中国科学院高能物理研究所

Progress of SPPC main ring lattice design

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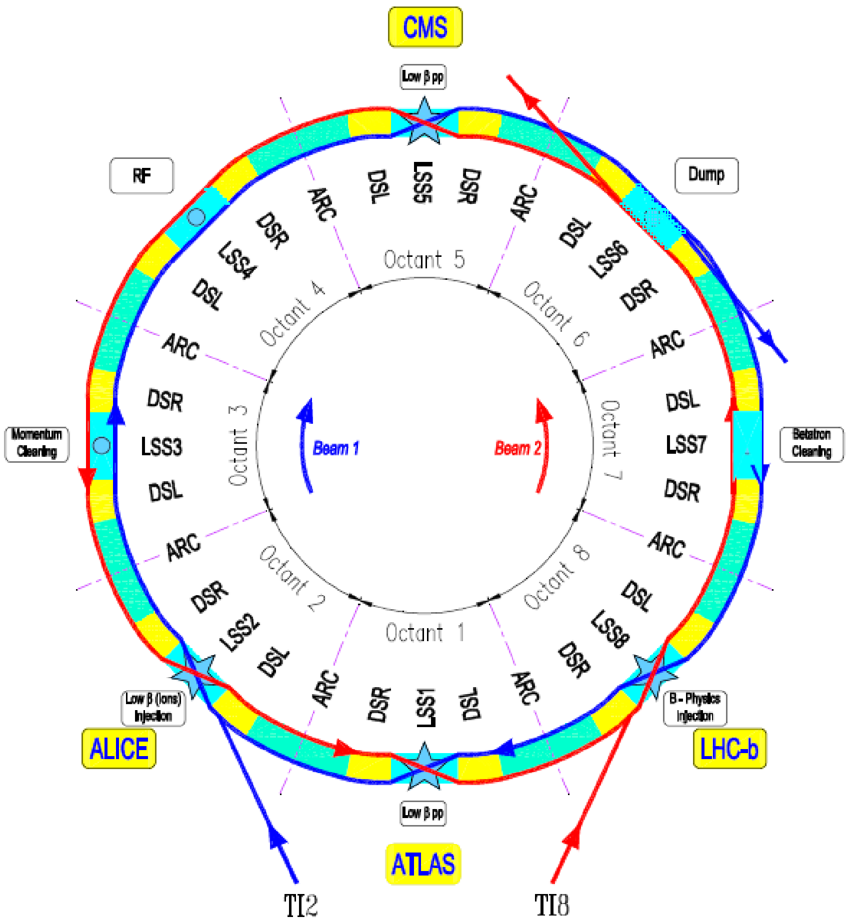
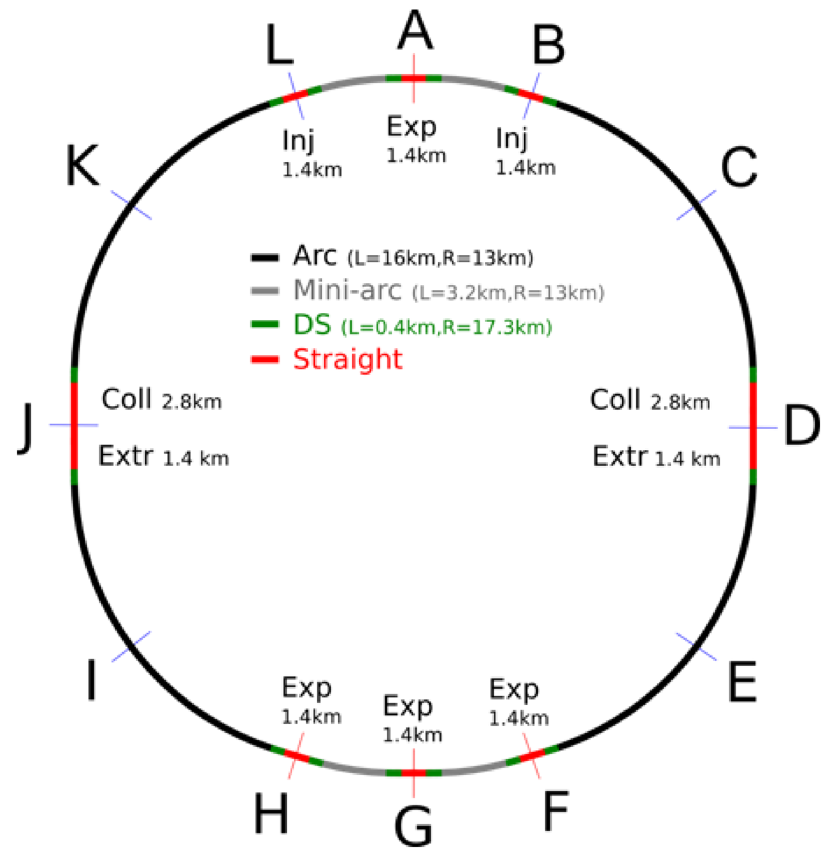
Outline

- Background
- ARC design
- Dispersion Suppressor
- Detouring Section
- Consideration of IR
- Another try of a 100 TeV collider lattice
- Summary

Background

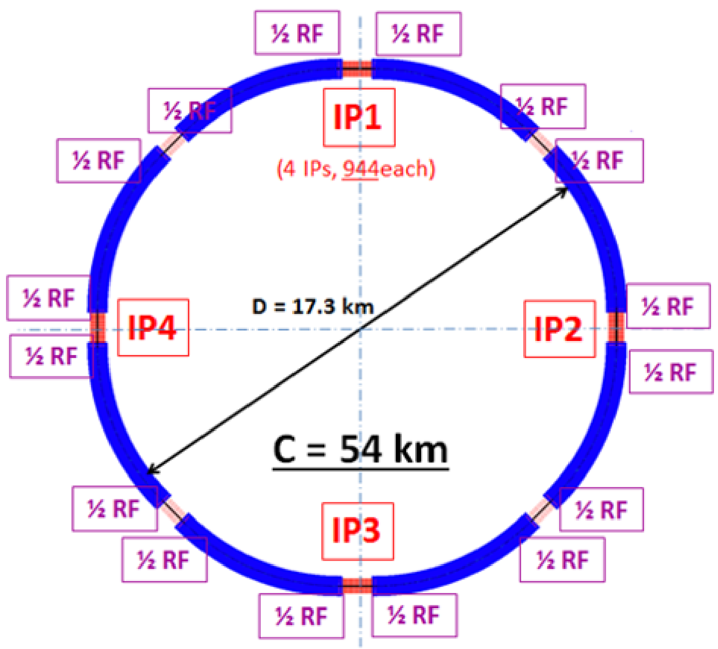


Layout of LHC



Layout of FCC

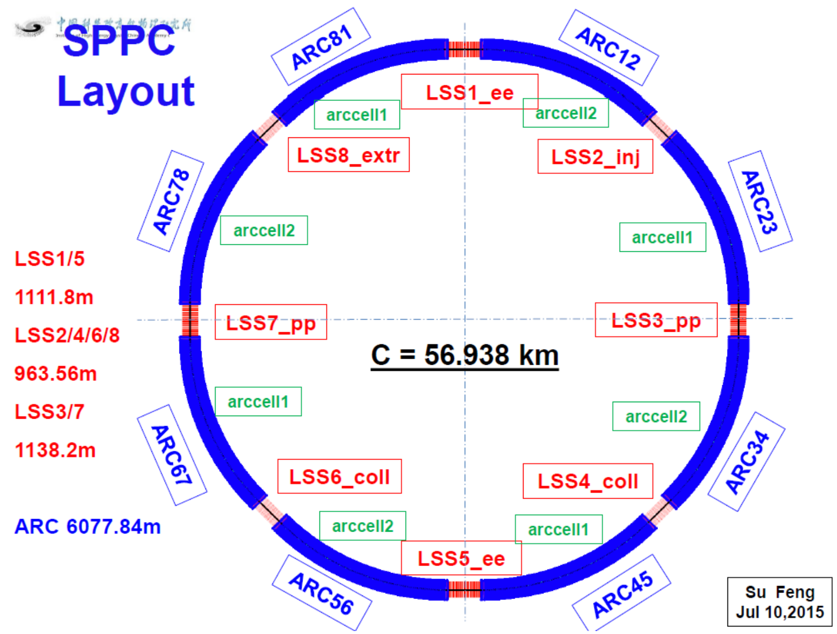
CEPC Lattice Layout (Feb 11, 2015)



(4 straights, 944 m each)

(8 arcs, 5852.8 m each)

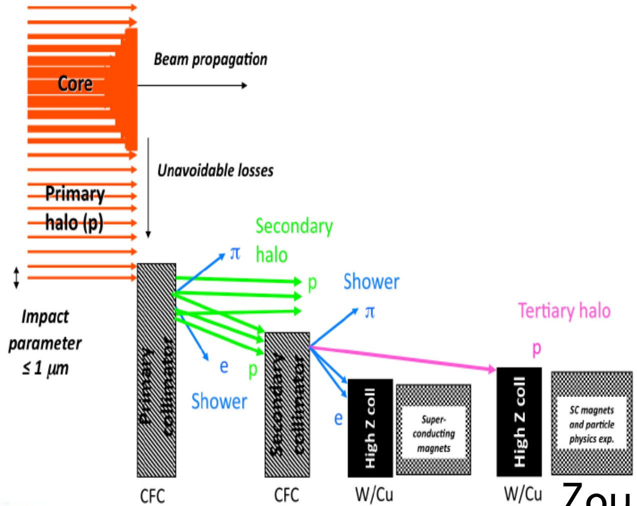
Huiping Geng



LSS for collimation scaled-up from LHC

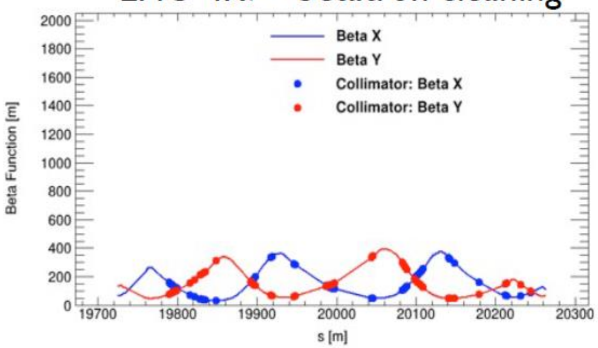
- Phase advances of secondary collimators are relatively fixed
- According to the formula:

$$\mu = \int \frac{ds}{\beta}$$

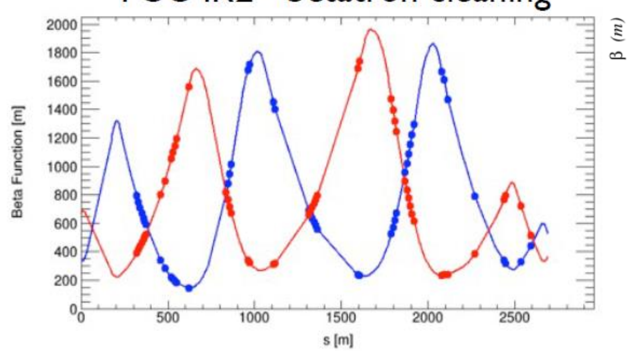


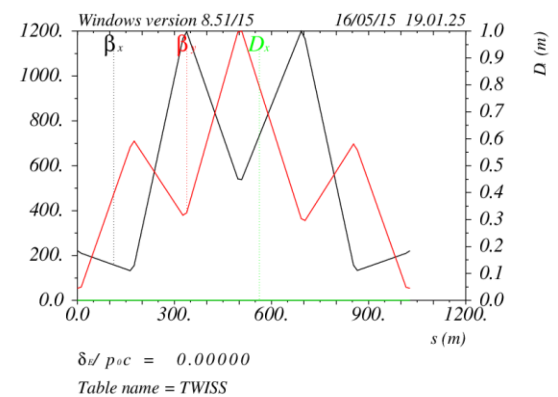
Zou Ye

LHC IR7 - betatron cleaning



FCC IR2 - betatron cleaning

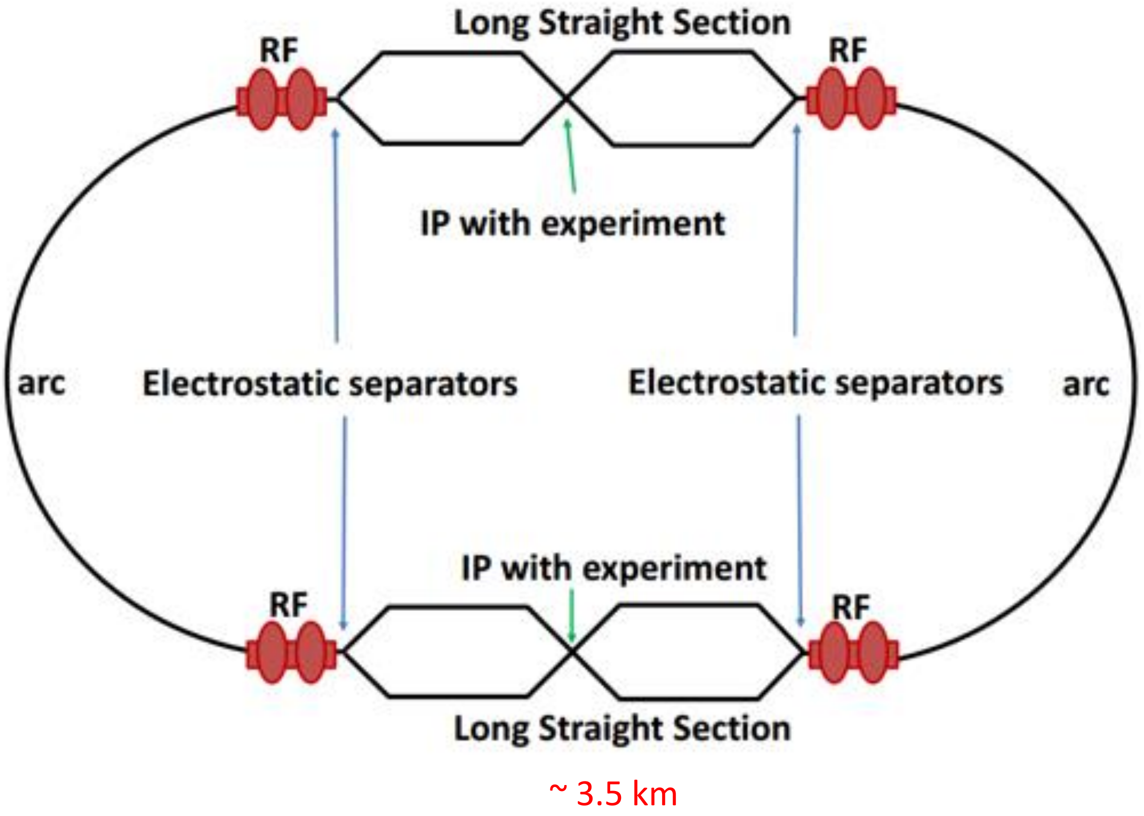




Insertion length ~ 2.7 or 2.8 km

Insertion length ~ 1.6 km

Layout of CEPC Partial double ring



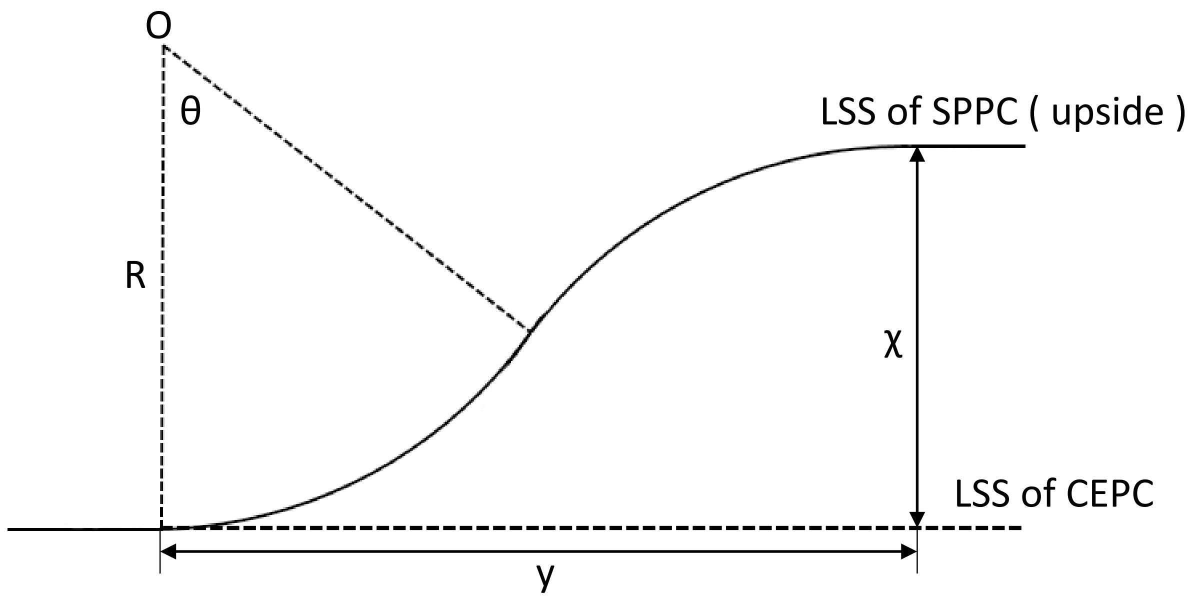
Consideration of detouring the CEPC detectors

Size of detectors in LHC

Parameter	ATLAS	CMS	ALICE	LHCb
Length (m)	46	21	26	21
Height (m)	25	15	16	10
Width (m)	25	15	16	13

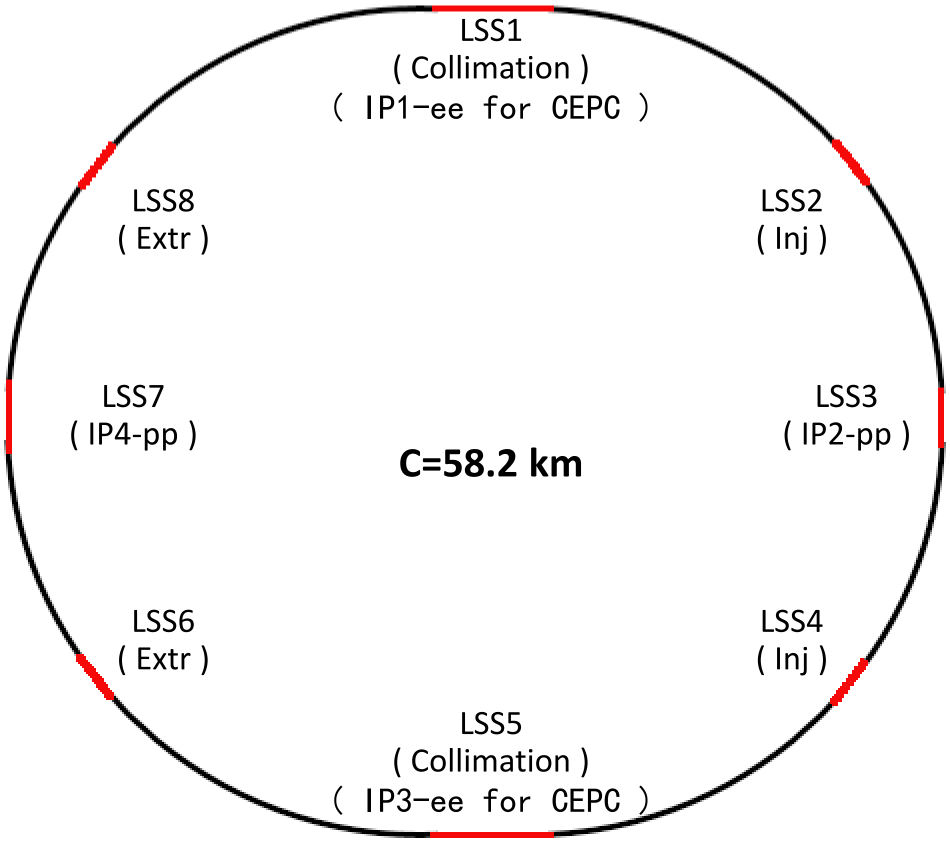
$H_{detouring}$ ~ 15 m?

Detouring the CEPC detectors from upside of the electron ring



- Partial double ring, length of LSS reach 3.5km.
- Detouring angle：θ
- $x = 2R(1 - cos\theta), y = 2Rsin\theta$
- If x=15 m，R=5837.4m，then y ≈600 m
- So the detouring section may reduce the LSS of 2 × 600 m=1200 m，there are more than 2 km for collimation.
- This scheme allows the proton ring to detour around the CEPC detectors.

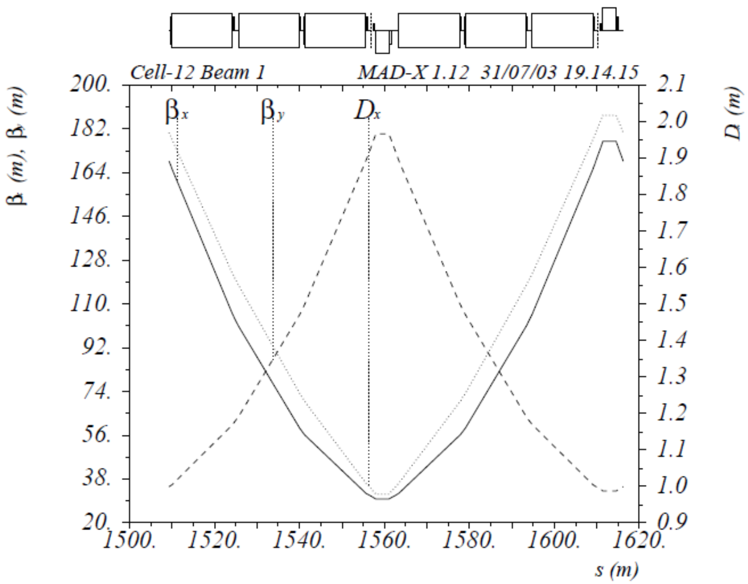
General layout of SPPC



- Use the same CEPC tunnel to build SPPC
- Maximize the beam energy to 70 TeV by using 20 T SC magnets
- 8 arcs, 5673.6 m each
- 4585.6 m dipole length each arc, filling factor is 0.808
- 2 IPs for pp, 975.15 m each
- 2 IRs for injection, 975.15 m each
- 2 IRs for extraction, 975.15 m each
- 2 IRs for collimation(ee for CEPC ）, 3.5 km each

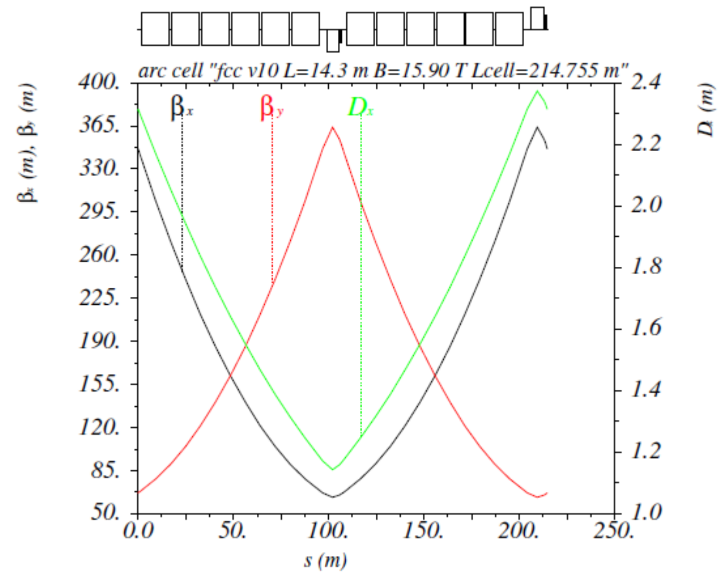
ARC design

ARC



LHC arc cell

- 90 degree phase advance
- 106.9 m length per cell



FCC arc cell

- 90 degree phase advance
- 214.755 m length per cell

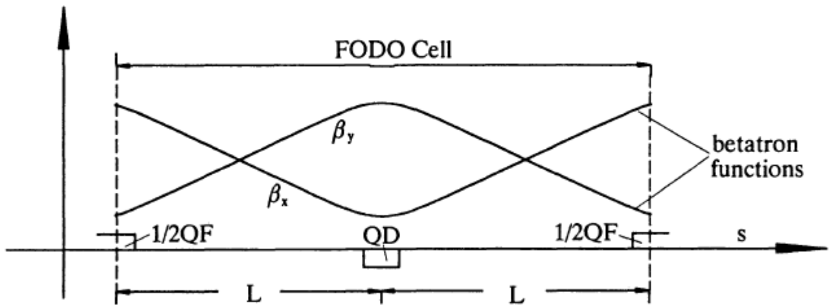


Fig. 6.2. Periodic betatron functions in a FODO channel

$$\mathcal{M}_{\text{FODO}} = \begin{bmatrix} 1-2\frac{L^2}{f^2} & 2L\cdot\left(1+\frac{L}{f}\right) \\ -\frac{1}{f^*} & 1-2\frac{L^2}{f^2} \end{bmatrix} = \begin{bmatrix} \cos\phi & \beta\sin\phi \\ \frac{1}{\beta}\sin\phi & \cos\phi \end{bmatrix}$$

Here $f_f = -f_d = f$, $1/f^* = 2\cdot(1-L/f)\cdot(L/f^2)$

$$\begin{cases} \beta^+ = L\cdot\dfrac{\frac{f}{L}\,\frac{f}{L+1}}{\sqrt{\frac{f^2}{L^2-1}}} = L\cdot\dfrac{\kappa\cdot(\kappa+1)}{\sqrt{\kappa^2-1}} \\ \beta^- = L\,\dfrac{\kappa\cdot(\kappa-1)}{\sqrt{\kappa^2-1}} \\ \cos\phi = 1-2\cdot\dfrac{L^2}{f^2} = \dfrac{\kappa^2-2}{\kappa^2} \end{cases}$$

$$\kappa = \frac{f}{L} > 1$$

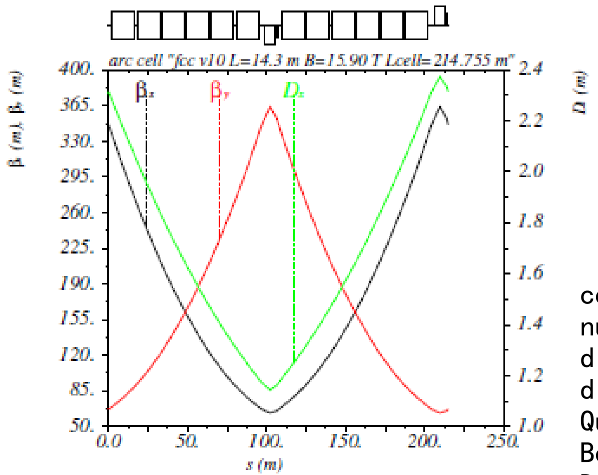
for a flat beam

$$d\beta^+/d\kappa = 0 \;\Rightarrow\; \begin{cases} \kappa_o = \frac{1}{2} \pm \sqrt{\frac{1}{4}+1} = 1.6180\ldots \\ \phi_o = 76.345\ \ldots^\circ \end{cases}$$

For a round beam $\epsilon_x \approx \epsilon_y$ beam diameter or $E_x^2 + E_y^2 \sim \beta_x + \beta_y$

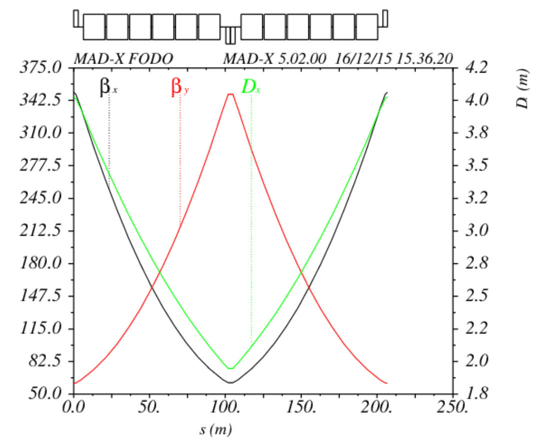
$$d(\beta_x+\beta_y)/d\varphi = 0 \;\Rightarrow\; \begin{cases} \kappa_{\text{opt}} = \sqrt{2} \\ \phi_{\text{opt}} = 90^\circ \end{cases}$$

Structure of FODO cell



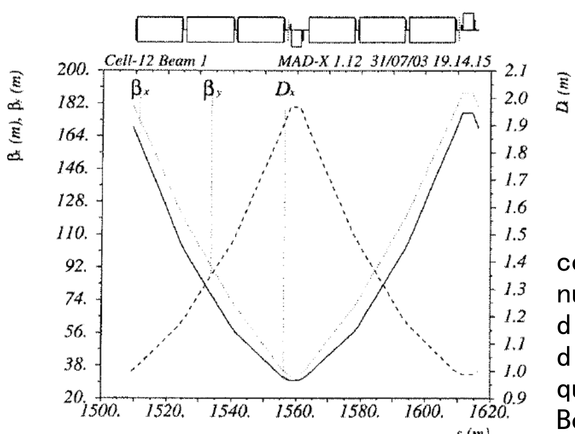
Fodo cell in the Arc of FCC

cell length: 214.755m
number of dipoles: 12
dipole field: 15.9 T
dipole length: 14.3
Quadrupole length: 6.29m
Beta_max: ~370 m
Dx_max: ~2.4 m



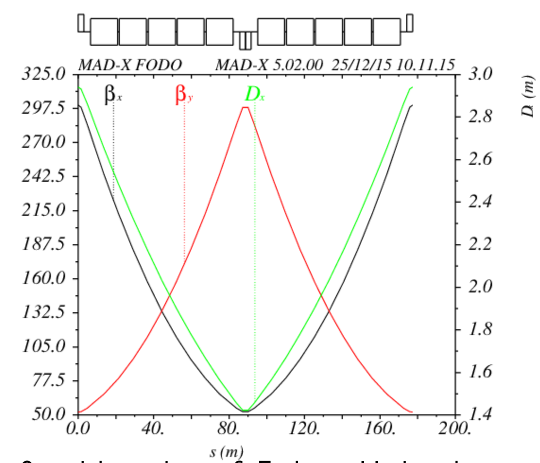
Consideration of Fodo cell in the Arc of SPPC

cell length: 206.8 m
number of dipoles: 12
dipole field: 20 T
dipole length: 14.15
quadrupole length: 6m
L_{BB}=1 m
L_{BQ}=3.5 m
Filling factor 0.821
Kq=0.002336321445
Beta_max: ~350 m
Dx_max: ~4 m



Fodo cell in the Arc of LHC

cell length: ~110m
number of dipoles: 6
dipole field: 8.33 T
dipole length: 14.3
quadrupole length: 3.1 m
Beta_max: ~180 m
Dx_max: ~2.018 m



Consideration of Fodo cell in the Arc of SPPC

cell length: 177.3 m
number of dipoles: 10
dipole field: 20 T
dipole length: 14.33
quadrupole length: 6m
L_{BB}=1 m
L_{BQ}=3.5 m
Filling factor 0.808
Kq=0.002720819308
Beta_max: ~300 m
Dx_max: ~2.94 m

Different length of fodo cell, different beta_max and Dx_max.

Dispersion Suppressor

If we simply want to continue the FODO structure of the arc through the Long straight section—but with vanishing dispersion. The boundary conditions are:

$$D(s) = D'(s) = 0,$$

$$\beta_x(s) = \beta_{x\,\mathrm{arc}}, \qquad \alpha_x(s) = \alpha_{x\,\mathrm{arc}},$$

$$\beta_y(s) = \beta_{y\,\mathrm{arc}}, \qquad \alpha_y(s) = \alpha_{y\,\mathrm{arc}}$$

Adjust the strength of dipoles? Or the strength of quadrupoles?

DS consideration

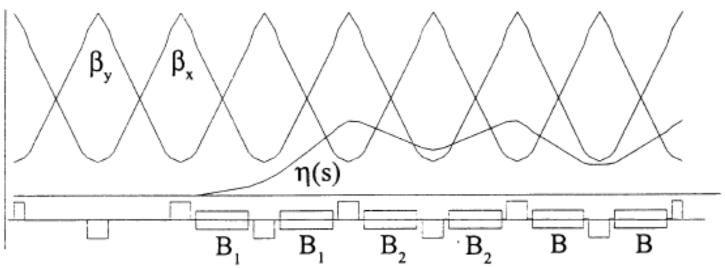


Fig. 6.14. Dispersion suppressor lattice

Change the strength of the bending magnets only

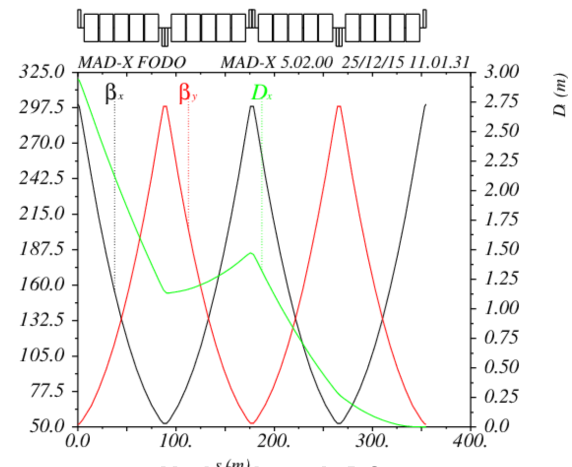
$$\theta_1 = \theta \cdot \left(1 - \frac{1}{4 \cdot \sin^2 \psi}\right)$$

and

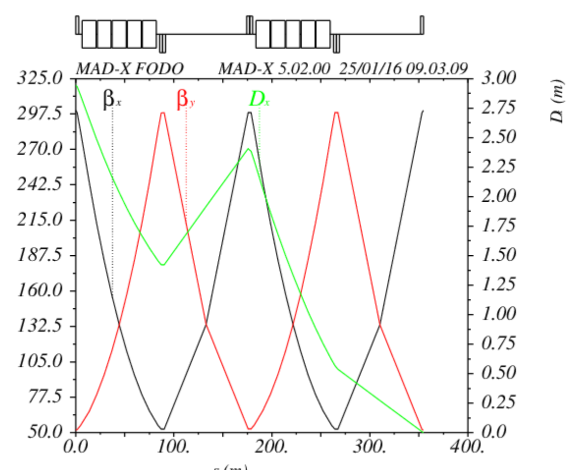
$$\theta_2 = \theta \cdot \left(\frac{1}{4 \cdot \sin^2 \psi}\right),$$

where

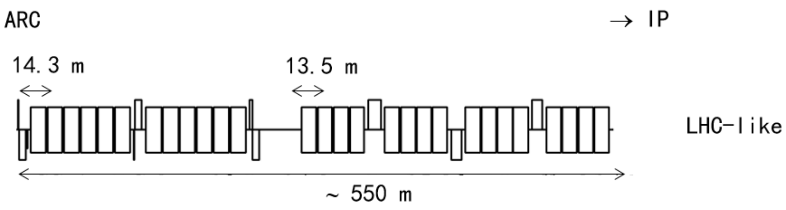
$$\theta = \theta_1 + \theta_2 .$$



Half bend DS



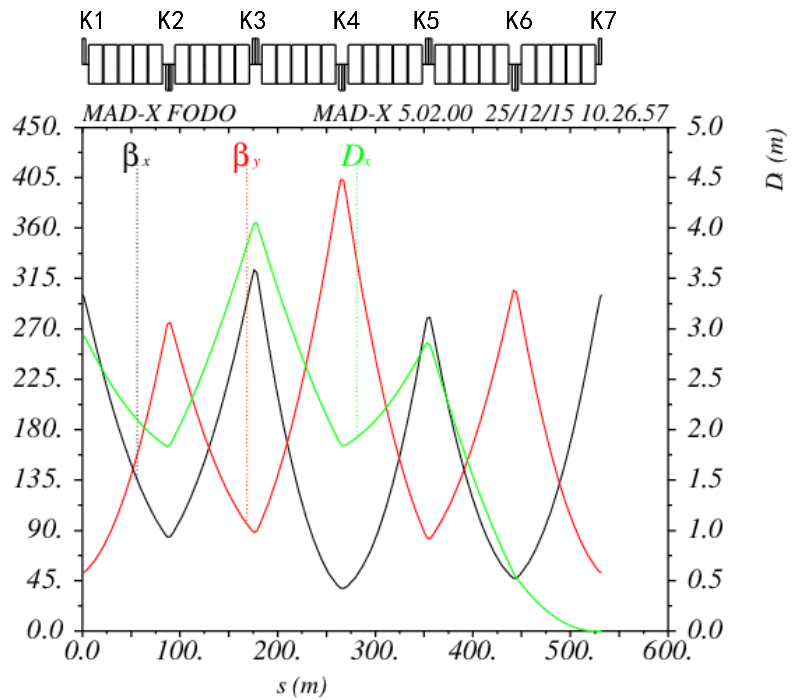
Missing bend DS



The aim of the DS in LHC:

- adapt the LHC reference orbit to the geometry of the LEP tunnel;
- cancel the horizontal dispersion;
- help in matching the insertion optics to the periodic solution of the arc.

LHC-like DS

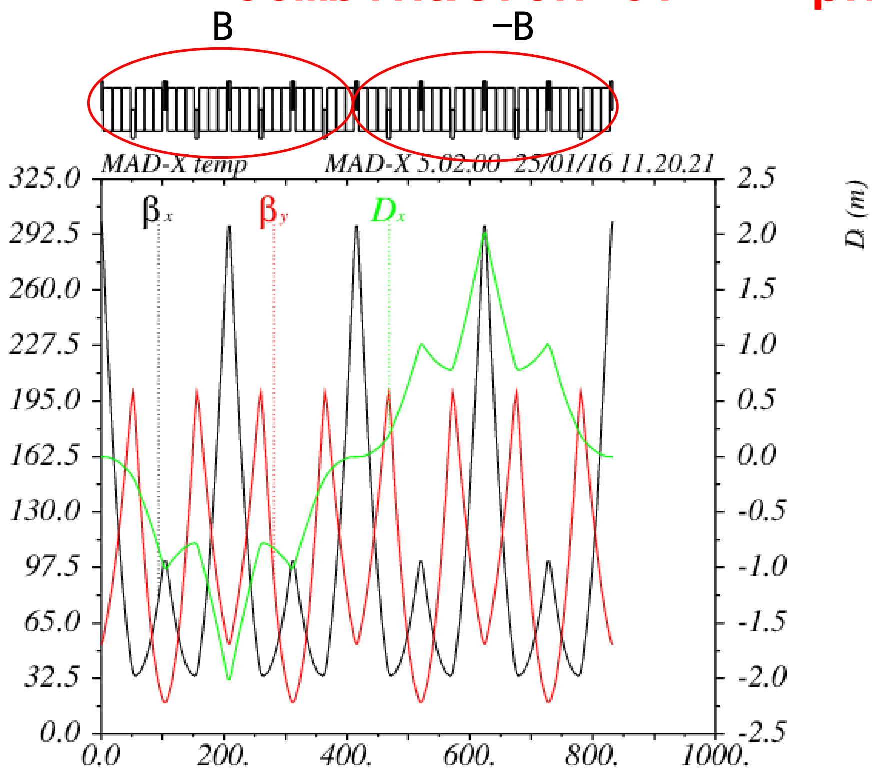


Full bend DS for SPPC(for discussing)

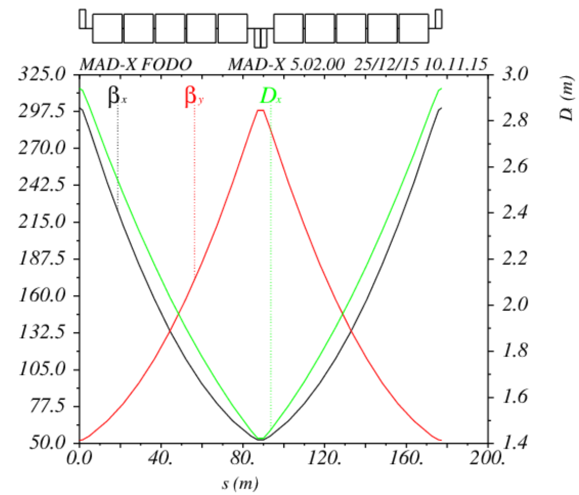
k1 = 0.002175287993 ;
k2 =-0.002399346694 ;
k3 = 0.002632583037 ;
k4 =-0.002309155859 ;
k5 = 0.002983161561 ;
k6 =-0.002465076854 ;
k7 = 0.002840436513 ;

Preliminary consideration of detouring the CEPC detectors

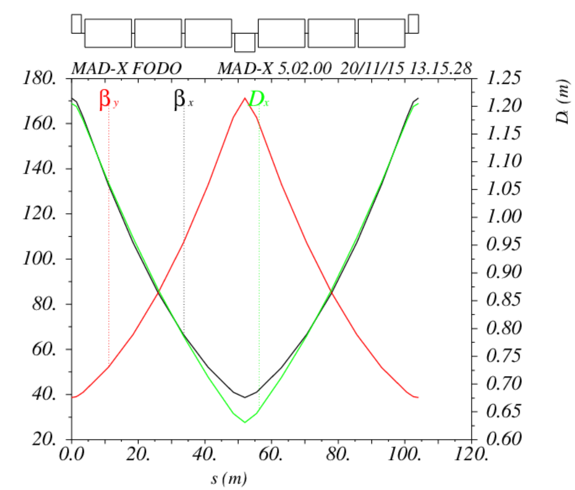
Combination of π phase shift sections



- Length: 830 m
- Including 4 detouring fodo cells
- L_{bend}: ~14 m
- L_{quad}: 6m
- L_{arc_fodo}:144 m
- k_{arc_fodo}:0.0033687
- L_{detour_fodo}:104 m
- k_{detour_fodo}:0.0042637
- Climb up to 24 m

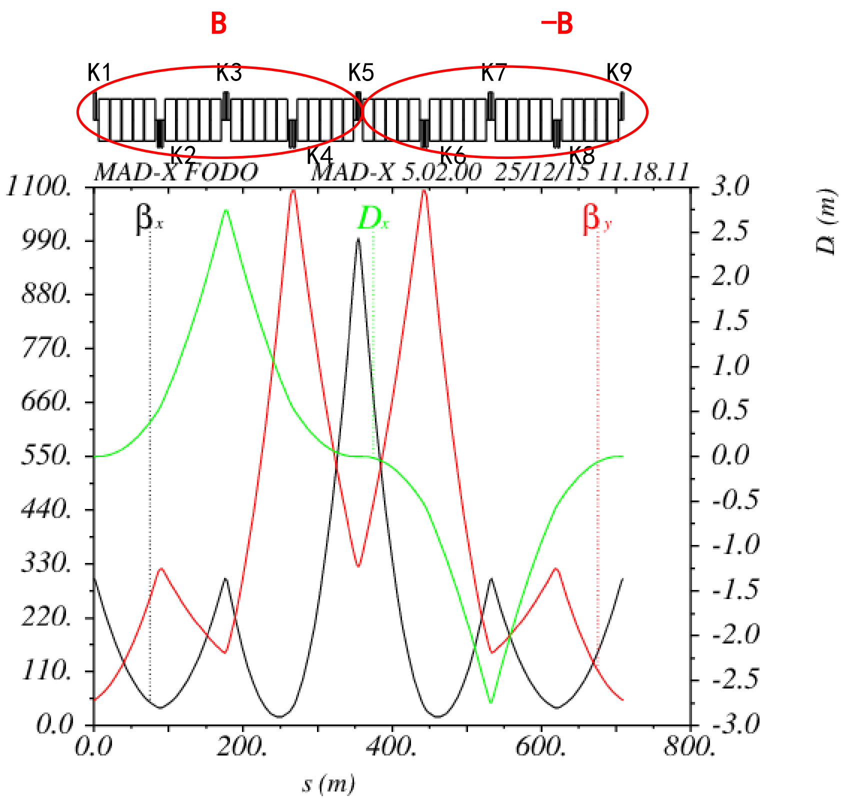


ARC FODO

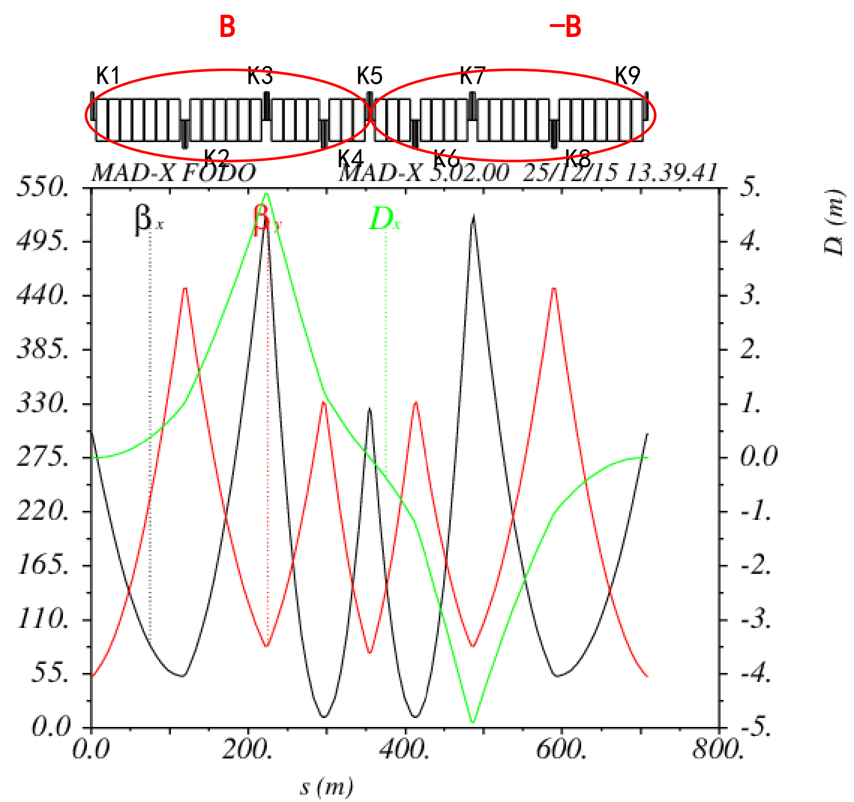


Detouring FODO

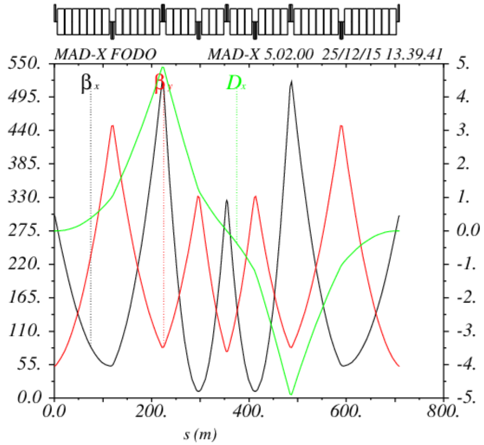
Detouring section



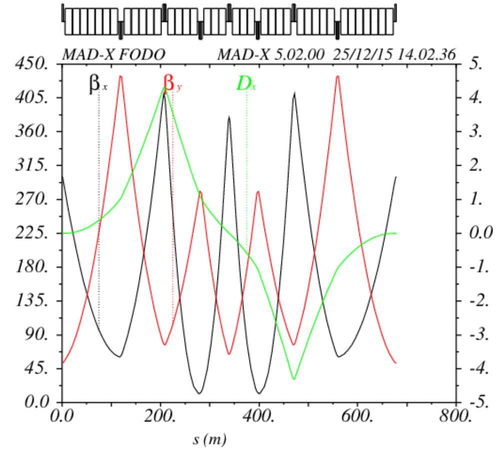
Combination of four regular FODO cells



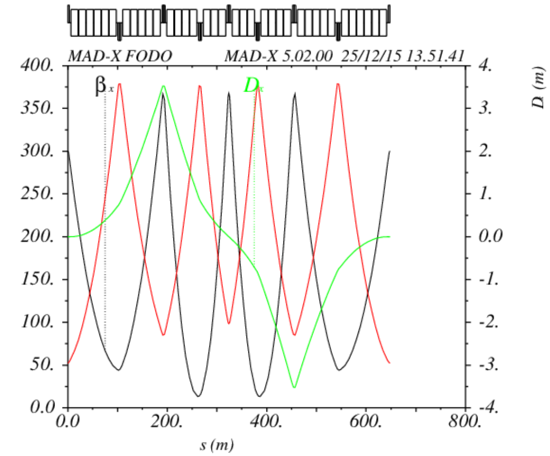
Combination of four irregular FODO cells



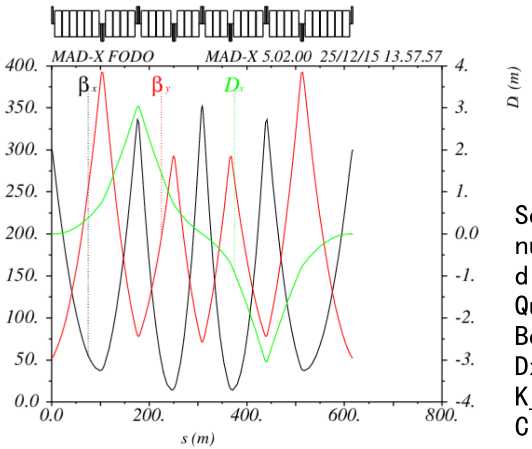
Section length: 709.2 m
number of dipoles: 40
dipole length: 14.33
Quadrupole length: 6m
Beta_max: ~520 m
Dx_max: ~4.9 m
K_max: 0.00566
Climb up to: 17.82 m



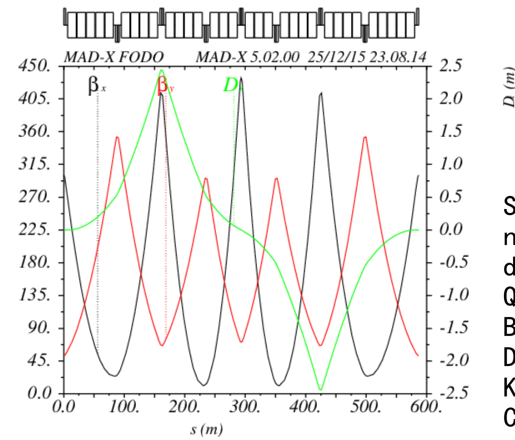
Section length: 678.5 m
number of dipoles: 38
dipole length: 14.33
Quadrupole length: 6m
Beta_max: ~434 m
Dx_max: ~4.3 m
K_max: 0.00532
Climb up to: 16.2 m



Section length: 647.9 m
number of dipoles: 36
dipole length: 14.33
Quadrupole length: 6m
Beta_max: ~379 m
Dx_max: ~3.5 m
K_max: 0.00522
Climb up to: 14.6 m

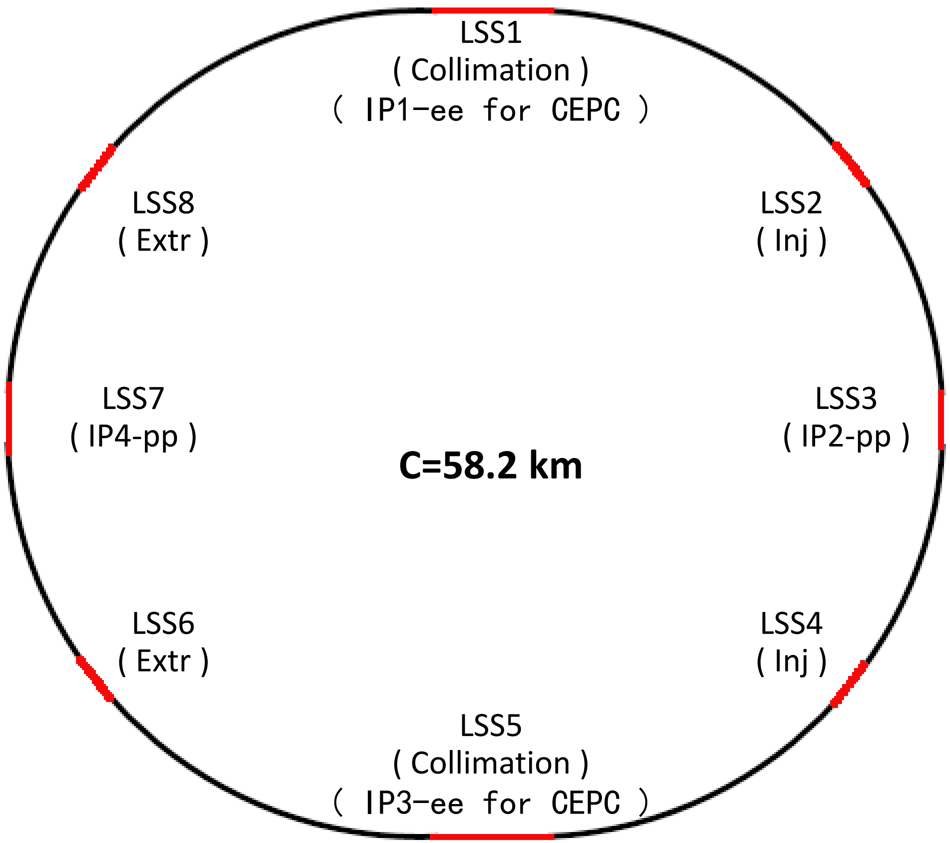


Section length: 617.2 m
number of dipoles: 34
dipole length: 14.33
Quadrupole length: 6m
Beta_max: ~393 m
Dx_max: ~3.04 m
K_max: 0.00515
Climb up to: 13.14 m



Section length: 586.6 m
number of dipoles: 32
dipole length: 14.33
Quadrupole length: 6m
Beta_max: ~434 m
Dx_max: ~2.43 m
K_max: 0.00548
Climb up to: 11.7 m

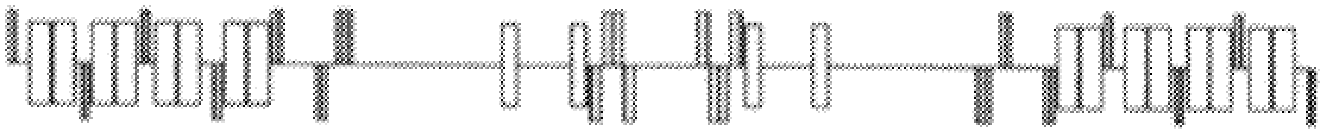
Consideration of SPPC Interaction Region (IR)



Parameters for the SPPC Interaction Region

Parameter	value
Beam energy	35 TeV
Number of IPs	2
Luminosity	1.2×10^{35} $cm^{-2}s^{-1}$
Length	~1000 m
β*	0.75 m
Normalized emittance	4.1 μm

Generally description of LHC interaction region



Lattice of LHC high-luminosity insertion

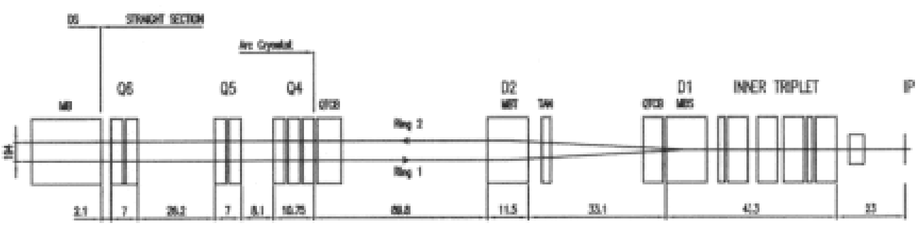


Figure 5: Layout of the left low-β Insertions 1 and 5

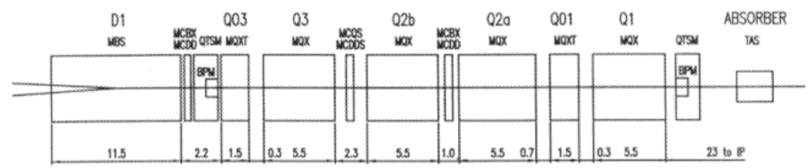


Figure 8: Layout of the left low-β triplet including D1

- Free space of 23 m on each side of the IP; note however that a secondary particle absorber is placed 19 m from the IPs;
- Low-β (or 'inner') quadrupole triplet;
- Pair of separation dipoles;
- The matching (or 'outer') quadrupole triplet.

- Q01, Q02a, Q02b, and Q03: 5.5 m long, 70 mm aperture, powered in series
- Trim quadrupoles Q01 and Q03: 1.5 m long, 85 mm aperture, powered independent.

Optics goals

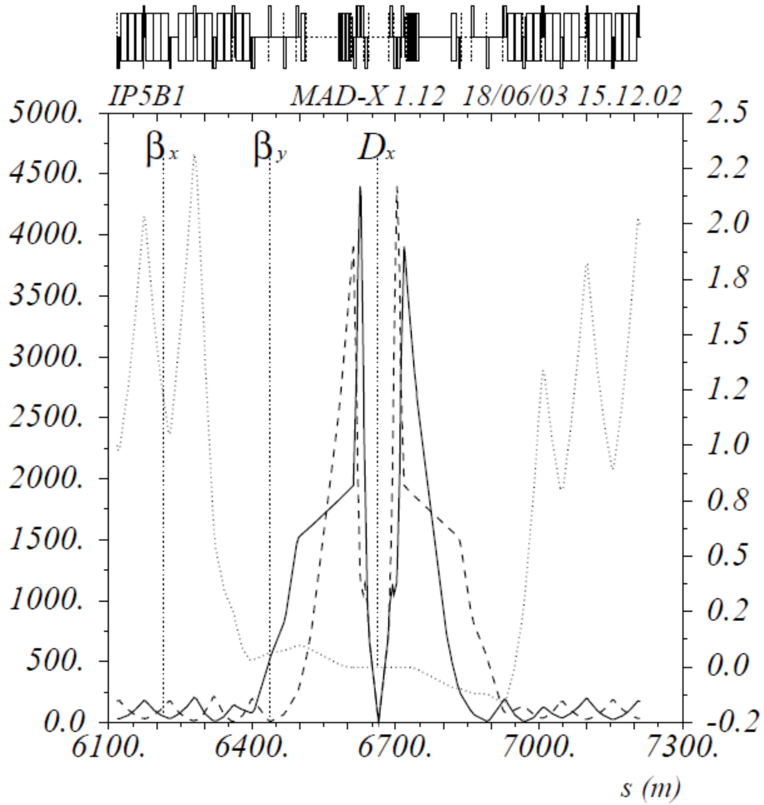
The optics design in IR1/5 is guided by two main requirements:

1. It must provide a range of accessible β^* values (18 m for the injection and 0.55 m for the collision optics) while keeping the total phase advance over the IR constant.
2. In order to have control over the beam size, the beam separation and the nonlinear chromaticity during the change from injection to collision optics, the quadrupole gradients must change smoothly with varying β^* (e.g. the slope of the quadrupole gradient versus time should not change its sign).

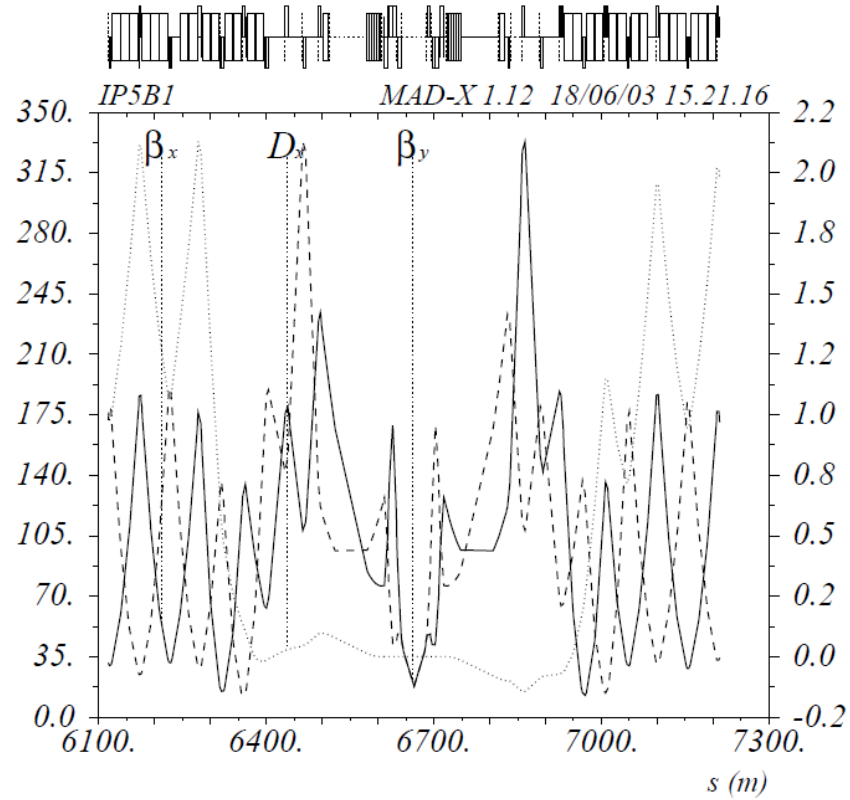
Hardware constraints

1. At the IP, the two rings of the LHC share the same vacuum chamber and the same low-beta triplet quadrupoles and the optics solutions for Ring 1 and Ring 2 must have the same triplet gradients.
2. The maximum gradients must not exceed the operating values given in Tab. 3.2.
3. The minimum gradient of the unipolar insertion quadrupoles at injection energy must be larger than 3% of the nominal gradient.
4. The overall beam size must be small enough to fit into the tight aperture of the LHC. The aperture of the insertions is limited by the crossing-angle separation orbit and the beam screen which is installed in all of the insertion region magnets.

Optics of LHC interaction region



Interaction region optics
（collision mode β*=0.55 m L*=23 m）



Interaction region optics
（injection mode β*=18 m L*=23 m）

Optics of FCC-hh interaction region

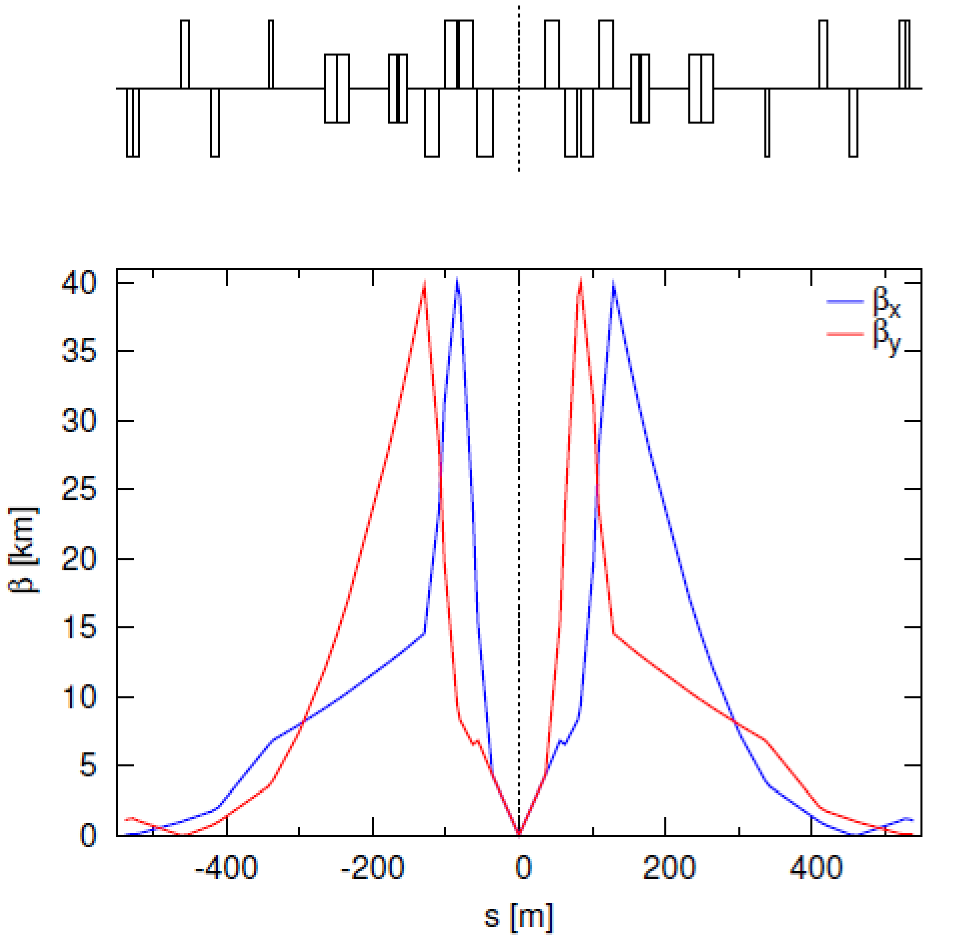


Figure 1: FCC-hh interaction region design with $\beta^* = 0.3$ m and $L^* = 36$ m.

Table 2: Parameters for the free aperture calculation.

B_{max}	11 T
crossing angle θ	$12\,\sigma_p$
Layer thickness [mm]	
- Shielding	15
- Liquid helium	1.5
- Kapton insulator	0.5
- Cold bore	2
- Beam screen	2.05
- Beam screen insulation	2

Aperture 100 mm

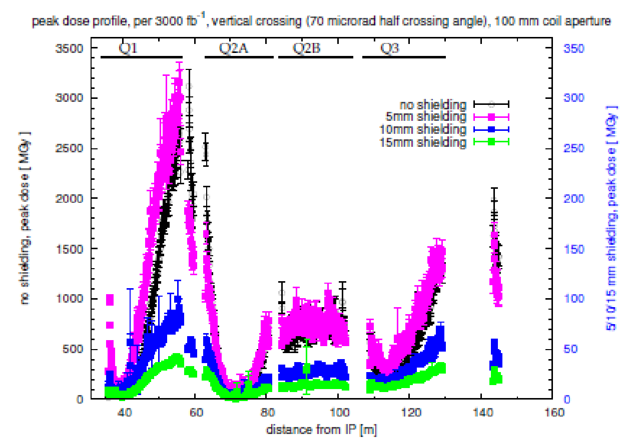
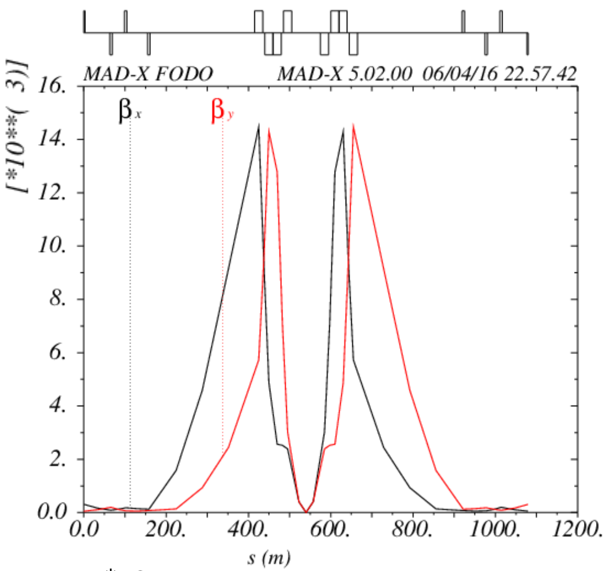
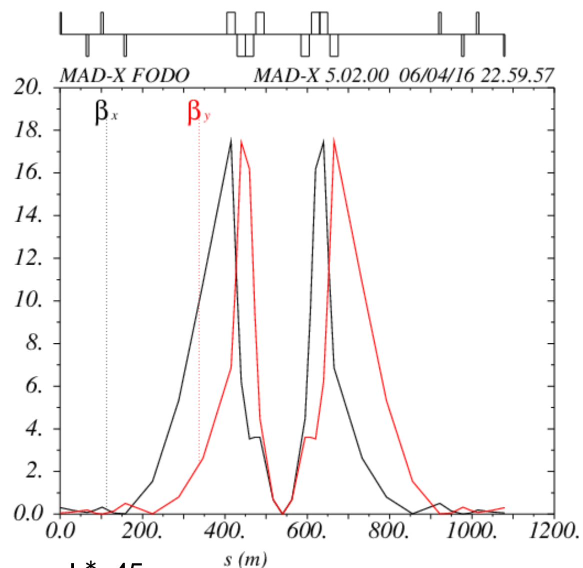


Figure 2: Radiation dose in the triplet magnets from physics debris with (right scale) and without (left scale) shielding. For 15 mm shielding and the shown integrated luminosity of 3000 fb^{-1}, the dose looks acceptable [4].

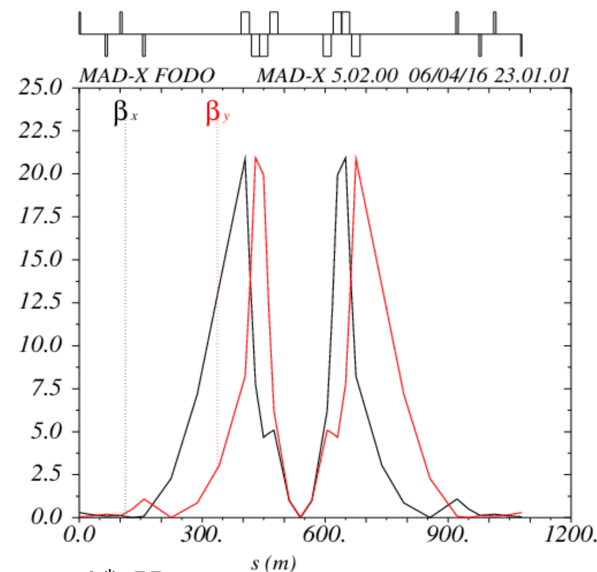
IR lattice with different L* of SPPC



L^*=35 m
β^*=0.75 m
L=1080 m
$L_{inner\ triplet}$=20 m
$L_{outer\ triplet}$=6 m
β_{max}=14724 m
kqc1 = 0.001394058811
kqc2 = -0.00107925583
kqc3 = 0.001234363129
kqc4 = -0.006836247018
kqc5 = 0.002545507501
kqc6 = -0.003919800356

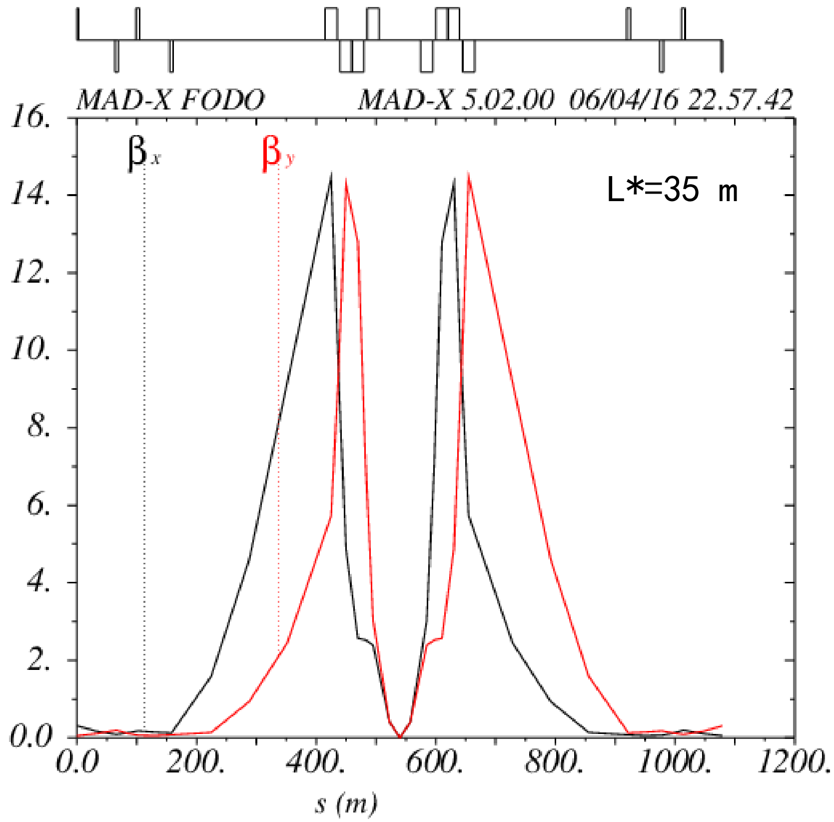


L^*=45 m
β^*=0.75 m
L=1080 m
$L_{inner\ triplet}$=20 m
$L_{outer\ triplet}$=6 m
β_{max}=17481 m
kqc1 = 0.001237058811
kqc2 = -0.00103935583
kqc3 = 0.001216805443
kqc4 = -0.005894270493
kqc5 = 0.006125350975
kqc6 = -0.006257202393



L^*=55 m
β^*=0.75 m
L=1080 m
$L_{inner\ triplet}$=20 m
$L_{outer\ triplet}$=6 m
β_{max}=20945 m
kqc1 = 0.001123058811
kqc2 = -0.00100155583
kqc3 = 0.001184559998
kqc4 = -0.004467178588
kqc5 = 0.006321284511
kqc6 = -0.002595967274

Estimate of aperture



$B_{pole\ max}$ =20 T

$\varepsilon_n = 4.1\ \mu m$

$\sigma = \sqrt{\varepsilon \cdot \beta}$

$R_{coil} = \frac{e}{p}\frac{B_{pole}}{k}$

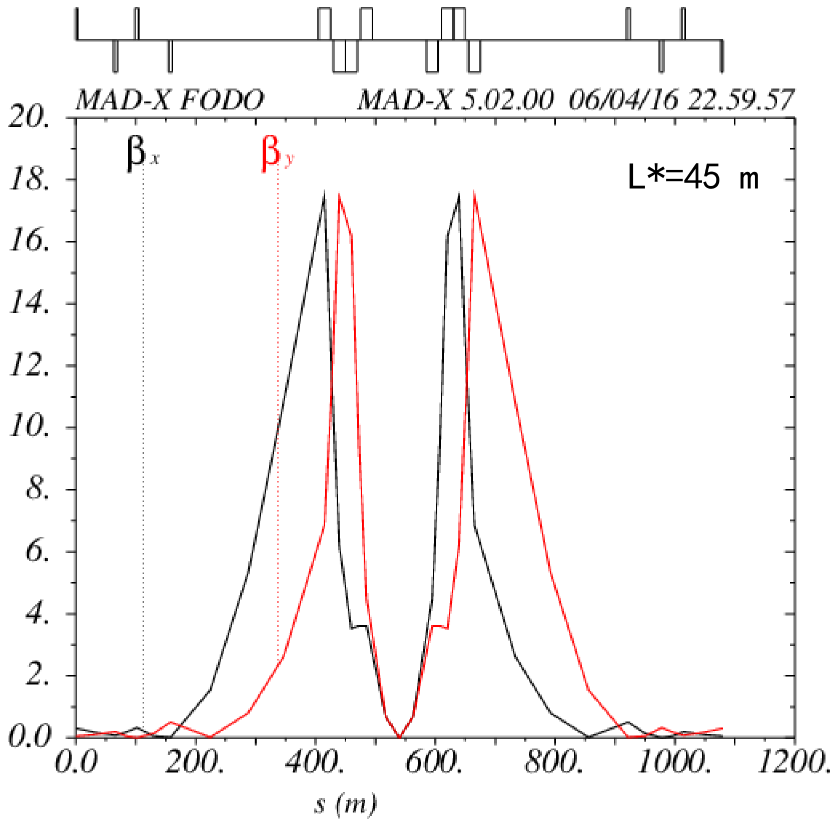
Beam stay clear: 20σ

	betx (m)	bety (m)	max(betx, bety)	k	Rmax (m)	20σ (m)	Space left (m)
QC1	2507.914	3162.335	3162.334871	0.001394	0.122886	0.011791	0.111094622
QC2A	2700.198	13001.68	13001.67751	0.001079	0.15873	0.023908	0.134821257
QC2B	5051.524	14662.16	14662.15659	0.001079	0.15873	0.025389	0.13334041
QC3	14724.35	6223.888	14724.34897	0.001234	0.138784	0.025443	0.113340997
QC4	866.596	1496.423	1496.423348	0.006836	0.025059	0.008111	0.016947975
QC5	493.5448	31.03385	493.5448409	0.002546	0.067299	0.004658	0.062640782
QC6	88.41062	192.9211	192.9211323	0.00392	0.043704	0.002912	0.040791415

Space left for:

- Shielding
- liquid helium
- beam screen

……



$B_{pole\ max}$ =20 T

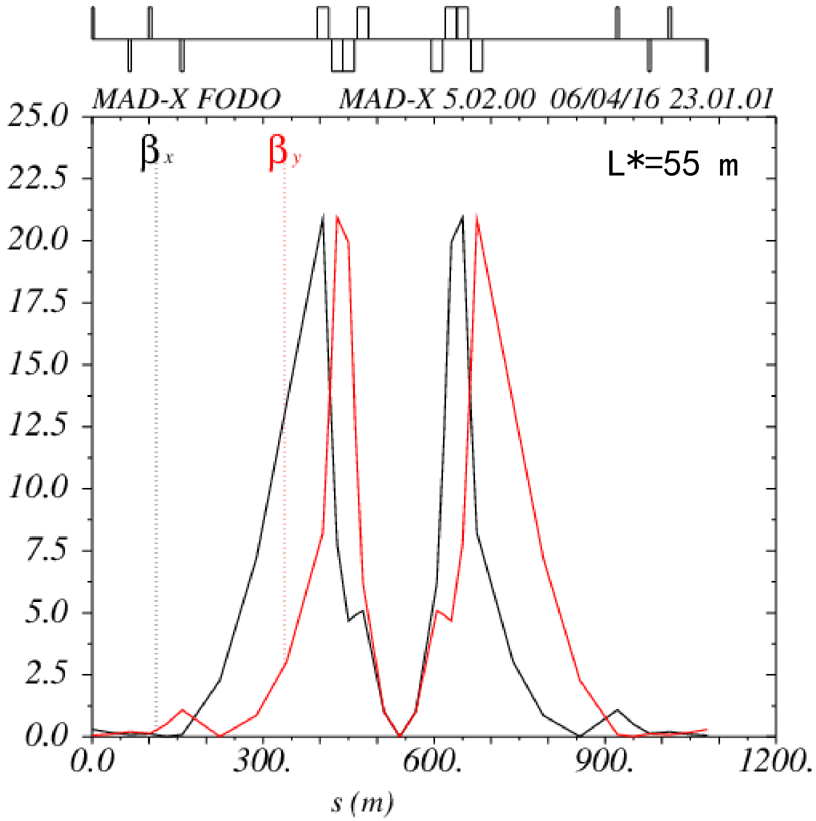
$\varepsilon_n = 4.1\ \mu m$

$\sigma = \sqrt{\varepsilon \cdot \beta}$

$R_{coil} = \frac{e}{p} \frac{B_{pole}}{k}$

Beam stay clear: 20σ

	betx (m)	bety (m)	max(betx,bety)	k	Rmax (m)	20σ (m)	Space left (m)
QC1	3611.588	4489.226	4489.225863	0.001237	0.138482	0.014049	0.12443293
QC2A	3528.351	16187.03	16187.02712	0.001039	0.164823	0.026677	0.138146311
QC2B	6213.328	17449.01	17449.00676	0.001039	0.164823	0.027697	0.137125927
QC3	17480.67	6865.033	17480.6737	0.001217	0.140787	0.027722	0.113064243
QC4	20.59461	508.0948	508.0947962	0.005894	0.029064	0.004726	0.02433748
QC5	322.1416	6.878193	322.1415625	0.006125	0.027967	0.003763	0.024204017
QC6	86.91007	196.2574	196.2573751	0.006257	0.027378	0.002937	0.024440634



$B_{pole\ max}$ =20 T

$\varepsilon_n = 4.1\ \mu m$

$\sigma = \sqrt{\varepsilon \cdot \beta}$

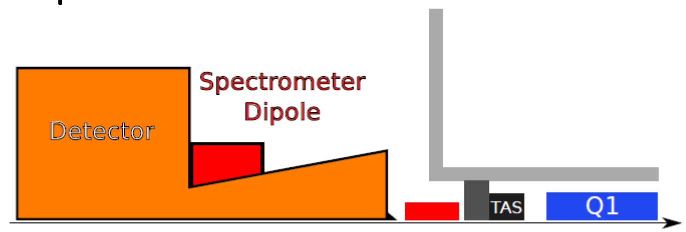
$R_{coil} = \frac{e}{p}\frac{B_{pole}}{k}$

Beam stay clear: 20σ

	betx (m)	bety (m)	max(betx,bety)	k	Rmax (m)	20σ (m)	Space left (m)
QC1	5085.453	6221.721	6221.720678	0.001123	0.152539	0.016539	0.135999822
QC2A	4669.837	19945.27	19945.27295	0.001002	0.171044	0.029612	0.141431571
QC2B	7771.317	20944.8	20944.80145	0.001002	0.171044	0.030345	0.140698652
QC3	20860.3	8218.014	20860.29823	0.001185	0.144619	0.030284	0.114335144
QC4	84.0685	1088.061	1088.061075	0.004467	0.038349	0.006916	0.031432208
QC5	118.317	142.2668	142.2668388	0.006321	0.027101	0.002501	0.024599559
QC6	84.06724	202.7928	202.7927759	0.002596	0.065991	0.002986	0.063004892

More to do:

- Confirm the requirement of L*



- **Spectrometer dipole** (10 Tm): $z = 14.8$ m to $z = 21$ m
- **Detector forward region**: $z = 21$ m to $z = 31.5$ m
- **End of conical beam pipe**: $z = 32.3$ m
- **Warm orbit corrector** $\mathcal{O}$(7 Tm): $z = 33$ m to $z = 37.5$ m
- **Shielding from TAS**: $z = 38$ m to $z = 40$ m
- **TAS**: $z = 40$ m to $z = 43$ m
- **Q1**: $z = 45$ m to $z = 75$ m

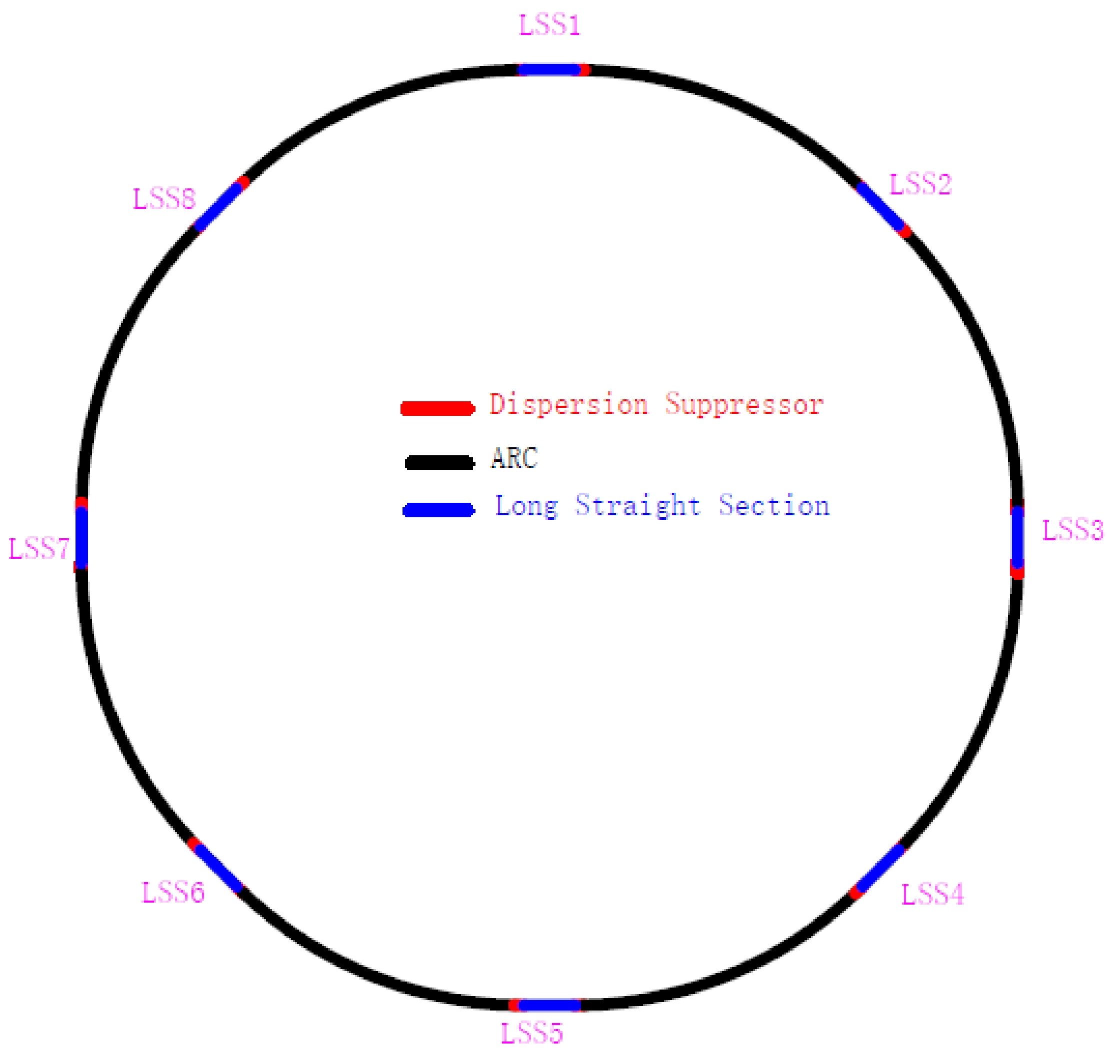
As presented by W. Riegler

One example case of L* = 45 m of FCC

- Confirm the $B_{pole\ max}$ of inner triplet
- Confirm the thickness of different layers of inner triplet. Shielding, liquid helium, beam screen and so on.
- Estimate the magnets' aperture and evaluate the beam stay clear

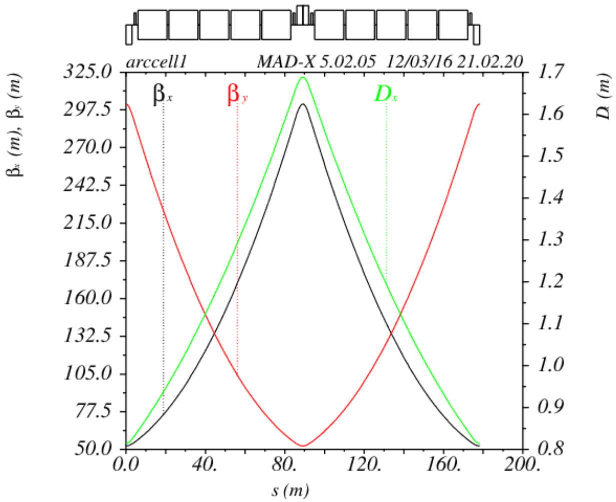
Another try of a 100 TeV collider

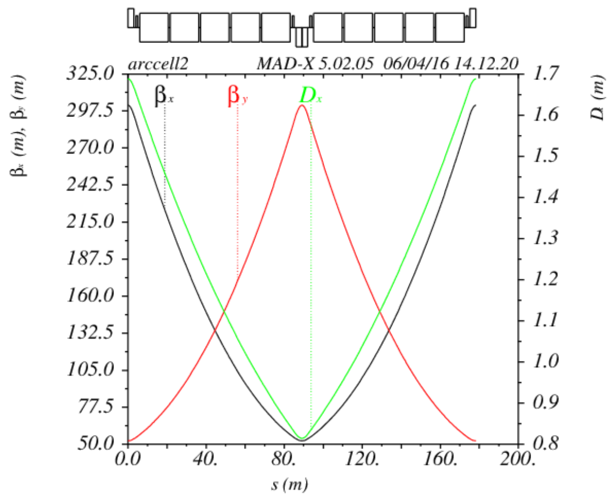
By Zhang Linhao



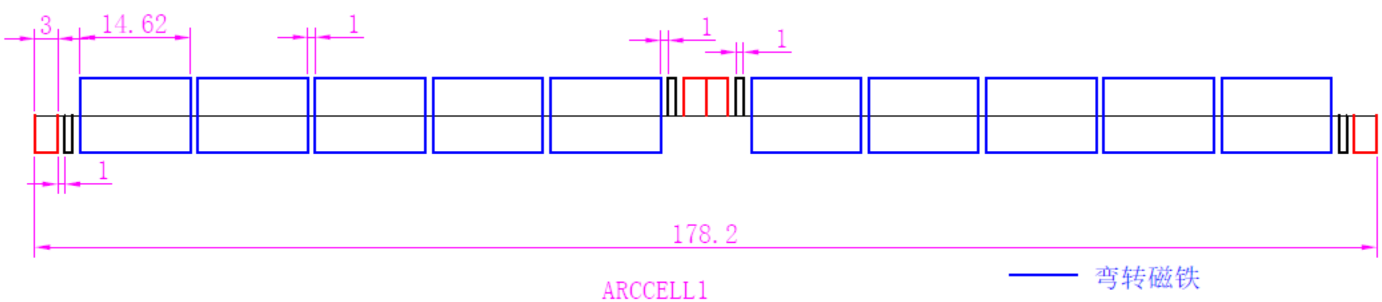
Parameter	Unit	Symbol	Final Scheme
Beam energy	TeV	W_{top}	50
Dipole field	T	B_{top}	16
Dipole curvature radius	m	ρ	10424.0732
Arc filling factor			0.79
Total dipole magnet length	m	L_D	65496.3861
Arc length	m	L_{ARC}	82906.8178
Circumference	km	C	100
Total straight section length	m	L_{str}	17093.1822

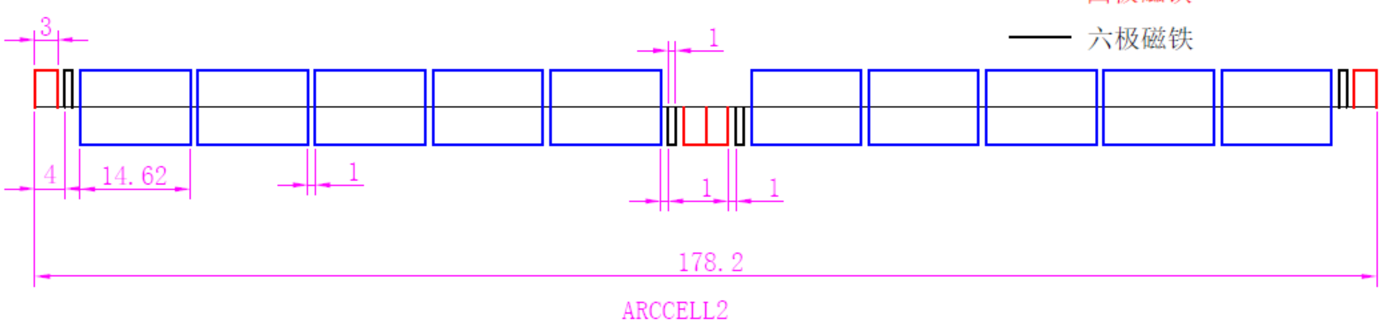
ARCCELL





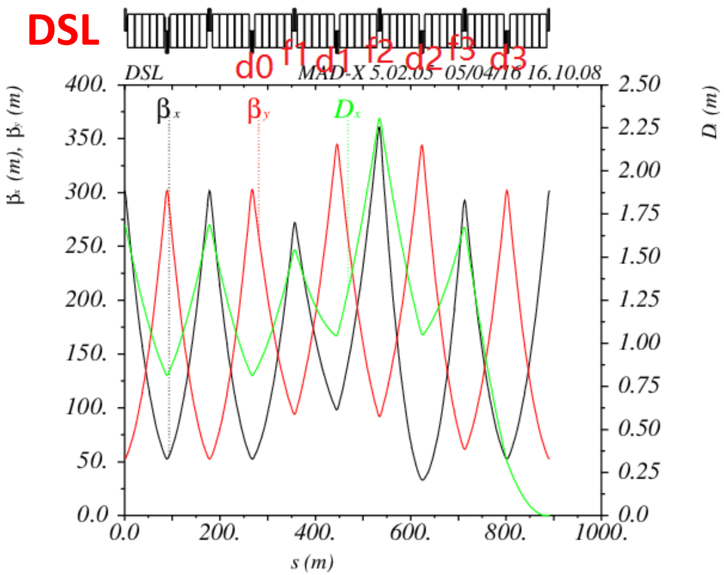
Length:178.2m
phase advance:90^0 x/y
β_{max}=301.7634248m
Dx_{max}=1.688097108m
k1=0.002706940548;
filling factor:0.8204





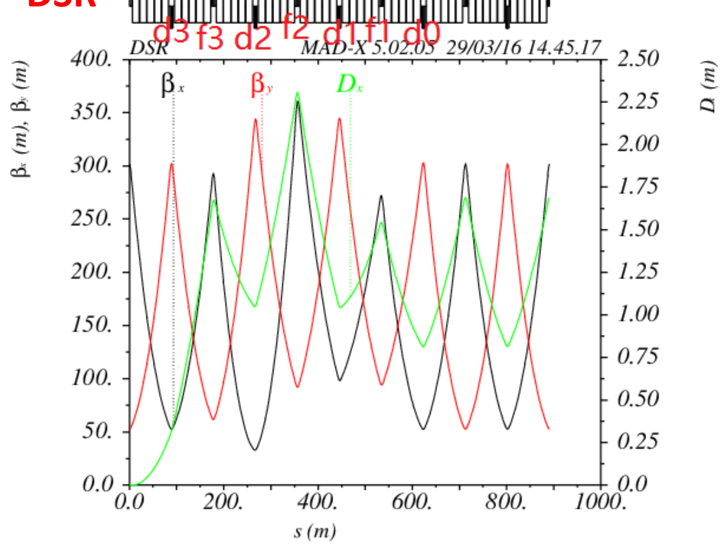
Dispersion Suppressor

DSL



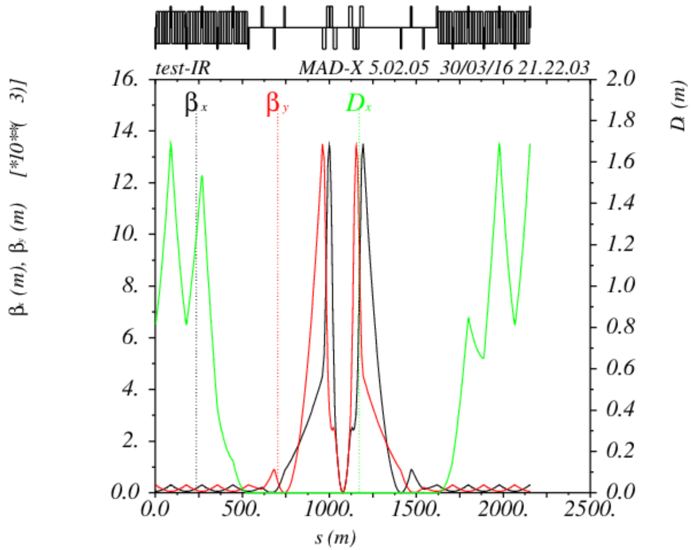
qd0->k1=-0.002368557062;
qf1->k1=0.002311339272;
qd1->k1=-0.0021714948;
qf2->k1=0.0026164517;
qd2-k1=-0.002345180445;
qf3->k1=0.002991198662;
qd3->k1= -0.002620304284;

DSR



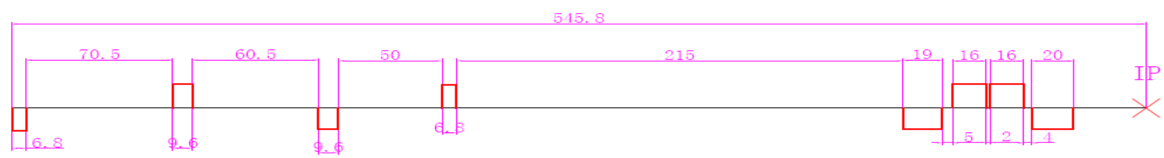
qd0->k1=-0.002368557062;
qf1->k1=0.002311339272;
qd1->k1=-0.0021714948;
qf2->k1=0.0026164517;
qd2-k1=-0.002345180445;
qf3->k1=0.002991198662;
qd3->k1= -0.002620304284;

Interaction Region



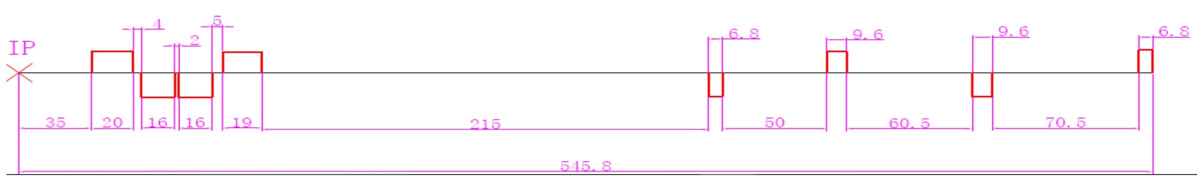
- quad length and strength:

k1=k2=k3=k = 0.00144768;
k4 = 0.001200228203;
k5 = 0.002842492845;
k6 = 0.002837144627;
k7 = 0.001935363832;
L1=20, L2.a=L2.b=16,
L3=19, L4=L7=6.8,
L5=L6=9.6



IR-L

IR-R



Summary

- Preliminary lattice design of a 70 TeV collider, using 20 T bending magnets.
- Another try of a 100 TeV collider, using 16 T bending magnets

Next to do

- Optimize the lattice design base on the current progress(Arc filling factor, DS matching, IR study)
- Chromaticity study
- Dynamic aperture study

Thanks！