CEPC Overall Design related to Accelerator Physics

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for CEPC team

June 1st, 2017

Outline

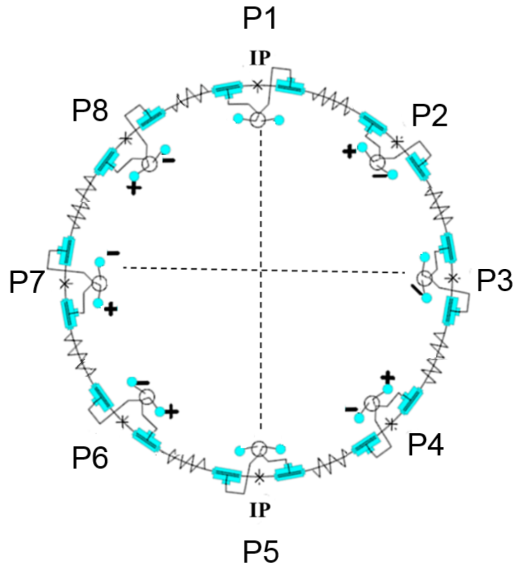
- **Physics goals and accelerator parameters**
- **Some items of the physics design**
- **Dynamic aperture**
- **Summary**

Physics goals of CEPC

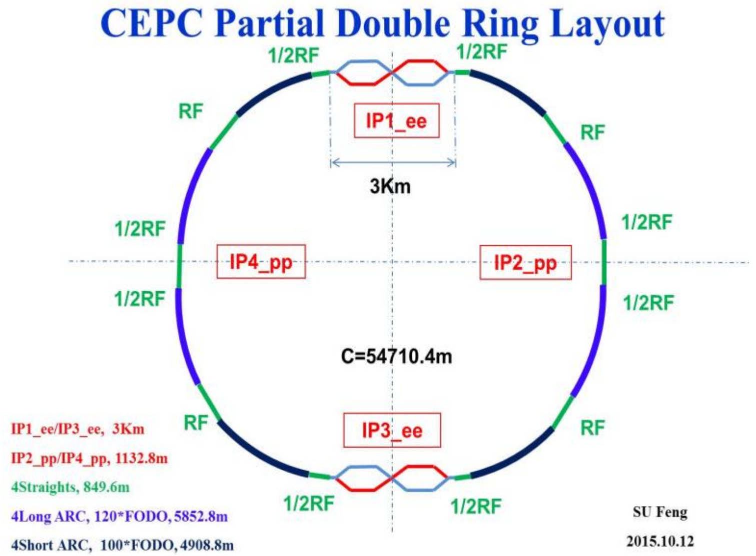
Electron-positron collider (45.5, 80, 120 GeV)

- Higgs Factory
  - Precision study of Higgs (m_H, J^{PC}, couplings)
  - Looking for hints of new physics
  - Luminosity > $2.0 \times 10^{34} cm^{-2} s^{-1}$
- Z & W factory
  - Precision test of standard model
  - Rare decays
  - Luminosity > $1.0 \times 10^{34} cm^{-2} s^{-1}$
- Flavor factory: b, c, t and QCD studies

Four stages towards CDR

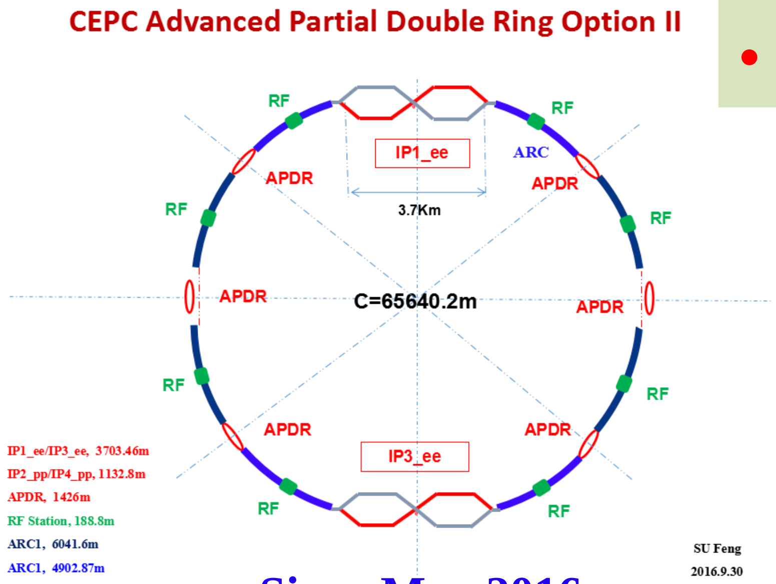


Since Oct 2012

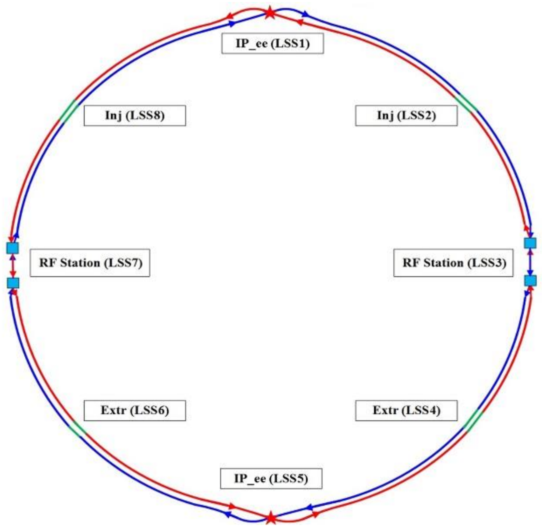


Since May 2015

- **Sawtooth effect**
- **Beam loading**
- **COD correction**
- **Collision tuning**



Since May 2016



Since Jan 2017

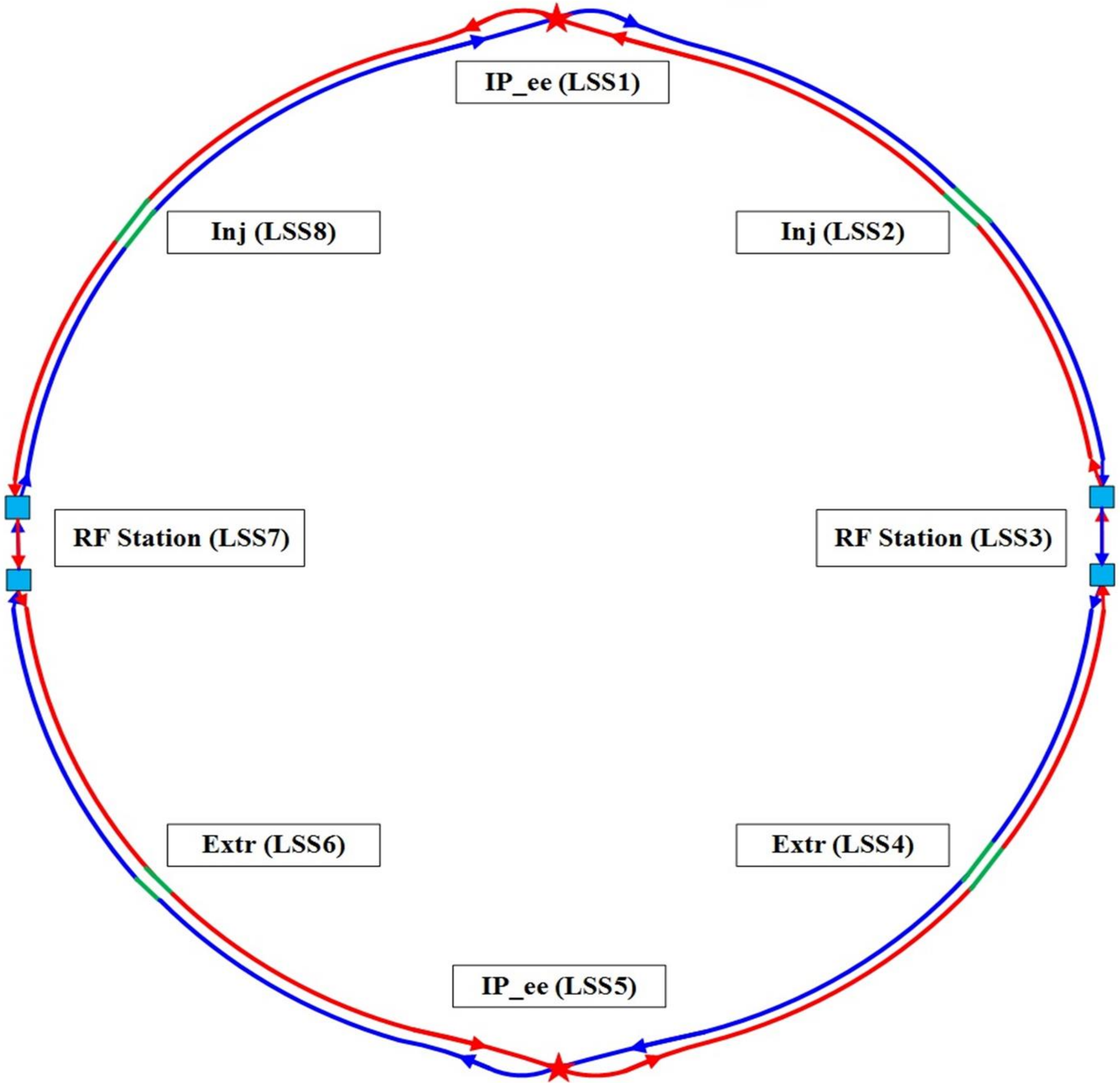
Key parameters of current CEPC

- Horizontal crossing angle at the IP θc=33mrad
- β_x^* / β_y^* =0.171m / 2mm
- L*=2.2m
- Detector solenoid= 3.0T
- Maximum strength of Anti-solenoid= 7.6T
- Maximum gradient of quadrupole= 150T/m (3.4T in coil)
- Two cell & 650MHz RF cavity
- Two dedicated survey in the RF region for Higgs and W & Z mode respectively
- **Maximum e+ beam power 32MW & e- beam power 32MW**
- 100km circumference while matching the geometry of SPPC.
- Crab-waist scheme with local chromaticity correction.

Parameters of CEPC double ring

	Higgs	***W***	***Z***
Number of IPs	2	2	2
Energy (GeV)	120	80	45.5
SR loss/turn (GeV)	1.67	0.33	0.034
Half crossing angle (mrad)	16.5	16.5	16.5
Piwinski angle	3.19	5.69	4.29
N_e/bunch (10^{11})	0.968	0.365	0.455
Bunch number	**412**	**5534**	**21300**
Beam current (mA)	19.2	97.1	465.8
SR power /beam (MW)	**32**	**32**	**16.1**
Bending radius (km)	11	11	11
Momentum compaction (10^{-5})	1.14	1.14	4.49
β_{IP} x/y (m)	0.171/0.002	0.171 /0.002	0.16/0.002
Emittance x/y (nm)	1.31/0.004	0.57/0.0017	1.48/0.0078
Transverse σ_{IP} (um)	15.0/0.089	9.9/0.059	15.4/0.125
ξ_x/ξ_y/IP	0.013/0.083	0.0055/0.062	0.008/0.054
RF Phase (degree)	128	126.9	165.3
V_{RF} (GV)	2.1	0.41	0.14
f_{RF} (MHz) (harmonic)	650	650 (217800)	650 (217800)
Nature σ_z (mm)	2.72	3.37	3.97
Total σ_z (mm)	2.9	3.4	4.0
HOM power/cavity (kw)	0.41(2cell)	0.36(2cell)	1.99(2cell)
Energy spread (%)	0.098	0.065	0.037
Energy acceptance (%)	1.5		
Energy acceptance by RF (%)	2.1	1.1	1.1
n_γ	0.26	0.15	0.12
Life time due to beamstrahlung (min)	52		
F (hour glass)	0.96	0.98	0.96
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	**2.0**	**5.15**	**11.9**

Layout of CEPC Double Ring



The geometry of CEPC is compatible for the SPPC

The definition of beam stay clear

- To satisfy the requirement of injection: **BSC=19σ**
- To satisfy the requirement of beam lifetime after collision

  BSC_x=20σ_x , BSC_y=40 σ_y

BSC_x =±(20σ_x +3mm), BSC_y =±(40σ_y +3mm), While coupling=1% , including the coupling of circulating beam and beam-beam effect.

(Magnets, vacuum chamber…)

Around the IP

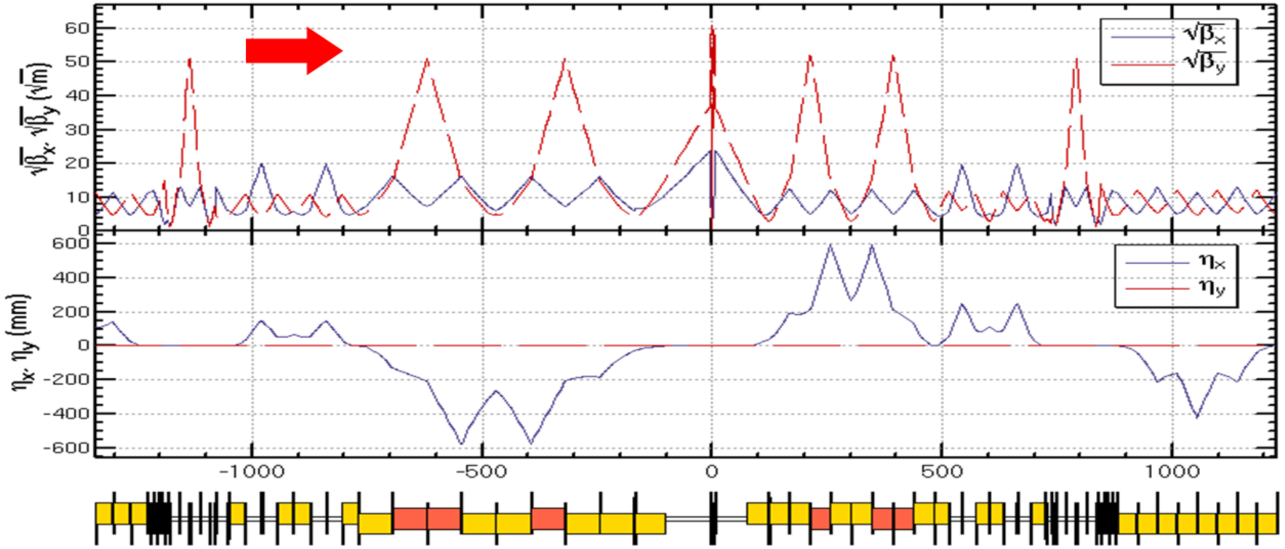
L*=2.2m, θc=33mrad, Detector solenoid=3.0T

- Lower strength requirements of anti-solenoids (~7.6T)
- Enough space for the quadrupole coils of two-in-one aperture.
- Lower strength requirements of Crab-Waist sextupoles.
- Maximum field in coil of quadrupole=3.4T, Gradient of Q=150T/m.
- The control of SR power from the superconducting quadrupoles.

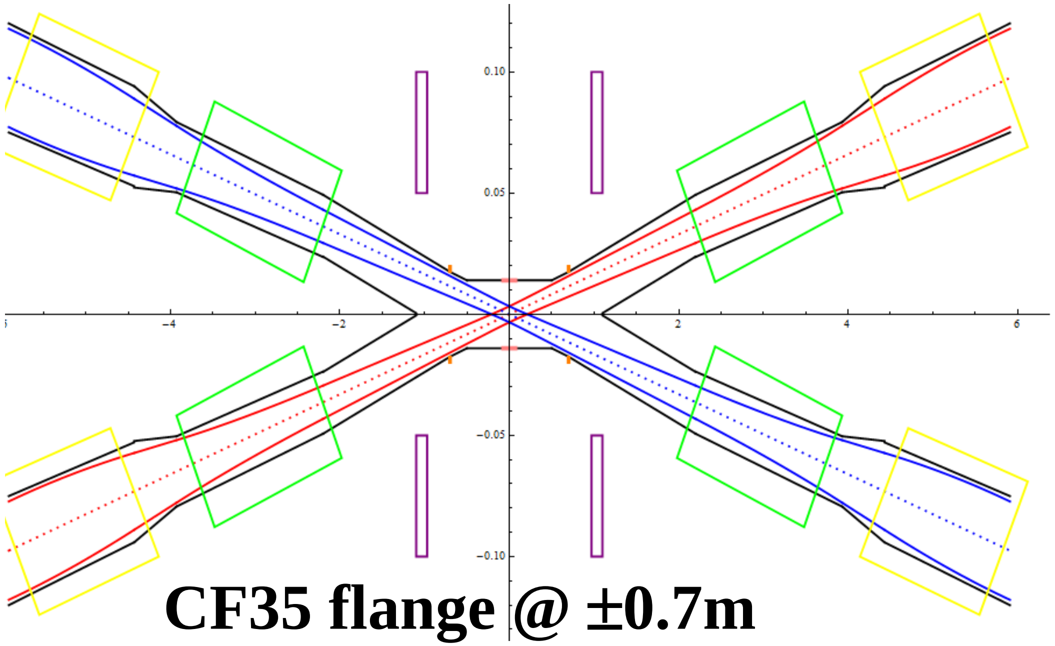
L*= 1.5m ✕

L*= 2.0m ✕

θc=30mrad ✕

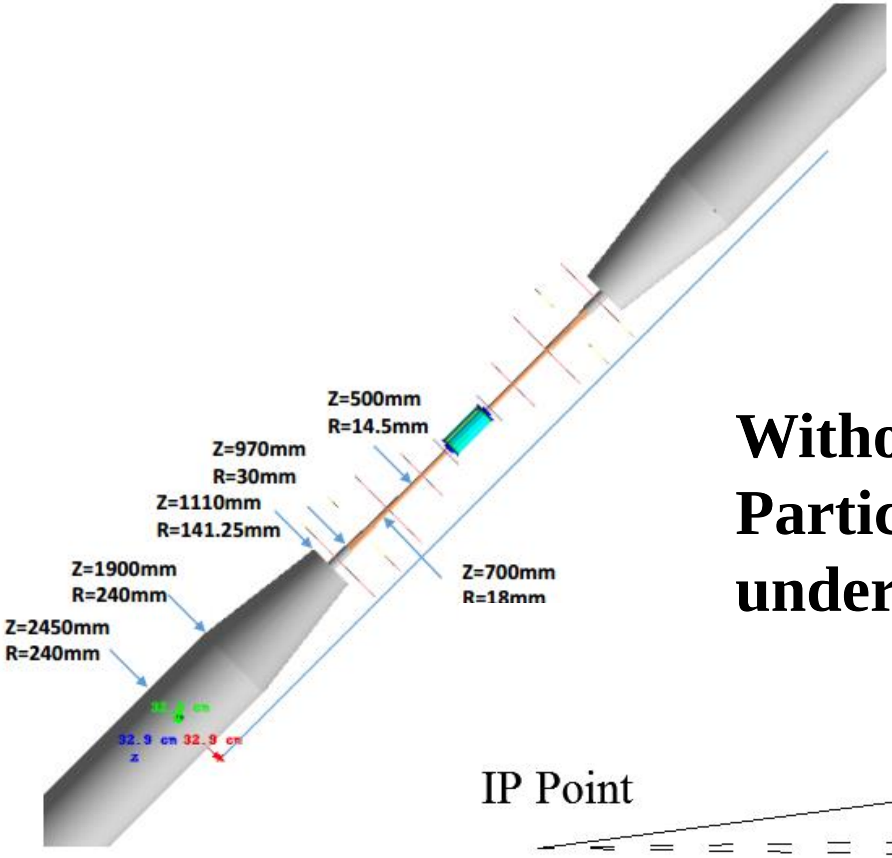


IR

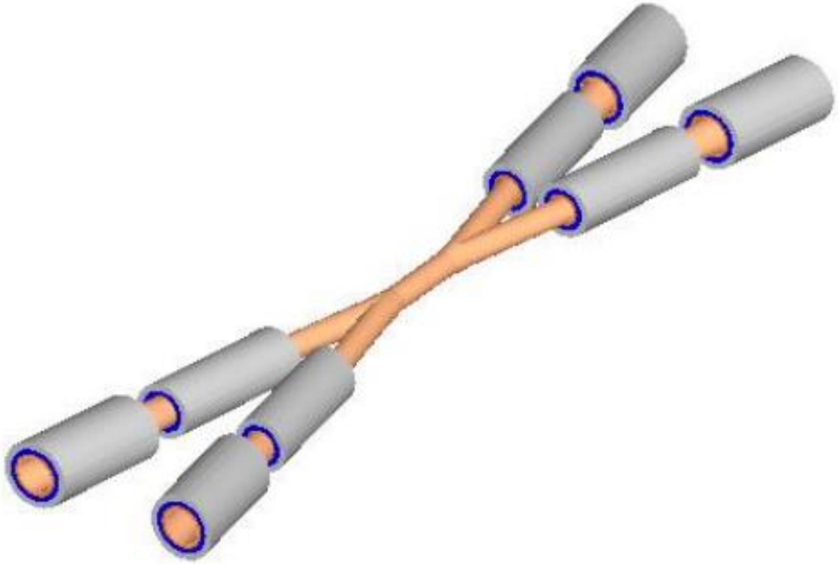


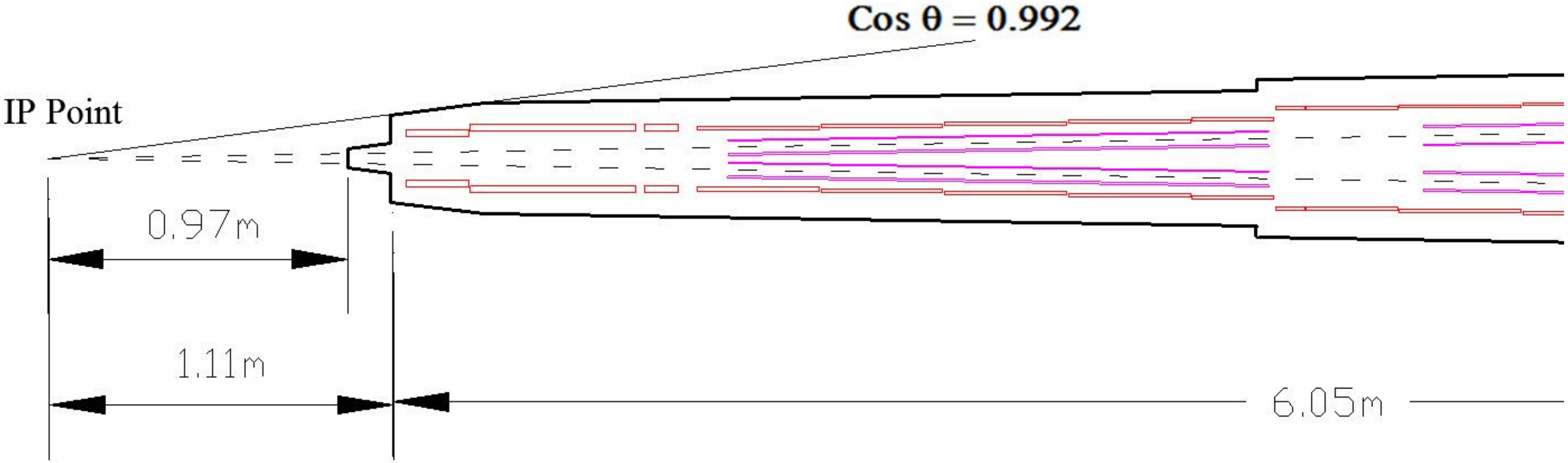
CF35 flange @ ±0.7m

The current design of superconducting magnets

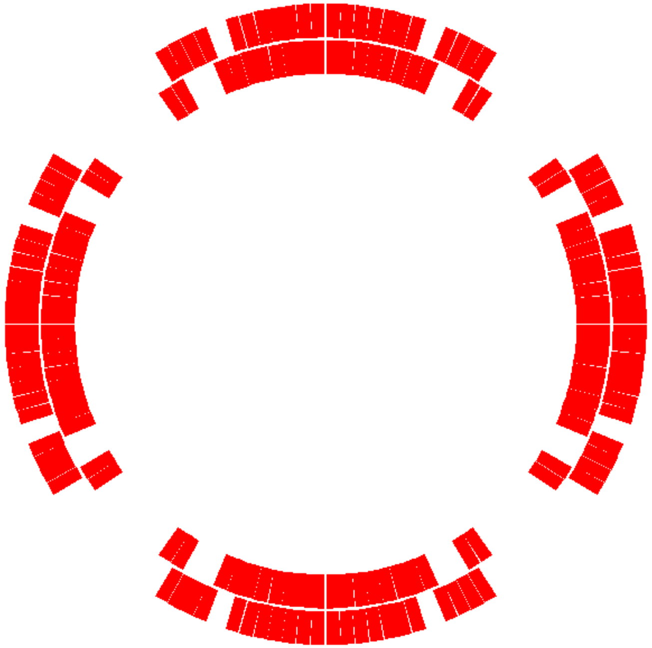


Without tungsten shield.
Particle background is under studying.

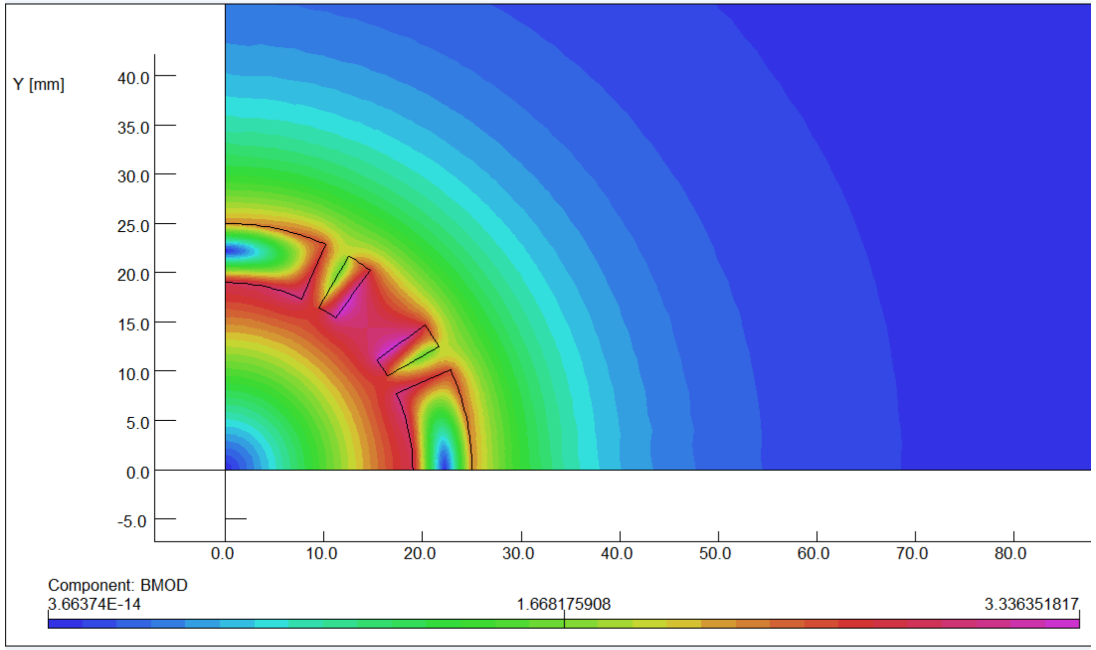


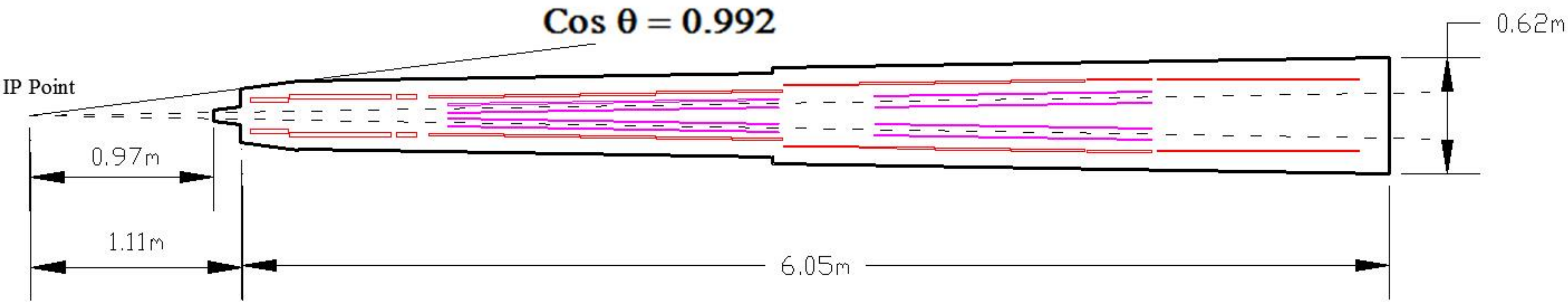


Magnetic field of superconducting QF and QD coils



Rutherford cable



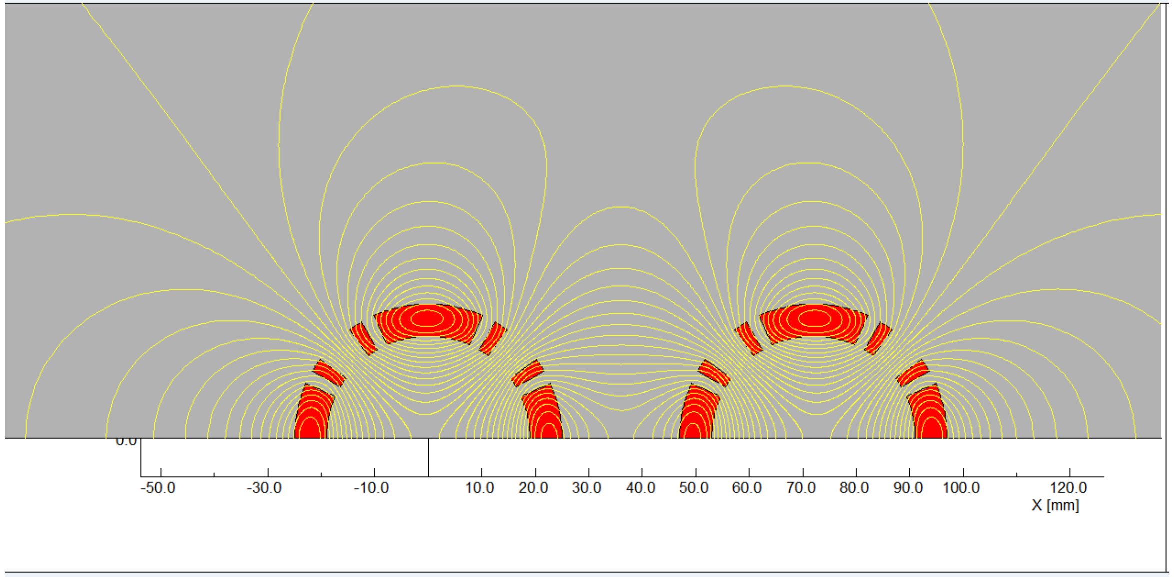


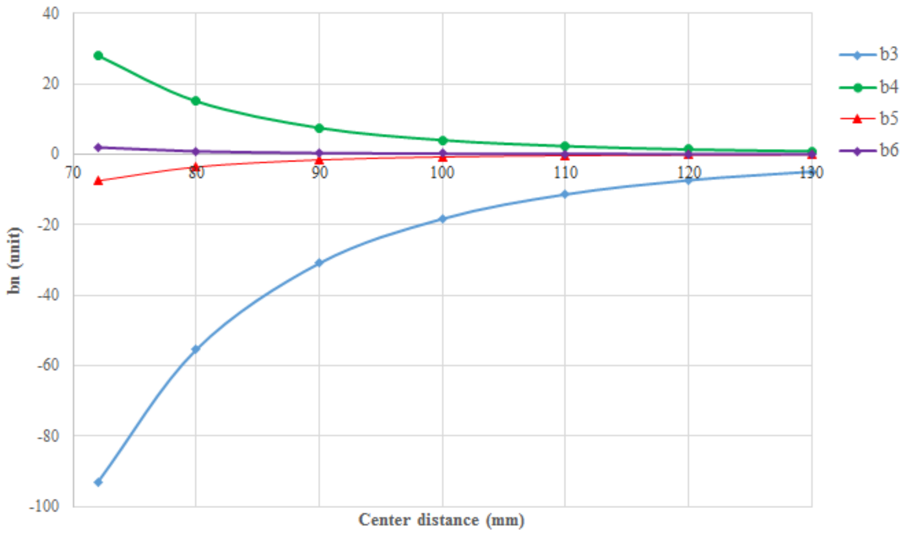
The specification of superconducting coils

Magnet name	QD0	QF1
Field gradient (T/m)	150	106
Magnetic length (m)	1.75	1.46
Start Z position（m）	2.2	4.45
Coil turns per pole	21	24
Excitation current (A）	2700	3000
Coil layers	2	2
Conductor size (mm)	Rutherford NbTi-Cu Cable, width 2.5mm, mid thickness 0.93mm	
Stored energy (KJ)	20.0	26
Inductance (H）	0.0054	0.006
Peak field in coil (T)	**3.4**	3.3
Coil inner diameter (mm)	38	52
Coil out diameter (mm)	50	64

Anti-solenoids	Before QD0	Within QD0	Within QF1
Central field（T）	7.2	2.8	1.8
Magnetic length（m）	1.1	1.75	1.46
Conductor (NbTi-Cu)	4×2mm	4×2mm	4×2mm
Coil layers	12	6	4
Excitation current（kA）	2.2	1.7	1.2
Stored energy (KJ)	500	163	64
Inductance（H）	0.21	0.11	0.09
Peak field in coil (T)	**7.6**	2.9	1.9
Number of sections	3	9	7
Solenoid inner diameter (mm)	140	190	310
Solenoid outer diameter (mm)	225	262	390

Field leakage between two apertures





unit 1×10^{-4}

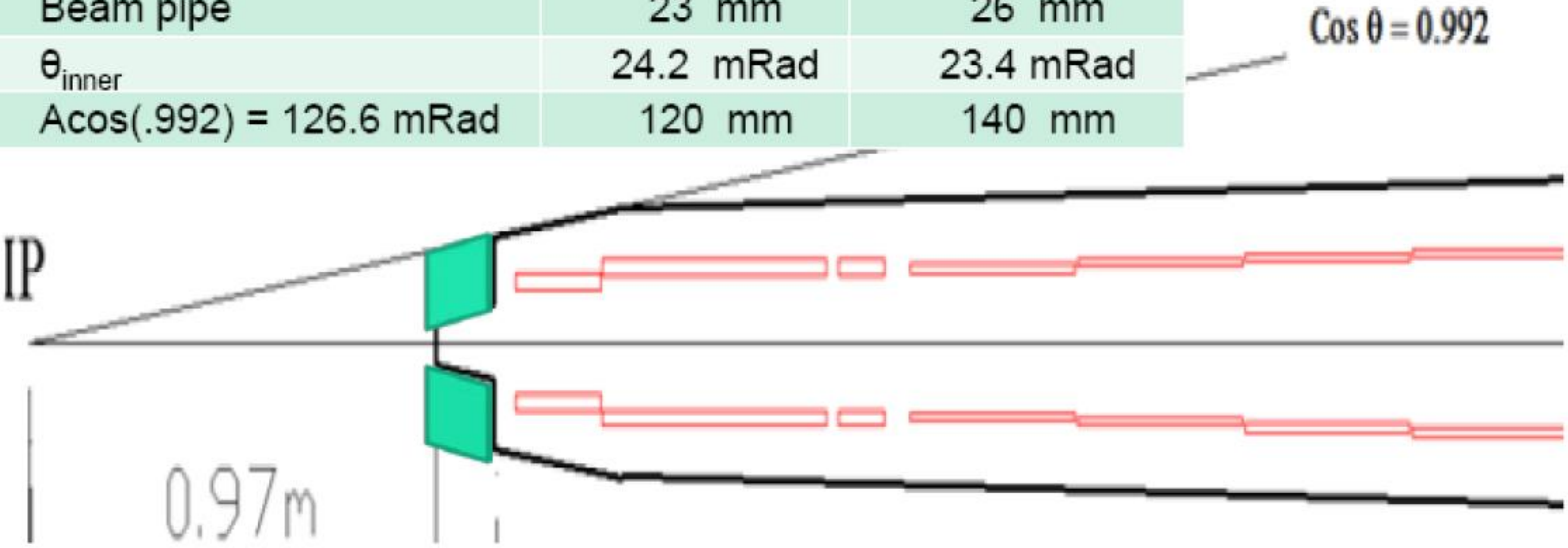
Besides the main coils:

- Correction coils to cancel b3, b4 and b5 components were designed.
- The skew quadrupole coils were designed to make fine tuning of Bz over the QF&QD region instead of the mechanical rotation.

The current design of Lumical detector

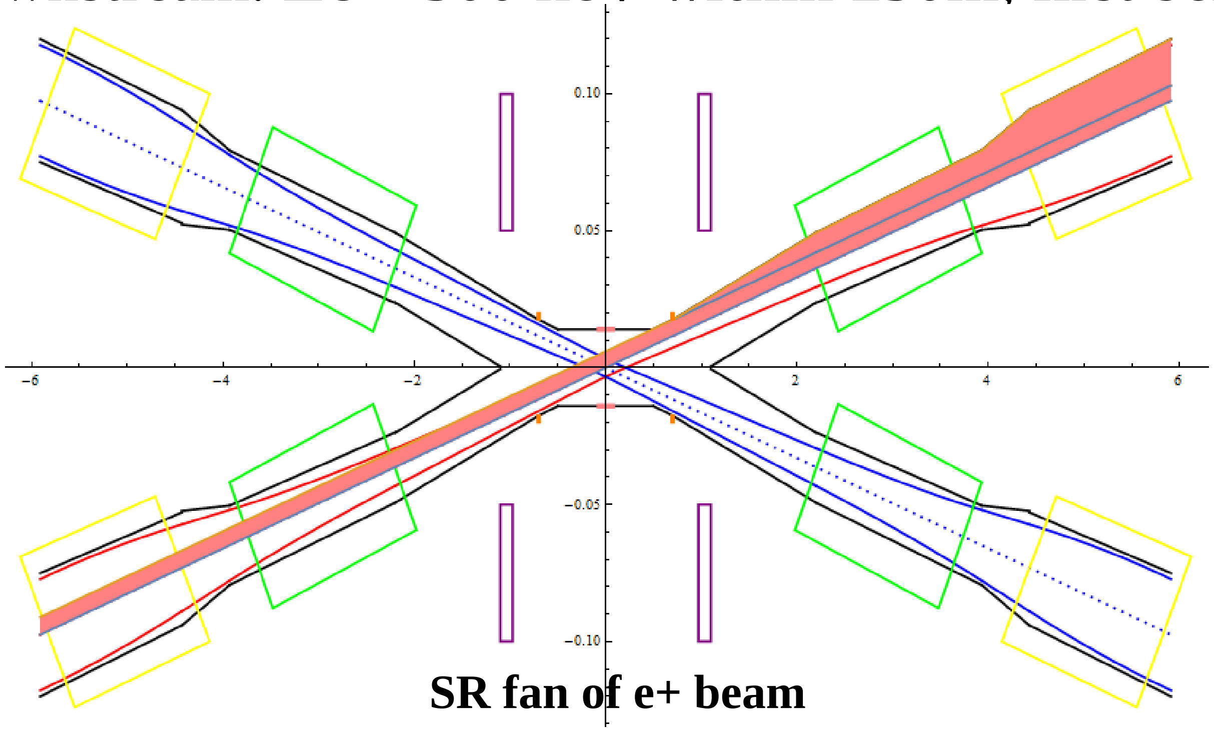
LumiCal parameters

IP to Lumi Cal	Front .95 m	Back 1.11 m
Beam pipe	23 mm	26 mm
θ_{inner}	24.2 mRad	23.4 mRad
Acos(.992) = 126.6 mRad	120 mm	140 mm



The synchrotron radiation in the IR

- The central part is Be pipe with the length of 14cm and inner diameter of 28mm.
- IP upstream: **Ec < 100 keV within 400m.** **Last bend**(100m)**Ec < 55 keV**
- IP downstream: **Ec < 300 keV within 250m**, first bend **Ec < 120 keV**



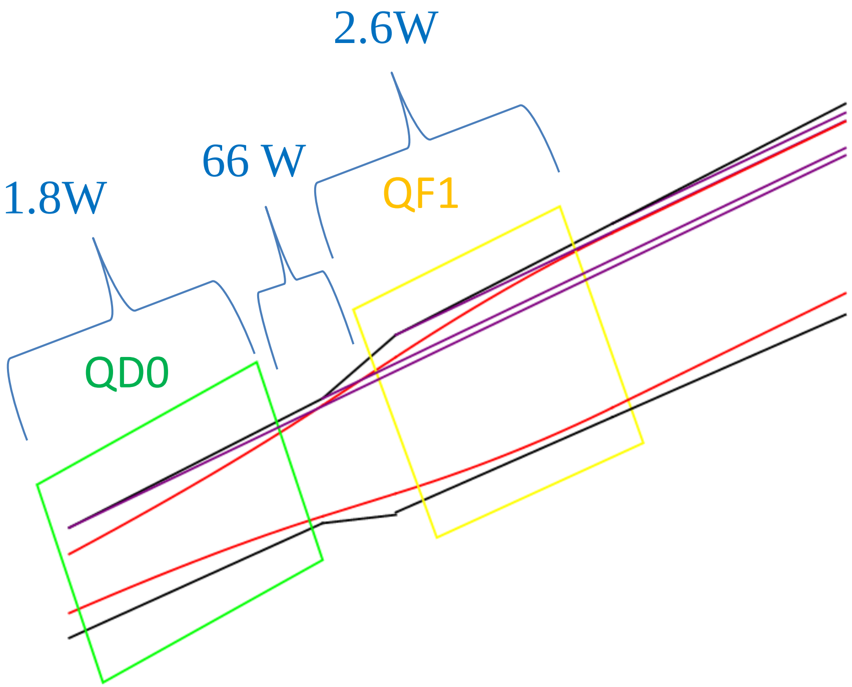
SR fan of e+ beam

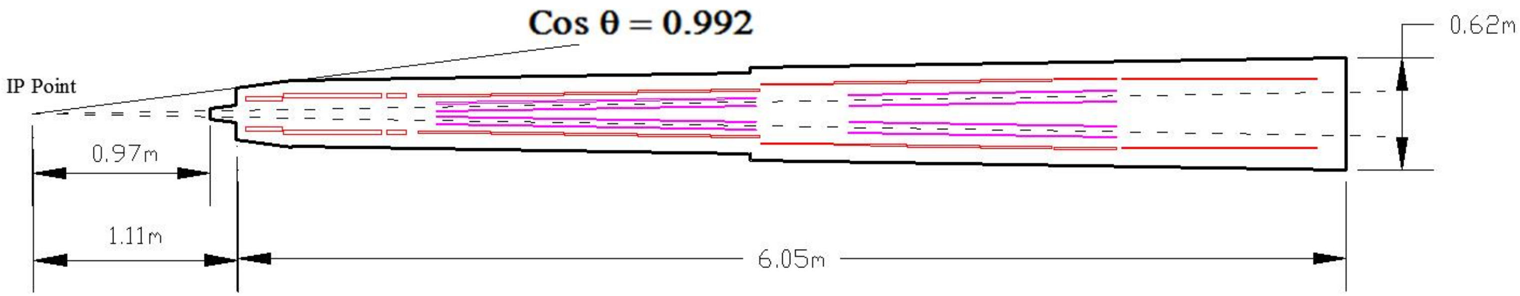
Background control
&
SR protection

No SR hits directly on the beryllium pipe. ~47W of SR power contributed by e+ within 10σ_x will go through the IP. Ec< 55kev

The synchrotron radiation in the IR

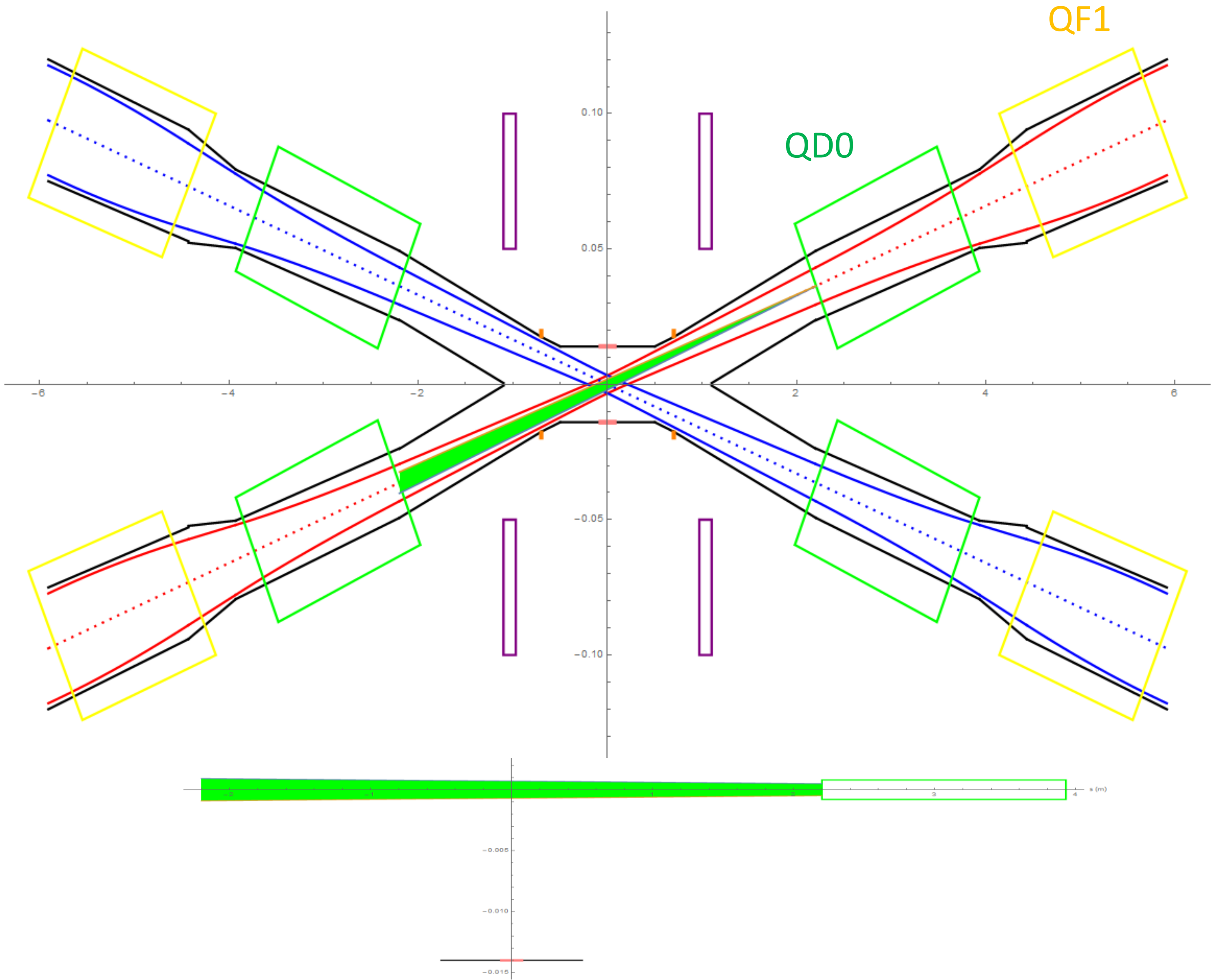
Cold vacuum chamber has to be adopted within SC magnet for the sufficient coils space. The design has been accepted by cryogenic sys.





The synchrotron radiation power within QD0 is **1.8W along1.73m**, on QF1 is **2.6W along 1.48m**. The region between QD0 and QF1 is **66 W (0.5m)** where has special cooling structure.

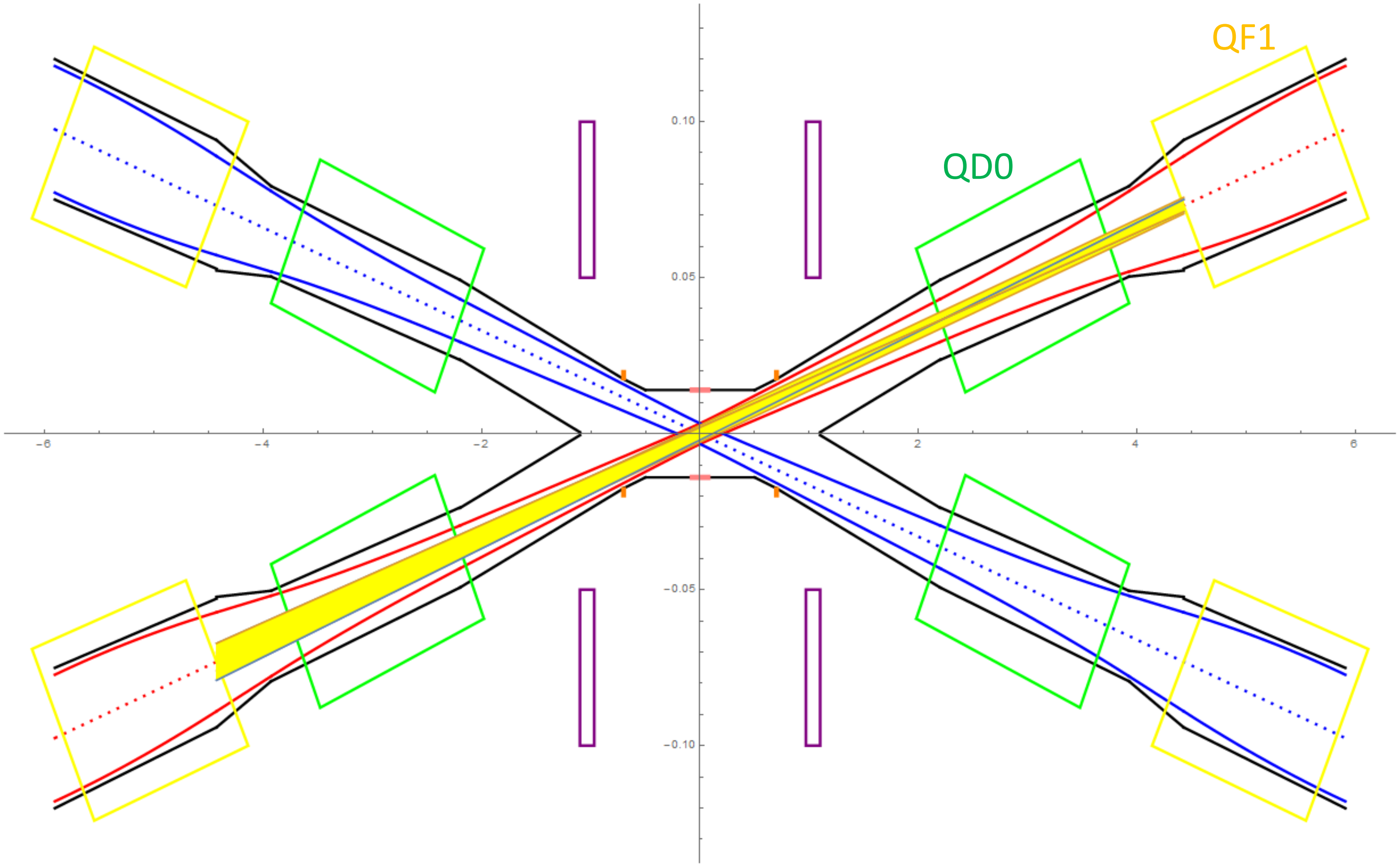
The synchrotron radiation in the IR



The total SR power generated by the QD magnet is 1470W in horizontal and 186W in vertical. The critical energy of photons is about 2.0 MeV. And 186W in vertical. The critical energy of photons is about 440 keV.

No SR hits directly on the IP chamber.

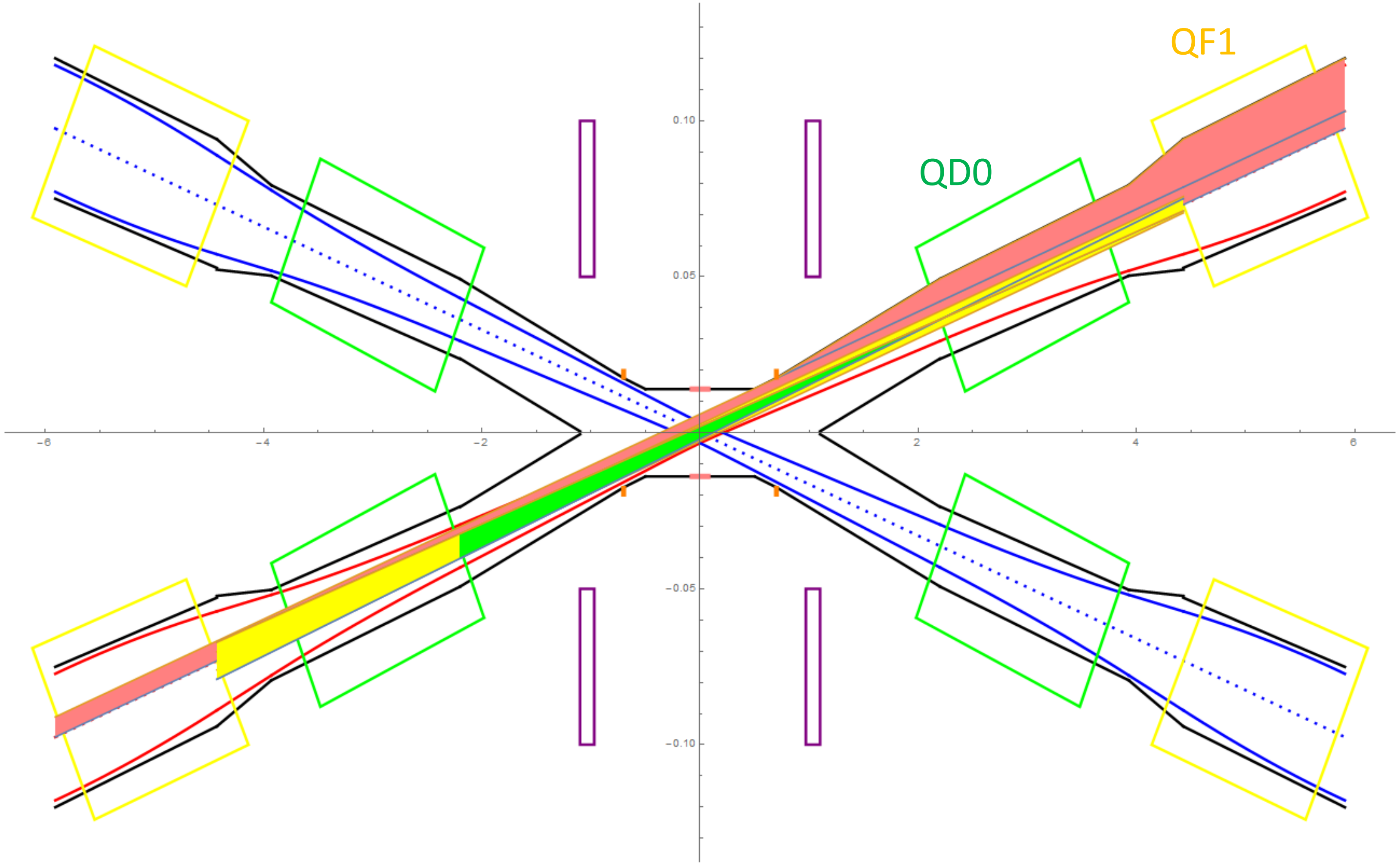
The synchrotron radiation in the IR



The total SR power generated by the QF1 magnet is 3490W in horizontal and 37W in vertical. . The critical energy of photons is about 2.4MeV. The critical energy of photons is about 200keV.

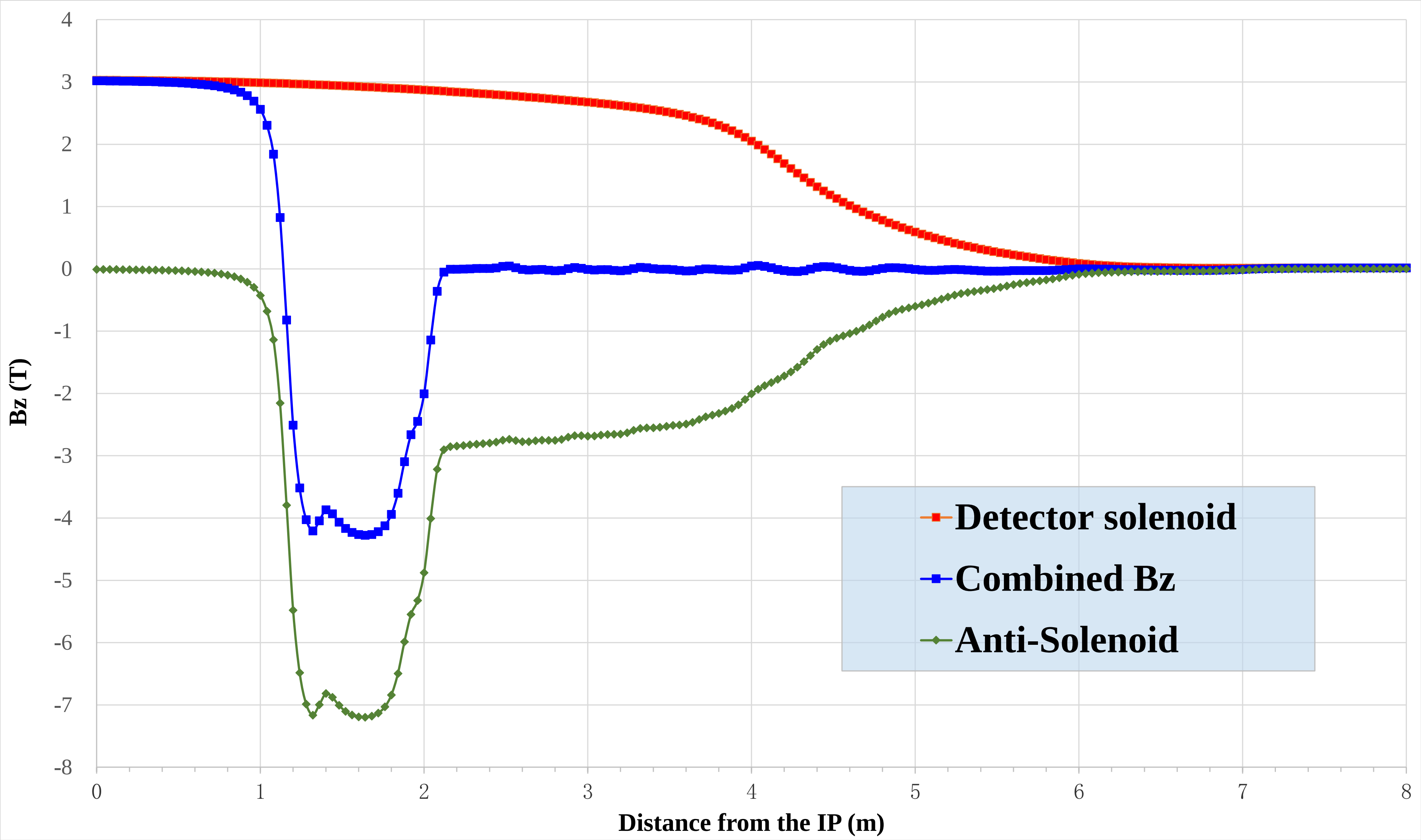
No SR hits directly on the IP chamber.

The synchrotron radiation in the IR



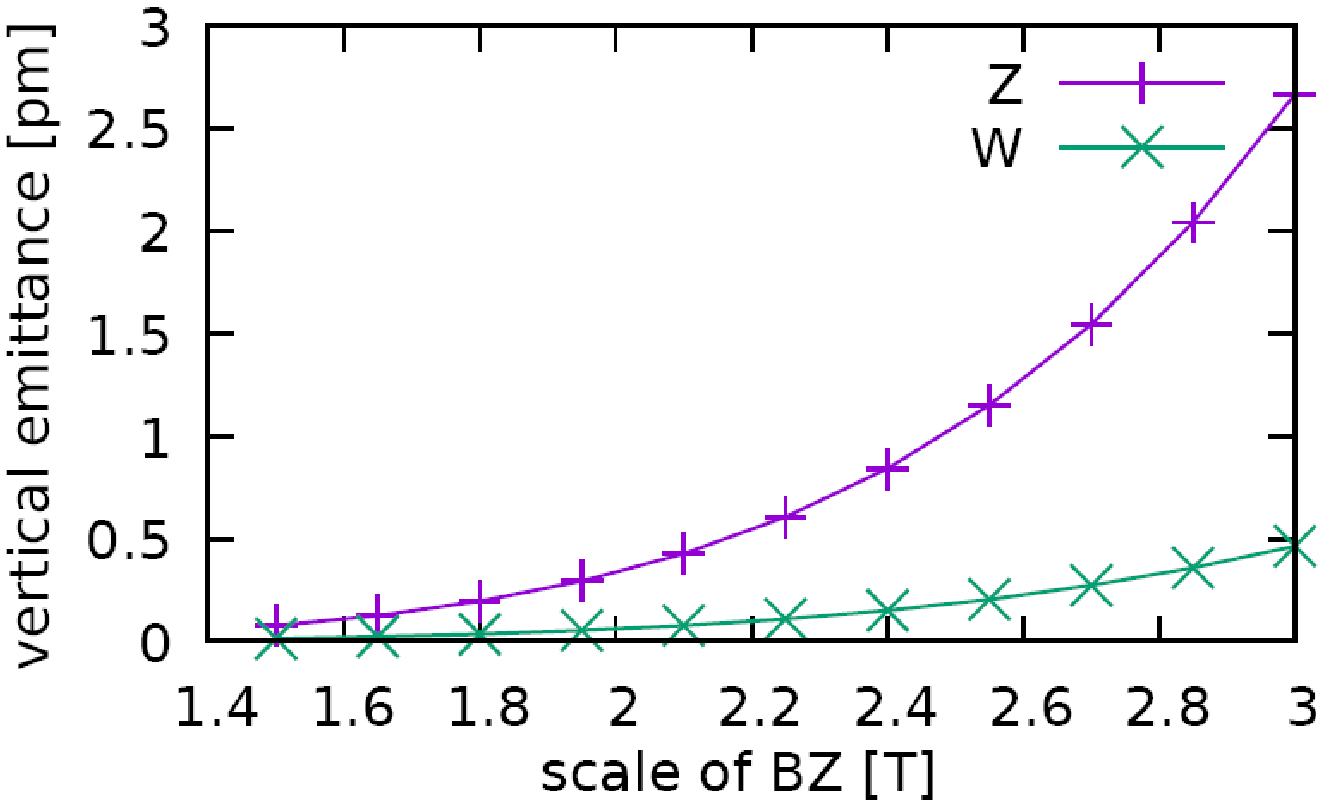
SR fans around the IP of e+ beam

The compensation scheme of detector solenoid



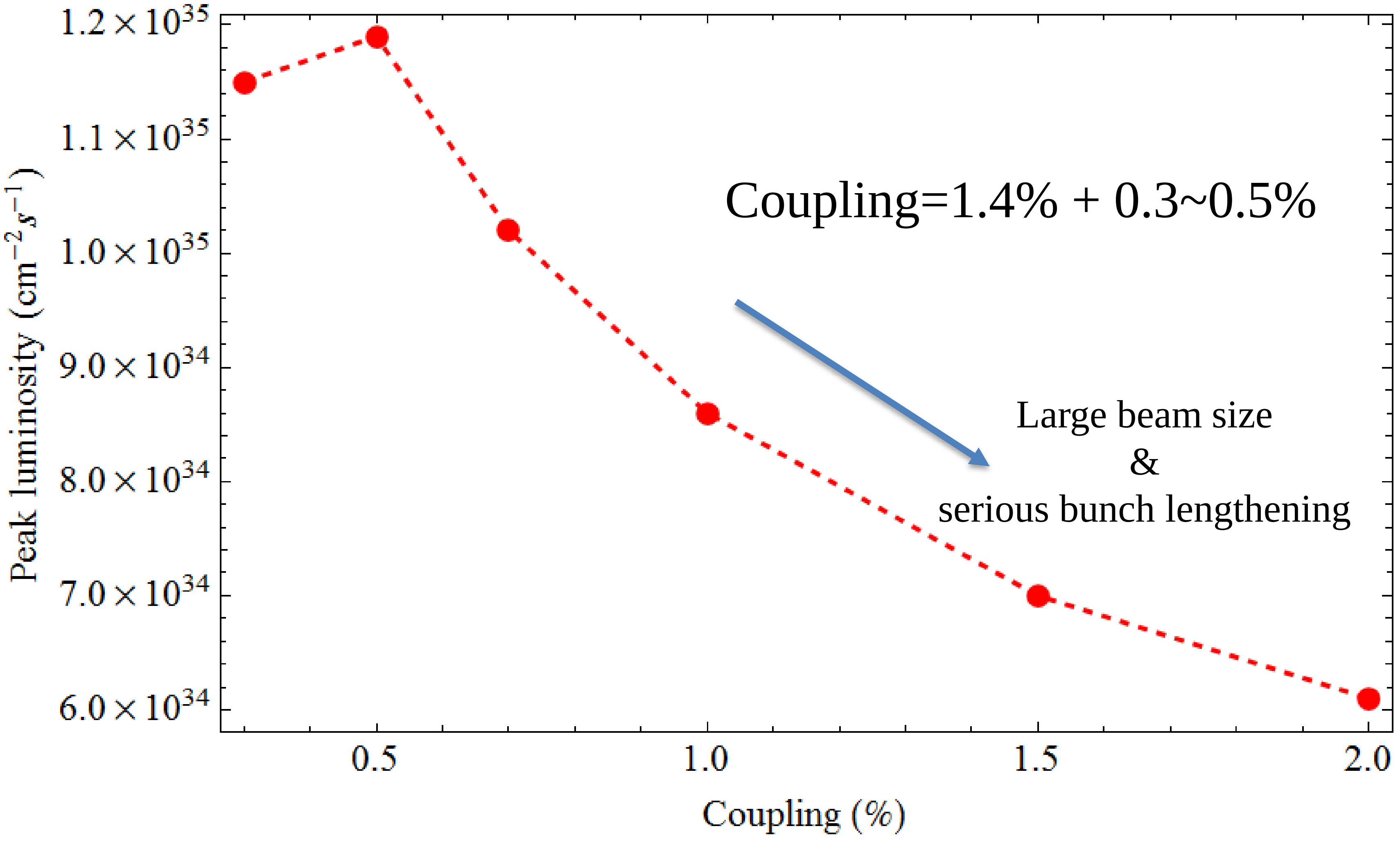
$\int B_z ds$ within 0~2.12m. Bz < 500Gauss away from 2.12m

Emittance growth caused by the fringe field of solenoids



Design emitY/emitX	expected contribution	Current contribution
H: 4.0pm/1.31nm (0.3%)	0.4pm	0.14pm (0.01%)
W: 2.0pm/0.57nm (0.3%)	0.2pm	0.47pm (0.08%)
Z: 1.0pm/0.20nm (0.5%)	0.1pm	**2.67pm (1.34%)**

Coupling Vs. Luminosity @ Z



For **the 2Cell cavity** operation, if the coupling lose control **$L \approx L_0/2 \sim L_0/4$**

Coupling Vs. Luminosity@Z

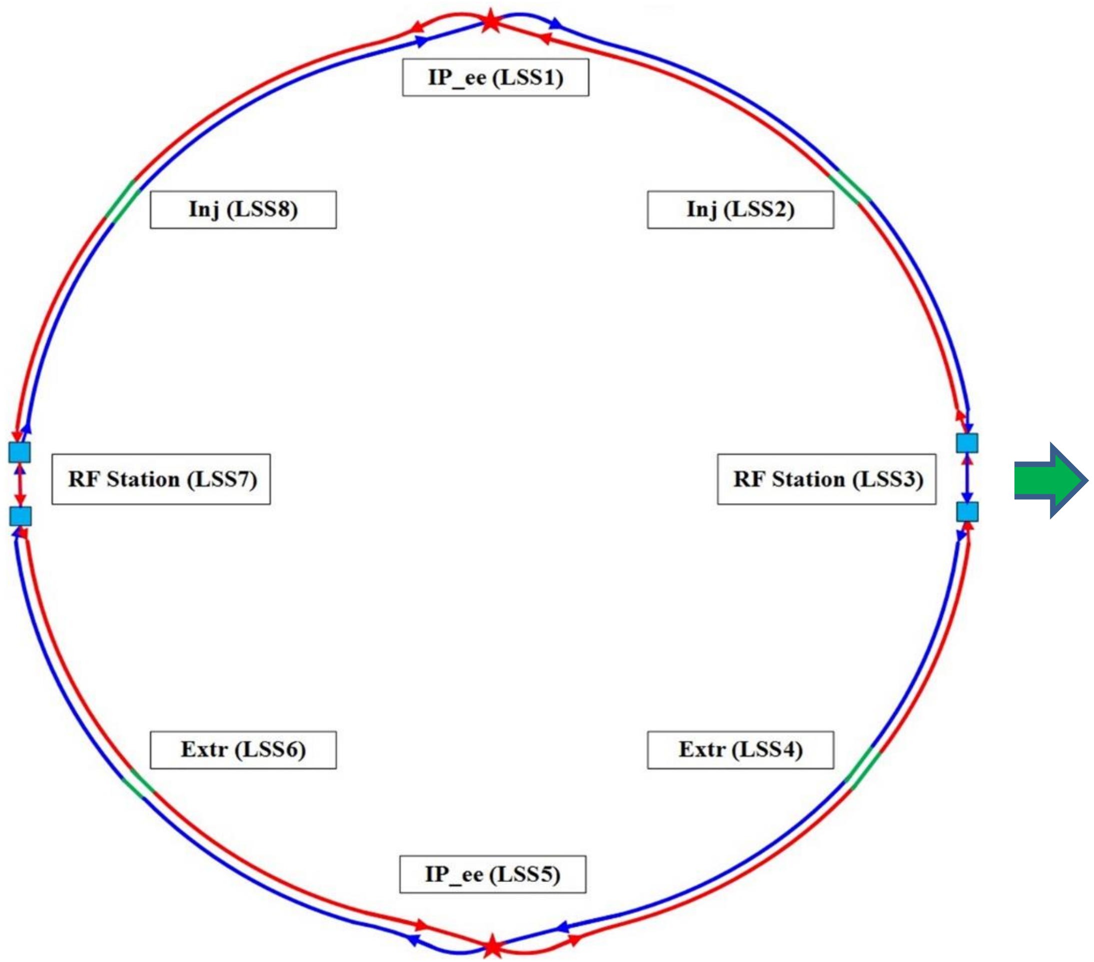
If CEPC has higher luminosity requirement @Z

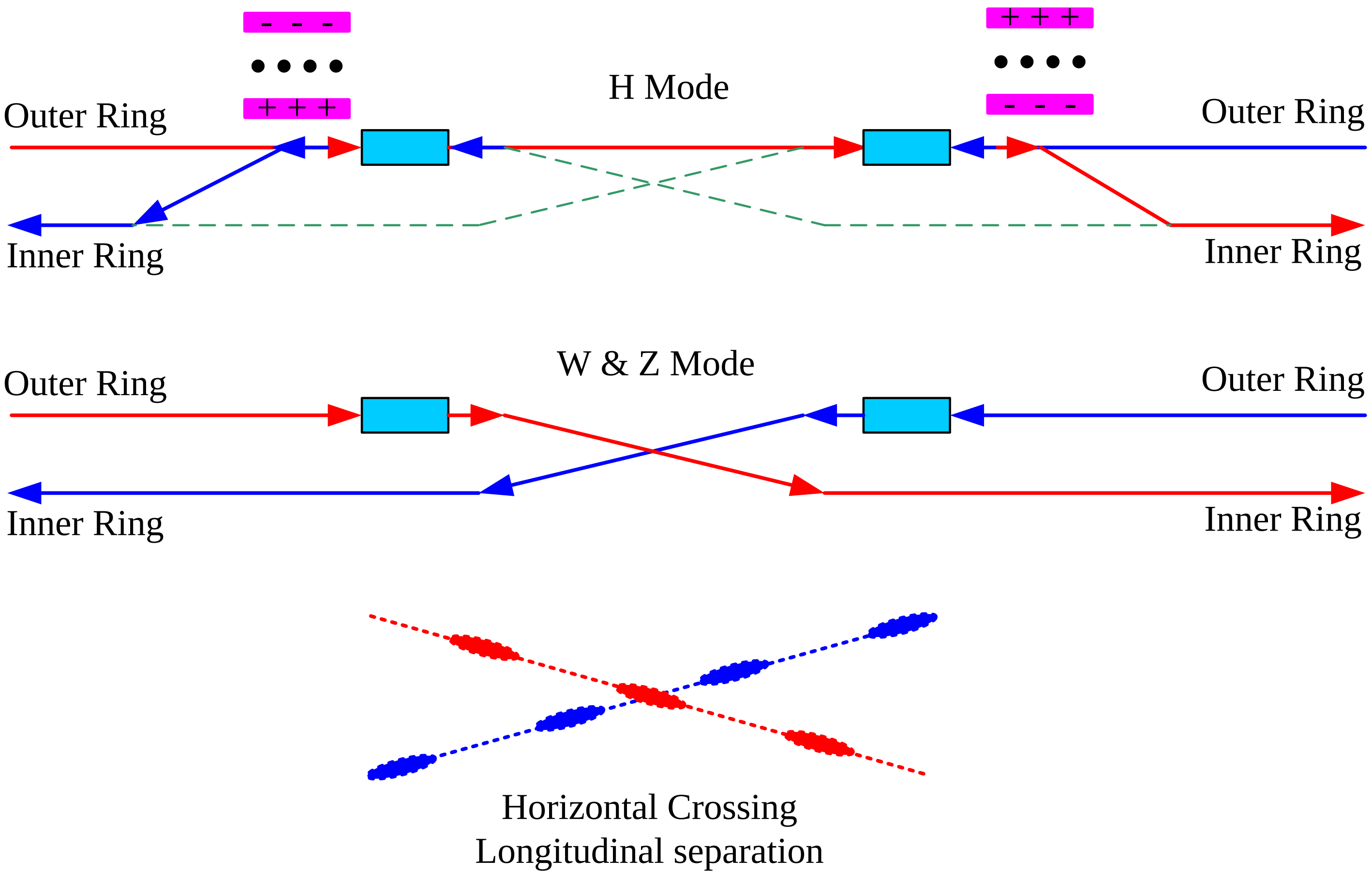
	Design emitY/emitX	expected contribution	Current contribution
Z:	1.0pm/0.20nm (0.5%)	0.1pm	2.67pm (1.34%)
Z:	**1.0pm/0.20nm (0.5%)**	**(2T solenoid)**	**0.16pm (0.08%)**
Z:	**7.8pm/1.48nm (0.5%)**	**1pm**	**2.67pm (0.18%)**

☺
- **Set the detector solenoid at 2T or < 2T during Z operation**
- **Dedicated lattice for Z with large emittance**
  - ✦ Linear lattice with emittance 1.48nm has been designed.

RF region

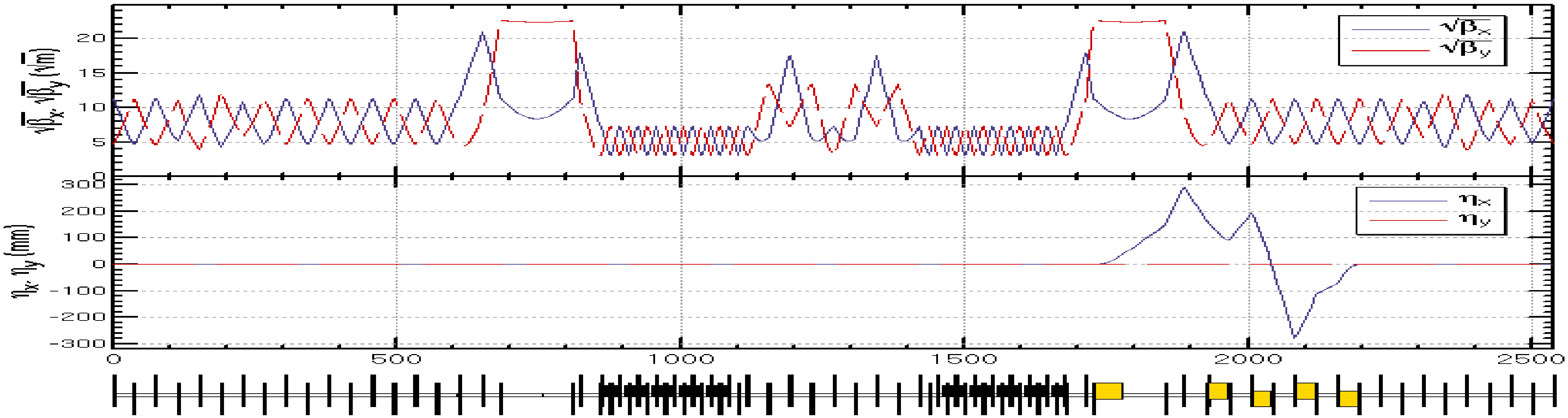
- **Common cavities** for Higgs mode, bunches filled in half ring for e+ and e-.
- **Independent cavities** for W & Z mode, bunches filled in full ring.
- The outer diameter of RF cavity is 1.5m. Distance of two ring is 1.0m.





RF region

Low beta functions in the RF region to reduce the instabilities caused by RF cavities. For Z mode the beam current threshold can be improved from 168mA to 673mA. Due to the **limitation of HOM 466mA** was chosen before the installation of the dedicated RF cavity.



Esep=1.8 MV/m , Lsep=50m

Lattice of ARC region

Higgs lattice

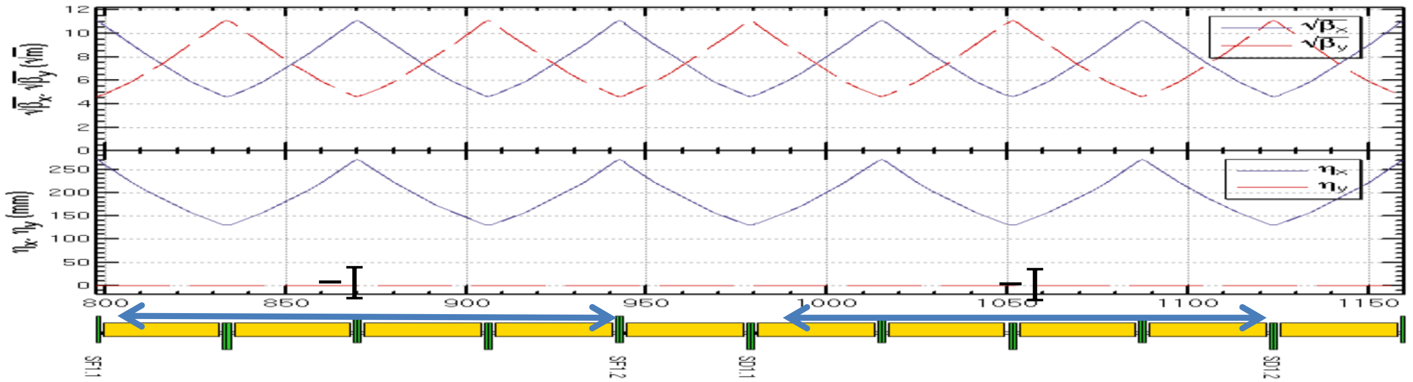
- **FODO cell, 90°/90°, non-interleaved sextupole scheme**
  - period N=5cells
  - all 3rd and 4th resonance driving terms (RDT) due to sextupoles cancelled, except small 4Qx, 2Qx+2Qy, 4Qy, 2Qx-2Qy
  - **tune shift dQ(Jx, Jy) is very small**
  - **Chromaticity dQ(δ) need to be corrected with many families**

A possible Z lattice

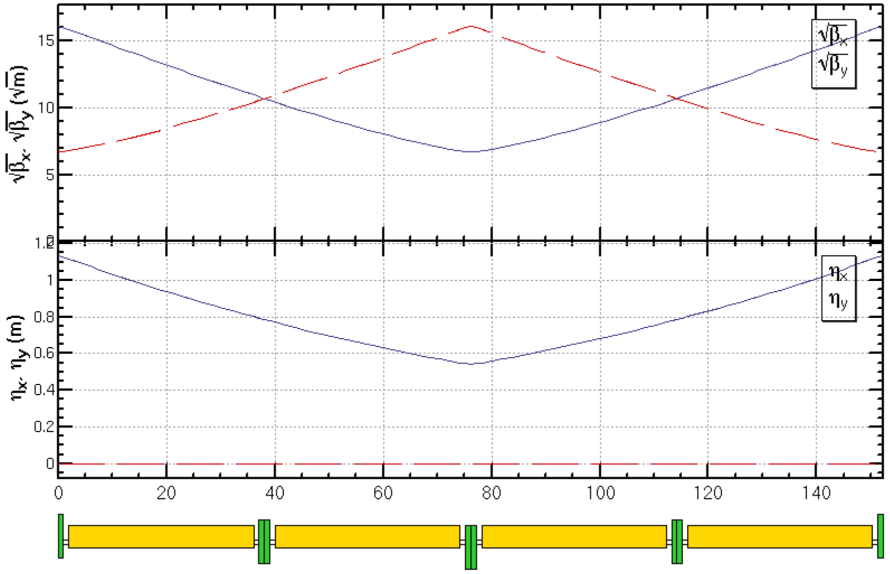
- Geometry of Z should be compatible with Higgs lattice.
  - The bends are kept
  - **Two FODO cells combined into one FODO cell**
  - Dispersion suppressor combined with FODO cells re-matched
  - Emittance=1.48nm

ARC region

FODO cells in H & a possible Z lattice



Higgs ARC region



A possible lattice of Z for large emittance

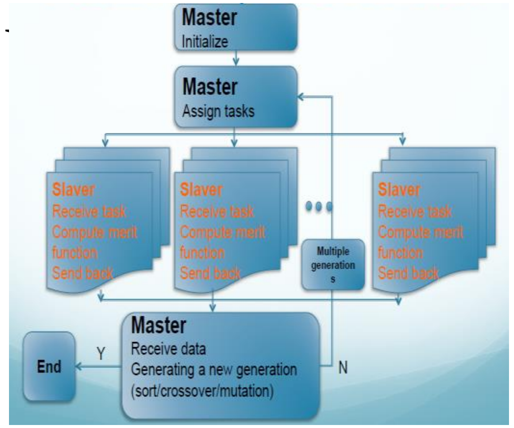
Dynamic aperture study by MOGA

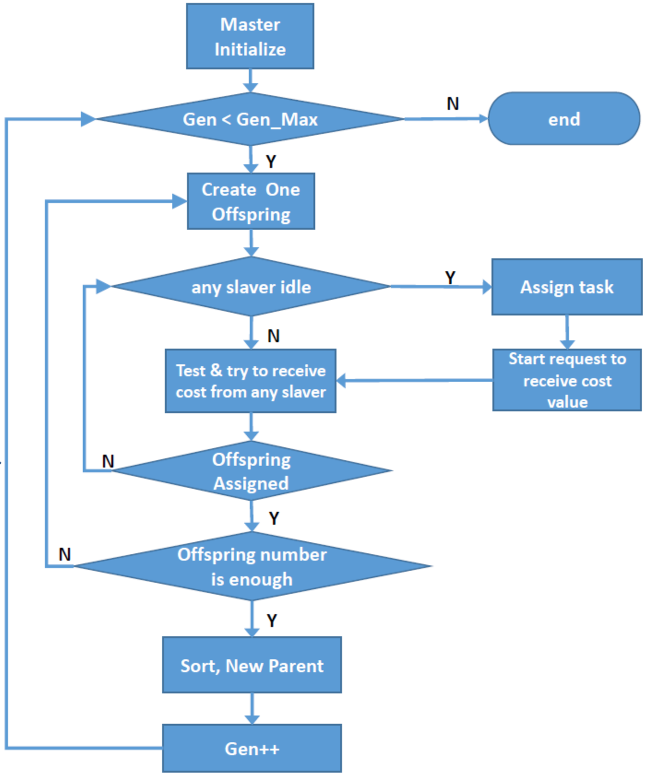
- Application in storage ring based light source is very popular and successful
  - APS/DLS, ELEGANT, M. Borland, in 48th ICFA Beam Dynamics Workshop on Future Light Sources
  - NSLSII， L. Yang, Y. Li, W. Guo and S. Krinsky, PRST-AB, 14, 054001 （2011）
  - SLS, BMAD, M. Ehrlichman , arXiv: 1603.02459
  - HEPS, Accelerator Toolbox, Y. Jiao and G. Xu, IPAC’16
- Different Algorithm
  - Particle Swarm, SPEAR3, X. Huang, J. Safranek, Nucl. Instr. Meth. In Phys. Research A. 757, 48, 2014
  - Differential Evolution, J. Qiang *et al.*, IPAC’13
  - Downhill Simplex, SuperKEKB, FCC, K. Oide *et al.*

DA optimization with code MODE

(**M**ulti-**O**bjective optimization by **D**ifferential **E**volution)

- The algorithm is referencing to J. Qiang(IPAC'13)
- Multi-objectives are classified into two kinds. The time consuming cost function be calculated only when the necessary constraints (or objective) be satisfied.
- ***High Parallel + High Scalability***
  - Even the time taken by different task is diff
  - Even some node is

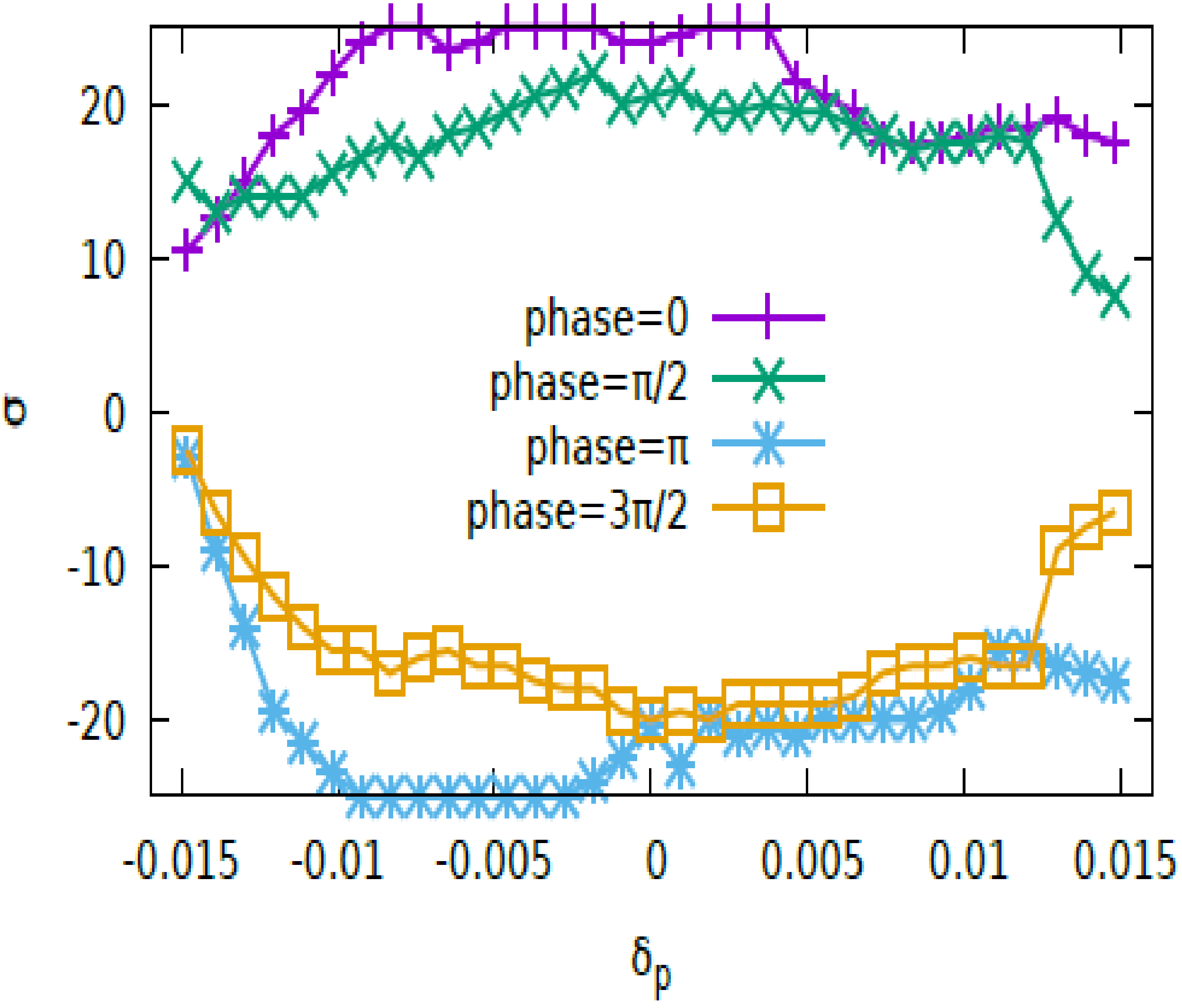




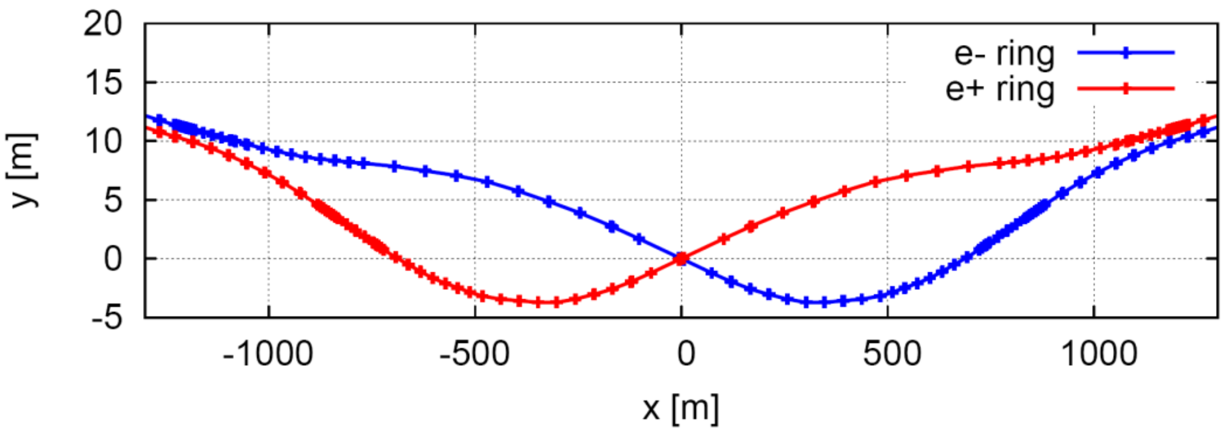
DA optimization with code MODE

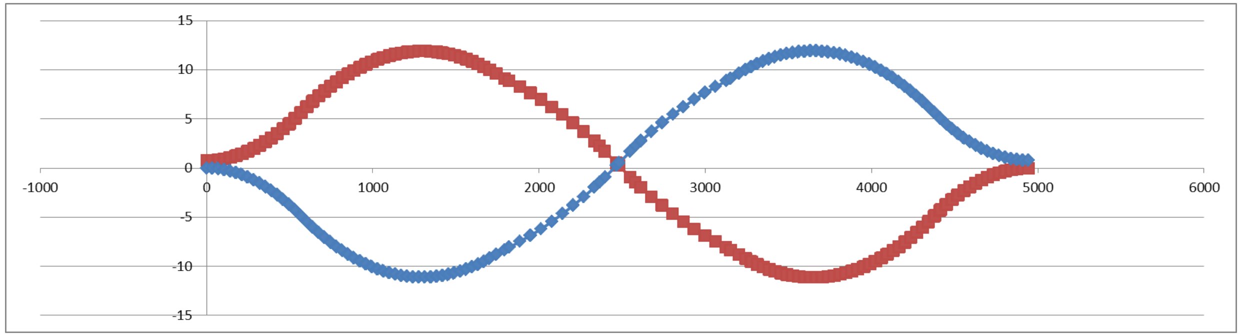
- SAD is used
- 200 turns tracked
- IR sextupoles + 32 arc sextupoles

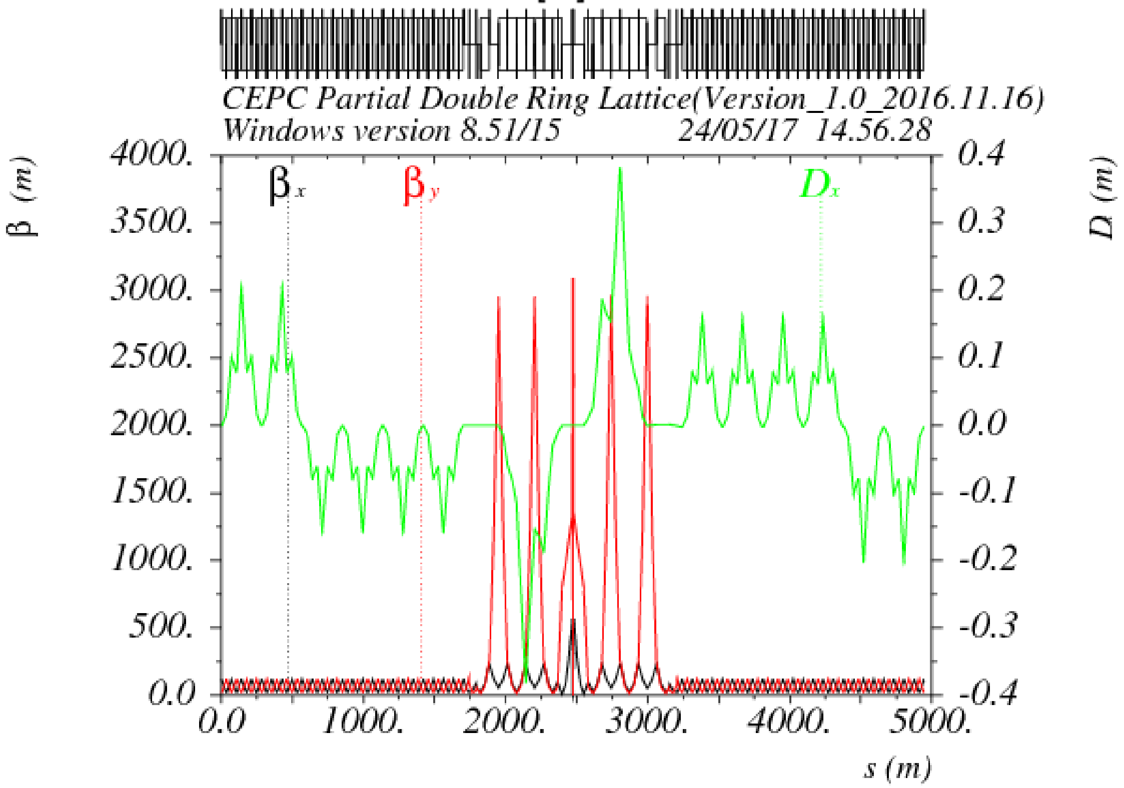
  (Max. free various=254)
- Damping at each element.
- RF on
- Seems good. But needs better.

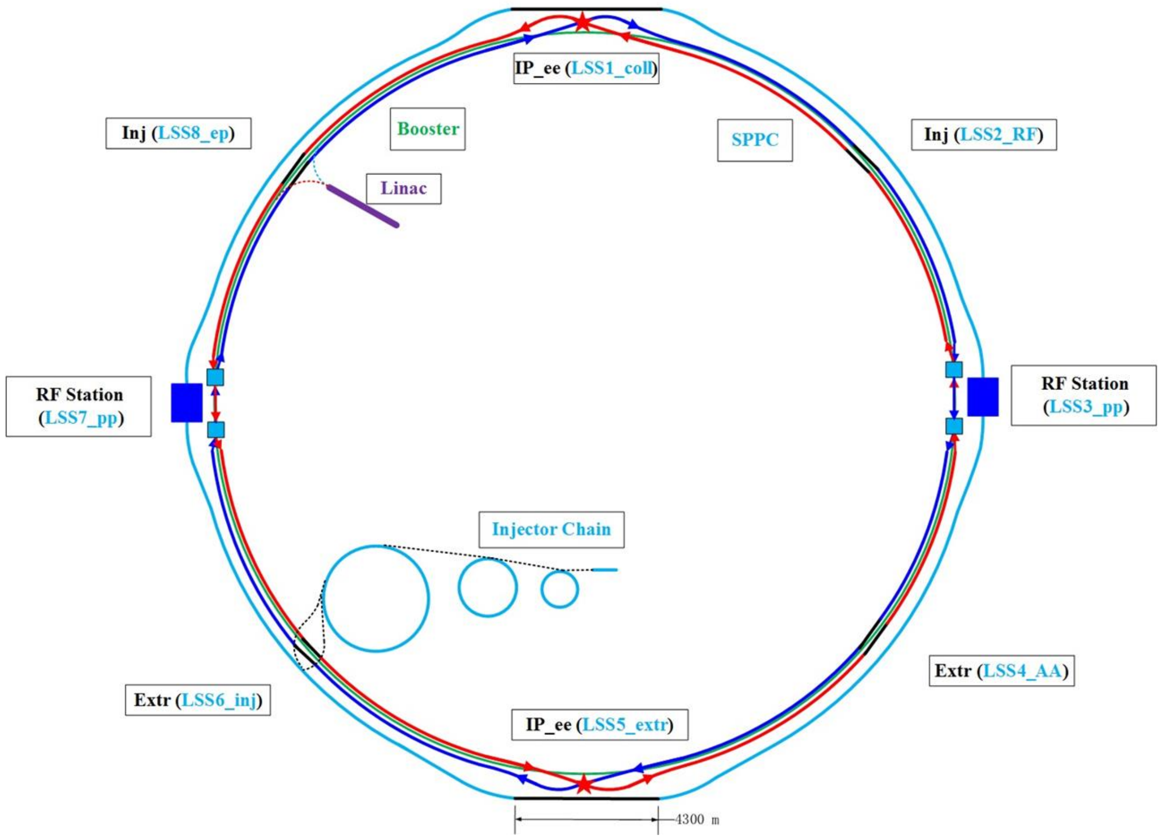


The study on the symmetric of IR for larger DA



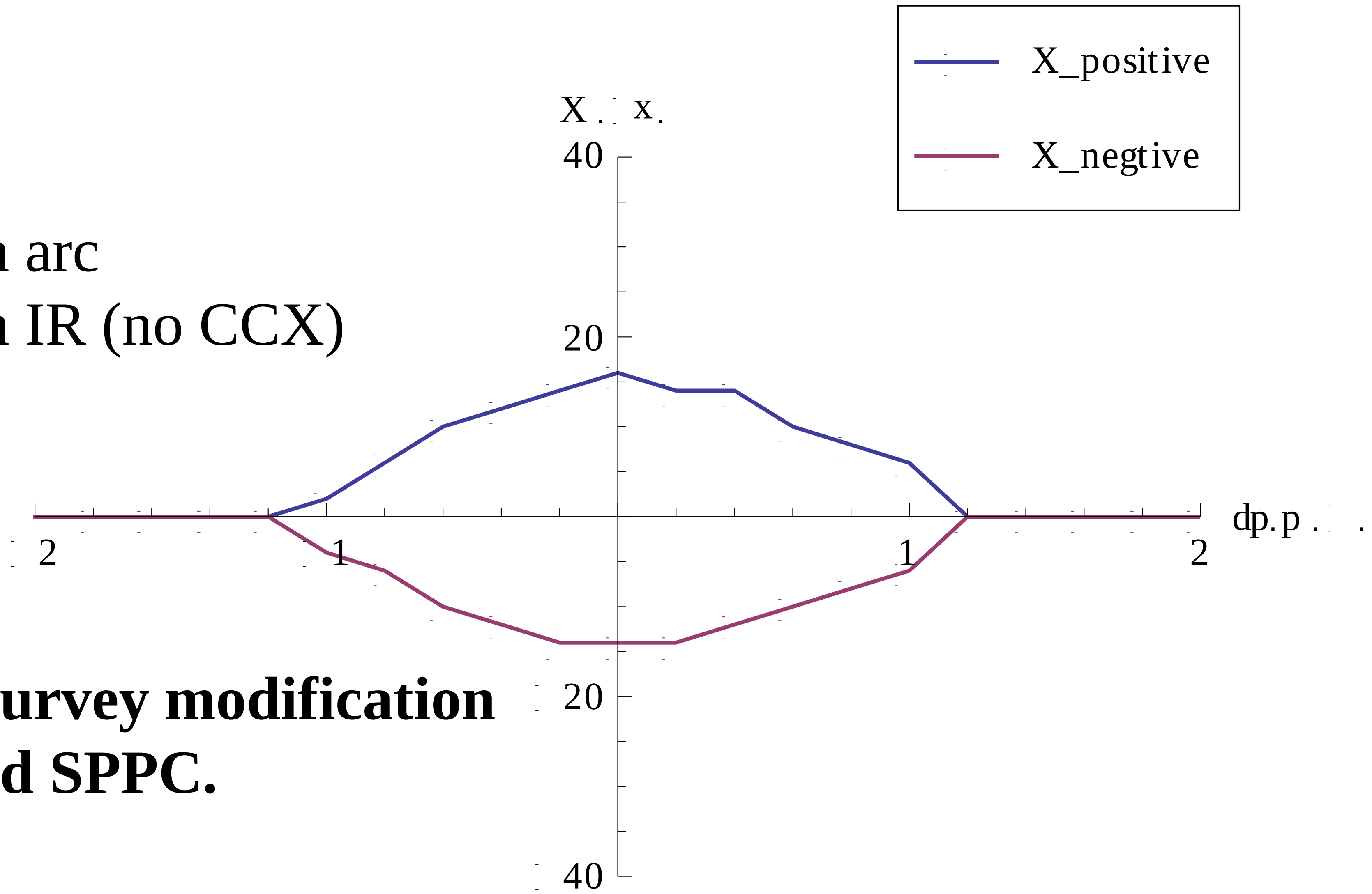






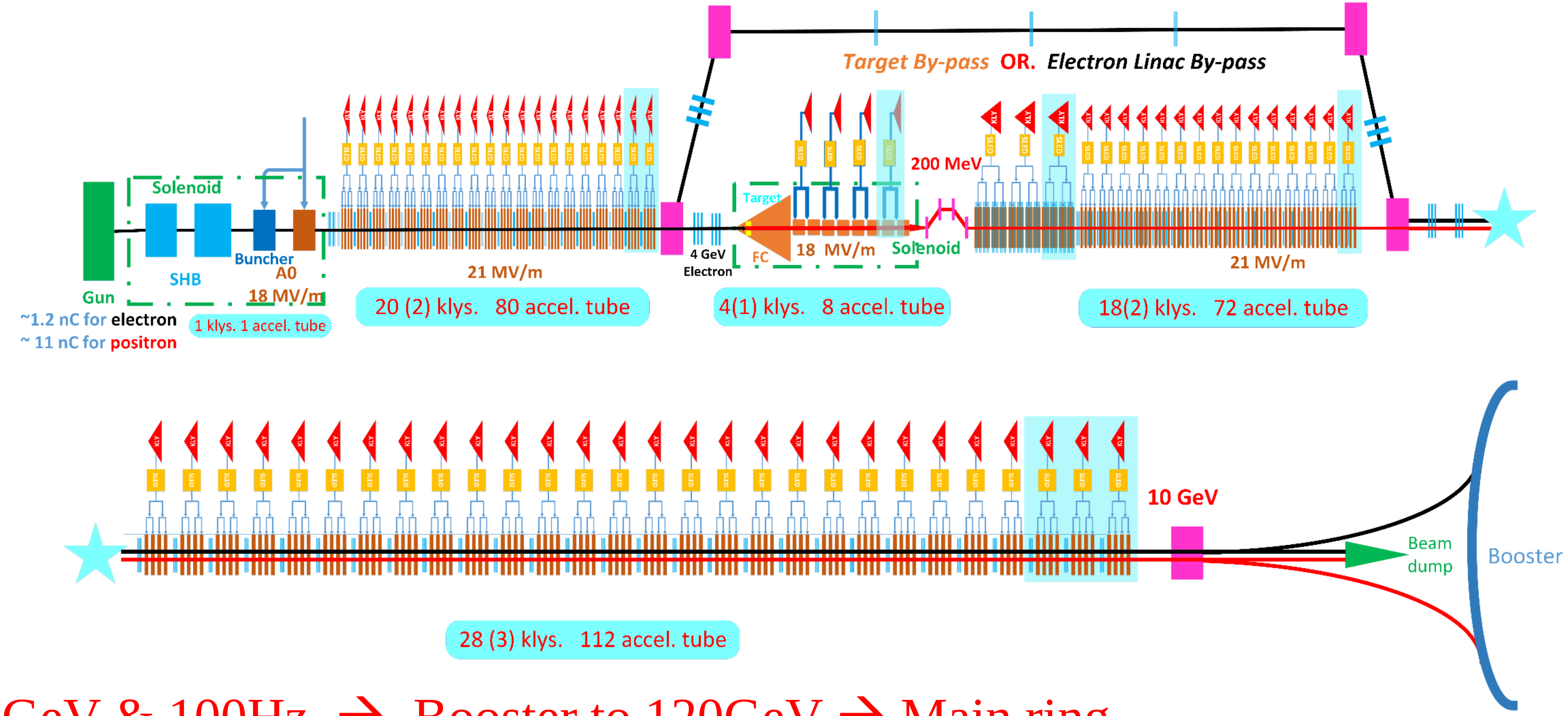
The study on the symmetric of IR for larger DA

- With damping
- 2 families sextupoles in arc
- 2 families sextupoles in IR (no CCX)
- 200 turns tracking



Longer length of IR. Survey modification is fine for both CEPC and SPPC.

Injection



- 10GeV & 100Hz → Booster to 120GeV → Main ring

  Satisfy the requirement of Topup operation.

  Low magnetic field, long damping time(125s), on axis injection

- 3GeV&100Hz→Booster1 to 30GeV →Booster2 to 120GeV→Main Ring

Summary

- The physical design can meet the luminosity requirements at Higgs and Z.
- Dedicated lattices in the RF region were designed for the optimized luminosity of Higgs and Z modes.
- The finalization of the beam parameters and the specification of special magnets in the IR is nearly finished. The hardware devices are all reasonable.
- The optimization on dynamic aperture is under studying.
- For the Z mode, 3T solenoid & anti-solenoids will be a limitation of beam performance. Two solutions are under studying.