Ruling Factors in the Impact of Collision Debris on the LHC High Luminosity Insertion Magnets

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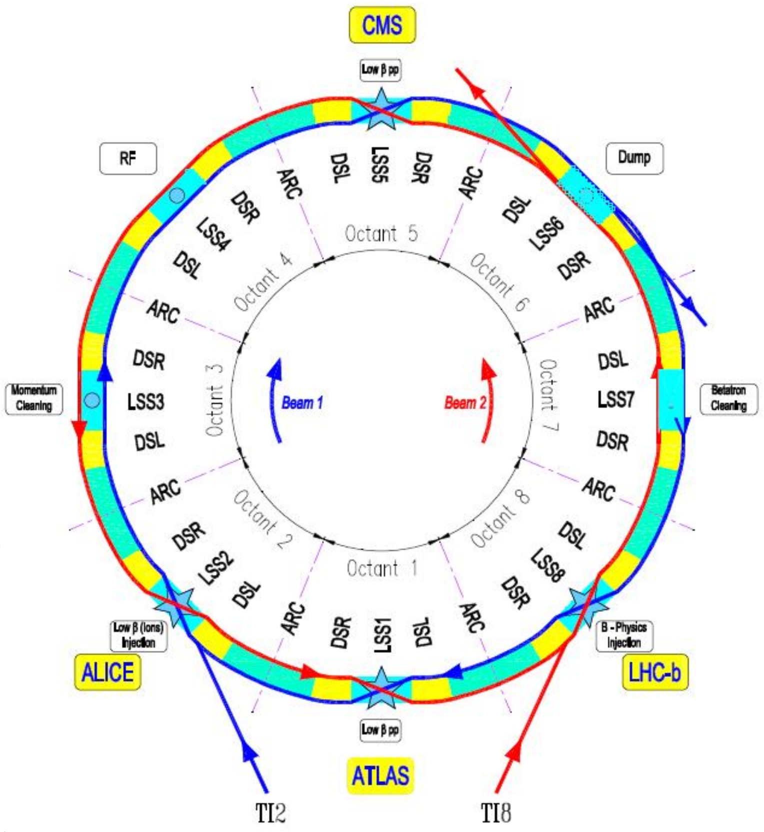
The LHC Upgrade (I)



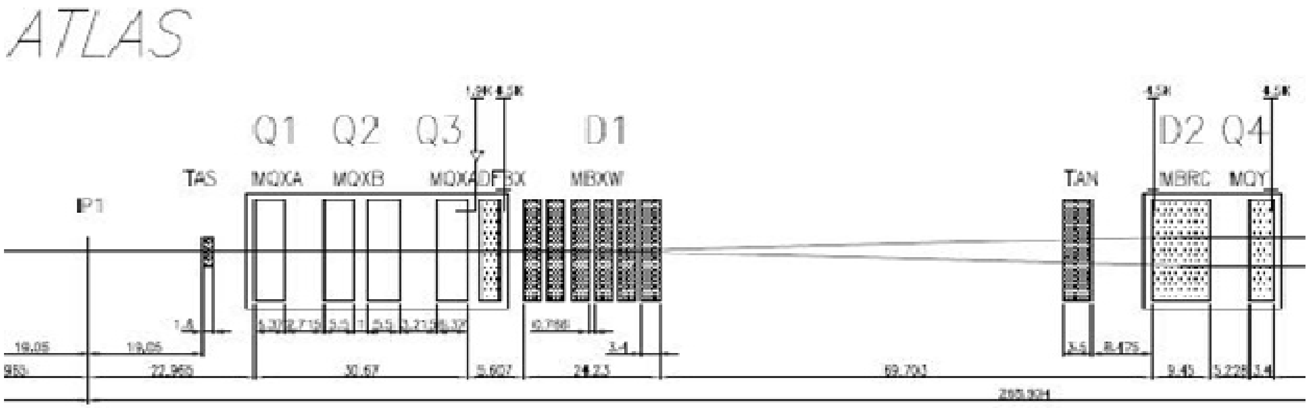
LHC Nominal Peak luminosity L_0 for the ATLAS and CMS experiment:
10^{34} cm^{-2} s^{-1}

Luminosity Upgrade:
- Phase **I**: **2-3** L_0;
- Phase **II**: final goal of **10** L_0;

How?
- increase current intensity;
- improve optics, in order to decrease β* from 0.55 m down to 0.3 m or less if possible;

The LHC Upgrade (II)

Actual layout of the beam line on one side of the ATLAS/CMS experiment:



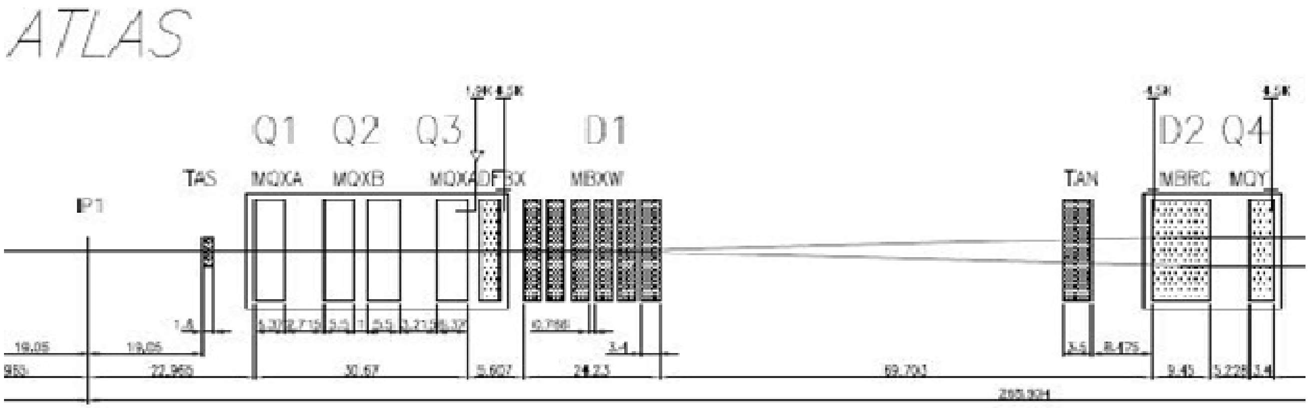
The inner **triplet** is responsible for **squeezing** the beam.

The actual triplet aperture of 70 mm does not allow a further squeeze: the beam would become too large in the triplet itself.

New design of the magnets around the insertion regions

The LHC Upgrade (III)

Actual layout of the beam line on one side of the ATLAS/CMS experiment:



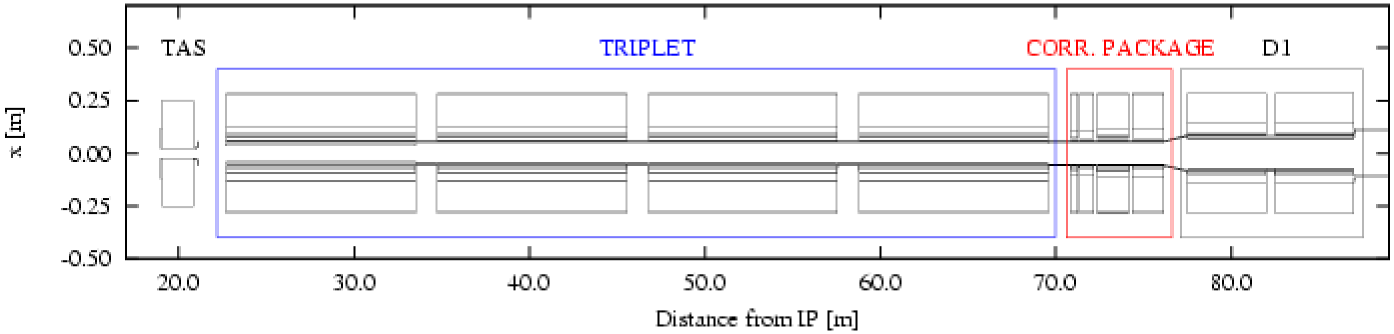
New layout:

- new triplet:
  - Technology of Nb-Ti Rutherford-type superconducting cables;
  - longer;
  - 120 mm aperture;
- corrector magnets grouped in one package at the non-IP side of the triplet;
- a two-module, RHIC-style, superconducting separation dipole, with a large aperture (180 mm);

Energy deposition studies: to identify shielding solutions against the risk of quench and optimize the design.

Simulation set-up

Layout used for the energy deposition studies for the Phase I Upgrade:



Parameters:
- luminosity at **2.5** 10^{34} cm^{-2} s^{-1};
- **225 μrad** half crossing angle;
-TAS aperture: **45 mm**;
- **FDDF** triplet wrt the horizontal plane for a positive charged particle escaping from IP;
- recommended limit for power deposition of **4.3 mW** $\mathbf{cm^{-3}}$ (same as for the actual triplet);

The Monte Carlo code **FLUKA** was used for energy deposition studies, provided with the event generator **DPMJET**;

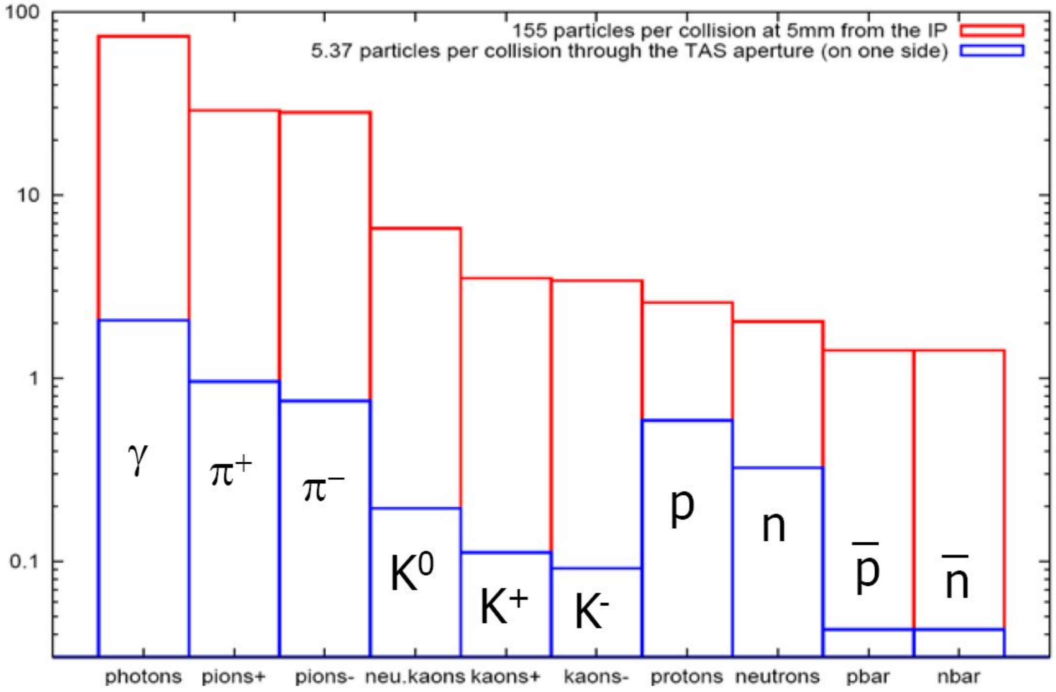
Statistical uncertainties:
- **10%** on **peak power** values;
- **1%** on **totals**;

Safety margin of **3** on the peak power density: to compensate for un-avoidable systematic uncertainties (e.g. extrapolation of cross sections of primary events at **14 TeV** centre-of-mass energy; crucial dependence on the pseudo-rapidity distribution tail).

The collision debris (I)

Radiation field from LHC collisions at the IP and at the TAS aperture:

10% of the **total number** of the particles generated in the proton-proton collisions go through the TAS aperture: they carry **80%** of the **energy**;



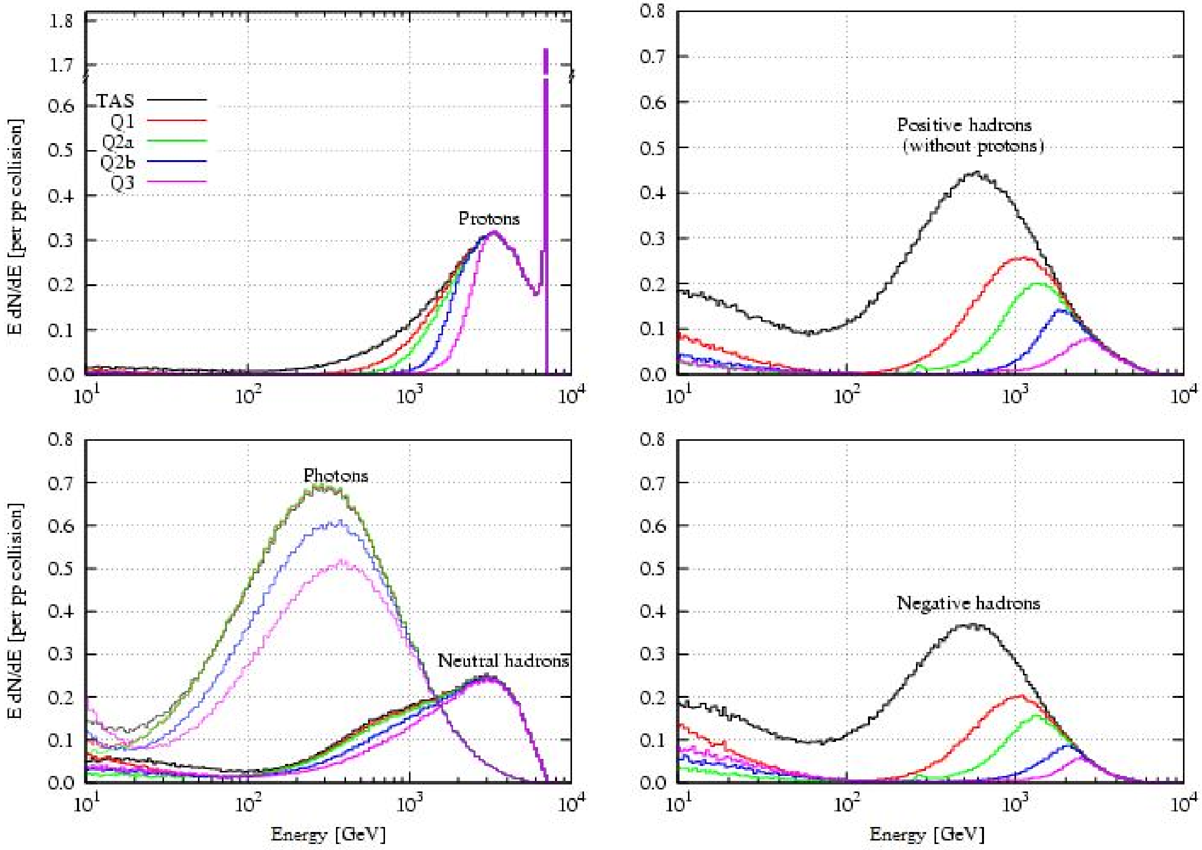
The collision debris (II)

Particle spectra in the vacuum chamber at the non-IP side of the TAS and of each triplet element.

Charged particles (especially pions) are **captured** by the triplet magnetic field;

Neutral particles show the **geometrical shadowing effect** provided by the TAS on the triplet.

Spectra reaching downstream elements are represented by the purple curves.



Triplet - Parametric study

Study of the dependence of the longitudinal profile of the peak power density on the triplet length.

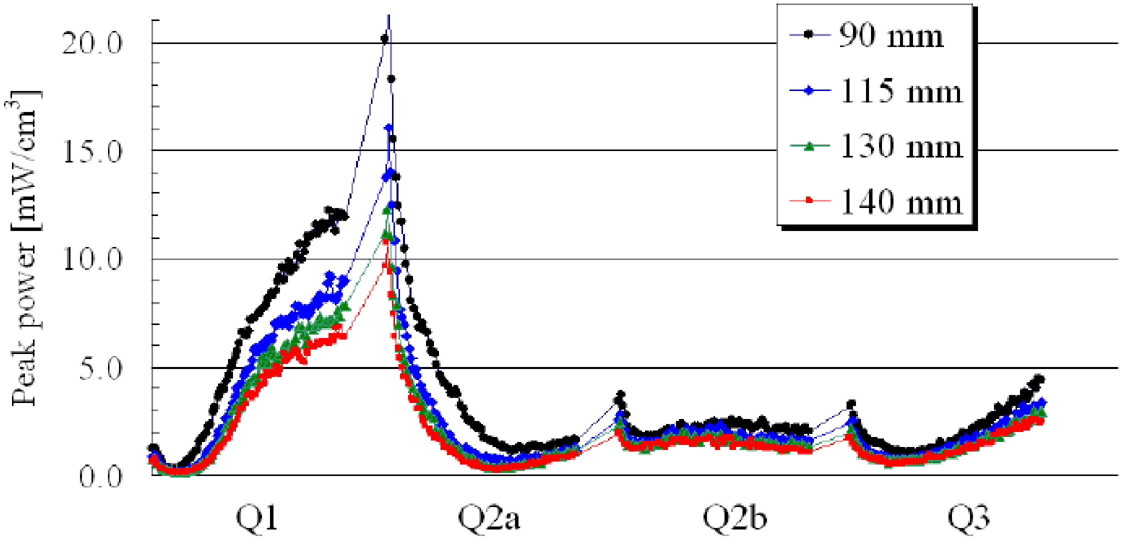
Aperture (mm)	Gradient (T/m)	L(Q1,Q3) (m)	L(Q2a,b) (m)	Total length (m)
90	156	8.69	7.46	36.2
115	125	9.98	8.42	40.7
130	112	10.81	9.04	43.6
140	104	11.41	9.49	45.7

TAS aperture: 55 mm

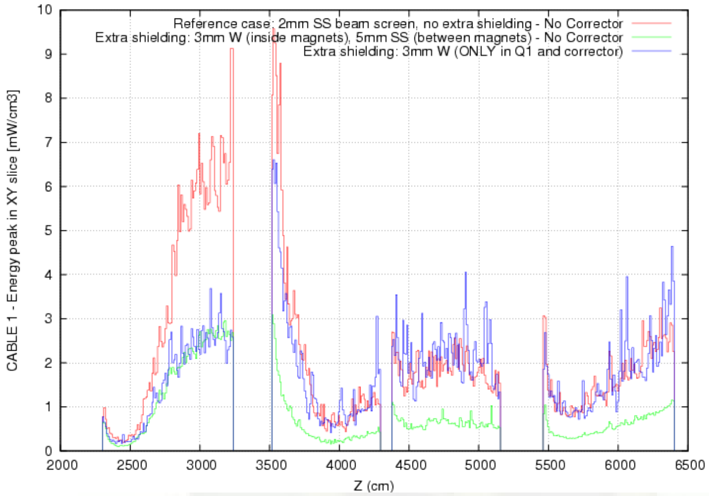
From 90 mm to 140 mm, the total load on the triplet ranges from 450 W to 375 W.

The **longer** the triplet, the **better**.

Values are above the quench limit on the **second half of the Q1** and at **the IP side of the Q2a**.



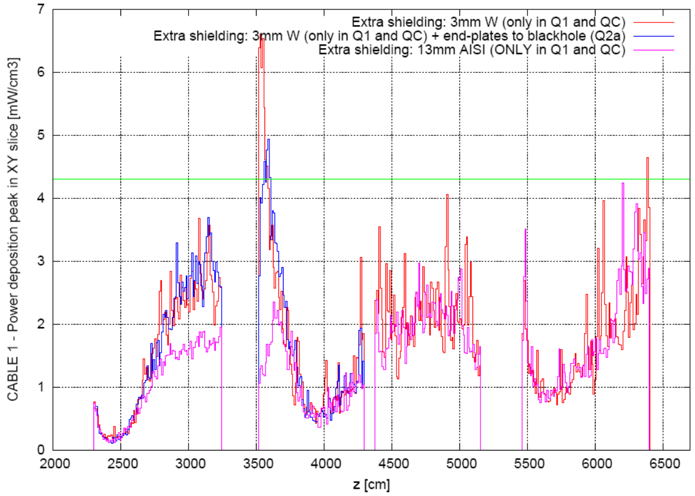
Triplet - Shielding options



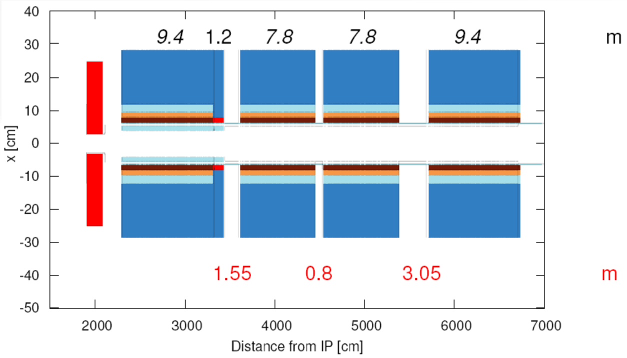
A **continuous liner** (e.g. 3 mm of Tungsten) is quite effective if placed **all along the triplet** and **in the interconnections** (green curve aside). Possible problems with the aperture requirements.

Longitudinal gaps between magnets imply the bump on the IP side of the downstream element.

Thick end-plates outside the CBT give only limited help, because of the main shower coming from the inside.



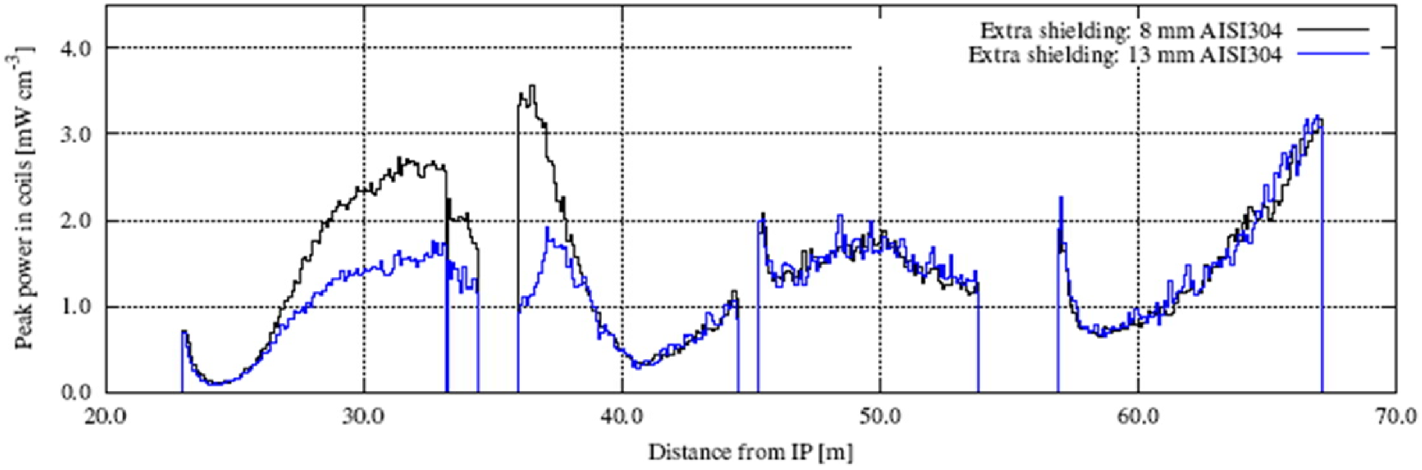
Would a **thick liner** in Q1 shadow the Q2a?



Triplet - A thick liner in the Q1

The smaller beam size in Q1 (wrt all the triplet) allows to lodge a thick liner in the BS.
The net benefit is at the beginning of the Q2a, not only in the Q1 itself.

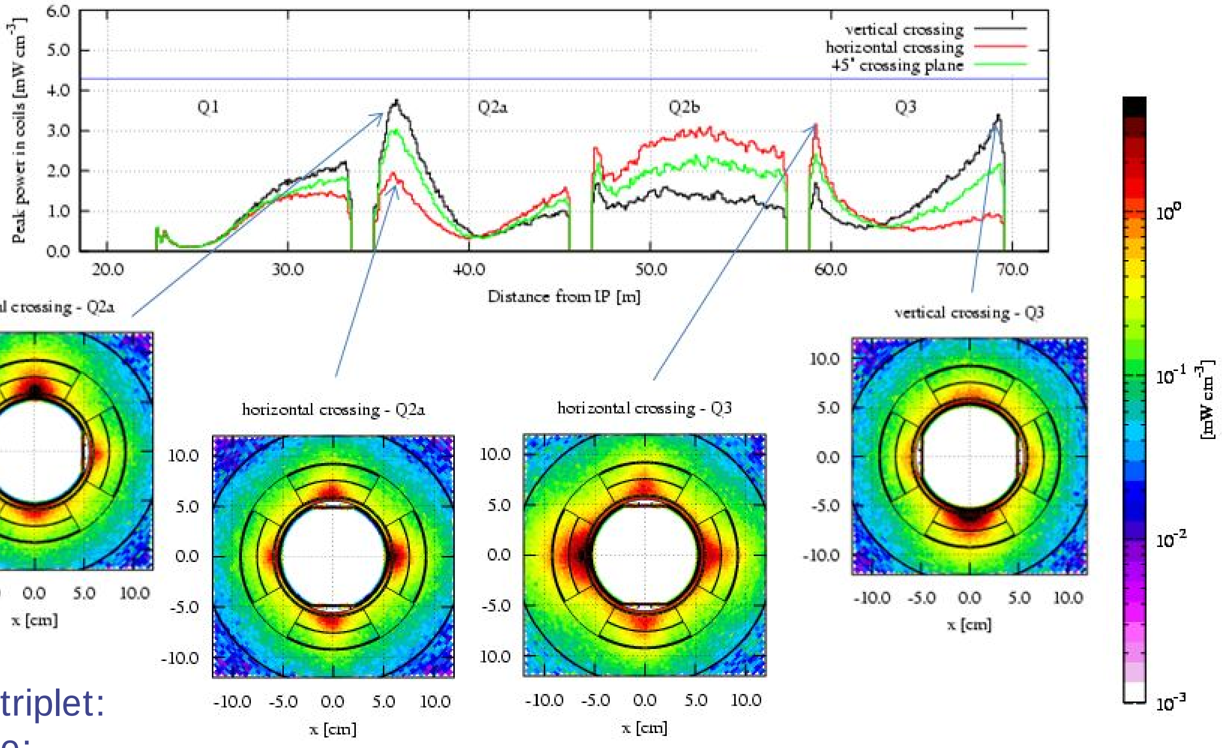
Peak power density in the triplet cables for different thicknesses of the additional shield inside the Q1.



The preferred 120 mm coil aperture design implements a 10 mm thick stainless steel liner in Q1.

Triplet - The crossing scheme

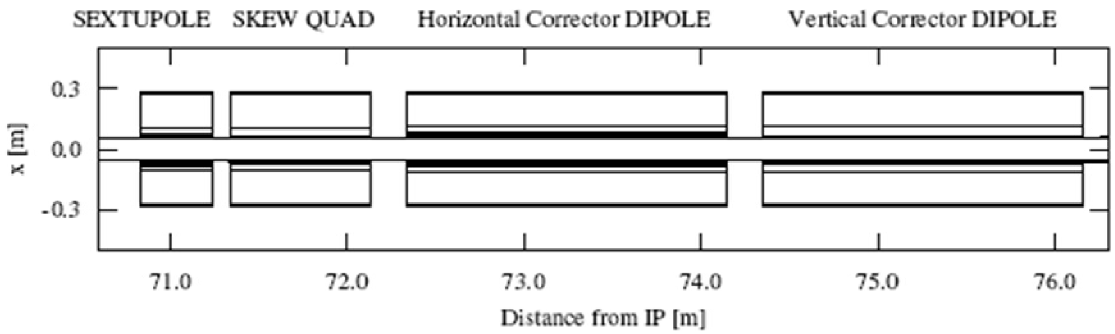
Proton-proton collisions will be featured by a crossing angle lying on the *horizontal* or on the *vertical* plane, symmetric wrt the longitudinal axis.



Magnetic configuration of the triplet:
- **FDDF** on the horizontal plane;
- **DFFD** on the vertical plane;

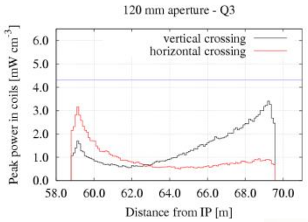
The pattern of the energy deposition is set by the coupling of the crossing scheme with the triplet magnetic configuration.

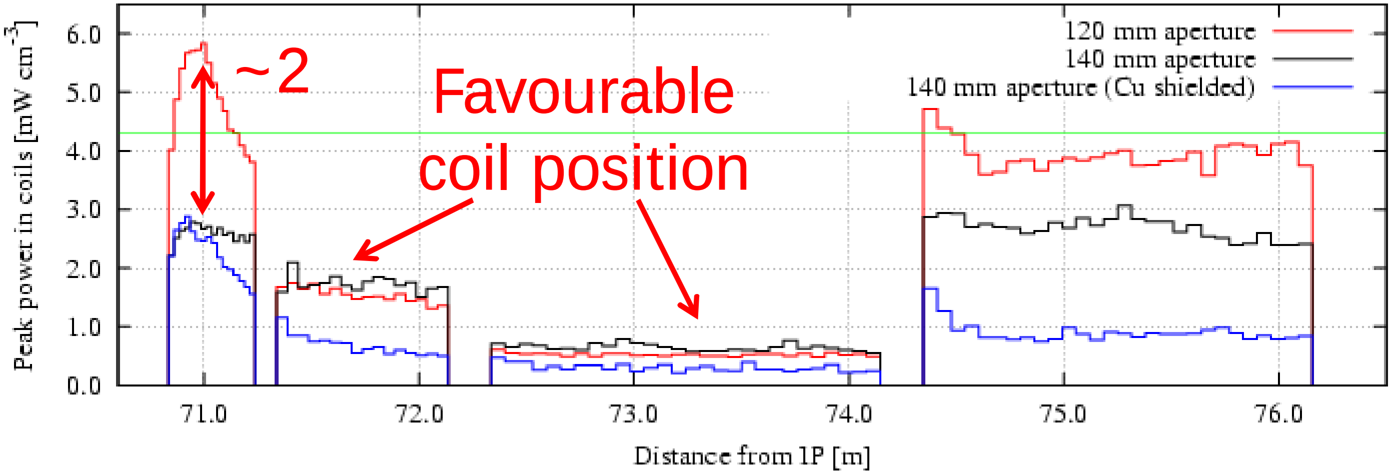
The corrector package



Layout of the corrector package for the Phase I Upgrade (FLUKA implementation).

Longitudinal profile of the peak power density in the corrector package for **vertical** crossing (worse case).





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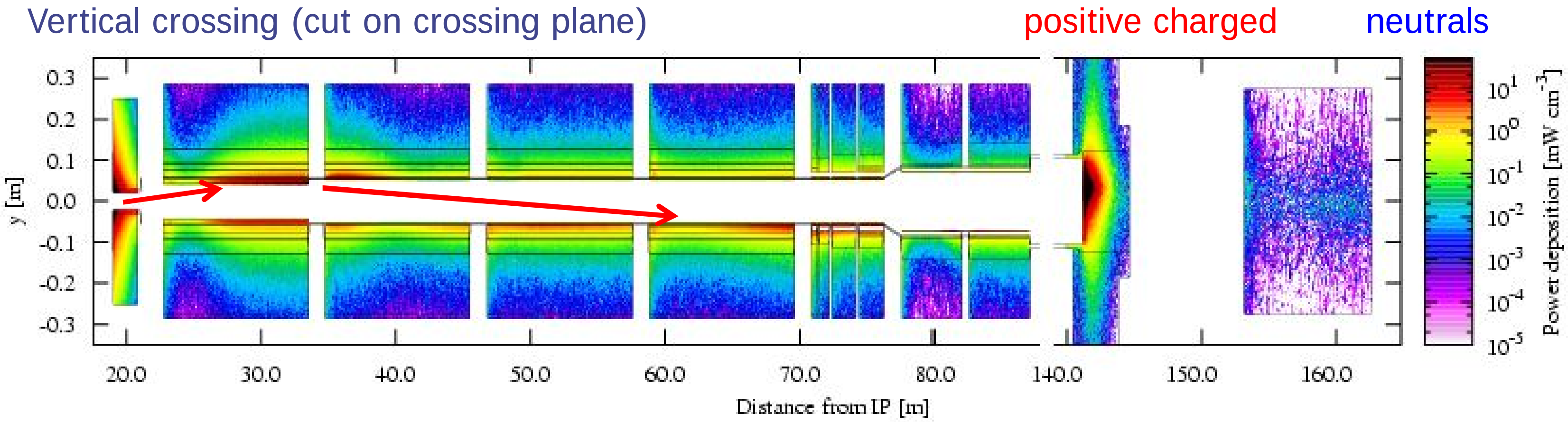
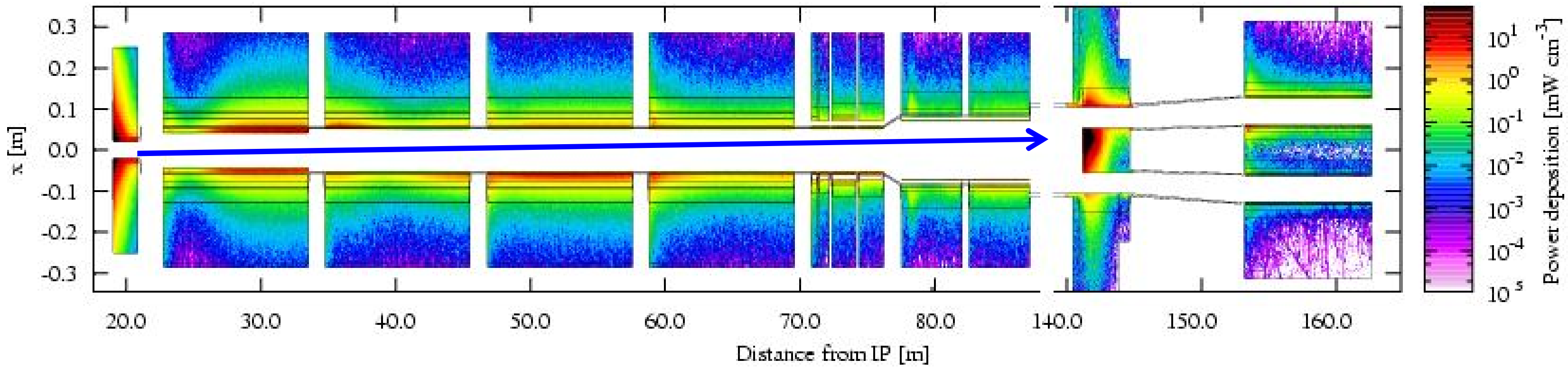
Favourable coil position

Global view

Vertical crossing (cut on crossing plane)

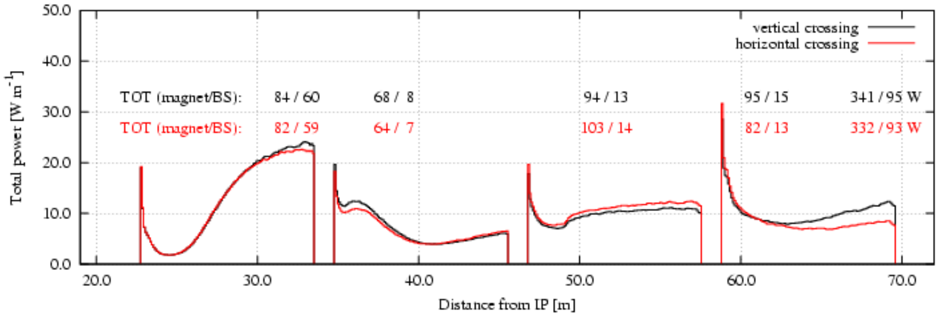


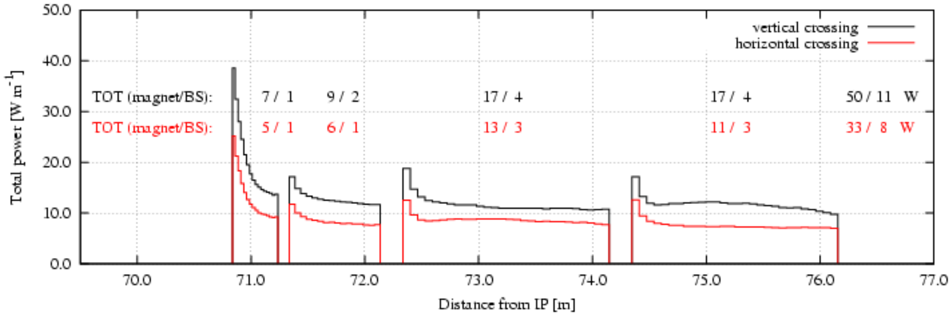
TAS Q1 Q2a Q2b Q3 Corr. D1 TAN D2

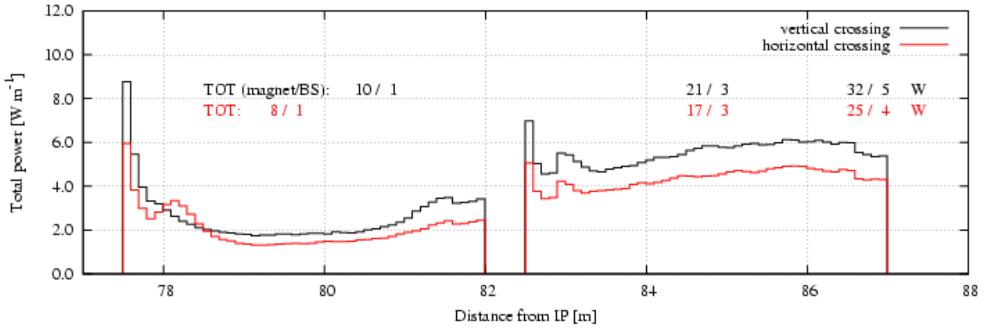


Horizontal crossing (cut on crossing plane)

Totals







Total Power [W]		*vertical crossing*		*horizontal crossing*	
		el.	*BS*	*el.*	*BS*
TAS		***384***	***-***	***382***	***-***
triplet	*TOT*	***341***	***95***	***332***	***93***
	Q1	84	60	82	59
	Q2a	68	8	64	7
	Q2b	94	13	103	14
	Q3	95	15	82	13
corr. package	*TOT*	***50***	***11***	***33***	***8***
	sext.	7	1	5	1
	skew	9	2	6	1
	hor. dip.	17	4	13	3
	vert. dip.	17	4	11	3
D1	*TOT*	***32***	***5***	***25***	***4***
	1st mod.	10	1	8	1
	2nd mod.	21	3	17	3
Total load		***807***	***111***	***772***	***106***

Conclusions

- the exposure of the superconducting cables of the magnets around the high luminosity experiments of the LHC to the debris originated by proton-proton collisions is an issue for the possible risks of quench;
- the magnetic field of the triplet plays a major role in:
  - capturing charged particles (mainly pions) and leading them to showering in the magnetic elements;
  - locating the peaks of the power deposition on the vertical/horizontal plane, depending on the crossing scheme;
  - reversing the transverse position of the peak (up->down, left->right) at the end of the triplet wrt the initial one;
- hot spots in the triplet are expected at the first gap between magnets;
- the superconducting coils need a protection from the main showering coming from *inside* the beam pipe:
  - the TAS is effective in reducing the load at the beginning of the triplet;
  - a continuous liner (e.g. 3 mm of Tungsten) inside each triplet element aperture *and* along the interconnections provides the SC cables with a substantial shield; problems with the aperture requirements can arise;
  - effective shadowing can be obtained by the use of increasing apertures:
    - the thick liner in the first triplet element;
    - the larger aperture of the corrector package wrt the one of the upstream triplet;
    - the largest aperture of the first separation dipole;

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