DE LA RECHERCHE À L'INDUSTRIE

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Arc design and lattice integration

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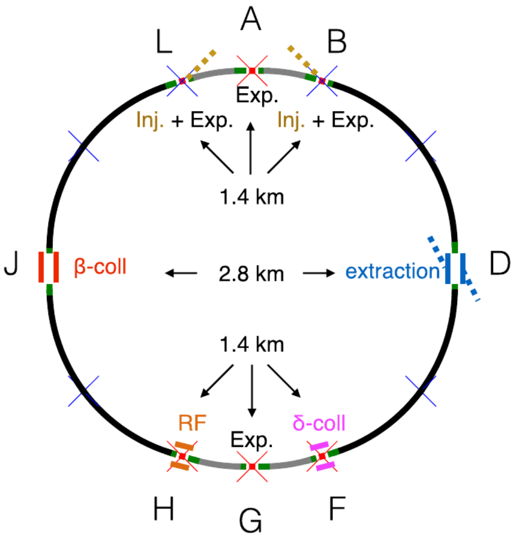
FCC week 2018

with many thanks to B. Dalena, D. Boutin, W. Bartmann, E. Cruz-Alaniz, M. Hofer, R. Martin, J. Molson, D. Schoerling, D. Schulte, ...

Outline

Status at the FCC week 2017

- Status at FCC week 2017:
  - The ring lattice has been updated to fit with the new layout.
  - The lattice is available on the git repository `https://gitlab.cern.ch/fcc-optics/FCC-hh-lattice.git`.
  - The dispersion suppressor has been modified to insert collimators.
  - The aperture model is being updated to take into account the last beam screen geometry.
  - A new spurious dispersion scheme has been integrated.
  - The coupling and tune correction is under integration.
  - Alternatives for the arc FODO cell have been provided (60 degrees and longer cell).
- Perspectives:
  - Inserting octupoles (with optimized location) for Landau damping.
  - To refine tune and chromaticity corrections (by freezing phase advances between IPs).
  - To refine alternatives for the arc cells.
  - To integrate other correction schemes (skew sextupoles,...).
  - Options of combined multipole lenses.



→ **see D. Schulte: "Parameters and Layout"**

- New arc FODO cells:
  - FODO cells a bit longer.
  - b_2 up to 50 units in the main dipoles.
  - More realistic magnet fields.
    - Courtesy D. Schoerling's group
  - Longer inter-dipole distance.
    - 1.36 m → 1.5 m
    - $\Rightarrow B_{MB} \uparrow$
- New experimental insertion region:
  - → **see R. Martin "Experimental insertions"** .
  - $L = 1.5$ km → $L = 1.4$ km.
    - LAR a bit longer.
    - $\Rightarrow B_{MB} \downarrow$
  - Alternative inner triplet.
- $B_{MB} = 15.71$ T → $B_{MB} = 15.96$ T

Integration strategy

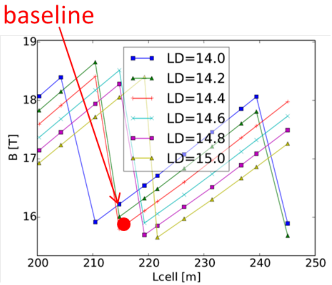
- A python script was written to generate the MAD-X files for the integration of the different lattices and of the insertions.
- The FODO cells of the arcs are generated according to some input parameters (e.g. range of the cell length).
- The dispersion suppressors are generated.
- The matching macros are generated.
- Some matching sections between the dispersion suppressors and insertions can be added.
- The insertions are optimized by different groups.
- The global tune is matched with the phase advance of the FODO cells in the long arcs.
  - Phase advances of the FODO cells in the SAR: $90°$.
  - Phase advances of the FODO cells in the LAR: $90+\epsilon_{x,y}°$.
  - Phase trombones can now be used to match the phase advances between insertions.
- The chromaticity is corrected by two sextupole families.

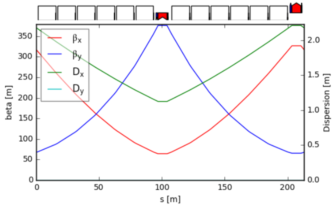
→ see Dalena's talk at the FCC week 2015 in Washington.

→ see CERN-ACC-2015-035 First results for a FCC-hh ring optics design

Parameters

- Circumference 3.75 × LHC ≈ 100 km.
- Maximum dipole field: 16 T.
- Magnetic dipole length:14.3 m → is calculated to fill the FODO cell.
- Phase advance per FODO cell: 90°.
- Maximum gradient in the QPole: 400 T/m → 360 T/m.
- ∅=50 mm.
- Spacing dipole-dipole: 1.36 m → 1.5 m.
- Min. spacing QPole-dipole: 3.67 m → Min. spacing dipole-SSS: 1.3 m.
- Spacing QPole-sextupole: 0.4 m → 0.35 m.
- Length sextupole: 1.2 m
- Length orbit corrector: 1.0 m → 1.2 m
- Length b_3 corrector: 0.11 m

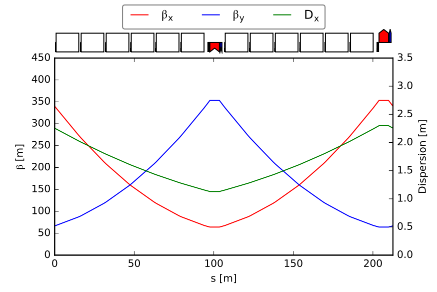




Impact of b_2

- Because of saturation effects in the main dipoles, $b_2 = \pm 50$ at collision.
- Integrated strength of one dipole for $b_2 = 50$: $\frac{b_2 L_d}{\rho R_{\text{ref}}} \approx 0.4 \times 10^{-3}$ to be compared with one quadrupole: 14×10^{-3}.
- Integrated strength of 6 dipoles is 17% of one quadrupole!

$b_2 = 0$



- $L_{MQ} = 7.2$ m
- $G_D = -317$ T/m
- $G_F = +315$ T/m

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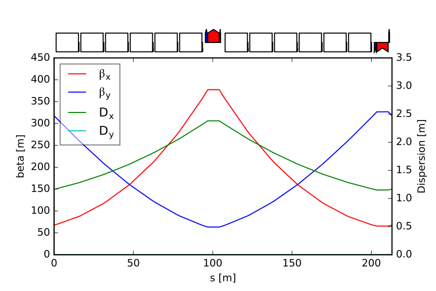
$b_2 = -50$ inner side



- $L_{MQ} = 7.2$ m
- $G_D = -267$ T/m
- $G_F = +358$ T/m
- The quadrupoles MQs are enlarged to handle the extra gradient.
- $b_2 = 0$ at collision enables to reduce the quadrupole length to 6.4 m.

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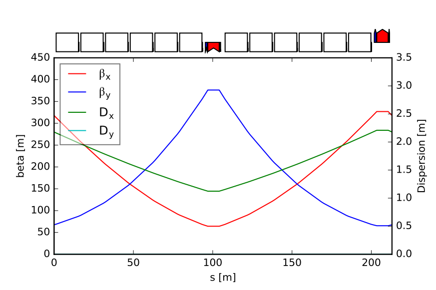
$b_2 = +50$ outer side



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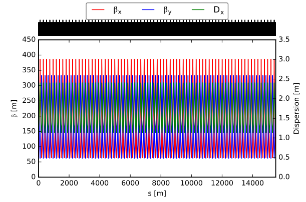
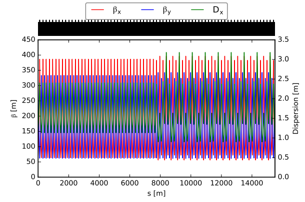
Impact of b_2 on the long arc

No missing dipole

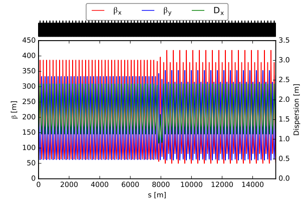


1 missing dipole



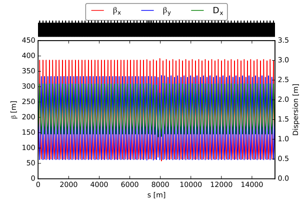
- A dipole is removed for technical straight sections.
- Dispersion and betatron wave.

2 missing dipoles at 180°



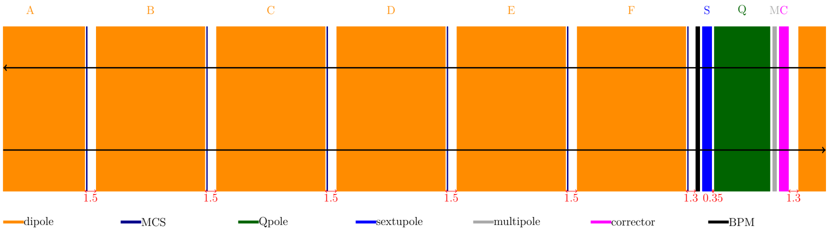
- Dispersion wave canceled by removing a 2nd dipole at 180°.
- Betatron wave not canceled.
- β-beating of 30% ($b_2 = 50$)!.

1 missing dipole with correction



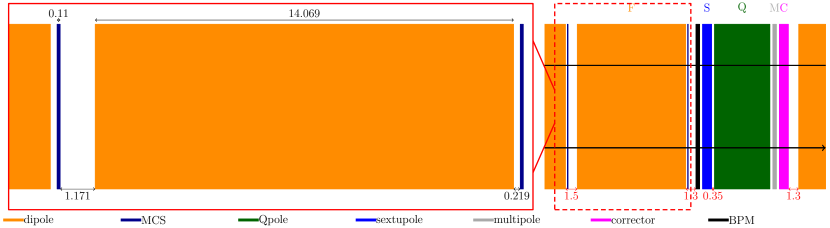
- Use of 8 trim quadrupoles to cancel the β-beating, dispersion beating and tune split.
- Only 1-2% of residual β-beating.

Arc cell: baseline



⇒ The FODO cell is 213.03 m long.

- The distance inter-dipole is 1.5 m.
- The main dipole MD is 14.069 m long.
- The maximum dipole field is 15.96 T with an aperture of 50 mm.
- MCS has the same length as in LHC: 0.11 m.
- The maximum quadrupole gradient is 360 T/m. MQs are lengthened in this aim.
- The maximum corrector field is 4 T.



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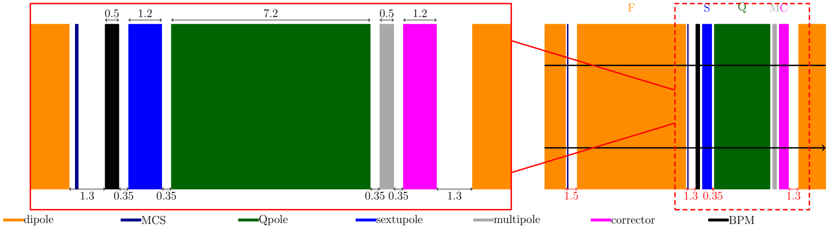

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→ see Schoerling: "Other magnets parameters" .

→ see Lorin: "Main quadrupoles" .

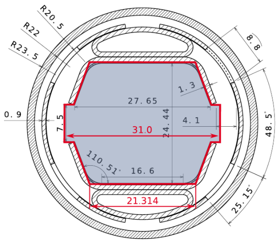
→ see Louzguilti: "Lattice sextupoles and octupoles" .

Magnet type	Distance (m)	Remarks
MB-MB	1.5	May be longer if stronger MCS required
MB-SSS	1.3	Does not include BPMs
MQ-Other	0.35	Other magnetic elements in SSS
Other-Other	0.35	

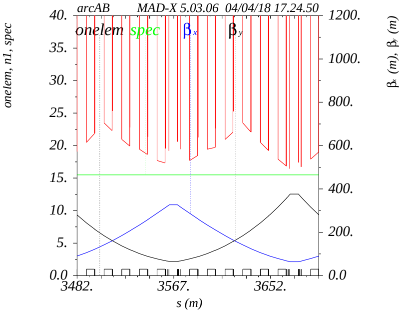
Magnet type	Number	Max. Strength	Length	SC material	LHC nominal strength (56 mm aperture)	LHC nominal strength scaled to 50 mm aperture
Main Dipole (MB)	4668	16 T	14.1 m	Nb_3Sn	8.33 T	8.33 T
Main Quadrupole (MQ)	744	360 T/m	7.2 m	Nb_3Sn	223 T/m	250 T/m
Trim Quadrupole (MQT)	120	220 T/m	0.5 m	Nb-Ti	123 T/m	140 T/m
Skew Quadrupole (MQS)	96	220 T/m	0.5 m	Nb-Ti	123 T/m	140 T/m
Main Sextupole (MS)	696	7000 T/m^2	1.2 m	Nb-Ti	4430 T/m^2	5560 T/m^2
Main Octupole (MO)	480	200,000 T/m^3	0.5 m	Nb-Ti	63,000 T/m^3	90,000 T/m^3
Sextupole Corrector (MCS)	9336	3000 T/m^2	0.11 m	Nb-Ti	1630 T/m^2	2050 T/m^2
Dipole Corrector (MCB)	792	4 T	1.2 m	Nb-Ti	3 T	3 T
DIS Trim Quadrupole (MQTL)	48	220 T/m	2.0 m	Nb-Ti	129 T/m	145 T/m
DIS Quadrupole (MQDA)	48	360 T/m	9.7 m	Nb_3Sn	129 T/m	145 T/m

- Contrary to LHC, the dipoles are assumed to be straight.
- A margin of 1.2 mm is added to the horizontal tolerance to handle the sagitta.

Courtesy: I. Bellafont *et al.*
Courtesy: R. Martin

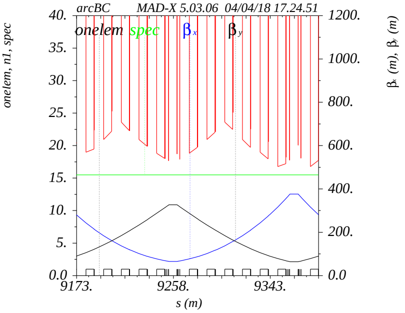


Arc AB: $b_2 = +50$



$n_{1,\text{min}} = 16.4$

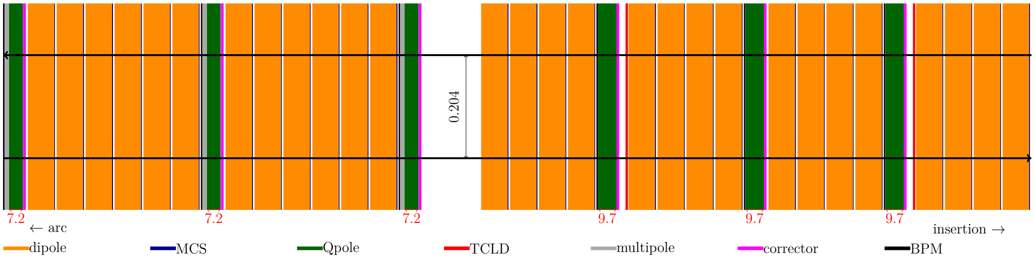
Arc BC: $b_2 = -50$



$n_{1,\text{min}} = 16.8$

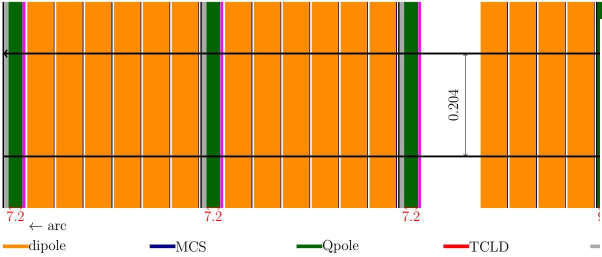
- Reduction of the beam-stay clear by 1.5σ because of the sagitta.

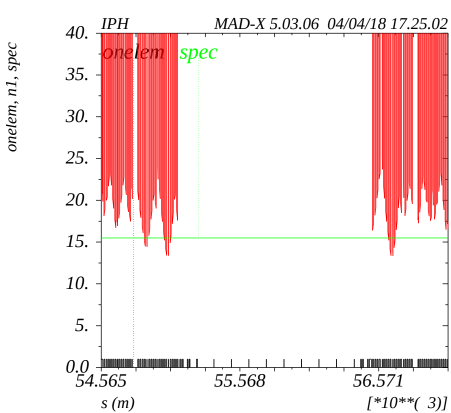
Dispersion suppressors



- The selected dispersion suppressor is similar to LHC: best compromise between filling factor and flexibility.
- Two collimators (TCLD) of 1 meter are inserted to clean the beam at the arc entrance (the needed space is 5 meters for each TCLD).
- Bottleneck for the machine aperture (location of betatron and dispersion peaks).

Dispersion suppressors





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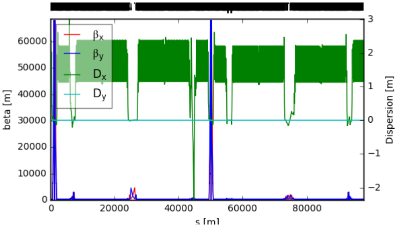
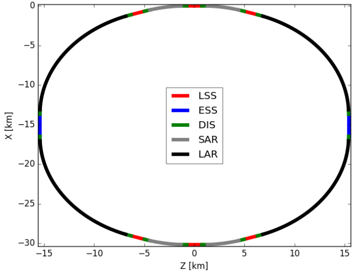




Parameters

Parameter		Value
Energy	TeV	50
Circumference	km	97.75
β^*	m	0.3
L^*	m	40
α	10^{-4}	1.024
γ_{tr}	-	98.80
Q_x coll	-	110.31
Q_y coll	-	108.32
Q_x inj	-	110.28
Q_y inj	-	108.31
Q'_x	-	2
Q'_y	-	2
MB field	T	15.96
MQ gradient	T/m	359
MS gradient	T/m^2	6998

Insertions: main experiments

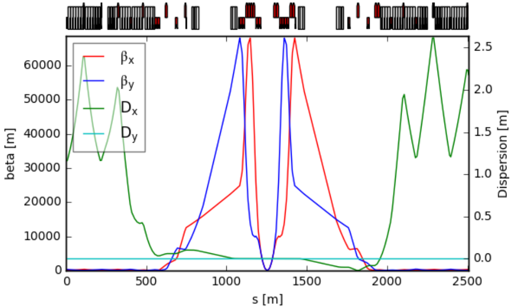
- Version 7 of the EIR.
- $L^* = 40$ m.
- Courtesy: R. Martin *et al.*.

→ **see Martin: "Experimental insertions"**

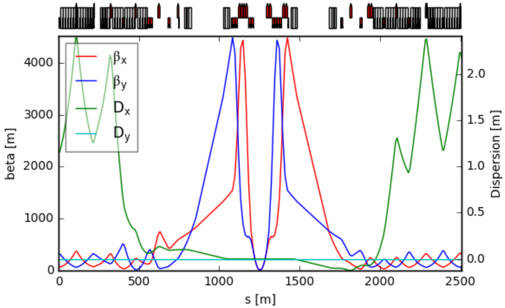
→ **see Abelleira: "Flat beam alternative"**

- Considered β^*:
  - 6.0 m (injection)
  - 4.6 m (baseline injection)
  - 1.1 m (baseline)
  - 0.3 m (ultimate)
  - 0.2 m (more ultimate)
  - 0.15 m (ultimate ultimate)

$\beta^* = 0.3$ m



$\beta^* = 4.6$ m



Insertions: injection + low-$\mathscr{L}$ experiment

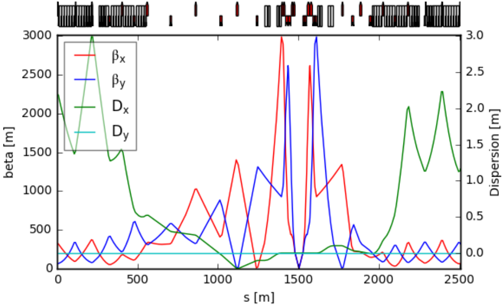
- Injection in the same section as the additional experiments.
- $L^* = 25$ m

→ **see Martin: "Experimental insertions"**

→ **see Renner: "FCC-hh injection and extraction: insertions and requirements"**

- New version of the insertion implemented.
- Courtesy: M. Hofer *et al.*
- Considered β^*:
  - 27 m (injection)
  - 3 m (collision)

Inj.+Exp. section: LSS B (@ collision)



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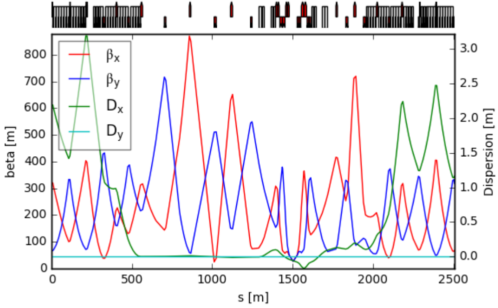

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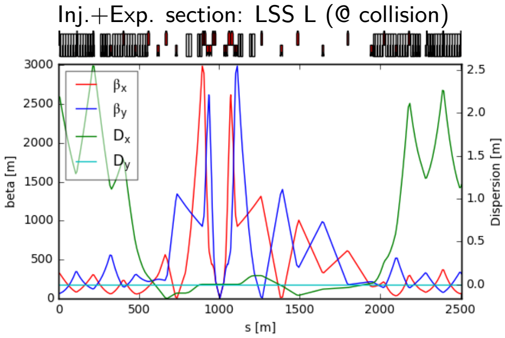
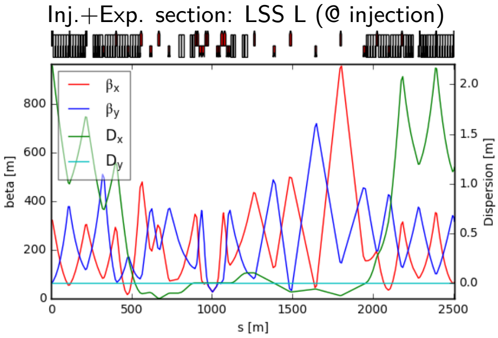




Insertions: collimation sections

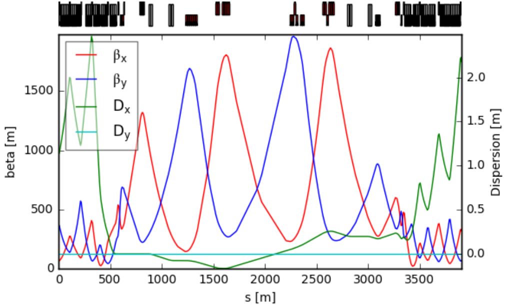
- Dedicated section to β-cleaning
- The DIS is optimized to enhance the losses coming from β and δ collimation.

→ **see Molson:“Betatron collimation system insertions”**

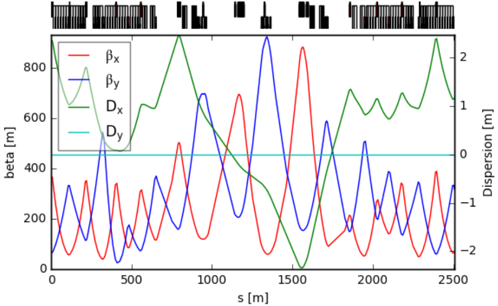
→ **see Bruce: “Collimation performance and issues”** .

- LHC-scaled δ-cleaning insertion
- Courtesy: J. Molson
- Alternative under development at FNAL.

β-cleaning section: ESS J



δ-cleaning section: LSS F

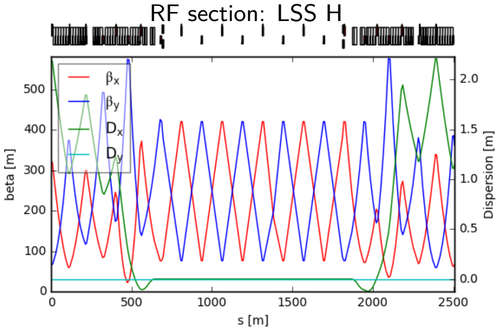


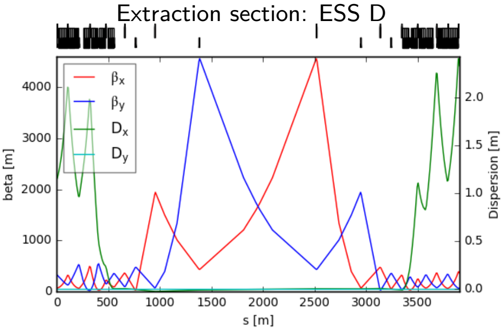
Insertions: RF+extraction

- RF section is made of FODO cells: it can be used to adjust phase advances between insertions.
- The lattice of this section has been implemented.

- Dedicated section for the extraction (2.8 km).
- New version of this insertion will be integrated soon.
- Courtesy: F. Burkart, W. Bartmann *et al.*

→ **see Renner: "FCC-hh injection and extraction: insertions and requirements"**





Tuning of the machine is the key

- 2 schemes are currently implemented to tune the ring:
  - FODO cells of long are slightly detuned ($90^\circ + \epsilon$). DIS are rematched.
  - Use of phase trombones in insertions. More straightforward but less realistic model.
- Studies have shown that phase advances between insertions have a major impact on dynamic aperture.
- Modification of an insertion can imply a dramatic DA reduction.
- **see Cruz-Alaniz: "Dynamic aperture at collision"**
- **see Dalena: "Dipole Field Quality and Dynamic Aperture for FCC-hh"**
- It is mandatory to understand the needs on the phase advances differences to freeze the first order optics.
- Next steps are only possible if this issue is correctly addressed.

Arc design: correction

- BPMs and dipole correctors are integrated in the lattice to correct the orbit.
- Trim quadrupoles are integrated to correct the horizontal spurious dispersion, the β-beating (still under investigation) and the dispersion-beating
- Skew quadrupoles are used to correct the coupling (sets of 4 skew quadrupoles separated by 90° each) and the vertical spurious dispersion.

  → **see Boutin: "Alignment"** .
- The dynamic aperture studies have shown that:
  - Correcting b_3 components in dipoles is mandatory.

  ⇒ We can correct up to 4 units of b_3 at collision with MCS (max. strength 3000 T/m^2).
  - Currently, b_4 and b_5 do not need any correctors.
  - These values have been checked with updated table (source: D. Schoerling).

  → **see Dalena: "Dipole Field Quality and Dynamic Aperture for FCC-hh"**
- Octupoles have been integrated to the lattice for Landau damping and beam-beam correction.

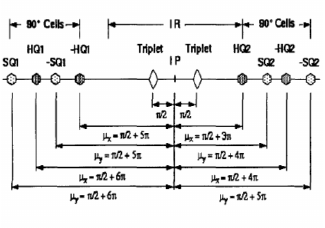
  → **see Tambasco: "Two beam stability and Landau damping"**
  → **see Pieloni: "Beam-beam effects"** .

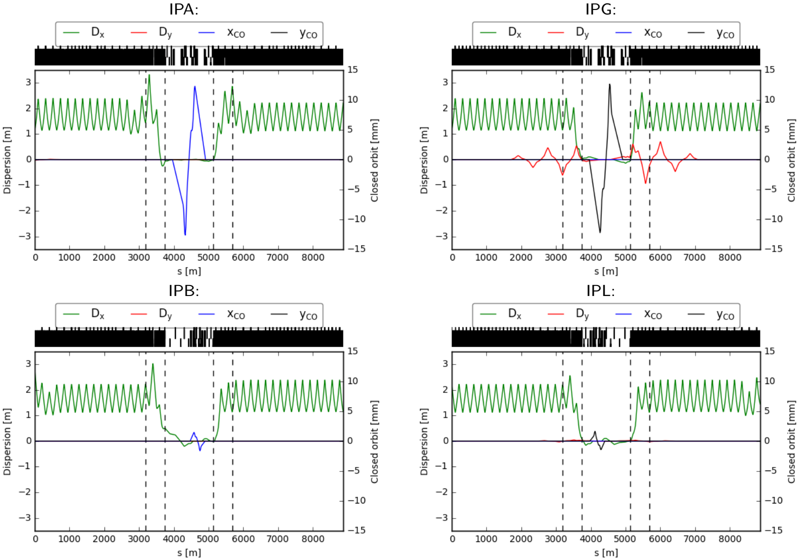
Spurious dispersion correction ($\beta^* = 0.3$ m)

- SSC-like scheme.

→ see D. Ritson, and Y. Nosochkov, "The Provision of IP Crossing Angles for the SSC", Proceedings of PAC 93

- Works for the vertical dispersion with skew quadrupoles





Alternatives for the FCC-hh ring

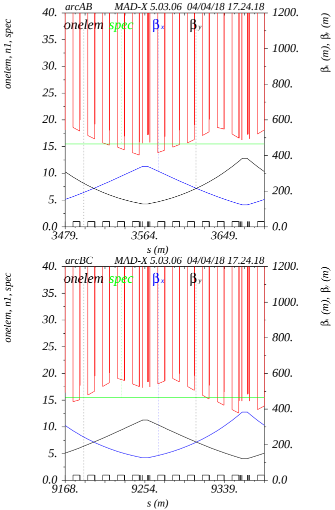
- Alternative triplet for the experiment insertion has been integrated (and flat optics)

→ **see Abelleira: "Flat beam alternative"**

- Phase advance of 60 degrees against 90 degrees (idea: E. Todesco).
  - The integrated quadrupole gradient is multiplied by $\frac{\sin 30°}{\sin 45°} \approx 0.7$.
  - ☺ With the same FODO cell length, the maximum quadrupole gradient is decreased from 360 T/m to 220 T/m ($b_2 = 0$) or 270 T/m ($b_2 = 50$).
  - With the same maximum gradient, the quadrupole can be shortened from 7.2 m to 5.4 m.
  - The FODO cell can then be shortened or dipole lengthened (by 0.3 m).
  - ☺ The reached dipole field we can get is 15.61 T (against 15.96 T before).
  - ☹ The correction schemes must be modified.
    - ☺ With a system of 6 trim quadrupoles with 60 degrees in between, possibility to correct beta-beating, dispersion beating, coupling (if skew),or tune as the system of 4 quadrupoles in the case of 90° by phase advance.
  - ☹ The dispersion is enlarged: reduction of the aperture.

Phase advance of 60 degrees

Apertures @3.3 TeV



$n_1 = 16.4 \rightarrow n_1 = 12.6$ below the target!

Parameters

Parameter		Value
Energy	TeV	50
Circumference	km	97.75
β^*	m	0.3
L^*	m	40
α	10^{-4}	2.046
γ_{tr}	-	69.91
Q_x coll	-	78.31
Q_y coll	-	75.32
Q_x inj	-	78.28
Q_y inj	-	75.31
Q'_x	-	2
Q'_y	-	2
MB field	T	15.61
MQ gradient	T/m	360
MS gradient	T/m^2	3308

Conclusion

- Current status:
  - The arc cells have been updated to fit with magnet requirements.
  - The quadrupole component b_2 of the main dipoles is taken into account in the lattice.
  - The aperture model has been updated and integrated to take into account the last beam screen geometry.
  - The bottleneck is the dispersion suppressors (too small aperture there).
  - The ring lattice has been updated.
  - The lattice is available on the git repository `https://gitlab.cern.ch/fcc-optics/FCC-hh-lattice.git`.
  - Multipole correctors (trim, skew quadrupoles and octupoles) are integrated.
  - Alternatives for the arc FODO cell have been provided (60 degrees).
- Perspectives:
  - To refine tune and chromaticity corrections (by freezing phase advances between IPs).
  - To refine alternatives for the arc cells.
  - To integrate other correction schemes (skew sextupoles,...).
  - To be ready for the CDR ;-)

Thank you for your attention!

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