC Run I
- Working framework is on place and the first results are encouraging
- Fruitful collaboration with other teams is ongoing

Thanks for your attention!

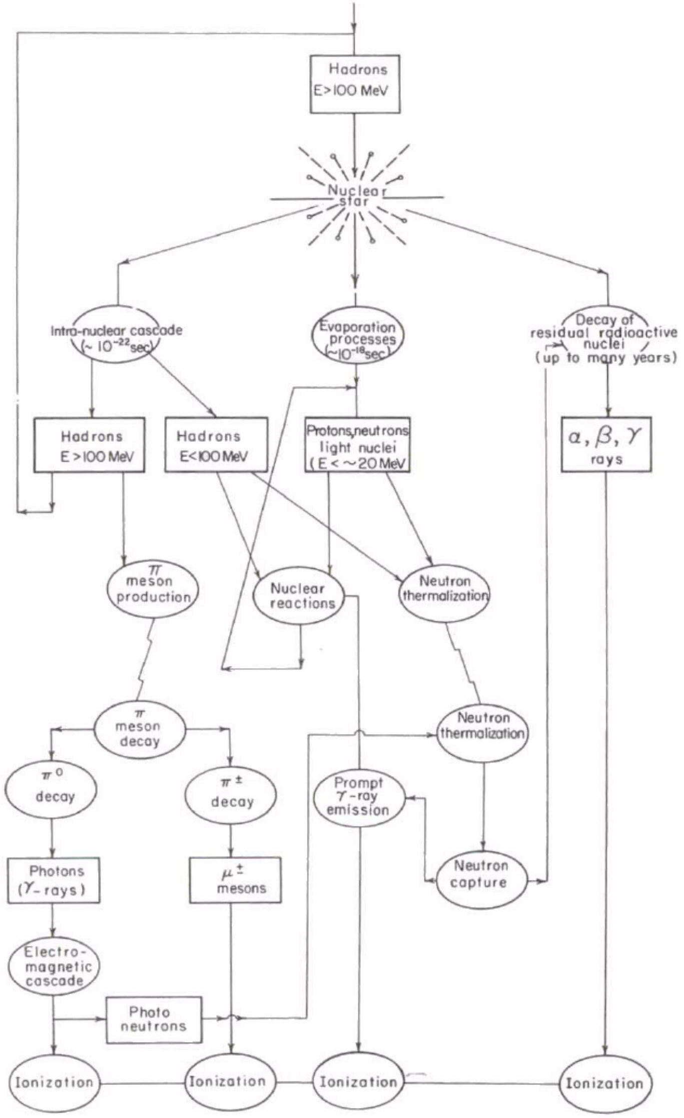
Back-up

Complex particle cascade

- ❑ Very high energy hadron interactions initiate a long and complex particle cascade down to low energy nuclear processes.

- ❑ Its description requires as essential pieces of information:
  - ○ reaction cross sections;
  - ○ exclusive fragment production;
  - ○ nuclide structure and decay data;
  - ○ evaluated quantities of neutron induced reactions

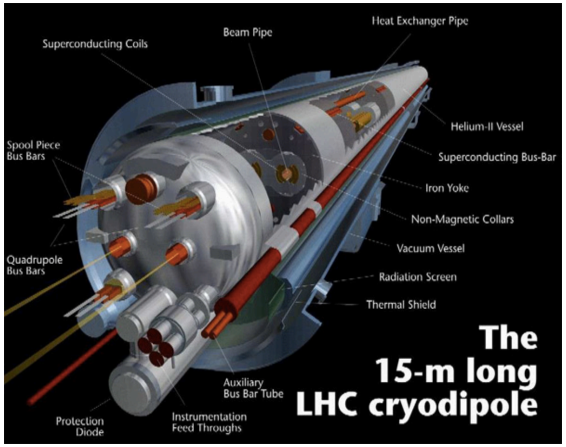
- ❑ Monte Carlo simulation is an effective way to calculate macroscopic quantities (like energy deposition, DPA, particle fluence, activation and residual dose rate) with an accuracy reflecting the quality of the critical processes implementation



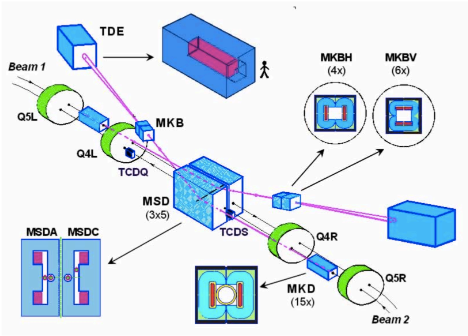
Why Monte Carlo simulations?

- **Machine protection** issues: operational/accidental load and long term damage

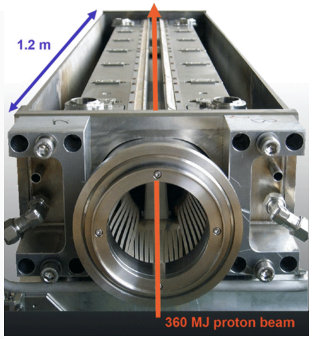
Sensitive equipment:



Intercepting devices:

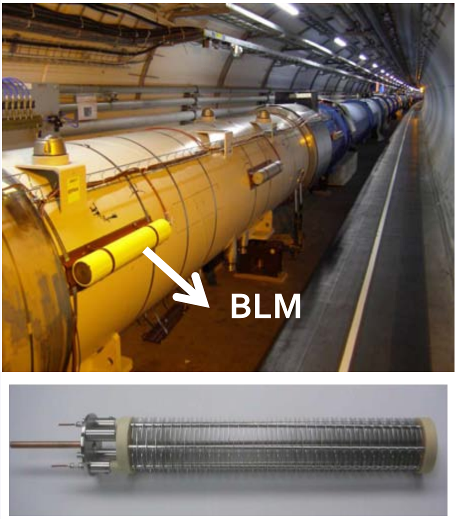


Beam dump



Collimators

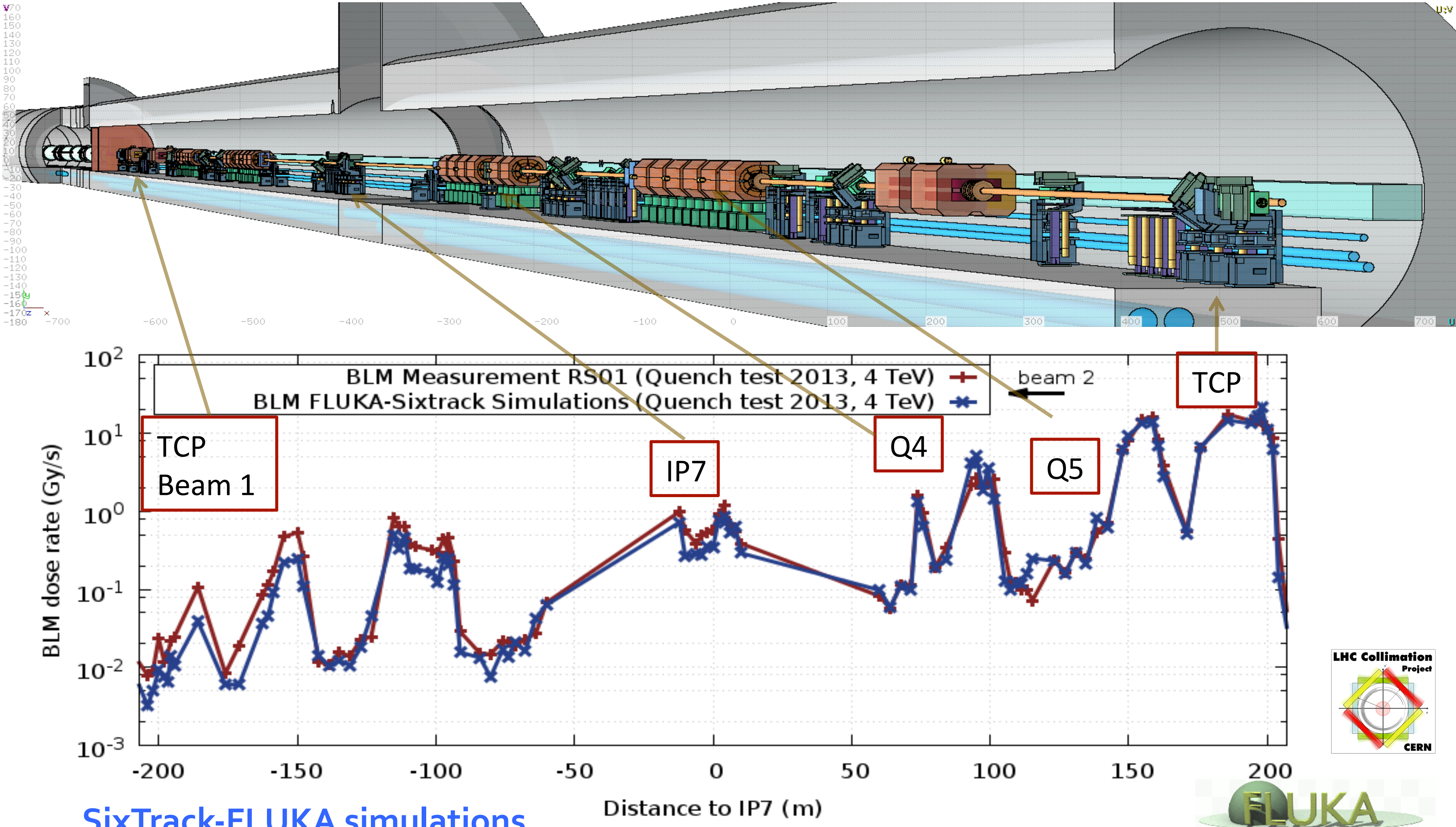
Monitors:



- **Experiments protection** issues:
  - Machine induced background (tertiary beam halo generated in the collimation system)
- **Radiation protection** issues:
  - Radiation to environment (prompt);
  - Activation / residual dose rates (decay).

- Energy deposition studies play a key role in the whole life of an accelerator:
  - Design;
  - Commissioning / operation / intervention;
  - Upgrade / disposal.

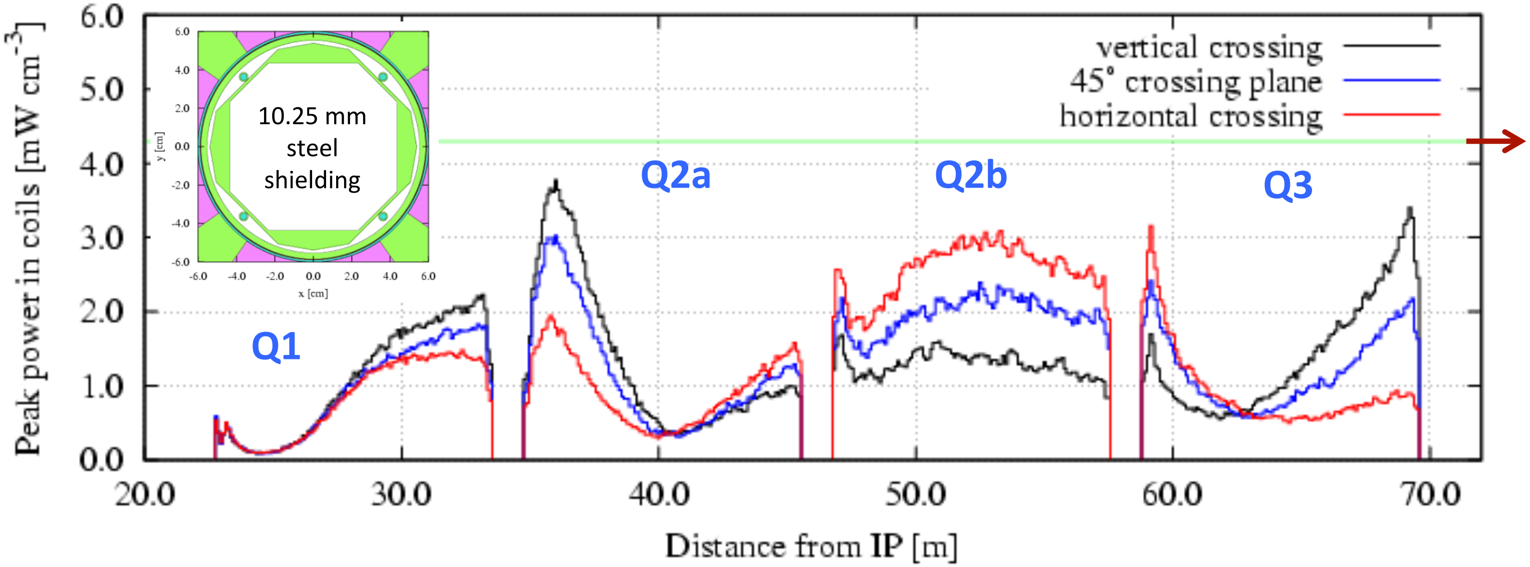
Validation: power load on collimators



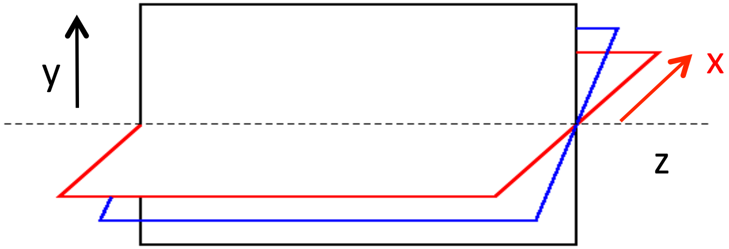
SixTrack-FLUKA simulations

Crossing Plane

7 TeV collisions, 120 mm coil aperture, 225 μrad half crossing angle



recommended limit for power density in coils to prevent magnet quench (steady state): 4.3 mWcm^{-3}



- The vertical crossing is the most challenging case
  - FDDF quadrupoles in the horizontal plane
  - DFFD quadrupoles in the vertical plane
- Difference: about a factor 2
  - the effect is mitigated by the presence of the shielding in Q1

Length of the inner triplet

Parametric study:

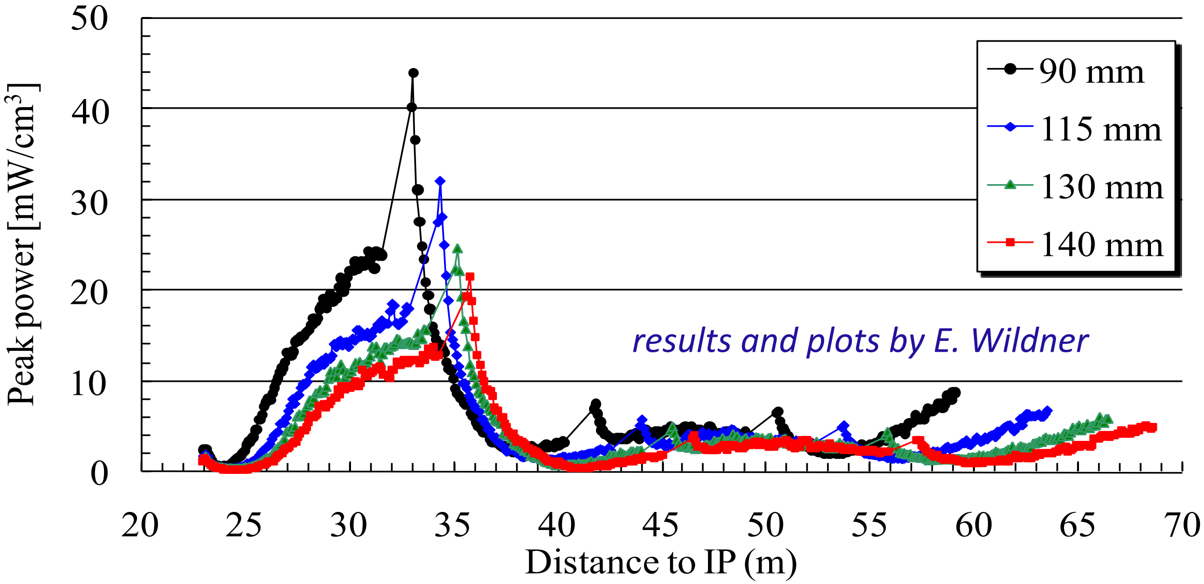
- ❑ inner triplet total length, gradient and aperture have been changed coherently

Total length (m)	Gradient (T/m)	Aperture (mm)
36.2	156	90
40.7	125	115
43.6	112	130
45.7	104	140

idea and numbers by E. Todesco

- ❑ energy deposition evaluated for each model

225 µrad half vertical crossing angle, 55 mm TAS aperture

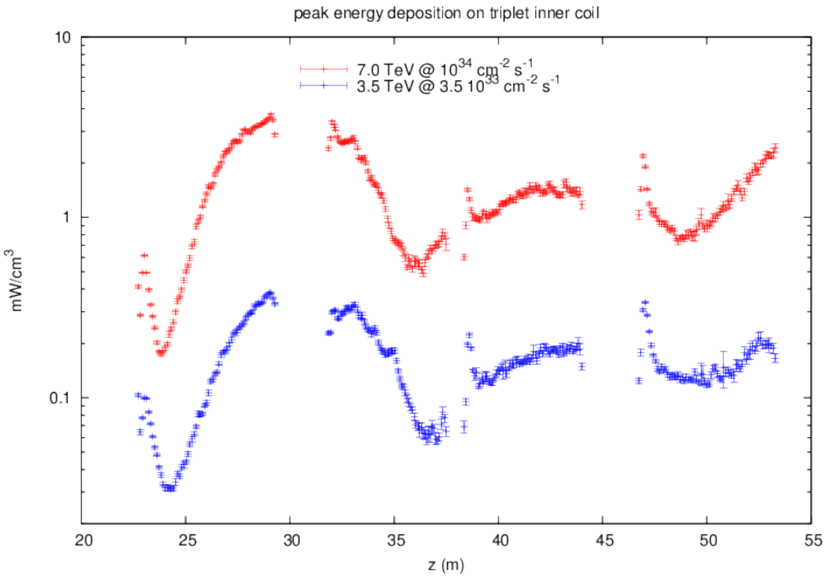


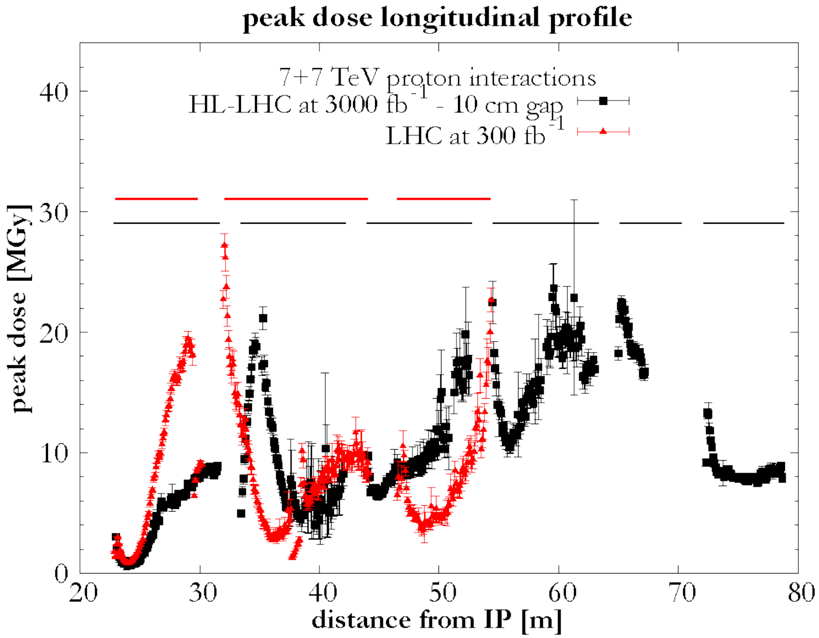
results and plots by E. Wildner

The longer the triplet, the better

Inner Triplet Design: LHC and HL-LHC

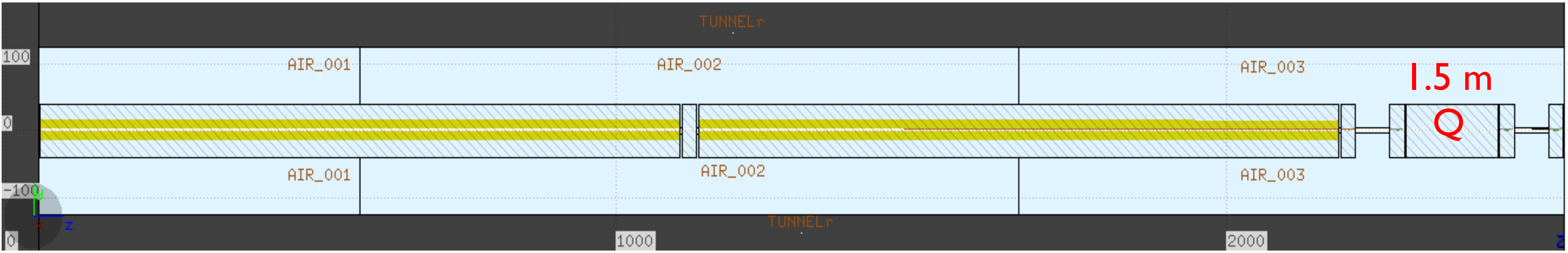
- Margin to quench:
    - LHC design phase: peak power density kept a factor of three below the expected quench limit

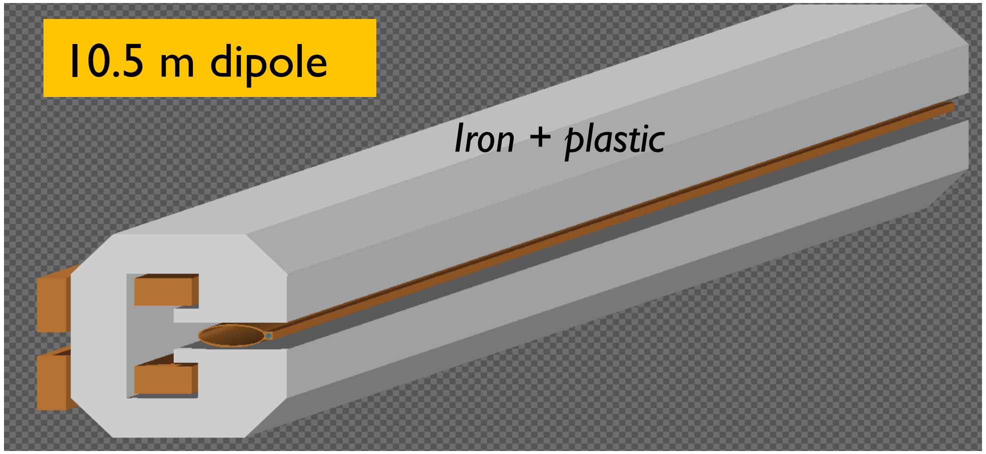




- Insulation damage:HL-LHC same energy as LHC, but luminosity will be increased by an order of magnitude.
    - expected increase of the peak dose by an order of magnitude
    - BUT: careful design of the shielding will enable to stay at the same peak dose values as for the LHC

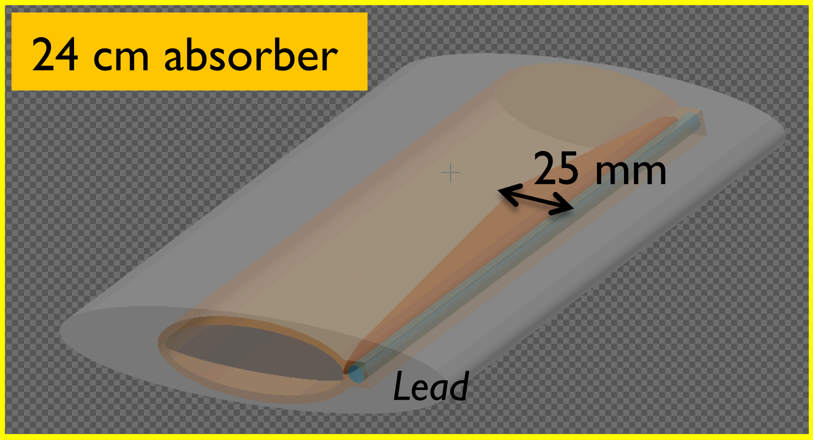
FCC-ee synchrotron radiation





10.5 m dipole

Iron + plastic



24 cm absorber

25 mm

Lead

Copper (2mm tube)
water cooling

FCC-ee synchrotron radiation