Interaction Region Design

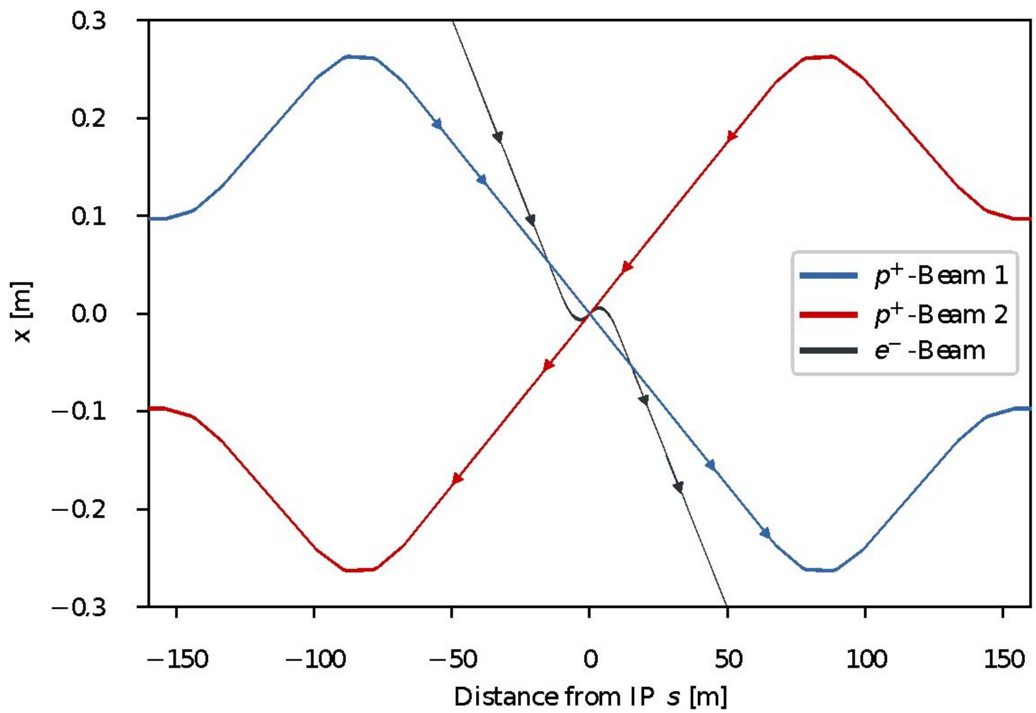
E. Cruz-Alaniz

Acknowledgments: R. Martin, B. Parker, R. Tomas

Electrons for the LHC
25th October, 2019

Interaction Region

Collide one of the proton beams with the electron beam while the other proton beam bypasses the interaction… in an IR originally designed for different purposes



Challenges IR Design

- **Interaction Point and inner triplet**
  - Magnets with normal and free field apertures
  - Luminosity vs Chromaticity
  - Luminosity vs Synchrotron Radiation
- **Interaction Region**
  - Optics at ends of interaction region
  - Strengths needed in matching section and dispersion suppressor regions
- **Integration into the HL lattice**
  - Extension of ATS scheme
  - Chromaticity Correction

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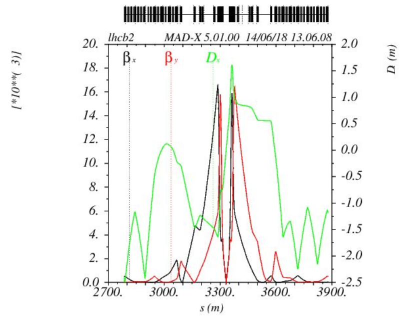
Compromise between Luminosity vs SR vs Chromaticity

Previous Design

- **Interaction Point and inner triplet**
  - Half quadrupole design
  - Recommendation: Change L* to 15 m to reduce SR



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  - Matching done but no strict limits taken into account for strengths of quadrupoles

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  - Achromatic Telescopic Squeezing (ATS) extended to arc 23
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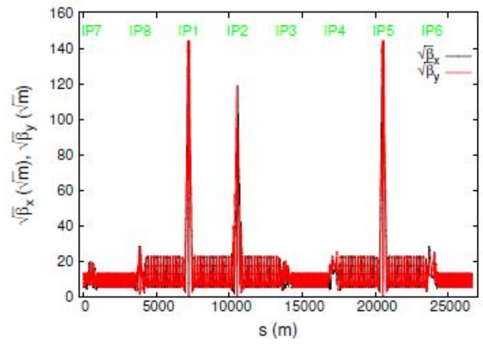

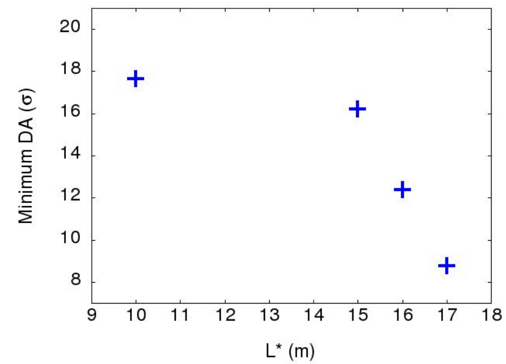

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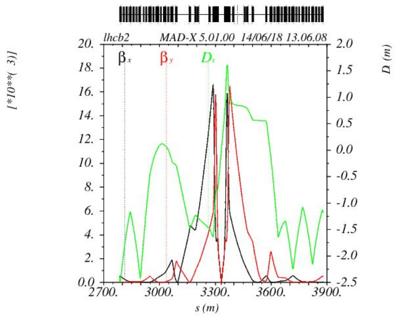

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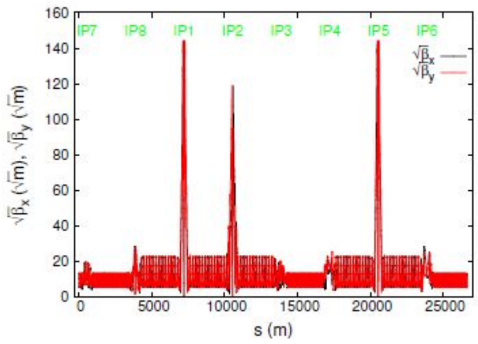

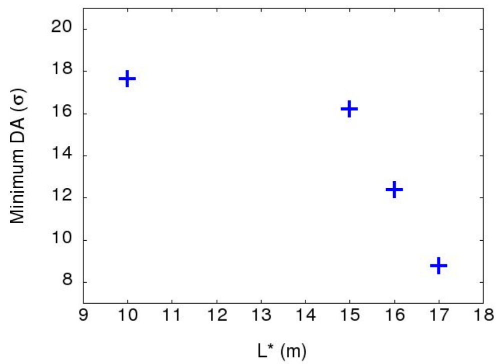

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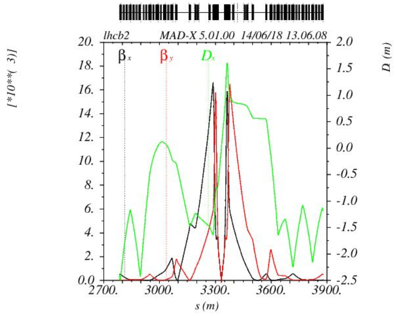

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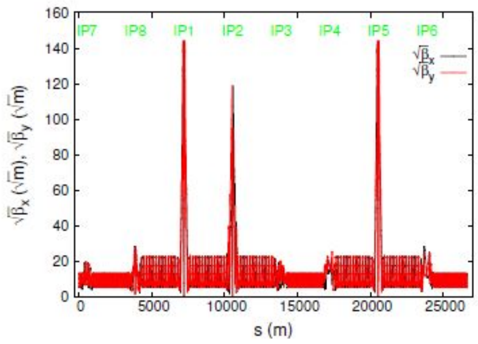

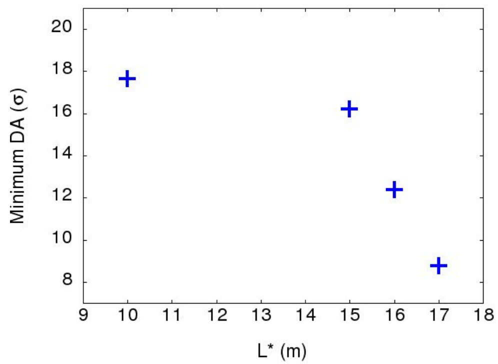

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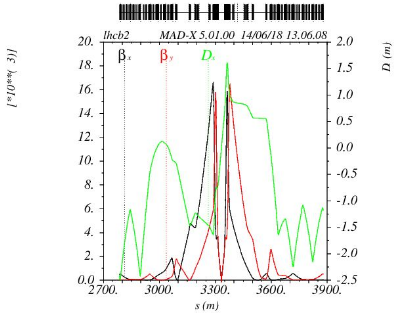

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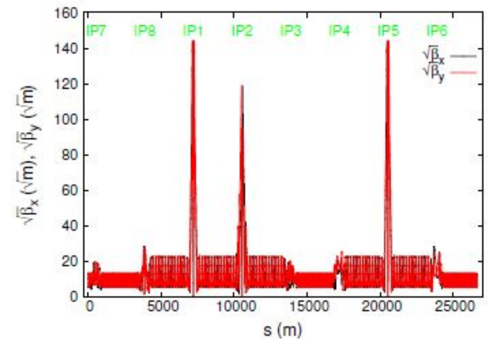

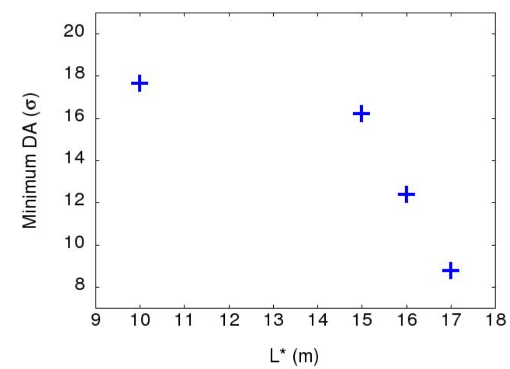

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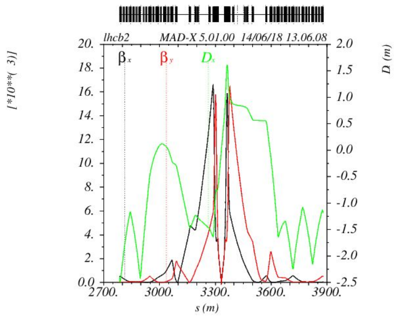

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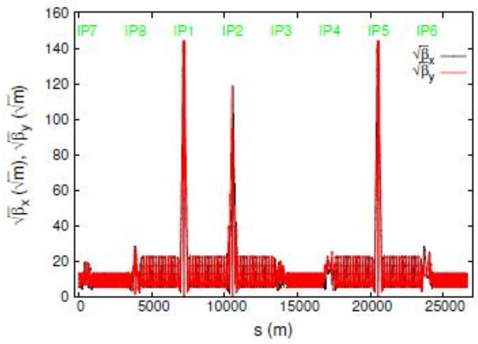
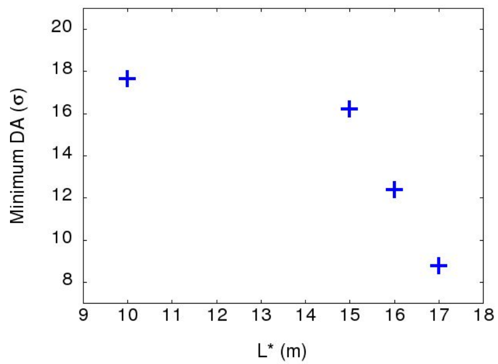
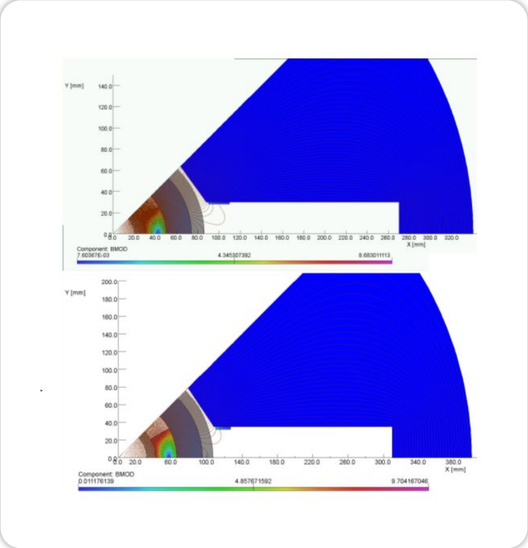




New IR: Magnets

- **Important for IR design:**
  - Aperture/Gradient achievable -> **Determines β^*/beam fits in the aperture**
  - Separation between apertures (normal and free-field) Q1. -> **Determines SR**
- **Previous design: Half quadrupole.**
  - Short separation between apertures (68 mm)
  - Problems field quality in both apertures
- **New design proposed by B. Parker**
  - Normal aperture for focused beam (no half quadrupole) and better quality on the field-free region.
  - Larger beam separation (168 mm), increased SR. We need L*=15 m

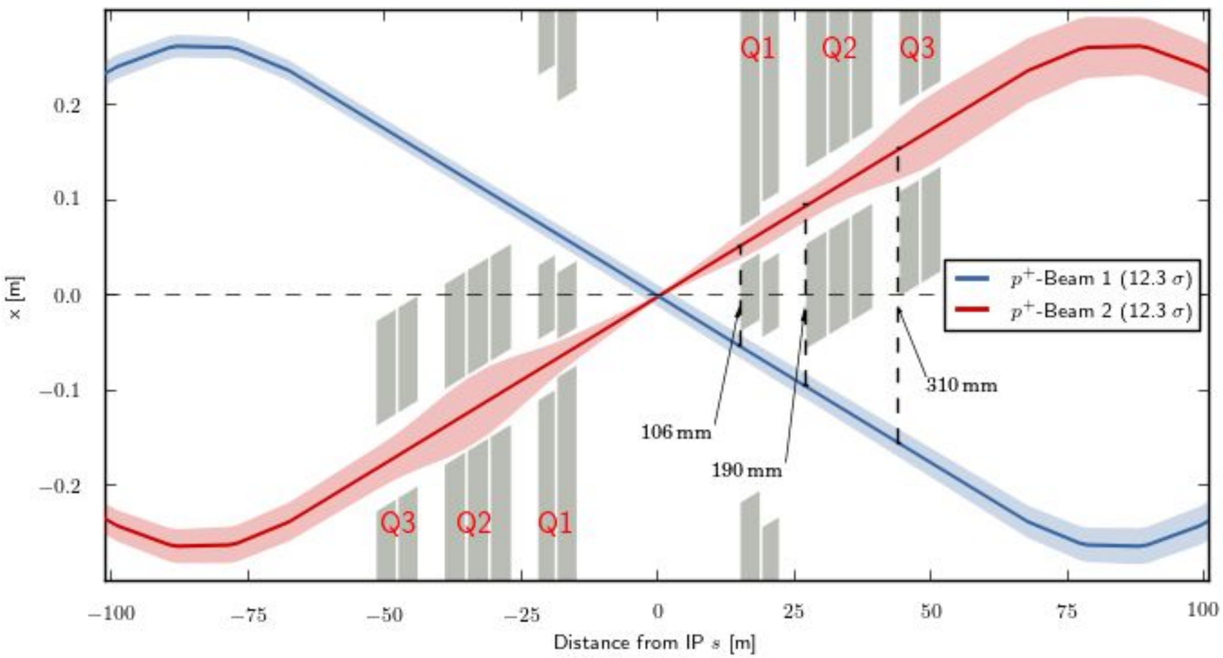


Case for β^*=10 cm at L*=15 m

Magnet	Gradient [T/m]	Length [m]	Free aperture radius [mm]
Q1a	252	3.5	20
Q1b	164	3.0	32
Q2 type	186	3.7	40
Q3 type	175	3.5	45

New IR: Triplet and beams

- New magnets with beam envelopes



R. Martin

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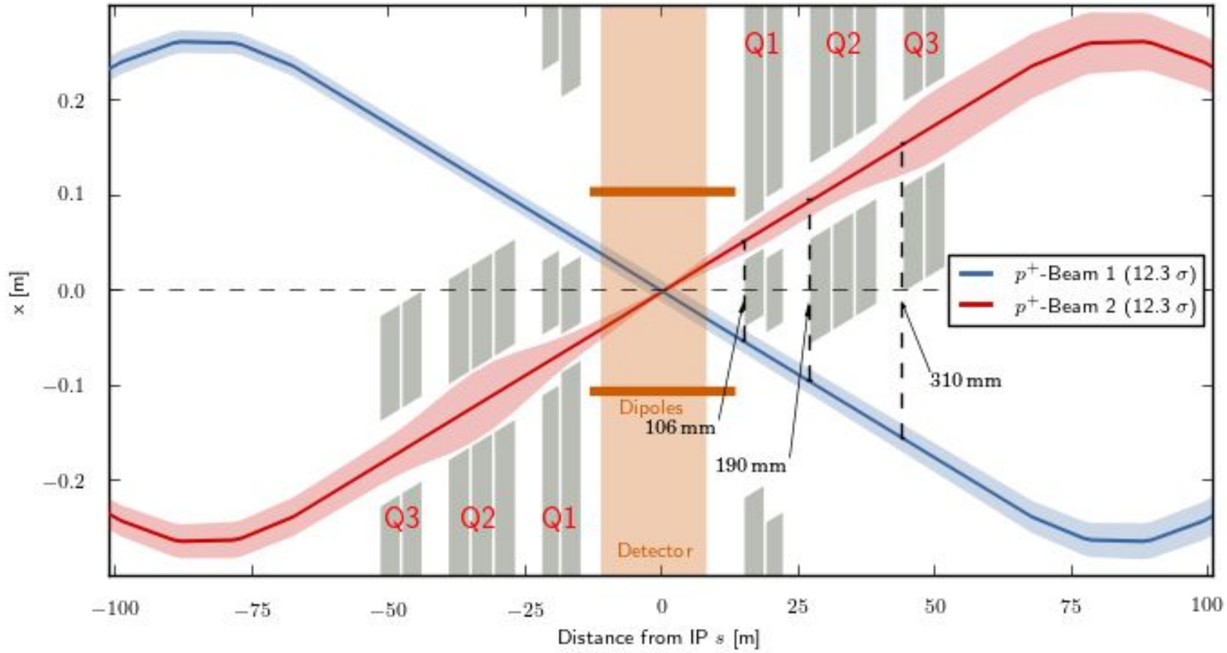

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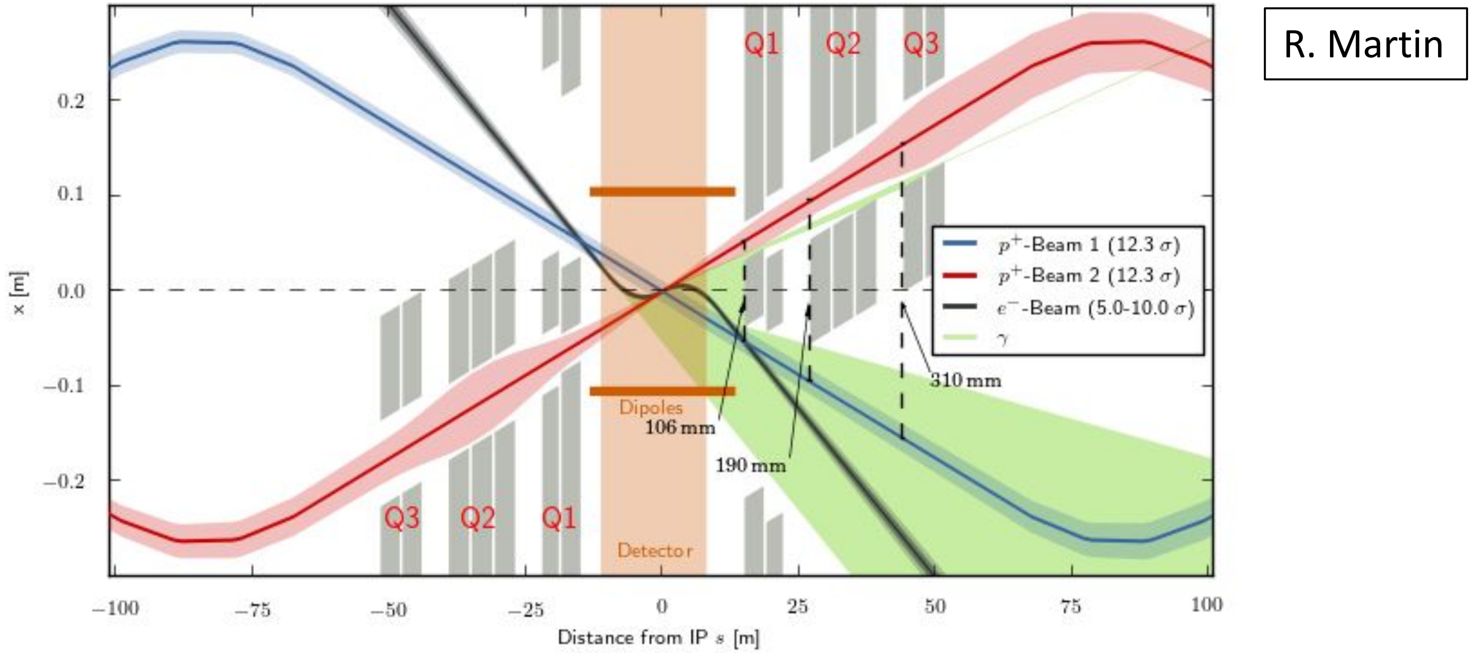

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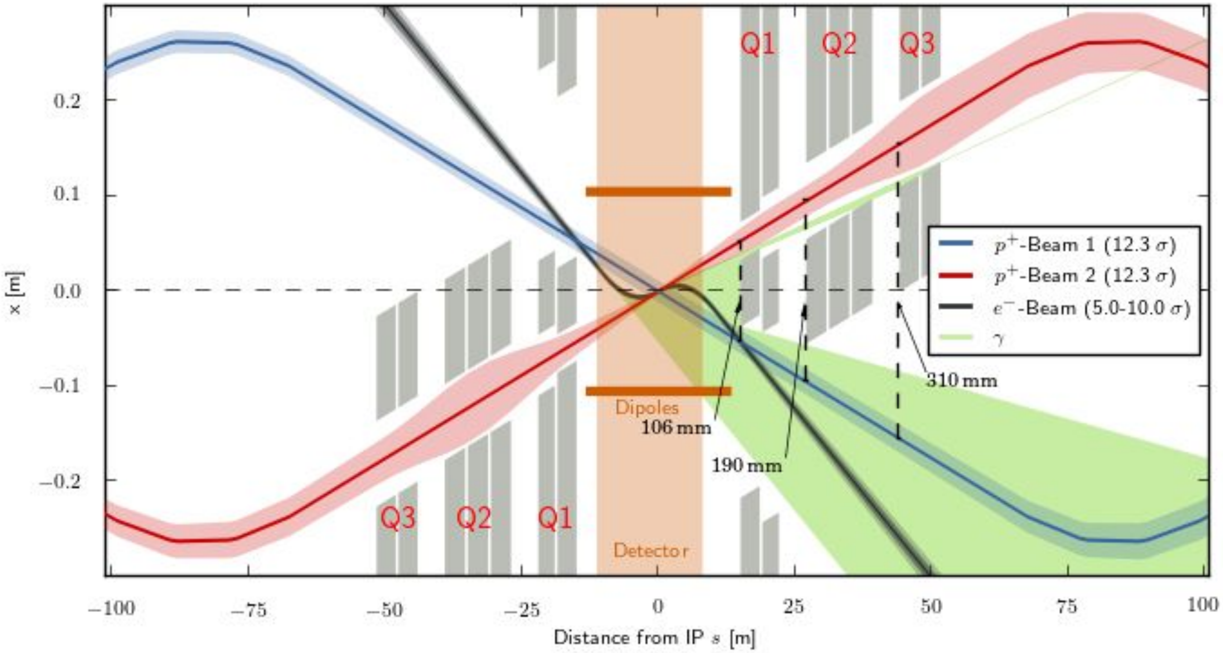


R. Martin

- Optimizing length dipoles 2/3L*= 10 m

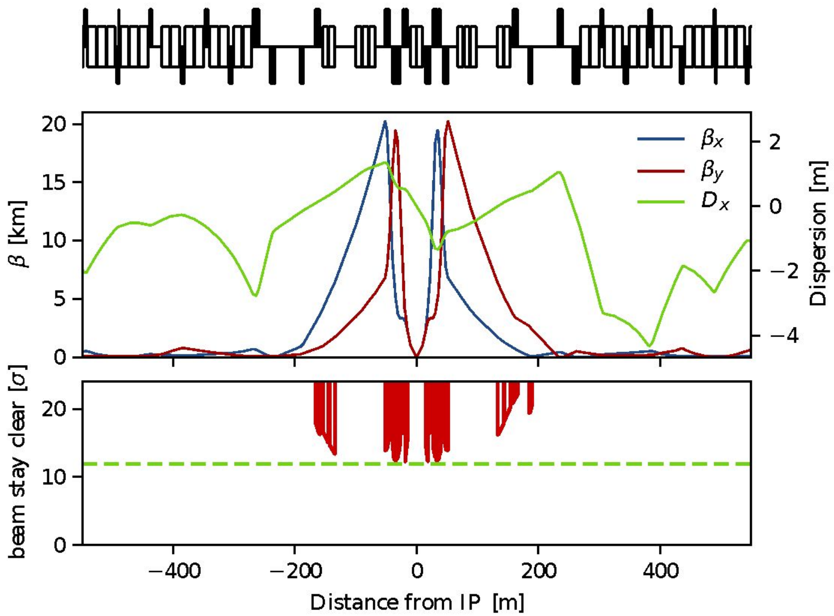
	50 GeV, 6.4 mA	50 GeV, 20 mA	60 GeV, 6.4 mA	60 GeV, 20 mA
P_{synch}	13 kW	40 kW	27 kW	83 kW
E_{crit}	296 keV		513 keV	

B. Holzer's talk

LHeC IR

- Integration in LHeC IR beam 2 (colliding beam)
- Ends of IR dictated by ATS optics
- Some issues
  - Q6 needs more strength and aperture
  - Some quadrupoles in dispersion suppressor are too strong
  - 15 mm residual dispersion at IP -> maybe improved with better macros
- Assumed 12.3 sigma beam stay clear
  - Require specific phase advances between extraction kicker and IP (more in integration into lattice)

R. Martin



Integration into HL-LHC lattice

- Mainly address TO DOs:
  - Integrate new IR into the HL-LHC lattice with Achromatic Telescopic Sceme (ATS) optics (allows further reduction of beta* and increases sextupole efficiency - phase-locks along the lattice)

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- Already have the IR2 that fulfills the optics requirements at ends for previous lattice, but need to address **(even bigger) challenge**:
  - To use apertures of the magnets we have phases restrictions between Kicker->IPs (R. Martin) Validated for version HLLHCV1.3 onwards.
  - Current lattice was integrated with HLLCHCV1.0. Even case for β^*=10 cm has still to be validated.

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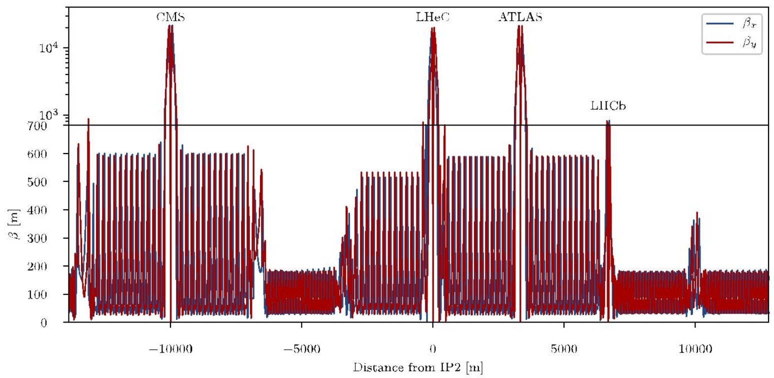
- **Solution**: Build from scratch new lattice using new version of HL (HLLHCV1.3). Validate apertures on IR matchings and also useful to have LHeC lattice with an updated HL version… Loads of work though!



- After many tries finally we have a lattice that fulfils the 4 requirements:

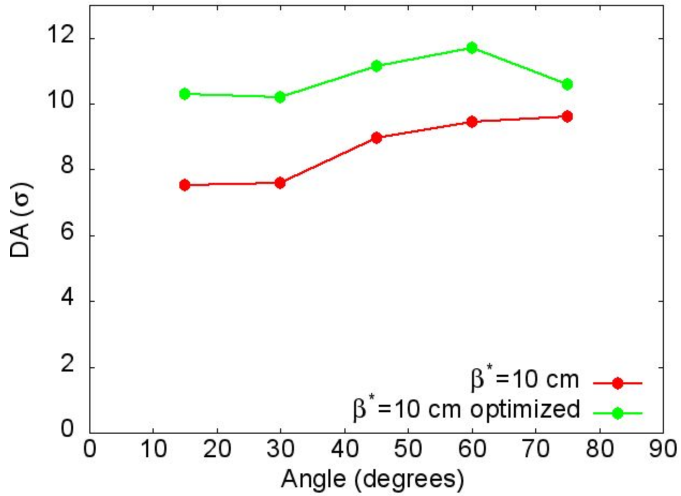
  1. Integrated to HLLHCV1.3 lattice
  2. New IR (Roman's matching and Brett design for triplet)
  3. ATS for 3 low-beta* (15 cm in IR1/5 and 10 cm in IR2)
  4. **New requirement:** Horizontal phase between kicker in IR6 and triplets < 30 degrees.

DA studies

- DA studies: 10^5 turns, 60 seeds, 5 angles, collision energy and errors in arcs.
- Initial DA around 7σ, bellow 10σ required for HL.

- Explore two things to improve the DA:

1. **Explore phase between IPs.**
   - Horizontal phase restricted. Kicker->triplet (1,2, 5) < 30°
   - Vertical phase. No restrictions.
2. **Non-linear correctors.**
   - Correctors in IR1 and IR5
     Consistent increase in DA
   - Correctors in IR2 (a3/b3/a4/b4/b6)
     Less (but necessary) increase



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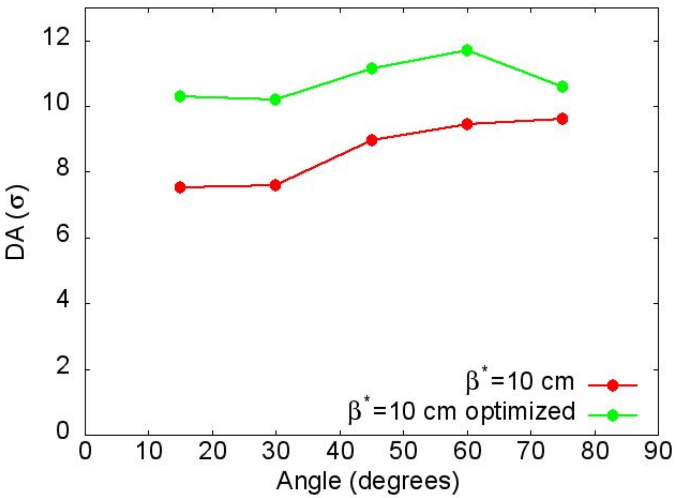
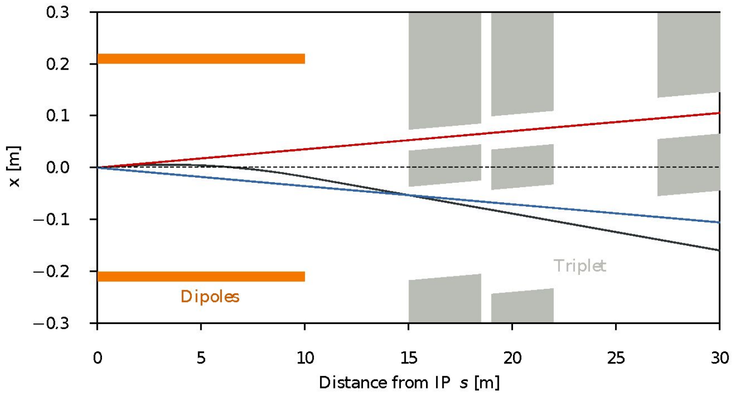


- Increase DA by finding good phase and adding non-linear correctors.
- New min DA: **10.2** σ. Not huge increase but enough to get **HL target.**

Case for lower β*

R. Martin

- Desirable case for particle physics -> lower β*. Desired: 5 cm, compromise: 7 cm.
- Smaller β* results in larger beam size in triplet -> Needs different final focus system.
- Larger apertures in magnets -> Gradients decrease -> Increase length
- Is there any available space? 5 m space between electron dipoles and triplet



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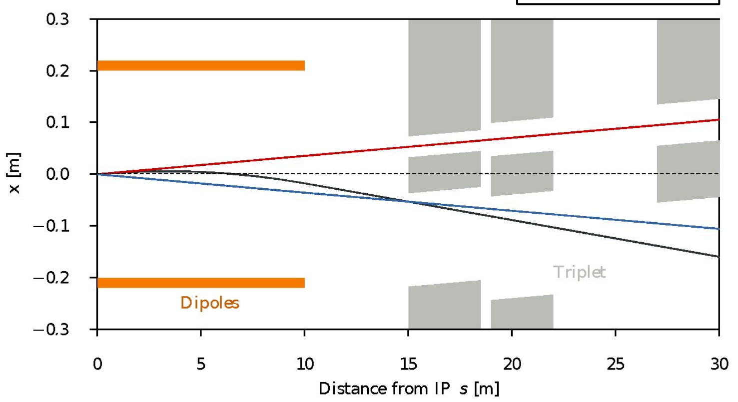
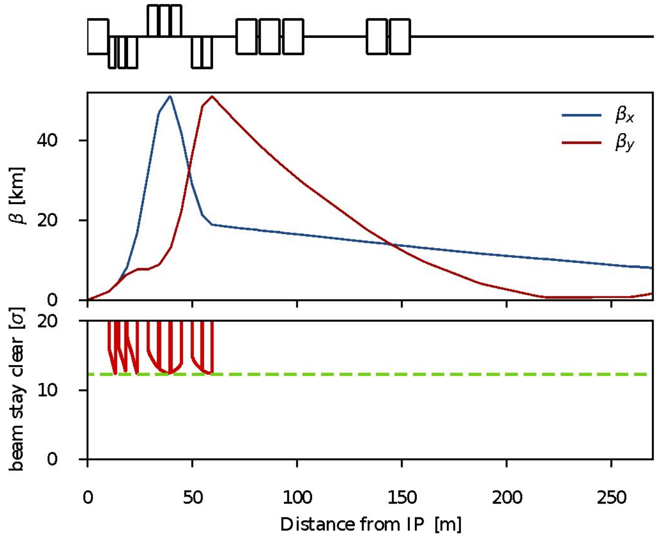


- No option of decreasing L* -> increase of SR
- Normal conducting quadrupole?
- Pole tip of 1 T assumed, 20 mm aperture, 50 T/m gradient

Magnet	Gradient [T/m]	Length [m]	Aperture radius [mm]
Q0 (nc)	50	3.0	20
Q1a	110	3.5	27
Q1b	162	5.0	37
Q2	123	5.0	62
Q3	123	4.5	62



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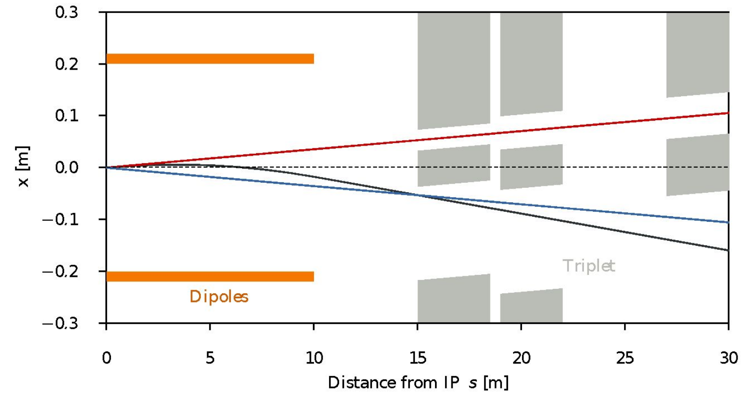

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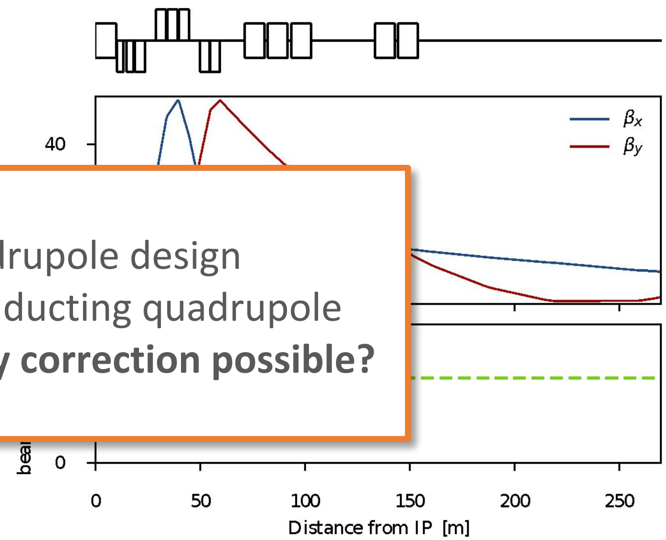

ISSUES

- Validation of septum quadrupole design
- Validation of modified superconducting quadrupole
- Integration into ring. **Chromaticity correction possible?**

DA studies – case for lower β*

- Ignoring temporarily the (important!) aperture/gradient issue in the triplet, we can see how it looks for the lattice, particularly to address chromaticity issue
- **Old method**: Reducing β* with ONLY quadrupoles in IR2
  - **Challenge**: Reducing β* increases chromaticity, beyond chromaticity correction of sextupole families.
- **New Method**: Reduce β* by re-matching ATS. Changing IR3, increases β function (and correction efficiency) in sextupoles in arc 23.
  - **Result**: Lattices have been made with lower β* and with chromaticity correction for β*=7,8,9
  - **Disclaimer 1:** Matching allows focusing families to contribute to (larger) defocusing chromaticity.
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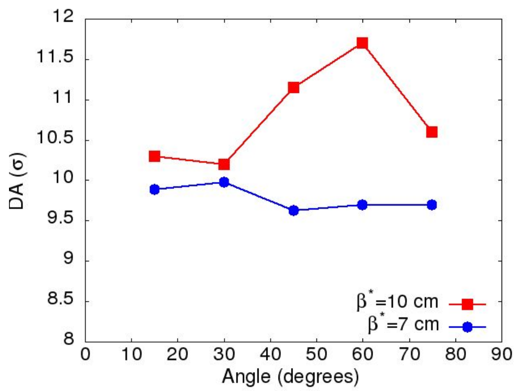

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- Phase optimization + non-linear correctors increase DA to 9.4σ

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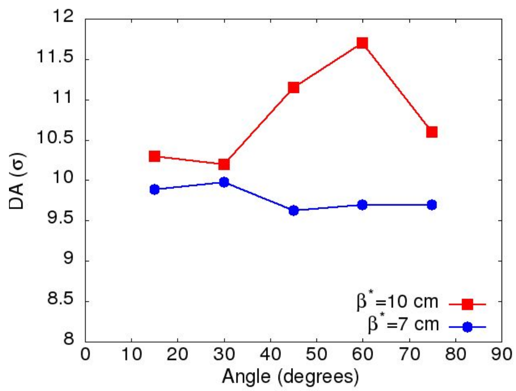

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- β*=7 cm chromatic correction achievable. DA slightly bellow target but no likely to be the biggest showstopper (magnet/SR).
- For β*= 5 cm even chromatic correction might be a problem.

IR Alternative

- Triplet final focus inherited from ALICE
  - Aperture is shared and antisymmetry guarantees same optics for both beams
  - Same optics -> similar chromaticity

- For LHeC case, antisymmetry is not strictly necessary
- Chromaticity meets limit only in vertical direction, more flexibility in horizontal

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Symmetric Doublet?

R. Martin

- Large beta function in one plane and relatively low in other plane
- Advantages:
  - Integrated strength is lower -> Reduction of chromaticity and length of final focus system
  - Sorter final focus -> Longer L* -> lower SR?
  - Choose large beta function in horizontal plane -> less problems with vertical chromaticity correction
- Disadvantages:
  - Higher peak β function -> validate with magnet design?
  - Breaking of sequence of focusing , defocusing quadrupoles -> need to break elsewhere

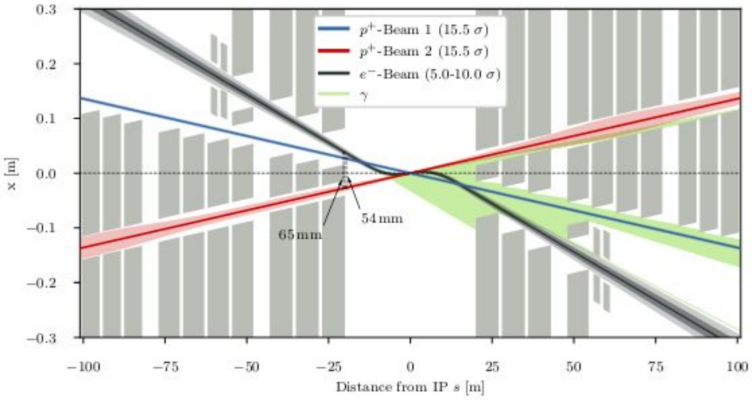
FCC-eh

- Magnets
- Synchrotron Radiation
- Chromaticity
- Dynamic Aperture

FCC-eh

- **Magnets**
  - Similar magnets but need to be validated for this design

    -L*p= 23 m
    -L*e=36 m
    -Start with β*=10 cm (Goal β*=15 cm)



- **Synchrotron Radiation**
- **Chromaticity**
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  - SR Power and Ecrit is more than halved in comparison with similar case with LHeC

	LHeC/FCC-eh 50 GeV, 20 mA	LHeC/FCC-eh 60 GeV, 20 mA
Psync (kW)	40 /16.7	83/34.7
Ecrit (keV)	296/165	513/286

- **Chromaticity**

- **Dynamic Aperture**

FCC-eh

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  - Some of the sextupole families are above the limit (k2=-0.0480 m^{-3})
  - Perhaps can be fixed by optimizing the chromaticity correction
  - Otherwise a different scheme must be implemented. ATS?
- **Dynamic Aperture**

FCC-eh

- **Magnets**
  - Similar magnets but need to be validated for this design
- **Synchrotron Radiation**
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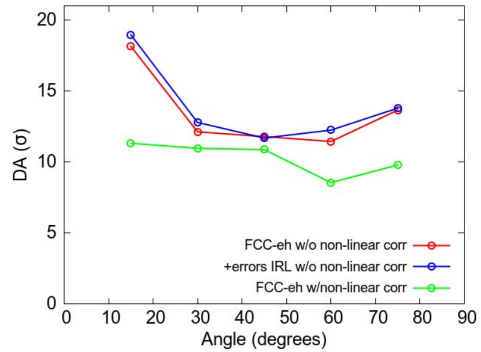
  - Acceptable DA (>10 σ) even without non-linear correctors on main IR



FCC-eh

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- **Dynamic Aperture**
  - Acceptable DA (>10 σ) even without non-linear correctors on main IR
- **Lower β^***
  - Available Space (longer magnets, not much space left)
  - Synchrotron Power (depends of how much we can take, much better than LHeC case)
  - Magnet aperture and gradients (perhaps the main limitation, needs validation still for the β^*=10 cm case)

Conclusions

- **We have a new realistic optics for beta*=10 cm:**
  - Realistic magnet design
  - Integrated into ring (now for HLLHCV1.3 and addressing aperture issue with kicker)
  - Chromaticity correction achievable
  - Dynamic aperture studies above target with the help of non-linear correctors
- **Case for lower beta* is more challenging:**
  - Ideas with a septum quadrupoles, but needs input from design
  - Chromaticity correction achievable using ATS, but on the limit for beta*=7 cm
  - Dynamic aperture slightly below target
  - Real showstopper might come from elsewhere (magnet design? SR?)
- **Looking for new ideas:**
  - Doublet better approach?
  - Might fix the chromaticity and SR issue, but need to make sure it works for magnets/arc integration
- **FCC-eh case:**
  - Some issues to address: validate magnet for this design, chromaticity meets limit
  - But some aspects are more optimistic: lower SR