DE LA RECHERCHE À L'INDUSTRIE

Arc design and lattice integration

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CEA/DRF/Irfu/DACM

FCC week 2017

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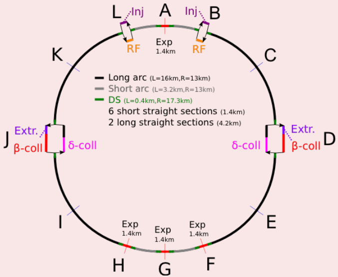
Outline

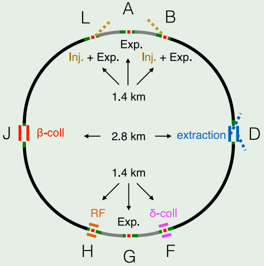
1. Layout
2. Arc lattice
3. Ring lattice
4. Spurious dispersion
5. Alternatives
6. Conclusions

Previous layout (99.97 km)



IPA	1.4 km	Main Exp.
IPB	1.4 km	Injection
IPD	4.2 km	Ext.+β coll.
IPF	1.4 km	Exp.
IPG	1.4 km	Main Exp.
IPH	1.4 km	Exp.
IPJ	4.2 km	δ coll.
IPL	1.4 km	RF

New layout (97.75 km)



IPA	1.4 km	Main Exp.
IPB	1.4 km	Inj.+Exp.
IPD	2.8 km	Extraction
IPF	1.4 km	δ coll.
IPG	1.4 km	Main Exp.
IPH	1.4 km	RF
IPJ	2.8 km	β coll.
IPL	1.4 km	Inj.+Exp.

→ see Schulte's presentation "Parameters and layout"

Integration strategy

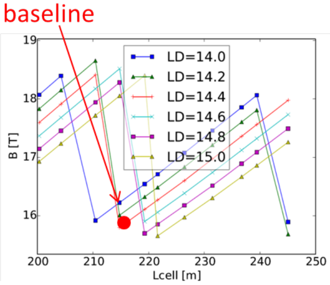
- A python script was written to generate the MAD-X files for the integration of the different lattices and of the insertions.
- The FODO cells of the arcs are generated according to some input parameters (e.g. range of the cell length).
- The dispersion suppressors are generated.
- The matching macros are generated.
- Some matching sections between the dispersion suppressors and the 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: $90+\epsilon_{x,y}{}^{\circ}$.
- The chromaticity is corrected by two sextupole families.

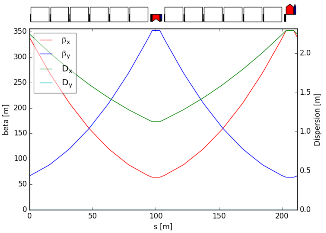
Arc cell length

- → 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

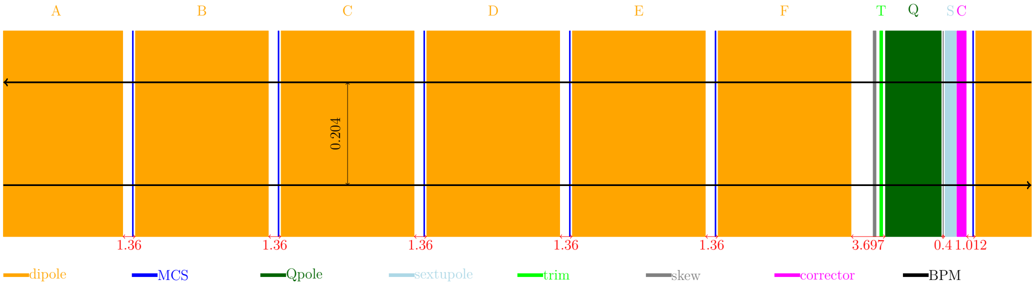
Parameters

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

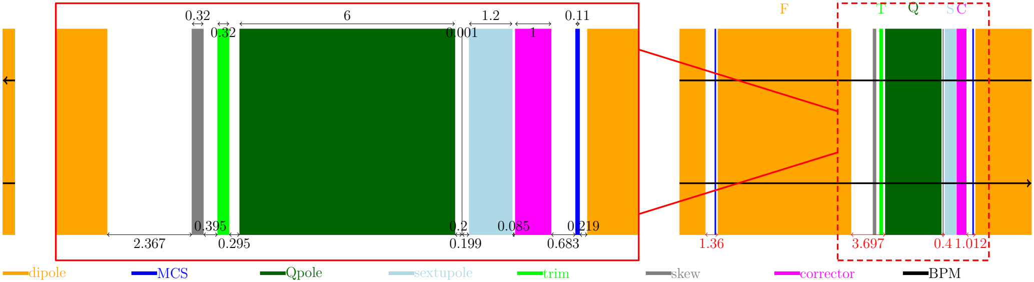




Arc design



- Each FODO cell has 12 dipoles (MD), 12 b_3 correctors (MCS), 2 quadrupoles (MQ), 2 sextupoles (MS), 2 BPMs, 2 dipole correctors.
- MD and MCS have the same length as in LHC: 14.3 m and 0.11 m.
- The FODO cell length is optimized to have the lowest dipole field.
  - The FODO cell length is 211.986 meters.
  - The maximum dipole field is 15.71 T with an aperture of 50 mm.
- The maximum quadrupole gradient is 381 T/m.



- Relative position of the BPM and the orbit corrector with respect to the MQ are different from LHC.
    - The orbit corrector needs an integrated field of 4 T.m.

  → see Boutin's talk "Alignment and beam-based correction".
- Each quadrupole is equipped with a trim and a skew quadrupole (will be refined with the correction schemes).
- Sextupole+BPM can be reverted with trim quadrupole to balance element distribution.

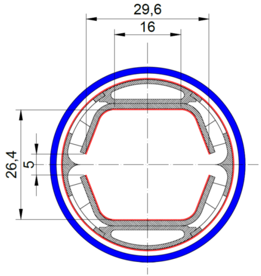
Arc design: correction

- The trim or skew quadrupoles may be used to correct the tune, beta-beating, or spurious dispersion.
  → see Boutin's talk "Alignment and beam-based correction".
- The dynamic aperture studies have shown that:
  - Correcting b_3 components in dipoles is mandatory.
  - ⇒ We can correct up to 6 units of b_3 at collision with MCS (max. strength 4430 T/m^2).
  - Currently, b_4 and b_5 do not need any correctors.
  - Correctors will be necessary if the b_4/b_5 component is above $0.142/2$ unit.
  - These values must be checked with the new table (source: D. Schoerling).

  → see Dalena's talk: "Dynamic aperture and alignment"
- Needs of octupoles for Landau damping.
  → see Kornilov's talk: "Landau damping of intra-bunch oscillations"
  → see Dalena's talk: "Dynamic aperture and alignment" for the first impact on dynamic aperture.

- Contrary to LHC, the dipoles are assumed to be straight.
- Use of a profile in cos with an offset of -1.2 mm at the dipole entrance/exit and +1.2 mm at the middle.

Courtesy: C. Garion

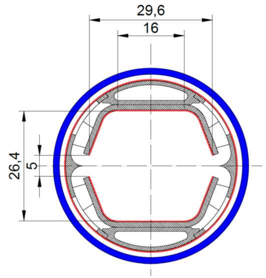


Parameters used for aperture calculation:

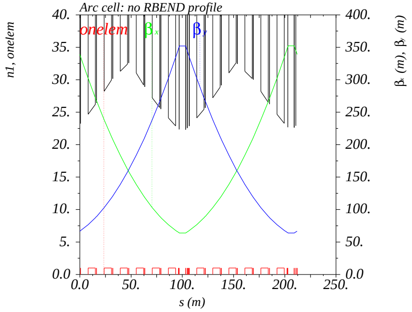
ϵ_N	2.2	μm
$\delta p/p$	6	10^{-4}
β-beating coefficient	1.05	-
Closed orbit uncertainty	2	mm
Fractional H/V parasitic dispersion	0.14	-
Peak linear dispersion	2.358	m
β_x in standard qf	355.13	m
Halo parameters	{6,6,6,6}	-

- Contrary to LHC, the dipoles are assumed to be straight.
- Use of a profile in cos with an offset of -1.2 mm at the dipole entrance/exit and +1.2 mm at the middle.

Courtesy: C. Garion

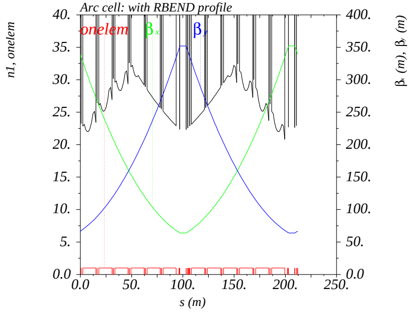


No profile @ 3.3 TeV



$n_{1,\mathrm{min}} = 22.3$

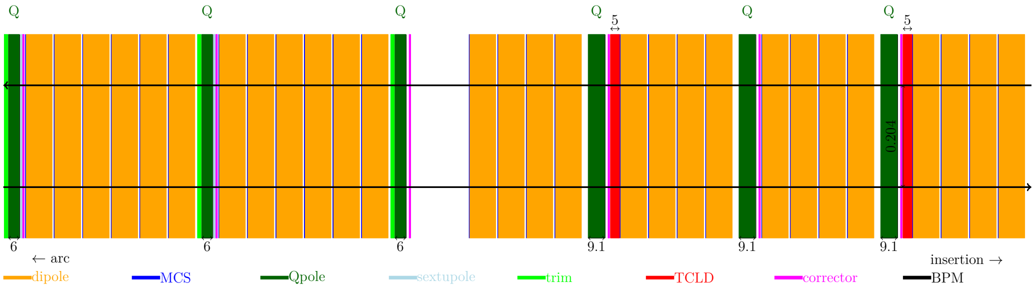
With profile @ 3.3 TeV



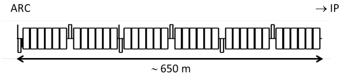
$n_{1,\mathrm{min}} = 20.8$

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

Dispersion suppressors



- Three kinds of dispersion suppressors (DIS) were investigated:
  - LHC-like DIS
  - 2 FODO cells with half-field.
  - 2 FODO cells by matching the quadrupole fields



- The selected dispersion suppressor is similar to LHC: best compromise between filling factor and flexibility.
- Two collimators (TCLD) of 5 meters are inserted to clean the beam at the arc entrance.

→ see Krainer's talk "Dispersion suppressor protection"

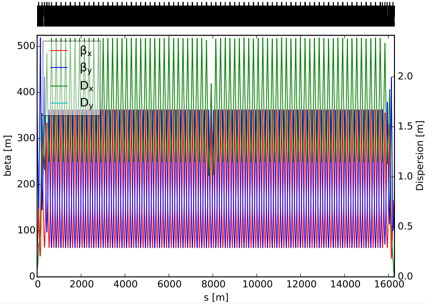
Technical straight section

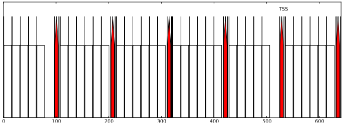
- For the shaft, some free space is needed at the middle of the long arcs.

⇒ One dipole is removed before the middle of long arcs.

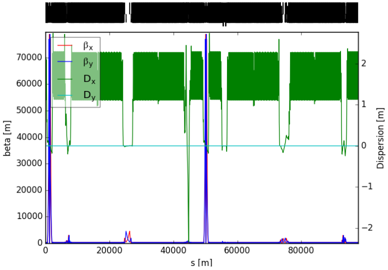
⇒ The dispersion wave is canceled by removing another dipole at 180° and thus at 2 FODO cells from the TSS.

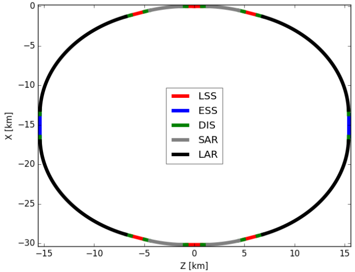
Optical functions in LAR





- ☺ Simple modification of the lattice.
- ☺ Small increase of the dipole field:
  - 15.72 T → 15.71 T.
- ☺ Very low dispersion beating (<1%).
- ☹ Freeze phase advance in the LAR.
- Other solution: use quadrupoles with opposite strength and phase advance of 180° in between.





Parameters

Parameter		Value
Energy	TeV	50
Circumference	km	97.75
β^*	m	0.3
L^*	m	45
α	10^{-4}	1.014
γ_{tr}	-	99.33
Q_x coll	-	111.31
Q_y coll	-	109.32
Q_x inj	-	111.28
Q_y inj	-	109.31
Q'_x	-	2
Q'_y	-	2
MB field	T	15.71
MQ gradient	T/m	379
MS gradient	T/m^2	7121

Insertions: main experiments

- Version 5c of the IR.
- $L^* = 45$ m
- β^* considered:
  - 0.3 m (ultimate)
  - 1.1 m (baseline)
  - 4.6 m (injection)
  - 6.0 m

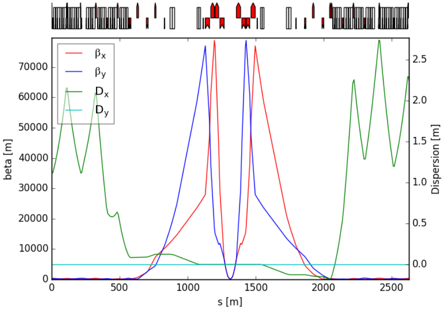
- Old scheme: Hor. spectrometer is considered (11 T.m). Has been switched off for the new baseline with a solenoid.

→ see Seryi's talk: "Experimental insertions"

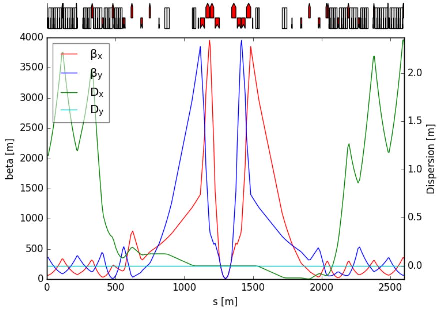
→ see Alaniz'talk: "Correction schemes for the IR of FCC-hh"

→ see Van Riesen-Haupt's talk: "Exploring the triplet parameter space to optimize the final focus of the FCC"

$\beta^* = 0.3$ m



$\beta^* = 6.0$ m



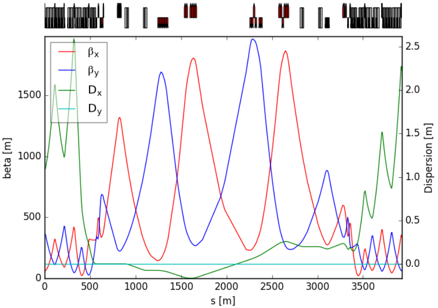
- Dedicated section to β-cleaning

→ see Langner's talk:"Betatron collimation system insertions"

- The DIS must be optimized to enhance the losses coming from β and δ collimation.

→ see Krainer's talk: "Dispersion suppressor protection".

β-cleaning section: ESS J

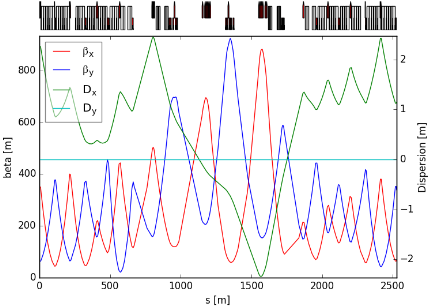


- LHC-scaled δ-cleaning insertion

→ see Faus-Golfe's talk: "Energy collimation system insertions"

- Additional chicane to enhance the beam separation: from 204 mm to 420 mm.

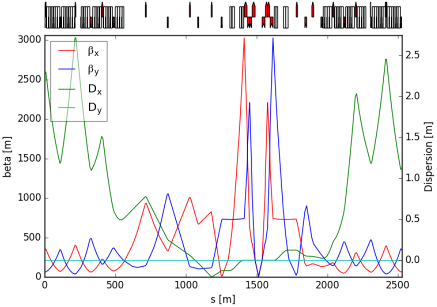
δ-cleaning section: LSS F



- Injection in the same section as the additional experiments.
- The lattice of this section has been implemented.

→ see Seryi's talk: "Experimental insertions"

Inj.+Exp. section: LSS B

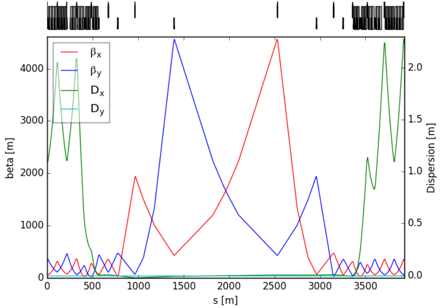


- Dedicated section for the extraction (2.8 km)

→ see Burkart's talk: "Injections and extraction insertions and dump lines"

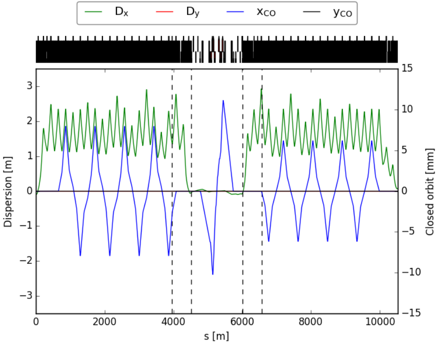
→ see Hofer's talk: "3.3 TeV beam injection into combined experimental and injection FCC machine insertions"

Extraction section: ESS D

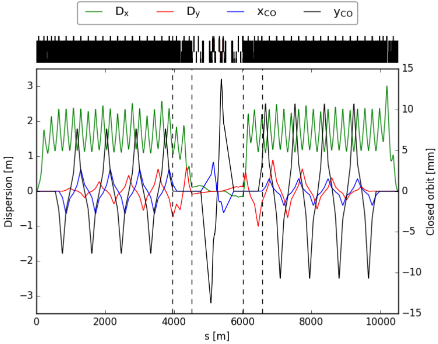


- First investigated scheme is the one of HL-LHC: an orbit distortion is made in the SAR.
- Orbit distortion generates some dispersion in quadrupoles to correct spurious dispersion.
- The obtained orbit bump is too large in the arcs (because of the beam screen) even with the ATS scheme (more than one order of magnitude to be gained).

IPA Xing scheme:

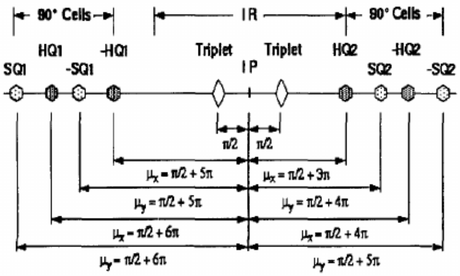


IPG Xing scheme:



Correction with the SSC scheme

- The main issue of previous scheme is too large orbit bumps (up to 10 mm).
- Another scheme has been implemented: the SSC-like scheme.
  - see D. Ritson, and Y. Nosochkov, "The Provision of IP Crossing Angles for the SSC", Proceedings of PAC 93
  - Couple of quadrupoles with opposite strength.
  - Phase advance of 180° in between.
  - The β wave cancels but not the dispersion wave.



$$\Delta\beta_x(s) = -\frac{l_q \delta G}{B\rho}\beta_{xq}\beta_x(s)\sin 2(\mu_x(s) - \mu_{xq})$$

$$\Delta\eta_x(s) = -\eta_q \frac{l_q \delta G}{B\rho}\sqrt{\beta_{xq}\beta_x(s)}\sin(\mu_x(s) - \mu_{xq})$$

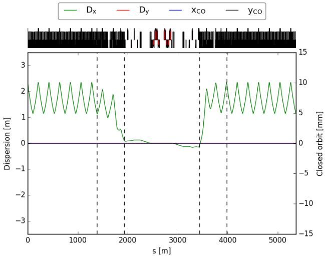
  - Works for the vertical dispersion: skew instead of normal QPoles ($x \rightarrow y$).

Hor.Plane	Left to IP	MQT.14	MQT.18 (opposite)	MQT.16	MQT.20 (opposite)
Hor.Plane	Right to IP	MQT.15	MQT.19 (opposite)	MQT.17	MQT.21 (opposite)
Vert.Plane	Left to IP	MQS.15	MQS.19 (opposite)	MQS.17	MQS.21 (opposite)
Vert.Plane	Right to IP	MQS.14	MQS.18 (opposite)	MQS.16	MQS.20 (opposite)

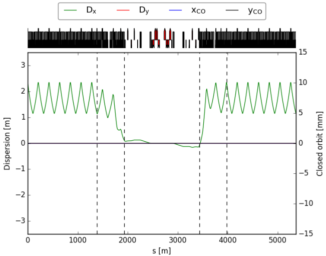
- Additional couples were used to reduce the needed strengths.

Correction of the spurious dispersion @ $\beta^{*}=0.3$ m

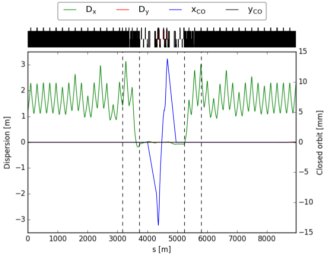
IPA no crossing:



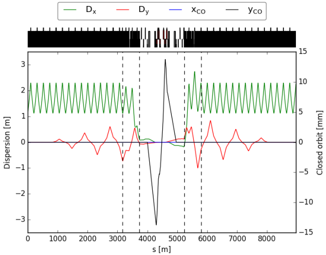
IPG no crossing:



IPA Xing scheme:



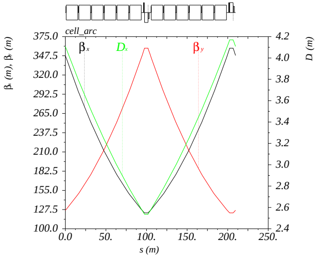
IPG Xing scheme:



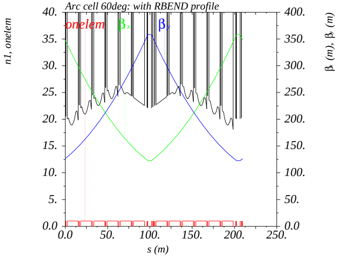
Alternatives for the FODO cell

- 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 381 T/m to 270 T/m.
  - With the same maximum gradient, the quadrupole can be shortened from 6 meters to 4.2 meters.
  - The FODO cell can then be shortened or dipole lengthened (by 0.3 m).
  - ☺ The reached dipole field we can get is 15.39 T (against 15.71 T before).
  - ☹ The correction schemes must be modified .
  - ☹ The dispersion is enlarged: reduction of the aperture.
- Longer FODO cells longer: 300 meters against 200 meters.
  - ☺ The integrated strength is multiplied by $\frac{200}{300} = 0.67$.
  - ☺ The maximum gradient is then reduced from 381 T/m to 254 T/m.
  - ☺ The quadrupoles can be shortened from 6 meters to 4 meters.
  - ☺ The dipole field can then be reduced to 15.14 T.
  - ☹ Larger dispersion and betatron functions (multiplied by 1.5).
  - ☹ The beam stay clear is reduced.

Phase advance of 60 degrees



Aperture @3.3 TeV

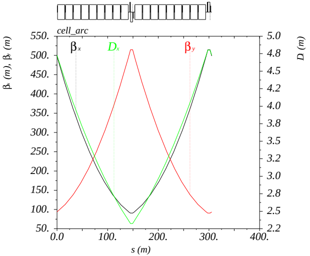


$n_1 = 20.8 \rightarrow n_1 = 18.1$

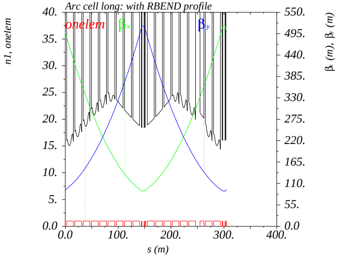
Parameters

Parameter		Value
Energy	TeV	50
Circumference	km	97.75
β^*	m	0.3
L^*	m	45
α	10^{-4}	2.006
γ_{tr}	-	70.61
Q_x coll	-	79.31
Q_y coll	-	76.32
Q_x inj	-	79.28
Q_y inj	-	76.31
Q'_x	-	2
Q'_y	-	2
MB field	T	15.55
MQ gradient	T/m	384
MS gradient	T/m^2	3514

Longer FODO cells



Aperture @3.3 TeV



$n_1 = 20.8 \rightarrow n_1 = 14.4$

Parameters

Parameter		Value
Energy	TeV	50
Circumference	km	97.75
β^*	m	0.3
L^*	m	45
α	10^{-4}	2.099
γ_{tr}	-	69.03
Q_x coll	-	81.31
Q_y coll	-	79.32
Q_x inj	-	81.28
Q_y inj	-	79.31
Q'_x	-	2
Q'_y	-	2
MB field	T	15.14
MQ gradient	T/m	370
MS gradient	T/m^2	3212

Conclusion

- Current status:
  - 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 has been 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.

Thank you for your attention!

Many thanks to all people who I have taken some material from and to all FCC-hh team.
Thanks to Schoerling's group for the multipole table of the dipoles and frutiful discussion on the arc layout.