Designing the interaction regions of the upgrades of the LHC

Emilia Cruz

September 21, 2015

About me

Guadalajara, Mexico

About me

Guadalajara, Mexico

- **Bachelors degree:**
  National Autonomous University of Mexico, Science Faculty.

UNAM

- **Academic Stays:**

Berkeley

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

University of Maryland 1856

- **Project:**
  Studied resolution of the Cherenkov Camera of the CREAM (Cosmic Rays Energetics and Mass).

About me

- **Master's degree:**
  National Autonomous University of Mexico, Institute of Physics.

UNAM

- **Academic Stays:**

- **Project:**
  Study of two different resonances ρ and φ in proton-proton collisions.

About me

- **PhD/ Marie Curie Fellowship**

UNIVERSITY OF LIVERPOOL

OPAC

The Cockcroft Institute of Accelerator Science and Technology

- **Academic Stays:**

CERN

- **Project:**

Effects of high luminosity collisions in the upgrades of the large hadron collider.

High Luminosity LHC

LHeC

About me

- **Postdoc**

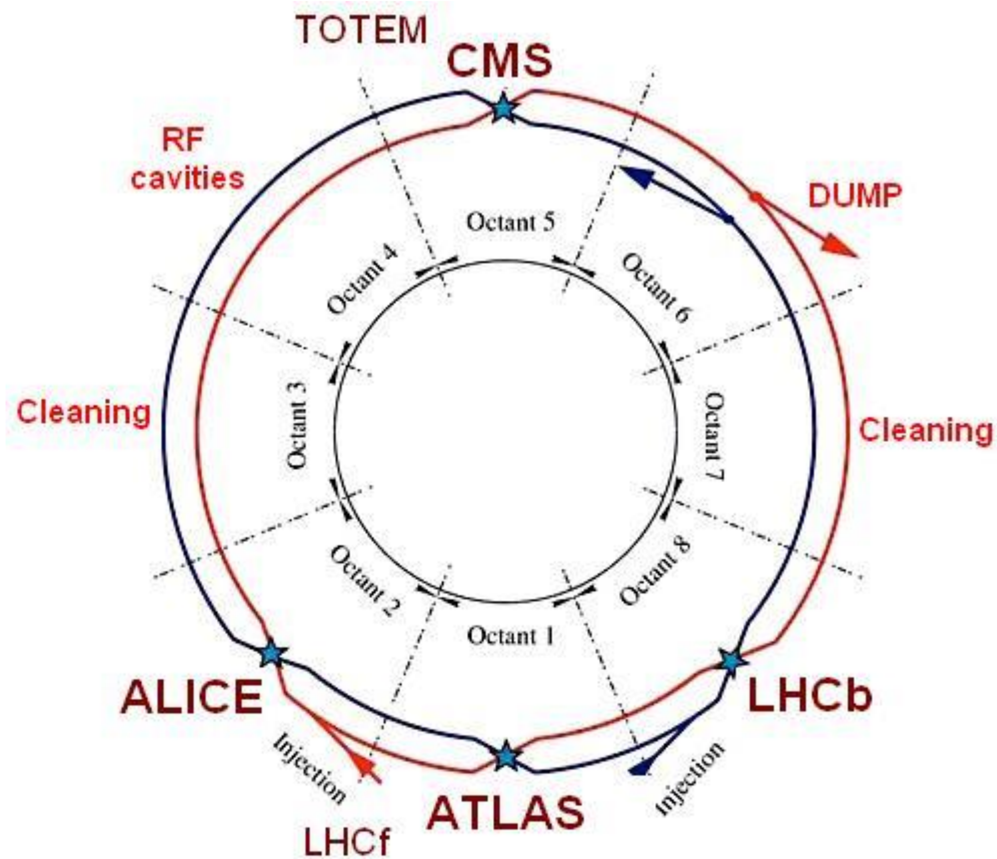
University of Oxford, JAI

- **Project:**

Contribute to the design of the IR optics for the FCC-hh project.

LHC Upgrade Program

The LHC has been providing hadron collisions since 2009 taking particle physics to a new era of Energy and Luminosity.

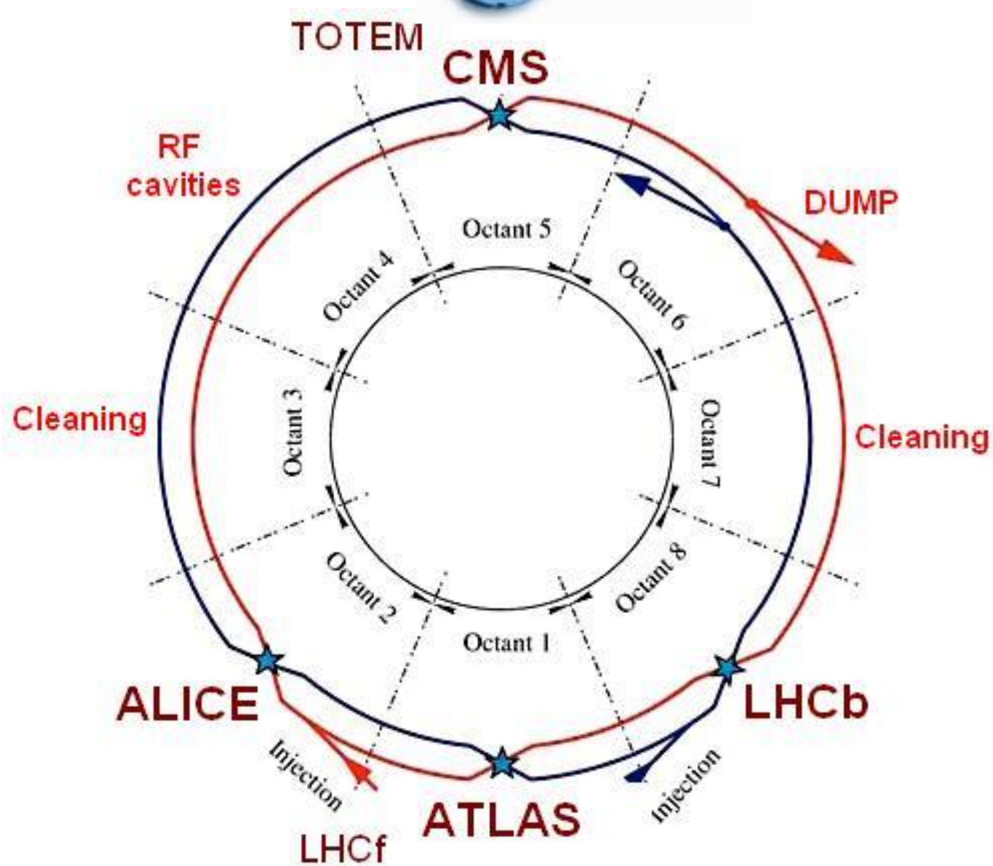


What are the next stages?

LHC Upgrade Program

High Luminosity LHC

Increase Luminosity(5×10^{34} $cm^{-2}s^{-1}$) in IP1 (ATLAS) and IP5 (CMS)

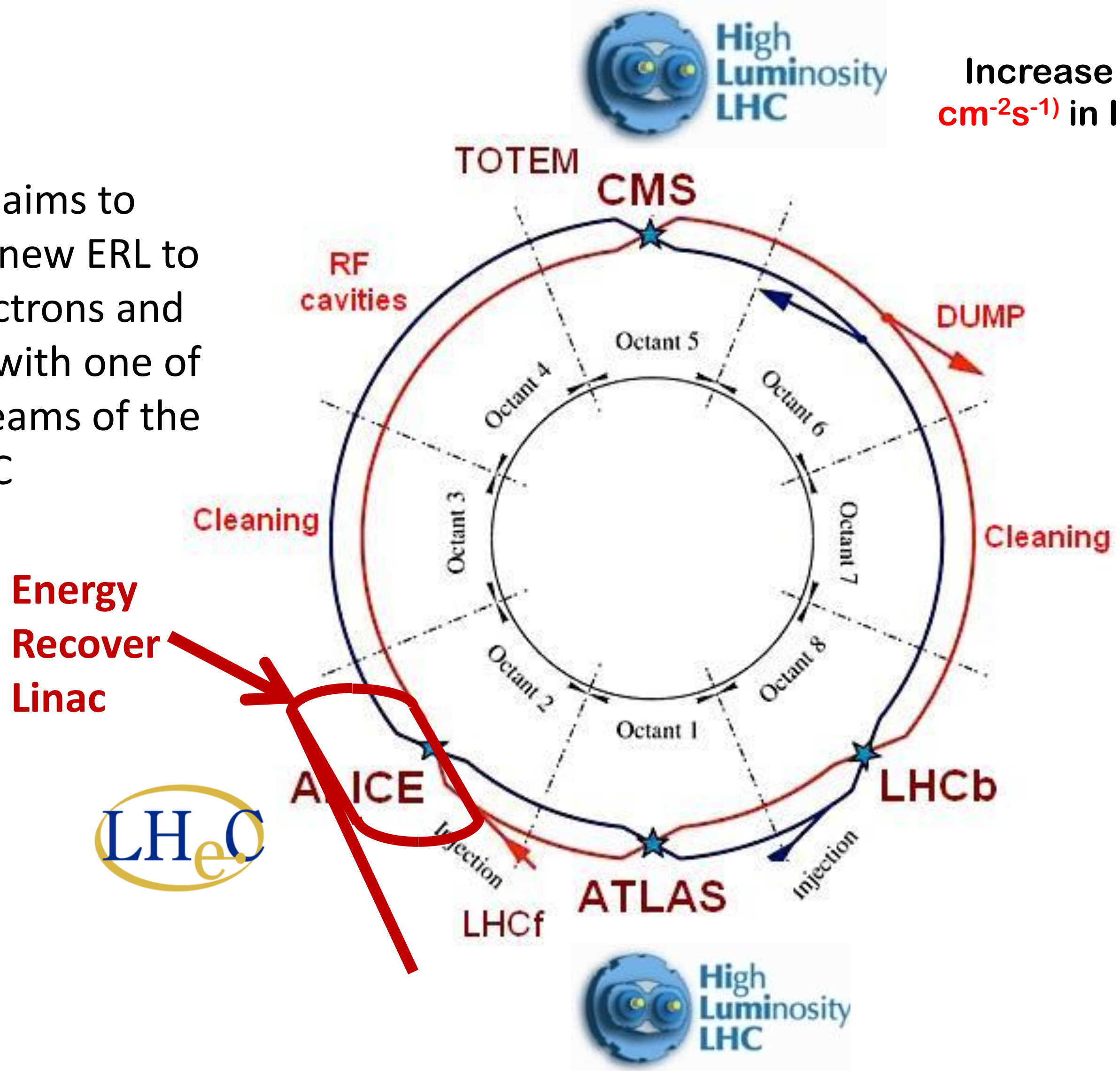


High Luminosity LHC

LHC Upgrade Program

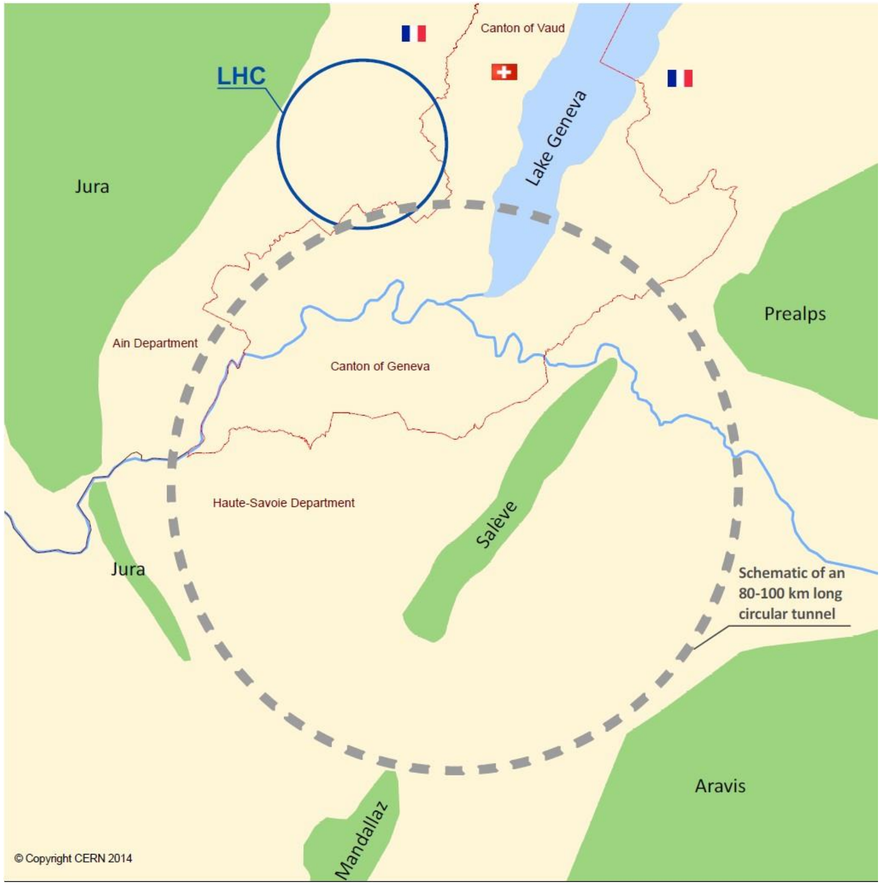
Increase Luminosity($5x10^{34}$ $cm^{-2}s^{-1}$) in IP1 (ATLAS) and IP5 (CMS)

The LHeC aims to implement a new ERL to circulate electrons and collide them with one of the proton beams of the LHC



LHC Upgrade Program

The FCC-hh project aims to construct a new 100 km tunnel and use the LHC as injector to have pp collisions with a **center-of-mass energy up to 100 TeV**.



Challenges in IR design

Designing an interaction region is an important part of the design of any particle collider. Beams are brought to a focus with small beam sizes and restrictions are given from both the accelerator and the detector.

Challenges in IR designs

Designing an interaction region is an important and challenging objective in the development of any particle collider. Beams are brought to a focus with small beam sizes and restrictions are given from both the accelerator and the detector.

High Luminosity LHC

Established design
High Beta functions in the IT
Do fringe fields have a bigger effect?

Challenges in IR designs

Designing an interaction region is an important and challenging objective in the development of any particle collider. Beams are brought to a focus with small beam sizes and restrictions are given from both the accelerator and the detector.

Established design
High Beta functions in the IT
Do fringe fields have a bigger effect?

New design in an IR design for a different type of collisions and range of energy.
Can we increase the luminosity? Reduce the SR?
Chromaticity Correction?

Challenges in IR designs

Designing an interaction region is an important and challenging objective in the development of any particle collider. Beams are brought to a focus with small beam sizes and restrictions are given from both the accelerator and the detector.

High Luminosity LHC

Established design
High Beta functions in the IT
Do fringe fields have a bigger effect?

LHeC

New design in an IR design for a different type of collisions and range of energy.
Can we increase the luminosity? Reduce the SR?
Chromaticity Correction?

FCC hh ee he

Flexibility in a design, find the best option.
Unprecedented energies

Interaction Region

General design of the IR in the LHC consist of 26 quadrupoles and 2 separation/recombination dipoles.

Interaction Region

General design of the IR in the LHC consist of 26 quadrupoles and 2 separation/recombination dipoles.

$$L = \frac{1}{4\pi e}\frac{N_{b,p}}{\varepsilon_p}\frac{1}{\beta_p^*} I_e H_{hg} H_D$$

Interaction Region

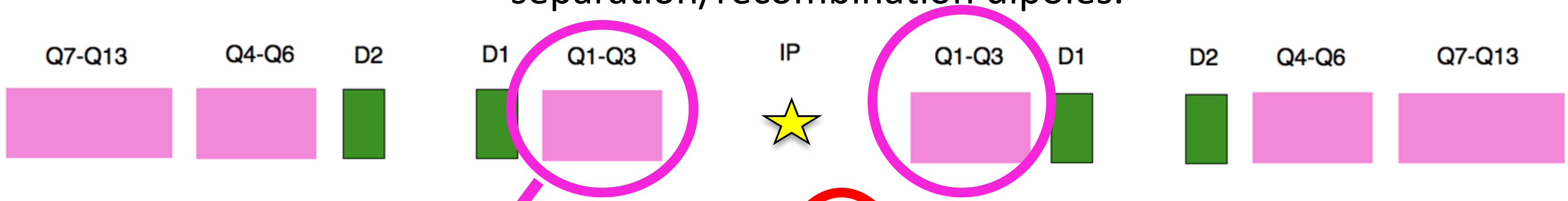
General design of the IR in the LHC consist of 26 quadrupoles and 2 separation/recombination dipoles.

$$L = \frac{1}{4\pi e}\frac{N_{b,p}}{\varepsilon_p}\frac{1}{\beta_p^*} I_e H_{hg} H_D$$

Luminosity inversely proportional to the size of the beam of the interaction point.

Increasing Luminosity

General design of the IR in the LHC consist of 26 quadrupoles and 2 separation/recombination dipoles.



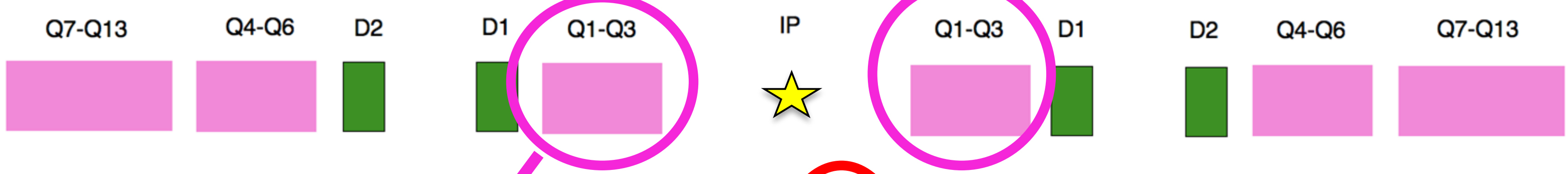
$$L = \frac{1}{4\pi e}\frac{N_{b,p}}{\varepsilon_p}\frac{1}{\beta_p^*} I_e H_{hg} H_D$$

FOCUSING. QUADRUPOLES. Implementation of new inner triplet Q1-Q3

Luminosity inversely proportional to the size of the beam of the interaction point.

Increasing Luminosity

General design of the IR in the LHC consist of 26 quadrupoles and 2 separation/recombination dipoles.



$$L = \frac{1}{4\pi e}\frac{N_{b,p}}{\varepsilon_p}\frac{1}{\beta_p^*} I_e H_{hg} H_D$$

FOCUSING. QUADRUPOLES. Implementation of new inner triplet Q1-Q3

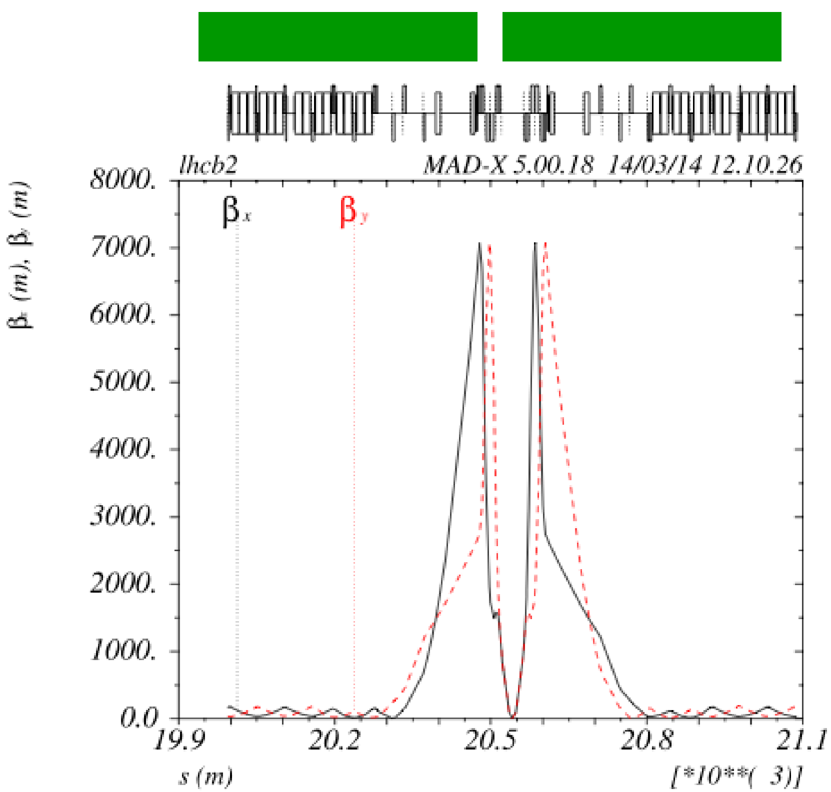
Luminosity inversely proportional to the size of the beam of the interaction point.

SEVERE LIMITATIONS

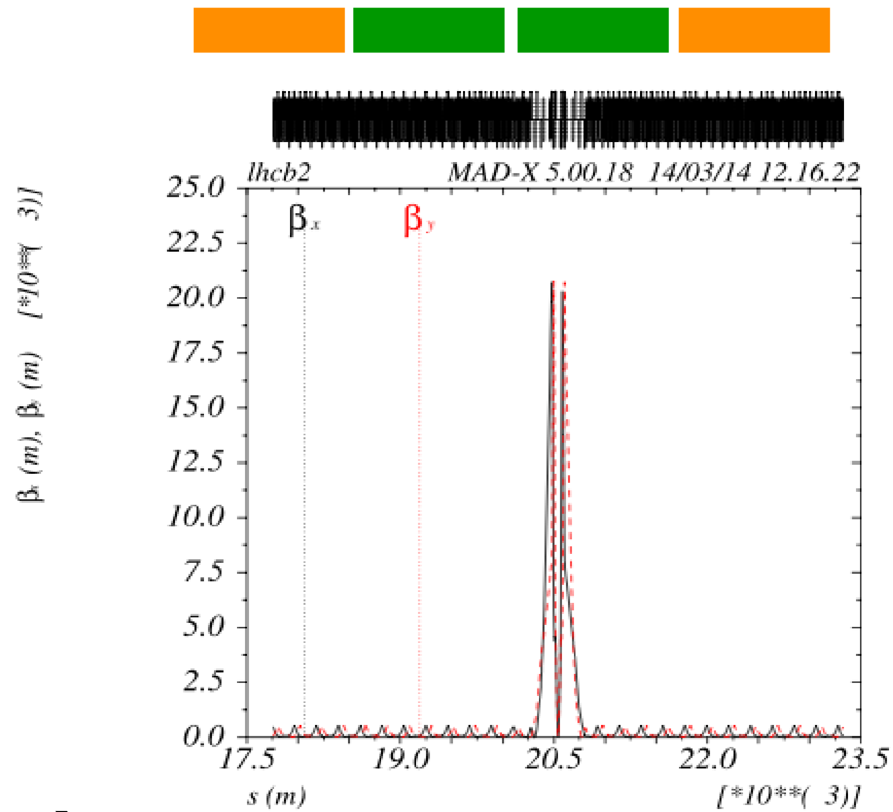
1. Quadrupole apertures
2. Quadrupole strengths
3. Efficiency of the chromatic correction

Achromatic Telescopic Squeezing Scheme (ATS) HL-LHC

IR5



IR4 arc IR5 arc IR6

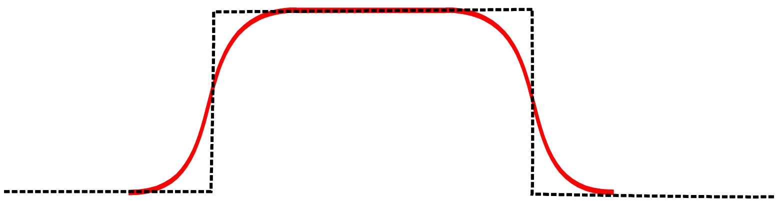


β^*=0.55 m → 0.15 m

Increases Beta function in location of sextupoles in arc

$$\xi^S_{x,y} = -\frac{1}{4\pi}\oint \mp\beta_{x,y}(s)S(s)D_x(s)ds$$

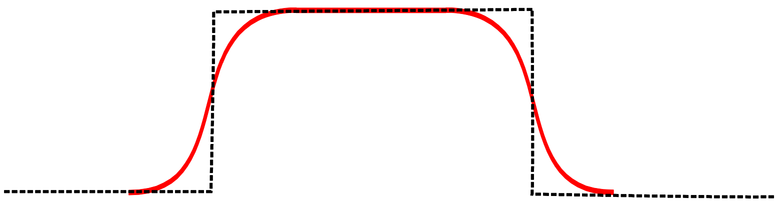
Integration of Fringe Fields



Challenges

- Previous studies have not taken into account the fringe fields. In particular dynamic aperture studies have been done with a thin version of the lattice.
- New quadrupoles have higher gradients and higher apertures. Fringe fields effects are expected to be more significant.

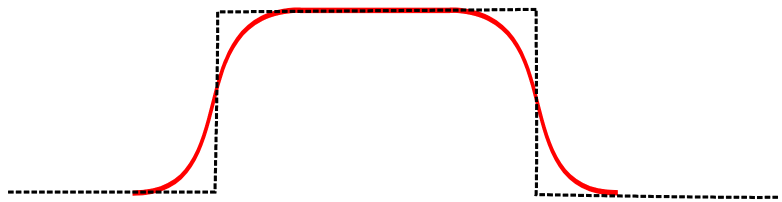
Integration of Fringe Fields



Fringe Field Studies:

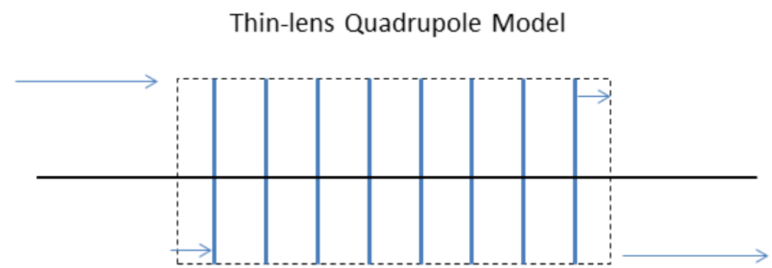
1. Model Fringe Fields.
2. Obtain Transfer Maps
3. Implement fringe field element using SAMM code

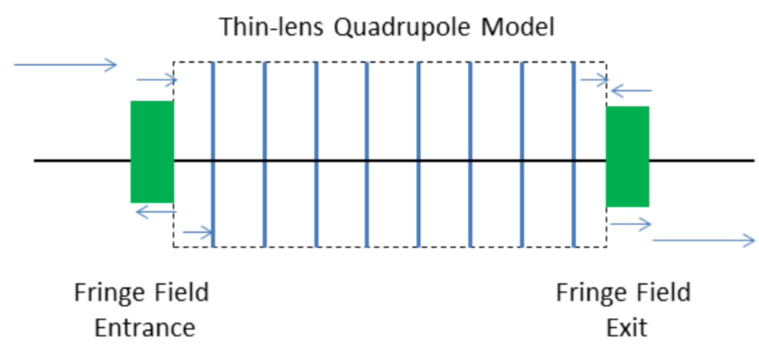
Integration of Fringe Fields



Fringe Field Studies:

1. Model Fringe Fields.
2. Obtain Transfer Maps
3. Implement fringe field element using SAMM code

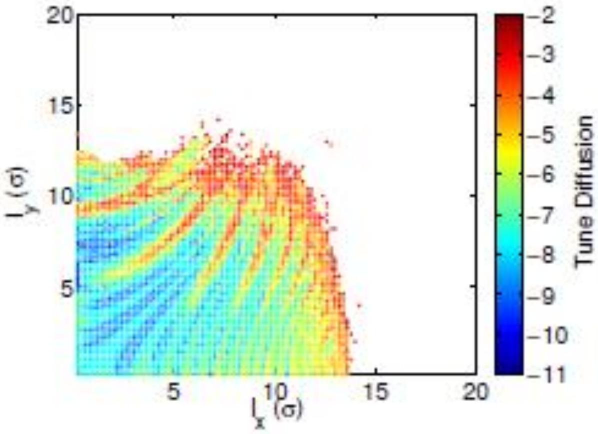


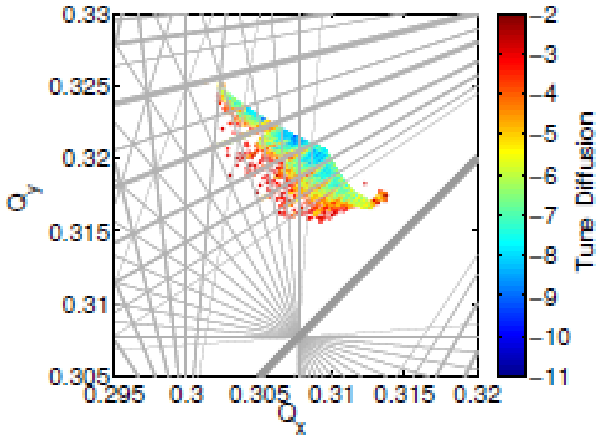


Integration of Fringe Fields

Measure effects of fringe fields via Frequency Map Analysis (FMA): Studying variation of the tunes over a certain number of turns.

$$D = \log_{10} \sqrt{(\Delta Q_x)^2 + (\Delta Q_y)^2}.$$

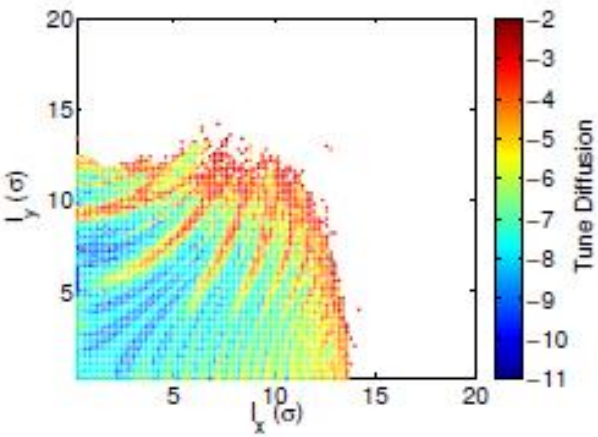


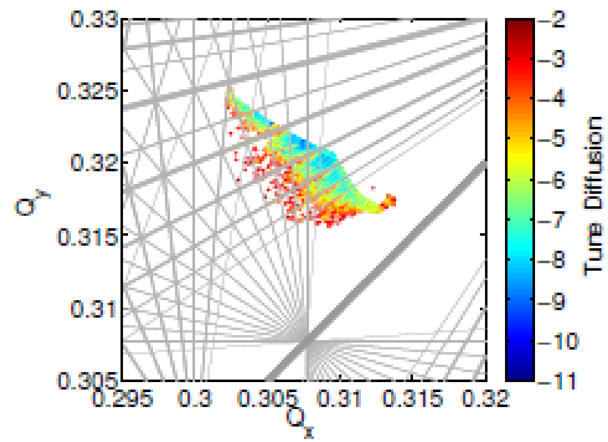


Integration of Fringe Fields

Measure effects of fringe fields via Frequency Map Analysis (FMA): Studying variation of the tunes over a certain number of turns.

$$D = \log_{10} \sqrt{(\Delta Q_x)^2 + (\Delta Q_y)^2}.$$

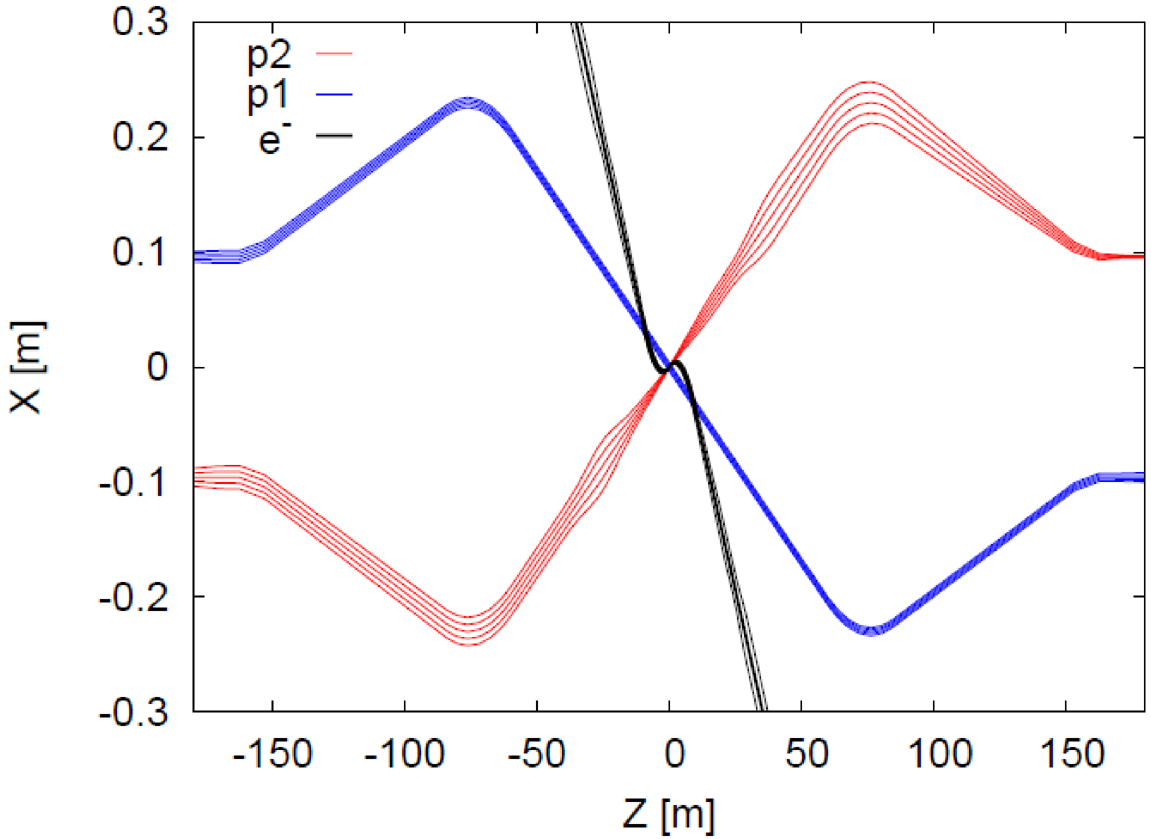




Results of fringe fields: change in dynamics for particles with large dynamic aperture, but no reduction in dynamic aperture (stable zone).

LHeC IR

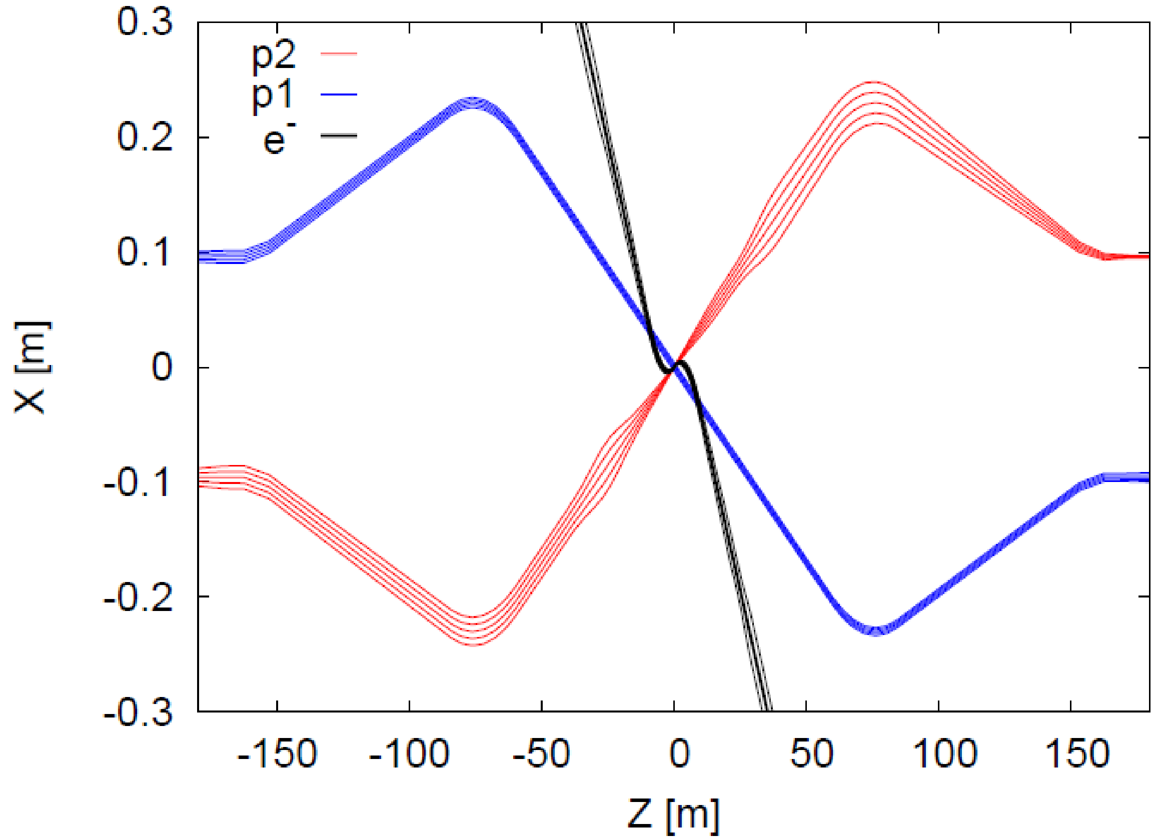
Focus one of the proton beams and collide it with the electron beam while the other proton beam bypasses the interaction.



Non-focused proton beam through free field aperture of (new) inner triplet.
Focus proton beam 2 → minimize β* (current value in IR2 10 m)

LHeC IR

Focus one of the proton beams and collide it with the electron beam while the other proton beam bypasses the interaction.

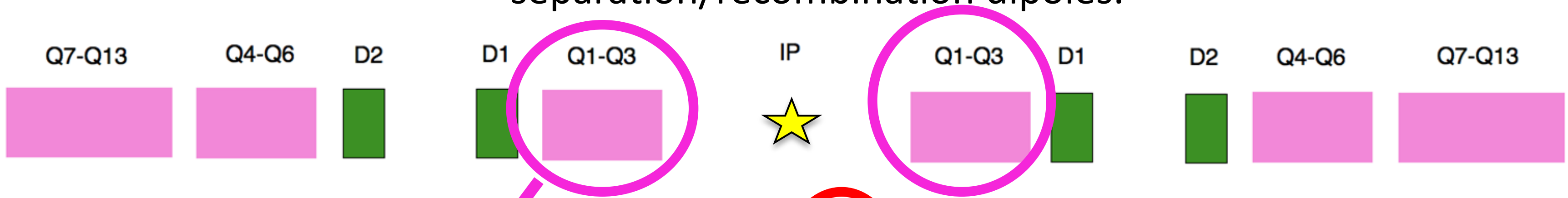


Non-focused proton beam through free field aperture of (new) inner triplet.

Focus proton beam 2 → minimize β* (current value in IR2 10 m)

LHeC IR

General design of the IR in the LHC consist of 26 quadrupoles and 2 separation/recombination dipoles.



$$L = \frac{1}{4\pi e}\frac{N_{b,p}}{\varepsilon_p}\frac{1}{\beta_p^*} I_e H_{hg} H_D$$

FOCUSING. QUADRUPOLES. Implementation of new inner triplet Q1-Q3

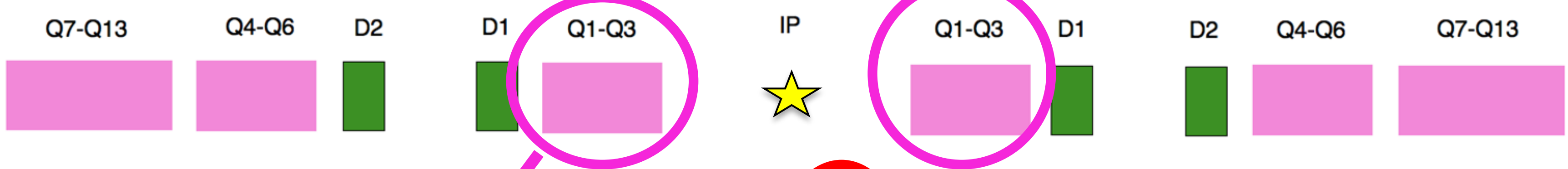
Luminosity inversely proportional to the size of the beam of the interaction point.

SEVERE LIMITATIONS

1. Quadrupole apertures
2. Quadrupole strengths
3. Efficiency of the chromatic correction

LHeC IR

General design of the IR in the LHC consist of 26 quadrupoles and 2 separation/recombination dipoles.



$$L = \frac{1}{4\pi e}\frac{N_{b,p}}{\varepsilon_p}\frac{1}{\beta_p^*} I_e H_{hg} H_D$$

FOCUSING. QUADRUPOLES. Implementation of new inner triplet Q1-Q3

Luminosity in...
proporti...
th...

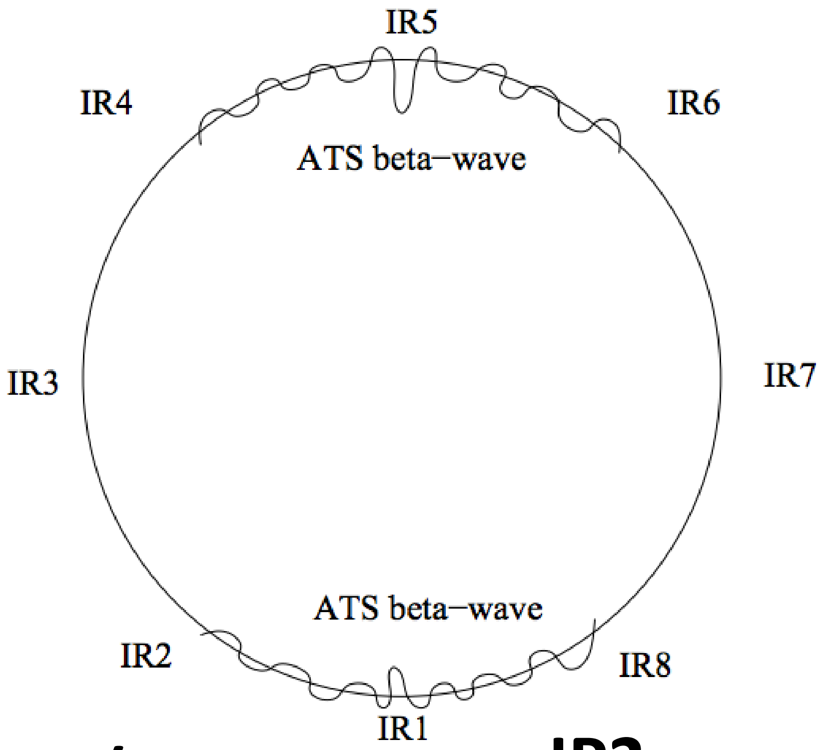
Repeat procedure of HL.
*New dipoles
*Magnets with free-field aperture

SEVERE ...

1. Quadru...
2. Quadrup...
3. Efficiency of the c... ...rection

Achromatic Telescopic Squeezing Scheme (ATS) HL-LHC+LHeC

HL-LHC



IP1/IP5

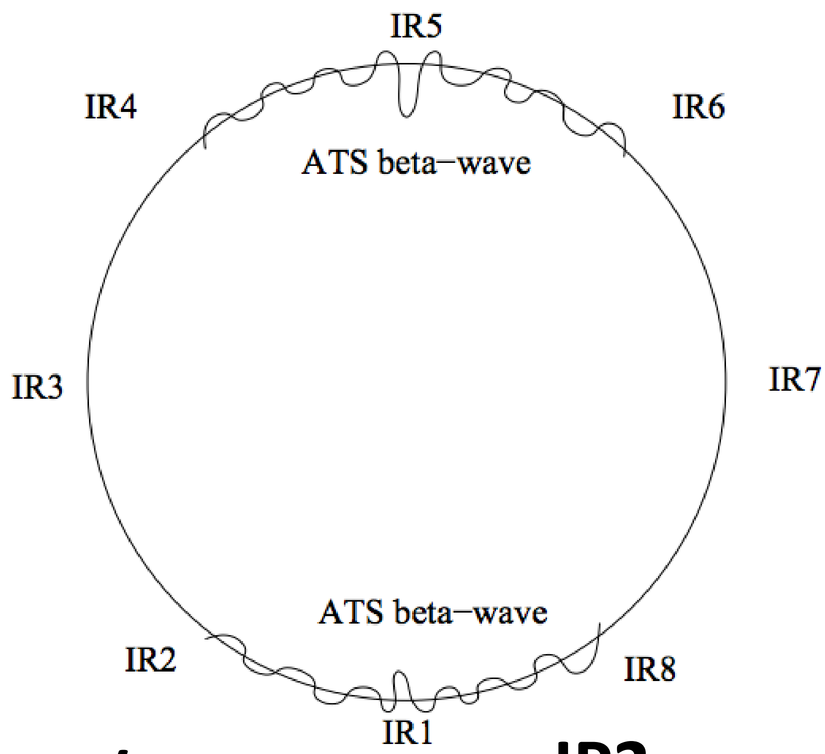
β^*=15 cm

IP2

β^*=10 m

Achromatic Telescopic Squeezing Scheme (ATS) HL-LHC+LHeC

HL-LHC



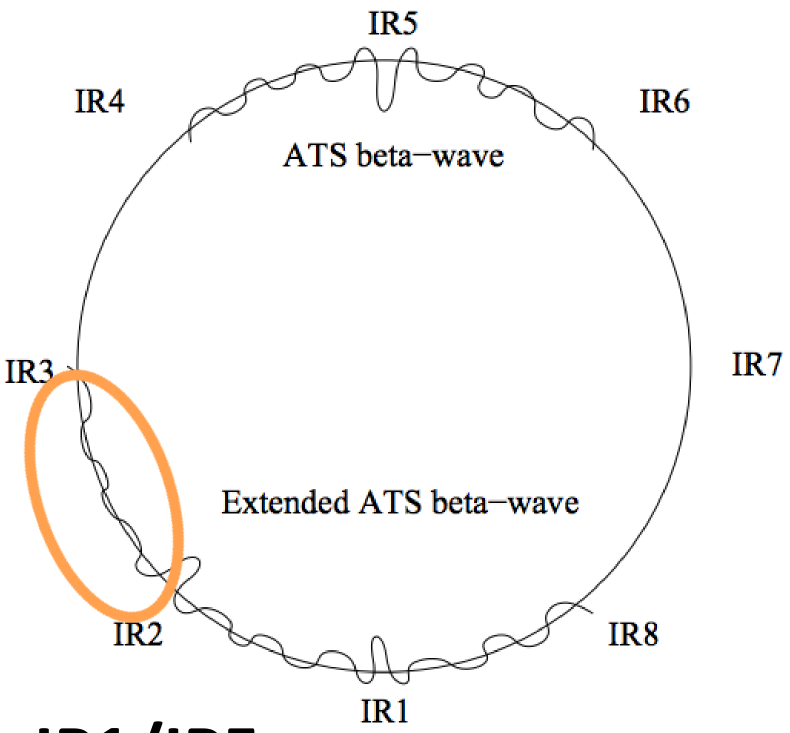
IP1/IP5

β*=15 cm

IP2

β*=10 m

HL-LHC + LHeC



IP1/IP5

β*=15 cm

IP2

β*=10 cm

Flexibility of the Design

	Disadvantages	Advantages	Cases found
Minimize β*	Increase **Chromatic Aberrations**	Increase **Luminosity**	**L*=10-20 m With β* fixed at 10 cm**
Increase L*	Increase **Chromatic Aberrations**	Minimize **Synchrotron Radiation**	**β*=5-10, 20 cm With L* fixed at 10 m**

Challenges Find the right balance between competing criteria. Where is the compromise?

Further studies, chromatic correction, synchrotron radiation, tracking studies.

Results in LHeC

- Optical Designs.
- Chromatic Correction
- Require nominal Luminosity
- Tracking studies
- SR and magnet design

L^* = 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20
β^*= 5, 6, 7, 8, 9, 10, 20

Results in LHeC

- Optical Designs.

  L^* = 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20
  β^*= 5, 6, 7, 8, 9, 10, 20

- Chromatic Correction

  L^* = 10, 11, 12, 13, 14, 15, 16, 17, 18, ~~19~~, ~~20~~
  β^*= 5, 6, 7, 8, 9, 10, 20

- Require nominal Luminosity

- Tracking studies

- SR and magnet design

Results in LHeC

- Optical Designs.

  L* = 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20
  β*= 5, 6, 7, 8, 9, 10, 20

- Chromatic Correction

  L* = 10, 11, 12, 13, 14, 15, 16, 17, 18, ~~19~~, ~~20~~
  β*= 5, 6, 7, 8, 9, 10, 20

- Require nominal Luminosity

  L* = 10, 11, 12, 13, 14, 15, 16, 17, 18, ~~19~~, ~~20~~
  β*= ~~5~~, ~~6~~, ~~7~~, ~~8~~, ~~9~~, 10, ~~20~~

- Tracking studies

- SR and magnet design

Results in LHeC

- Optical Designs.
  L* = 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20
  β*= 5, 6, 7, 8, 9, 10, 20
- Chromatic Correction
  L* = 10, 11, 12, 13, 14, 15, 16, 17, 18, ~~19~~, ~~20~~
  β*= 5, 6, 7, 8, 9, 10, 20
- Require nominal Luminosity
  L* = 10, 11, 12, 13, 14, 15, 16, 17, 18, ~~19~~, ~~20~~
  β*= ~~5~~, ~~6~~, ~~7~~, ~~8~~, ~~9~~, 10, ~~20~~
- Tracking studies
  L* = 10, 11, 12, 13, 14, 15, ~~16~~, ~~17~~, ~~18~~, ~~19~~, ~~20~~
  β*= ~~5~~, ~~6~~, ~~7~~, ~~8~~, ~~9~~, 10, ~~20~~
- SR and magnet design

Results in LHeC

- Optical Designs.
  L* = 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20
  β*= 5, 6, 7, 8, 9, 10, 20
- Chromatic Correction
  L* = 10, 11, 12, 13, 14, 15, 16, 17, 18, ~~19~~, ~~20~~
  β*= 5, 6, 7, 8, 9, 10, 20
- Require nominal Luminosity
  L* = 10, 11, 12, 13, 14, 15, 16, 17, 18, ~~19~~, ~~20~~
  β*= ~~5~~, ~~6~~, ~~7~~, ~~8~~, ~~9~~, 10, ~~20~~
- Tracking studies
  L* = 10, 11, 12, 13, 14, 15, ~~16~~, ~~17~~, ~~18~~, ~~19~~, ~~20~~
  β*= ~~5~~, ~~6~~, ~~7~~, ~~8~~, ~~9~~, 10, ~~20~~
- SR and magnet design
  L* = ~~10~~, ~~11~~, ~~12~~, ~~13~~, 14, 15, ~~16~~, ~~17~~, ~~18~~, ~~19~~, ~~20~~
  β*= ~~5~~, ~~6~~, ~~7~~, ~~8~~, ~~9~~, 10, ~~20~~

β*=10 cm L*=14-15 m

Results in LHeC

- Optical Designs.

  L* = 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20
  β*= 5, 6, 7, 8, 9, 10, 20

- Chromatic Correction

  L* = 10, 11, 12, 13, 14, 15, 16, 17, 18, ~~19~~, ~~20~~
  β*= 5, 6, 7, 8, 9, 10, 20

- Require nominal Luminosity

  L* = 10, 11, 12, 13, 14, 15, 16, 17, 18, ~~19~~, ~~20~~
  β*= ~~5~~, ~~6~~, ~~7~~, ~~8~~, ~~9~~, 10, ~~20~~

- Tracking studies

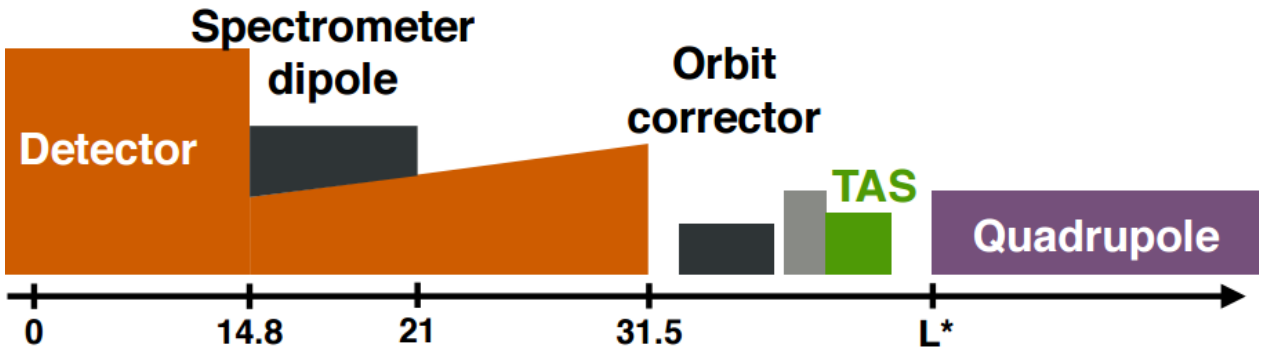
  L* = 10, 11, 12, 13, 14, 15, ~~16~~, ~~17~~, ~~18~~, ~~19~~, ~~20~~
  β*= ~~5~~, ~~6~~, ~~7~~, ~~8~~, ~~9~~, 10, ~~20~~

- SR and magnet design

  L* = ~~10~~, ~~11~~, ~~12~~, ~~13~~, 14, 15, ~~16~~, ~~17~~, ~~18~~, ~~19~~, ~~20~~
  β*= ~~5~~, ~~6~~, ~~7~~, ~~8~~, ~~9~~, 10, ~~20~~

β*=10 cm
L*=14-15 m

FCC IR



Choose parameters:

Options L*= 36, 45 and 61 m. L*= 45 good compromise between detector requirements and keeping inner triplet “short”.

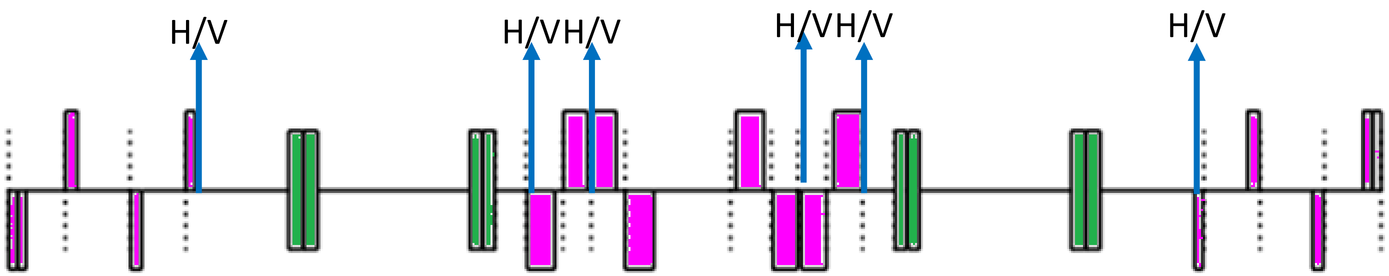
Options β*= 1,1 m (Baseline –not an issue), 0.3 m (Ultimate, reachable), 0.05 m limited by beam stay clear limitations.

Radiation load in the quadrupoles is the main driver. Shielding required inside the quadrupole reduces β* reach.

FCC Correction Scheme

Objectives of the correct Scheme:

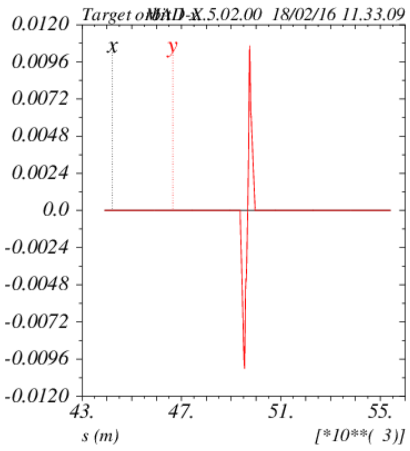
Control possible misalignments of the quadruples, field/tilt errors of the interaction region (in particular the IT, D1 and D2) while maintaining the crossing angle.



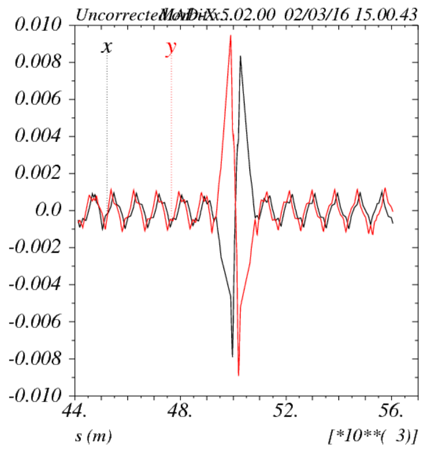
FCC Correction Scheme

The ideal corrected orbit would restore the original orbit in the presence of alignment errors by adjusting the strength of the correctors.

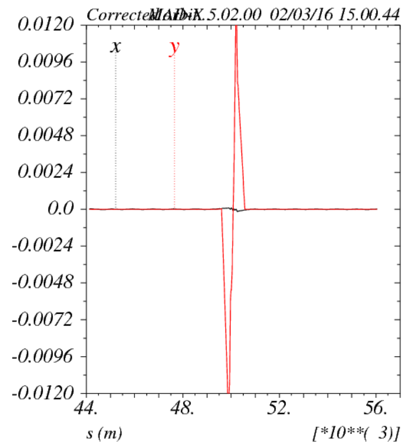
No errors



Added IT errors



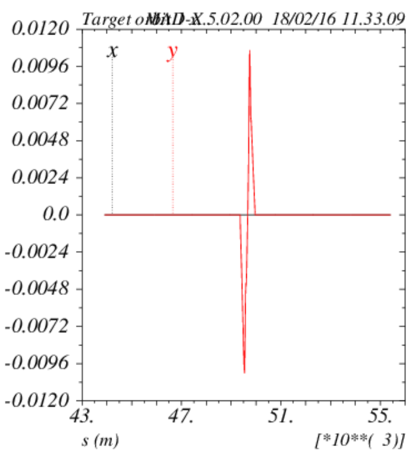
Correction



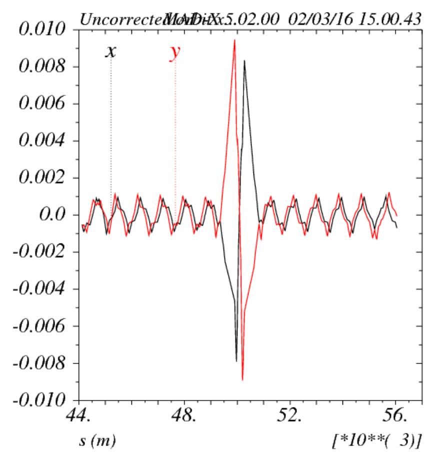
FCC Correction Scheme

The ideal corrected orbit would restore the original orbit in the presence of alignment errors by adjusting the strength of the correctors.

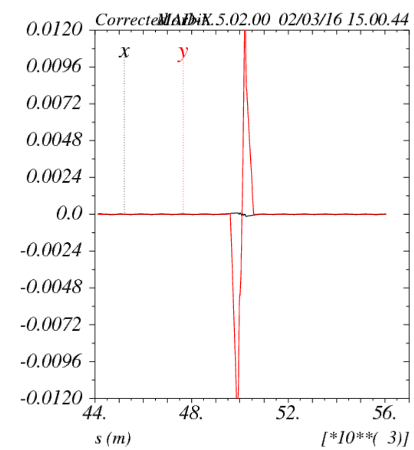
No errors



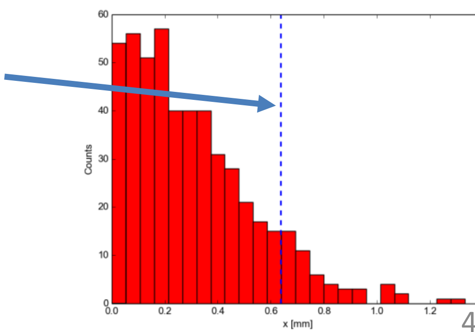
Added IT errors



Correction



1. Calculate maximum orbit deviation in IR after correction.
2. Repeat for 500 seeds
3. Calculate value of the maximum orbit deviation for which 90% of the seeds are included (x_{90})



Conclusions

- Designing an interaction region is an important objective of any new accelerator and often compromises must be made.
- The upgrades of the large hadron collider comes with further challenges, mainly driven by the unprecedented ranges of energy and luminosity.
  - Fringe Fields in the HL-LHC.
  - LHeC IR accomodated in previous IR2.
  - Correction Scheme for FCC.

Thank you!

e.cruz-alaniz@liverpool.ac.uk