John Adams Institute for Accelerator Science

Imperial College London

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Experimental Interaction Region

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On behalf of EuroCirCol WP3 EIR design team: CERN, CI, EPFL, INFN, JAI, TU

FCC meeting in Berlin

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EuroCirCol A key to New Physics

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FCC hh ee he

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EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

MANCHESTER 1824 The University of Manchester

Plan

- **Overview**
- **Final Focus optics**
  - **Longer triplet FF**
  - **Shorter triplet FF & Flat beam FF**
  - **Low luminosity IR FF**
  - **Correction schemes**
- **Energy deposition and protection**
- **Machine Detector Interface**
  - **Proton cross talk / muon cross talk**
  - **SR background**
- **Beam-beam effects**
- **Conclusions and outlook**

Overview - parameters

We have two parameter sets

- Beam current is the same
- But luminosity differs

$$\mathcal{L} \propto \frac{N}{\epsilon} \frac{1}{\beta_y} N n_b f_r$$

They have the same current but the ultimate set has more challenging collision parameters

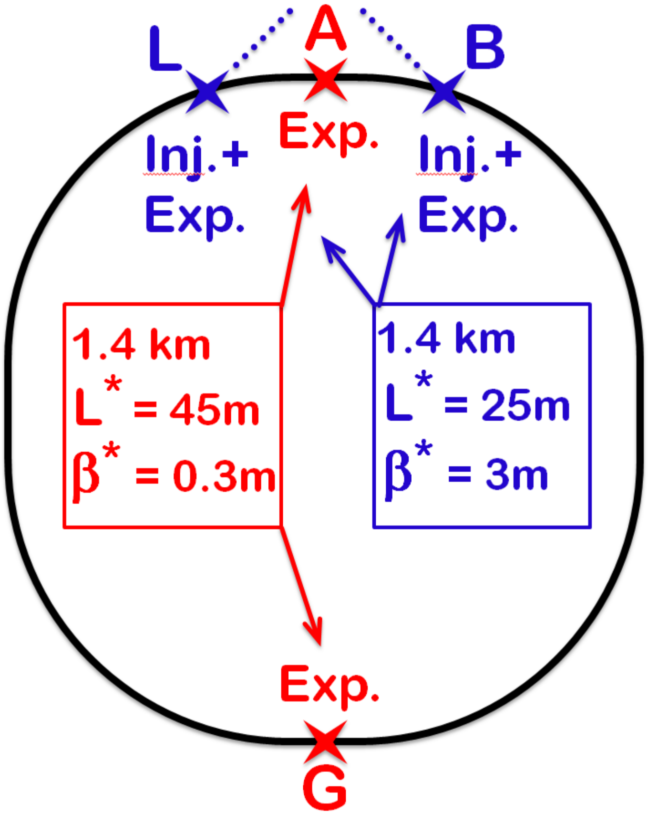
The "baseline" in EuroCirCol should be capable to run with the **ultimate** parameters

	FCC-hh Baseline	FCC-hh Ultimate
Luminosity L [10^{34}cm^{-2}s^{-1}]	5	20-30
Background events/bx	170 (34)	<1020 (204)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	**0.3**
IP beam size σ [μm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [σ']	12	Crab. Cav.
Turn-around time [h]	5	4

Slide from Daniel Schulte

Overview - layouts

The experimental interaction region (EIR) is one of the key areas that define the performance of the Future Circular Collider



The FCC-hh, housed in a 97.75 km perimeter racetrack tunnel filled with 16 T SC magnets, includes four EIRs -- two for nominal/high luminosity and two for low-luminosity experiments

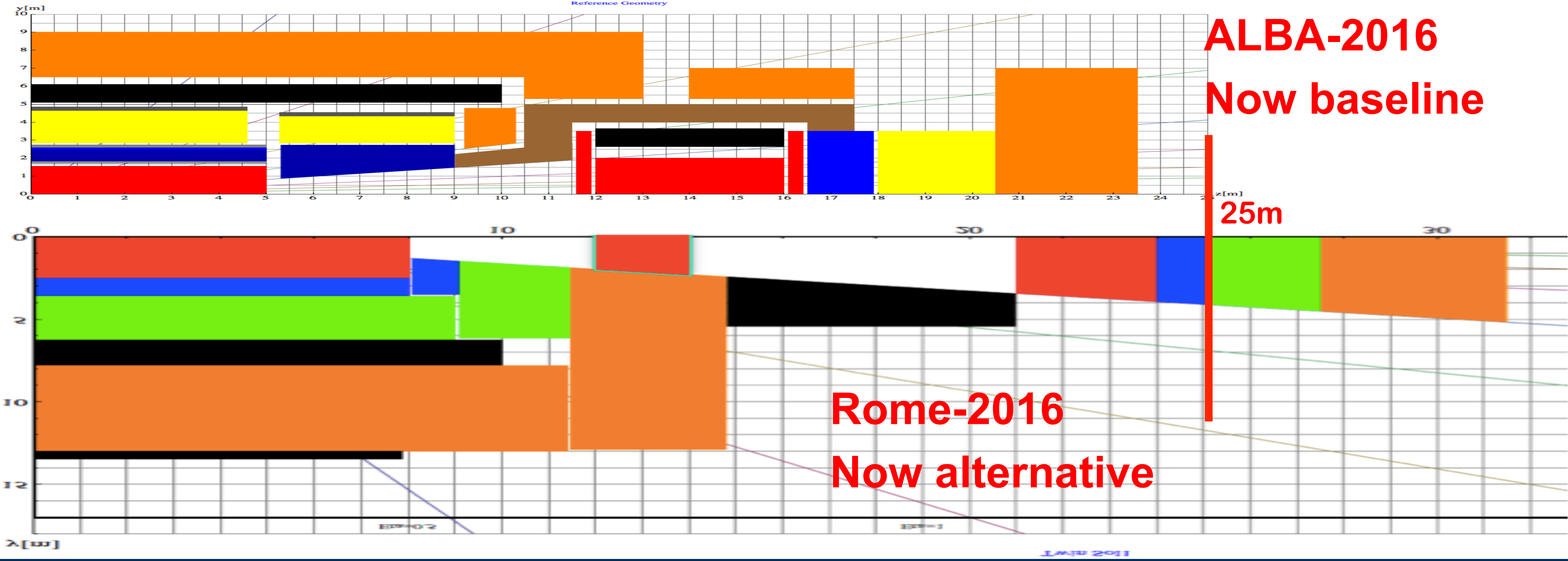
Each of the EIR straight sections is 1400 m long, while in low-luminosity EIR sections the experiments are combined with injection sections

FCC-hh layout and key parameters of the main and low-luminosity EIR

FF optics and L*

In the main EIR the present L* is 45m – is can accommodate the baseline detector (unshielded solenoid with balanced conical / cylindrical solenoid) or the alternative longer detector (twin shielded solenoid with dipole spectrometers)

Older and the newer detector in the same scale:



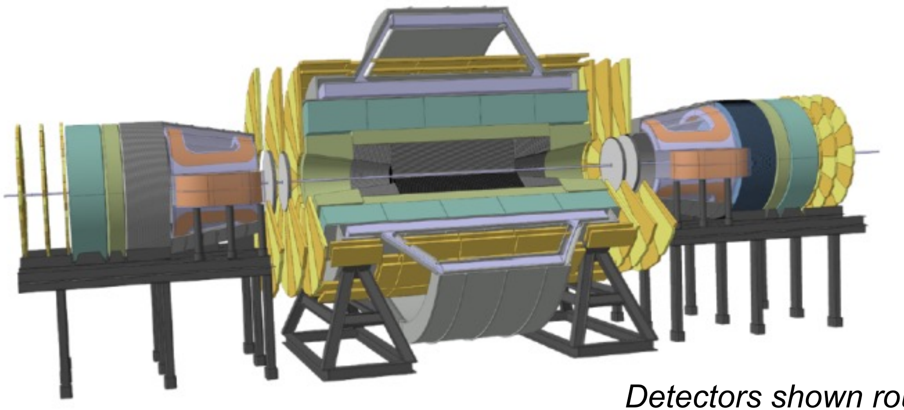
Detectors and main EIR FF L*

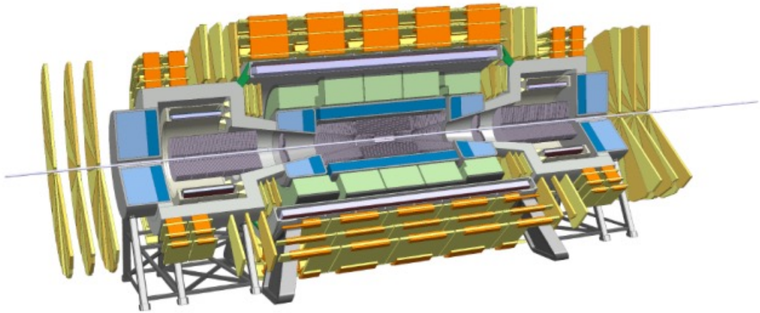
6T, 12m bore solenoid, 10Tm dipoles, shielding coil

→ 65 GJ Stored Energy
→ 28m Diameter
→ >30m shaft
→ Multi Billion project

4T, 10m bore solenoid, 4T forward solenoids , no shielding coil

→ 14 GJ Stored Energy
→ Rotational symmetry for tracking !
→ 20m Diameter (≈ ATLAS)
→ 15m shaft
→ ≈ 1 Billion project





Detectors shown roughly in the same scale

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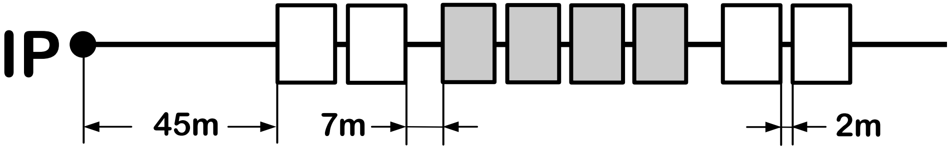
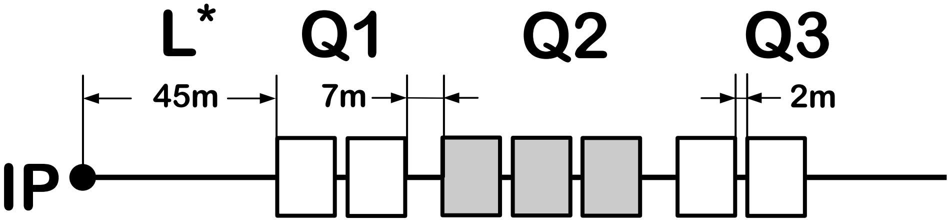
Main EIR FF optics - triplets

Coil Radius (mm)	95	120	120
Aperture Ø (mm)	72	119	119
Gradient (T/m)	115	94	94
Shielding (mm)	48	48	48
Length (m)	15	13.2	15





Length (m)	15	15	15
Shielding (mm)	44.2	33.2	24.2
Gradient (T/m)	106	111	97
Aperture Ø (mm)	86	108	126
Coil Radius (mm)	98.3	98.3	98.3

Versions of main EIR FF optics under study are:

the longer triplet version

and the so-called flat optics with shorter triplet

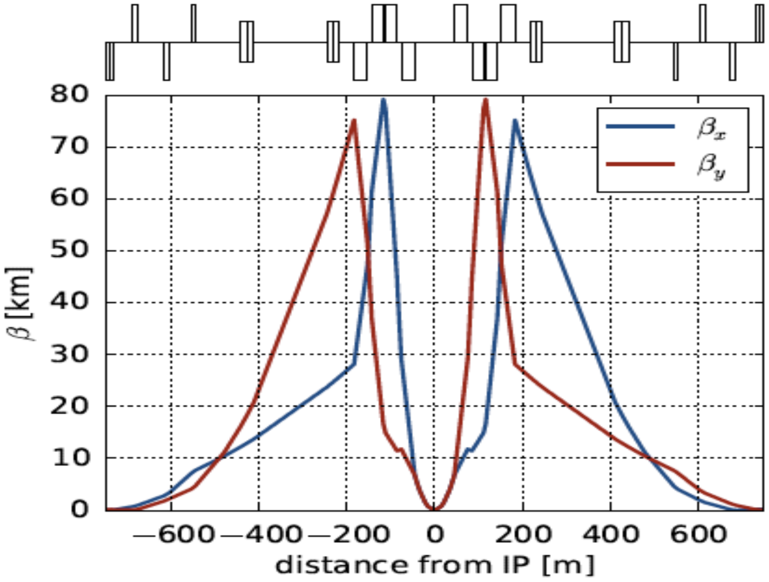
Main EIR inner triplets, long and short triplet optics version – inner coil radius, clear aperture, gradient, thickness of shielding and length of individual quadrupole

Longer triplet FF

- The present design of the longer triplet FF provides the most flexibility in terms of β* reach and the best performance in terms of energy deposition protection

- Large apertures of the quadrupoles allow reaching β* below 0.1 m (with 15 mm shielding) or significantly increasing shielding still with good β* reach of 0.2 m

- However, this optics is 1500 m long
- The possibility of reducing its length to the allocated 1400 m is currently under study

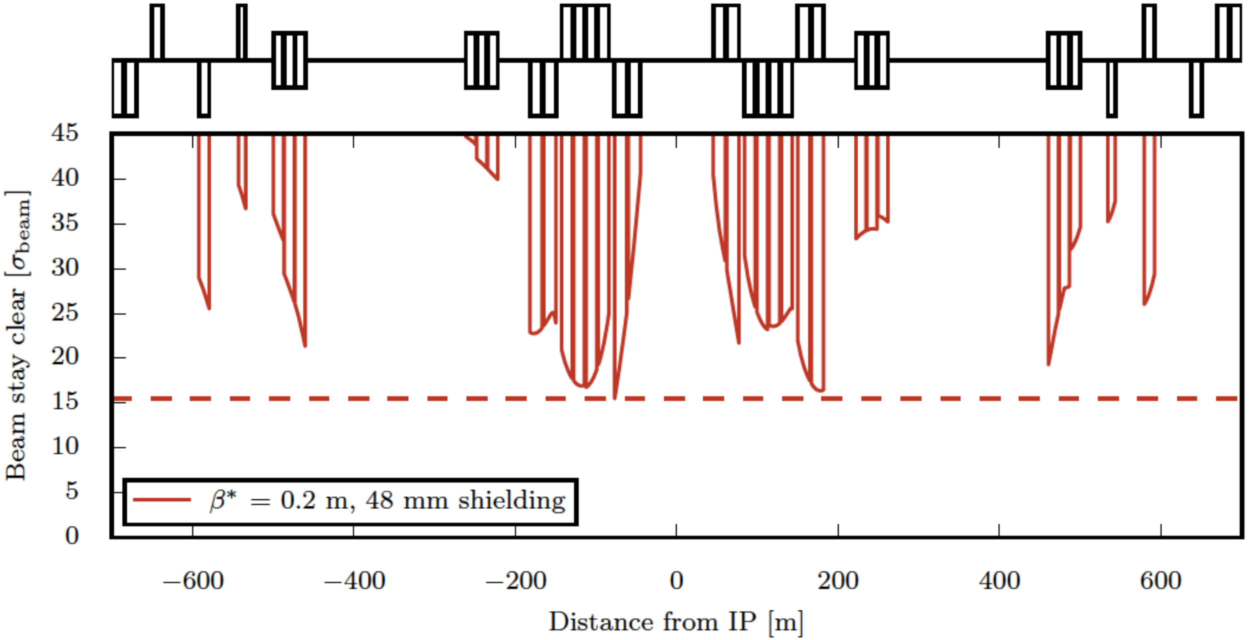


Optics for $\beta^* = 0.3$ m

More details, as well as most recent long triplet optics, in the poster of R. Martin, et al

Longer triplet FF – Beam Stay Clear

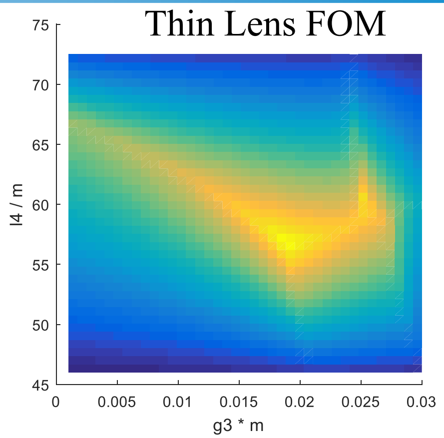
- Triplet aperture still allows for β* below 0.1m at beam stay clear of 15.5σ and with 15mm thick shielding inside quadrupole apertures
- Alternative option with thick shielding of 48mm still allows to reach β* = 0.2m

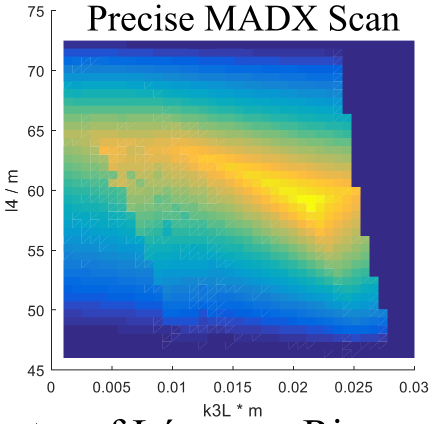


Main EIR – shorter triplet FF

- Since the length of the inner triplet translates into the total length of EIR FF with a large multiplication factor, the shorter by ten meters triplet of the other FF option fits comfortably to the allocated 1400 m space

- Dedicated code has been used to optimize this optics to be compatible with round beam collisions as well as for flat beam collisions with β^* x/y = 1.0/0.2 m which can be suitable for the option of operation without crab cavities

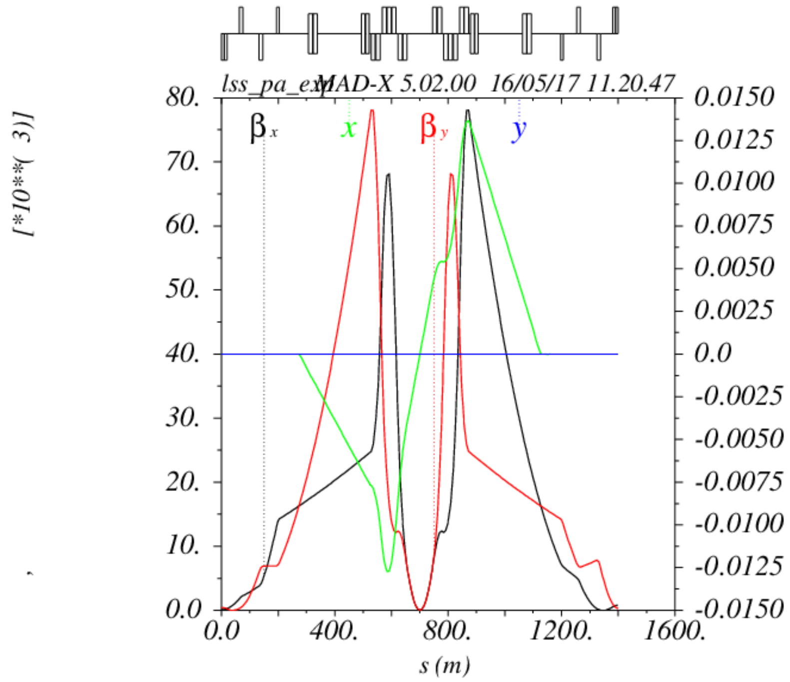




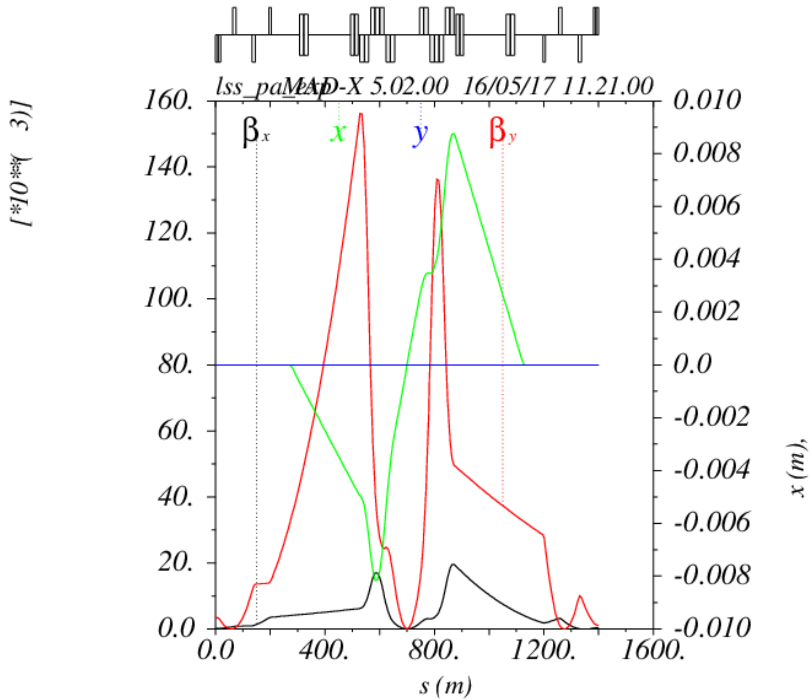
See poster of Léon van Riesen-Haupt

Main EIR – shorter triplet FF

Round

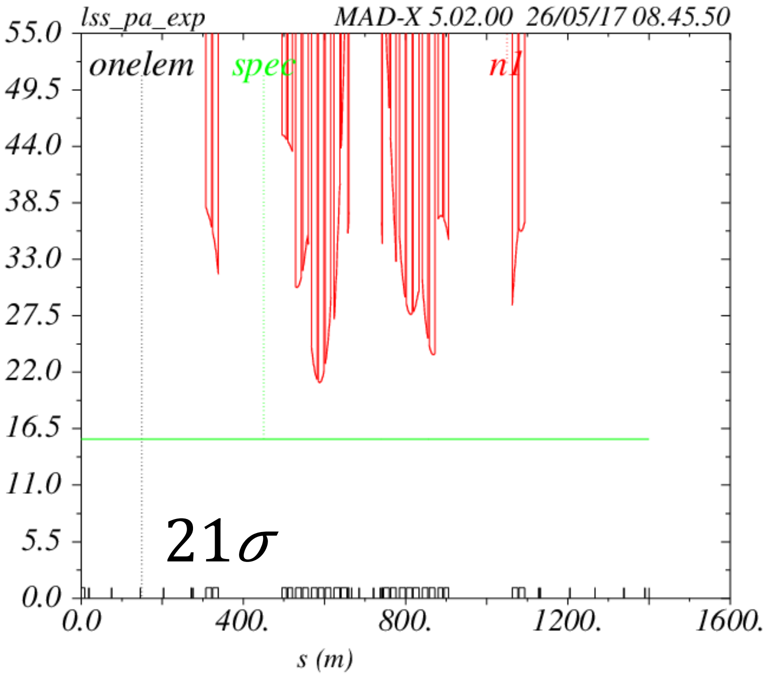


Flat



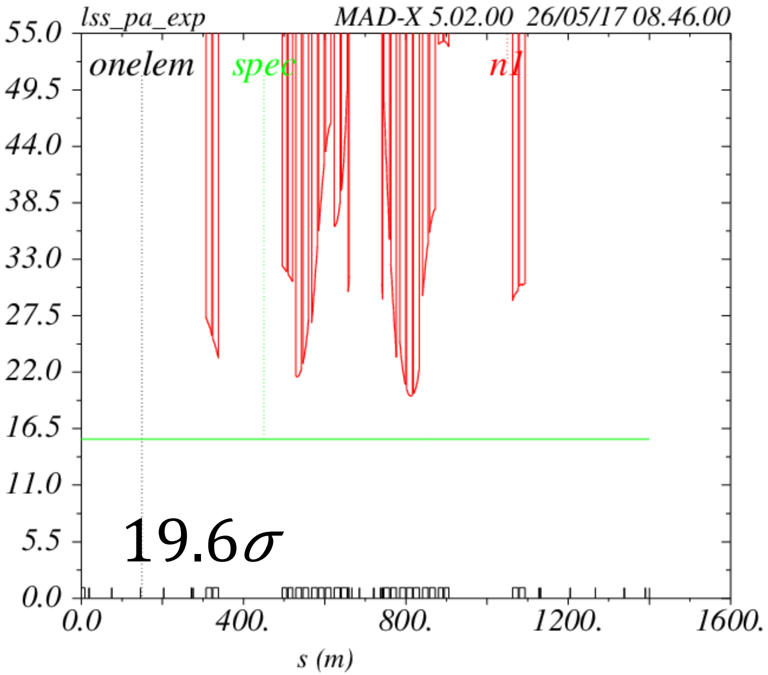
Short triplet FF - Beam Stay Clear

Round



21σ

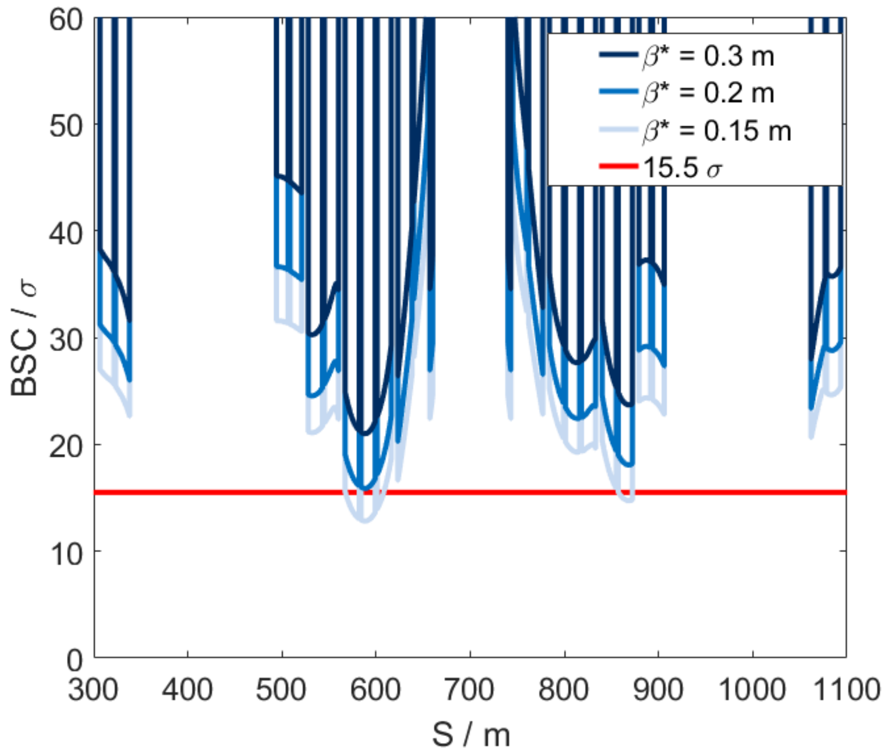
Flat



19.6σ

Short triplet FF – β* reach

- **Can balance, at the design stage, between amount of shielding and β* reach**



See poster of Léon van Riesen-Haupt

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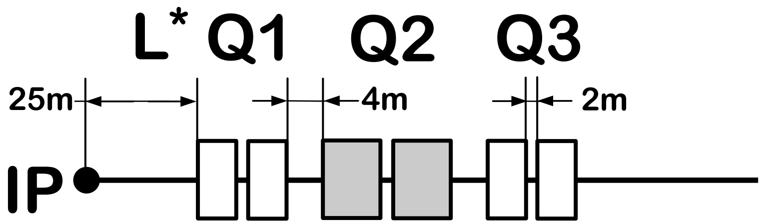
Low Lumi EIR FF - triplets



	Q1	Q2	Q3
Length (m)	10	15	10
Shielding (mm)	10	10	10
Gradient (T/m)	265	270	260
Aperture Ø (mm)	28	28	28
Coil Radius (mm)	32	32	32

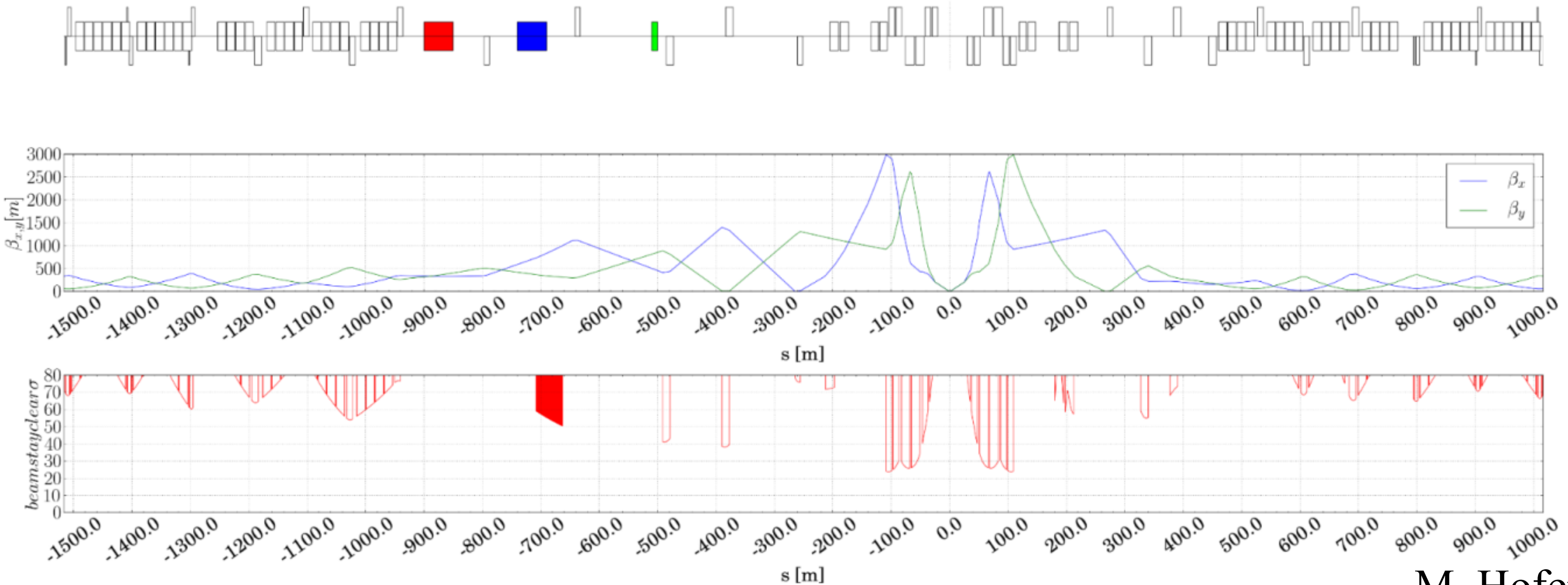
The optics of low-luminosity EIR, where FF is co-located with injection, take into account additional requirements imposed from the need to protect the cold elements from mis-kicked injected beams

Low Lumi EIR inner triplet – inner coil radius, clear aperture, gradient, thickness of shielding and length of individual quadrupole

M. Hofer, et al

Low Lumi EIR optics

- In the new, more compact FCC-hh layout injection and the low luminosity experiment are combined in Points B & L
- The straight section length remains at 1.4 km
- A layout for these insertion has been designed, which uses a L* of 25 m and achieves β* = 3 m



M. Hofer, et al

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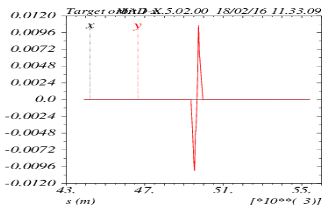
Correction Scheme

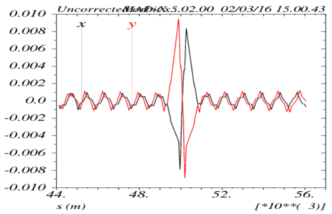
- Studies have been done to test the effect of different errors on the interaction region. These include alignment errors in the triplet, matching section and separation/ recombination dipoles, and field errors on the triplet.

- For the case of alignment errors, studies have been done to test how well the orbit is restored in comparison to the original one, and the strength of the correctors needed.

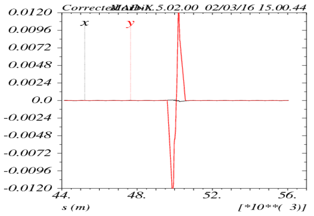
No errors



Misalignment errors



Correction

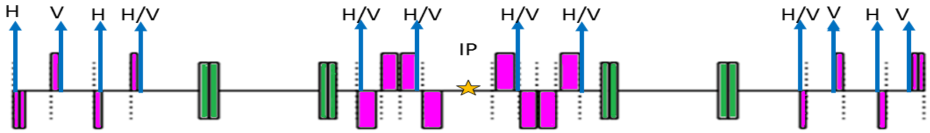


- For the case of field errors non-linear correctors have been implemented into the lattice to minimize the resonance driving terms arising from the errors of the triplet. Dynamic aperture studies are then performed to study the impact of this correction.

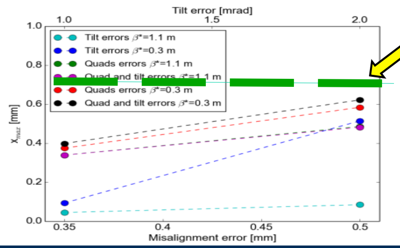
E. Cruz-Alaniz

Alignment Errors & Linear Correctors

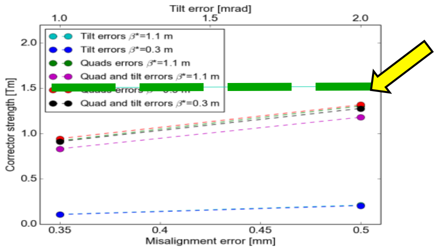
- Misalignment errors have been added to the quadrupoles on the triplet, matching section and the separation/recombination dipoles.
- The corrector scheme used for these studies include correctors next to the triplet, matching section and dispersion suppressor, as well as BPM's installed along the IR.



- Method: use the CORRECT method in MADX, followed by calculating the max orbit deviation in the IR and the strength of the correctors needed, and then repeating the procedure for 100 seeds.
- All the studies have a max deviation below 0.7 mm and require a strength of the correctors for the non-crossing orbit below 1.5 Tm for all cases (achievable). Some of the correctors in the crossing orbit require larger strengths (up to 8 Tm) but are compensated by the length of the correctors.



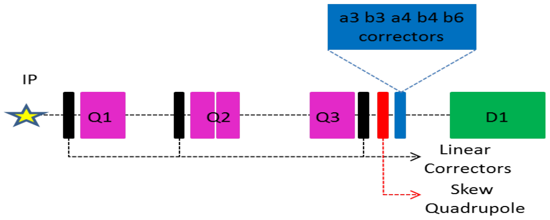
0.7 mm



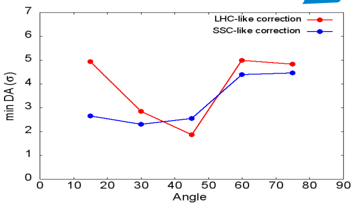
1.5 Tm

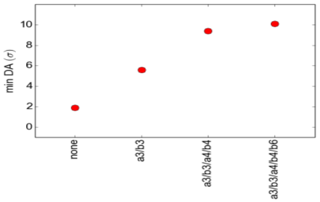
Field Errors & non-linear Correctors

- Non linear correctors added to the lattice to compensate for the errors errors in the triplet



- Method: adjust strengths of the correctors such that the resonance driving terms arising from the errors in the triplet are set to zero. Each pair of non-linear correctors corrects resonance driving terms arising from two different resonance lines chosen by its proximity to the working point.
- The effect of the implementation of non-linear correctors gave encouraging results, increasing the dynamic aperture from 1.9σ (without correctors) up to 10.1σ (with a3/b3/a4/b4/b6 correctors)





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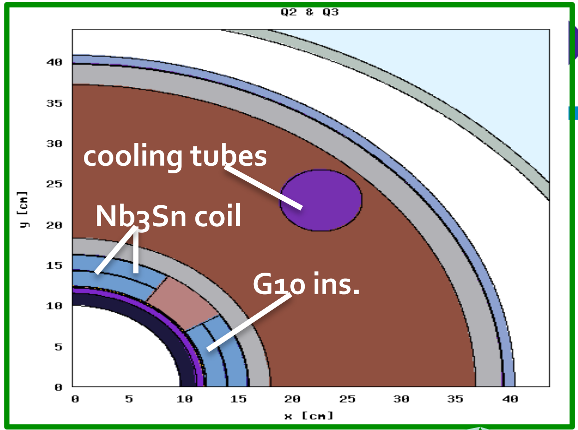
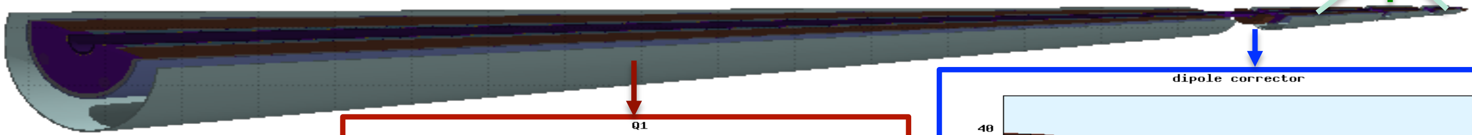
Main IR Layout

- **Interaction region parameters:**
  - L* 45 m, 89 μrad half crossing angle

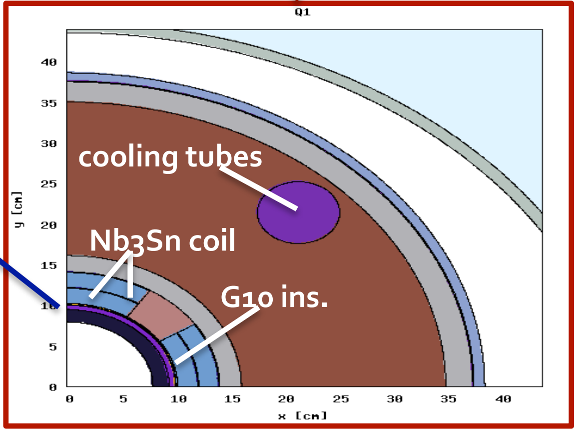
Magnet	Q1	Q2A-B	Q3
coil inner diameter [mm]	205	248	248
length [m]	30.8	26.4	30.8
gradient [T/m]	107	86	89

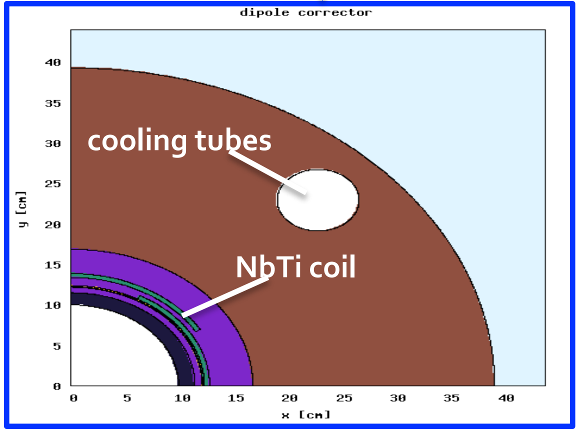




3 m long copper **TAS** at 2 m from Q1, 50 mm ID aperture

Shielding, 2 cases considered: **15 mm** and **55 mm** thick **tungsten** (INERMET180) shielding inside the cold bore with tentative gaps in the interconnects





M. I. Besana

15 mm Case: Power

- **Total Power** for 5 10^{34} $cm^{-2}s^{-1}$:

Magnet	Power [kW] vertical crossing			Power [kW] horizontal crossing		
	Total	Shielding	Cold Mass	Total	Shielding	Cold Mass
Q1	2.7	2.0	0.72	2.7	2.0	0.71
C1	0.14	0.11	0.04	0.14	0.1	0.03
Q2A	0.5	0.34	0.14	0.5	0.33	0.13
Q2B	2.15	1.6	0.51	2.4	1.8	0.54
Q3	1.8	1.4	0.4	1.25	1.0	0.3
C2	0.17	0.11	0.06	0.1	0.07	0.03

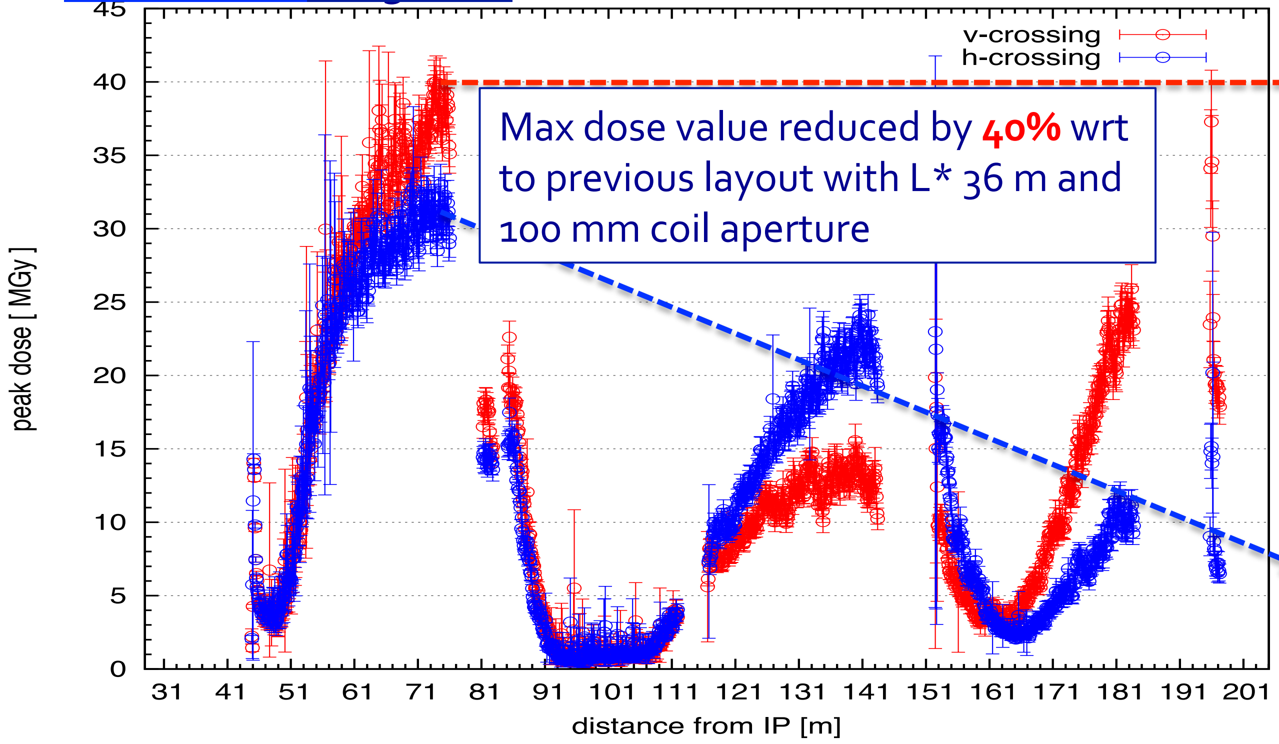
  - maximum power per meter is on Q1 and it is 23 W/m, similar to LHC

- **Peak power density** for 5 10^{34} $cm^{-2}s^{-1}$:
  - the maximum on the quadrupole inner coils is at the end of Q1 for both crossing schemes and it is equal to **2.3 mWcm^{-3}** (**1.8 mWcm^{-3}**) for vertical crossing (horizontal crossing):

    for 30 10^{34} $cm^{-2}s^{-1}$ we expect **13.8 mWcm^{-3}** (**11.8 mWcm^{-3}**) for v-(h-)crossing.

15 mm Case: Peak Dose

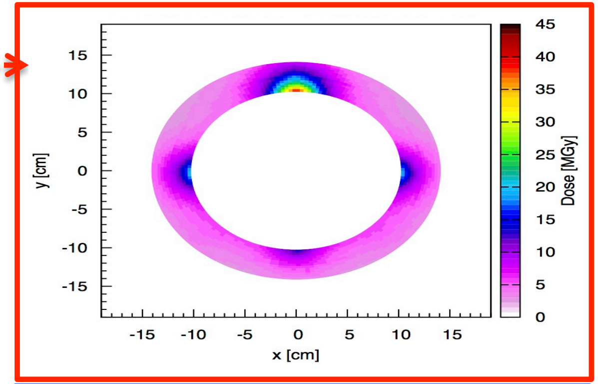
Peak dose for 5 ab^{-1}:

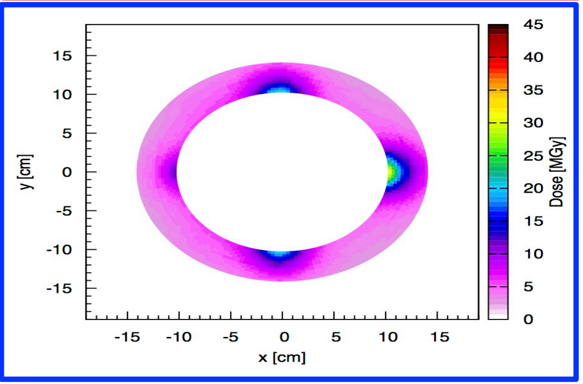


Max dose value reduced by **40%** wrt to previous layout with L* 36 m and 100 mm coil aperture

Resolution:

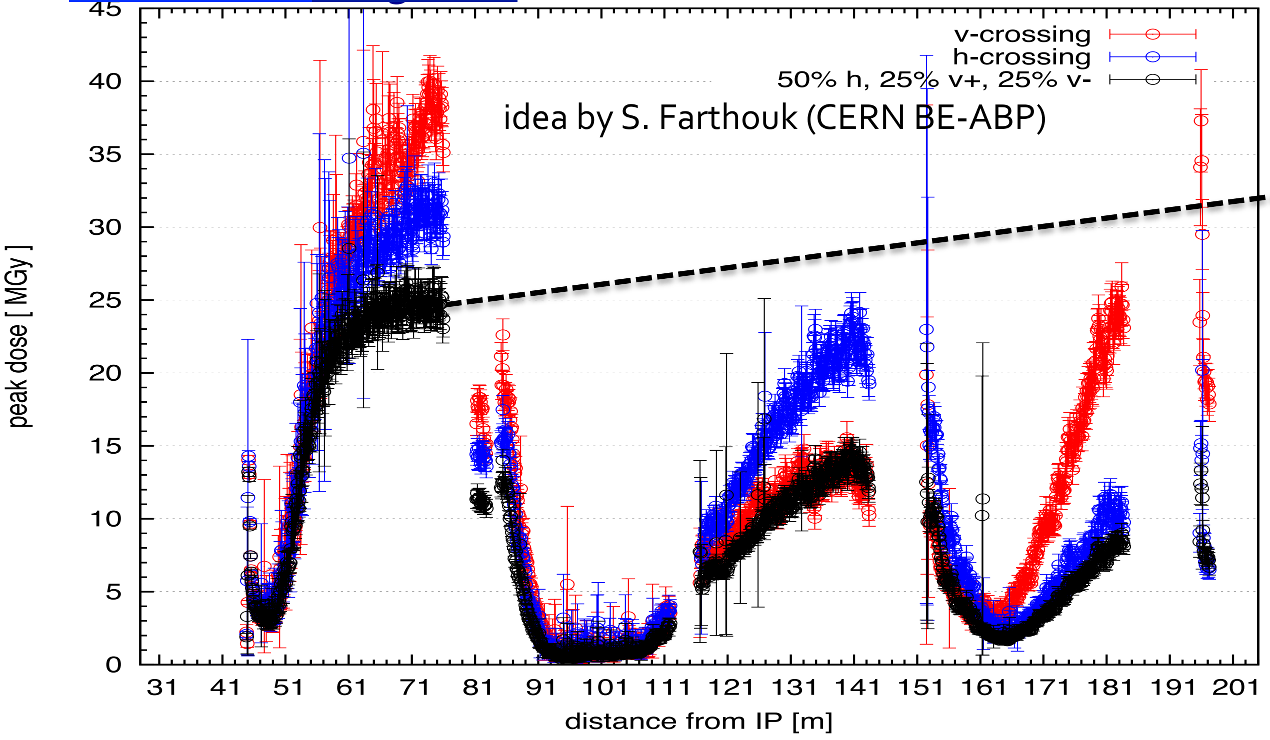
Δz = 10 cm, Δϕ = 2 deg, 2-3 mm





15 mm Case: Peak Dose

Peak dose for 5 ab^{-1}:



Resolution:
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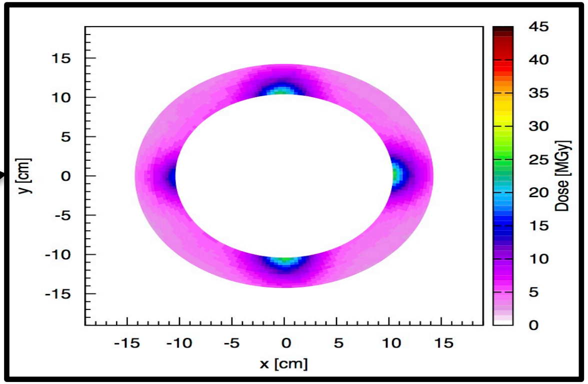
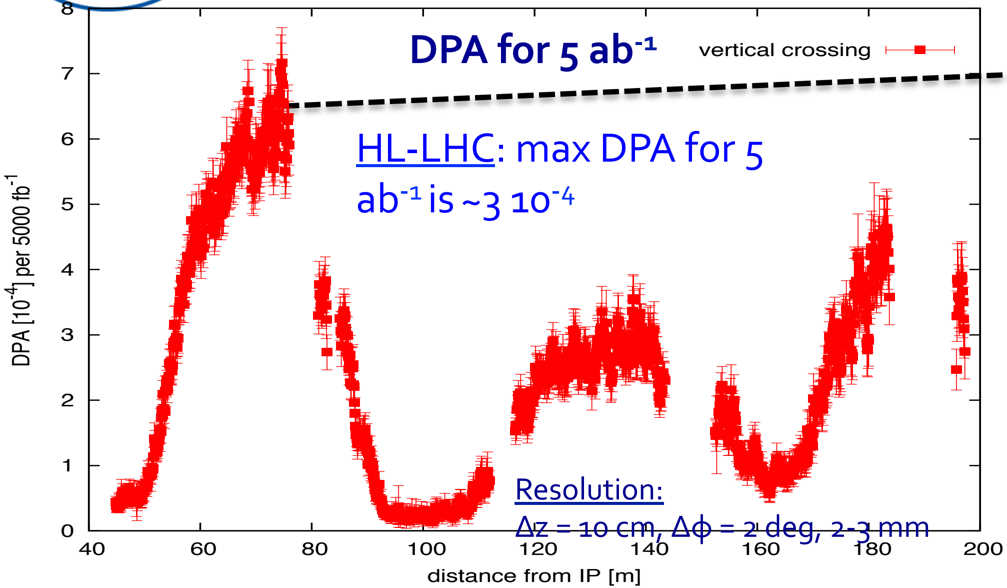


Assuming a peak dose limit of 30 MGy, the triplet can survive an entire high luminosity Run.

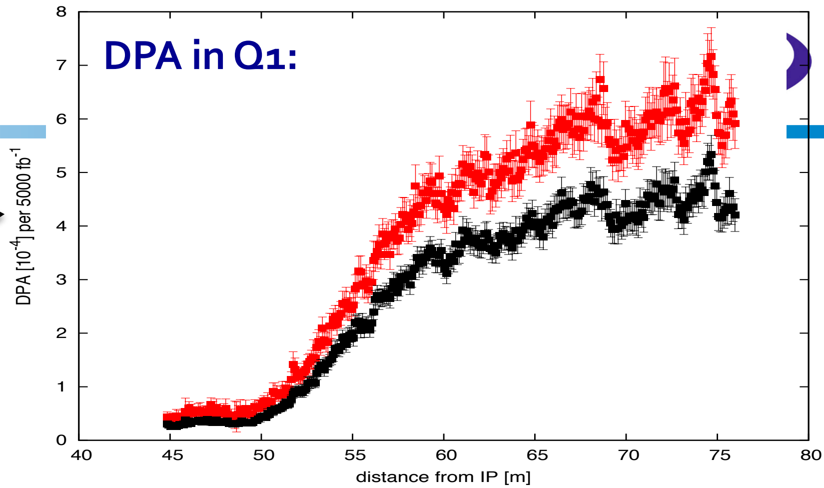
For 30 ab^{-1} the dose would be **150 MGy**.

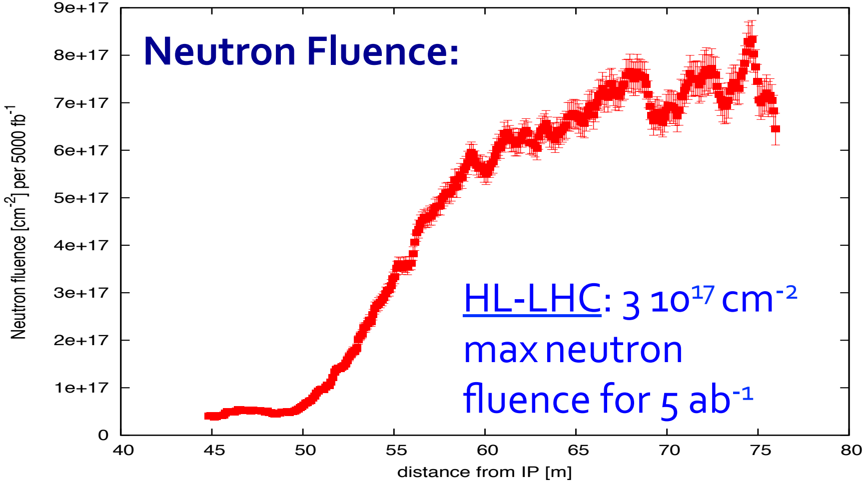
EuroCirCol A key to New Physics

15 mm Case: DPA



Particles	Contribution to DPA
neutrons < 20 MeV	78%
residual nuclei	19%
protons	1.5%
electrons	1%





55 mm Case (v-crossing): Power

EuroCirCol
A key to New Physics

FCC hh ee he

Total power for 5 10^{34} $cm^{-2}s^{-1}$ [kW]:

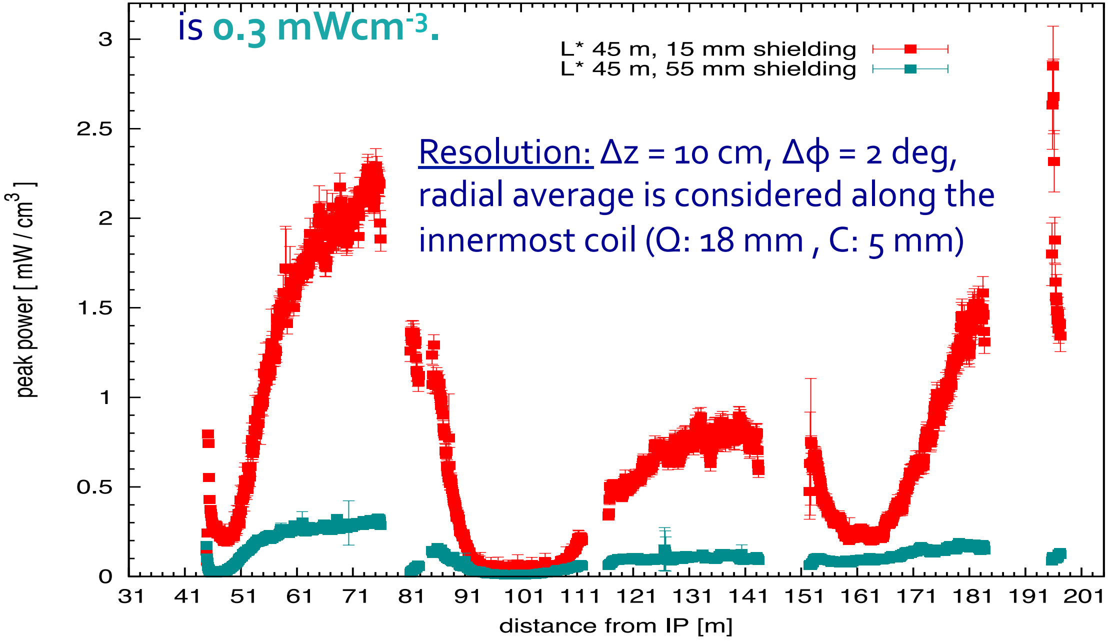
Magnet	Total	Shielding	Cold Mass
Q1	4.1	3.7	0.37
C1	0.061	0.056	0.005
Q2A	0.76	0.7	0.07
Q2B	2.3	2.1	0.17
Q3	2.5	2.3	0.18
C2	0.13	0.12	0.01

Ratio of the power on the cold mass wrt the 15 mm thick shielding case:

Q1	0.5
C1	0.11
Q2A	0.5
Q2B	0.3
Q3	0.4
C2	0.17

Peak power density for 5 10^{34} $cm^{-2}s^{-1}$:

for baseline luminosity the maximum peak power is 0.3 $mWcm^{-3}$.

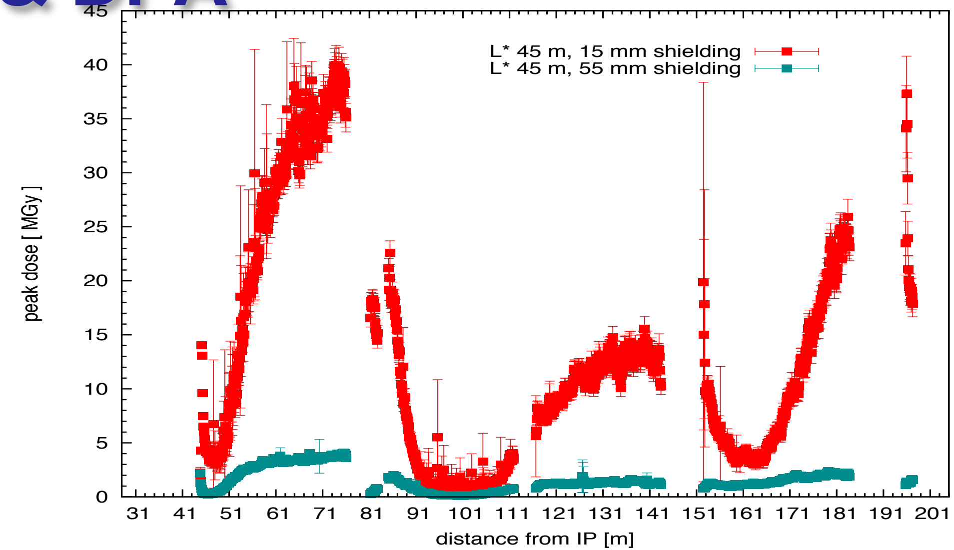


Resolution: Δz = 10 cm, Δϕ = 2 deg, radial average is considered along the innermost coil (Q: 18 mm , C: 5 mm)

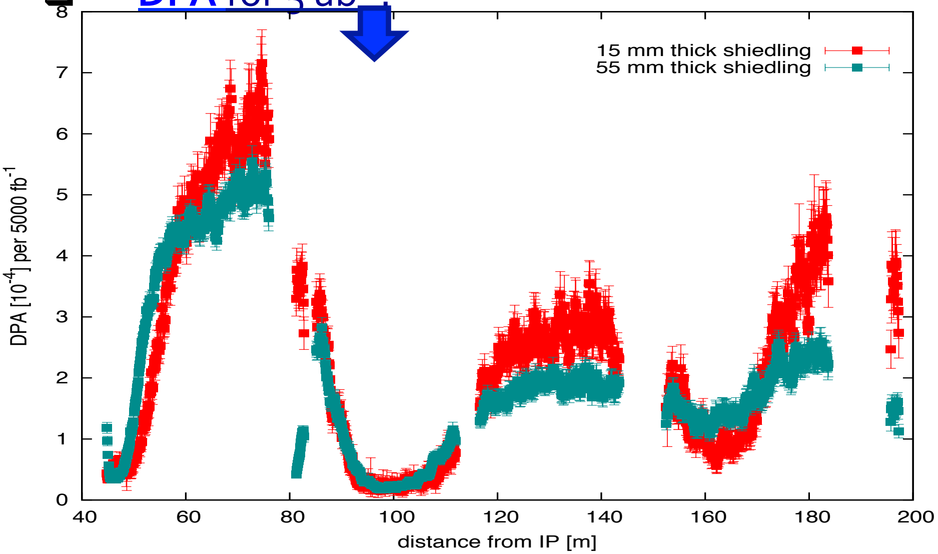
The expected peak power density for 30 10^{34} $cm^{-2}s^{-1}$ is ~2 $mWcm^{-3}$

55 mm Case (v-crossing): Dose & DPA

- **Peak dose** for 5 ab^{-1}:
  - The peak dose is ~5 MGy for 5 ab^{-1} → 30 MGy for 30 ab^{-1}
  - The triplet can survive for the whole data-taking



- **DPA** for 5 ab^{-1}:



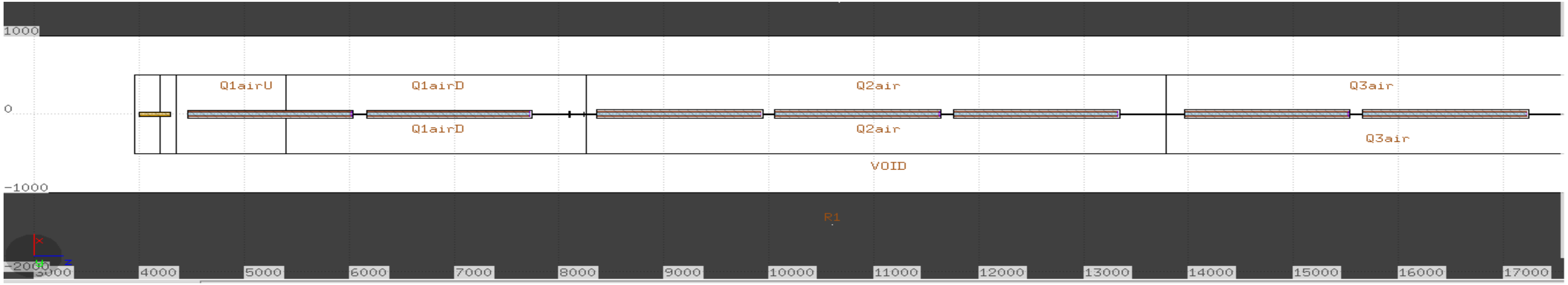
- The shielding increase has a small impact on DPA
- After 30 ab^{-1} DPA are 4.2 10^{-3} → challenging
- Studies and discussions are on-going to determine the limits of the coil material

Longer triplet FF – to do

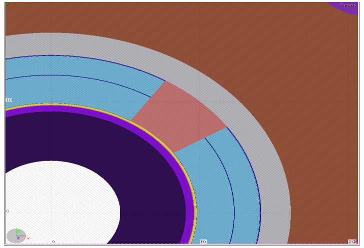
- To do lists:
  - magnets are too long:
    - Q1 and Q3: 30.8 m
    - Q2A and Q2B: 26.4 m
  - they need to be split to reach a maximum value of 15 m and a 2 m gap between each pair has to be included
  - ➢ simulations will be repeated with the new layout as soon as it is finalized

M. I. Besana

Shorter triplet FF

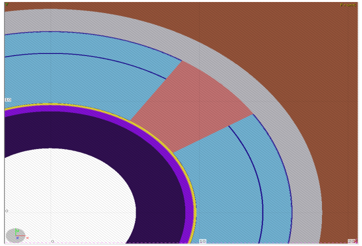


Q1
106 T/m



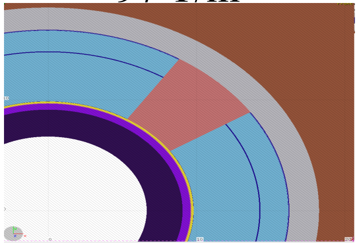
Abs:4.4 cm

Q2
111 T/m



Abs:3.3 cm

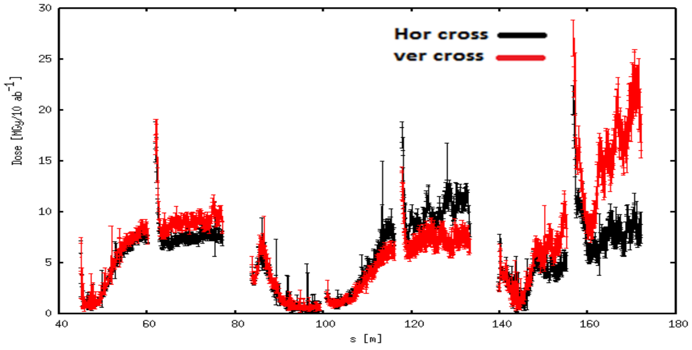
Q3
97 T/m



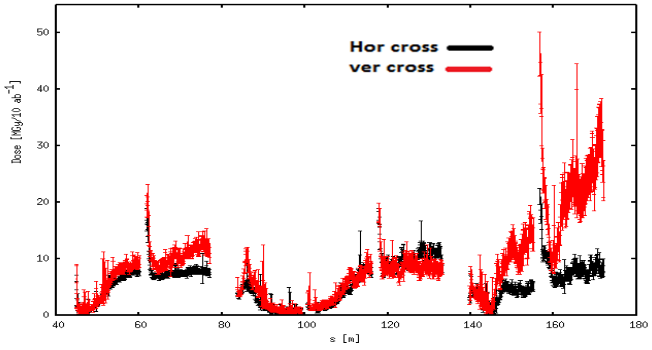
Abs: 2.4cm

J. L. Abelleira

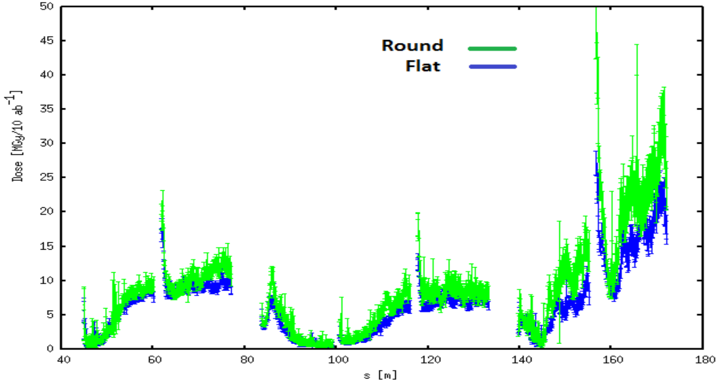
Shorter triplet FF



Peak dose for round optics (0.3 m).



Peak dose for flat optics (1.2, 0.15).



Peak dose (50 % hor, 50% vertical cross.)

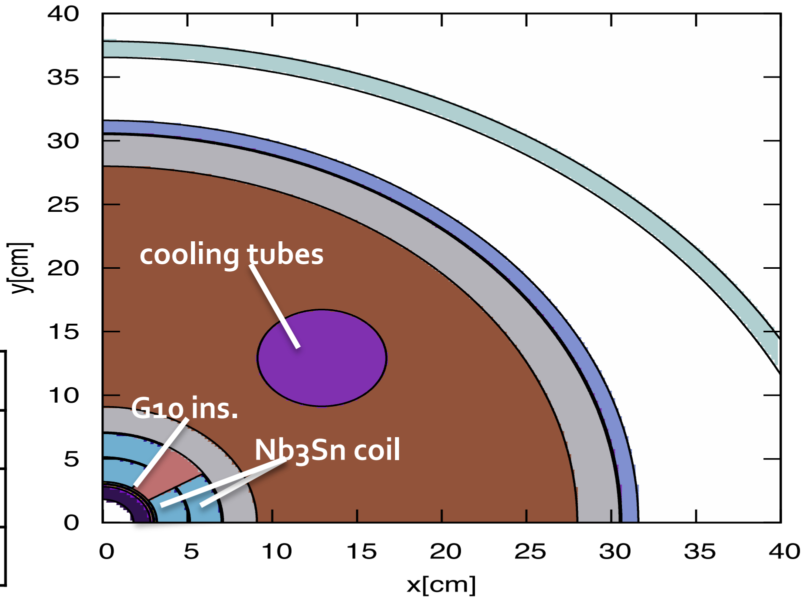
J. L. Abelleira

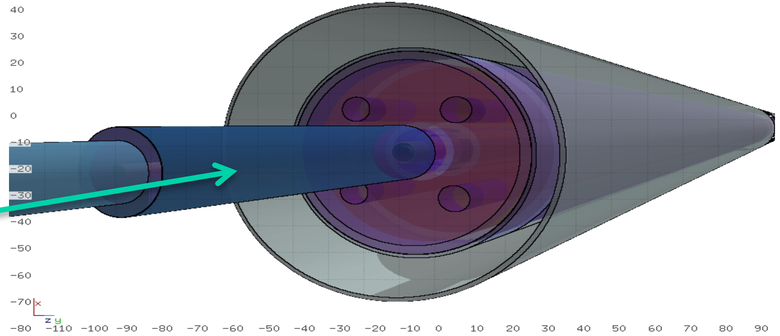
Low L IR Layout

- **Interaction region parameters:**
  - L* 25 m
  - crossing angle of 19 μrad, both vertical and horizontal crossing considered
- **Magnets:**

Magnet	Q1	Q2	Q3
coil aperture radius [mm]	32	32	32
length [m]	10	15	10
gradient [T/m]	265	270	260

  - orbit correctors with the same coil aperture
- **A 10 mm thick tungsten (INERMET180) shielding considered all along the triplet**
  - free aperture: 18.25 mm inner radius
  - 70 cm long tentative gaps in the interconnects
- **Tungsten mask in front of Q1A:**
  - 13.25 mm inner radius & 8 cm outer radius
  - almost 80 cm long

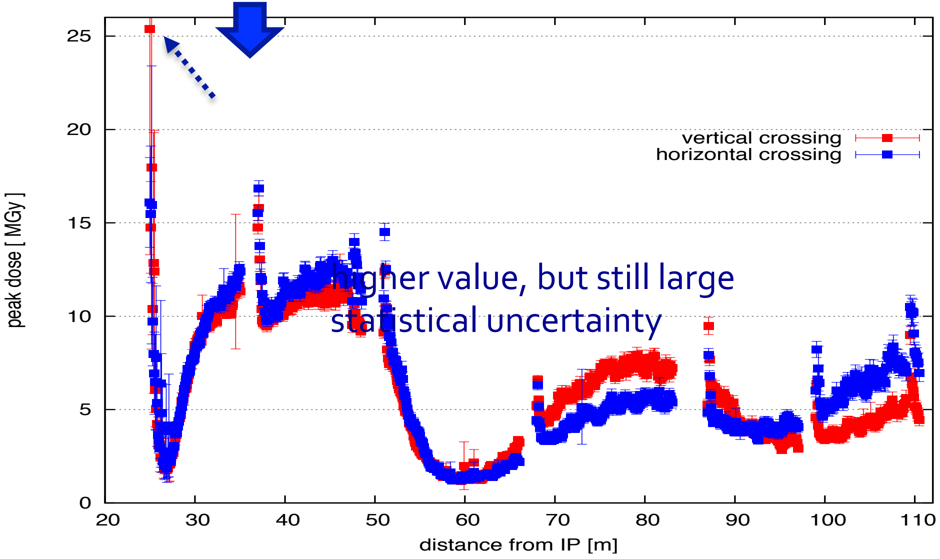




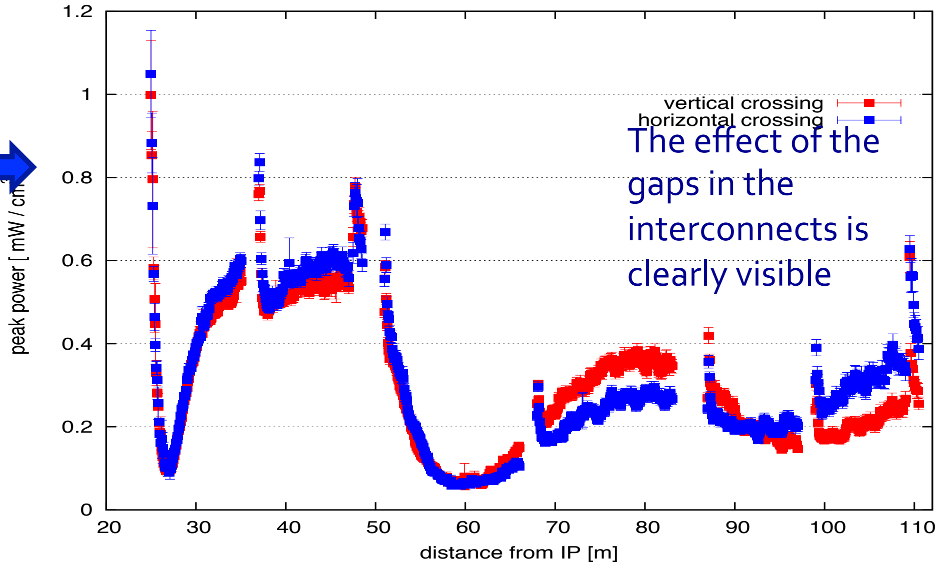
M. I. Besana

Low Lumi Energy Deposition

- **Total Power** for 5 10^{33} $cm^{-2}s^{-1}$ on the inner triplet cold mass = 404 W
  - maximum power per meter on Q1A for both crossing schemes: ~14.4 W/m
- **Peak power density** for 5 10^{33} cm:
- **Peak dose** for 500 fb^{-1}:



Maximum power at the beginning of Q1A



Peak dose below 20 MGy, for 500 fb^{-1}, below present baseline limits

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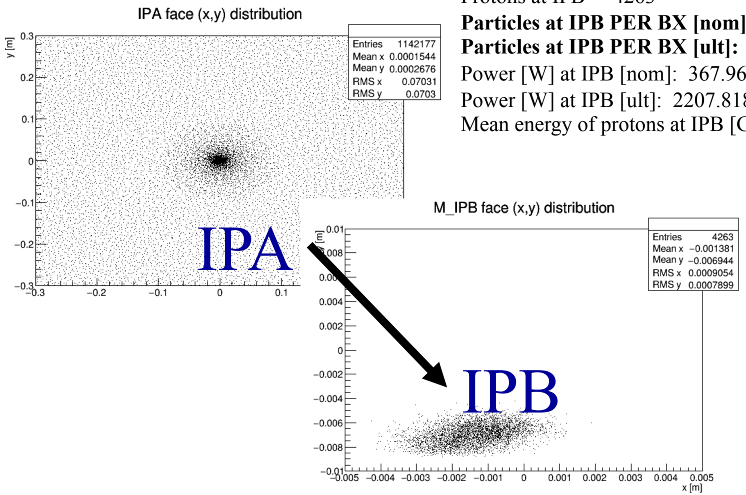
- Conclusions and outlook

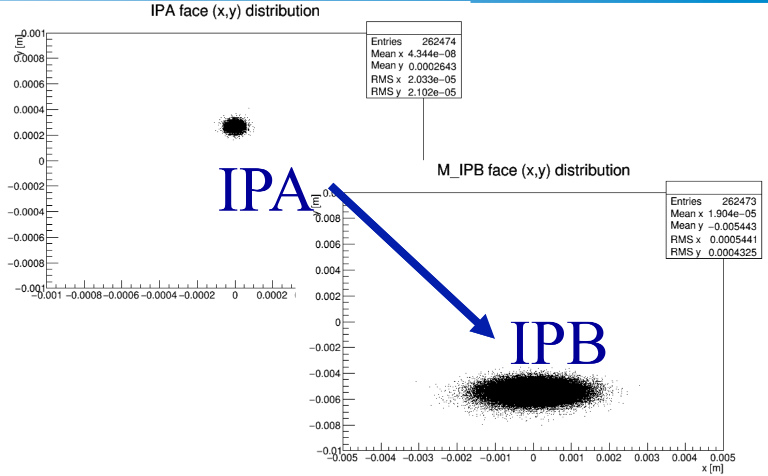
Proton Detector Cross-Talk

H. Rafique, R. B. Appleby

Inelastic protons are mostly lost before the next detector, transmission is minimal



Protons at IPA = 1142177
Protons at IPB = 4263
Particles at IPB PER BX [nom]: 1.457946
Particles at IPB PER BX [ult]: 8.747676
Power [W] at IPB [nom]: 367.969721204
Power [W] at IPB [ult]: 2207.81832722
Mean energy of protons at IPB [GeV]: 49889.6530665

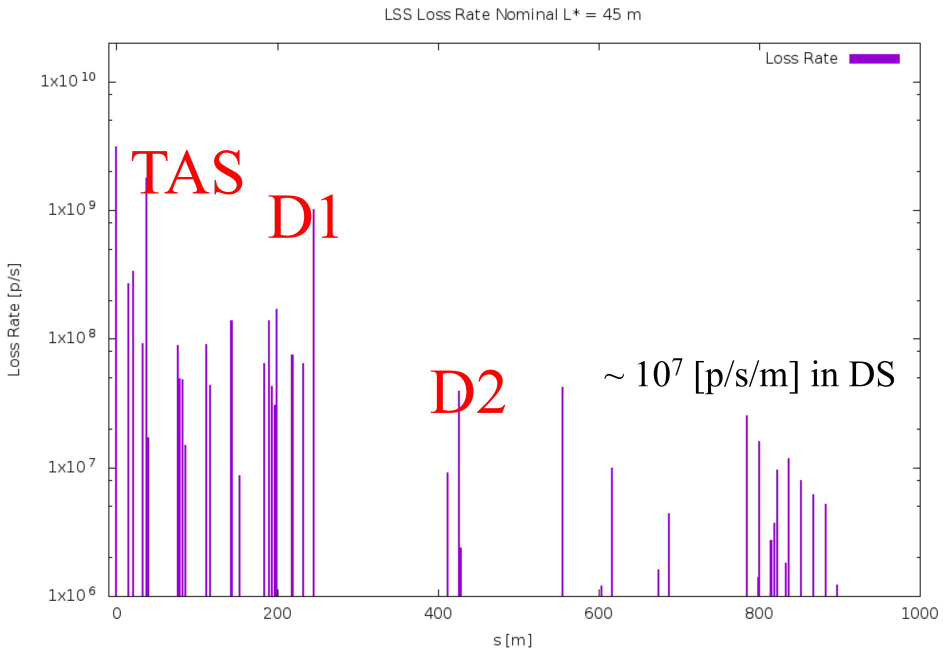


Elastic protons all reach the next detector, this leads to some emittance growth

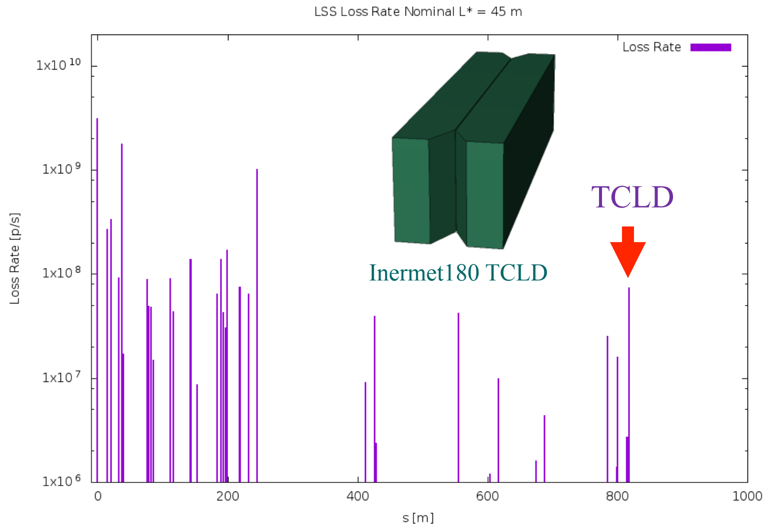
All collision debris generated using DPMJET-III in FLUKA

Inelastic Protons Lost in DS

H. Rafique, R. B. Appleby, A. M. Krainer



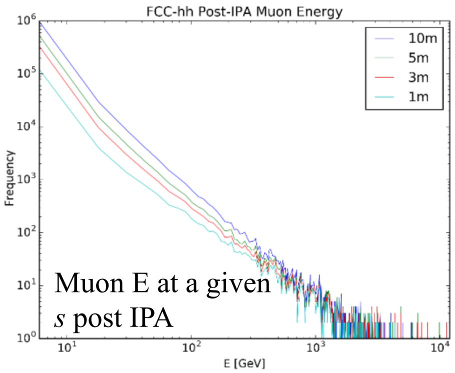
DS losses identified as a concern.
Mitigated using existing TCLD DS collimator design and nominal jaw openings. No violation of betatron collimation hierarchy.

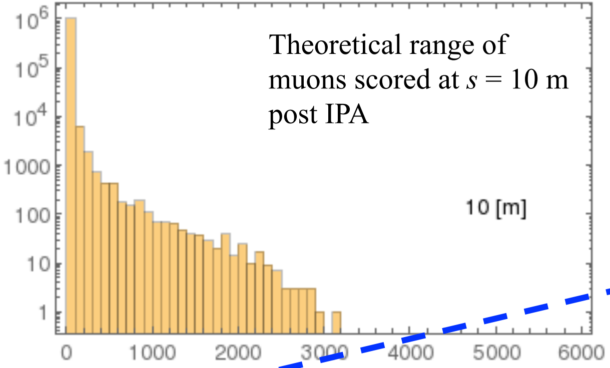


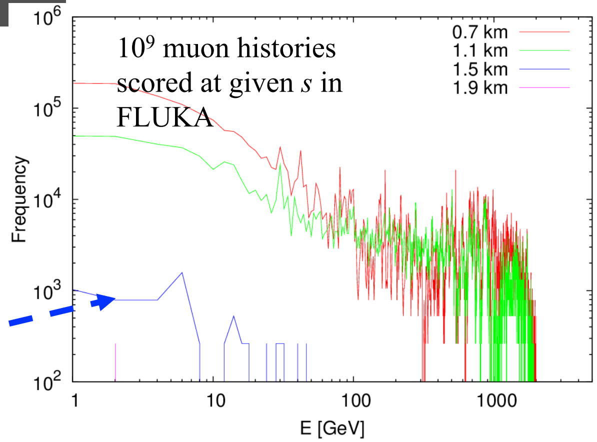
Muon Detector Cross-Talk

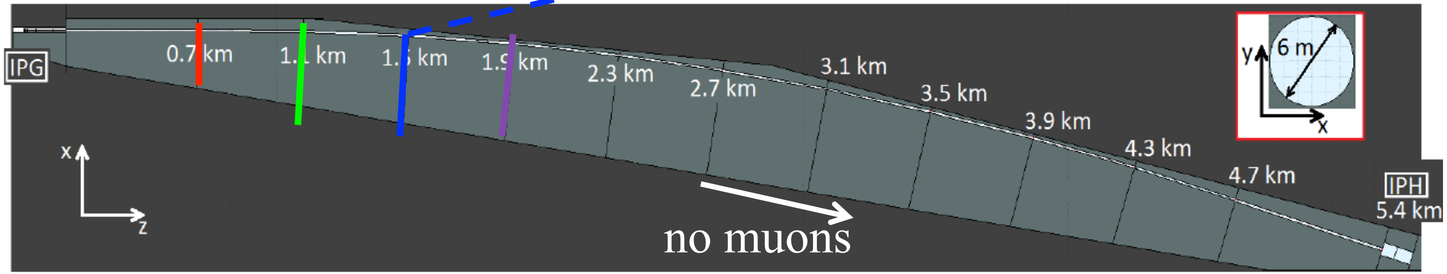
H. Rafique, R. B. Appleby, J. L. Abelleira

Muons can travel far in dense materials. Theoretical calculations estimate a range of ~ 3km. This has been confirmed using FLUKA simulations. Muons should not reach the next IP.









Synchrotron Radiation Backgrounds for the FCC-hh experiments*

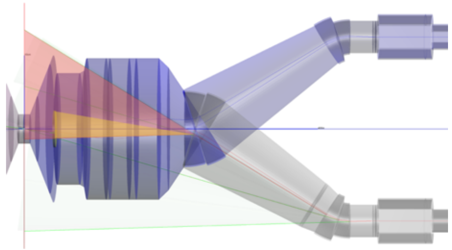
$P \propto \gamma^4 \rightarrow P \propto m^{-4}$ → $P_p \sim 10^{-13} \times P_e$

However, at FCC-hh energies this effect starts to be visible!

Poster presented by
F. Collamati – INFN ROME
M. Boscolo – INFN LNF
H. Burkhardt, R. Kersevan - CERN

- About 100W of SR power are emitted by the last 4 bending magnets:

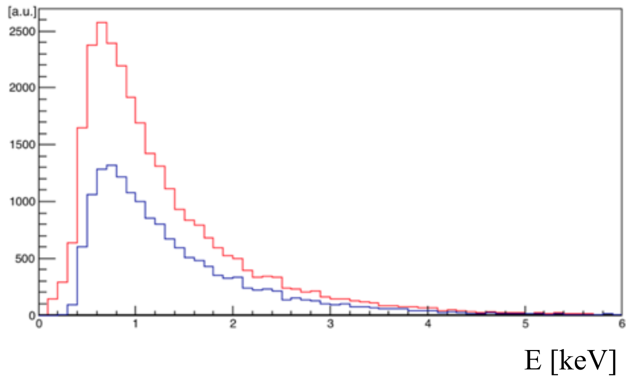
Element	S [m]	l [m]	B [T]	E_{crit} [keV]	P [W]
$D1_A$	231	12.5	-4.3	1.15	32
$D1_B$	245	12.5	-4.3	1.15	32
$D2_A$	427	15	3.6	0.96	27
$D2_B$	443	15	3.6	0.96	27



Presented as a peer-reviewed paper @IPAC 17: TUPVA004

- **MDISim** was used to import the beam pipe geometry, magnetic fields and beam characteristics obtained with MAD-X into GEANT4 to perform a full simulation of SR creation and tracking
- For the two cases with and without the crossing angle scheme we expect about **15-30W** to enter the TAS and thus the Interaction Region
- About **1W** is expected to hit the inner Beryllium pipe
- Spectrum of photons entering the TAS with (red) and without (blue) the crossing angle scheme:

  ➜ The amount of these photons **traversing** the Be Pipe is **negligible**
- This study has been performed also with **SYNRAD+**, with similar results



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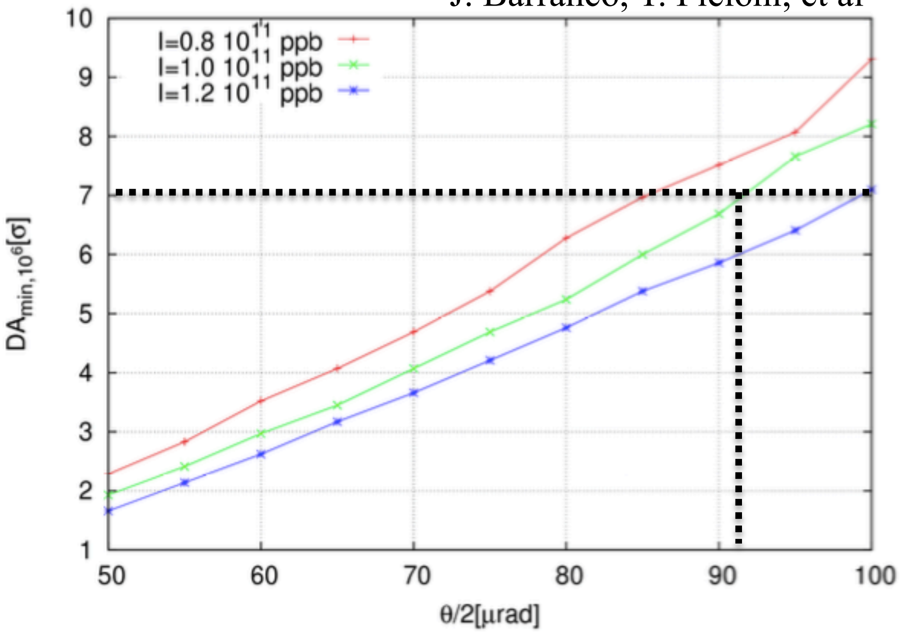
Beam-beam effects DA

- DA criteria from LHC 7.2 σ is ensured for a crossing angle of 180 μrad corresponding to a separation of 15.5 σ at long-range encounter
- No margins left for multipolar errors and for stability requirements (octupoles and RF-Q)
- Larger angles will be required and magnets tolerances defined
- Two low luminosity (but high BB) are under study and set "transparent to main"

Studies presented @ IPAC2017: TUPVA026,TUPVA027, TUPVA030, THPAB056, THPAB042

J. Barranco, T. Pieloni, et al

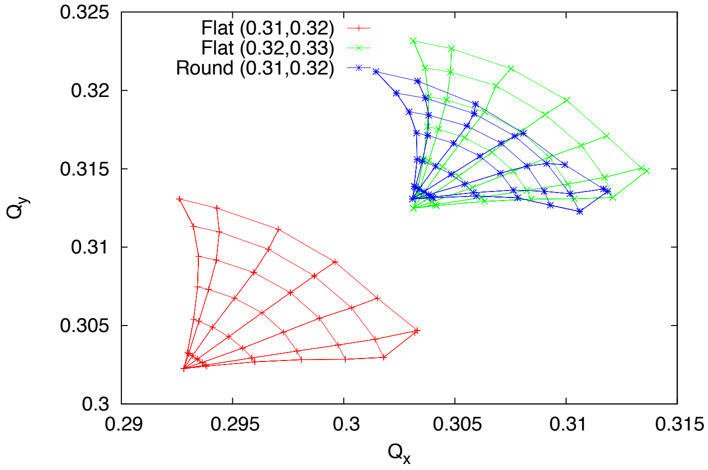


Min dynamic aperture for different beam-beam normalized separations for round optics.

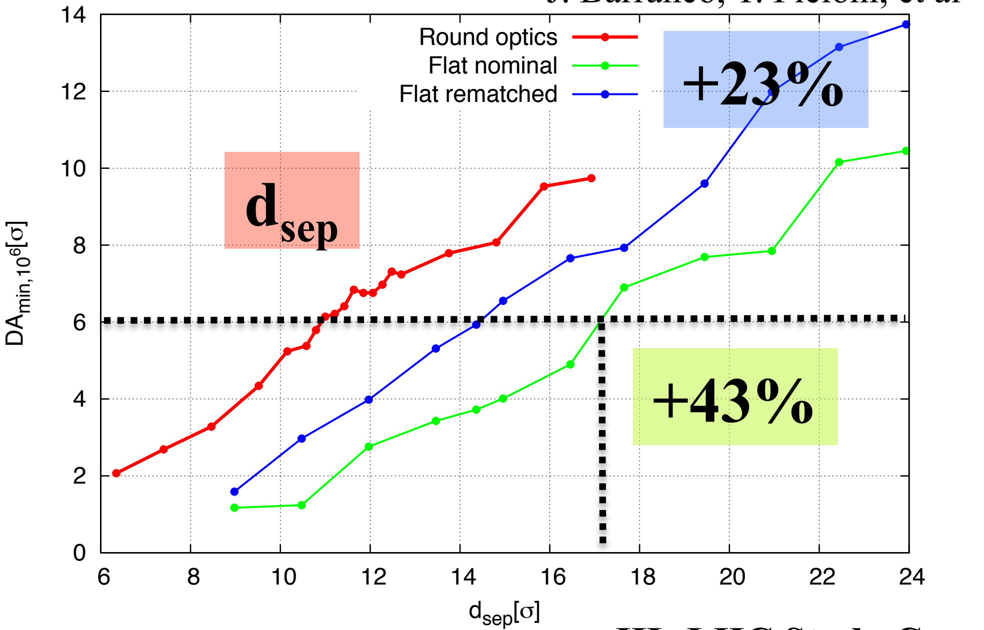
2 IPs only shows the need for 200μrad

Beam-beam alternatives DA

- **Alternatives: Flat optics are normally investigated assuming same normalized separation**
- **Flat optics for bunch trains need larger normalized separations!**



J. Barranco, T. Pieloni, et al



HL-LHC Study Case

DA loss can partially be compensated with tune corrections but not all!

Conclusions and outlook-1

The current tentative design of EIR is consistent with the overall FCC-hh design and its performance goals. In particular, we reiterate that:

- The separation of the points with experiments A, B and L is large enough to avoid significant background from one experiment into the other.
- The power deposited by SR in the experimental beam pipe is in the order of 1 W, which is considered negligible.
- Preliminary designs of the low luminosity EIR have been made matching the newly proposed collider layouts. Their luminosity is limited by β^* and the envisaged triplet shielding adequate for providing triplet survivability for luminosity ten times below that of the main EIR.
- The main EIR length can be made to be 1400 m significantly decreasing the operational margins and flexibility. In particular the final quadrupoles might only survive one 5-year run, while with 1500 m three runs are at reach. This has an effect on the eventual choice of L* and also motivates R&D to develop materials more resilient to radiation.

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- **The inner triplet design respects the manufacturing and installation requirements of the max length of quads 15 m and min separation of 2 m. These constraints affect the operational margins and triplet lifetime. It is important to explore further the margins on these values.**
- **The field quality of the final focusing triplets strongly affects the achievable DA and requires accurate corrections with dedicated coils, challenging machine operational phases before corrections are applied. It should be explored if better field quality can be achieved. Reducing L* even by 10% will have great benefits in terms of field quality tolerances, operational margins and triplet lifetime.**
- **Beams are separated in the common beam-pipe with a half crossing angle of about 90 μrad. This is assessed sufficient but without considering the impact from the triplet non-linearities, octupoles and RFQs for Landau damping and the low luminosity experiments**
- **Crab cavities are foreseen, which require 20 m of space.**
- **Alternative operational scenarios w/o crab cavities, using flat beams, have shown to yield integrated luminosity very close to the design goal but Beam-beam studies highlights limitations in the achievable separations**

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Conclusions and outlook-3

- The presently chosen L* of 45 m is affecting the length of the EIR straight section (presently 1500 m for one of the EIR optics options, i.e. longer than 1400 m allocated).
- A longer insertion can be allocated, but would either require significant modifications of civil engineering, or would decrease the arc length, which requires to increase the field in magnets in the arcs – this increases their cost or eat up the margins.
- The value of L* is kept at 45 m to preserve the option of the dipole spectrometer in the detector, while the baseline detector is smaller and may use shorter L*. Thus, keeping the option of dipole spectrometer in detector increases the cost of arc magnets. Dropping the option of dipole spectrometer, and better use of EIR space in the detector hall (where each extra meter translates into the total EIR length with a multiplication factor of around fifteen), may allow some reduction of L*, reduction of length of FF and reducing the risks for arcs and arc magnets.
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