The LHeC IR and its compatibility with the HL-LHC

EIC 14
March 20, 2014

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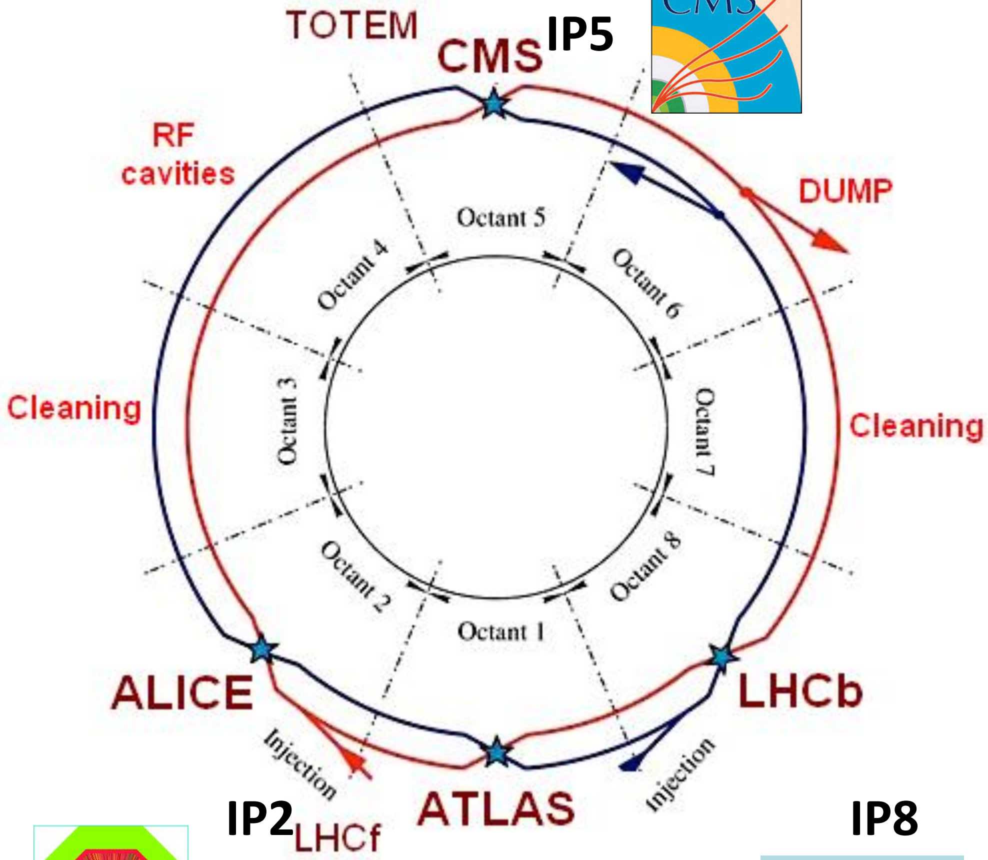
LHC Layout

- Total length 27 km.
- Located in the border between Switzerland and France.
- Providing collisions since 2008.
- 4 interaction points
- p-p √s=7 TeV
- Pb-Pb √s=2.76 TeV



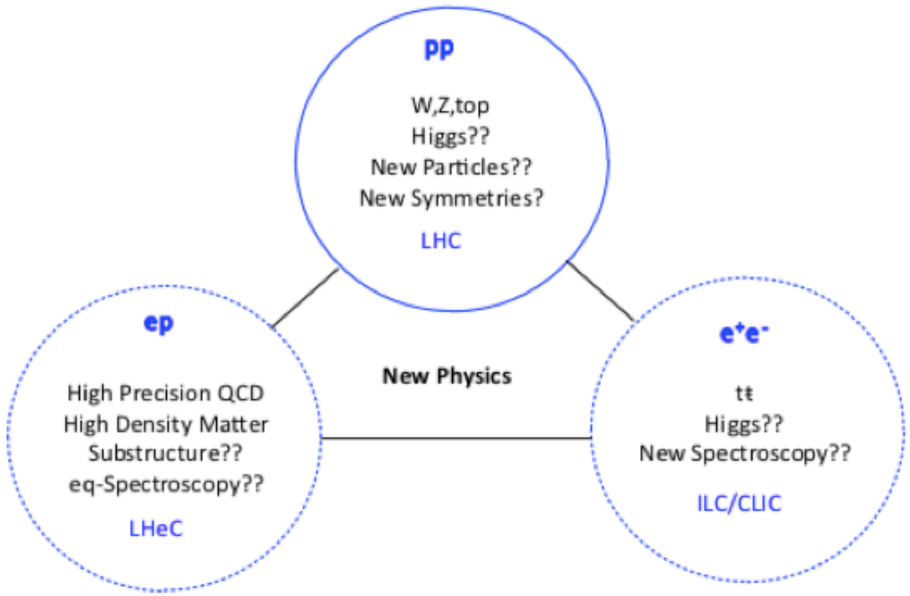
IP8

IP1

- **Upgrades?**

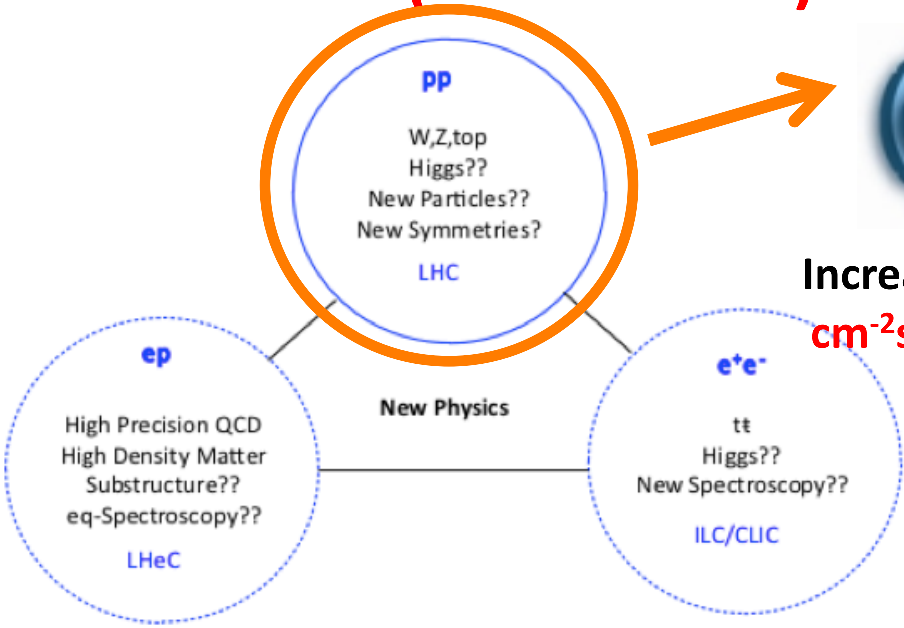
Upgrades LHC

TeV Scale (2010-2035..)



Upgrades LHC

TeV Scale (2010-2035..)



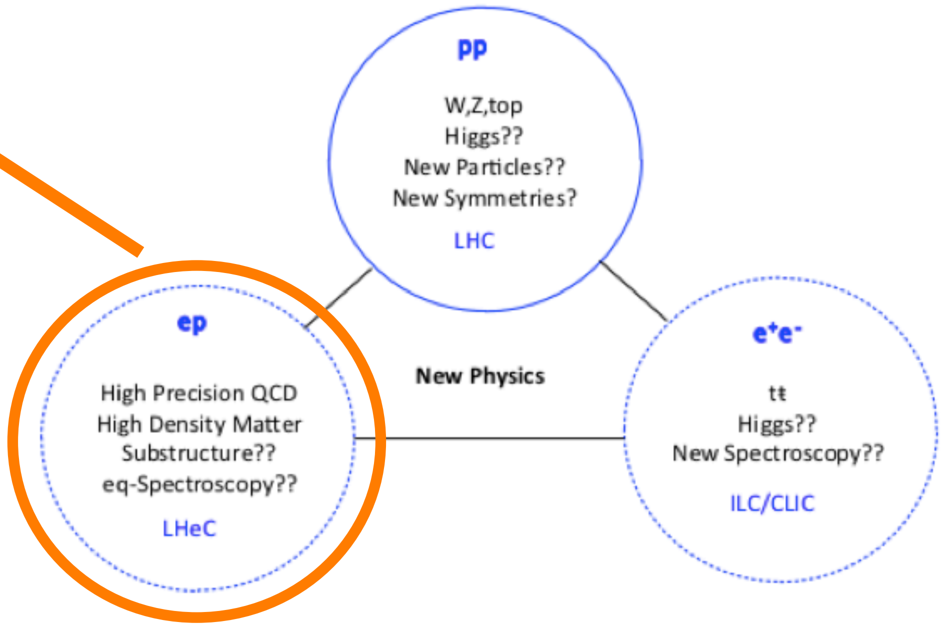
High Luminosity LHC

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

Upgrades LHC

TeV Scale (2010-2035..)

Energy ($\sqrt{s}$= 1.2 TeV) 4 times higher Luminosity (10^{33} $cm^{-2}s^{-1}$) 100 higher as HERA

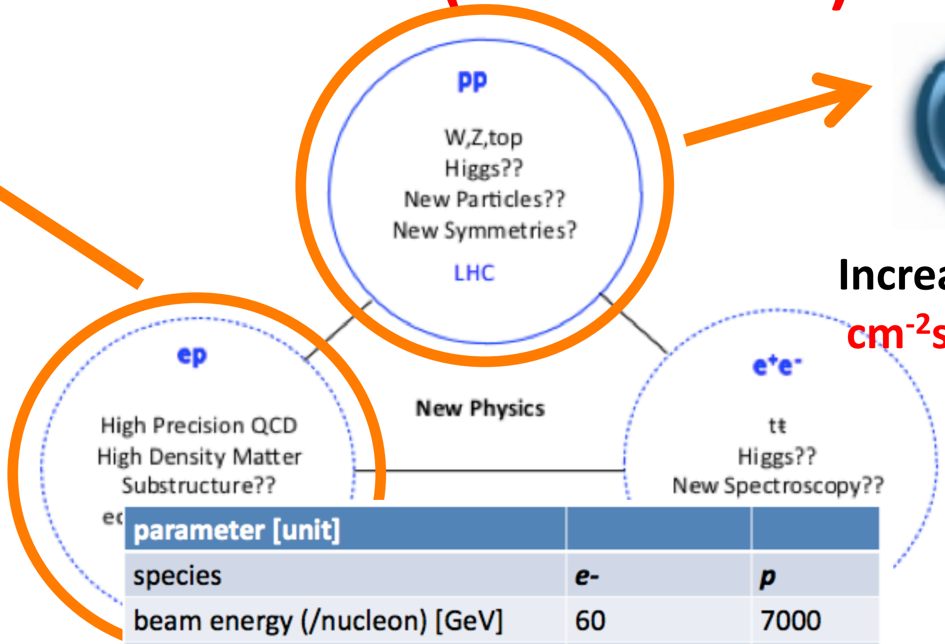


Upgrades LHC

TeV Scale (2010-2035..)

LHeC

Energy ($\sqrt{s}$= 1.2 TeV) 4 times higher Luminosity (10^{33} $cm^{-2}s^{-1}$) 100 higher as HERA

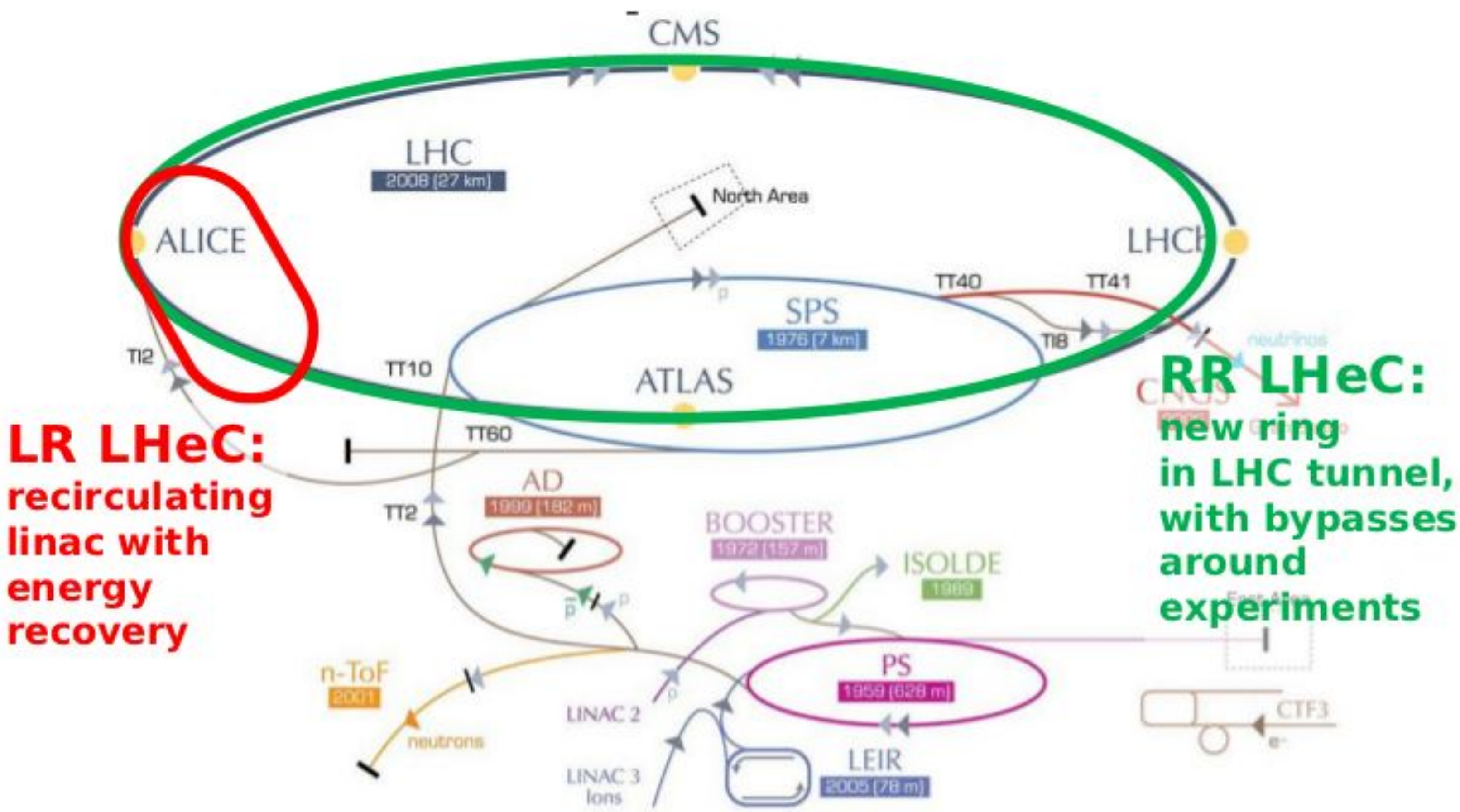


High Luminosity LHC

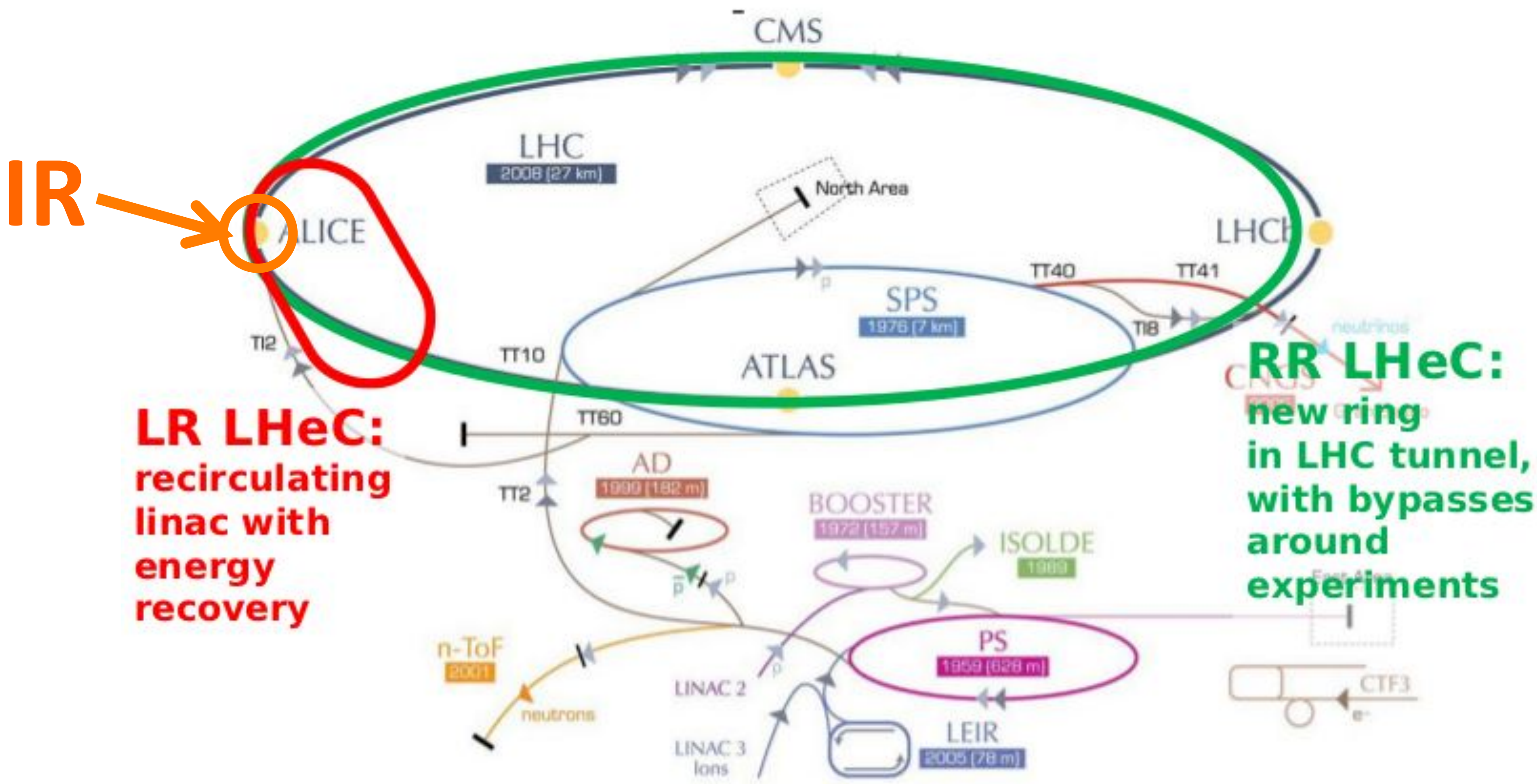
Increase Luminosity($5x10^{34}$ $cm^{-2}s^{-1}$) in IP1 (ATLAS) and IP5 (CMS)

parameter [unit]		
species	*e-*	*p*
beam energy (/nucleon) [GeV]	60	7000
bunch spacing [ns]	25 (50)	25 (50)
bunch intensity (nucleon) [10^{10}]	**0.1 (0.2)**	**17**
beam current [mA]	**6.4**	**860**
rms bunch length [mm]	**0.6**	**75.5**
polarization [%]	90	none
normalized rms emittance [μm]	50	3.75
geometric rms emittance [nm]	**0.43**	**0.50**
IP beta function $\beta_{x,y}$* [m]	**0.12**	**0.10**

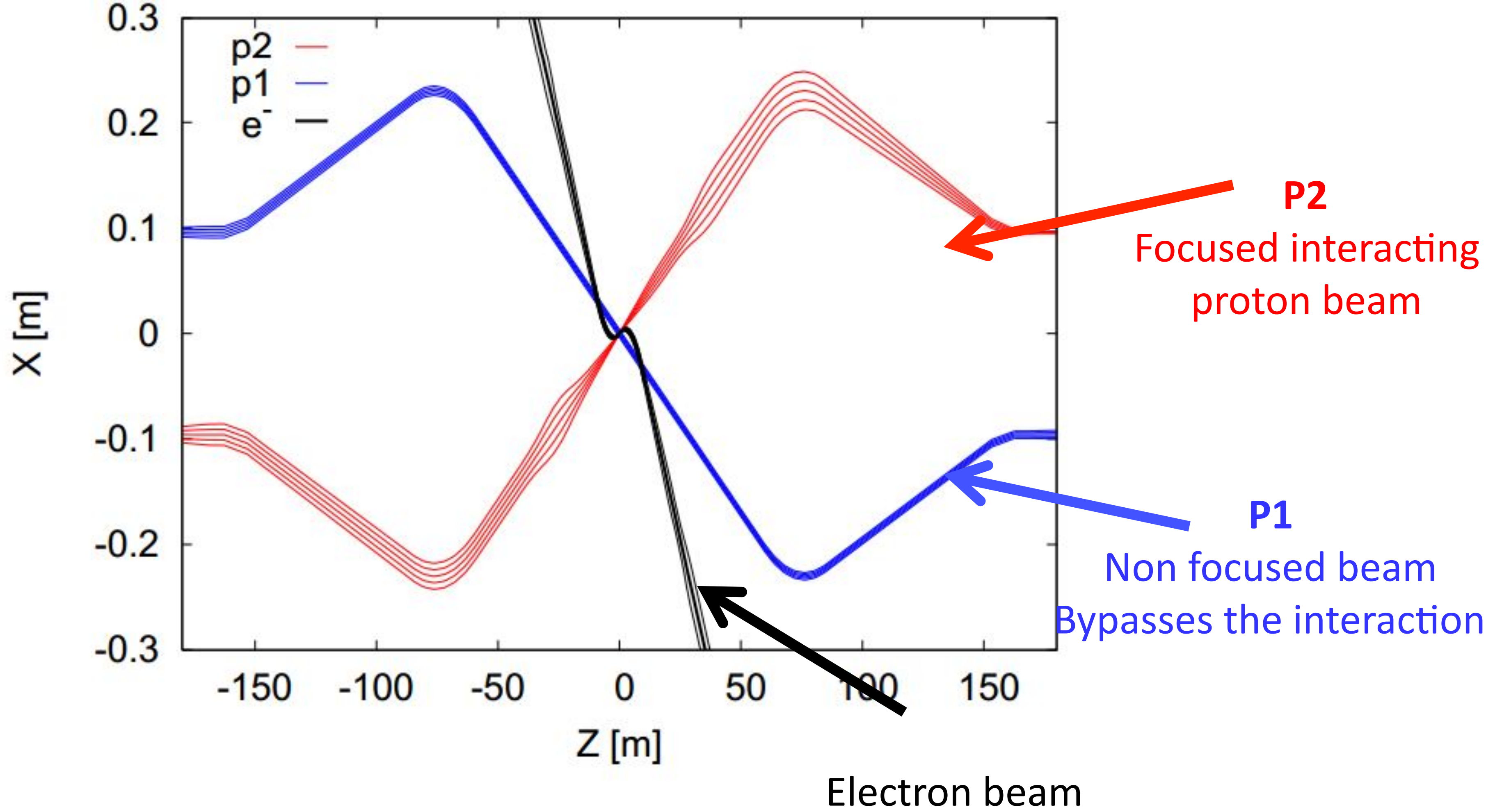
LHeC Design


CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
RR LHeC:
new ring
in LHC tunnel,
with bypasses
around
experiments
LR LHeC:
recirculating
linac with
energy
recovery
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
PS
1959 (628 m)
n-ToF
2001
neutrons
LINAC 2
LINAC 3
Ions
LEIR
2005 (78 m)
CTF3
e-

Linac-Ring LHeC IR

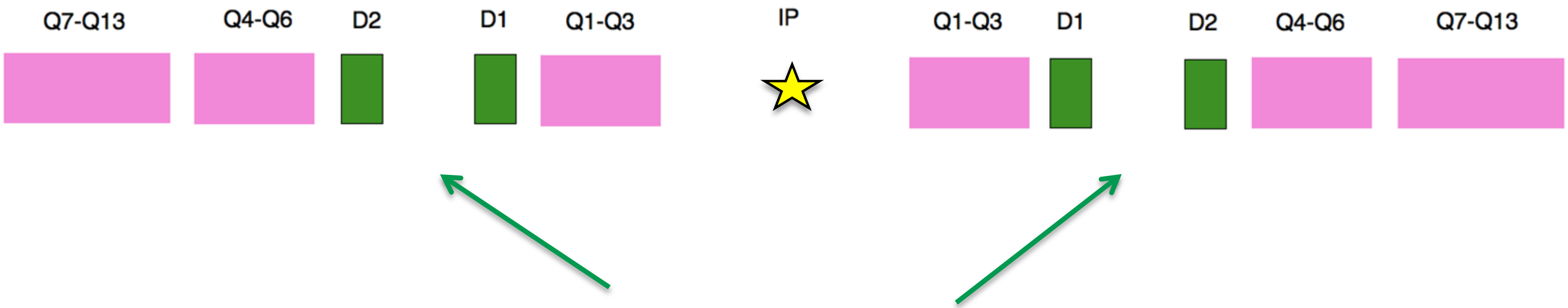


Interaction Region Design



Interaction Region Lattice

Interaction Region Lattice

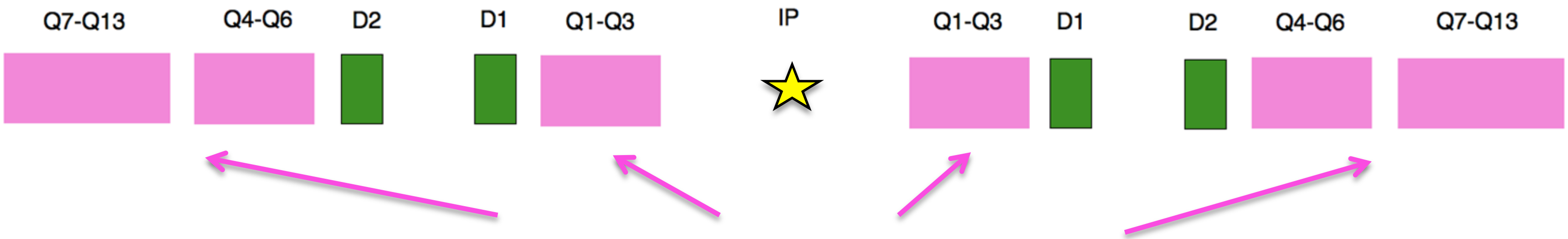


2 Recombination Dipoles

Change trajectory of proton beams

```
kd1.l2        := ad1.l2/l.mbx  ;
kd1.r2        := ad1.r2/l.mbx  ;
kd2.l2        := ad2.l2/l.mbrc ;
kd2.r2        := ad2.r2/l.mbrc ;
```

Interaction Region Lattice



26 Quadrupoles for each beam.
13 each side. 23 independent.
Focus proton beams

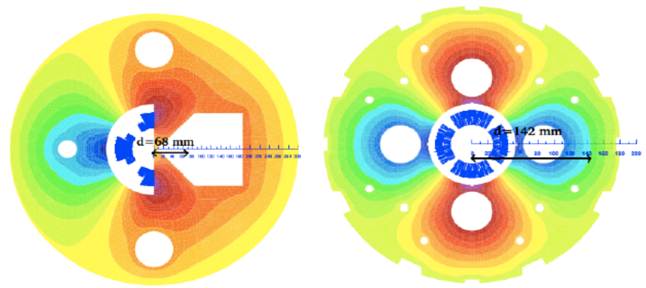
IT antisymmetric

```
KQX.L2      :=   0.877985714100E-02 ;
KTQX1.L2    :=   0.000000000000E+00 ;
KTQX2.L2    :=   0.000000000000E+00 ;
KQX.R2      :=             -KQX.L2   ;
KTQX1.R2    :=             -KTQX1.L2 ;
KTQX2.R2    :=             -KTQX2.L2 ;
```

```
 !Beam1
KQ4.L2B1     :=  -0.258592456320E-02 ;
KQ4.R2B1     :=   0.371540198462E-02 ;
KQ5.L2B1     :=   0.289870812115E-02 ;
KQ5.R2B1     :=  -0.364729424407E-02 ;
KQ6.L2B1     :=  -0.469531641707E-02 ;
KQ6.R2B1     :=   0.432365742510E-02 ;
KQ7.L2B1     :=   0.745357182830E-02 ;
KQ7.R2B1     :=  -0.640978067866E-02 ;
KQ8.L2B1     :=  -0.529525684936E-02 ;
KQ8.R2B1     :=   0.671971927152E-02 ;
KQ9.L2B1     :=   0.703623363164E-02 ;
KQ9.R2B1     :=  -0.651667220851E-02 ;
KQ10.L2B1    :=  -0.644030443578E-02 ;
KQ10.R2B1    :=   0.730142490022E-02 ;
KQTL11.L2B1 :=   0.294599974395E-03 ;
KQTL11.R2B1 :=  -0.711502410599E-04 ;
KQT12.L2B1  :=   0.208264468927E-02 ;
KQT12.R2B1  :=  -0.237270956314E-02 ;
KQT13.L2B1  :=   0.296816023135E-02 ;
KQT13.R2B1  :=  -0.206932585417E-02 ;
```

```
 !Beam2
KQ4.L2B2     :=   0.185133533486E-02 ;
KQ4.R2B2     :=  -0.309985129373E-02 ;
KQ5.L2B2     :=  -0.349664775637E-02 ;
KQ5.R2B2     :=   0.469937679927E-02 ;
KQ6.L2B2     :=   0.442385030629E-02 ;
KQ6.R2B2     :=  -0.370019633193E-02 ;
KQ7.L2B2     :=  -0.813254954261E-02 ;
KQ7.R2B2     :=   0.733992956089E-02 ;
KQ8.L2B2     :=   0.700517746627E-02 ;
KQ8.R2B2     :=  -0.560890926907E-02 ;
KQ9.L2B2     :=  -0.701852180932E-02 ;
KQ9.R2B2     :=   0.681308273586E-02 ;
KQ10.L2B2    :=   0.702844127608E-02 ;
KQ10.R2B2    :=  -0.525944973661E-02 ;
KQTL11.L2B2 :=   0.381920898127E-02 ;
KQTL11.R2B2 :=   0.399409216637E-03 ;
KQT12.L2B2  :=  -0.333493643883E-02 ;
KQT12.R2B2  :=  -0.194961708850E-02 ;
KQT13.L2B2  :=   0.278690239431E-03 ;
KQT13.R2B2  :=   0.482280250116E-02 ;
```

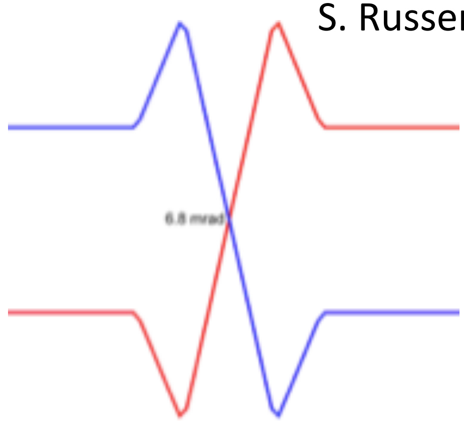
Changes IR2 Lattice



Q1 Q2

S. Russenschuck

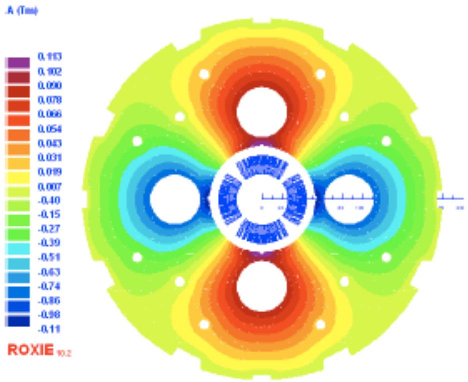
FOCUSING. QUADRUPOLES. Implementation of new inner triplet Q1-Q3 (L*=10 m) with normal (for P2) and field free holes (P1).

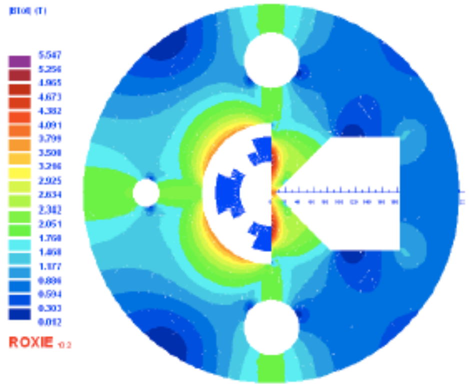


TRAJECTORY. DIPOLES. Inverse polarity of D1 and D2. D2 1.21 stronger. D1 3.43 Stronger to give crossing angle θ=6.8 mrad.

Magnets Q1 Q2

S. Russenschuck





Nb3Sn: 8600 A, 311 <T/m, at 83% LL

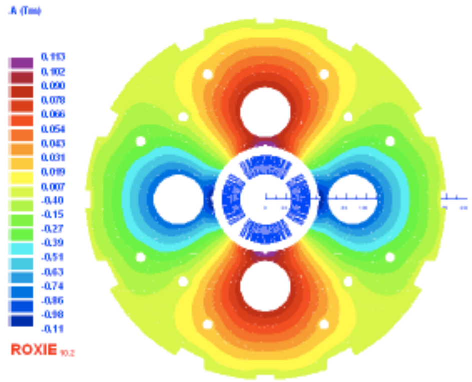
23 mm aperture
87 mm septum

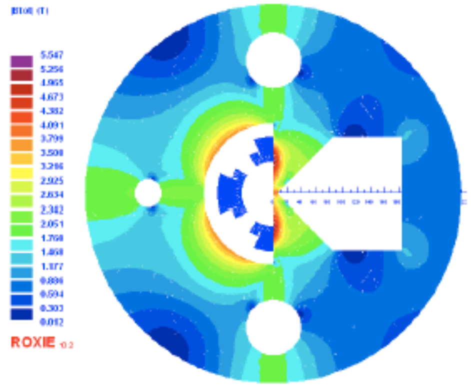
Nb3Sn: 5700 A, 175 T/m, 4.7 T at 8.2% on LL

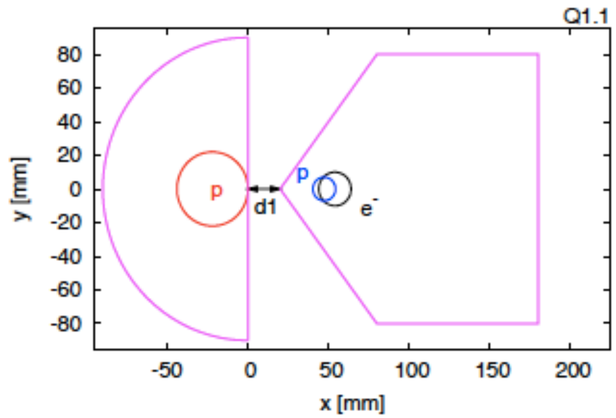
46 mm (half) aperture
63 mm septum

Magnets Q1 Q2

S. Russenschuck







Nb3Sn: 8600 A, 311 <T/m, at 83% LL

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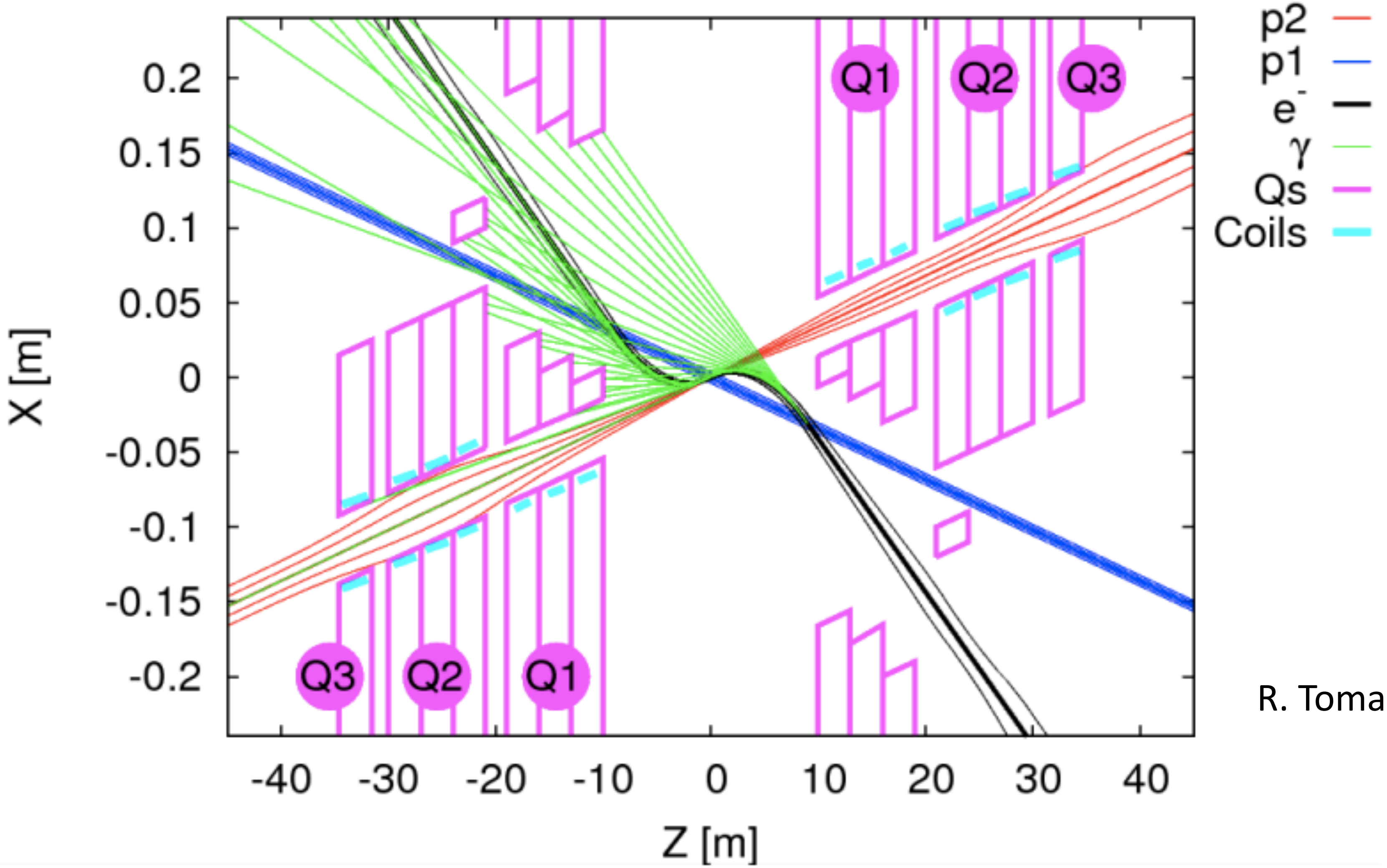
ZOOM IR2



R. Tomas

IR2 Optics

Towards Luminosity **$\geq 10^{33}$ cm^{-2}s^{-1}**

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

IR2 Optics

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

Minimize β* = More Luminosity!

$$\sigma_x = \sqrt{\epsilon\beta(s)}$$

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MADX

Vary	Constraints
Q1-Q13 in IR2	Twiss parameters IP2 and ends of IR2

$\longrightarrow$ ***β^*=0.3 m***

IR2 Optics

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Minimize β* = More Luminosity!

$$\sigma_x = \sqrt{\epsilon\beta(s)}$$

MADX

Vary	**Constraints**
Q1-Q13 in IR2	Twiss parameters IP2 and ends of IR2

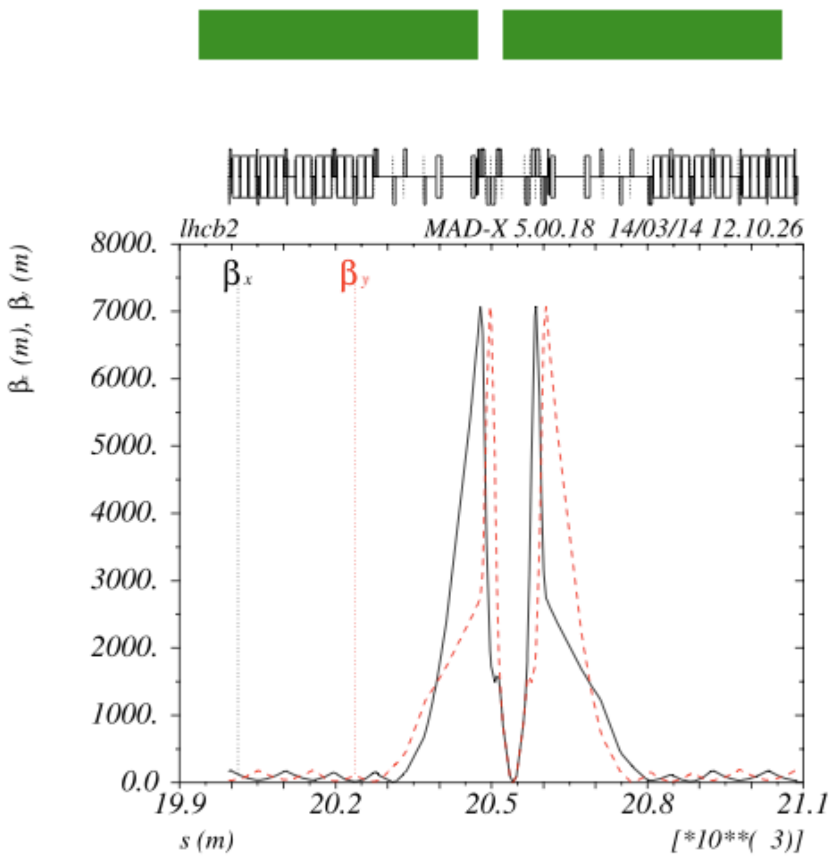
$\longrightarrow$ ***β*=0.3 m***

β*=0.1 m?

Limits quadrupole strengths.
IT causes huge chromatic aberrations

Achromatic Telescopic Squeezing (ATS) Scheme - HL-LHC

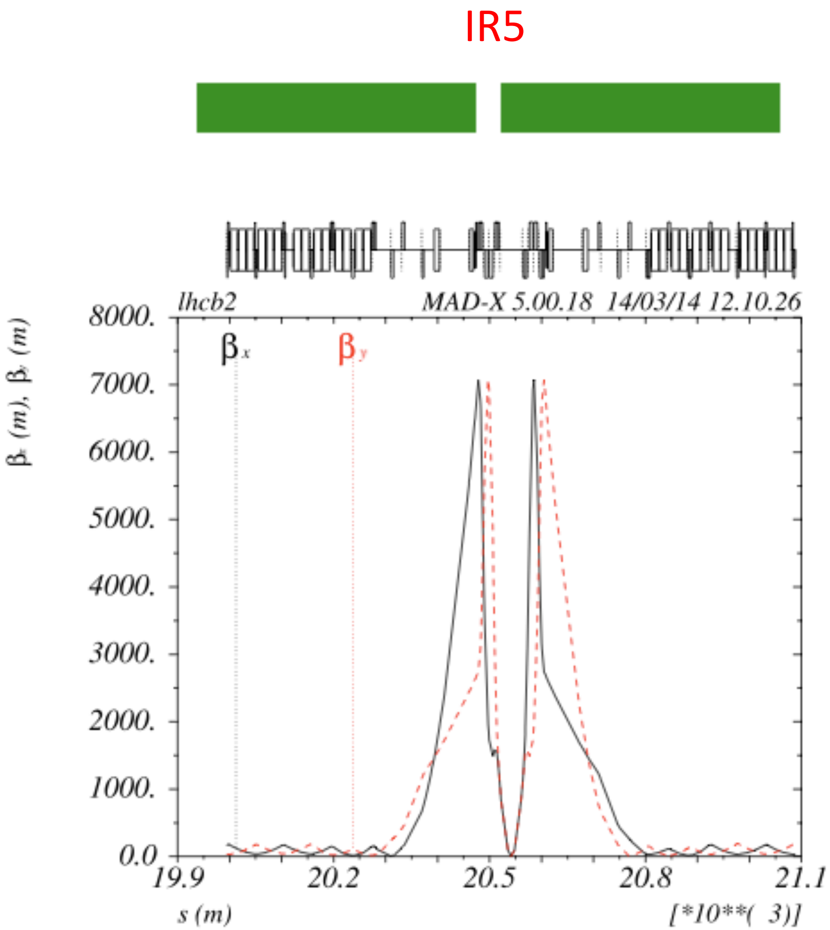
IR5

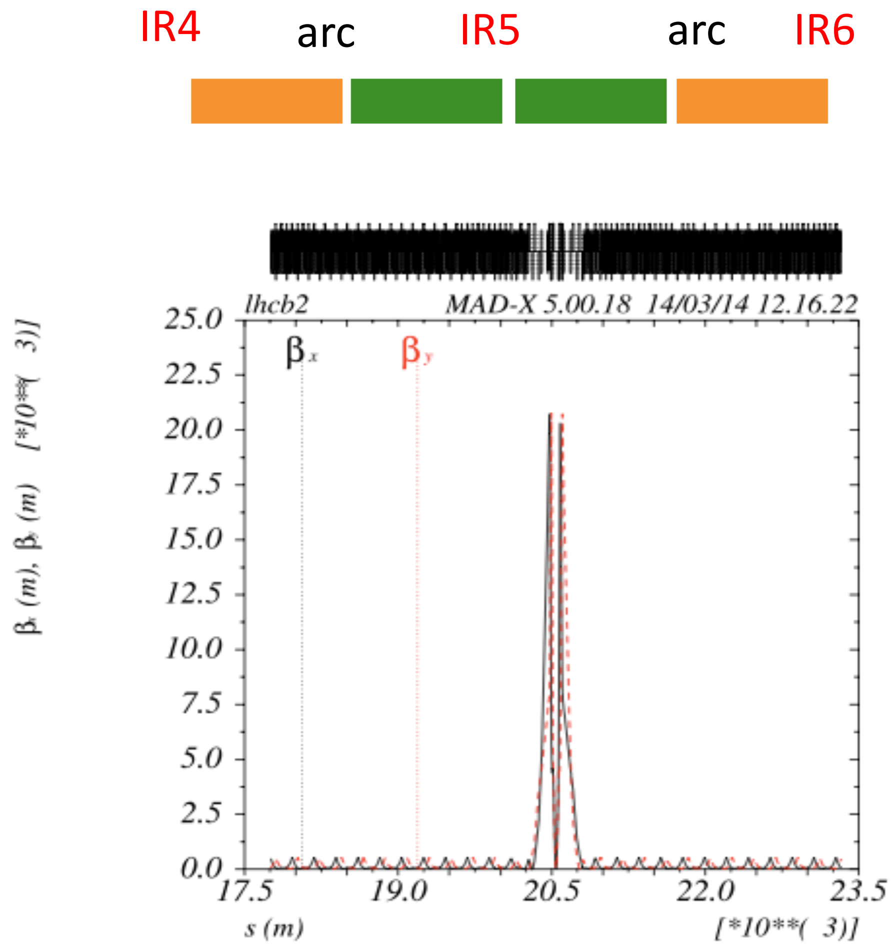


MADX

Vary	Constraints
Q1-Q13 in IR2	Twiss parameters IP2 and end of IR2

Achromatic Telescopic Squeezing (ATS) Scheme - HL-LHC

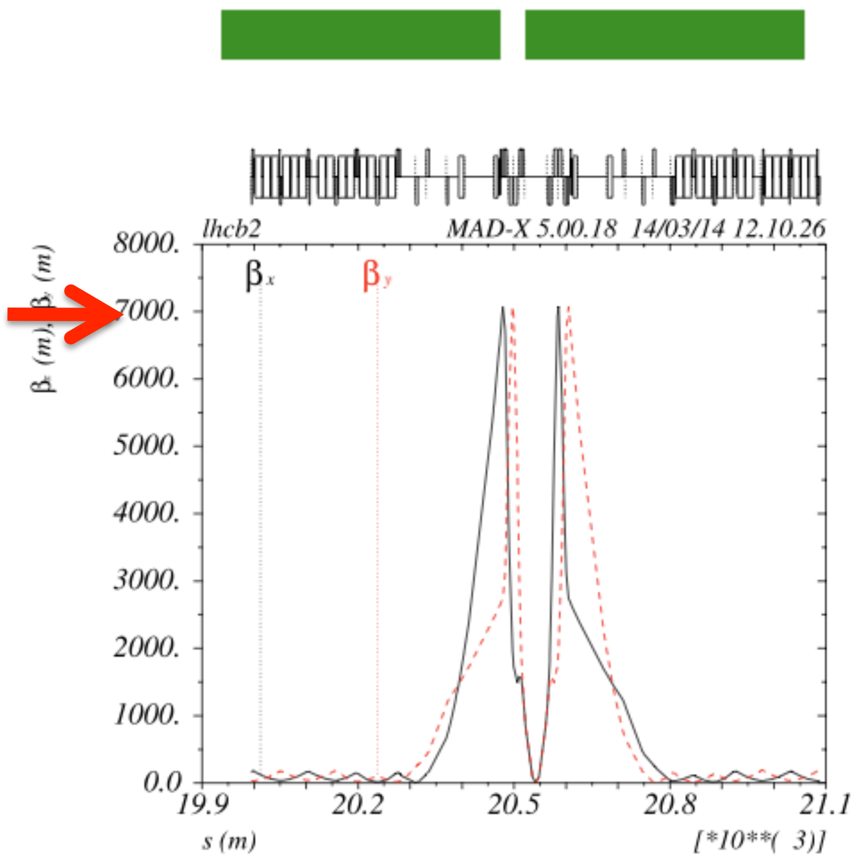




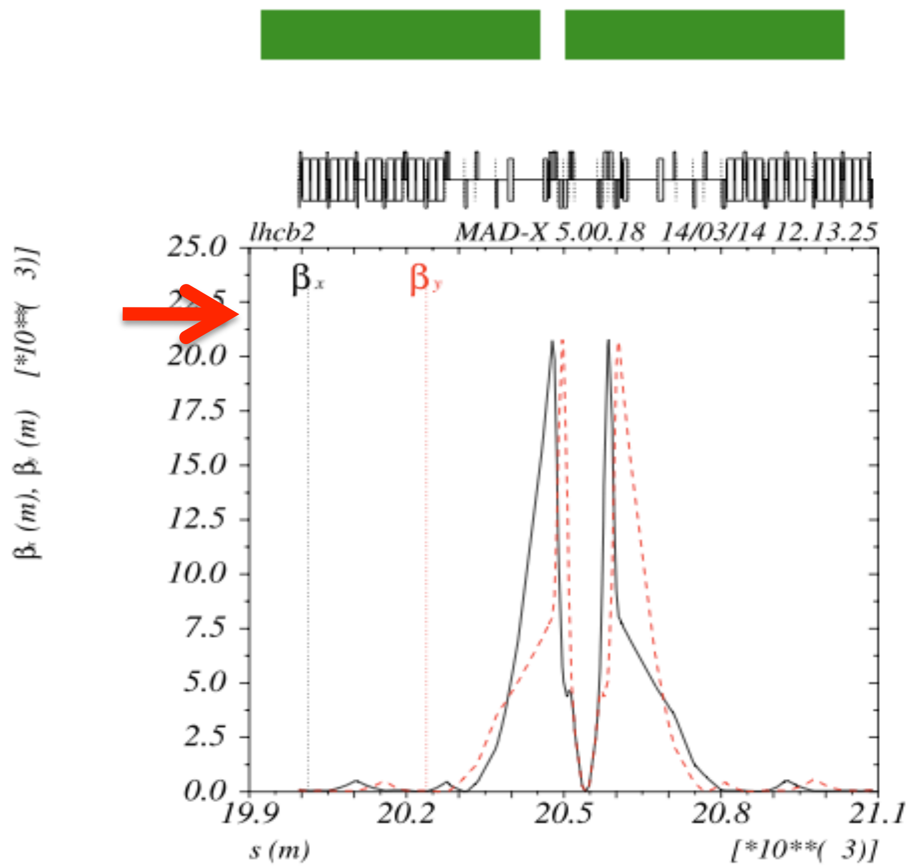
$$\left(\beta^*_{x,y} \times \beta^{\mathrm{SF1,SD2}}_{x,y}\right)_{\mathrm{pre-squeeze}} \equiv \mathbf{Cst}$$

Achromatic Telescopic Squeezing (ATS) Scheme - HL-LHC

IR5

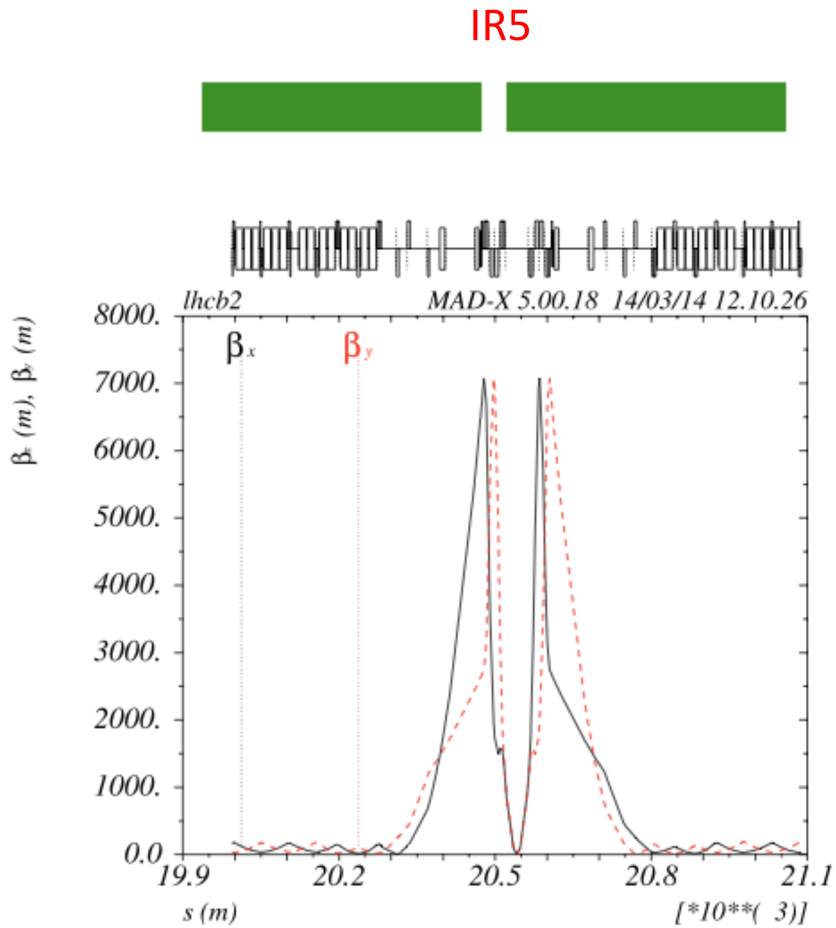


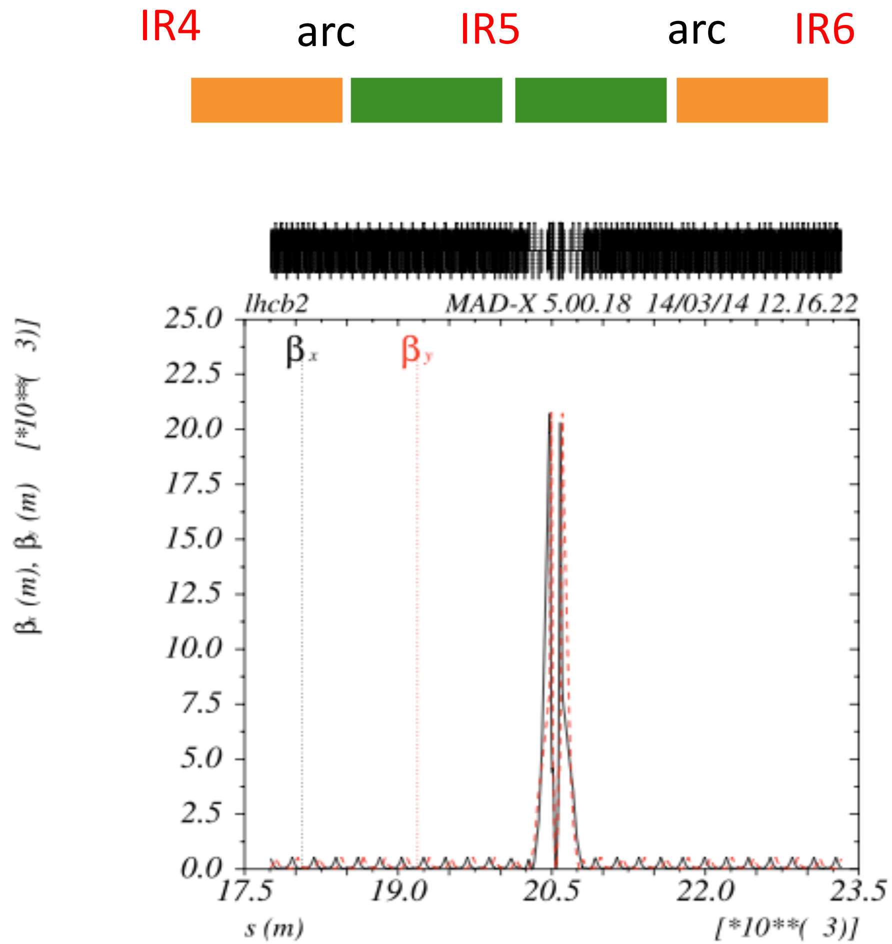
IR5



$$\left(\beta^*_{x,y} \times \beta^{\mathrm{SF1,SD2}}_{x,y}\right)_{\mathrm{pre-squeeze}} \equiv \mathbf{Cst}$$

Achromatic Telescopic Squeezing (ATS) Scheme - HL-LHC



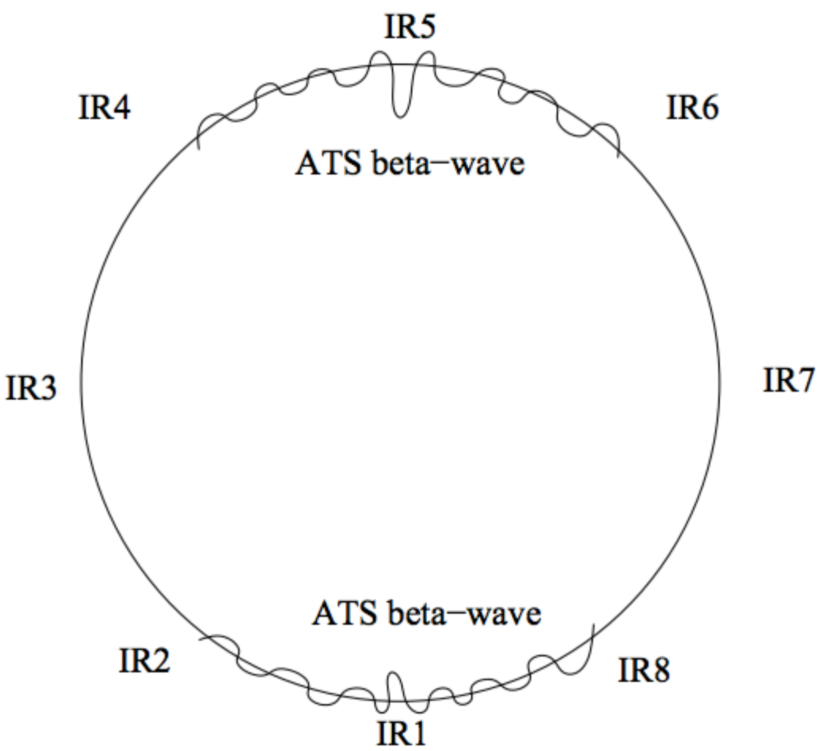


Increases Beta function in location of sextupoles in arc

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

Achromatic Telescopic Squeezing (ATS) Scheme - HL-LHC

HL-LHC

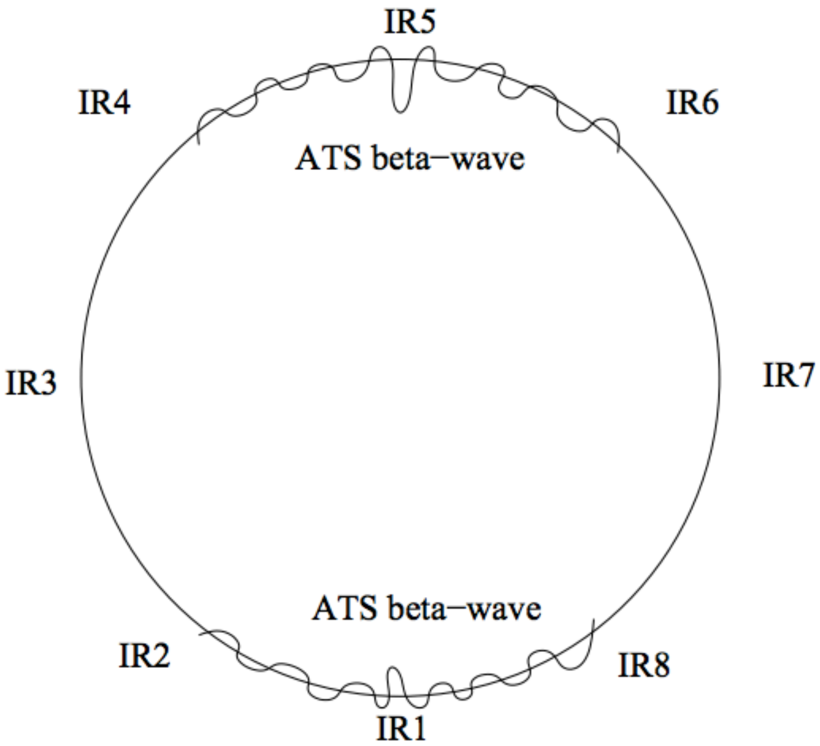


MADX

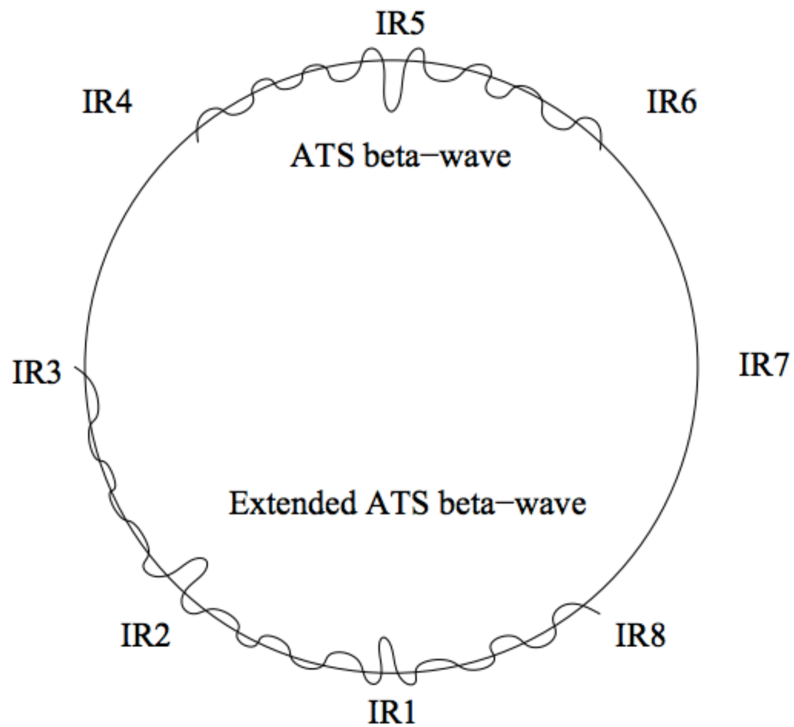
Vary	Constraints
Q1-Q13 in IR4, IR6	Twiss parameters end IR5 (beginning IR6), beginning IR5 (end IR4) Phase advance

Achromatic Telescopic Squeezing (ATS) Scheme

HL-LHC

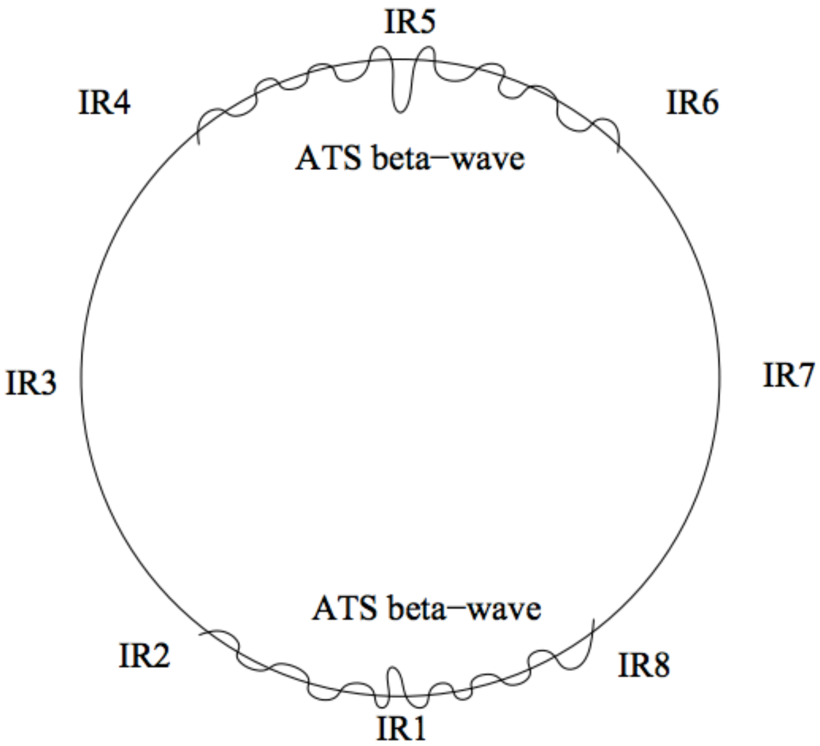


HL-LHC + LHeC

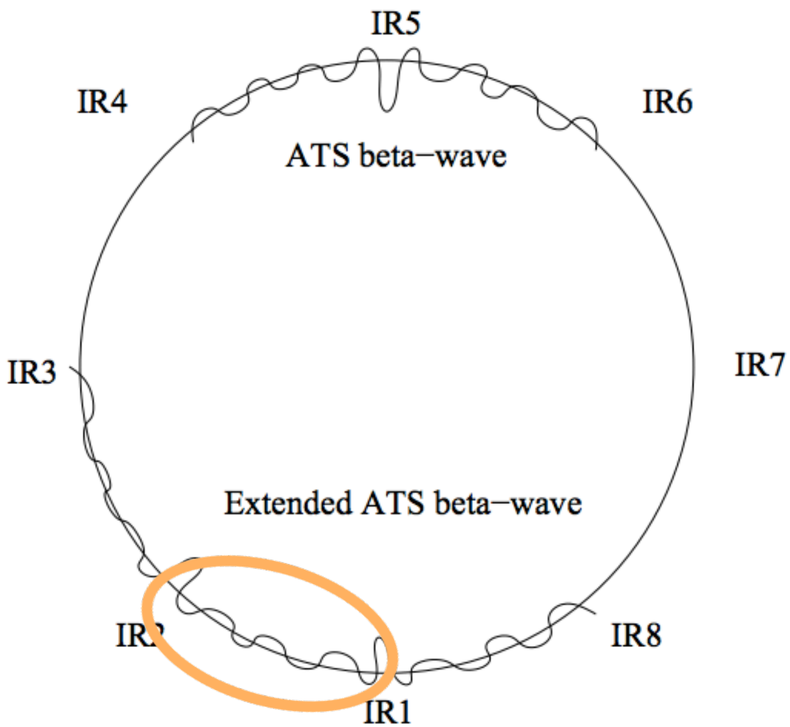


Achromatic Telescopic Squeezing (ATS) Scheme

HL-LHC

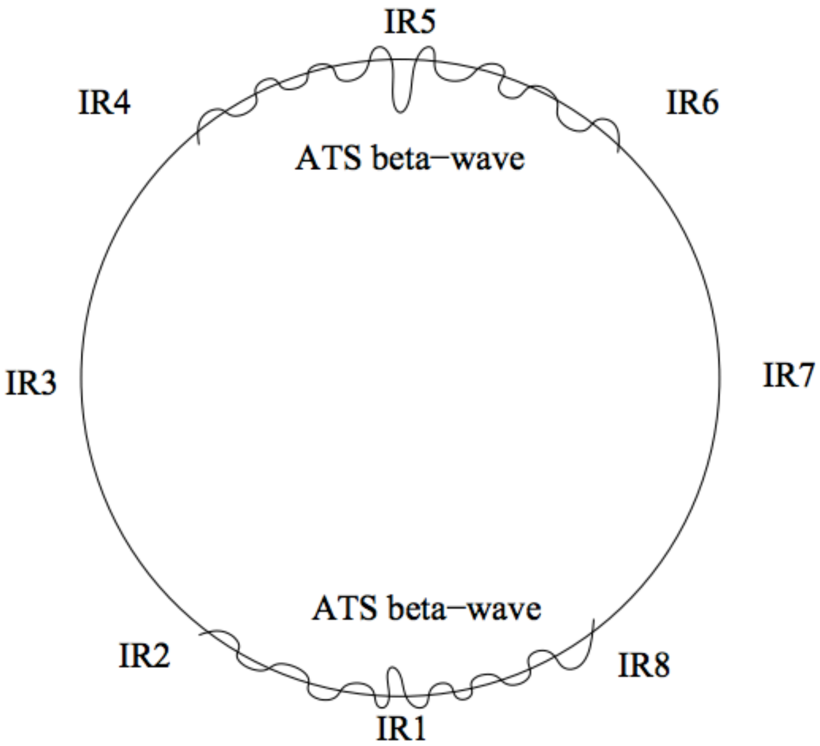


HL-LHC + LHeC

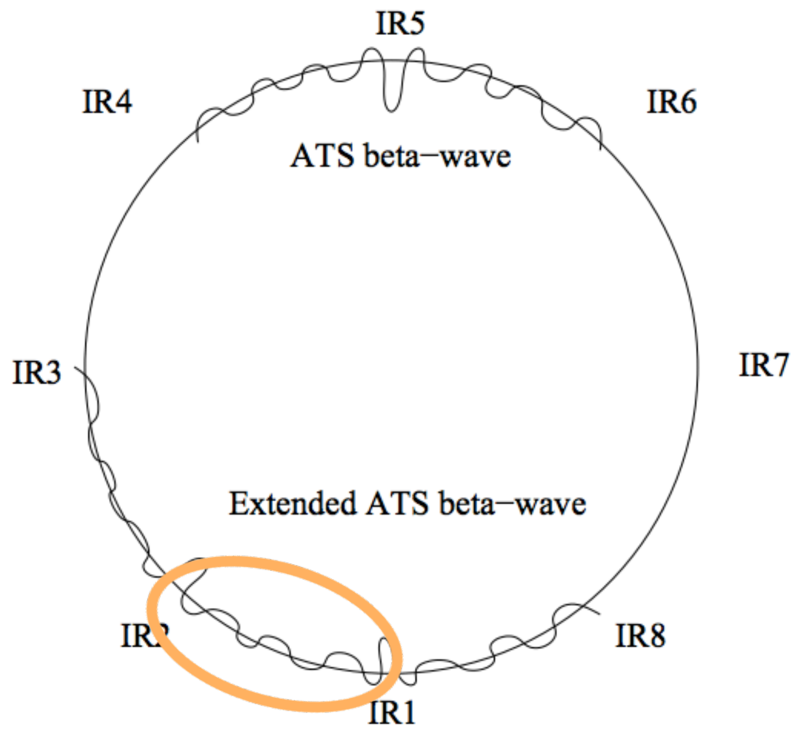


Achromatic Telescopic Squeezing (ATS) Scheme. HL-LHC+LHeC

HL-LHC



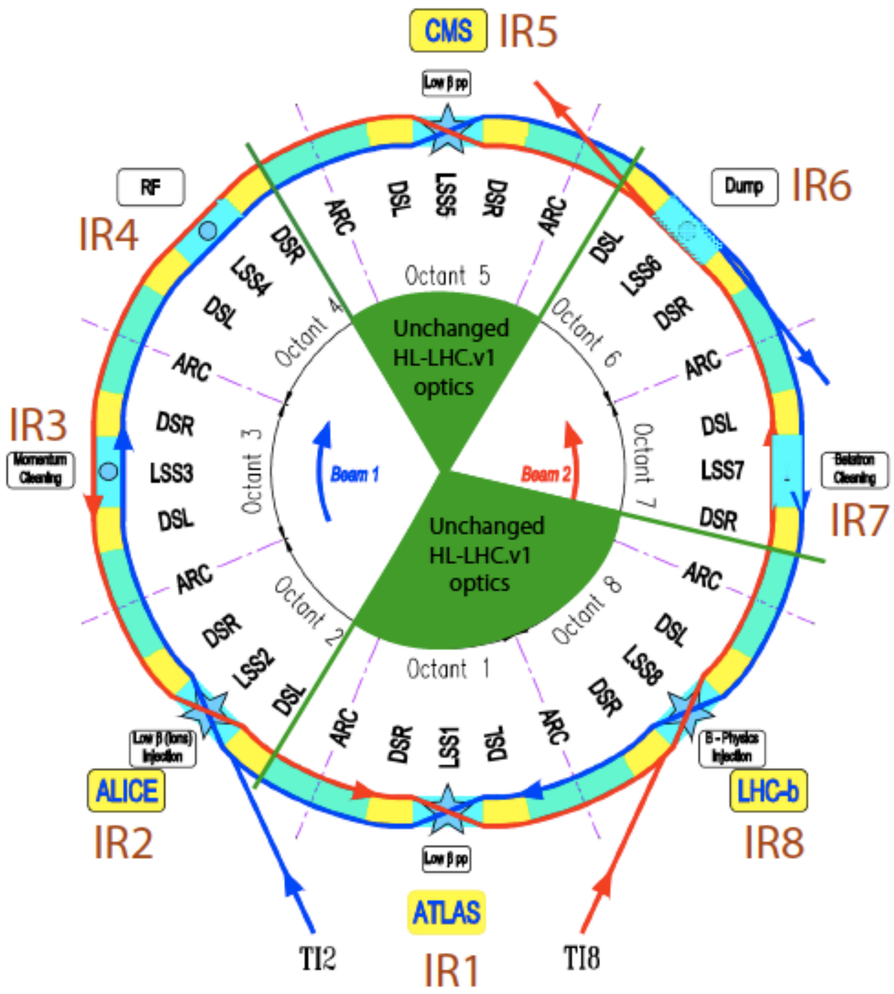
HL-LHC + LHeC



β^*=0.1 m?

Chromaticity corrected?

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



- Tuning of the arc cells in the sector 23 to 90 degree
- Re-matching for the IR3 to provide absorption of the beta-beating wave
- Tuning of the arc cells in the sectors 34 and 67 to restore the betatron tunes of the machine to 62.31/60.32
- Re-matching for the IR4, IR6 and IR7 to adjust modified arc sectors 34 and 67

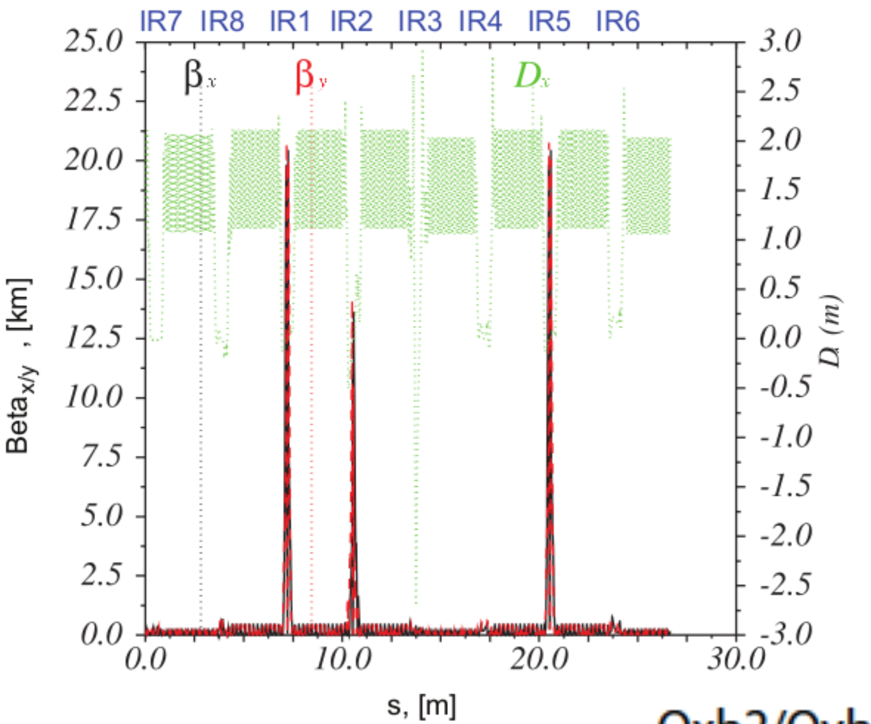
HL+LHeC ATS Optics. Beam 2

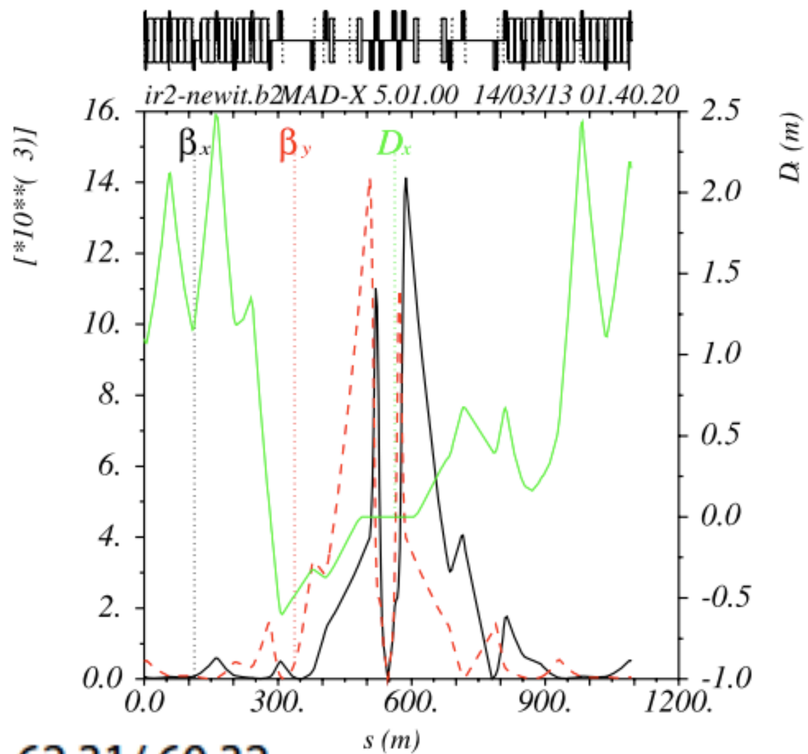
M. Korostelev

New triplet
Q1=187 T/m
Q2=310 T/m
Q3=182 T/m
Length=9 m

IR2 β^*=10 cm

IR1/IR5 β^*=15 cm





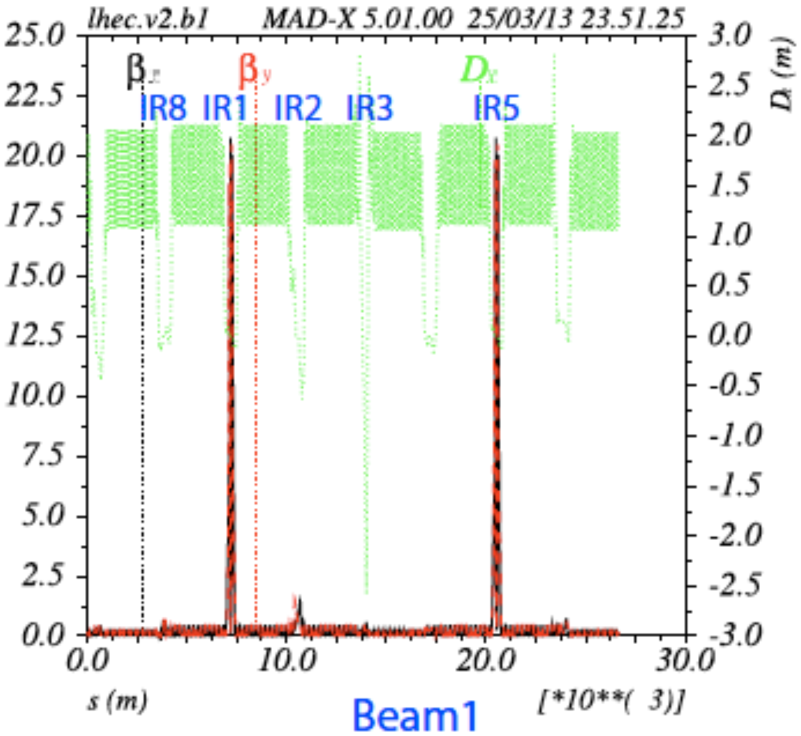
Qxb2/Qyb2 = 62.31/ 60.32

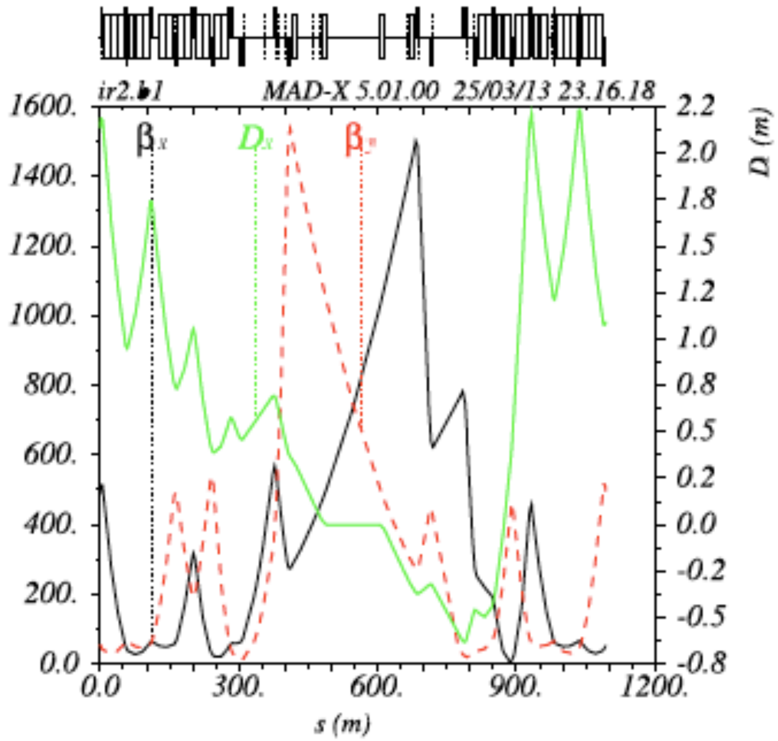
HL+LHeC ATS Optics. Beam 1

IR1/IR5

M. Korostelev

β*=15 cm





Qxb1/Qyb1 = 61.31/ 59.32

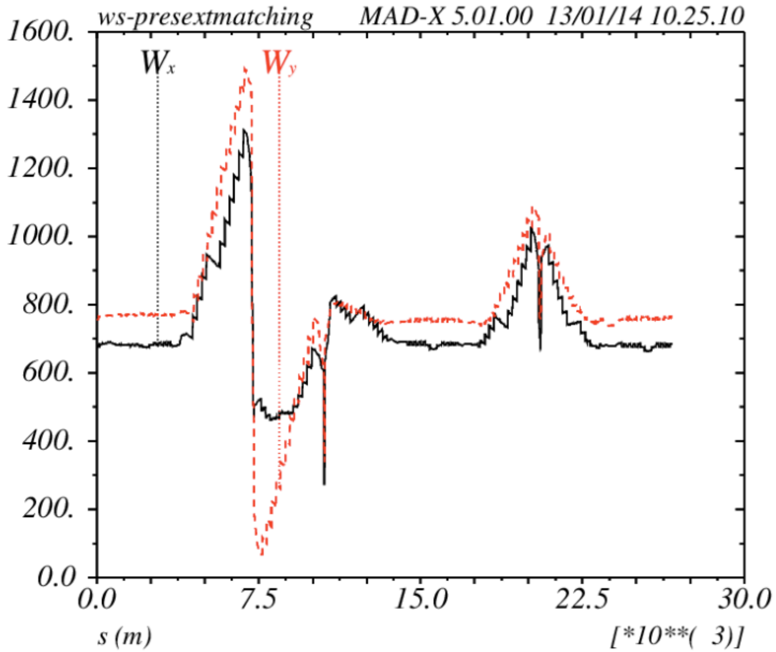
Chromaticity correction, L*=10 m, β*=10 cm

MADX

Vary	Constraints
KSF1, KSF2, KSD1, KSD2 all arcs	dq1=2, dq2=2 Wx, Wy<200 in IR3 and IR7

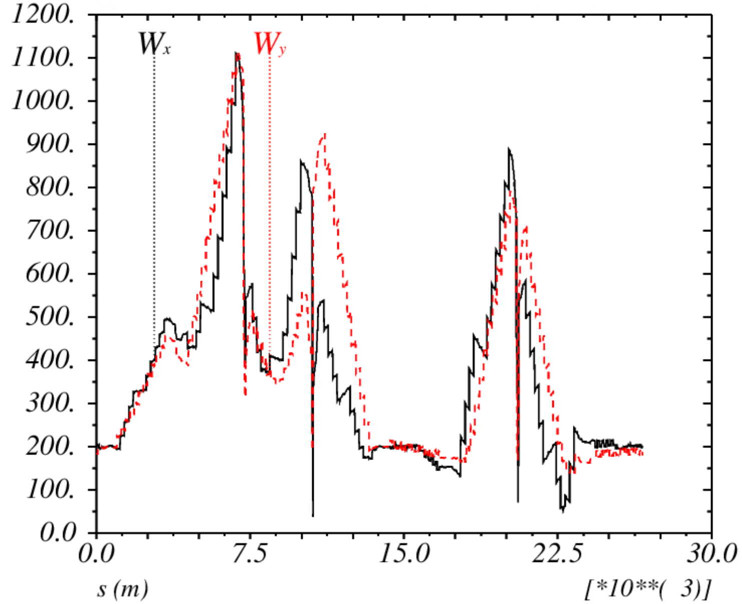
Before correction

dq1= -99.38
dq2= -103.86



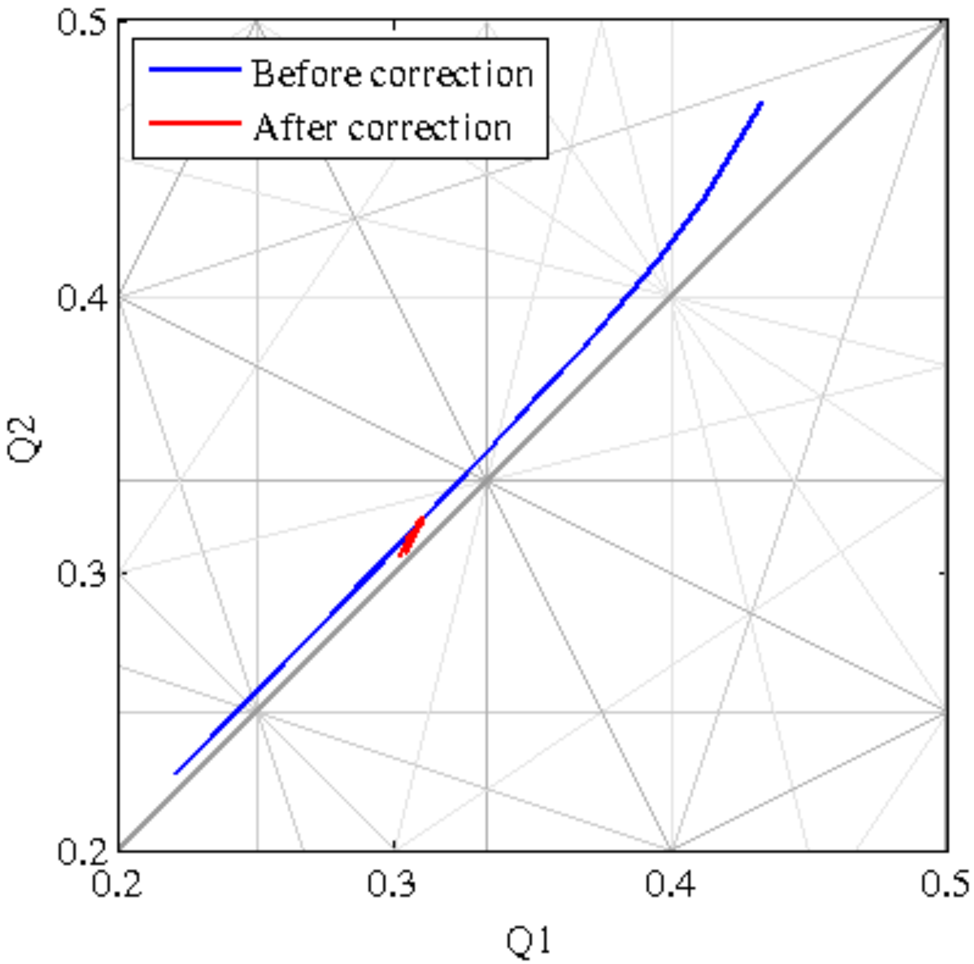
After correction

dq1= 2
dq2= 2



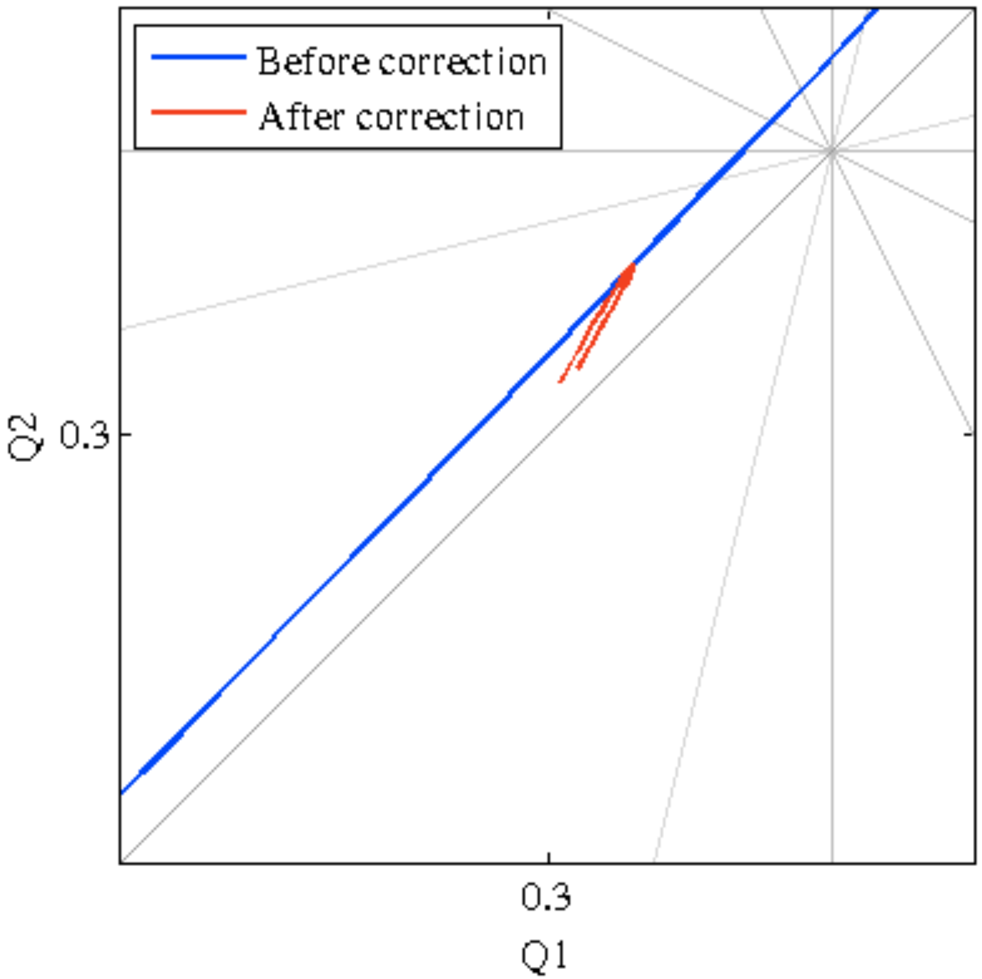
Frequency map-Order 5

L*=10 m, Beta*=0.1 m, Δp=±0.001



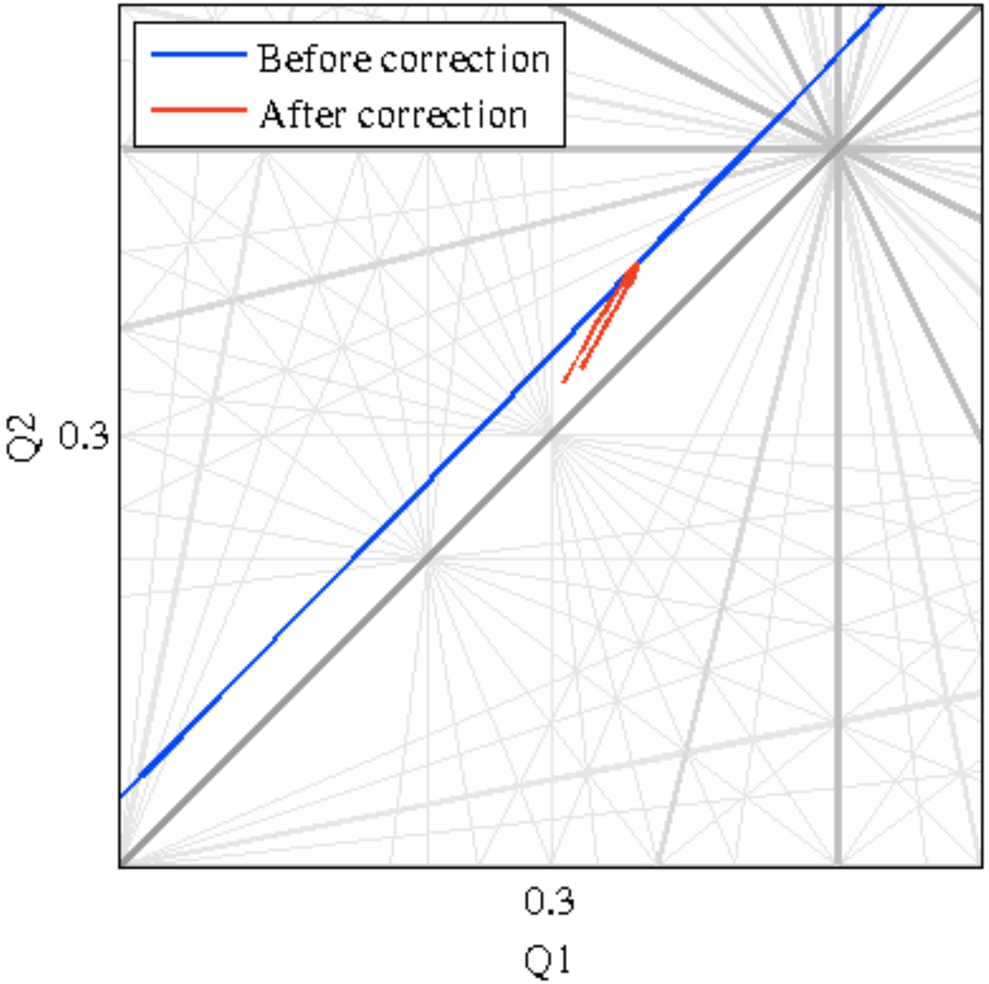
Zoom-Frequency Map-Order 5

L*=10 m, Beta*=0.1 m, Δp=±0.001



Zoom Frequency Map-Order 10

L*=10 m, Beta*=0.1 m, $\Delta p=\pm 0.001$



Competing Criteria

- **Luminosity vs Aperture**

  Increased beam growth ($\beta(s)= \beta^*+s^2/\beta^*$) bigger beam size in the location of the inner triplet

- **Luminosity vs Chromatic Aberration**

  Increased beta function in the triplets, more natural chromaticity produced.

- **SR vs Aperture**

  More distance, less bending electron beam, bigger beam size on proton beam.

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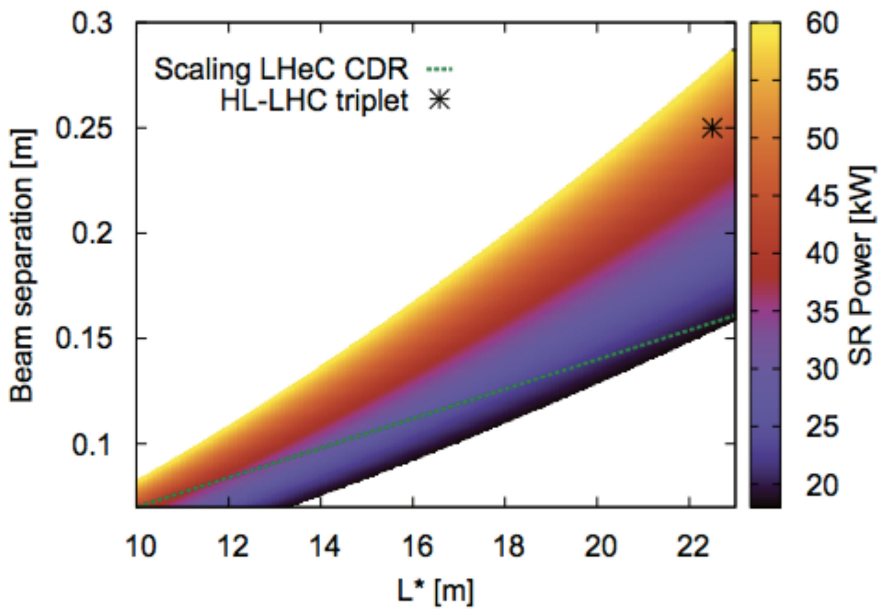

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Initial solution. L^*=10 m, β^*=10 cm. We have values at ends of IR2 that produce beta beating. Change parameters?

Change Parameters

- **Increase L***

Less synchroton radiation, more space, useful for quadrupole design. **More chromaticity**.

MADX

Vary	Constraints
Q1-Q13 Left/Right in IR2	Beforehand: Location IT Same twiss parameters at IP and ends of IR

- **Minimize β***

Increase Luminosity. Inner triplet forced, possible? **More chromaticity**.

MADX

Vary	Constraints
Q1-Q13 Left/Right in IR2	Same twiss parameters at ends of IR2. Adjusted β* in IP

Change Parameters

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Vary	Constraints
Q1-Q13 Left/Right in IR2	Beforehand: Location IT Same twiss parameters at IP and ends of IR

→ L*=10-19 m

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→ β*=5-10, 20 cm

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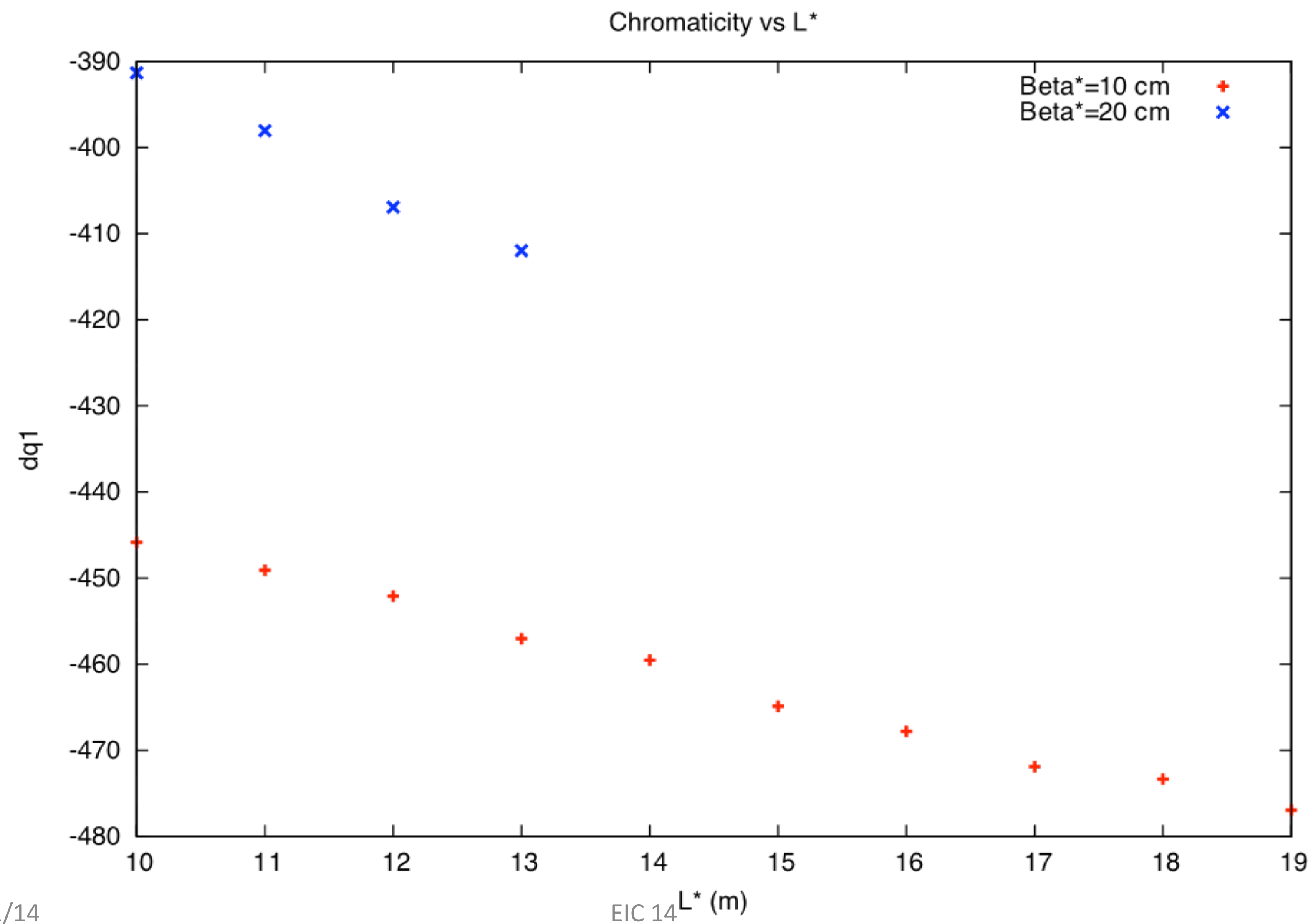
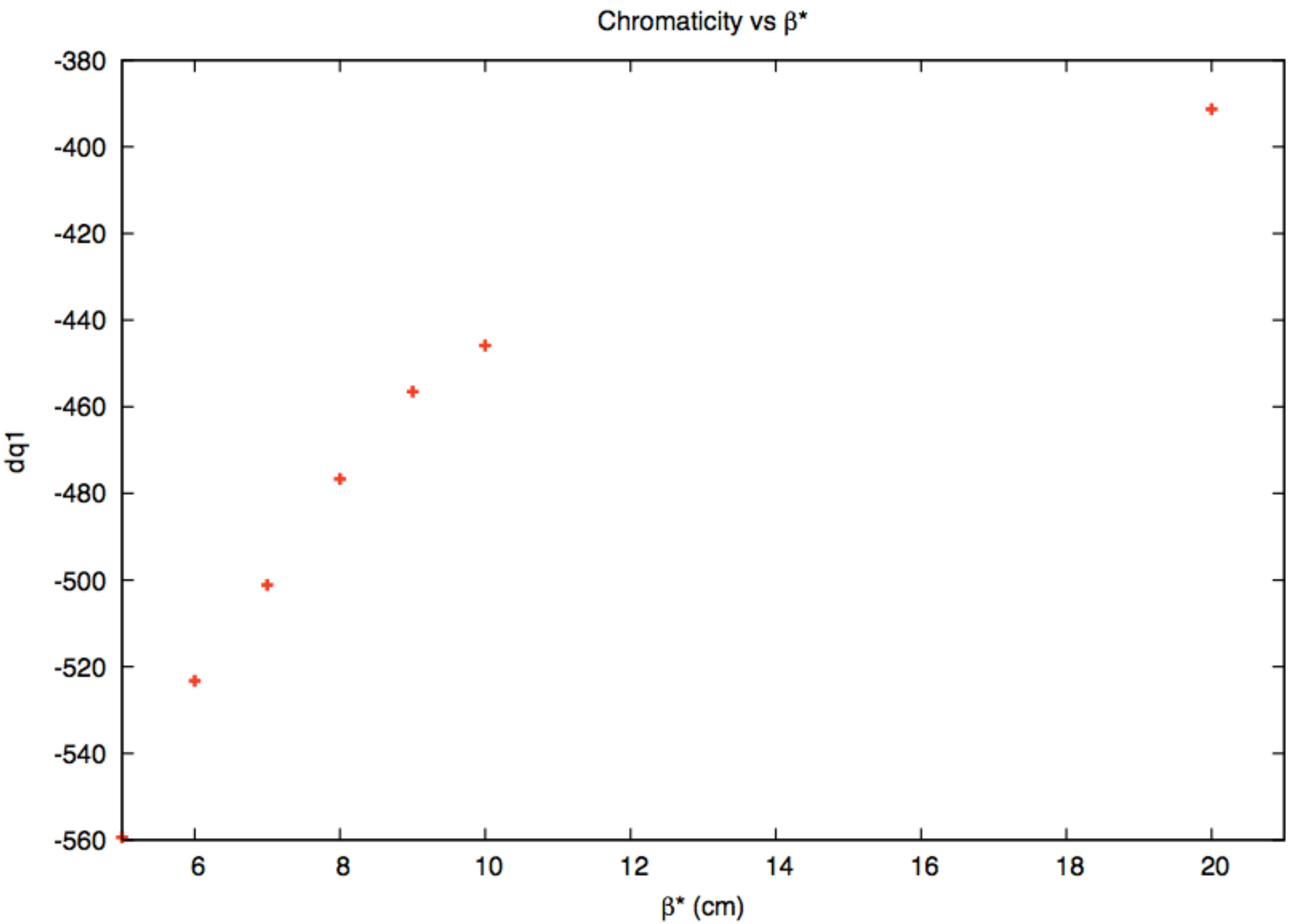
How much more chromaticity? Sextupoles to zero, check natural chromaticity

Natural Chromaticity vs L*



Natural chromaticity vs β*



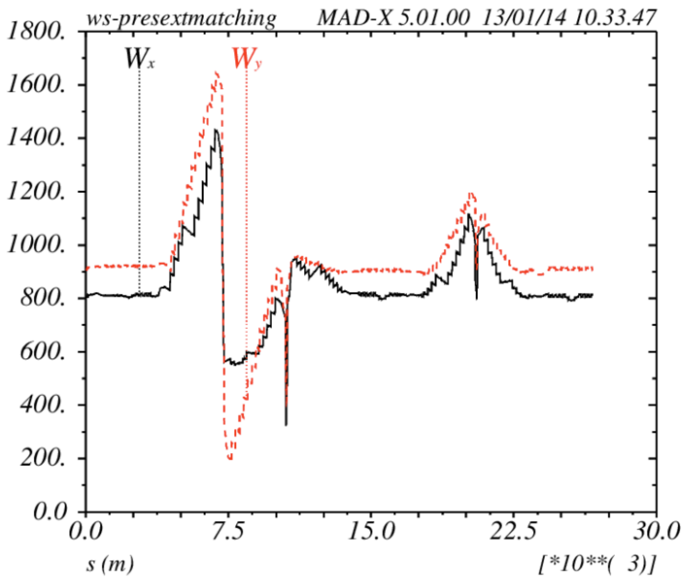
Case L*=15 m, β*=10 cm

- Distance and strength of Q1 (164 T/m) useful for Quadrupole design.
- Less synchroton radiation

Chromaticity correction

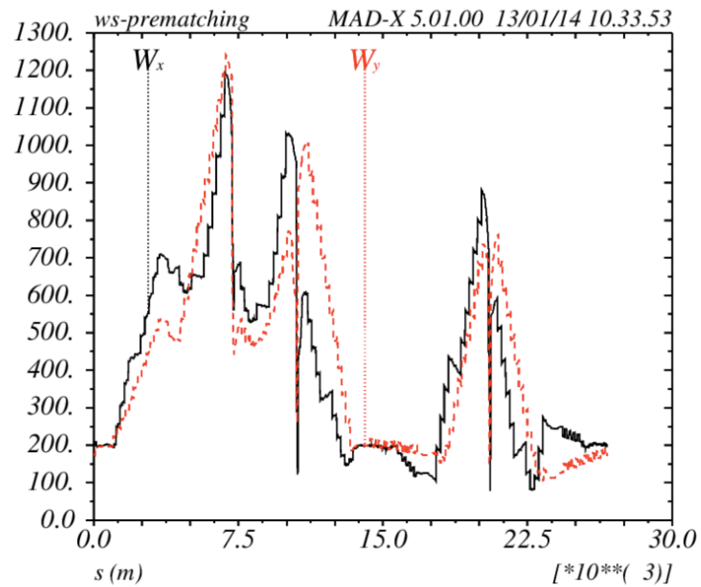
Before correction

dq1= -118.44
dq2= -125.60



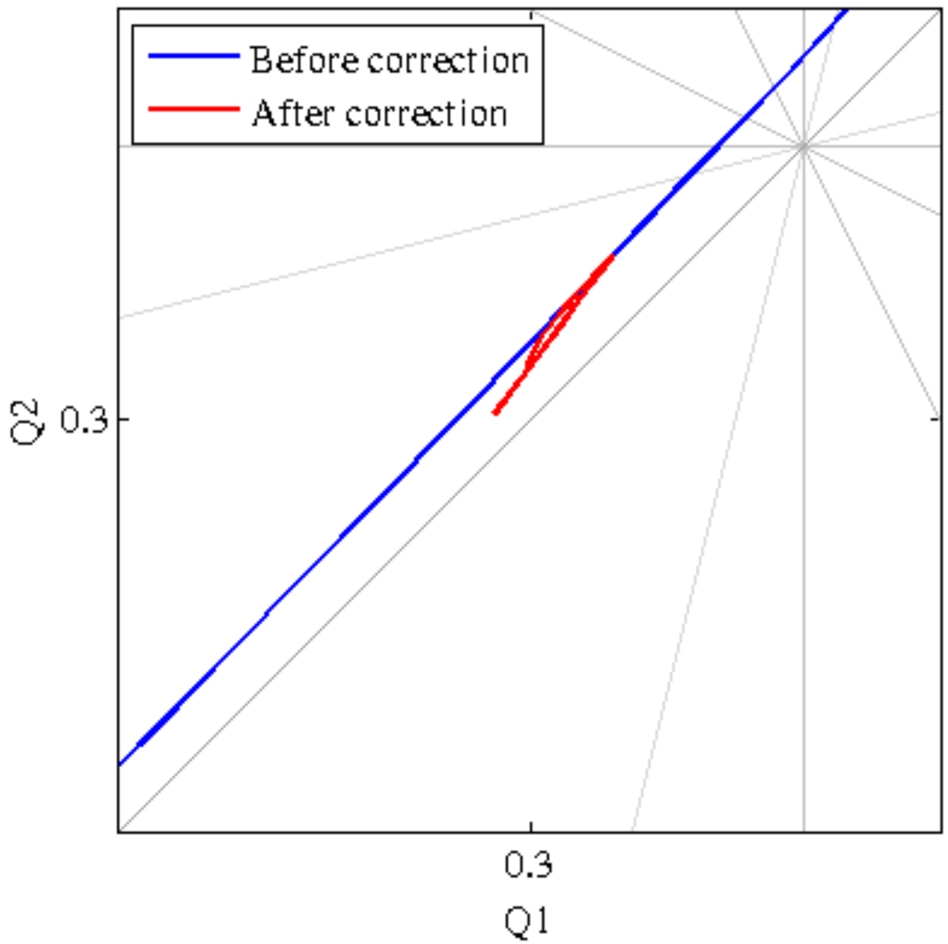
After correction

dq1= 2
dq2= 2



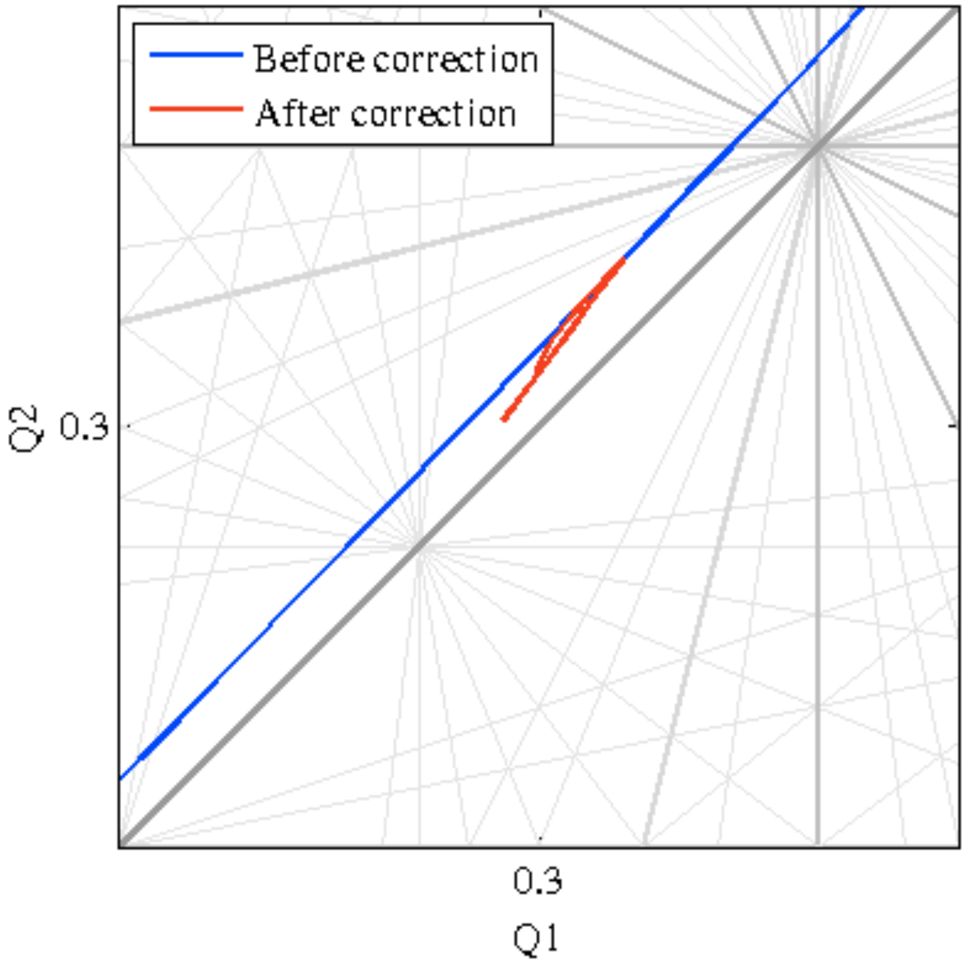
Frequency map-Order 5

L*=15 m, Beta*=0.1 m, Δp=±0.001



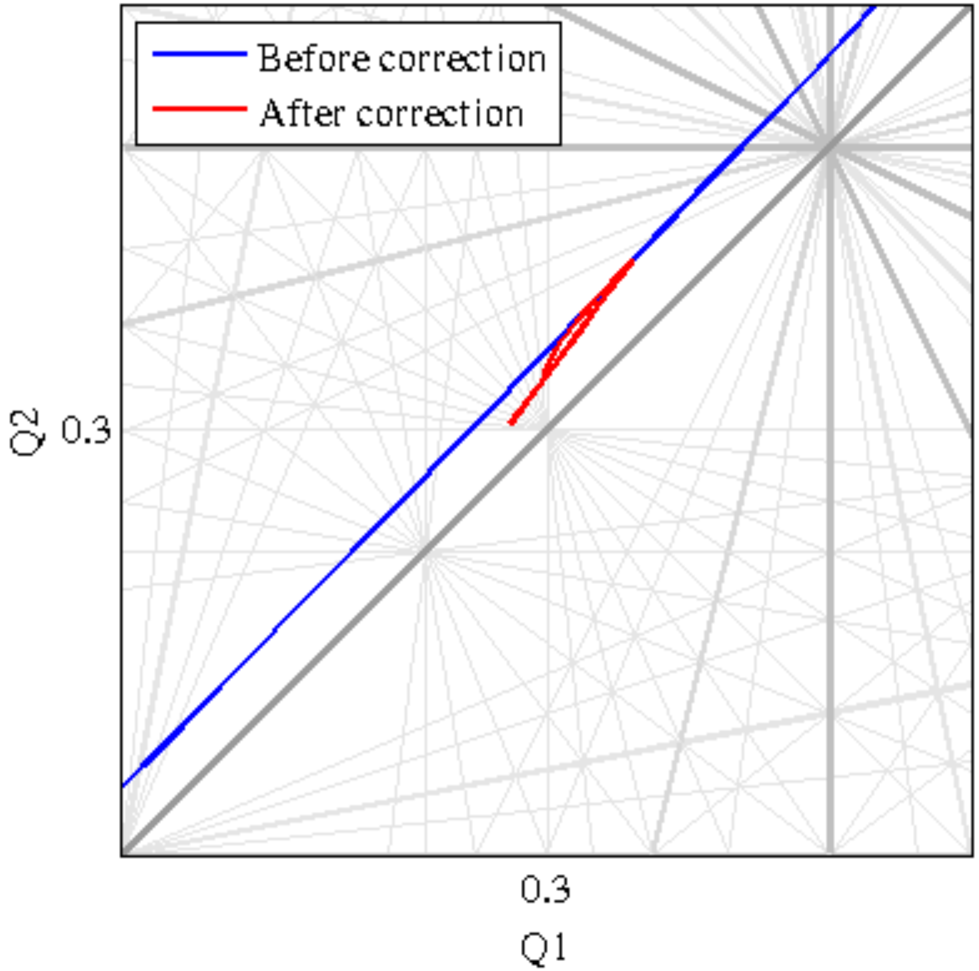
Frequency Map - Order 9

L*=15 m, Beta*=0.1 m, Δp=±0.001



Frequency map-Order 10

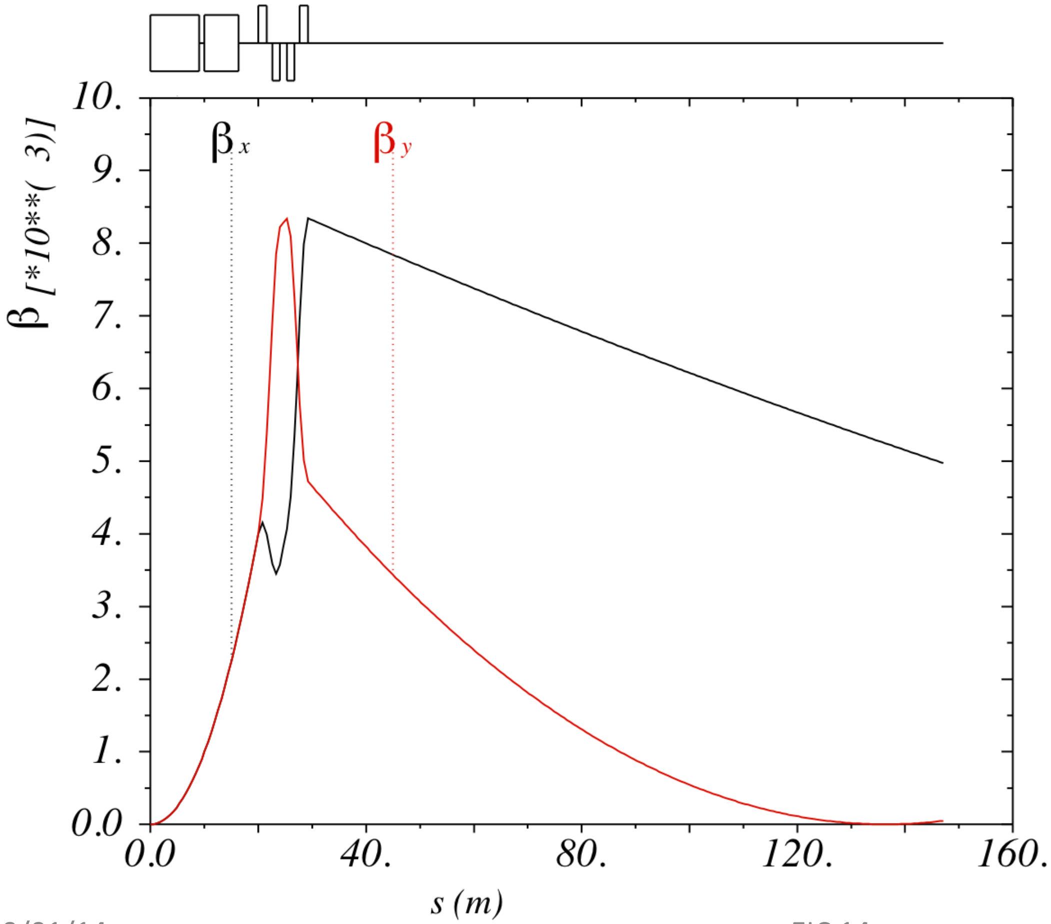
L*=15 m, Beta*=0.1 m, Δp=±0.001

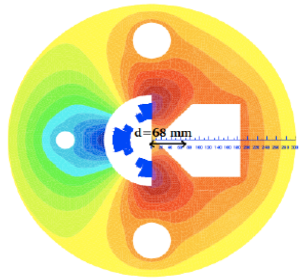


Electron Optics. Original Design

L*$_p$=10 m

L*$_e$=20m (outside)



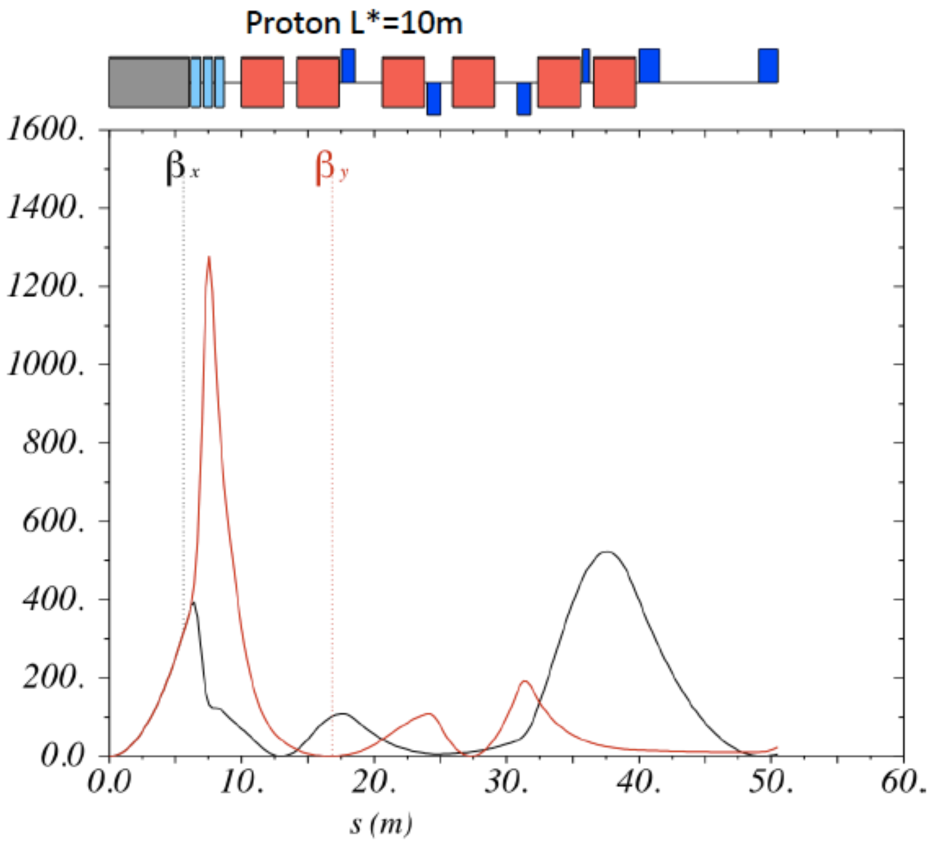


- **PROBLEM.** Stray Fields in free field hole of Q1 . 7 T/M
- Cannot successfully match with stray fields

Electron Optics. Option 1

L*$_p$=10 m

L*$_e$=6m (outside)



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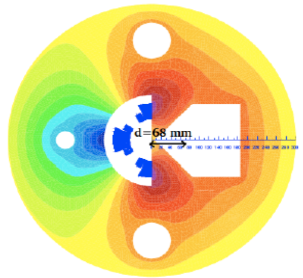


Electron final triplet (offset)

Electron matching

Proton final triplet

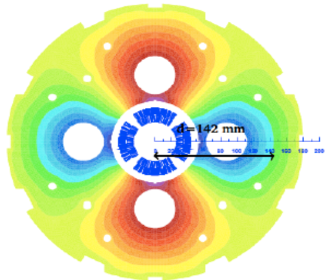
Electron dipoles

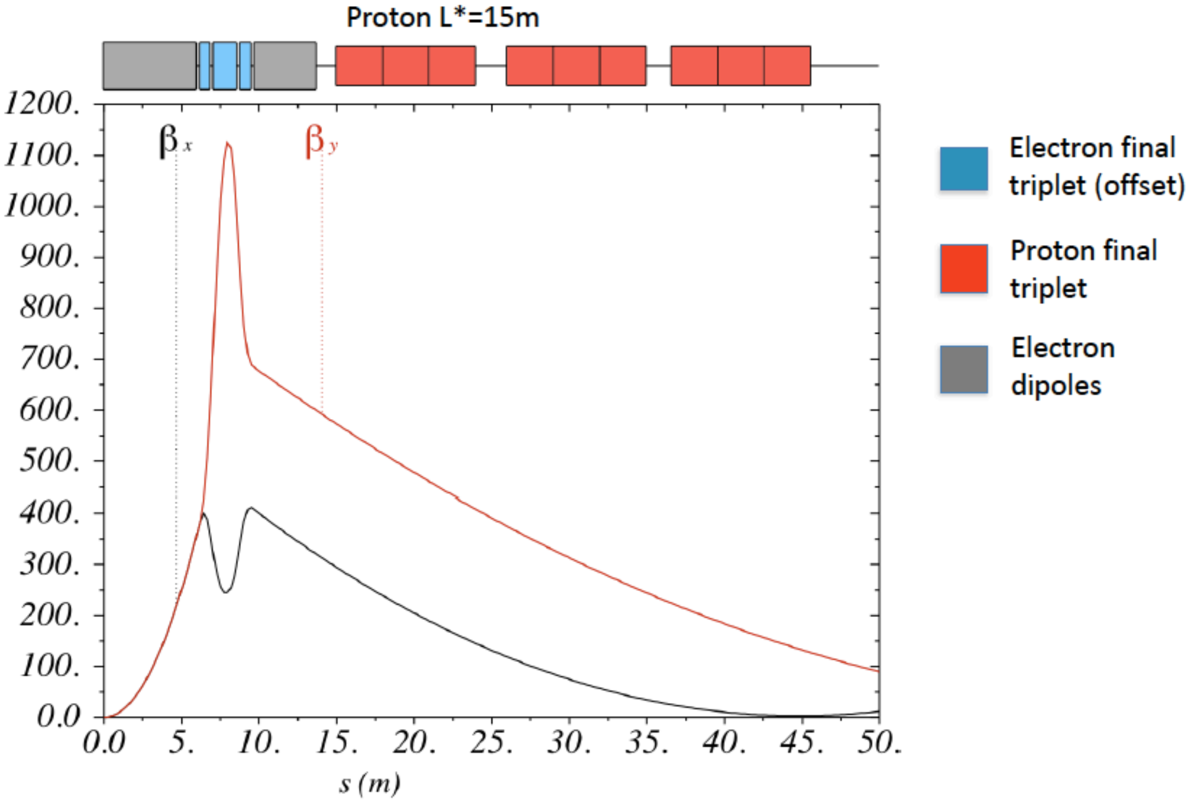
- Optics and layout around proton elements.
- Matching quadrupoles correct **linear stray fields** does not deal with higher order yet.

Electron Optics. Option 1

L^*_p=15 m

L^*_e=6m (inside)





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- Removal half-quadrupole. Higher order stray fields negligible, more control synchrotron radiation.

- Still advantageous to have early electron focusing. After increases electron L* significantly.
- SR 22 kW

Summary and Future Work

- 2 Different options: $L^*=10$ m and $L^*=15$ m seem feasible. Option $L^*=15$ m works better for magnet and e^- beam.
- Explore limits chromaticity correction. Current script $L^*=19$ m, $\beta^*= 8$ cm. Do we need bigger L^*?
- Dynamic Aperture on SixTrack studies to validate ATS scheme in the 3 interaction points.
- Work further with e^-beam. Explore other options location triplet.

Thank you!

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