CEPC Machine Optimization and Final Focus Design

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Outline

- 50 km CEPC optimized design
- 70 km CEPC optimized design
- Primary results of final focus design

1. 50 km Circular electron-positron Collider (CEPC) design

Constraints from IP

- Beam-beam parameter limit coming from beam emittance blow-up

Gao's theory:

$$\xi_y \leq \frac{2845}{2\pi}\sqrt{\frac{T_0}{\tau_y \gamma N_{IP}}}$$

- Beam lifetime limit due to beamstrahlung

Valery Telnov' theory

$$\frac{N_e}{\sigma_x \sigma_z} \leq 0.1\eta \frac{\alpha}{3\gamma r_e^2}$$

- Extra energy spread due to beamstrahlung

$$\delta_{BS} \leq \frac{1}{3}\delta_0$$

luminosity of circular collider

$$L[cm^{-2}s^{-1}] = 2.17\times10^{34}\left(1+r\right)\xi_y \frac{eE_0(GeV)N_bN_e}{T_0\beta_y^*(cm)}F_h$$

$$\xi_{y,\max} = \frac{2845}{2\pi}\sqrt{\frac{T_0}{\tau_y\gamma N_{IP}}}$$

Number of IPs

$$L_0\left[cm^{-2}s^{-1}\right] = 0.7\times10^{34}\left(1+r\right)\frac{1}{\beta_y^*[cm]}\sqrt{\frac{E_0[GeV]I_b[mA]P_0[MW]}{\gamma N_{IP}}}$$

$$L_{\max} = L_0F_h$$

SR power

Beam parameters calculation

Input parameters

Energy E_0	Circumference C_0	Goal luminosity L_0	IP number N_{IP}	SR power /beam P_0	Bending radius ρ	aspect ratio r	Coupling κ_ε	Energy acceptance η
120GeV	50 km	$1\sim6\times10^{34}$ cm^{-2}s^{-1}	1~2	50 MW	5~6.2 km	200	0.005	5%~12%

$$U_0 = 88.5\times10^3 \frac{E_0^4(GeV)}{\rho}$$

$$I_b = \frac{P_0}{U_0}$$

$$\delta_0 = \gamma\sqrt{\frac{C_q}{J_\varepsilon \rho}}$$

$$\xi_{y,\max} = \frac{2845}{2\pi}\sqrt{\frac{U_0}{2\gamma E_0 N_{IP}}}$$

$$\beta_y^* = \frac{0.7\times10^{34}(1+r)}{L_0}\sqrt{\frac{E_0 I_b P_0}{\gamma N_{IP}}}$$

$$\sigma_x = \frac{5.77\delta_0\beta_y^*}{\pi\eta\alpha\xi_y\gamma r}$$

$$\sigma_y = r\sigma_x$$

$$\varepsilon_x = \frac{\varepsilon_y}{\kappa_\varepsilon} \qquad \varepsilon_y = \frac{\sigma_y^2}{\beta_y^*}$$

$$\beta_x^* = \frac{\sigma_x^2}{\varepsilon_x}$$

$$N_e = \frac{2\pi\gamma\xi_y}{r_e\beta_y^*}\sigma_x\sigma_y$$

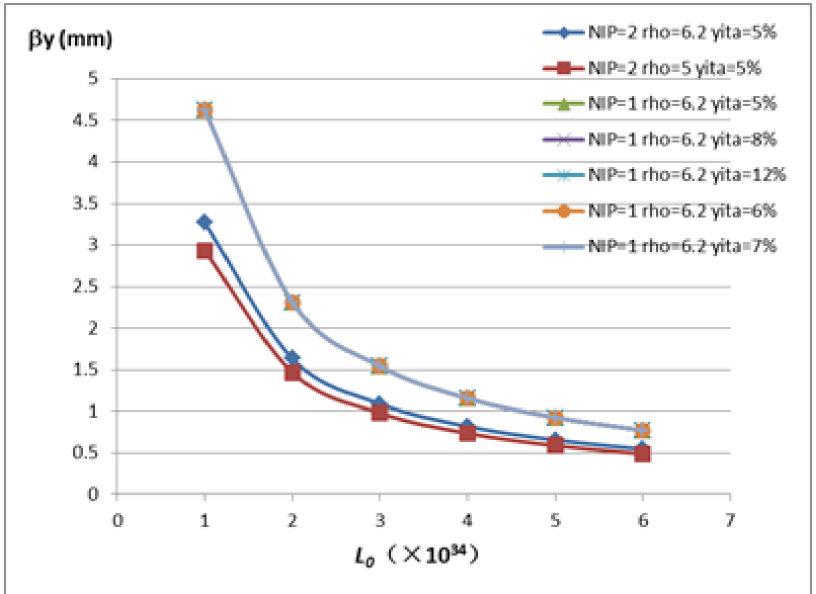
$$\sigma_z = \frac{3\gamma r_e^2 N_e}{0.1\eta\alpha\sigma_x}$$

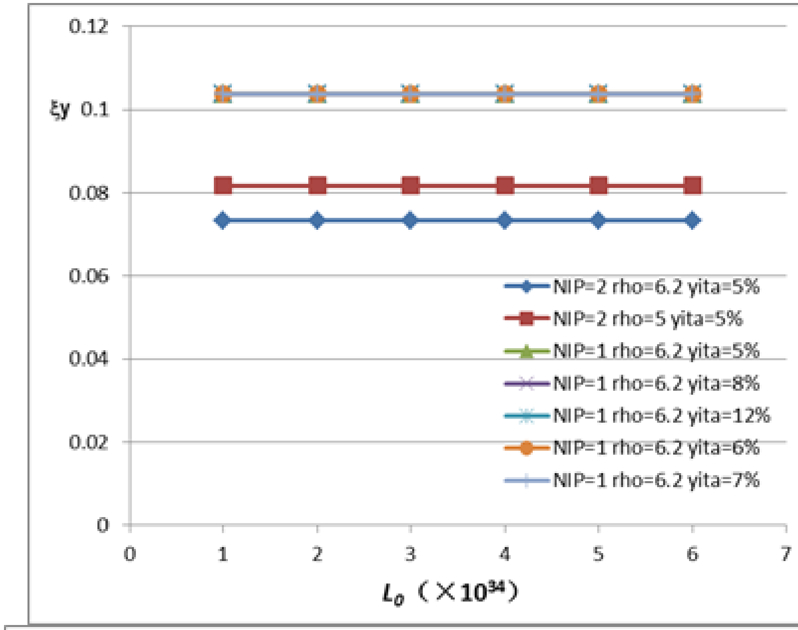
$$F_h = \frac{\beta_y^*}{\sqrt{\pi}\sigma_z}\exp\left(\frac{\beta_y^{*2}}{2\sigma_z^2}\right)K_0\left(\frac{\beta_y^{*2}}{2\sigma_z^2}\right)$$

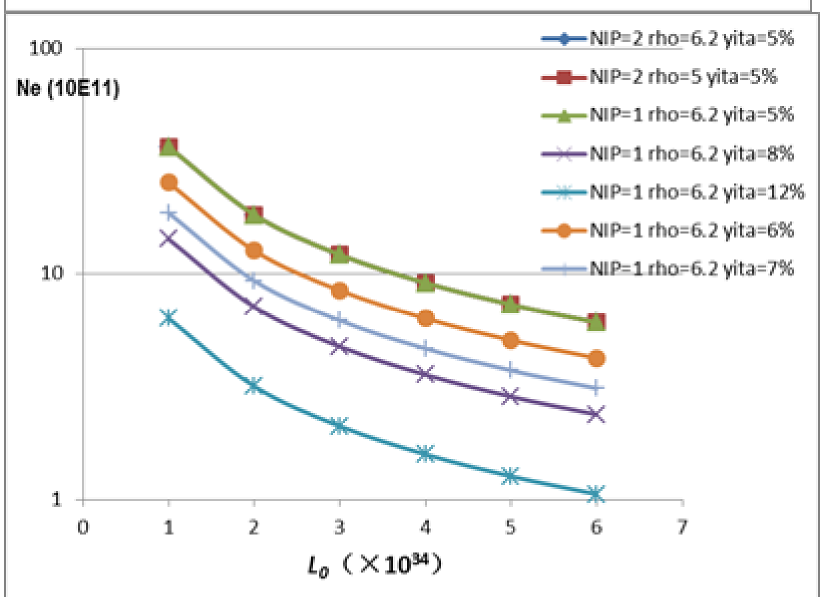
$$N_b = \frac{I_b T_0}{eN_e}$$

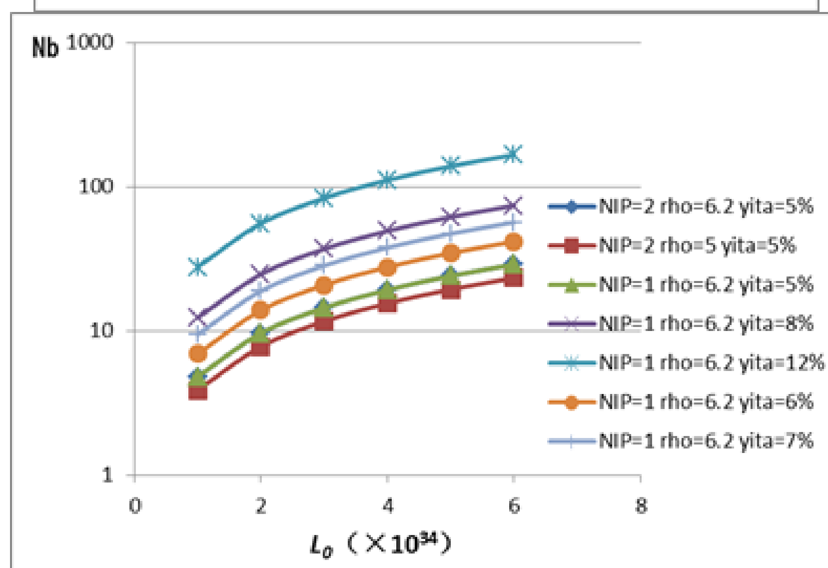
$$L = L_0 F_h$$

Beam parameter scan-1

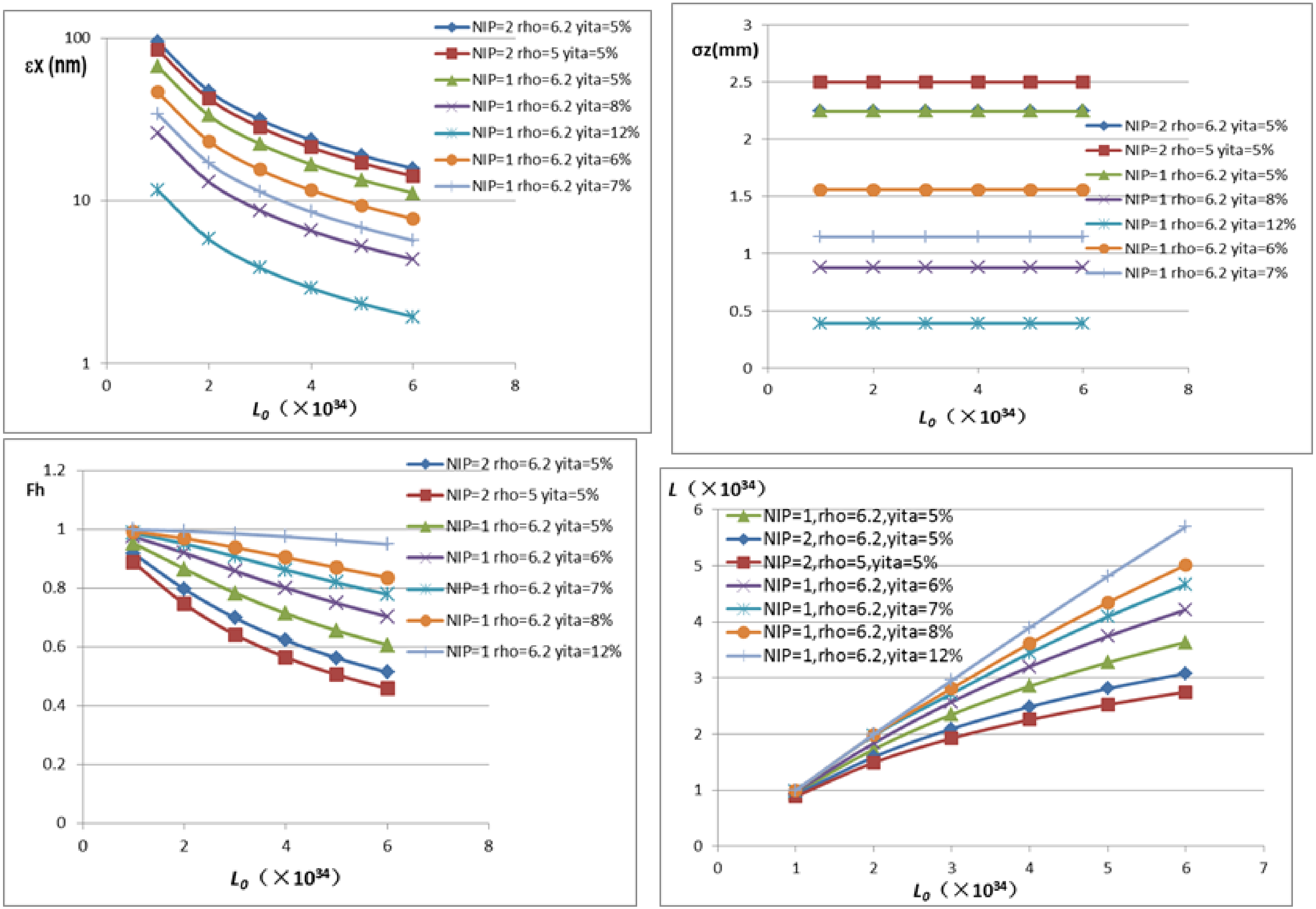








Beam parameter scan-2



Machine parameter choice

- *Less IP give higher luminosity*

  choose N_{IP}=1

- *Larger bending radius give higher luminosity*

  choose ρ=6.2 m （80% filling factor for bending dipoles）

- *Higher momentum acceptance give higher luminosity*

  How to choose η?

  decided by RF parameters

Constraints from RF system

- Synchrotron radiation loss per turn

$$U_0 = eV_{rf}\sin\phi_s$$

- Synchrotron phase

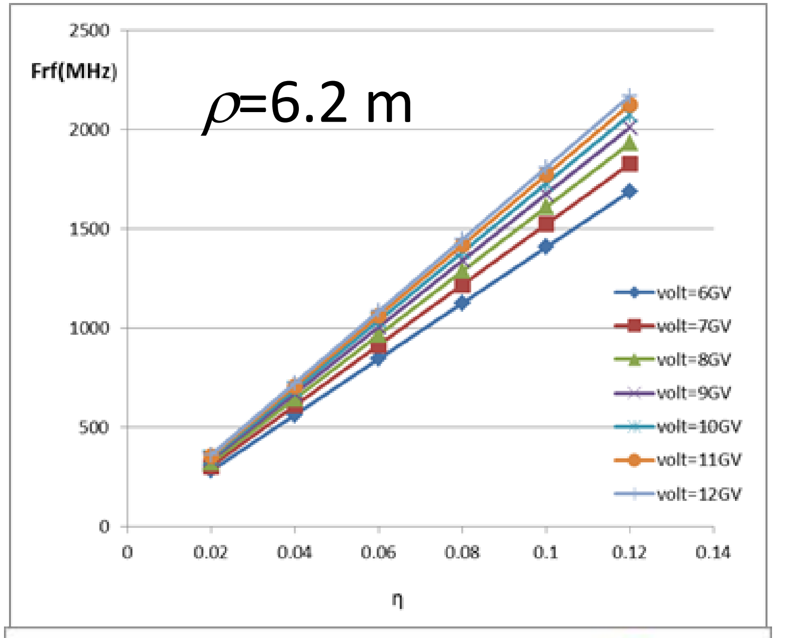
$$\phi_s = \pi - \arcsin\left(\frac{U_0}{eV_{rf}}\right)$$

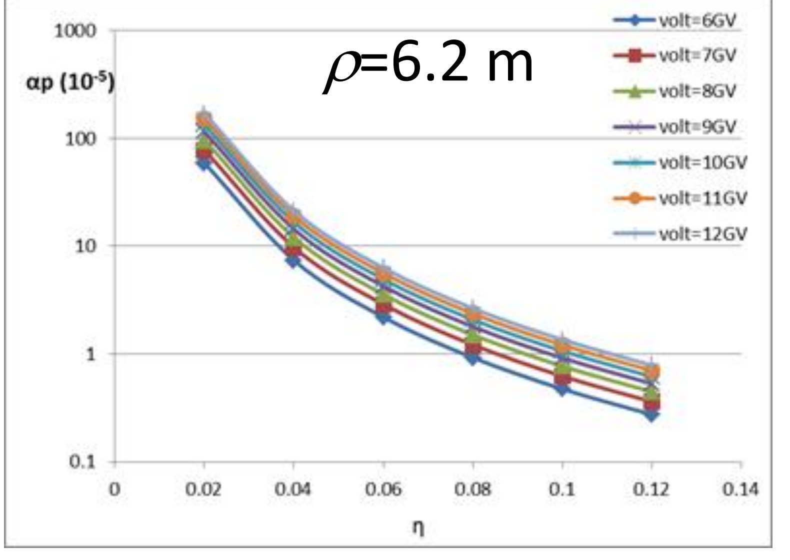
- Nature bunch length

$$\sigma_z = \sqrt{-\frac{2\pi E_0 \alpha_p}{f_{rf} T_0 eV_{rf}\cos\phi_s}}\bar{R}\delta_0$$

- Momentum acceptance

$$\eta = \sqrt{\frac{2U_0}{\pi\alpha_p f_{rf} T_0 E_0}\left(\sqrt{q^2-1} - \arccos\left(\frac{1}{q}\right)\right)} \quad \left(q = \frac{eV_{rf}}{U_0}\right)$$





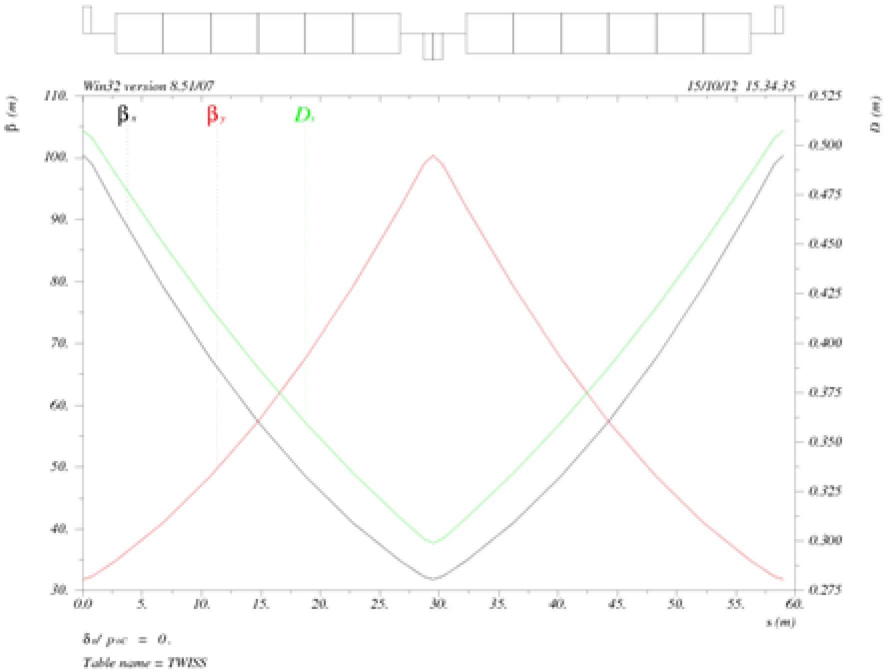
Choice for RF technology

- the maximum luminosity which we can obtain is decided by the RF technology (frequency). Higher RF frequency will give larger luminosity.
- From the beam dynamics point of view, lower RF frequency is a better choice because the cavities with lower frequency have larger aperture and hence lower impendence which is a favor for the collective instabilities.
- there are still technical difficulties to directly use ILC 1.3 GHz SC technology on storage rings, it’s better to choose the frequency lower than 1GHz. 700 MHz is a good candidate with better gradient and lower impedance.
- the requirement of enlarging energy acceptance is translated to design a low momentum compaction lattice and also larger RF voltage will relax this tolerance and lose the difficulties of lattice design. So we need to make a reasonable choice for the total RF voltage while balancing the constraints from the RF frequency and momentum compaction.

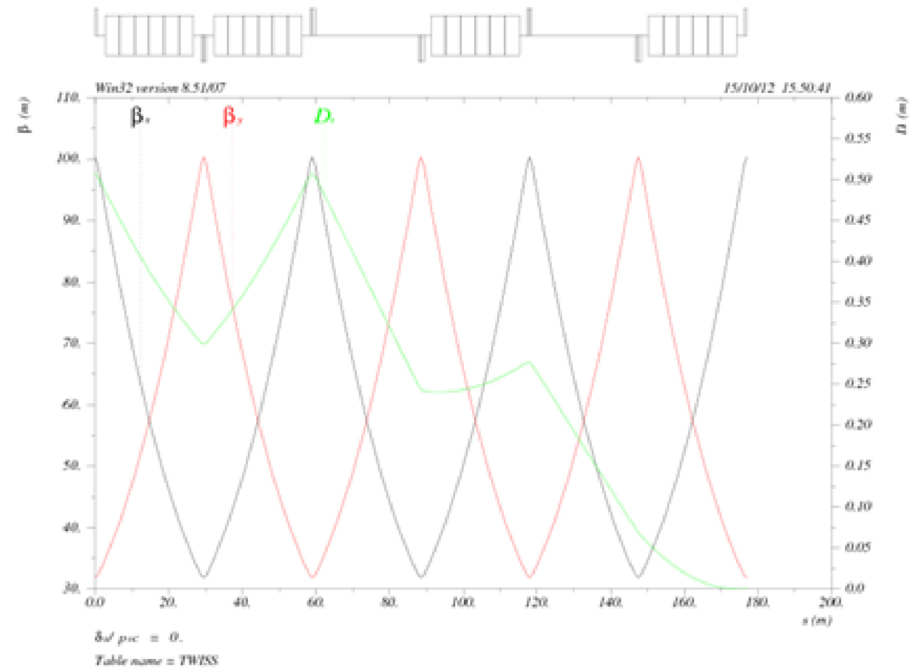
Optimization Parameter Design of CEPC

	350 MHz (LEP2-like) technology	700 MHz technology		1.3 GHz (LEP3-like) technology
Number of IPs	1	1	2	1
Energy (GeV)	120	120	120	120
Circumference (km)	50	50	50	50
SR loss/turn (GeV)	2.96	2.96	2.96	2.96
N_e/bunch (10^{12})	1.61	0.79	1.12	0.33
Bunch number	11	22	16	53
Beam current (mA)	16.9	16.9	16.9	16.9
SR power /beam (MW)	50	50	50	50
B_0 (T)	0.065	0.065	0.065	0.065
Bending radius (km)	6.2	6.2	6.2	6.2
Momentum compaction (10^{-4})	0.43	0.38	0.38	0.21
β_{IP} x/y (m)	0.2/0.001	0.2/0.001	0.2/0.001	0.2/0.001
Emittance x/y (nm)	29.7/0.15	14.6/0.073	29.1/0.15	6.1/0.03
Transverse σ_{IP} (um)	77/0.38	54/0.27	76/0.38	35/0.17
ξ_x/IP	0.103	0.103	0.073	0.103
ξ_y/IP	0.103	0.103	0.073	0.103
V_{RF} (GV)	4.1	6	6	9.3
f_{RF} (MHz)	350	704	704	1304
σ_z (mm)	4.6	2.2	2.2	0.95
Energy spread (%)	0.13	0.13	0.13	0.13
Energy acceptance (%)	3.5	5	5	7.7
γ_{BS} (10^{-4})	9.7	13.8	13.8	21.3
n_γ	0.86	0.6	0.6	0.39
δ_{BS} (10^{-4})	4.3	4.3	4.3	4.3
Life time due to beamstrahlung (minute)	30	30	30	30
F (hour glass)	0.49	0.68	0.68	0.87
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	2.2	3.1	2.2	4.0

Linear lattice design



Dispersion suppressor

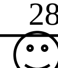
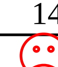
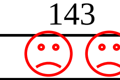


- 60° FODO cells in arc
- 16-fold symmetry
- SC cavities and other cryogenic system are inserted in 14 linear sections.

Lower power design of CEPC

	Baseline	***Low power design***		
Number of IPs	1	1	1	1
Energy (GeV)	120	120	120	120
Circumference (km)	50	50	50	50
SR loss/turn (GeV)	2.96	2.96	2.96	2.96
N_e/bunch (10^{12})	0.79	0.38	0.33	0.28
Bunch number	22	23	21	19
Beam current (mA)	16.9	8.45	6.76	5.07
SR power /beam (MW)	50	25	20	15
B_0 (T)	0.065	0.065	0.065	0.065
Bending radius (km)	6.2	6.2	6.2	6.2
Momentum compaction (10^{-4})	0.38	0.38	0.38	0.38
β_{IP} x/y (m)	0.2/0.001	0.071/0.00048	0.056/0.00042	0.041/0.00035
Emittance x/y (nm)	14.6/0.073	9.5/0.035	9.1/0.031	8.9/0.026
Transverse σ_{IP} (um)	54/0.27	25.9/0.13	22.7/0.11	19.2/0.096
ξ_x/IP	0.103	0.076	0.069	0.06
ξ_y/IP	0.103	0.103	0.103	0.103
V_{RF} (GV)	6	6	6	6
f_{RF} (MHz)	704	704	704	704
σ_z (mm)	2.2	2.2	2.2	2.2
Energy spread (%)	0.13	0.13	0.13	0.13
Energy acceptance (%)	5	5	5	5
γ_{BS} (10^{-4})	13.8	13.8	13.8	13.8
n_γ	0.6	0.6	0.6	0.6
δ_{BS} (10^{-4})	4.3	4.3	4.3	4.3
Life time due to beamstrahlung (minute)	30	30	30	30
F (hour glass)	0.68	0.48	0.45	0.41
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	3.1	2.31	1.97	1.58
AC power for RF source/two beam (MW)	286	143	114	86

CEPC low power scheme with recovered luminosity

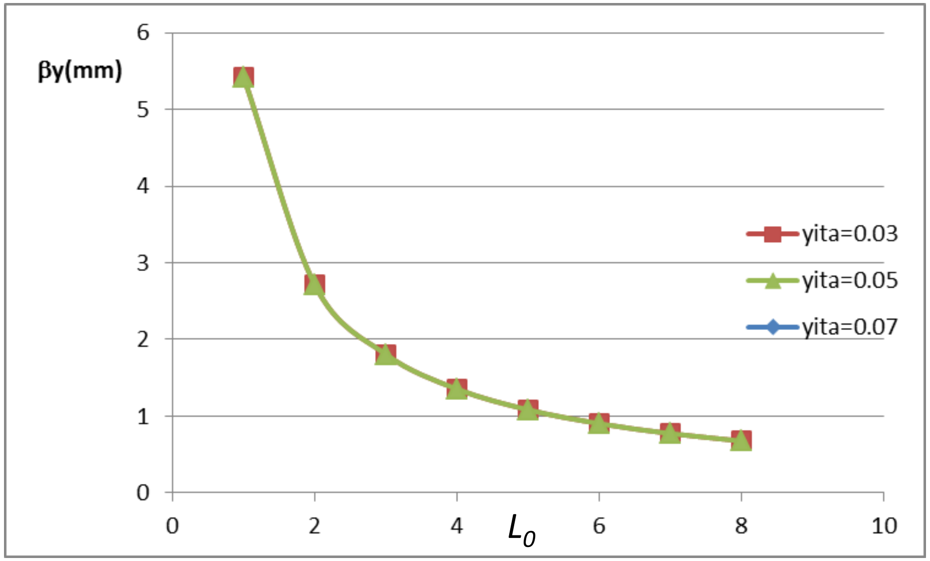
	Baseline – 50 MW	**Low power design – 25 MW**		
Aspect ratio (coupling factor)	~200	~200	~550	~1200
Number of IPs	1	1	1	1
Energy (GeV)	120	120	120	120
Circumference (km)	50	50	50	50
SR loss/turn (GeV)	2.96	2.96	2.96	2.96
N_e/bunch (10^{12})	0.79	0.38	0.51	0.079
Bunch number	22	23	17	111
Beam current (mA)	16.9	8.45	8.45	8.45
SR power /beam (MW)	50	25	25	25
B_0 (T)	0.065	0.065	0.065	0.065
Bending radius (km)	6.2	6.2	6.2	6.2
Momentum compaction (10-4)	0.38	0.38	0.38	0.38
β_{IP} x/y (m)	0.2/0.001	0.071/0.00048	0.13/0.00024	0.11/0.0001
Emittance x/y (nm)	14.6/0.073	9.5/0.035	9.4/0.017	9.4/0.0073
Transverse σ_{IP} (um)	54/0.27	25.9/0.13	34.9/0.063	32.4/0.027
ξ_x/IP	0.103	0.076	0.103	0.016
ξ_y/IP	0.103	0.103	0.103	0.103
V_{RF} (GV)	6	6	6	6
f_{RF} (MHz)	704	704	704	704
σ_z (mm)	2.2	2.2	2.2	2.2
Energy spread (%)	0.13	0.13	0.13	0.13
Energy acceptance (%)	5	5	5	5
γ_{BS} (10^{-4})	13.8	13.8	13.8	13.8
n_γ	0.6	0.6	0.6	0.6
δ_{BS} (10^{-4})	4.3	4.3	4.3	4.3
Life time due to beamstrahlung (minute)	30	30	30	30
F (hour glass)	0.68	0.48	0.32	0.18
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	**3.1**	2.31	**3.1**	4.1
AC power /two beam (MW) *	286	143	143	143
Technology Maturity				

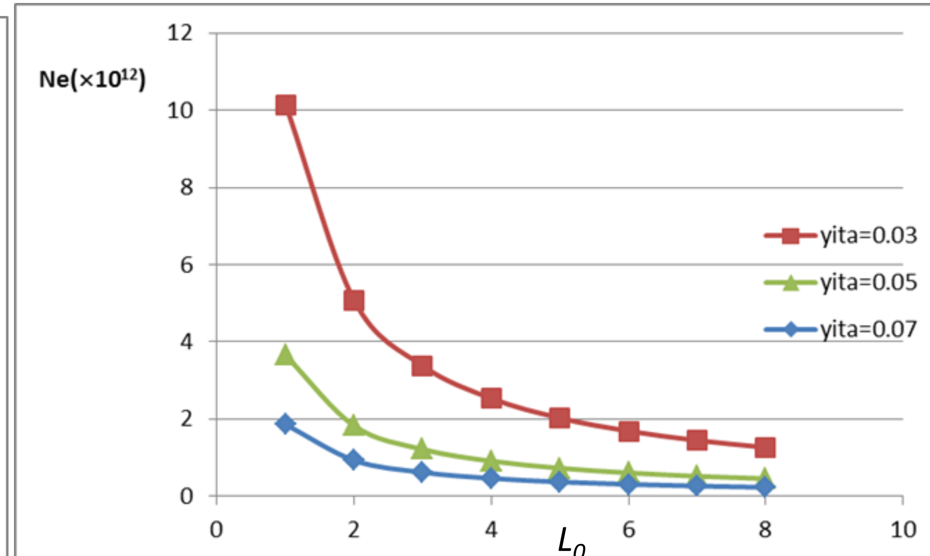
Parameter comparison with exist machine

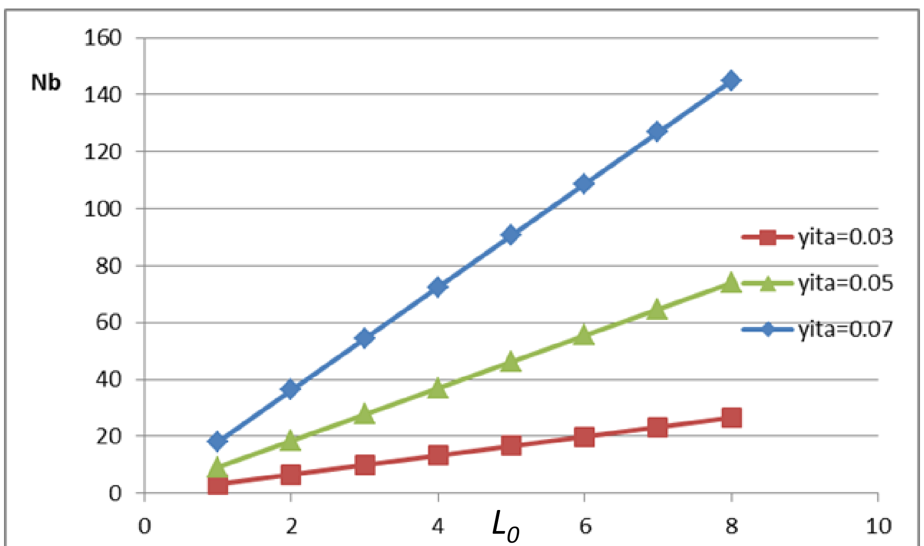
Parameters	PEP-X	ESRF	SSRF	Swiss Light Source	Diamond	PETRA III Positron Machine	NSLS-II	Spear-III	TLS	TPS	NSRL	CEPC-25MW		
												β_{IP} x/y (m)		
												0.071/0.00048	0.13/0.00024	0.11/0.0001
E(GeV)	4.5	6.03	3.5	2.4	3	6.0	3	3	1.5	3	0.8	120	120	120
Circumference(m)	2199.32	844	432	288	561.6	2304	620	234.126	120	518.4		50	50	50
Emittance(nm-rad)	0.094	4/0.025	3.9	4.8	2.74/0.0274	1/0.01	1.5/0.008	18.6	25.5(nature)	1.7(nature)		9.5/0.035	9.4/0.017	9.4/0.0073
γ (E/m_0c^2)	8806.26	11800.39	6849.32	4696.67	5870.84	11741.68	5870.84	5870.84	2935.42	5870.84	1565.56	234833.66	234833.66	234833.66
Normalized Emittance (nm-rad)	827.79	47201.56/295.01	26712.348	22544.03	16086.10/ 160.86	11741.68/ 117.42	8806.26/ 46.97	109197.62	74853.21	9980.43		2230919.77/ 8219.18	2207436.39/ 3992.17	2207436.39/1714.29
κ(Coupling Factor)		160			100	100	187.5					271.43	552.94	1287.67
Momentum compaction factor(E-4)	0.472			7	1.7	12	3.7	11.3	67.8	2.0		0.38	0.38	0.38
Energy loss per turn(keV)	3270			512	1250	20.9	286.4	912	128	853		2960000	2960000	2960000
Energy spead(%)	0.112			0.09		0.1	0.094	0.097	0.0756			0.13	0.13	0.13
Beam current(mA)		200	300--500	400	300(500)							8.45	8.45	8.45
Beam life time (h)			>10	<10	>10(20)							0.5	0.5	0.5

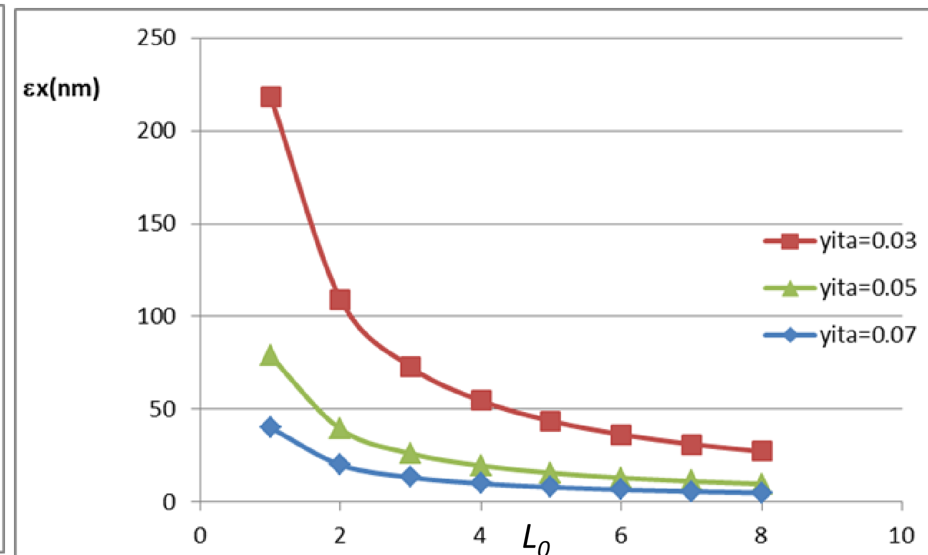
2. 70 km Circular electron-positron Collider (CEPC) design

Beam parameter scan -1

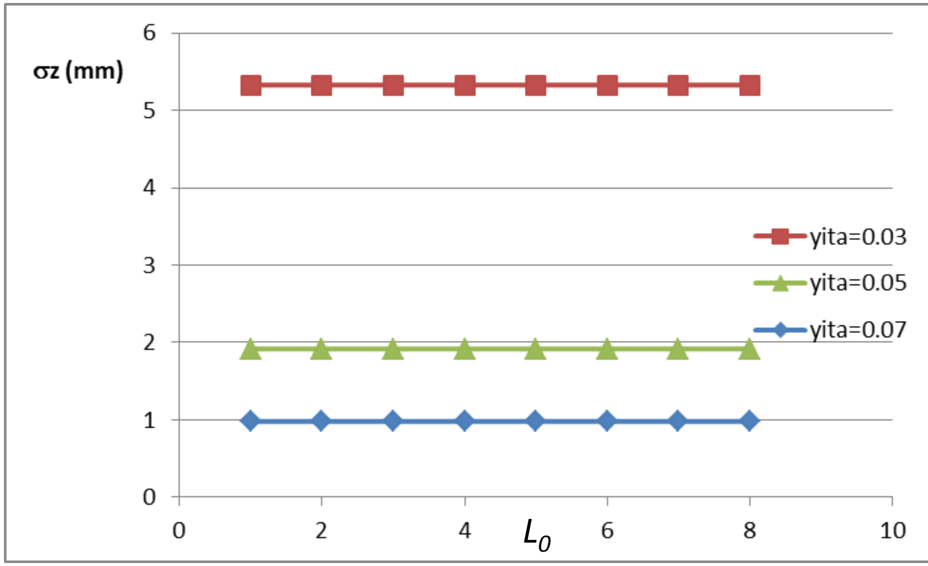


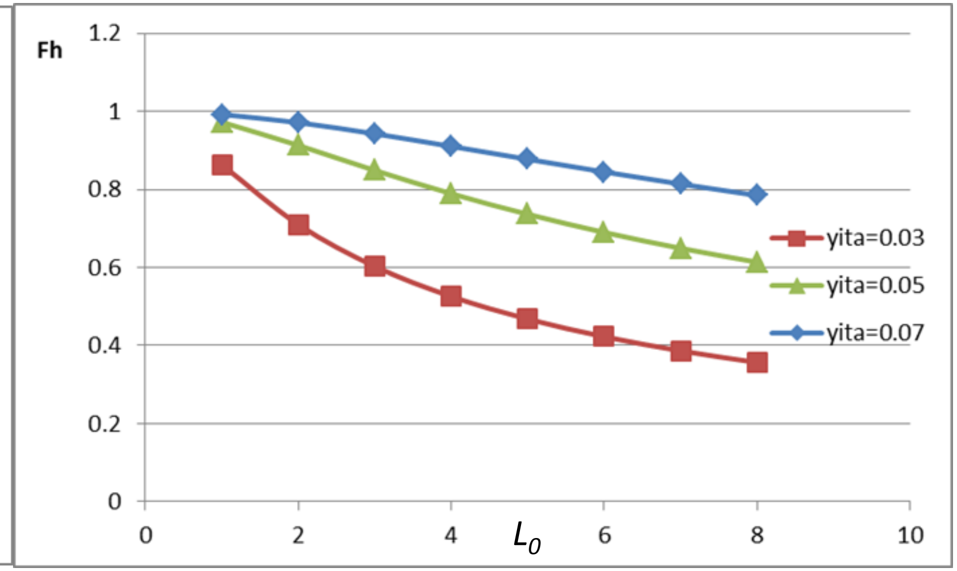


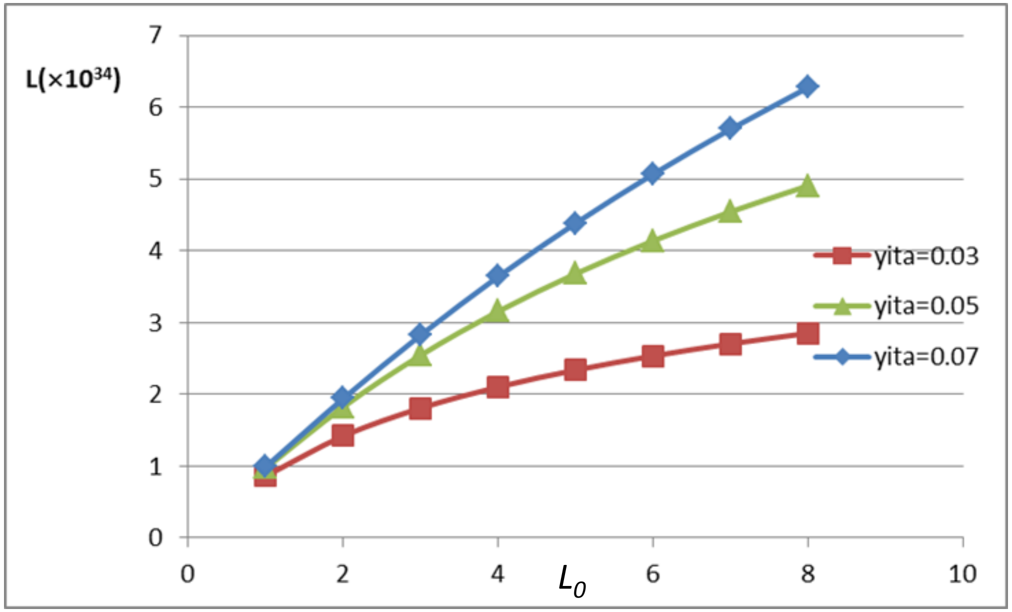




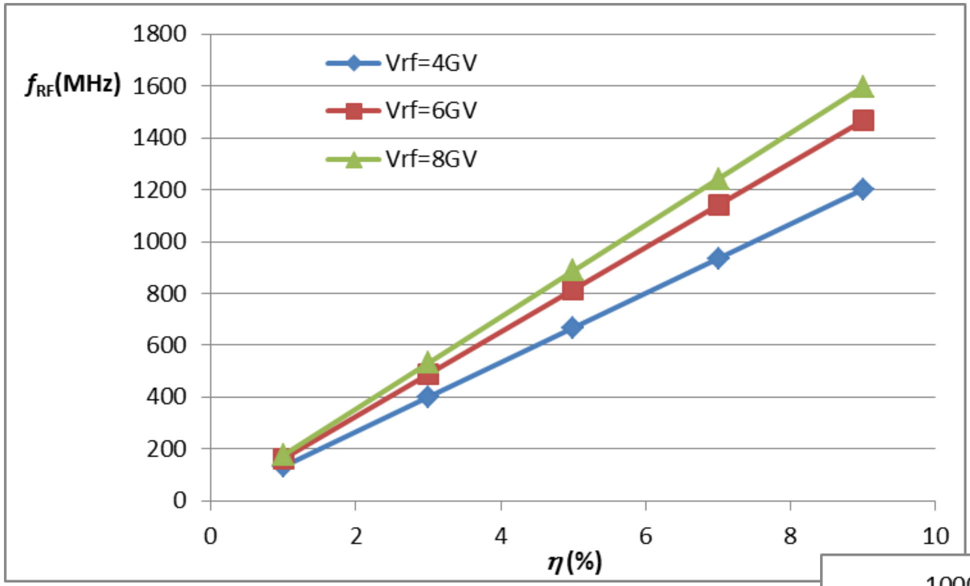
Beam parameter scan -2

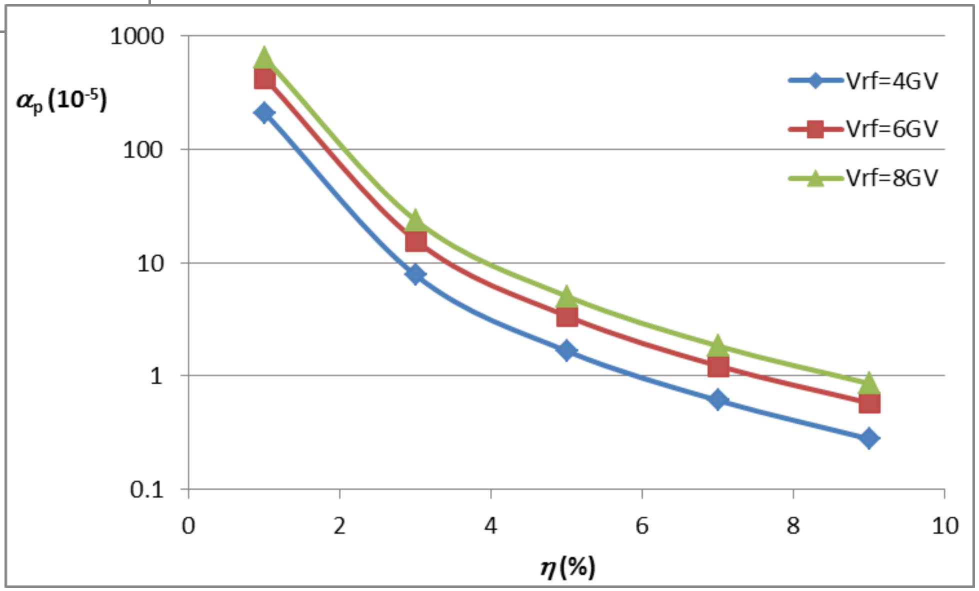




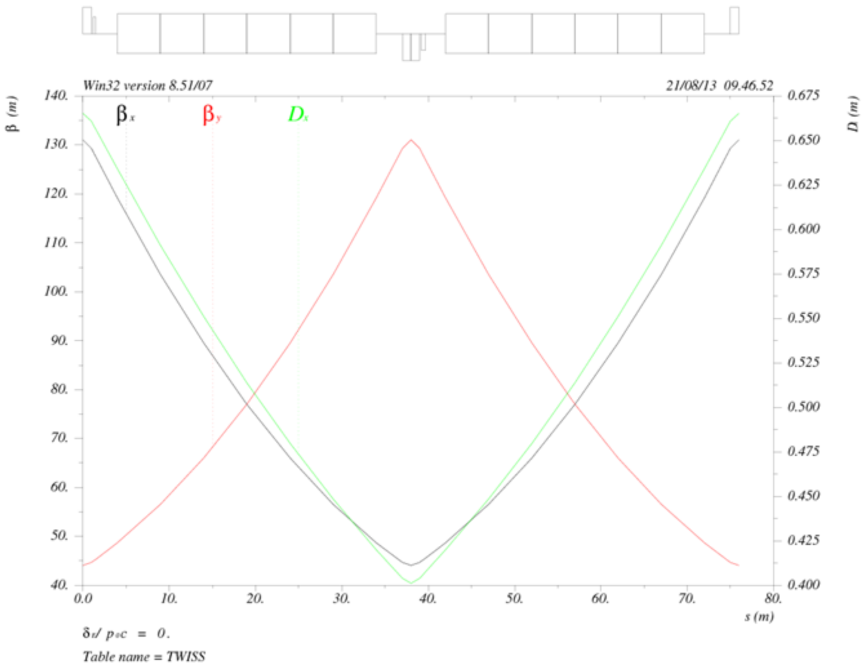


RF parameter scan for 70km CEPC



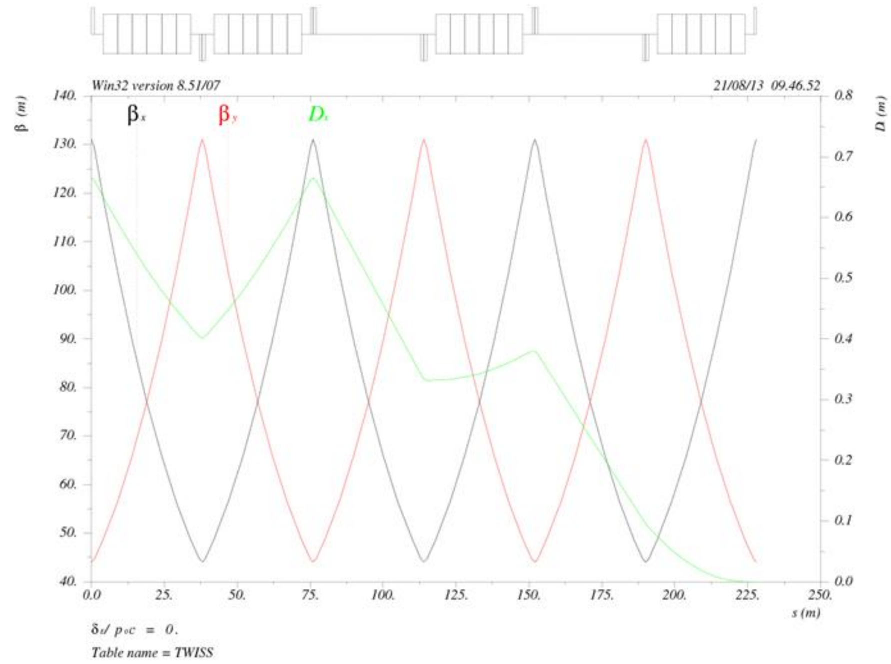


Lattice design for 70km CEPC



60° FODO ARC cell

Dispersion suppressor



Parameters from lattice design:

- ρ=8.56 km
- ε_x=9.5 nm
- α_p=4.7×10^{-5}

Optimized machine parameters for 70km CEPC

	Baseline design		Low power design	
Number of IPs	1	2	1	2
Energy (GeV)	120	120	120	120
Circumference (km)	70	70	70	70
SR loss/turn (GeV)	2.14		2.14	
N_e/bunch (10^{12})	0.87	1.23	0.44	0.61
Bunch number	39	28	39	28
Beam current (mA)	23.3	23.3	11.7	11.7
SR power /beam (MW)	50		25	
B_0 (T)	0.047		0.047	
Bending radius (km)	8.56		8.56	
Momentum compaction (10^{-5})	4.7		4.7	
β_{IP} x/y (m)	0.4/0.001	0.79/0.001	0.1/0.0005	0.2/0.0005
Emittance x/y (nm)	9.5/0.094	9.5/0.19	9.5/0.047	9.5/0.094
Transverse σ_{IP} (um)	61.6/0.31	86.6/0.43	30.8/0.15	43.3/0.22
ξ_x/IP	0.175	0.245	0.087	0.123
ξ_y/IP	0.088	0.062	0.088	0.062
V_{RF} (GV)	5.8		5.8	
f_{RF} (MHz)	709		709	
σ_z (mm)	2.5		2.5	
Energy spread (%)	0.11		0.11	
Energy acceptance (%)	4.4		4.4	
γ_{BS} (10^{-4})	12.2	12.2	12.2	12.2
n_γ	0.58	0.58	0.58	0.58
δ_{BS} (10^{-4})	3.7	3.7	3.7	3.7
Life time due to beamstrahlung (minute)	30	30	30	30
F (hour glass)	0.65		0.47	
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	3.5	2.5	2.5	1.8
AC power for RF source/two beam (MW)	286		143	

3. Primary results of final focus design

Thanks to Sha Bai and Yiwei Wang in our group!

Local compact FFS design

$L^*=1.5m$

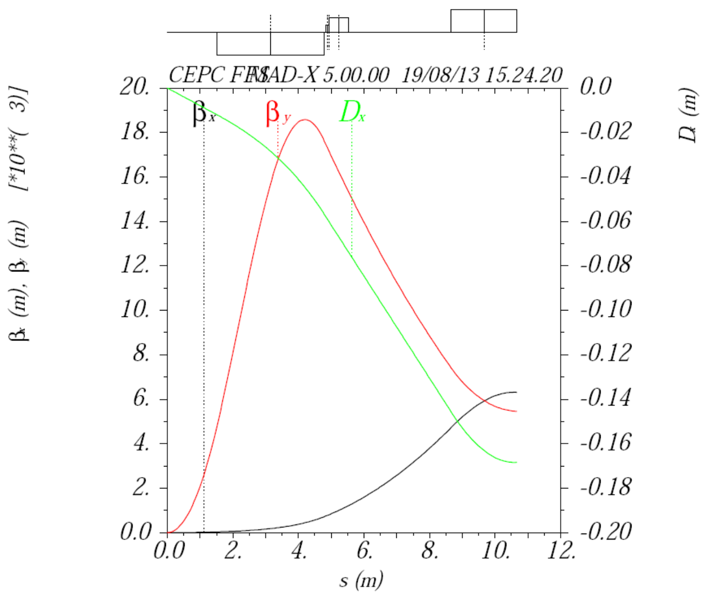
IP parameters (25MW, 1.5m)

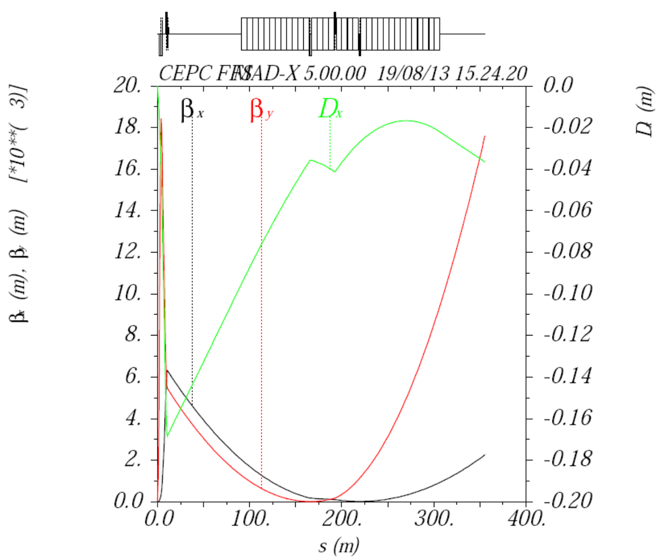
- IP parameters
  - BETX := 0.071;
  - ALFX := 0;
  - BETY := 0.00048;
  - ALFY := 0;
  - DX := 0;
  - DPX := -0.00795452718;
  - BLENG := 2.2E-3; !bunch length (m)
  - ESPRD := 1.3E-3; !energy spread (1)
  - EMITX := 9.5E-9;
  - EMITY := 0.035E-9;
  - D0->L = 1.5;

From Sha Bai (baisha@ihep.ac.cn)

Refit IP to QF1

- Fit five variables :
  - QD0 length
  - QF1 length
  - Pole-tip strength of QD0
  - Pole-tip strength of QF1
  - Distance between QD0&QF1

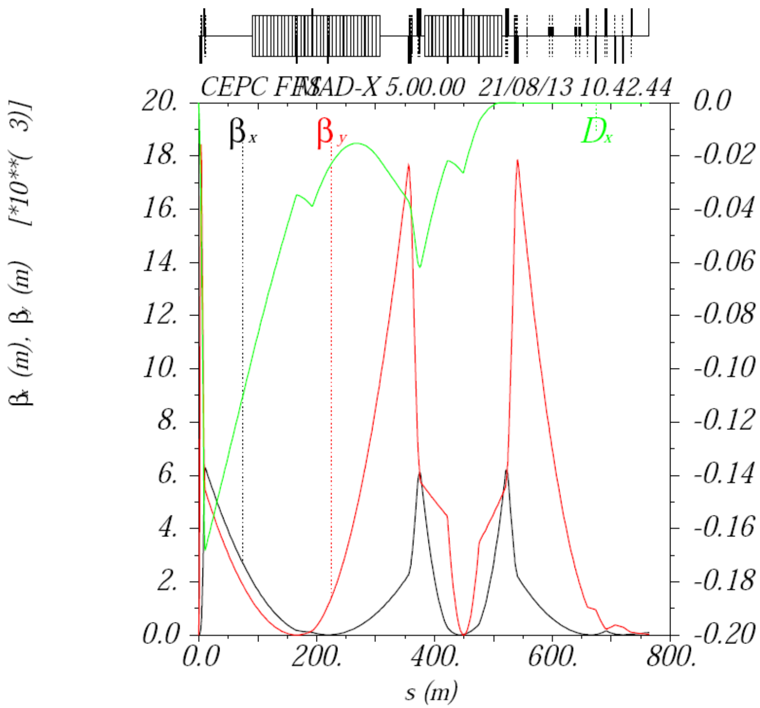


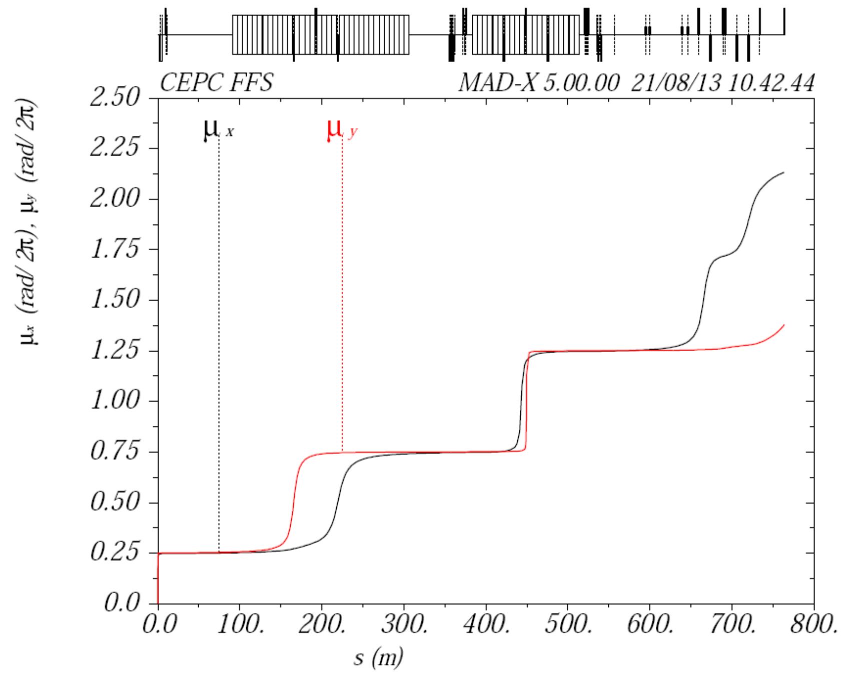


From Sha Bai (baisha@ihep.ac.cn)

Linear lattice

- fit B1, B2 and B5 to obtain Dx=0 and Dpx=0 at exit of B5
- reverse the system, refit QMs to match β and α.

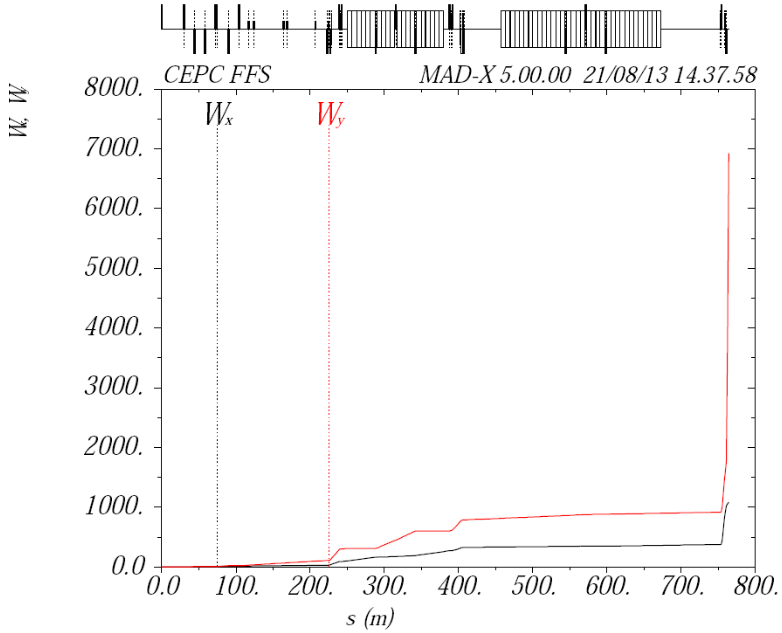


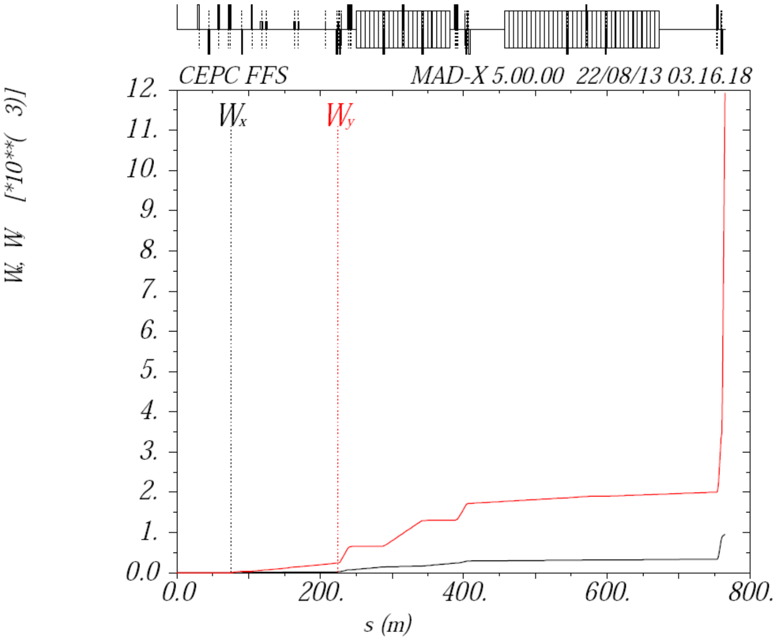


From Sha Bai (baisha@ihep.ac.cn)

Chromaticity

- natural chromaticity decreased (compared with L*=3.5m)

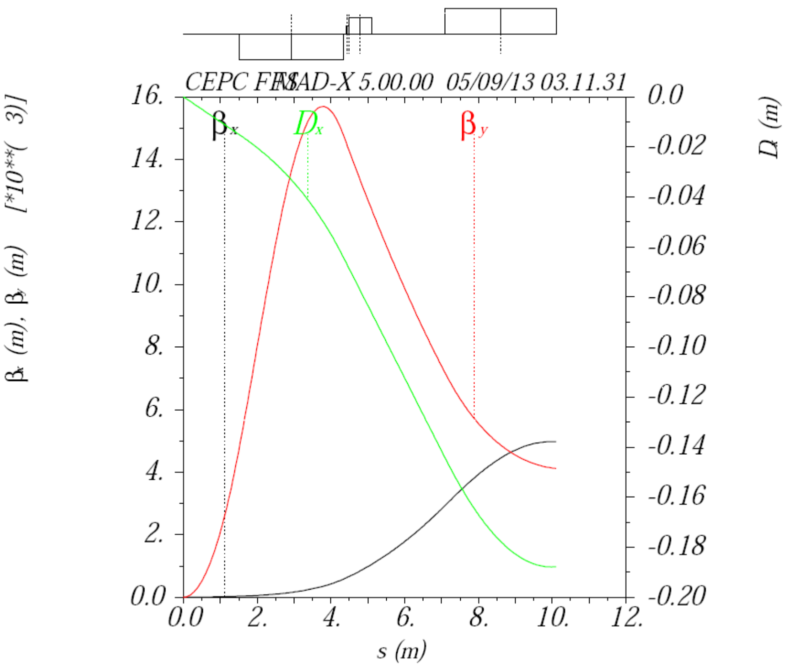


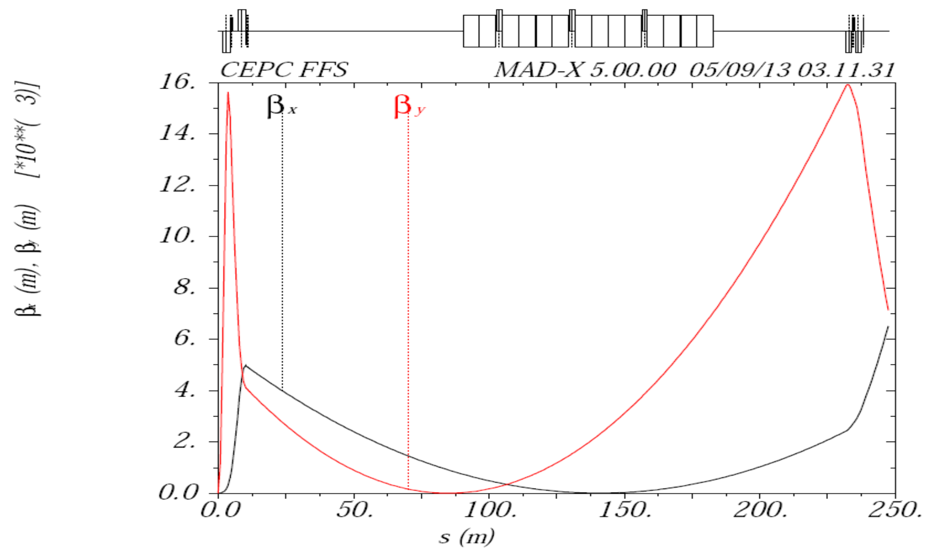


From Sha Bai (baisha@ihep.ac.cn)

Reduce the length of Bend

- We are trying to reduce the length of the bends as the beam energy of CEPC is lower than the 500GeV ILC.





From Sha Bai (baisha@ihep.ac.cn)

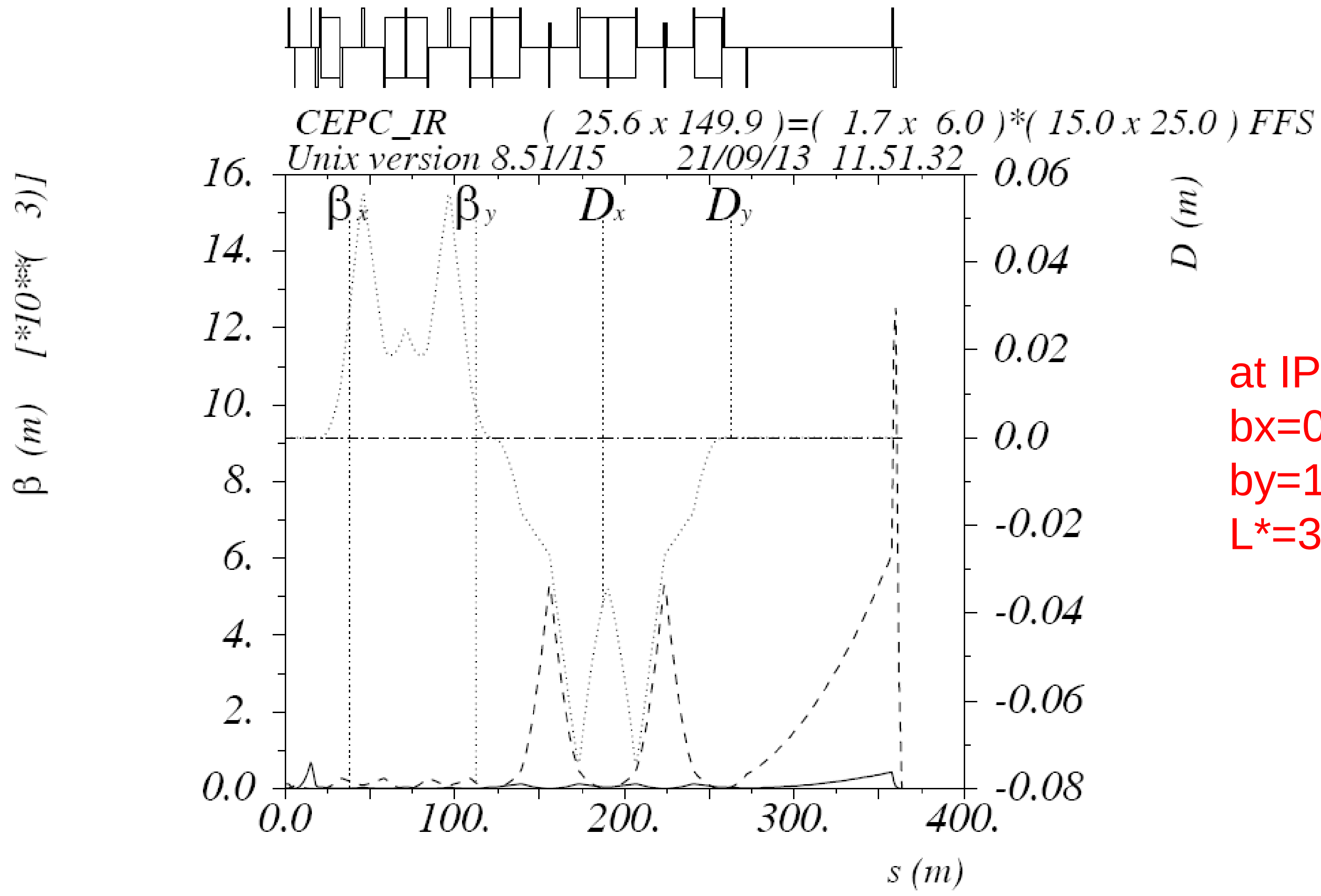
Local non-compact FFS design

Procedure & Method

- The CEPC design parameters :
  two cases of β_y=1mm and β_y=0.35mm.
- FFADA program
- Matching section, CCS, Final Doublet.
- Non-interlaced sextupoles

From Sha Bai (baisha@ihep.ac.cn)

IP β_y=1mm



at IP:
bx=0.2 m
by=1 mm
L*=3.5 m

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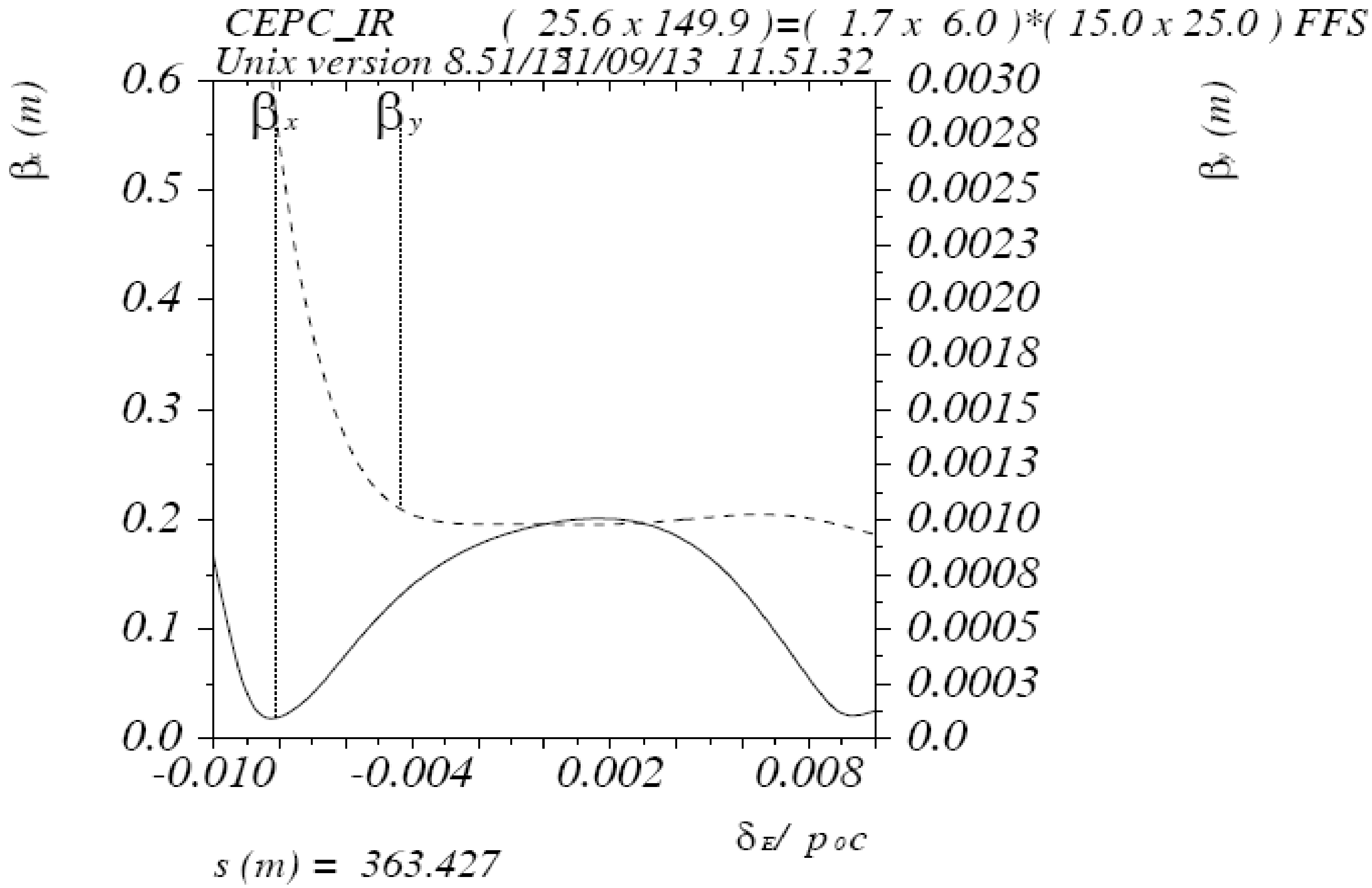
Beta Function at IP vs momentum



Good region of ±0.4% in Dp/p is necessary for the core in beam distribution.

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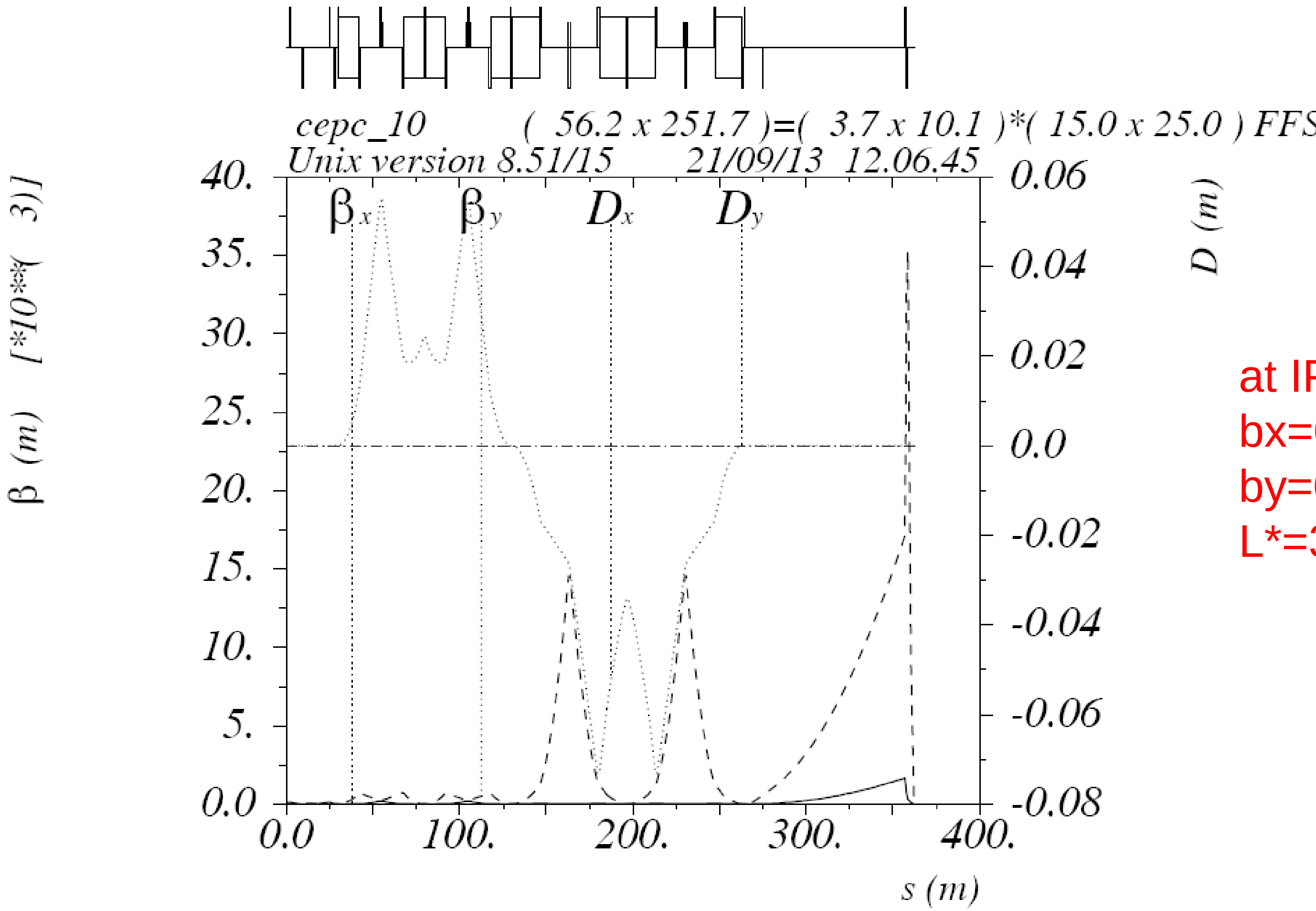
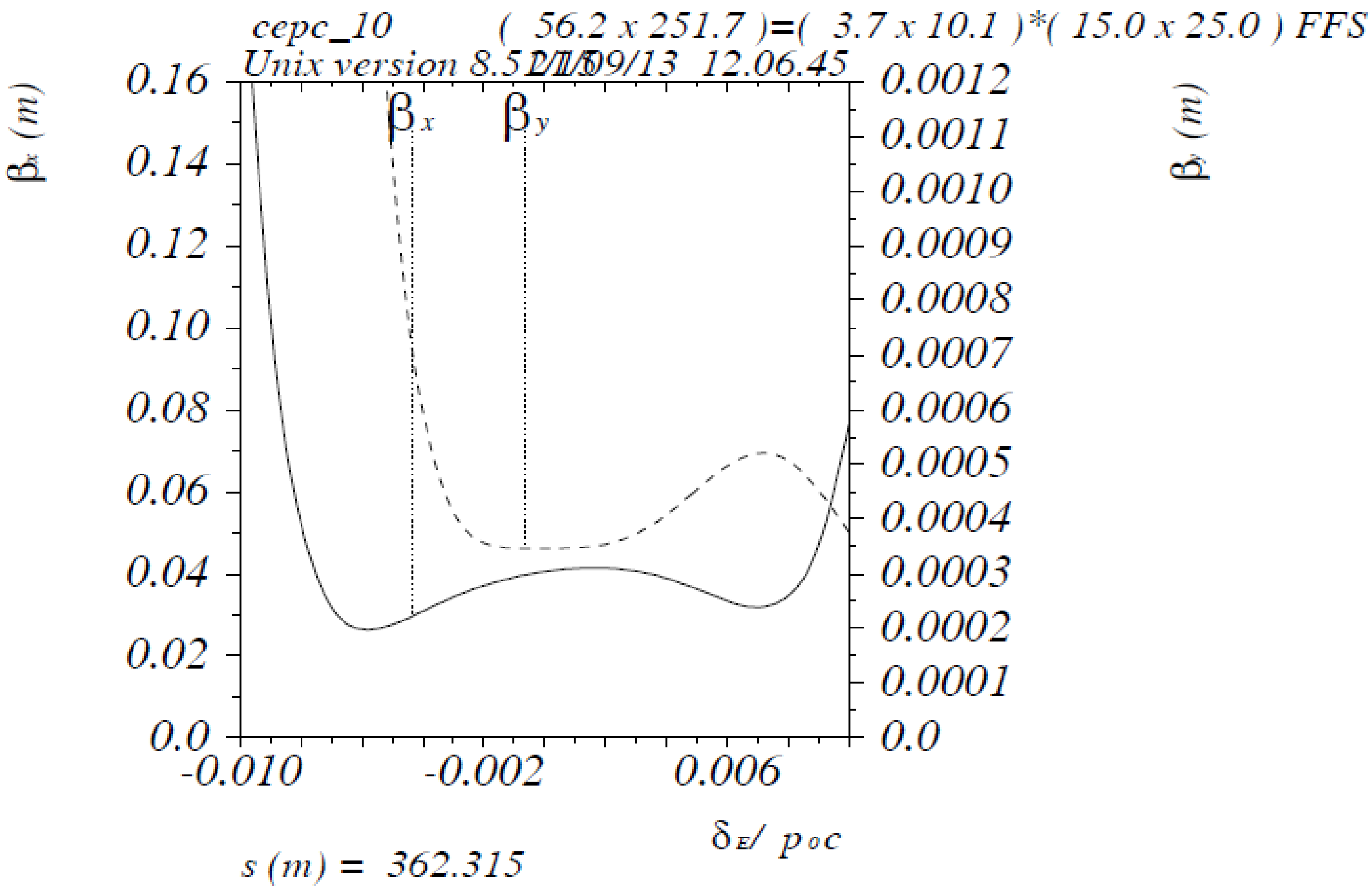
IP lowβ_y=0.35mm



at IP:
bx=0.041 m
by=0.35 mm
L*=3.5 m

From Sha Bai (baisha@ihep.ac.cn)

Beta Function at IP vs momentum



Optical bandwidth needs optimization.

From Sha Bai (baisha@ihep.ac.cn)

Summary

- A general method of how to make an optimized parameter design of a circular e+e- Higgs Factory was given.
- Based on beam parameters scan and RF parameters scan, a set of optimized parameter designs for 50 km Circular e-e+ Collider (CEPC) with different RF frequency was proposed.
- In order to reduce the total AC power, we decrease the SR power from 50 MW (baseline design) to 25 MW even to 15 MW (low power design) .
  Luminosity: 3.1→2.3 $\times 10^{34}$ $cm^{-2}s^{-1}$
- Recover the luminosity to the baseline design (3.1 $\times 10^{34}$ $cm^{-2}s^{-1}$) by the low power scheme. But we undertake the challenge of technology (ultra-low β^* and ultra-flat beam).
- 70km CEPC optimized design was done, including normal and low power scheme.
- There are two FFS Design considerations: the local-compact FFS Desgin which we tried to reduce the L* to reduce the chromatic aberrations and local non-compact FFS Desgin which using the non interleaved sextupoles to reduce the third order "kick".

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Thank you!