

Electron Positron Circular Collider Planning/Progress in China

J. Gao

IHEP

**LCWS2014
Belgrade, Oct. 6-10, 2014**

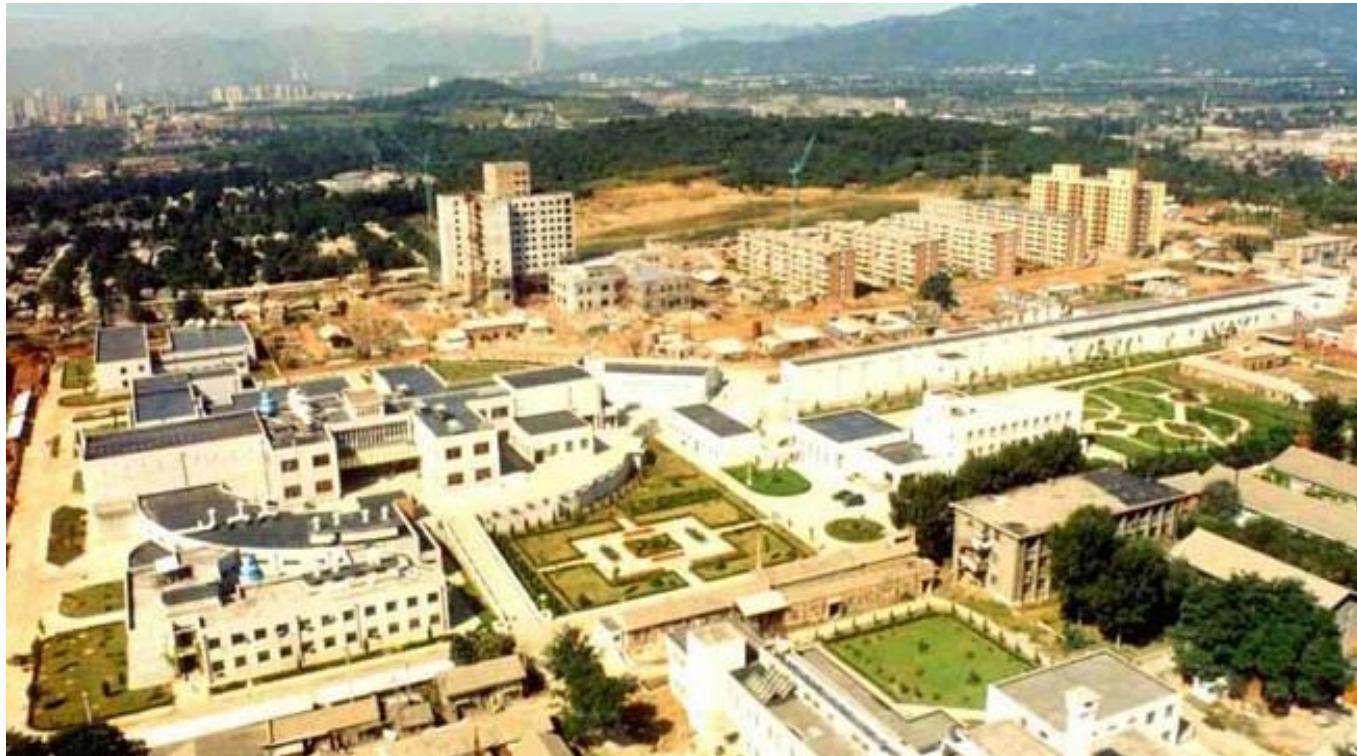


From BEPC to BEPCII

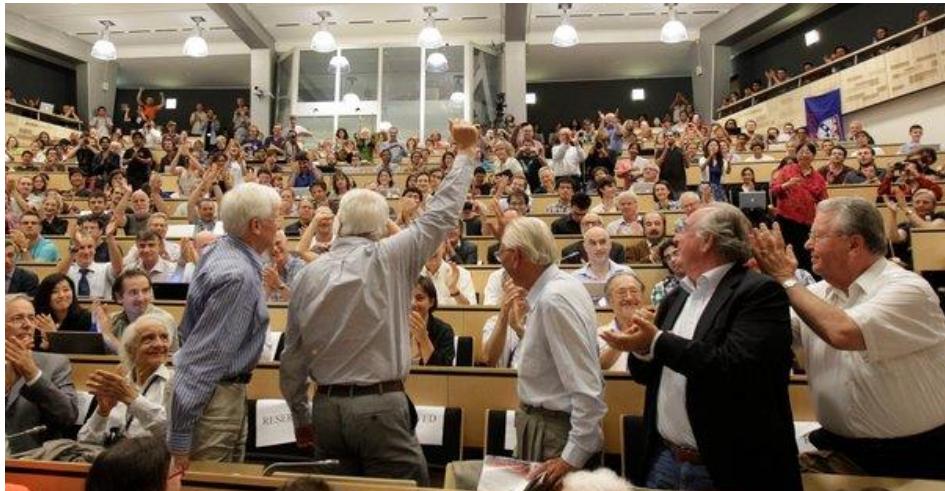
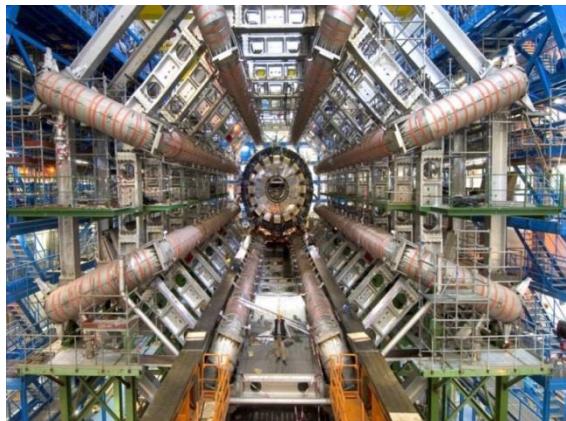
BEPC was completed in 1988 with luminosity $1 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$ @1.89GeV

BEPC II was completed in 2009 with Luminosity reached: $7 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ @1.89GeV

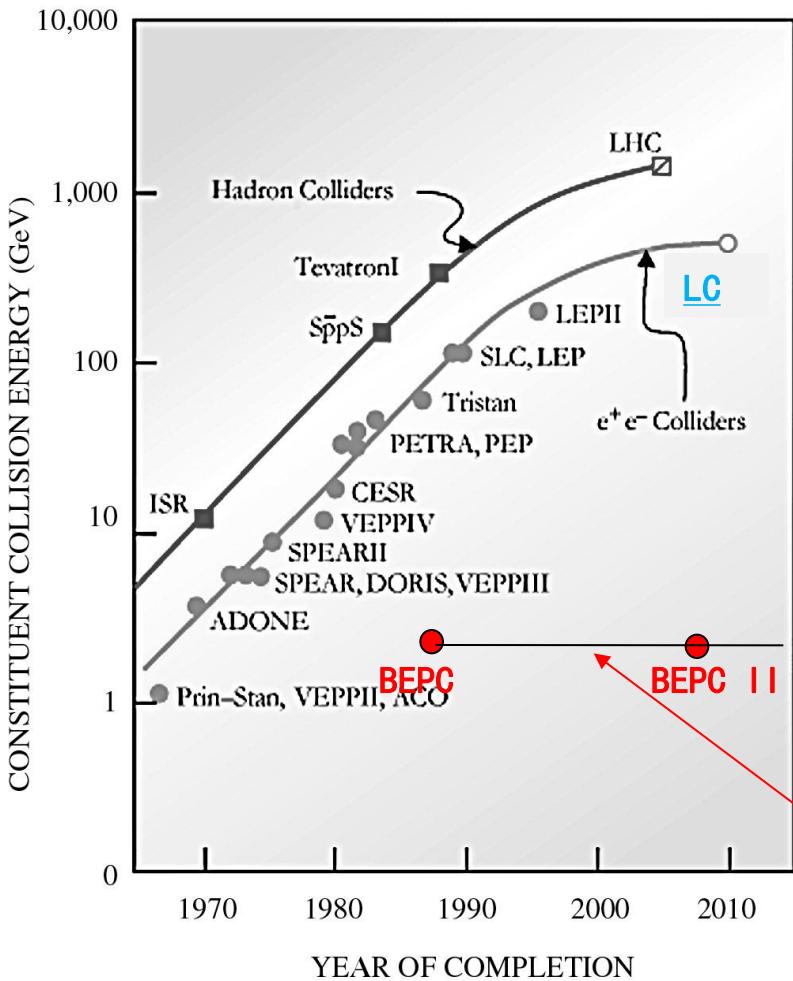
After BEPCII what is the next high energy collider?



On July 4, 2012, at CERN LHC Higgs Boson was announced found around 126GeV
(Scientific opportunity arrived)



Lepton and Hadron Colliders' History and China Accelerator based High Energy Physics Development in the Future



CEPC+SppC

CEPC: Ecm=240GeV e+e- Circular Collider

SppC: Ecm=50-100TeV pp Collider

CEPC+SppC will be constructed with international collaboration and participation

HIEPAF: High Intensity Electron Positron Accelerator Facility

History of BEPC and BEPC II

Old picture!

Strategy on Future High Energy Colliders of China

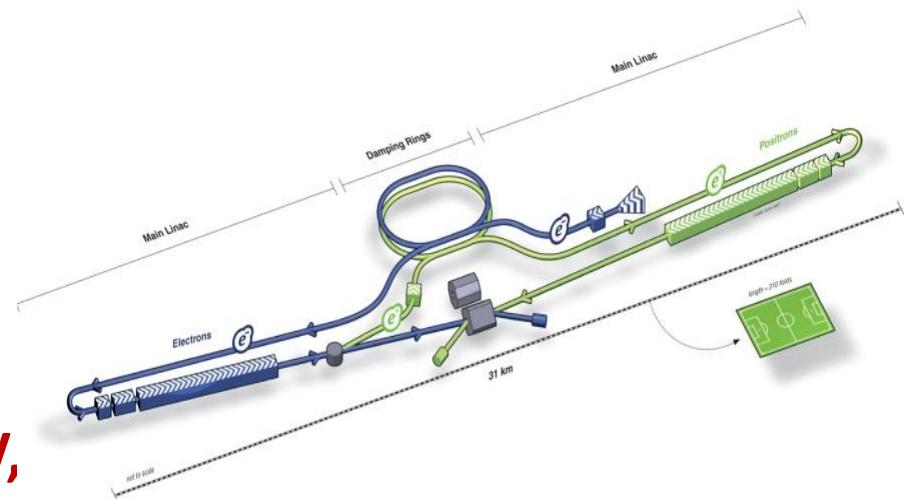
- 1) On “**The 464th Fragrant Hill Meeting, June 12-14, 2013**”, Chinese High Energy Physics Community arrived at the following consensus:
 - a) China supports ILC and will participate to **ILC** construction with in-kind contributions and requests R&D fund from government
 - b) After the discovery of Higgs, as next collider after BEPCII in China, a circular e+e- Higgs factory (**CEPC**) and a Super proton-proton Collier (**SppC**) afterwards in the same tunnel is an important option and historical opportunity.
- 2) During the meeting of **Chinese High Energy Physics Association** on “**China High Energy Physics based on Particle Accelerators**”, Feb. 28, 2014, it was concluded that: “**Circular e+e- Circular Higgs Factory(CEPC) +Super pp Collider (SppC) is the first choice for China’s future high energy physics accelerator.**
 - It is considered that **CEPC (250GeV upper limit)** is *supplementary to ILC in terms of its energy range down to W and Z boson and to the number of detectors from both machines*
 - *International collaboration and participation are necessary*

Ways to the future

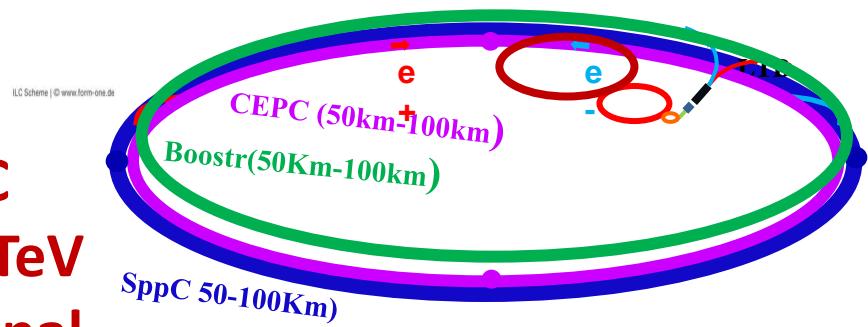
-Larger accelerators:

- Higher energy
- Higher precision

1) Linear colliders: ILC-CLIC
(from Higgs energy to 5TeV,
China participates)



2) Circular Colliders: CEPC-SppC
e+e- Higgs factory-pp 50~100TeV
(machine at home with international
Participation)



Precision @ e+e- collider
Energy frontier @ pp collider

1) China's ILC R&D Related Activities after TDR

The key subjects of R&D for accelerators in China (with ILC collaboration)

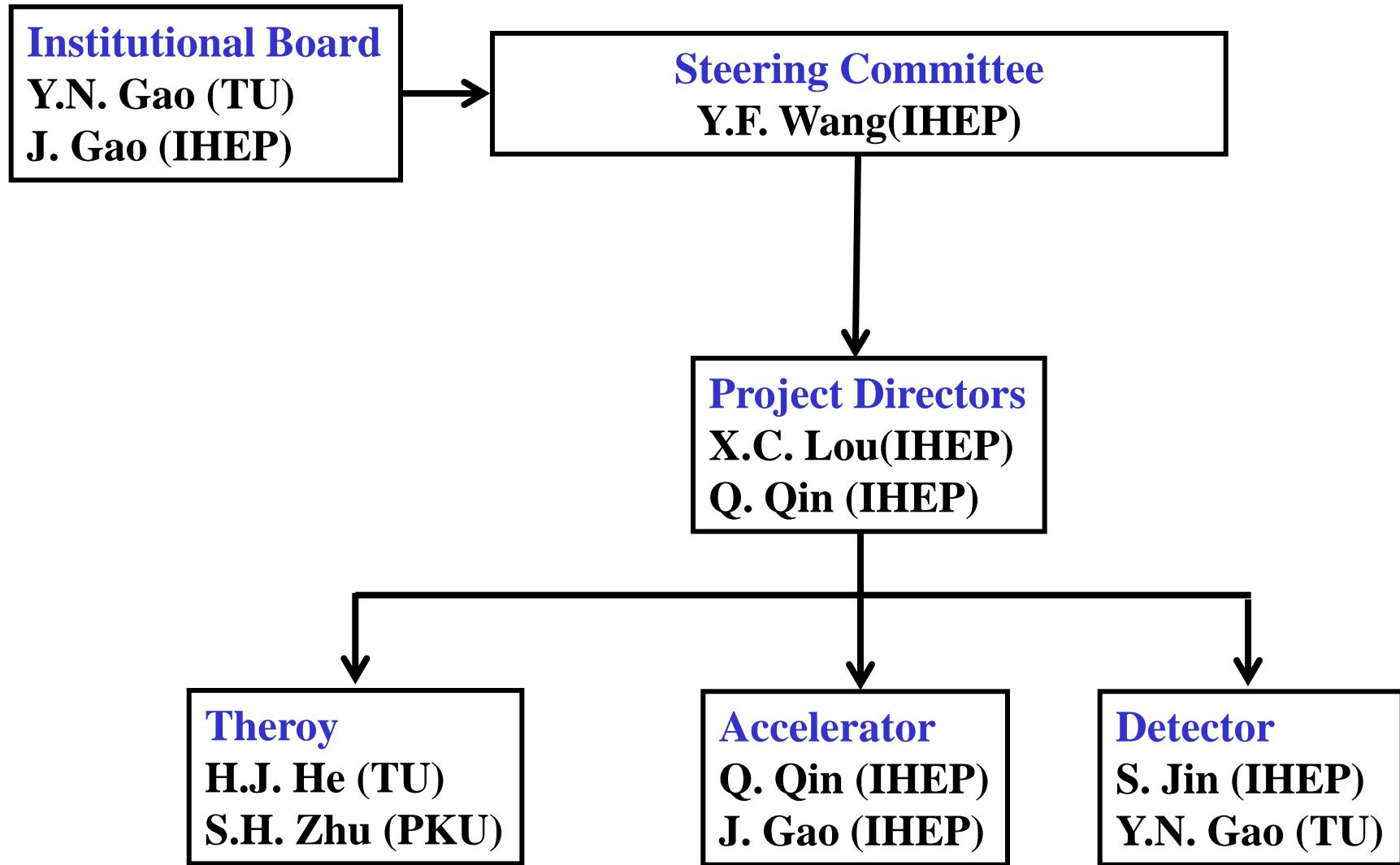
- 1) ILC luminosity and background improvements
- 2) ILC SCRF technology mastering
- 3) ILC positron source R&D efforts

Three talks in LCWS2014:

- 1) Dou Wang (IHEP), Yiwei Wang (IHEP), Philip Bambade (LAL), Jie Gao (IHEP),
Study of alternative ILC final focus optical configurations
- 2) *J. Zhai, et al, IHEP ILC Test Cryomodule Status*
- 3) S. Jin (IHEP), P. Sievers (CERN), T. Omori (KEK), J.Gao (IHEP),
Progress on Stress Analysis of Positron Source Target by AWB Simulation



2) CEPC-SppC Organization



Internationalization

- This is a machine for the world and by the world: not a Chinese one
- As a first step, “Center for Future High Energy Physics (CFHEP)” is established
 - Prof. Nima Arkani-Hamed is now the director
 - Many theorists(coordinated by Nima and Tao Han) and accelerator physicists(coordinated by Weiren Chou) from all the world have signed to work at CFHEP from weeks to months.
 - More are welcome → need support from the related management
 - Current work:
 - Workshops, seminars, public lectures, working sessions, ...
 - Pre-CDR
 - Future works (with the expansion of CFHEP)
 - CDR & TDR
 - Engineer design and construction
 - A seed for an international lab →
Organized and managed by the community
- We established closely collaborate with FCC@CERN



CEPC/SppC starts

FERMILAB-CONF-13-037-APC
IHEP-AC-2013-001
SLAC-PUB-15370
CERN-ATS-2013-032
arXiv:1302.3318 [physics.acc-ph]

Report of the ICFA Beam Dynamics Workshop
“Accelerators for a Higgs Factory: Linear vs. Circular”
(HF2012)

Alain Blondel¹, Alex Chao², Weiren Chou³, Jie Gao⁴, Daniel Schulte⁵ and
Kaoru Yokoya⁶

¹ U. of Geneva, Geneva, Switzerland

² SLAC, Menlo Park, California, USA

³ Fermilab, Batavia, Illinois, USA

⁴ IHEP, Beijing, China

⁵ CERN, Geneva, Switzerland

⁶ KEK, Tsukuba, Japan

Many workshops, seminars in
China and in the world

- Sep. 2013, Dec. 2013, March. 2014,
Spet. 2014, Oct. 2014(ICFA HF2014)...

CEPC+SppC Kick off Meeting
(Sept. 13-14,2013, Beijing)



CEPC/SppC and FCC

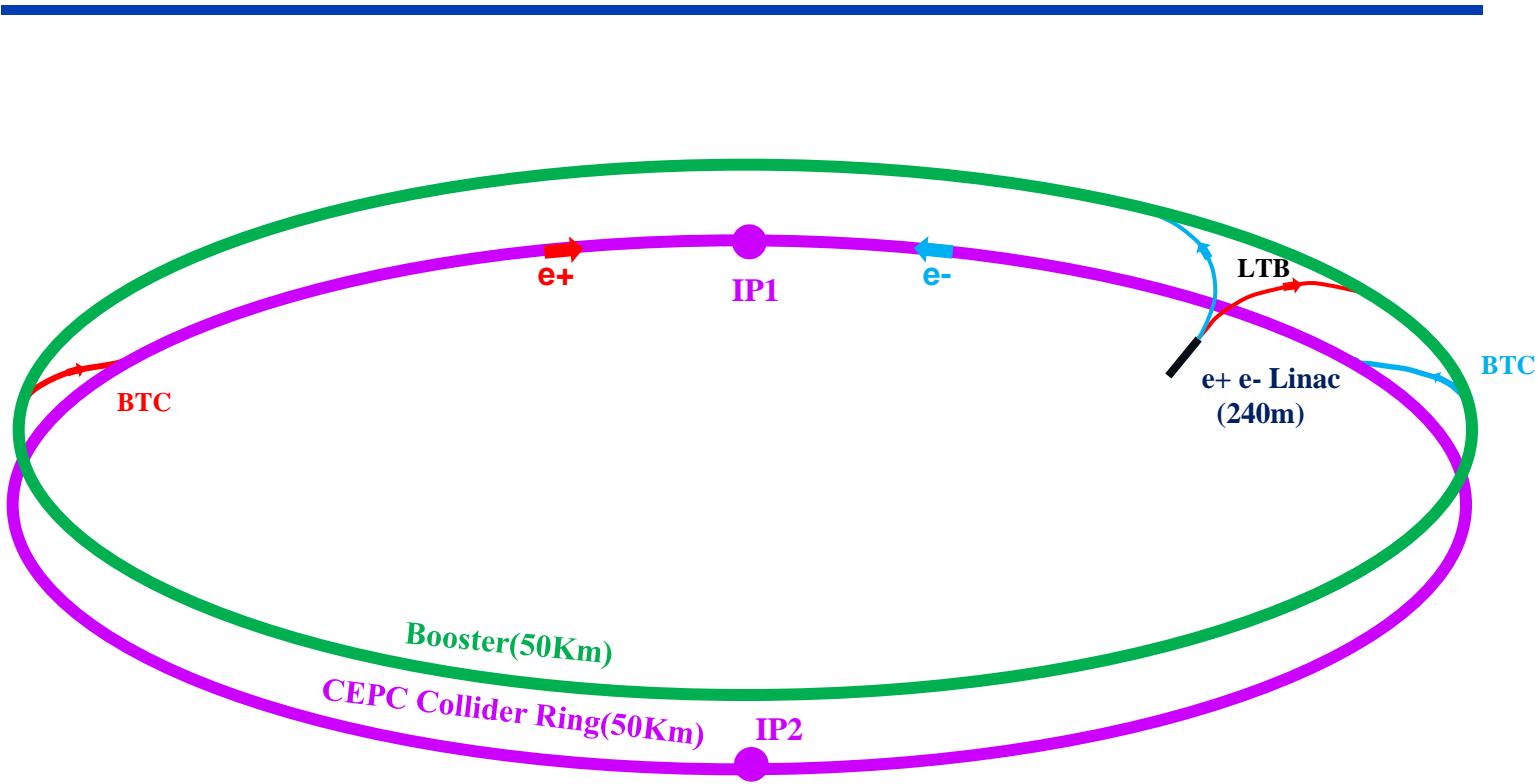
- CERN started the Future Circular Collider effort since last year
- FCC kick-off meeting in Feb., 2014
- ICFA statement On Feb. 21, 2014 at DESY:

ICFA supports studies of energy frontier circular colliders and encourages global coordination



ICFA: international committee for Future accelerators
<http://www.fnal.gov/directorate/icfa/>

CEPC layout



LTB : Linac to Booster

BTC : Booster to Collider Ring

CEPC+SppC Schedule (Preliminary)

- BEPC II will stop in ~2020
- CPEC
 - Pre-study, R&D and preparation work
 - Pre-study: 2013-15 → Pre-CDR by 2014
 - R&D: 2016-2020
 - Engineering Design: 2015-2020
 - Construction: 2021-2027
 - Data taking: 2030-2036
- SPPC
 - Pre-study, R&D and preparation work
 - Pre-study: 2013-2020
 - R&D: 2020-2030
 - Engineering Design: 2030-2035
 - Construction: 2036-2042
 - Data taking: 2042 -

Preliminary Conceptual Design Report of CEPC-SppC

Table of Contents (Draft, February 10, 2014)

Executive summary

1. Introduction
2. Sciences of CEPC and SppC
3. Machine layout and performance
4. CEPC – accelerator physics
 - 1) Main parameters
 - 2) Lattice
 - 3) Interaction region and machine-detector interface
 - 4) Beam instability
 - 5) Beam-beam effects
 - 6) Synchrotron radiation
 - 7) Injection and beam dump
 - 8) Background
 - 9) Polarization
5. CEPC – technical systems
 - 1) Superconducting RF system
 - 2) Cryogenic system
 - 3) Magnets
 - 4) Vacuum
 - 5) Power supplies
 - 6) Instrumentation
 - 7) Control system
 - 8) Radiation shielding
 - 9) Survey and alignment
6. CEPC – injectors
 - 1) e^+ and e^- sources
 - 2) Linac
 - 3) Booster ring
7. Upgrade to SppC
 - 1) Key accelerator physics issues
 - i. Main parameters
 - ii. Synchrotron radiation
 - iii. Beam-beam effects
 - iv. Electron cloud effect
 - 2) Key technical systems
 - i. High field superconducting magnet
 - ii. Vacuum and beam screen
 - 3) Reconfiguration of the accelerator complex
8. Other possible upgrades
 - 1) ep
 - 2) $\gamma\gamma$
9. Civil construction
10. Environment, safety and health considerations
11. R&D programs
12. Project plan and cost estimate

Luminosity from colliding beams

- For equally intense Gaussian beams

$$L = f \frac{N_b^2}{4\pi\sigma_x\sigma_y} R$$

Collision frequency

Particles in a bunch

Geometrical factor:
- crossing angle
- hourglass effect

Transverse beam size
(RMS)

- Expressing luminosity in terms of our usual beam parameters

$$L[\text{cm}^{-2}\text{s}^{-1}] = 2.17 \times 10^{34} (1+r) \xi_y \frac{E[\text{GeV}] I[\text{A}]}{\beta_y [\text{cm}]}$$

where

$$\xi_y = \frac{r_e N_e \beta_y}{2\pi\sigma_y(\sigma_x + \sigma_y)} :$$

For lepton collider:

$$\xi_{y,\max} = \frac{2845}{2\pi} \sqrt{\frac{T_0}{\tau_y \gamma N_{IP}}} \quad \xi_{y,\max} = \frac{2845 \gamma}{1} \sqrt{\frac{r_e}{6\pi R N_{IP}}}$$

r_e is electron radius
 γ is normalized energy
 R is the dipole bending radius
 N_{IP} is number of interaction points

$$\xi_{x,\max} = \sqrt{2} \xi_{y,\max}$$

J. Gao, Nuclear Instruments and Methods in Physics Research A 533 (2004) 270–274

For hadron collider:

$$\xi_{\max} = \frac{2845 \gamma}{f(x)} \sqrt{\frac{r_p}{6\pi R N_{IP}}}$$

J. Gao, Nuclear Instruments and Methods in Physics Research A 463 (2001) 50–61

r_p is proton radius

where

$$f(x) = 1 - \frac{2}{\sqrt{2\pi}} \int_0^x \exp\left(-\frac{t^2}{2}\right) dt$$

Formulae from private note of J. Gao

$$x^2 = \frac{4f(x)}{\pi \xi_{\max} N_{IP}} = \frac{4f^2(x)}{2845 \pi \gamma} \sqrt{\frac{6\pi R}{r_p N_{IP}}}$$

Difference between an e+e- Linear Collider and an e+e- storage ring collider

Linear Collider

$$L \left[\text{cm}^{-2} \text{s}^{-1} \right] = \frac{N_e \cdot P_b [\text{MW}]}{4\pi \times 10^7 e \cdot \sigma_x^* [m] \sigma_y^* [m] E_0 [\text{GeV}]} H_{Dx} H_{Dy}$$

Storage ring collider

$$L \left[\text{cm}^{-2} \text{s}^{-1} \right] = 0.7 \times 10^{34} (1 + R) \frac{1}{\beta_{y,IP} [\text{cm}]} \sqrt{\frac{P_b [\text{MW}] P_0 [\text{MW}]}{\gamma N_{IP}}} \cdot F_{hg}$$

$$F_{hourglass} = \frac{a}{\sqrt{\pi}} \exp\left(\frac{a^2}{2}\right) K_0\left(\frac{a^2}{2}\right) \quad a = \frac{\beta_y^*}{\sigma_l}$$

P₀ is single beam radiation power
P_b is single beam power

where for storage ring luminosity expression,

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

has been used

Roughly speaking, linear collider is background limited and circular collider is AC power limited, which corresponds to aiming to reduce background and to reduce AC power for given Luminosities, respectively.

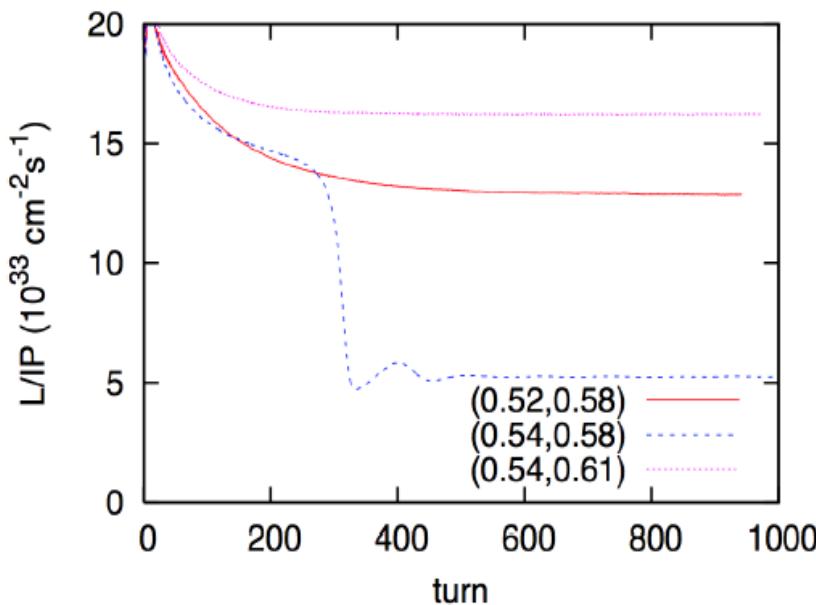
Main parameters for CEPC (Oct. 1, 2014)

Parameter	Unit	Value	Parameter	Unit	Value
Beam energy [E]	GeV	120	Circumference [C]	m	54420
Number of IP[N _{IP}]		2	SR loss/turn [U ₀]	GeV	3.11
Bunch number/beam[n _B]		50	Bunch population [N _e]		3.71E+11
SR power/beam [P]	MW	51.7	Beam current [I]	mA	16.6
Bending radius [ρ]	m	6094	momentum compaction factor [α _p]		3.39E-05
Revolution period [T ₀]	s	1.82E-04	Revolution frequency [f ₀]	Hz	5508.87
emittance (x/y)	nm	6.12/0.018	β _{IP} (x/y)	mm	800/1.2
Transverse size (x/y)	μm	69.97/0.15	ξ _{x,y} /IP		0.116/0.082
Beam length SR [σ _{s.SR}]	mm	2.17	Beam length total [σ _{s.tot}]	mm	2.53
Lifetime due to Beamstrahlung	min	80	lifetime due to radiative Bhabha scattering [τ _L]	min	52
RF voltage [V _{rf}]	GV	6.87	RF frequency [f _{rf}]	MHz	650
Harmonic number [h]		117900	Synchrotron oscillation tune [v _s]		0.18
Energy acceptance RF [h]	%	5.98	Damping partition number [J _ε]		2
Energy spread SR [σ _{δ.SR}]	%	0.13	Energy spread BS [σ _{δ.BS}]	%	0.08
Energy spread total [σ _{δ.tot}]	%	0.16	n _γ		0.23
Transverse damping time [n _x]	turns	78	Longitudinal damping time [n _ε]	turns	39
Hourglass factor	Fh	0.692	Luminosity /IP[L]	cm ⁻² s ⁻¹	2.01E+34

CEPC Beam-beam simulations

Strong-strong simulation

- Luminosity behavior depends on tune operating points.



The current main parameters has been checked with beam-beam simulation, proved the reasonability.
(Ohmi, Zhang Yuan, Demitry Shatilov)

Beam-beam tune shift limit analytical calculations

For lepton collider:

$$\xi_{y,\max} = \frac{2845\gamma}{1} \sqrt{\frac{r_e}{6\pi R N_{IP}}} = 0.072(CEPC)$$

J. Gao, Nuclear Instruments and Methods in Physics
Research A 533 (2004) 270–274

$$\xi_{x,\max} = \sqrt{2}\xi_{y,\max} = 0.11(CEPC)$$

J. Gao, Nuclear Instruments and Methods in Physics
Research A 463 (2001) 50–61

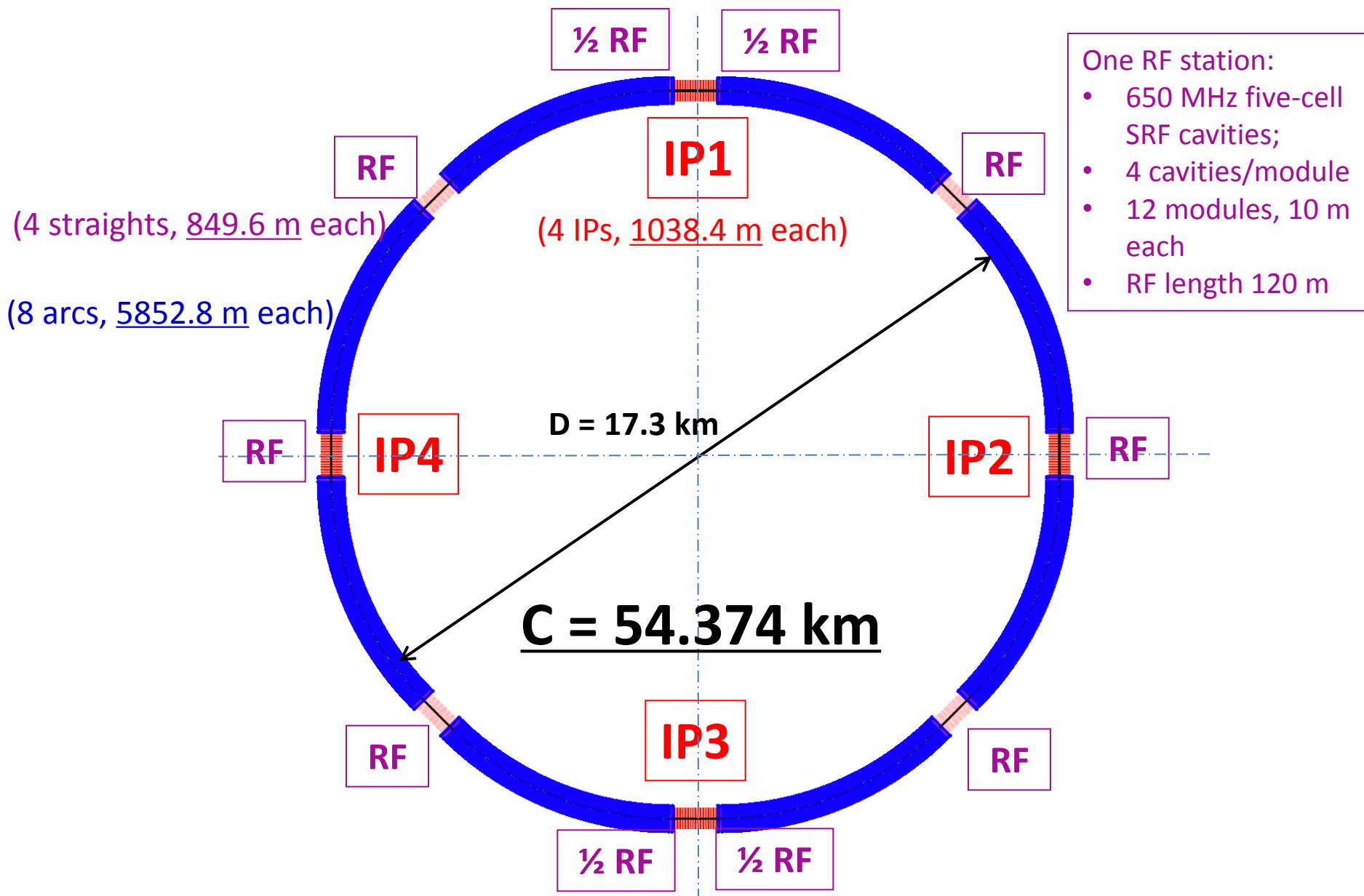
r_e is electron radius

γ is normalized energy

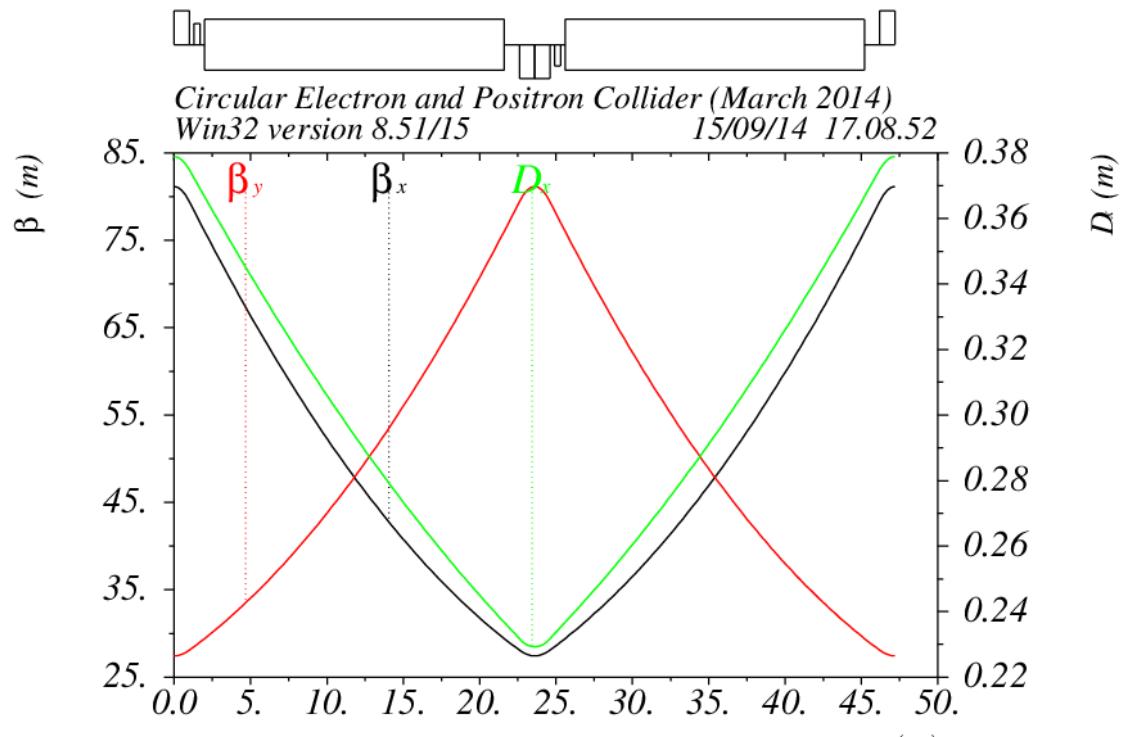
R is the dipole bending radius

N_IP is number of interaction points

CEPC Lattice Layout (September 24, 2014)



FODO Cells



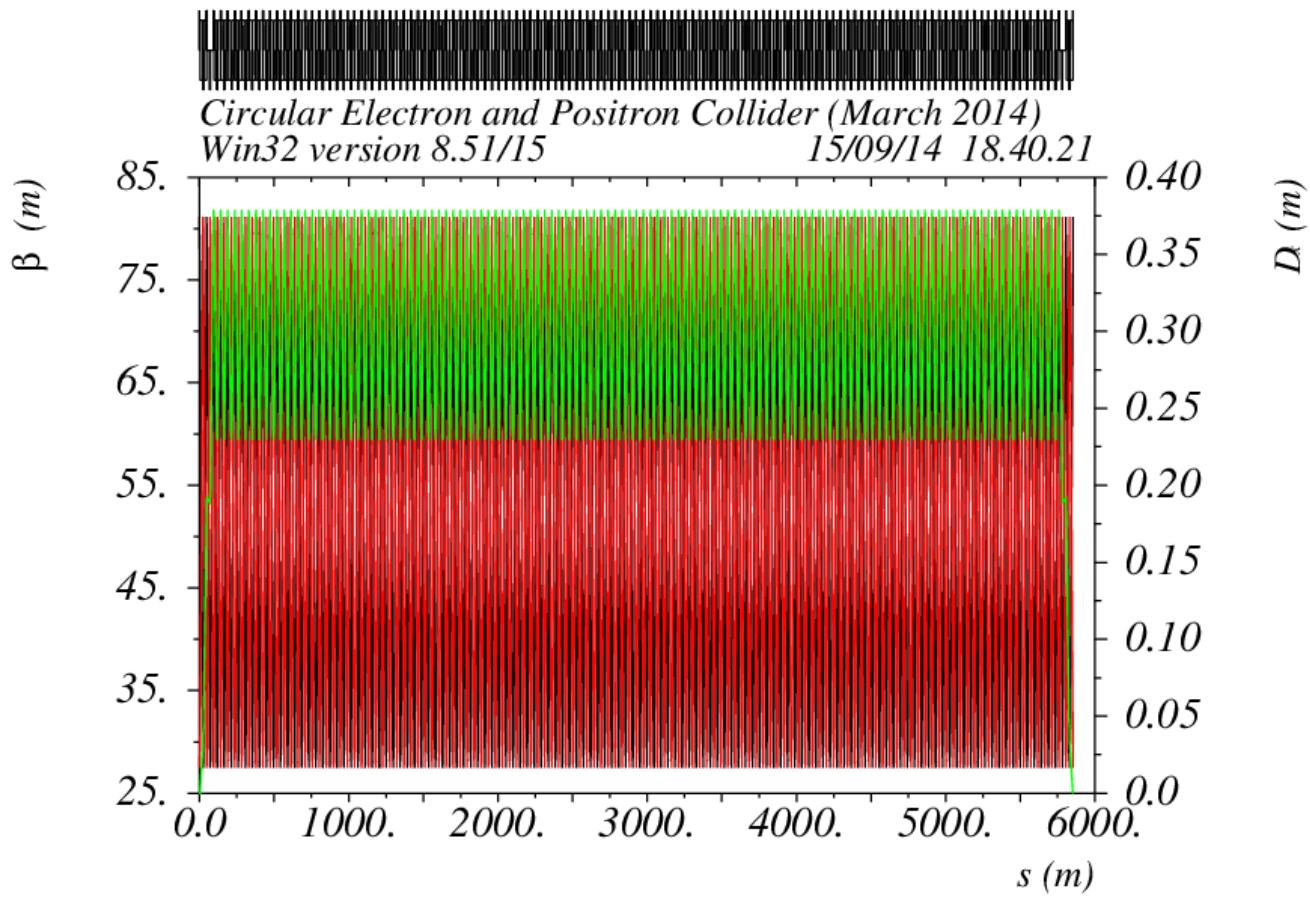
$$\delta_E / p_0 c = 0.$$

Table name = TWISS

Length of bending magnet: 19.6m
Bending radius: 6089m

Length of Qs: 2.0m
Length of sextupoles: 0.4m
Distance between magnets: 0.3m
Length of each cell: 47.2m

Arc



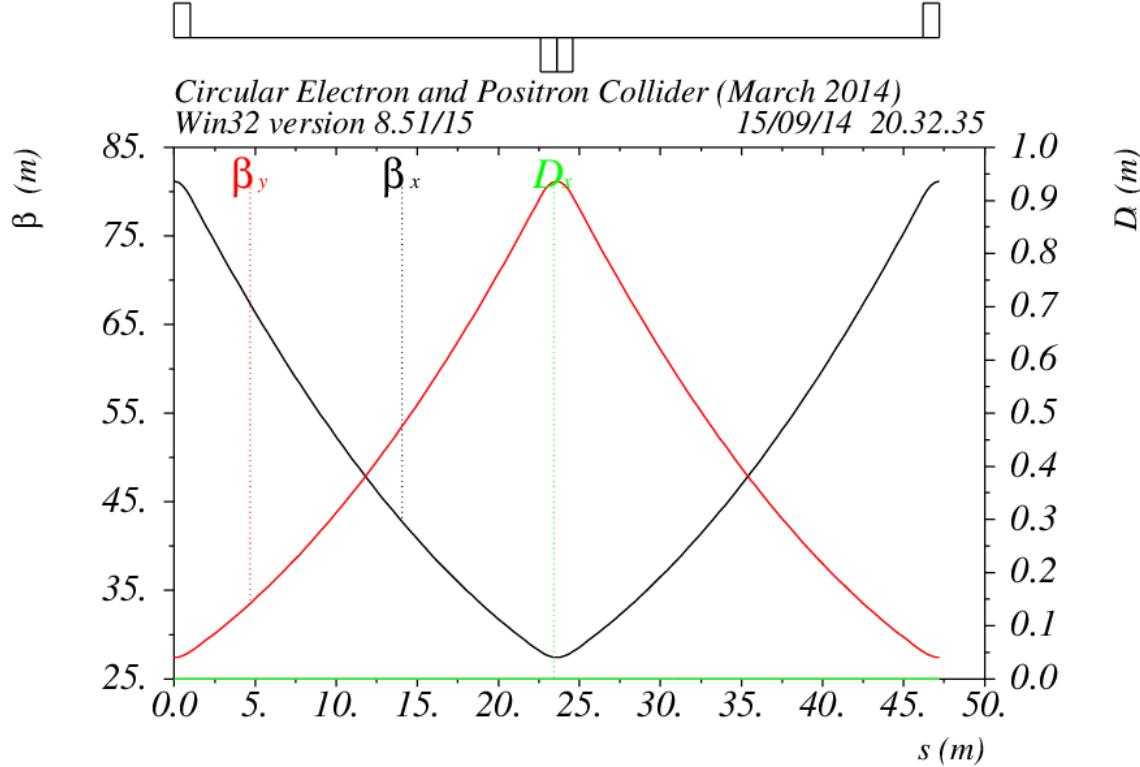
120*FODO cells
+ dispersion
suppressors at
both sides

Total length:
5852.8m

$$\delta_E / p_0 c = 0.$$

Table name = TWISS

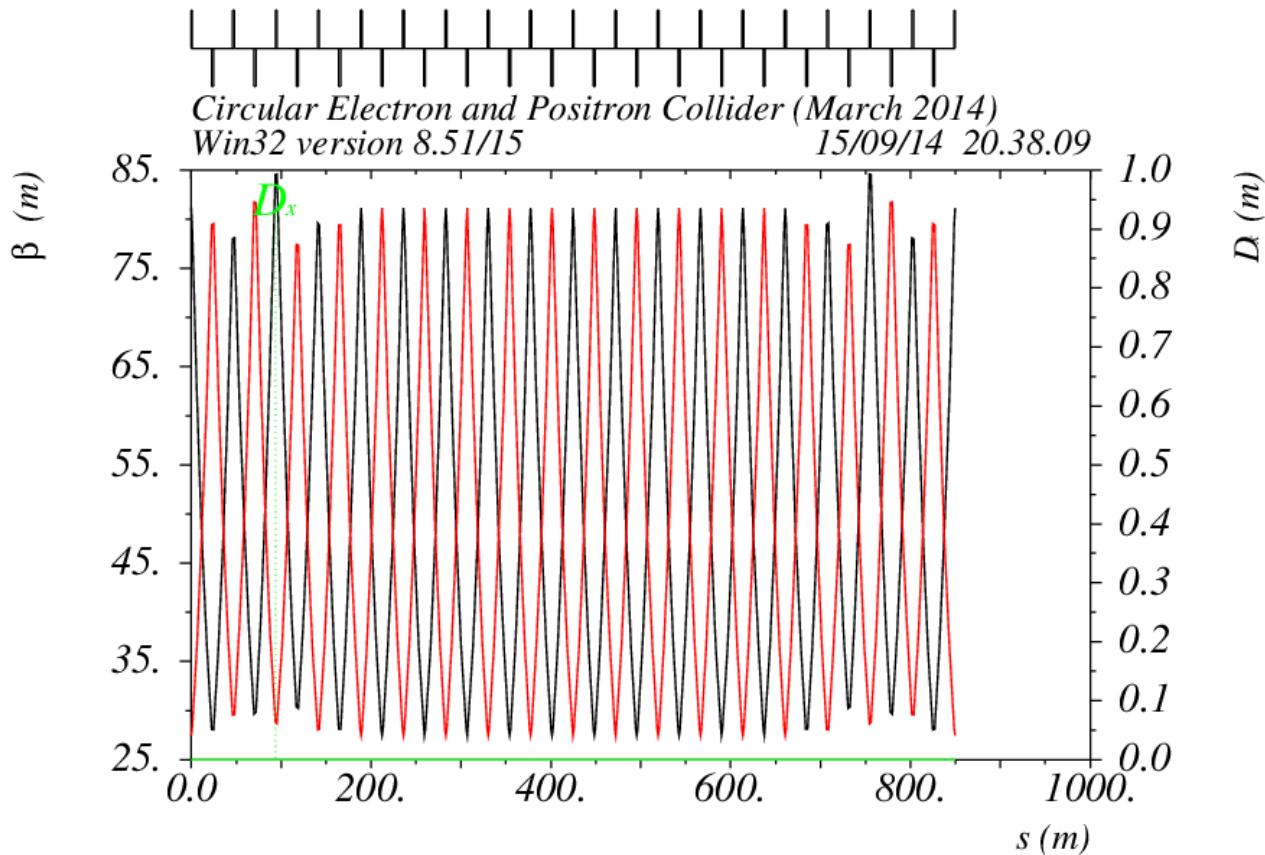
FODO cell at straight section



$$\delta_E / p_0 c = 0.$$

Table name = TWISS

Straight section



$10^*FODO+4$
matching cells on
each side

Used for work
point adjustment

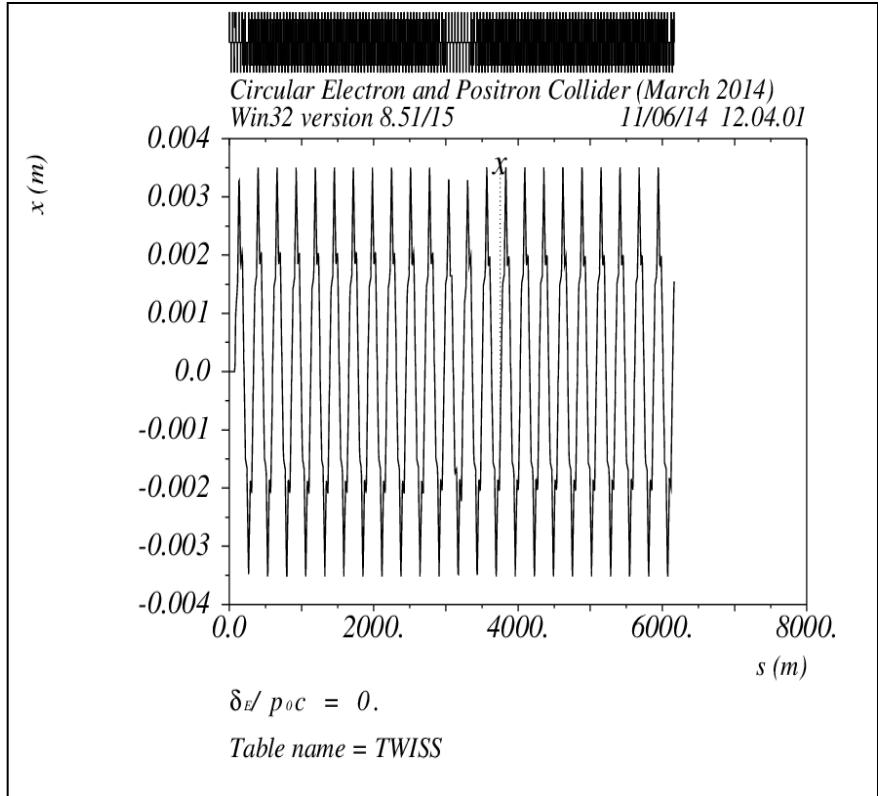
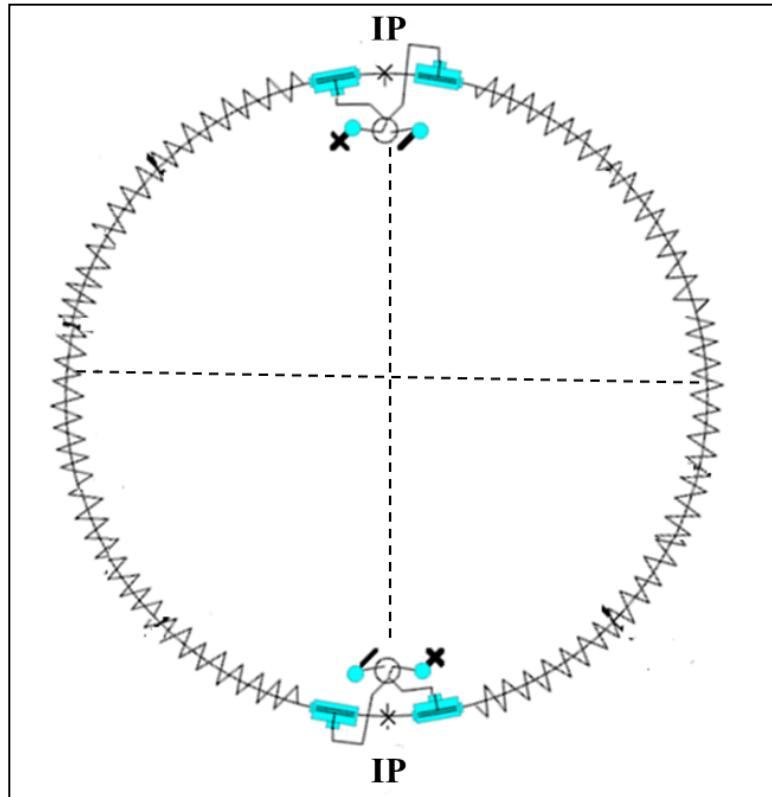
Total length:
849.6m

$$\delta_{E/c} = 0.$$

Table name = TWISS

Pretzel scheme

- ◆ Use 2 pairs of electrostatic separators
- ◆ Beam separated at horizontal plane with orbit offset of $5\sigma_x$
- ◆ Maximum bunch number: 96



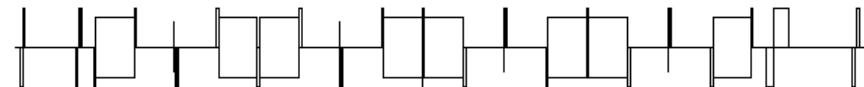
CEPC Magnets' specifications

Dipole magnet	type A	type B
Quantity	1984	
Beam energy (GeV)	120	
Bending angle (rad)	3.17E-03	
Bending radius (m)	5683.74	
Magnetic gap (mm)	100 (as LEP)	
Magnetic Length (m)	18	
Maximum field strength (T)	0.07	
Good field region, GFR (mm)		
Field uniformity across GFR		
Integral field deviation (magnet to magnet)		
Quadrupole magnet	type A	type B
Quantity	2304	
Beam energy (GeV)	120	
Aperture diameter(mm)	125	
Magnetic Length (m)	2	
Maximum field gradient (T/m)	10	
Good field region, GFR radius (mm)		
Harmonic field errors across GFR		
Integral field deviation (magnet to magnet)		
Sextupole magnet	type A(SF)	type B(SD)
Quantity	992	992
Beam energy (GeV)	120	120
Aperture diameter(mm)	150 (as LEP)	150
Magnetic Length (m)	0.4	0.7
Strength of sextupole field (T/m ²)	180	180
Good field region, GFR radius (mm)		
Harmonic field errors across GFR		

Whole FFS optics

IP:
 $\text{betx}^*=0.8\text{m}$
 $\text{bety}^*=0.0012\text{m}$
 $L^*=1.5\text{m}$

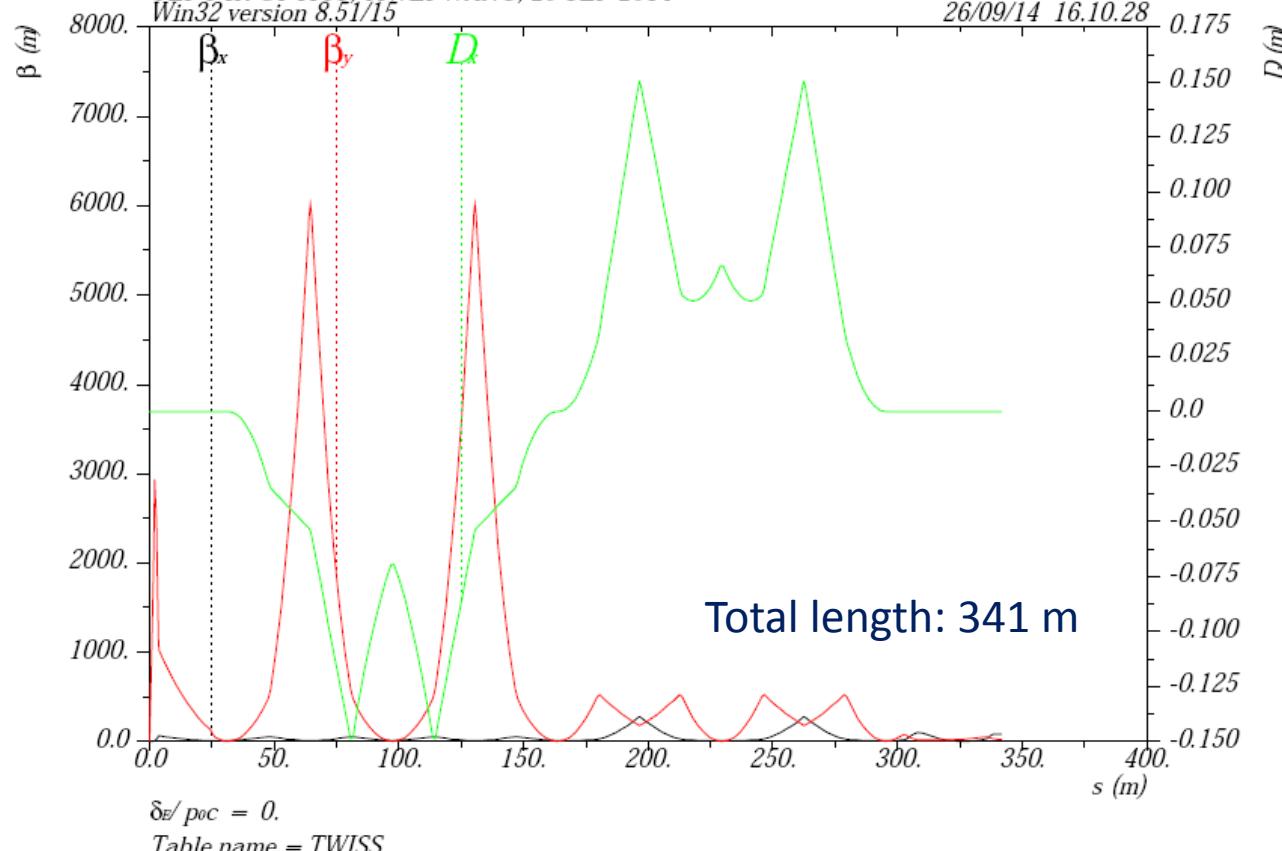
IP



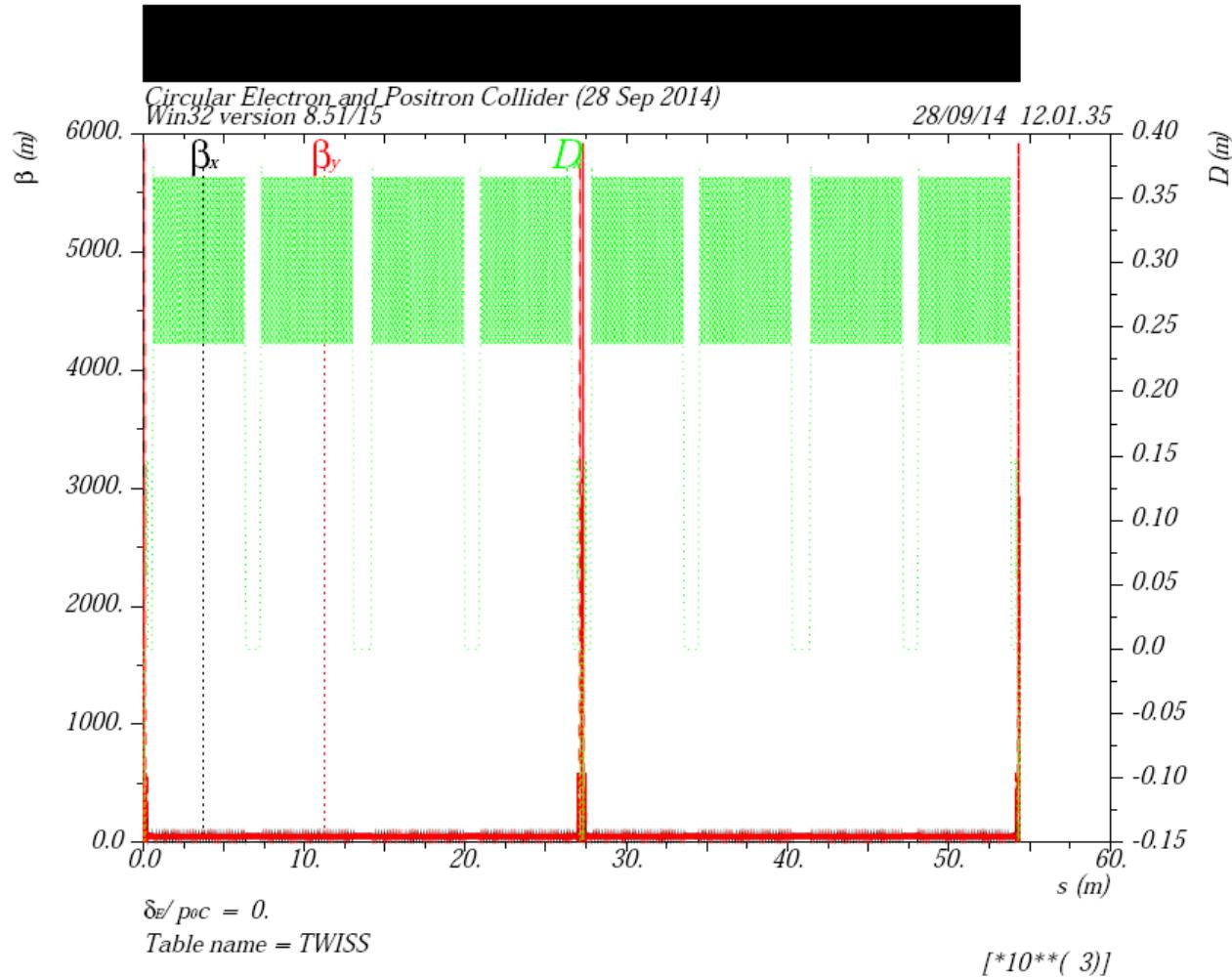
$L^*=1.5\text{m}$
CEPC IR OPTICS, YIWEI WANG, 25 SEP 2014
Win32 version 8.51/15

26/09/14 16.10.28

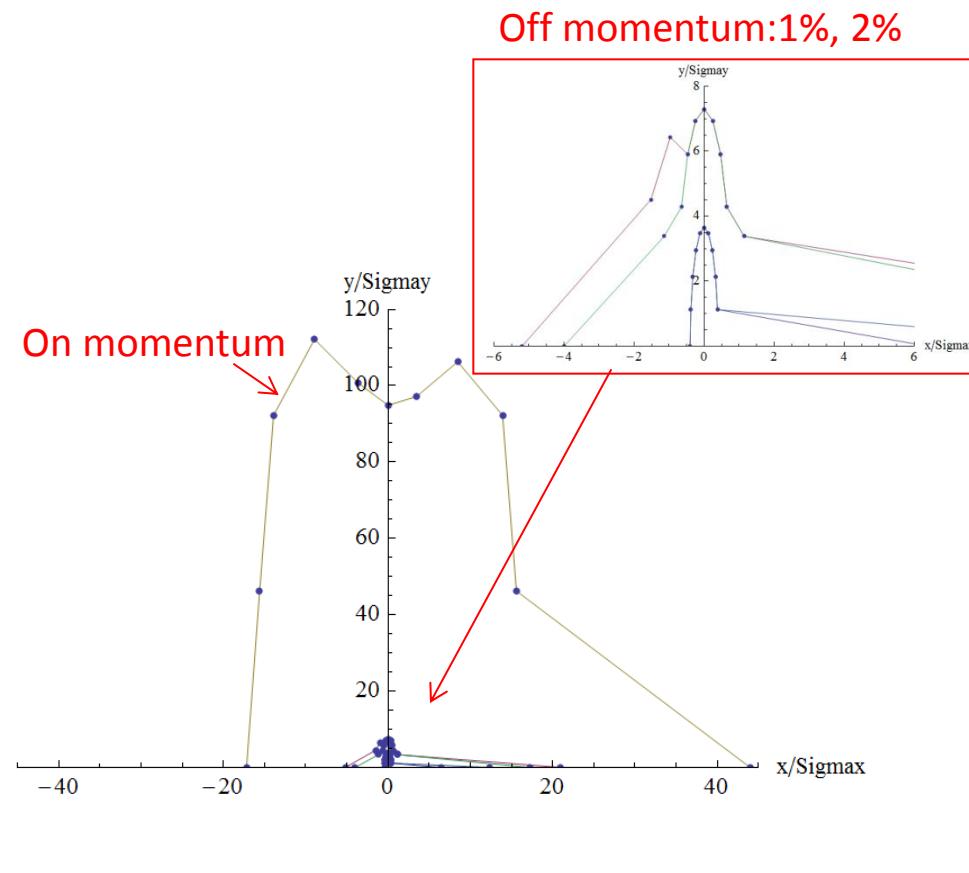
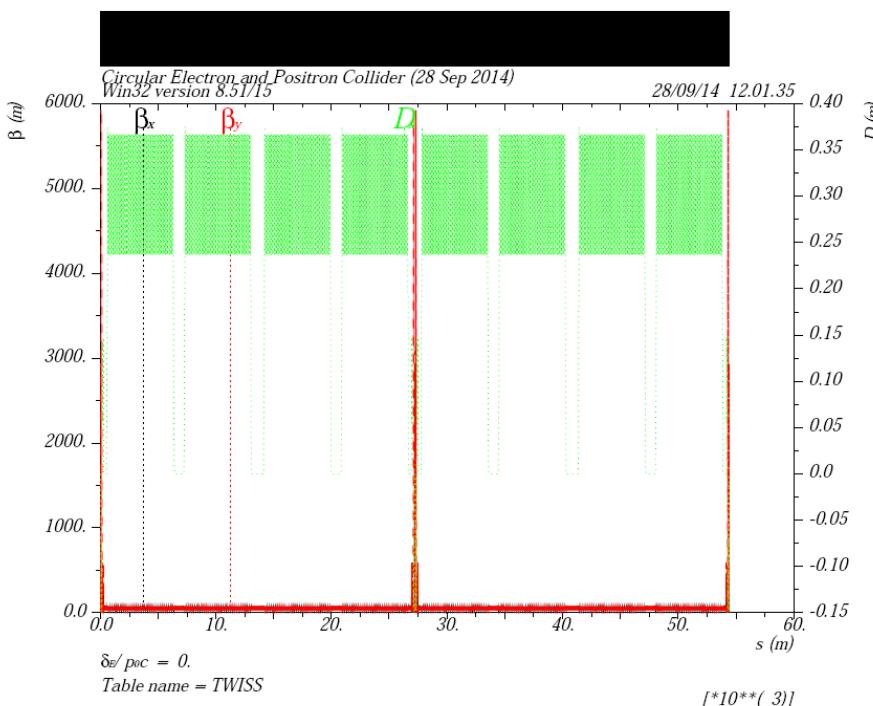
Entrance:
 $\text{betx}=81\text{m}$
 $\text{bety}=27\text{m}$



CEPC lattice with FFS



Lattice of the whole ring

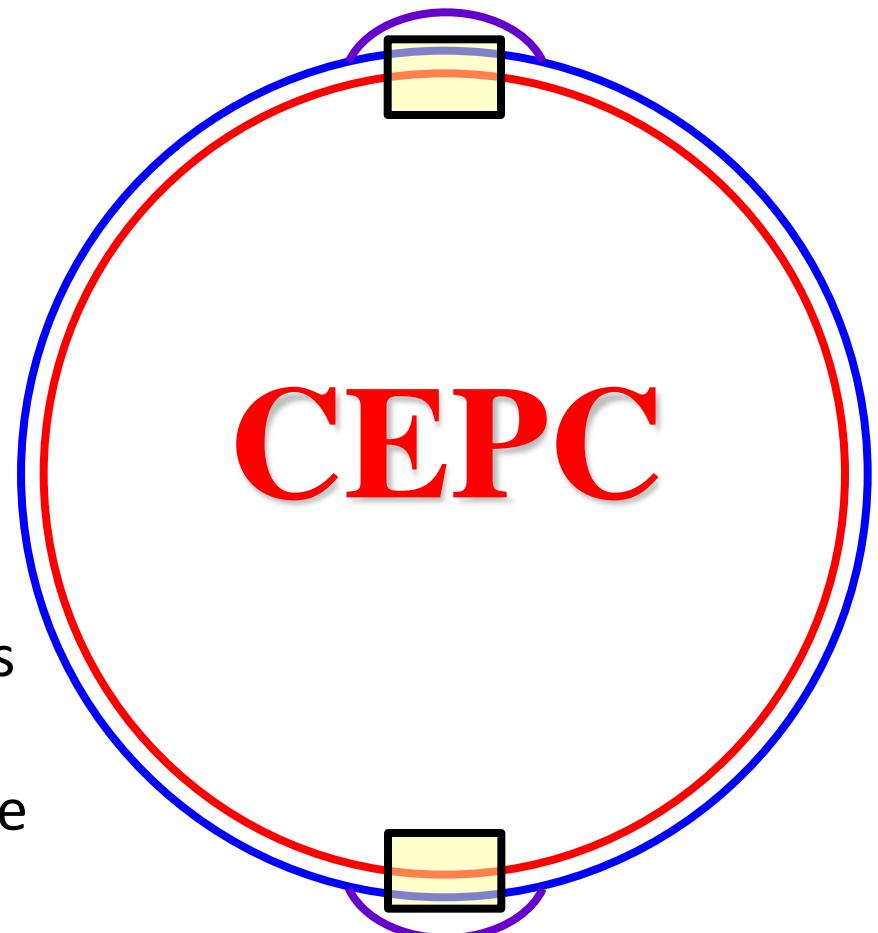


- ◆ Dynamic aperture: $\sim 20\sigma_x / 100\sigma_y$ for on momentum particles
- ◆ For first try, zero length of sextupoles in FFS used

Booster bypass design

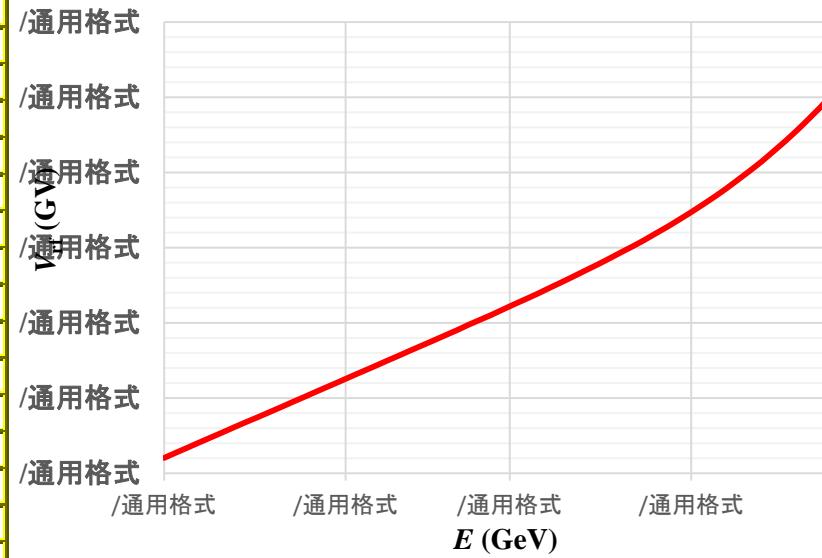
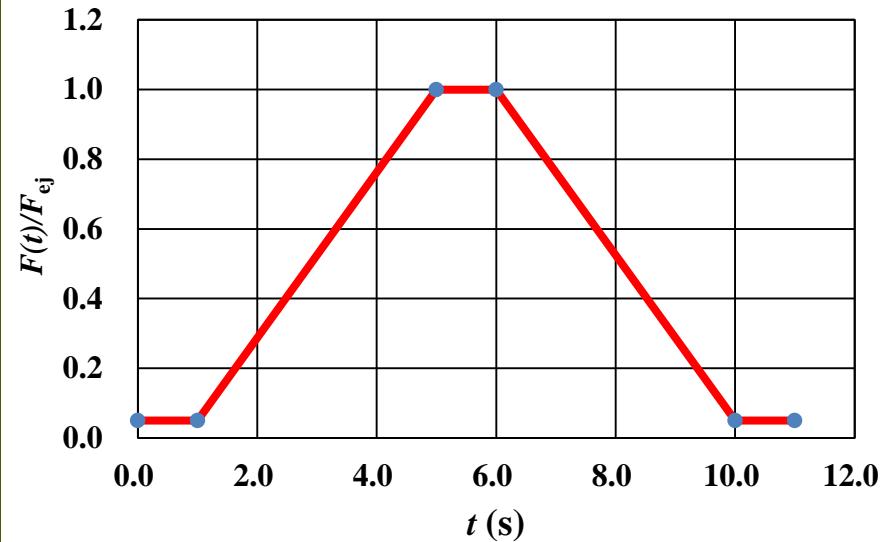
Booster: Outer of Collider

- For the moment, the energy of Booster is chosen 6GeV, the ratio Energy gain is 20.
- There are two issues rest to be checked carefully on the booster energy choice:
 - 1) The low dipole field of 37 Gauss at 6GeV with 1/5 being the residual magnetic field of dipole magnets
 - 2) The space charge effect



Booster key parameters

Parameter	Symbol	Unit	Value
Injection energy	E_{inj}	GeV	6
Ejection energy	E_{ej}	GeV	120
Circumference	C	km	53.6192
Revolution frequency	f_0	kHz	5.591
Bending radius	ρ	km	6.520
Main bending field	B_0	T	0.0614
SR loss/turn	U_0	GeV	2.814
Bunch number	n_b		50
Bunch population	N_b	10^{10}	1.96
Beam current	I_{beam}	mA	0.889
Momentum compaction	α_p	10^{-5}	7.774
Chromaticity	ξ/ξ		-47.58/-50.36
Emittance	$\epsilon_{e\theta,\text{ej}}$	nm	24.02
RF frequency	f_{RF}	MHz	1300.0
RF Voltage	V_{RF}	GV	5.12
Harmonic number	h		232511
Energy spread	$\sigma_{E,\text{ej}}$	10^{-3}	1.273
Bunch length	σ_z	mm	3.89
Length of normal cells	L_{cell}	m	71.3
Number of cells	N_{cell}	m	752
Transverse phase advance in a cell	μ_x/μ_y		60°/60°
Quadrupole strength in a cell	$K_{\text{QF}}/K_{\text{QD}}$	m^{-2}	2.8315/-2.8315
Maximum β in cells	$\beta_{x,c,\text{max}}/\beta_{y,c,\text{max}}$	m	123.21/123.21
Maximum β in ring	$\beta_{x,\text{max}}/\beta_{y,\text{max}}$	m	127.00/124.94
Maximum dispersion in cells	$D_{c,\text{max}}$	m	0.8744
Maximum dispersion in ring	D_{max}	m	0.8744
Sixupole strength	$K_{\text{SF}}/K_{\text{SD}}$	m^{-3}	0.1924/-0.3124
Transverse tune	ν_x/ν_y		119.72/119.73
Longitudinal tune	ν_z		0.320
Damping time	$\tau_x/\tau_y/\tau_z$	ms	15.2/15.2/7.63

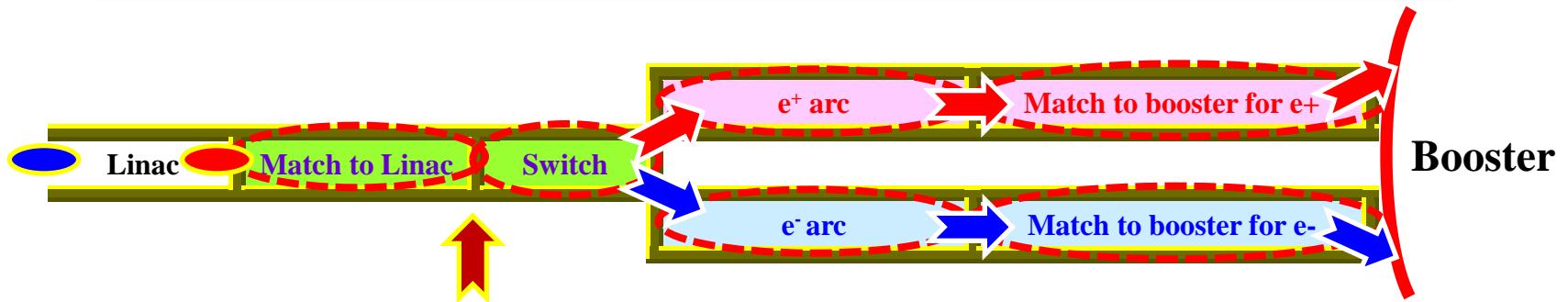


Booster lattice parameters

scale to cell length

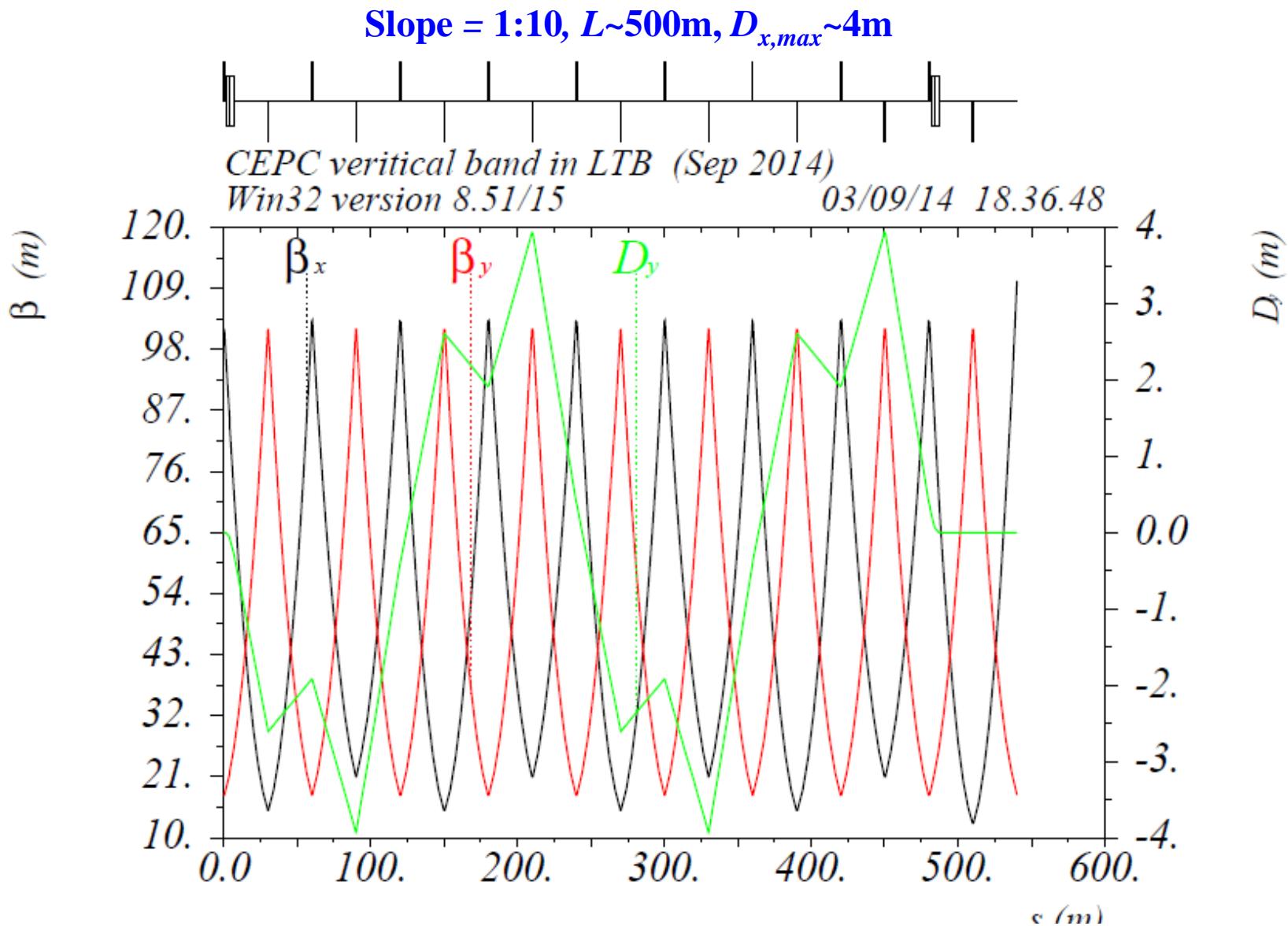
FODO cell Length L		47.2	71.3	94.4	m
Quadrupole strength	$ k_Q l_Q \propto L^{-1}$	0.044	0.029	0.022	m^{-1}
Maximum beta function in a cell	$\beta_{\max} \propto L$	81.2	122.6	162.3	m
Maximum dispersion in a cell	$D_x \propto L^2$	0.38	0.86	1.52	m
Betatron tune	$\nu_{x,y} \propto L^{-1}$	189.2	125.3	94.6	
Momentum compaction factor	$\alpha_p \propto L^2$	3.43	7.83	13.72	10^{-5}
Chromaticity	$\xi \propto L^{-1}$	86.4	57.2	43.2	
Sextupole strength SF/SD	$ k_s l_s \propto L^{-3}$	0.15/0.24	0.044/0.070	0.019/0.030	m^{-2}
Nature emittance	$\epsilon_{x0} \propto L^3$	6.8	23.44	54.40	nm
Synchrotron tune ($V_{RF}=5$ GV)	$\nu_s \propto L$	0.204	0.31	0.41	
Maximum Betatron beam size x/y	$\sigma_\beta \propto L^2$	0.74/0.53	1.70/1.20	2.97/2.10	mm
Maximum Beam orbit spread	$\sigma_{xE} \propto L^2$	0.49	1.12	1.97	mm
Maximum horizontal m beam size	$\sigma_x \propto L^2$	0.89	2.03	3.57	mm
Bunch length ($V_{RF}=5$ GV)	$\sigma_z \propto L$	1.84	2.78	3.68	mm

Transfer from linac to booster

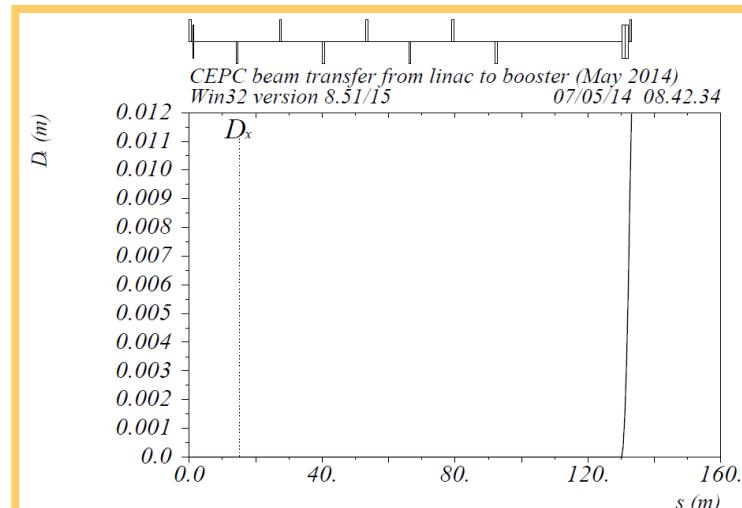
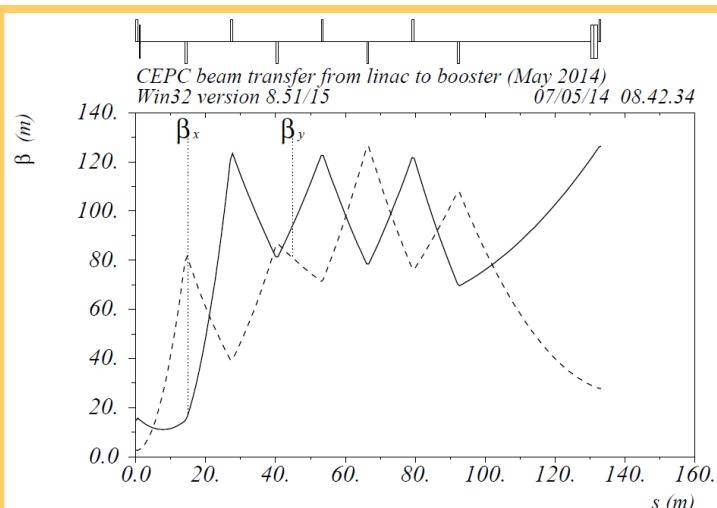


- Switch Yard Arcs
- Match to the Linac
- Match to the Booster
- Vertical slope line

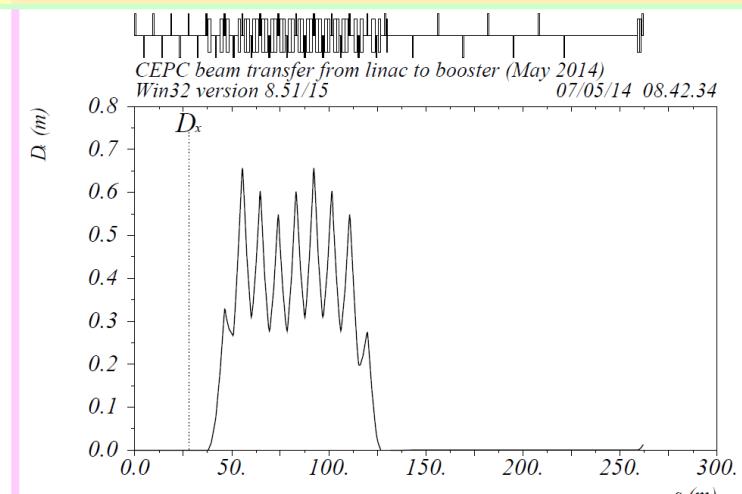
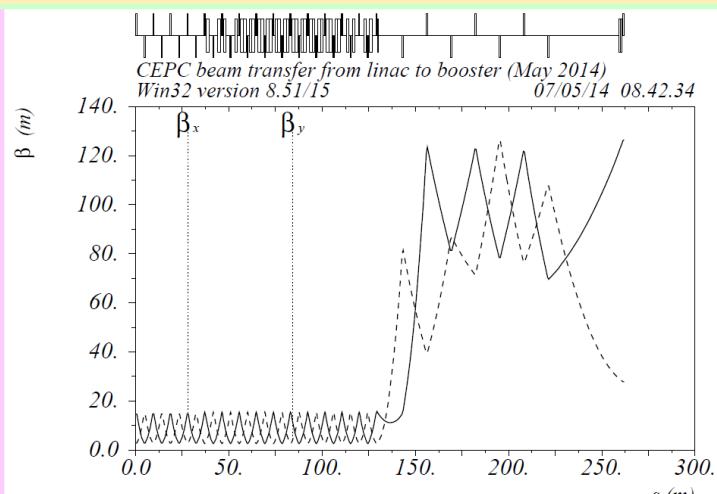
Vertical slope line (from surface to underground channel)



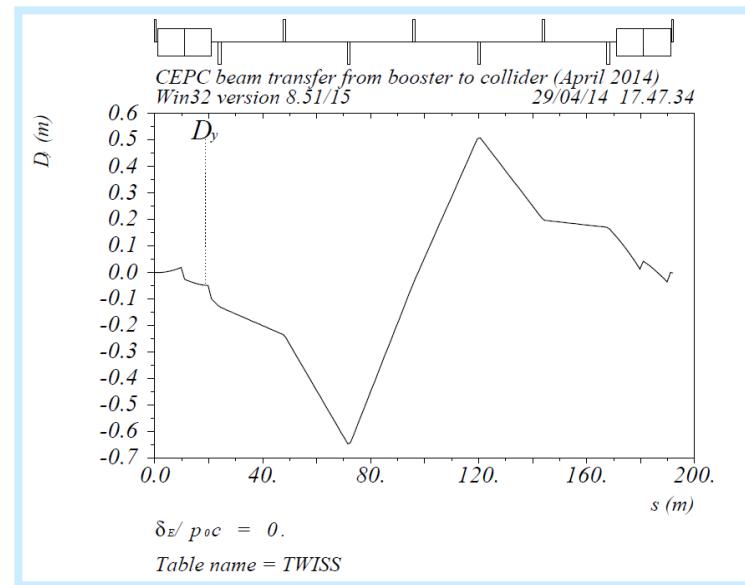
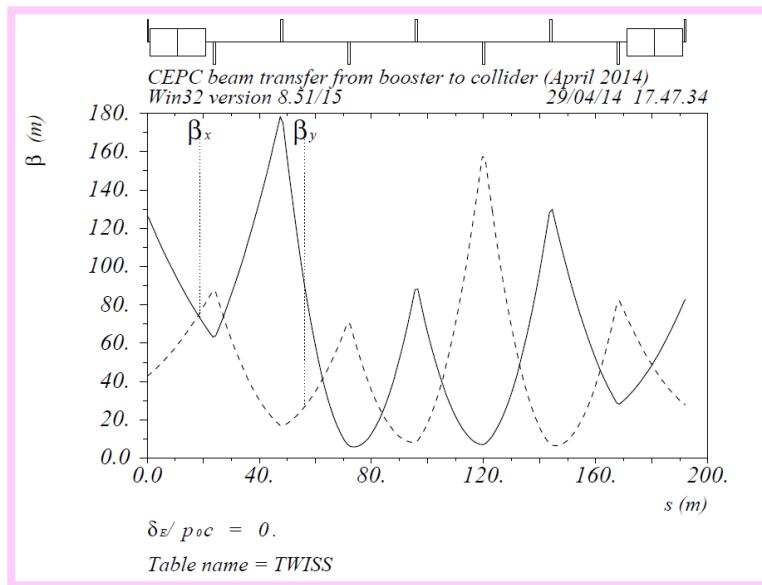
Match from linac to booster



$$\Delta\varepsilon_{\delta,x} \approx \beta_x^T (\delta D_x')^2 S_S = 127 \times (1 \times 10^{-3} \cdot 0.006)^2 = 4.6 \text{ nm}\cdot\text{rad} \ll \varepsilon_{x,L} \text{ of } 0.1 \text{ mm}\cdot\text{rad} \text{ from linac}$$



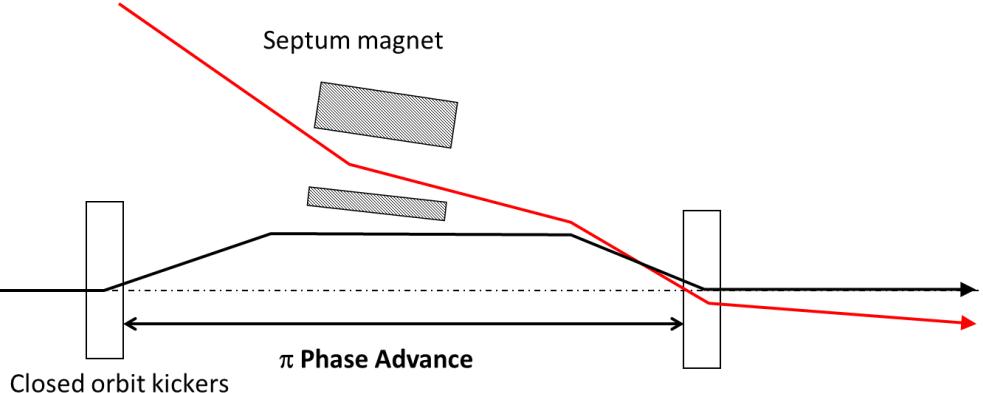
Transfer from booster to collider



CEPC Injection Scheme

1. Betatron Injection

2. Two Kicker Bumps

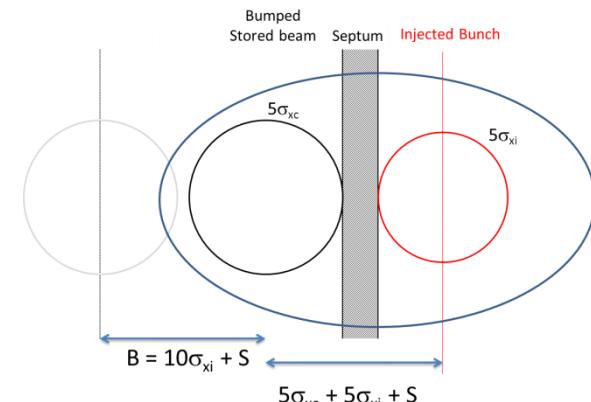


Kicker ramp up and down between bunches: ramping time < 1 μ m

50 bunches are injected one by one

$T_{\text{life}}(\text{s})$	Lum Drop	dN	$f_{\text{injection}}(\text{s})$
1800	10%	9E11	190s

For a bump height 10mm, angle_k1=2.3843e-004=**0.0137** deg
angle_k2=1.8426e-004=**0.0106** deg, septum x=**13.5** mm,
x'=-2.1846e-004=**-0.0125** deg.



Requirement on the Acceptance

Half length of the acceptance ellipase:

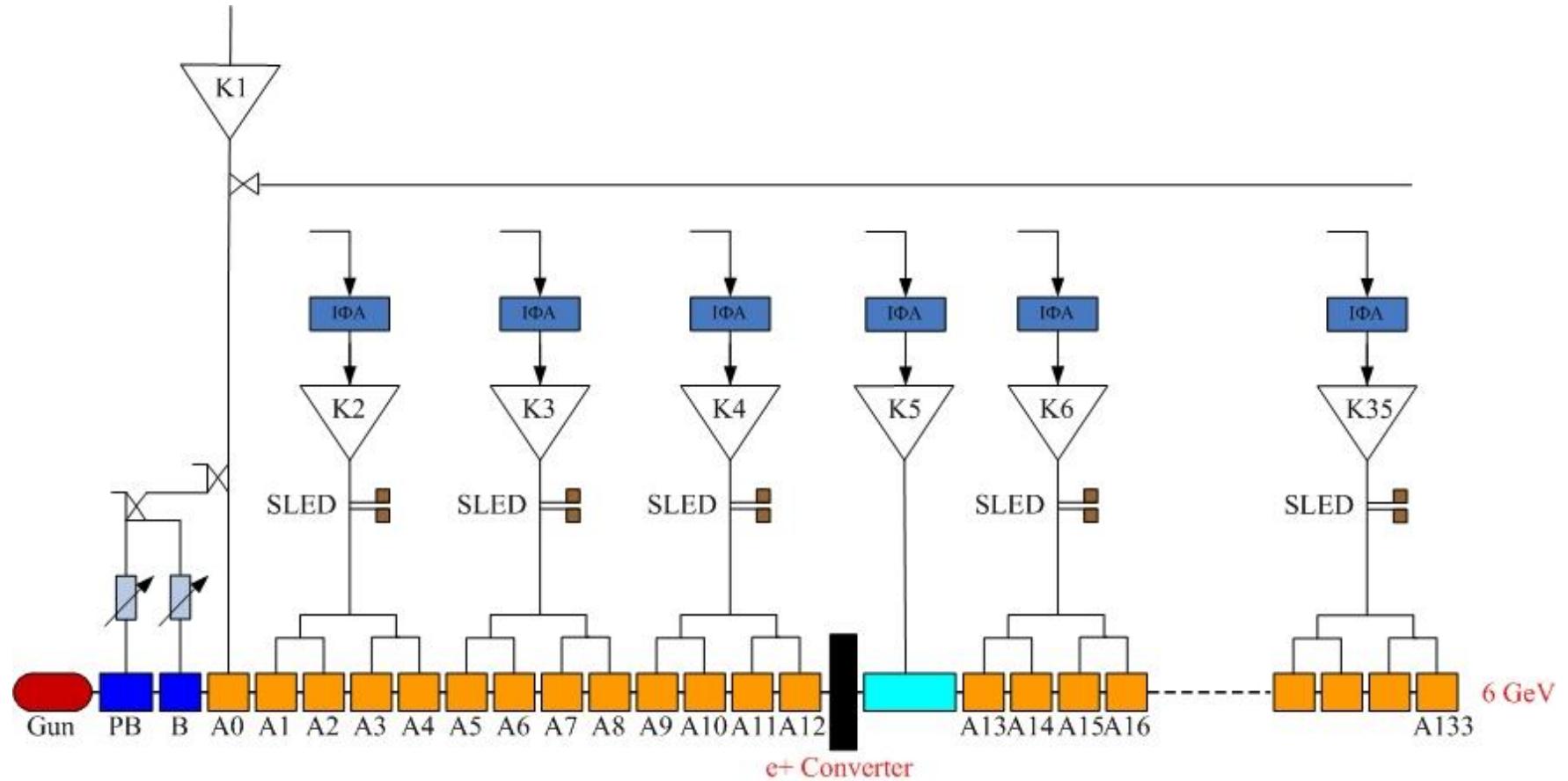
$$5\sigma_{xc} + 10\sigma_{xi} + S$$

$$\epsilon_x = 6.9 \times 10^{-9} \quad \epsilon_y = 2.1 \times 10^{-11}$$

$$S = 3 \text{ mm}, \text{Beta}_x = 100 \text{ m}$$

$$\sigma_x = 0.8 \text{ mm}, \sigma_y = 0.045 \text{ mm}$$

Injection linac



6GeV Conventional Linac (option I)

Option II is 6GeV 1.3GHz ILC type linac with XFEL usage

Injection linac

- Main parameters

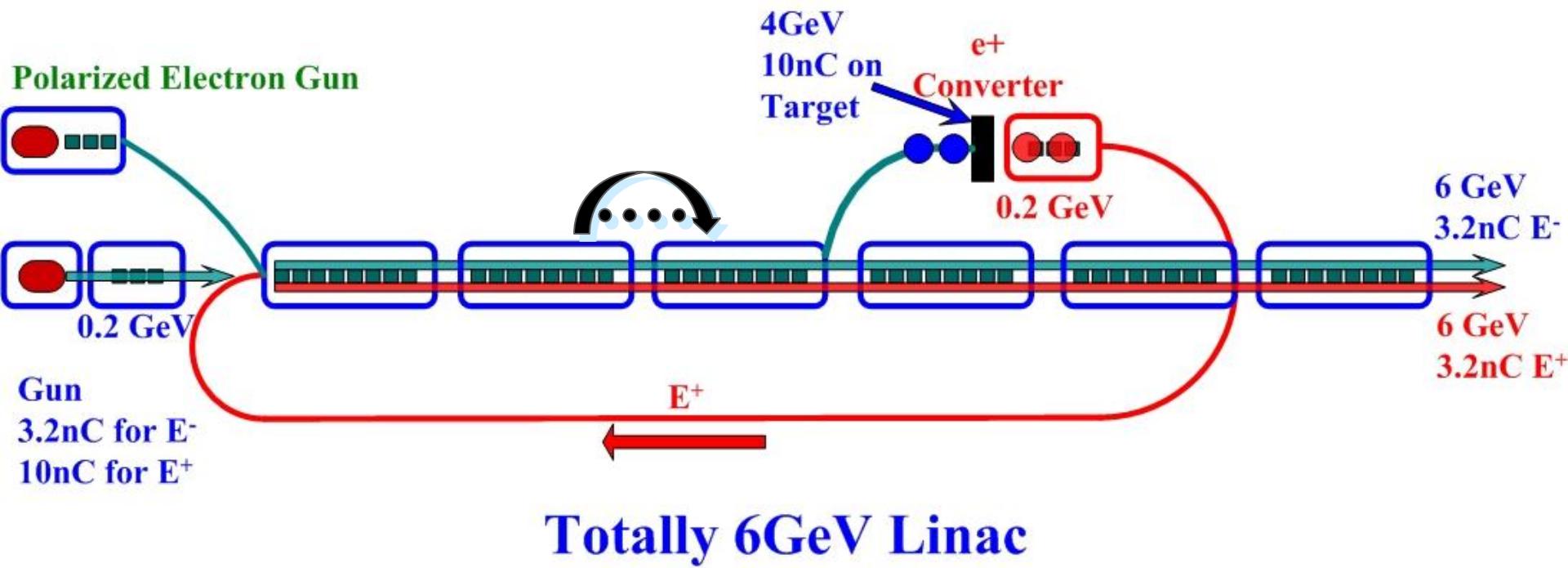
Parameter	Symbol	Unit	Value
E ⁻ beam energy	E_{e^-}	GeV	6
E ⁺ beam energy	E_{e^+}	GeV	6
Pulse width	Δt	ns	0.7
Repetition rate	f_{rep}	Hz	100
E ⁻ bunch population	N_{e^-}		2×10^{10}
E ⁺ bunch population	N_{e^+}		2×10^{10}
Energy spread (E ⁺ /E ⁻)	σ_E		<1 × 10 ⁻³

- Challenge

1. $N_{\text{bunch } e^+} = 2 \times 10^{10}$ 3.2nC/bunch e^+

2. *Polarization*

Injection linac



- Linac Frequency: 2856MHz Normal conducting
- Conventional Positron Source and a 0.2GeV Positron Beam Transport Line

Electron source

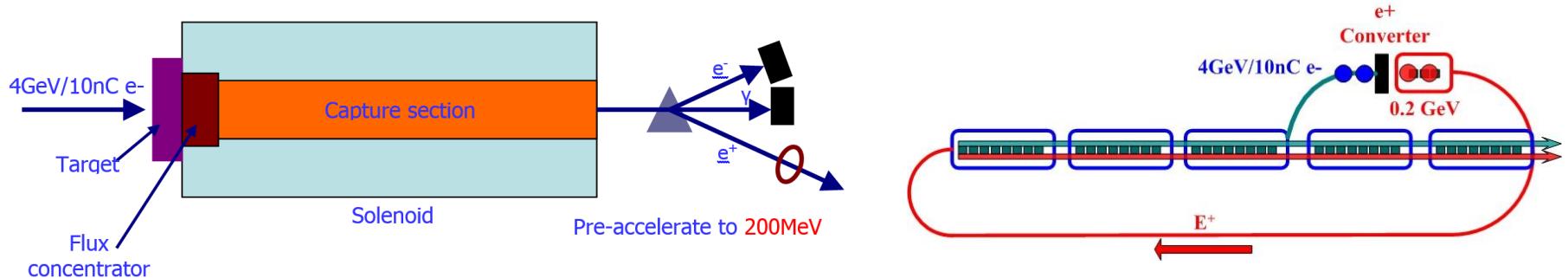
- **Unpolarized Electron Source (Baseline)**

Electron Gun			
Gun type	Thermionic Triode Gun		
Cathode	Y824 (Eimac) Dispenser		
Beam Current (max.)		A	10
High Voltage of Anode		kV	150-200
Bias Voltage of Grid		V	0 ~ -200
Pulse duration		ns	0.7
Repetition Rate		Hz	50~100

- **Polarized Electron Source (R&D)**
 1. R&D on a superlattice GaAs/GaAsP photocathode
 2. R&D on a (100kV-150kV) DC gun

Positron source

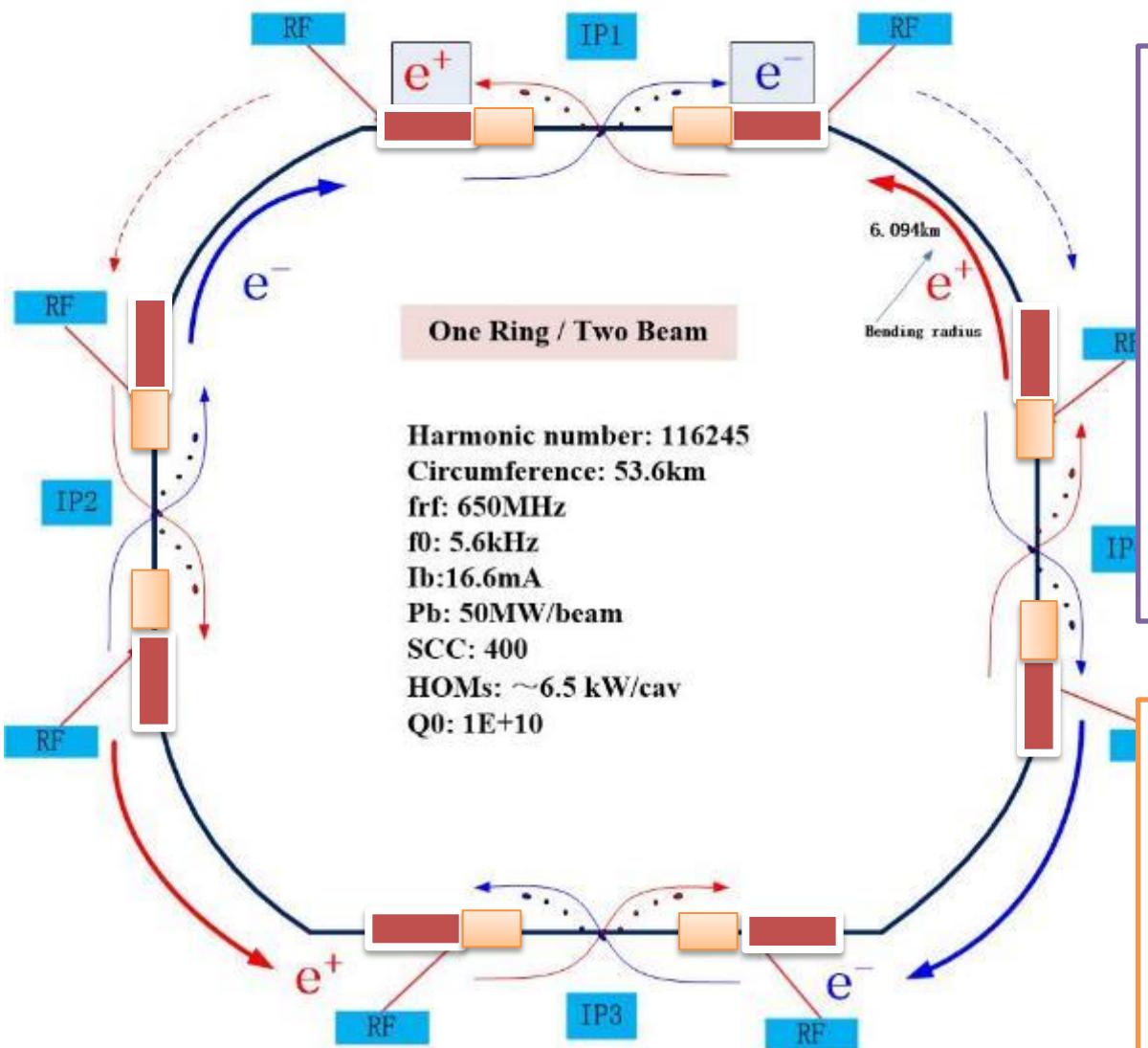
- Unpolarized Positron Source



Conventional Positron Source + 0.2Gev e^+ transport line

Positron source		
E ⁻ beam energy on the target	GeV	4
E ⁻ bunch charge on the target	nC	10
Target material	W-Re	
Target thickness	mm	14
E ⁺ Yield		
Focus device	Flux Concentrator	5Tesla
E ⁺ Energy pre-accelerate	MeV	200

CEPC SRF System Layout



8 RF sections
In each ~ 120m section

Main ring:

- 12 x 10m cryomodules
- 650 MHz 5-cell SRF cavity
- 4 cavities / cryomodule

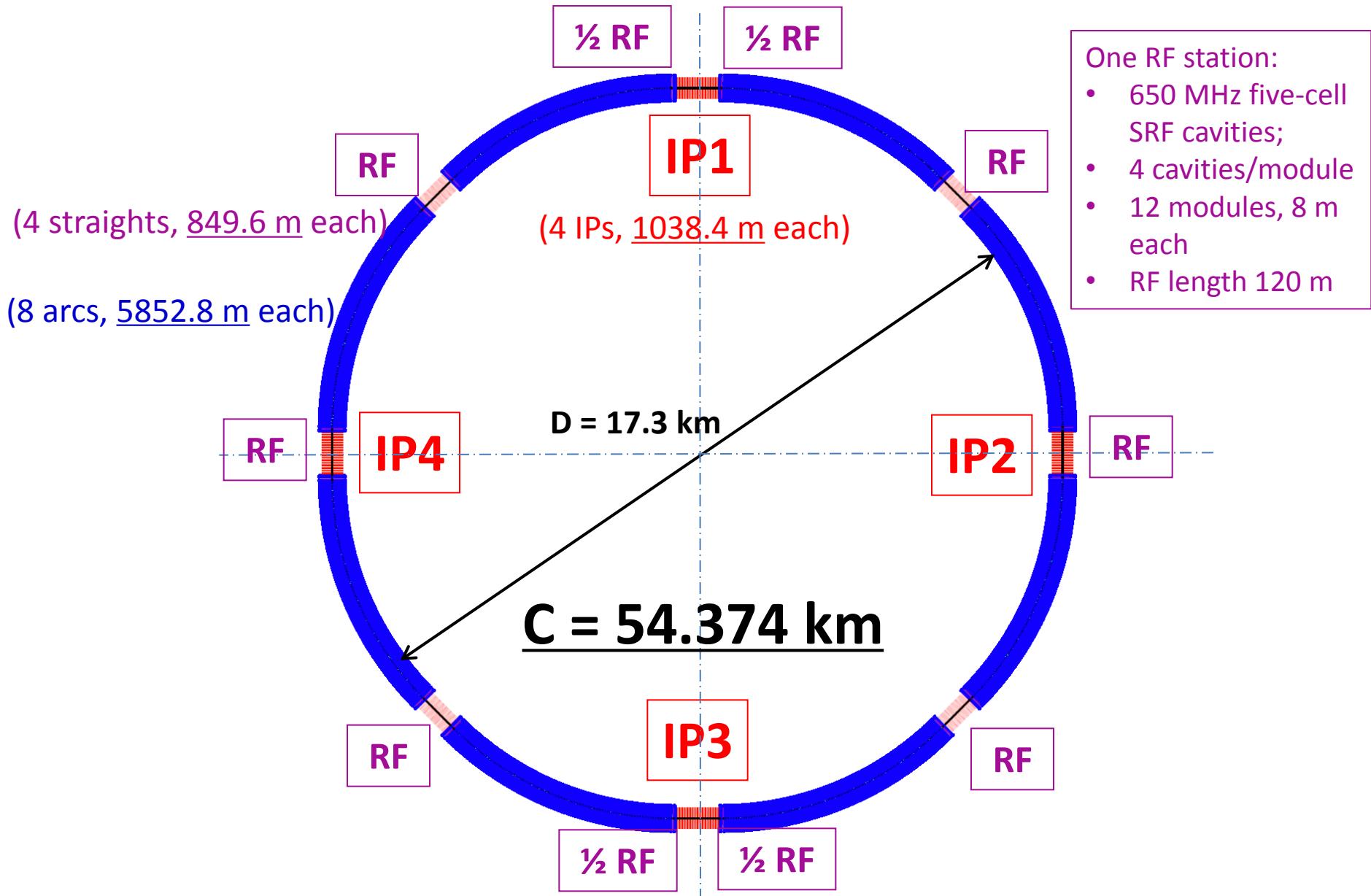
Booster:

- 4 x 12m cryomodules
- 1.3 GHz 9-cell SRF cavity
- 8 cavities / cryomodule

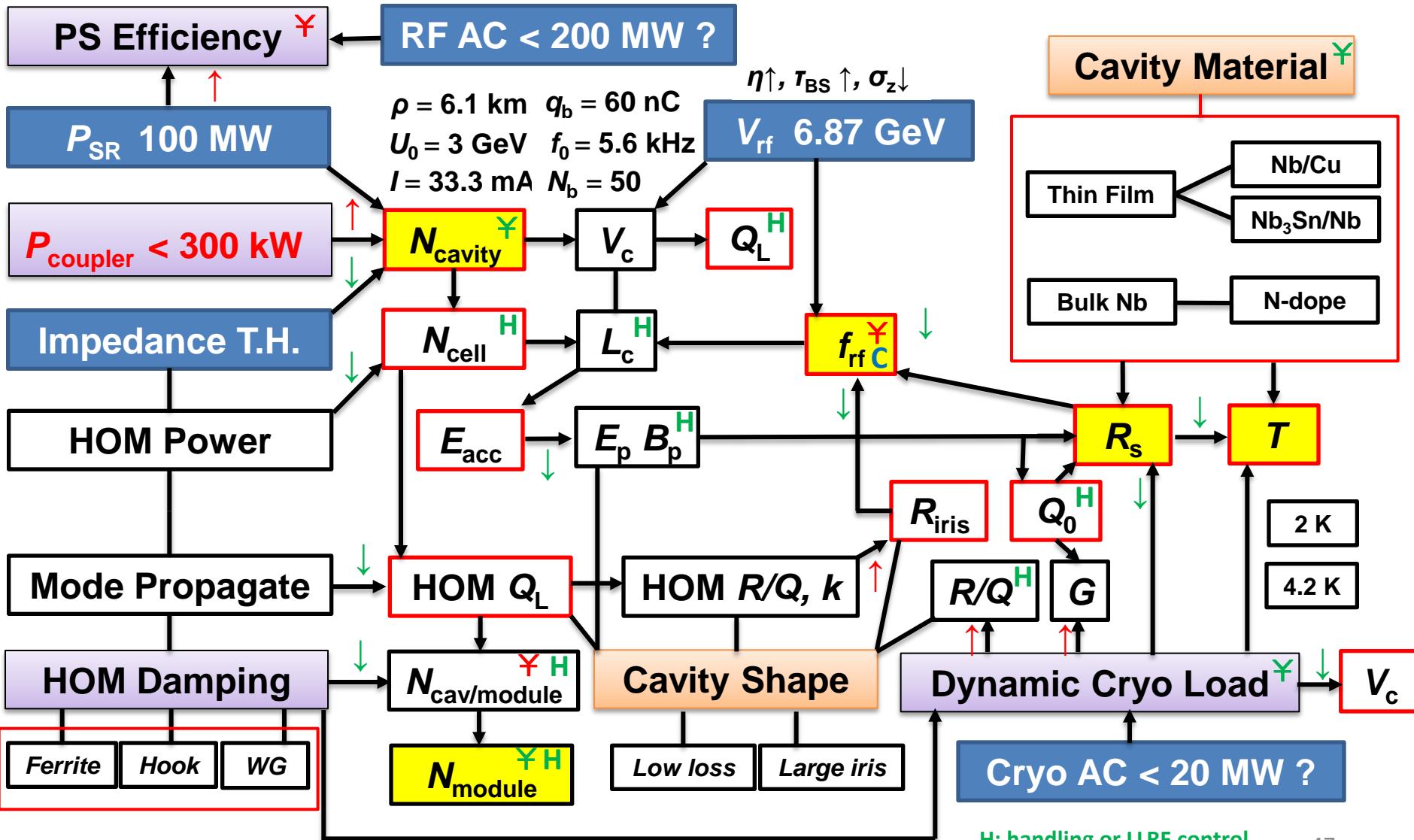
Superconducting RF Cavity

- ~ 20 x CW gradient
 - less disruption to beam
 - 100s times more efficient
 - LLRF benefits
- compared to normal conducting

CEPC Lattice Layout (September 23, 2014)



CEPC SRF System Design Criteria



CEPC SRF Cavity Parameters (v2-2014-09-21)

Parameter	Symbol	Unit	Main Ring	Booster
RF frequency	f_{RF}	MHz	650	1300
RF voltage	V_{RF}	GV	6.87	5.04
Operating gradient	E_{acc}	MV/m	15.5	19.0
Number of cells	N_{cell}	-	5	9
Effective length	L_{eff}	m	1.154	1.038
Operating voltage	V_c	MV	17.9	19.7
R/Q	R/Q	Ω	514	1036
Geometry factor	G	Ω	268	270
Operating temperature	T	K	2	2
Quality factor at operating gradient	Q_0	-	2E+10	2E+10
Duty factor	DF	-	100%	22%*
HOM 2K cw heat load per cavity	W_{HOM2K}	W	6.5	0.15
HOM 5K cw heat load per cavity	W_{HOM5K}	W	19.5	0.3
HOM 80K cw heat load per cavity	W_{HOM80K}	W	195	14.55
External Q of input coupler	Q_{ext}	-	2.4E+06	1E+07
RF power per cavity	P_{in}	kW	260	20
Number of cavities	N_{CV}	-	384	256
Cavities in one cryomodule	$N_{\text{CV/CM}}$	-	4	8
Cryomodule length	L_{CM}	m	10	12
Number of cryomodules	N_{CM}	-	96	32
Cryomodules per RF section	$N_{\text{CM/RFS}}$	-	12	4

* Duty factor of the booster dynamic cryogenic heat load in 6 s for electron or positron (1 s 6 GeV injection from linac to booster, 4 s linear ramping to 120 GeV of booster RF voltage, and 1 s full energy ejection to main ring). The duty factor is 5.2 % in the whole 90 s injection period (first electron and then positron) if the cryogenic response is slow enough. For injection to main ring from zero current, the duty factor is 7.8 %.

SRF parameters of CEPC

	units	Main Ring	Booster
fRF	MHz	650	1300
U0 (single beam)	GeV	3	3
Beam current of e-&e+	mA	$2*16=32$	0.9
Total beam power (SR)	MW	100	2.7
total RF voltage	GV	7	6
Eacc	MV/m	8.8	15
cavity cells		5	9
cavity numbers		720	320
Input power per cavity	kW	139	20
Total RF power	MW	100	6.4
LLRF station numbers		720	320
Cryo module numbers		180 (4cav/ module)	40

Another key R&D collaboration item is on CEPC SRF systems, both for main ring and for booster

SRF selections of CEPC

parameters	CEPC –4.5K	CEPC—2K	LEP-2 4.5K
5cell SCC	720 sputtered?	400 Bulk Nb	4cell 288 sputtered
Eacc MV/m	9	15	6 / 7.5
Q0	1E+9	1E+10	3.2E+9
R/Q	500	500	400
Vc/cav (MV)	9.72	17.5	12
Pc/cav (W)	189	61.3	70.1
Heat (kW)	209*720=150.5	81.3*400=32.5	92.5*288=26.64
Total cryo power (MW)	150.5*230=34.6	32.5*900=29.3	26.64*230=6.13
Number Cryo. module	180	100	72
RF input power (kW)	139kW/cav	250kW/cav ?	125kW/cav
Number of SSA	720	400	--
Number of klystron	180*(700kw/4cav)	100*(1.2Mw/4cav)	36*(1200kw/8cav)
Power supply (MW)	222+35 / 182+35	222+29 / 182+29	79+6
HOM (hook/ferrite) W	500?/6500	500?/6500	500?

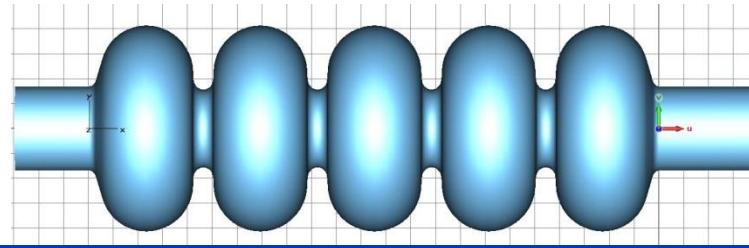
HOM damper

	units	LEP-2	CEPC	CEPC hook
E0	GeV	104.5	120	120
circuference	km	26.7	53.6	53.6
fRF	MHz	352.2	650	650
U0 (single beam)	GeV		3	3
Beam current of e-&e+	mA		32	2*16
Total beam power (SR)	MW		100	100
total RF voltage	GV	3.6	6.7	7
Eacc	MV/m	6	20	8.8
cavity cells		4	5	5
cavity numbers		288 sc+56 cu	400 bulk	720 sputtered
Input power per cavity	kW	125	250	139
Total RF power	MW	40	100	100
P(HOM)/cav.	W	500?	6500	500 ?
Cryostat module numbers		72 (4cavities/ module)	200	180

SRF of booster of CEPC

parameters	CEPC –4.5K	CEPC—booster2K	LEP-2 4.5K
9cell SCC	720 sputtered?	320 Bulk Nb	4cell 288 sputtered
Eacc MV/m	9	20	6 / 7.5
Q0	1E+9	2E+10	3.2E+9
R/Q	500	900	400
Vc/cav (MV)	9.72	20.9	12
Pc/cav (W)	189	24.4	70.1
Heat (kW)	209*720=150.5	44.4*320=14.2	92.5*288=26.64
Total cryo power (MW)	150.5*230=34.6	14.2*900=12.8	26.64*230=6.13
Number Cryo. module	180	40	72
RF input power (kW)	139kW/cav	20kW/cav ?	125kW/cav
Number of SSA	720	--	--
Number of klystron	180*(700kw/4cav)	40*(160kw/8cav)	36*(1200kw/8cav)
Power supply (MW)	222+35 / 182+35	1.2*6.4+12.8=20.5	79+6
HOM (hook/ferrite) W	500?/6500	100?	500?

Cavity Design



Frequency(MHz)	f_{RF}	650
Gradient(MV/m)	E_{acc}	15MV/m
Operating voltage	V_c	17.18MV
Cell NO.	N_{cell}	5
Effective length	L_c	1153mm
Cavity NO.	N_{cav}	400
Module length(m)	L_{module}	3.053
Module NO. (1 cavities/ module)	N_{module}	400
R/Q(Ω)	R/Q	506
Quality factor (2K)	Q_0	$Q_0=2*10^{10}$
RF coupler Q_{ext}	Q_{ext}	$2.33*10^6$

Parameters Related to RF System

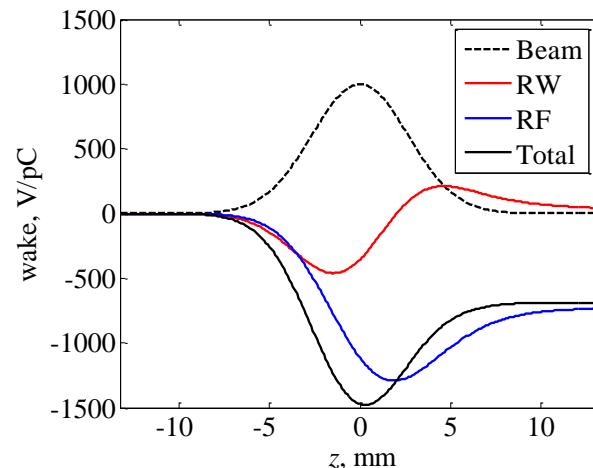
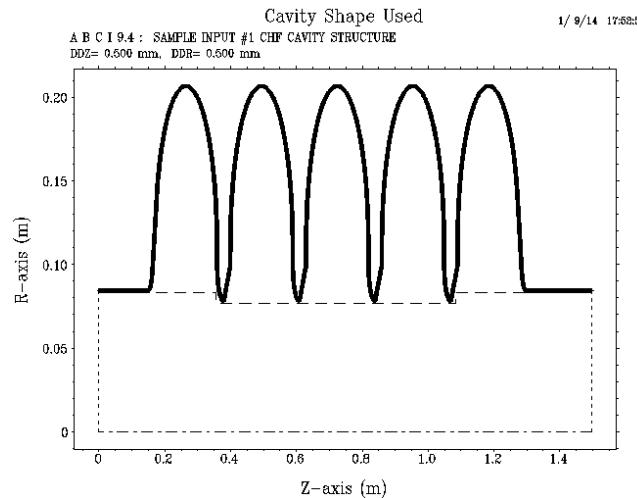
Frequency(MHz)	f_{RF}	650
Voltage(GV)	V_{RF}	6.87
SR power(MW)	P_{SR}	100
Power/cavity (kW)	P_0	250
Operating temperature(K)	T	2
Quality factor (2K)	Q_0	$Q_0=2*10^{10}$
2K heat load(kW)	W_{2K}	19.05
5K heat load (kW)	W_{5K}	37.97
80 K heat load (kW)	W_{80K}	189.85
Total Cryogenic AC power(MW)	$W_{cyo.}$	29
Total AC power(MW warm absorber)	W_{AC}	251

In order to extract the large number of HOM power: 1 cavity/module.
HOM damper at room temperature (6.5 kW/cavity);

Impedance budget

- Resistive wall impedance is calculated with analytical formulas
- Impedance of the RF cavities is calculated with ABCI

Object	Contributions			
	R [kΩ]	L [nH]	k _{loss} [V/pC]	Z _{//} /n _{eff} [Ω]
Resistive wall (Al)	6.6	87.1	210.9	0.0031
RF cavities (N=378)	29.3	--	931.2	---
Total	35.9	87.1	1142.1	0.0031



$$W(s) = -Rc\lambda(s) - Lc^2\lambda'(s)$$

Single-bunch effects

Parameter	Symbol, unit	Value
Beam energy	E , GeV	120
Circumference	C , km	53.6
Beam current	I_0 , mA	16.6
Bunch number	n_b	50
Natural bunch length	σ_{l0} , mm	2.66
Emittance (horz./vert.)	$\varepsilon_x/\varepsilon_y$, nm	6.79/0.02
RF frequency	f_{rf} , GHz	0.65
Harmonic number	h	116245
Natural energy spread	σ_{e0}	1.5E-3
Momentum compaction factor	α_p	4.15E-5
Betatron tune	ν_x/ν_y	179.08/179.22
Synchrotron tune	ν_s	0.199
Damping time (H/V/s)	$\tau_x/\tau_y/\tau_z$, ms	14/14/7

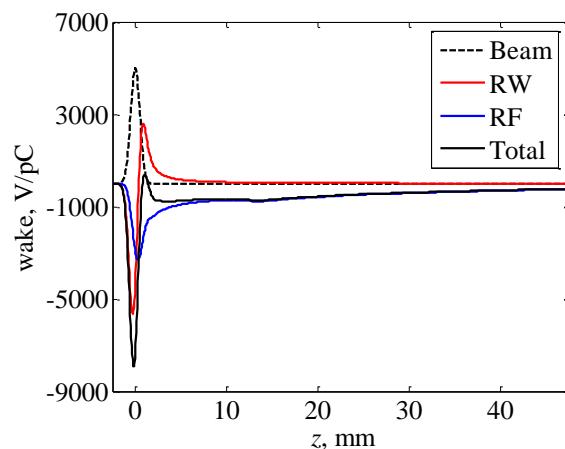
- **Longitudinal microwave instability**

- Keil-Schnell criterion:
- The threshold of the longitudinal impedance is $|Z_{||}/n| < 0.026 \Omega$.

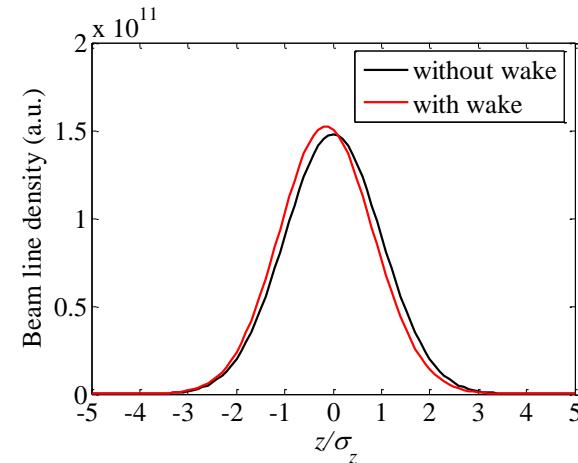
$$I_{th} = \frac{\sqrt{2\pi}\alpha_p \frac{E}{e} \sigma_{e0}^2 \sigma_l}{R \left| \frac{Z}{n} \right|_{eff}}$$

- **Bunch lengthening**

- Steady-state bunch shape is obtained by Haissinski equation
- Bunch is shortened due to the capacitive impedance of the RF cavity(**only resistive wall and RF cavity considered**)



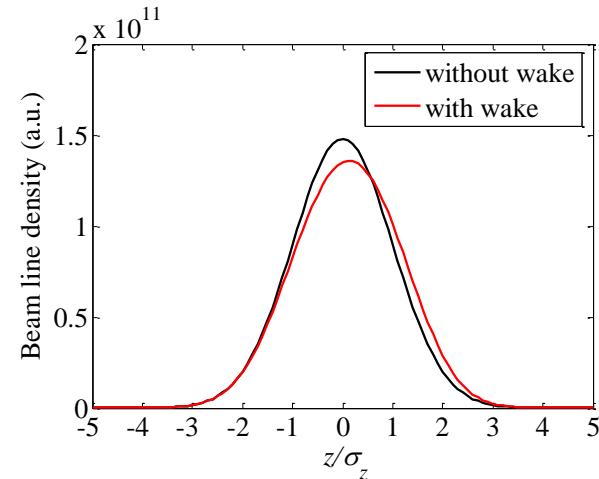
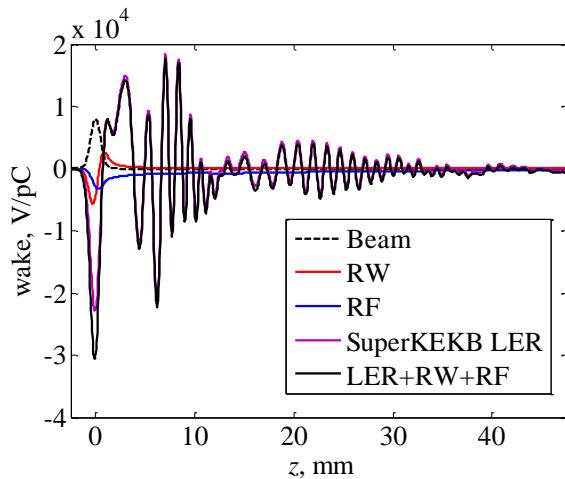
Pseudo-Green function wake ($\sigma_z=0.5\text{mm}$)



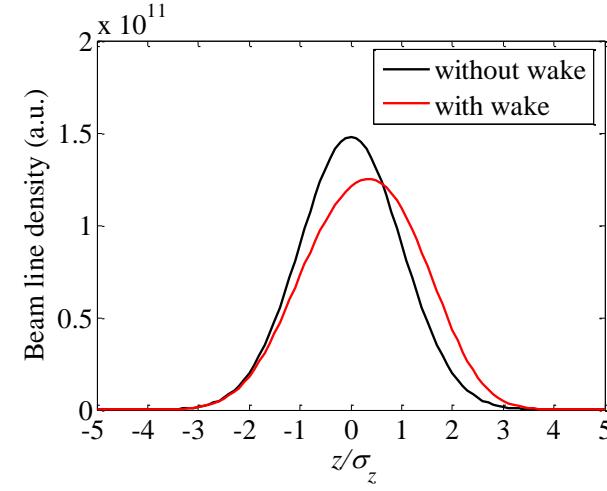
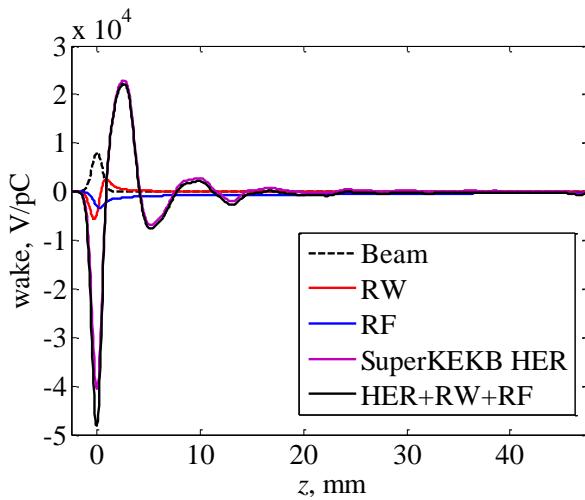
Steady-state bunch shape

- **Bunch lengthening with SuperKEKB's geometry wake**

- LER wake+RW+RF (bunch is lengthened by 9.0%)



- HER wake+RW+RF (bunch is lengthened by 18.5%)



- **Coherent synchrotron radiation**

(K. Bane, Y. Cai, G. Stupakov, PRST-AB, 2010)

- $\sigma_z \rho^{1/2} / h^{3/2} = 9.2$ (\Rightarrow CSR shielded)
- The threshold of bunch population for CSR is given by

$$S^{\text{th}} = 0.50 + 0.12\Pi \quad S = \frac{r_e N_b \rho^{1/3}}{2\pi\nu_s \gamma \sigma_\delta \sigma_z^{4/3}}, \quad \Pi = \frac{\sigma_z \rho^{1/2}}{h^{3/2}}$$

- The CSR threshold in BAPS is $N_{b,\text{Th}} = 5.0 \times 10^{12} \gg N_b = 3.7 \times 10^{11}$.
- CSR is not supposed to be a problem in BAPS.

- **Space charge tune shift**

$$\Delta\nu_{x,y} = -\frac{r_e N_b}{(2\pi)^{3/2} \gamma^3 \sigma_z} \oint \frac{\beta_{x,y}(s)}{\sigma_{x,y}(s)(\sigma_x(s) + \sigma_y(s))} ds$$

$$\Delta\nu_y = -1.7e-4, \quad \Delta\nu_x = -5.0e-6$$

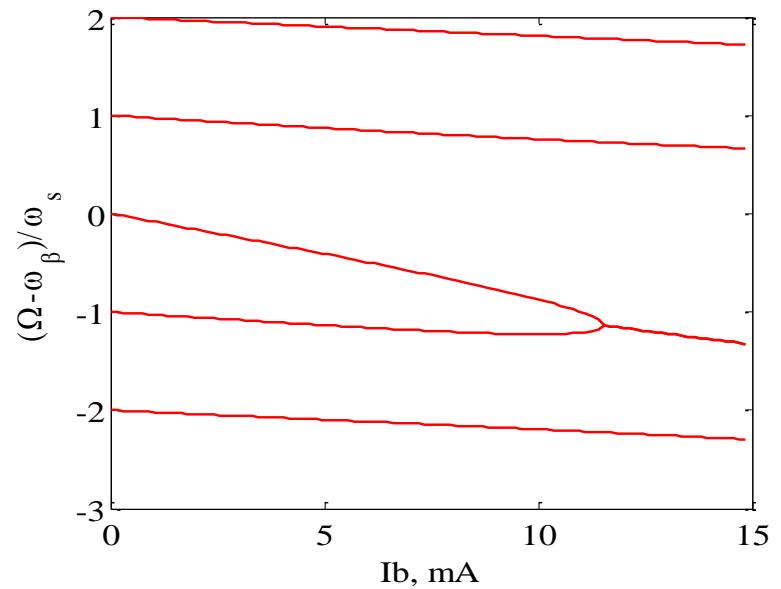
- **Transverse mode coupling instability (TMCI)**

$$|Z_{\perp}| \leq \frac{4\nu_s E b}{e I_b R < \beta_{\perp} >}$$

- The threshold of transverse impedance is $|Z_{\perp}| < 28.3 \text{ M}\Omega/\text{m}$.
- The equivalent longitudinal impedance is 2.66Ω , which is much larger than that of the longitudinal instability.

- **Eigen mode analysis**

- Considering only resistive wall impedance
- Beam current threshold:
 $I_b^{\text{th}} = 11.6 \text{ mA}$ ($I_0^{\text{th}} = 578 \text{ mA}$)



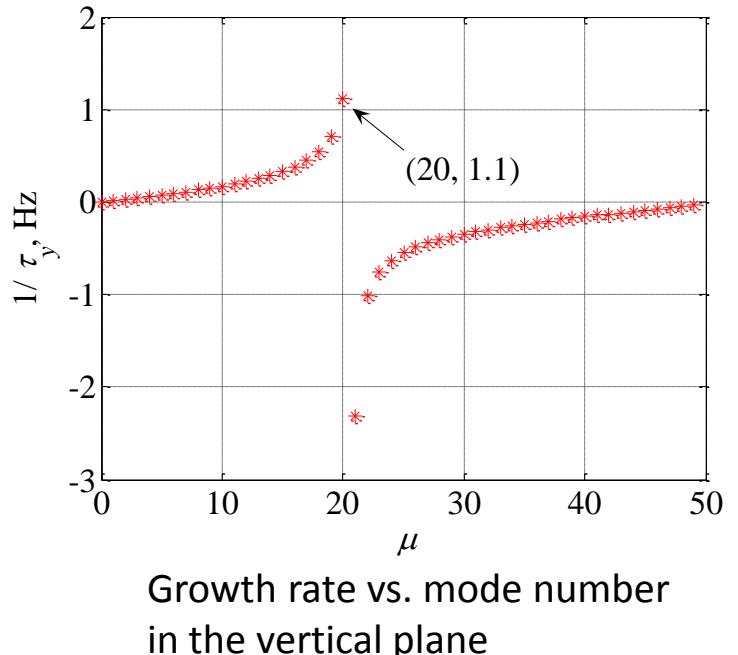
Multi-bunch effects

- Transverse resistive wall instability

$$\frac{1}{\tau_{\perp}} = - \frac{n_b I_b c}{4\pi(E/e)v_{x,y}} \sum_{p=-\infty}^{\infty} e^{-(\omega_{pn} - \xi\omega_0/\alpha_p)^2 \sigma_{\tau}^2} \operatorname{Re} Z_{\perp}(\omega_{pn})$$

with $\omega_{pn} = 2\pi f_{rev} \times (pn_b + n + v_{x,y})$

- The growth rate for the most dangerous instability mode is **1.1 Hz ($\tau=0.9$ s)** in the vertical plane with mode number of **$\mu = 20$** .
- The growth time is much higher than the transverse radiation damping time.
- The resistive wall instability is not supposed to happen in the main ring!



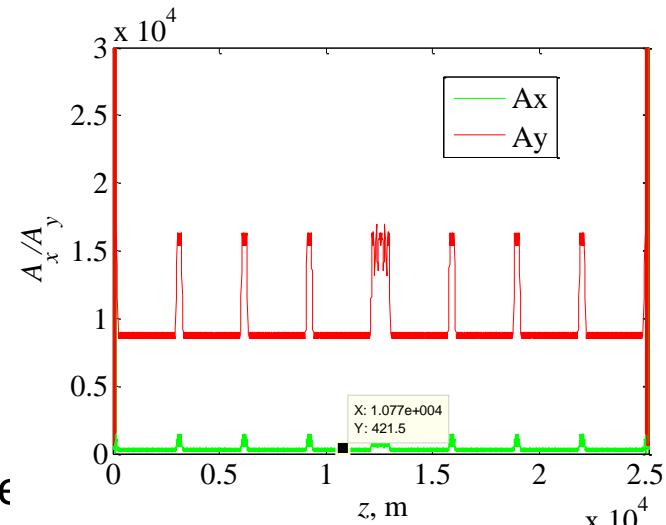
Electron cloud instability

	KEKB	SuperKEKB	SuperB	CEPC
Beam energy E , GeV	3.5	4.0	6.7	120
Circumference L , m	3016	3016	1370	53600
Number of e^+ /bunch, 10^{10}	3.3	9	5.74	37.1
Emittance H/V $\varepsilon_x/\varepsilon_y$, nm	18/0.36	3.2/0.01	1.6/0.004	6.79/0.02
Bunch length σ_z , mm	4	6	5	2.66
Bunch space Lsp, ns	2	4	4	3575.8
Single bunch effect				
Electron freq. $\omega_e/2\pi$, GHz	35.1	150	272	183.9
Phase angle $\omega_e \sigma_z/c$	2.94	18.8	28.5	10.3
Threshold density $\rho_{e,\text{th}}$, 10^{12}m^{-3}	0.7	0.27	0.4	1.1
Multi-bunch effect				
p-e per meter n_γ , p/(m)	5.0E8	1.5E9	3.6E9	1.1E10
Characteristic frequency ω_G , MHz	62.8	87.2	69.6	5.9
Phase angle $\omega_G L_{\text{sp}}/c$	0.13	0.35	0.28	21.2

- Threshold density for the single bunch effect is considerable high.
- The phase angle for the multi-bunch effect is about two orders higher, so the electrons are not supposed to accumulate and the multipacting effects is low.⁶²

Beam ion instability

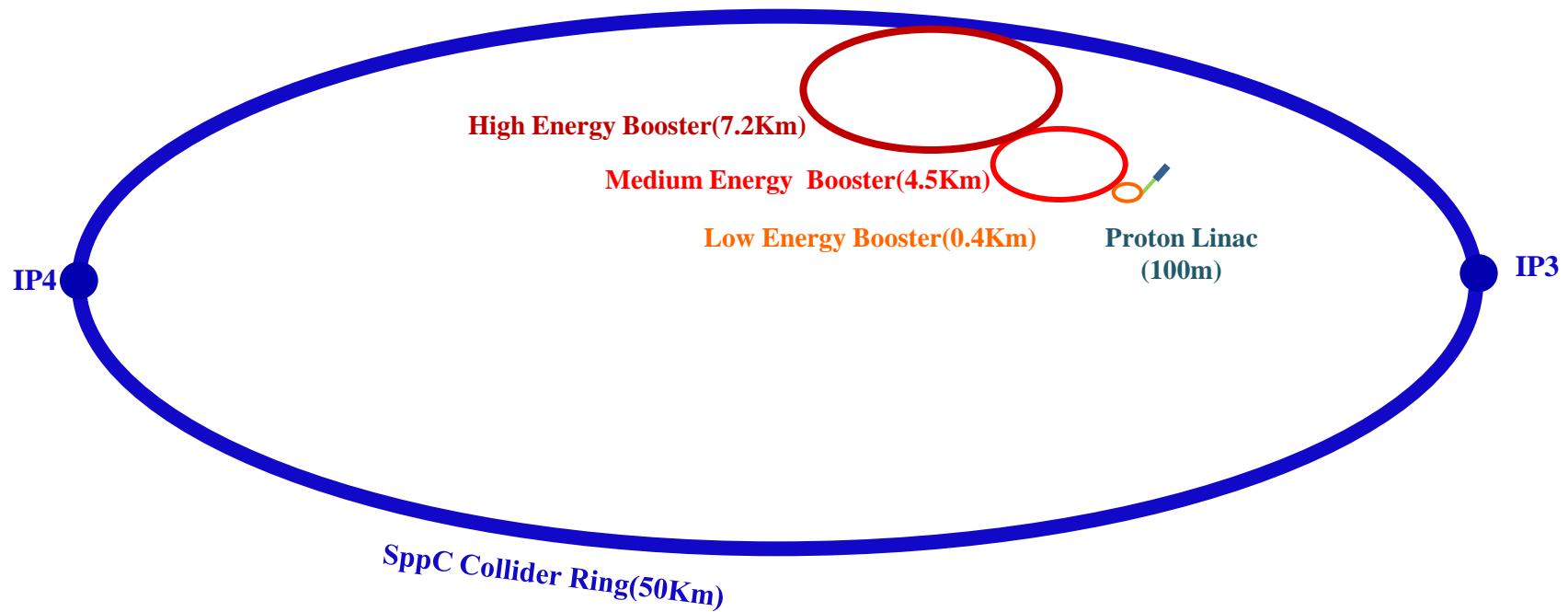
- Ion trapping
 - With uniform filling pattern, the ions with a relative molecular mass larger than $A_{x,y}$ will be trapped.
 - The ions will not be trapped by the beam.
- Fast beam ion instability
 - With uniform filling, the growth time frequency spread is 6.9ms, which is lower than the damping time.
 - Fast beam ion instability could occur with uniform filling.



$$\tau_{inst}^{-1} [s^{-1}] = 5 p [\text{Torr}] \frac{N_b^{3/2} n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{\gamma \sigma_y^{3/2} (\sigma_x + \sigma_y)^{3/2} A^{1/2} \omega_\beta}$$

$$\tau_{inst}'^{-1} = \tau_{inst}^{-1} \frac{c}{2\sqrt{2} L_{sep} n_B \Delta \omega_{ions}}$$

SppC Layout



SppC main parameters

Parameter	Value	Unit
Circumference	52	km
Beam energy	35	TeV
Dipole field	20	T
Injection energy	2.1	TeV
Number of IPs	2 (4)	
Peak luminosity per IP	1.2E+35	cm ⁻² s ⁻¹
Beta function at collision	0.75	m
Circulating beam current	1.0	A
Max beam-beam tune shift per IP	0.006	
Bunch separation	25	ns
Bunch population	2.0E+11	
SR heat load @arc dipole (per aperture)	56	W/m

Beam-beam tune shift limit analytical calculations

For hadron collider:

$$\xi_{\max} = \frac{2845\gamma}{f(x)} \sqrt{\frac{r_p}{6\pi R N_{IP}}} \quad r_p \text{ is proton radius}$$

where

$$f(x) = 1 - \frac{2}{\sqrt{2\pi}} \int_0^x \exp\left(-\frac{t^2}{2}\right) dt$$

$$x^2 = \frac{4f(x)}{\pi\xi_{\max} N_{IP}} = \frac{4f^2(x)}{2845\gamma} \sqrt{\frac{6\pi R}{r_p N_{IP}}} \quad \left. \right\}$$

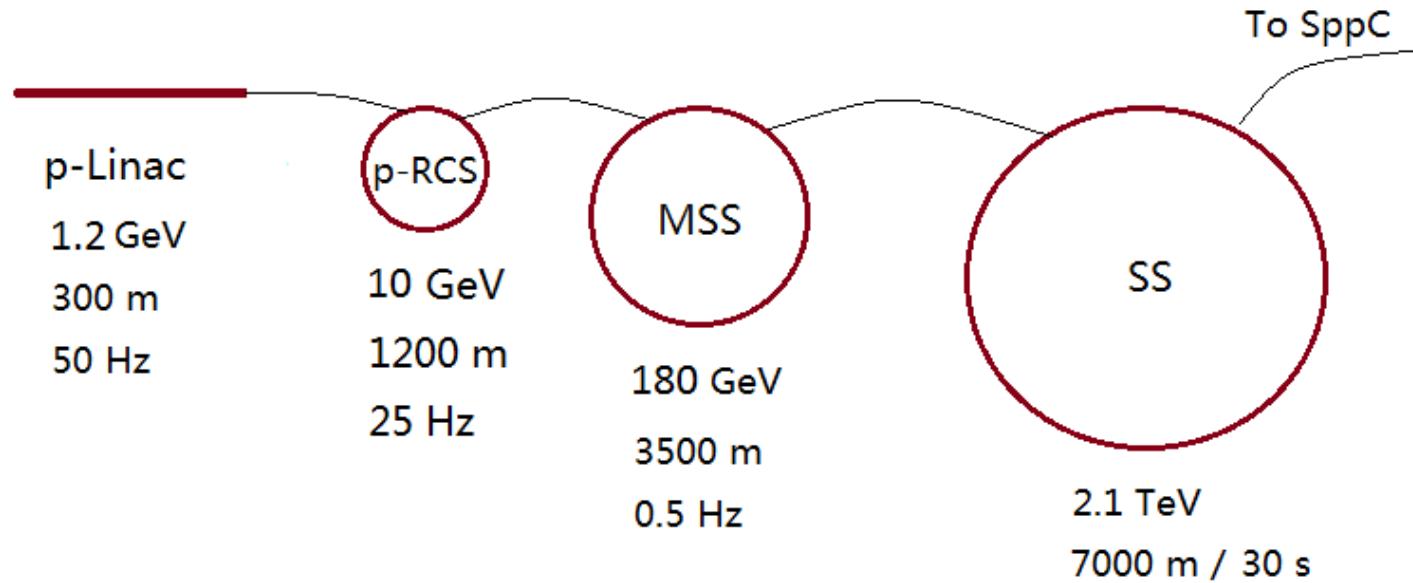
SppC (actual parameter list)

$$\begin{cases} x = 2.03656 \\ f(x) = 0.0417 \\ \xi_{\max} = 0.0064 \end{cases}$$

FCC (pp) 0.005 (theory and design)

Formulae from private note of J. Gao

Injector chain (for proton beam)



p-Linac: proton superconducting linac

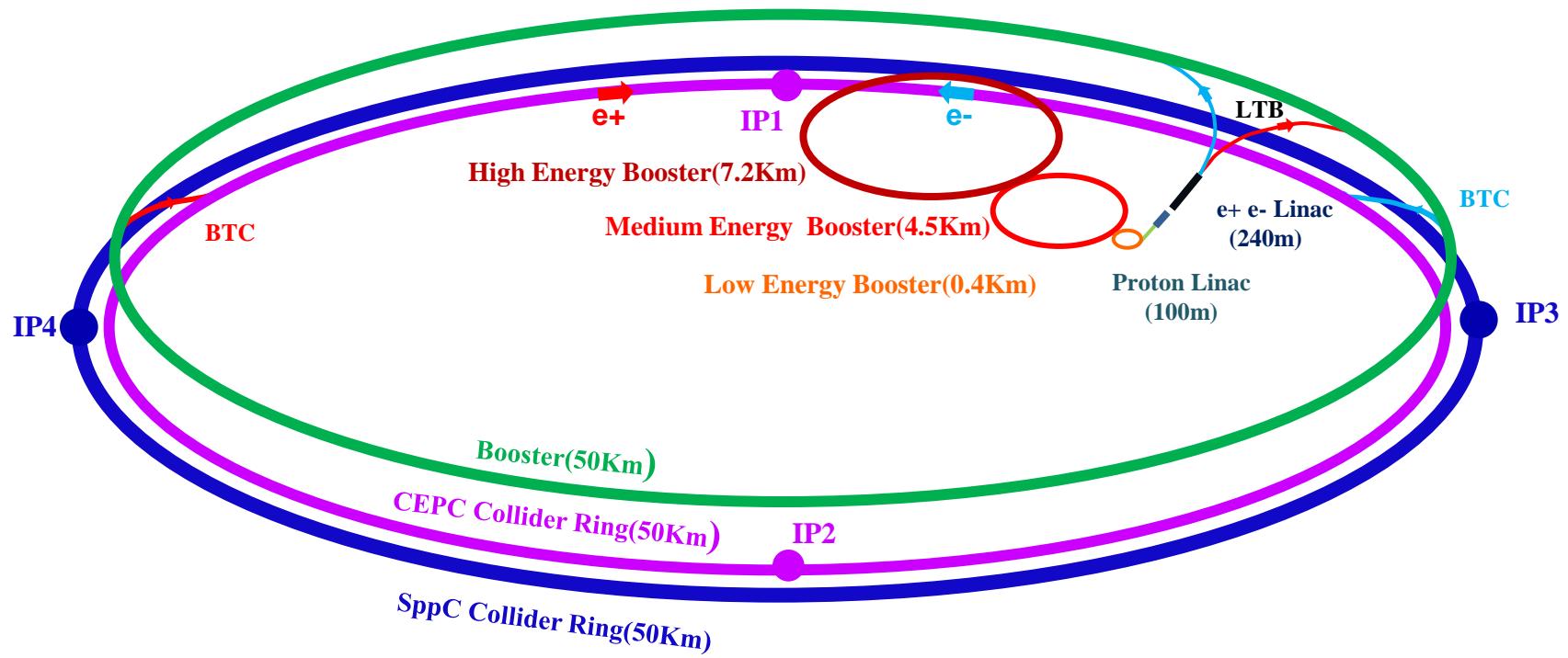
p-RCS: proton rapid cycling synchrotron

MSS: Medium-Stage Synchrotron

SS: Super Synchrotron

Ion beams have
dedicated linac (I-Linac)
and RCS (I-RCS)

CEPC+SppC Layout

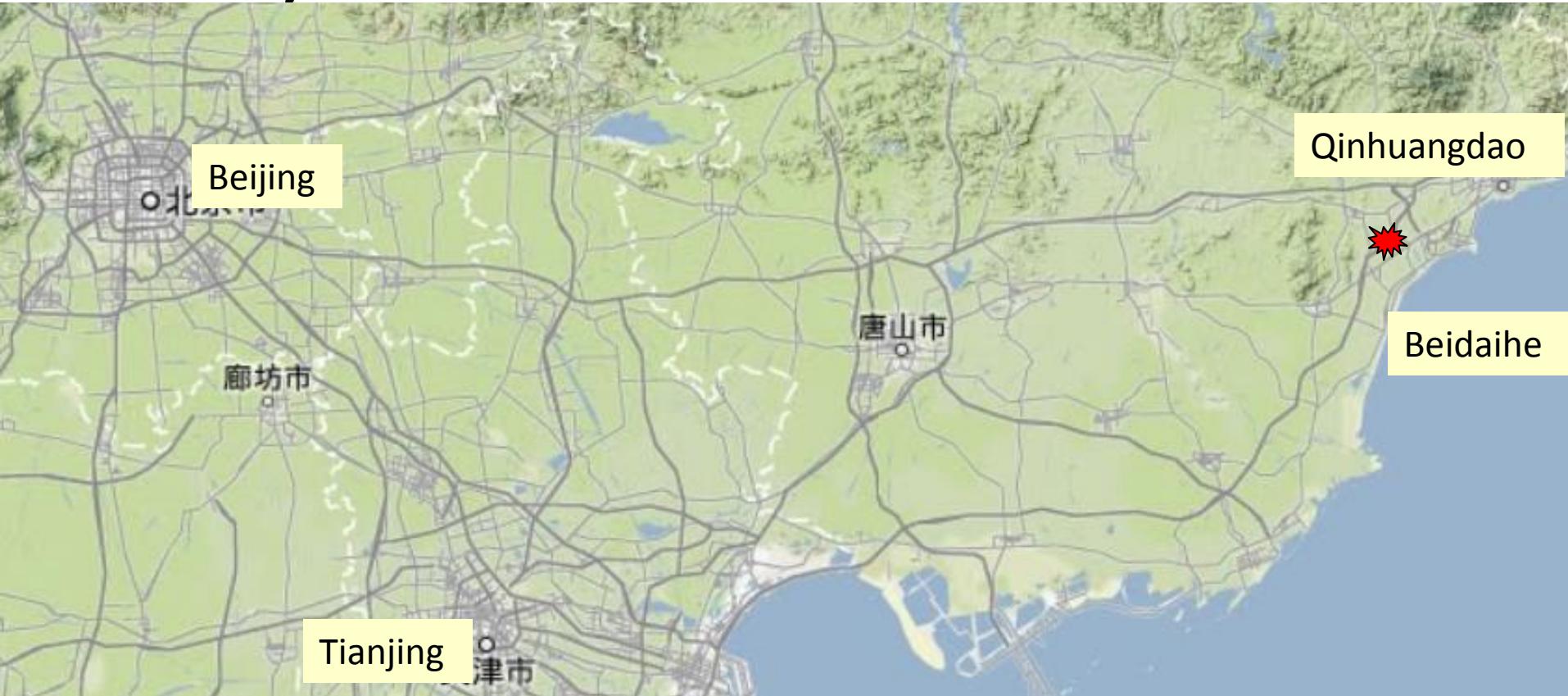


LTB : Linac to Booster

BTC : Booster to Collider Ring

Possible site (example)

- 300 km from Beijing
- 3 h by car
- 1 h by train



CEPC/SppC Siting (example)

- Preliminary selected Qinhuangdao (秦皇岛) (one of the candidate sites)
- Strong support by the local government



Good geological condition

- Base rock type: granite
- Base rock depth: 0.5 - 2 m
- Earth quake: no more than 7 , 0.10g
- Earth vibration(RMS, nm):



	Zhangjiakou	Huailai	Qinhuangdao	Tianjing	Huai rou
1~100hz	~12	~40	~1.9	~470	~60
4~100hz	~7	~14	~0.8	~24	

Building the tunnel in granite will have lowest cost

High Energy Accelerators Comparisons

LHC

CEPC-SppC

Tevatron

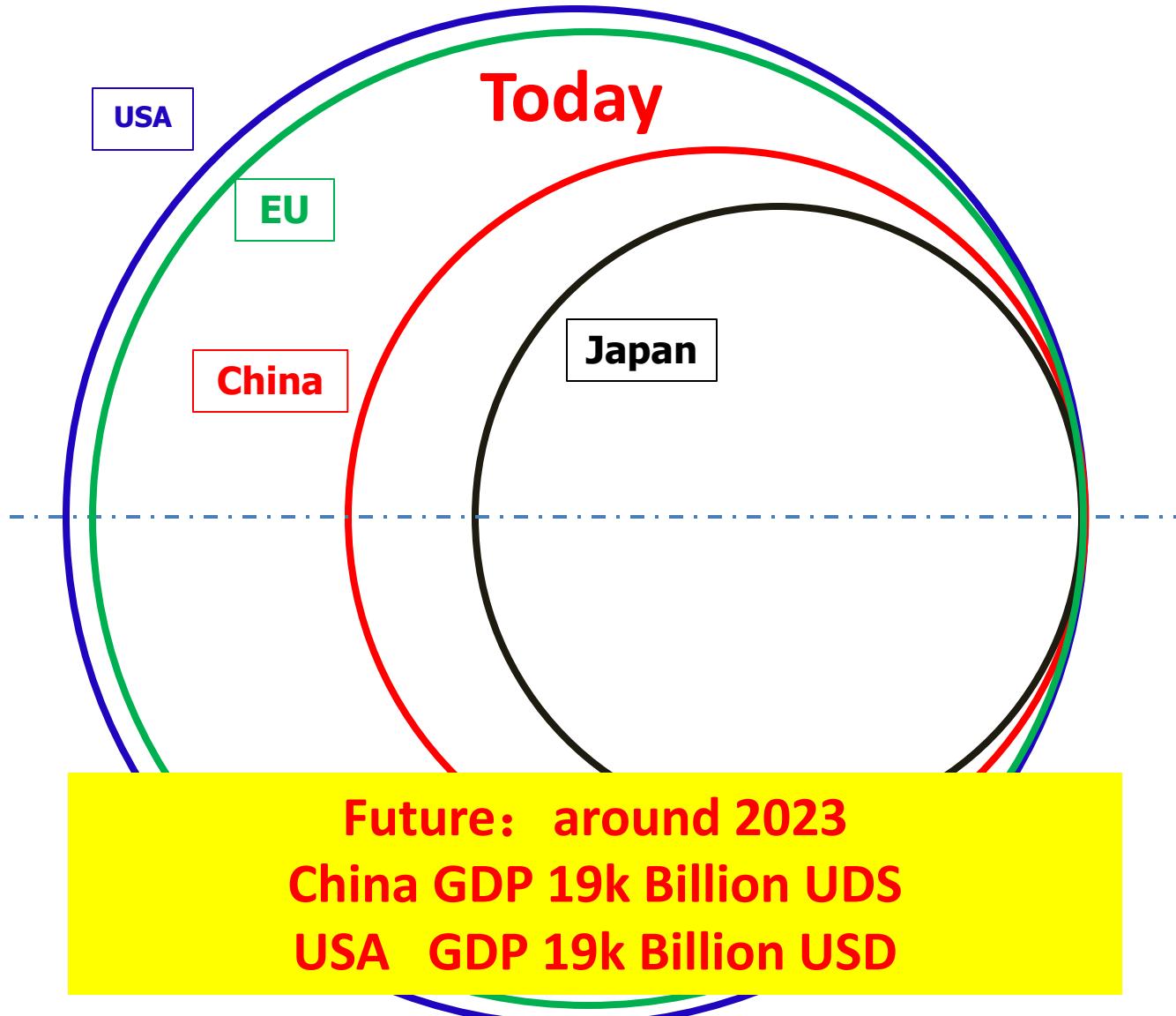
KEKB

BEPC

ILC

- BEPC cost/4 y/GDP of China in 1984 ≈ 0.0001
- SSC cost/10y/GDP of US in 1992 ≈ 0.0001
- LEP cost/8y/GDP of EU in 1984 ≈ 0.0002
- LHC cost/10y/GDP of EU in 2004 ≈ 0.0003
- ILC cost/8y/GDP of Japan in 2018 ≈ 0.0002
- CEPC cost/6y/GDP of China in 2020 ≈ 0.00007
- SppC cost/6y/GDP of China in 2036 ≈ 0.0001

World economic repartition evolution



ICFA Chairman's view

ICFA Chairman, Fermi National Lab director, Prof. Nigel Lockyer wrote an article:
“Particle physics: Together to the next frontier”,
Nature, Volume 504, Issue 7480, 18 December 2013.
(<http://www.nature.com/news/particle-physics-together-to-the-next-frontier-1.14364>)

Prof. Nigel Lockyer wrote:
“If China does jump ahead, it will change the landscape of science.”



Summary (1)

1. Discovery of Higgs boson around 126GeV provides more opportunities for future colliders around the world
2. In addition to **ILC** collaboration, **CEPC/SppC** has the highest priority among all the proposals for future HEP accelerators in China
3. We are experiencing a very excited period of time and China should and could take more responsibilities for the high energy physics community world wide in both international projects, such as **ILC** and homed based **CEPC/SppC** with world participation
4. CEPC/SppC will collaborate closely with **ILC** and **FCC**

Summary (2)

1. The most urgent is collider lattice design including FFS with enough dynamic aperture
2. Once the collider is working in design, one could try to optimize the machine design in reducing beam radiation power, or, AC power
3. Key technologies for CEPC/SppC need dedicated R&D in the next five years (the 13th five year plan of China), such SCRF technologies, RF sources, SC magnets, Detector technologies, Vacuum chamber...infrastructure SC lab...



Acknowledgements



- 1. Thanks to organizing committee to invite me to give this talk**

- 2. During preparation of this talk, I have benefited many discussions and materials both from the CEPC/SppC Group and from ILC Group**

Thank you for your attention