CEPC Booster Design

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Presented for Chuang Zhang

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The CEPC Booster

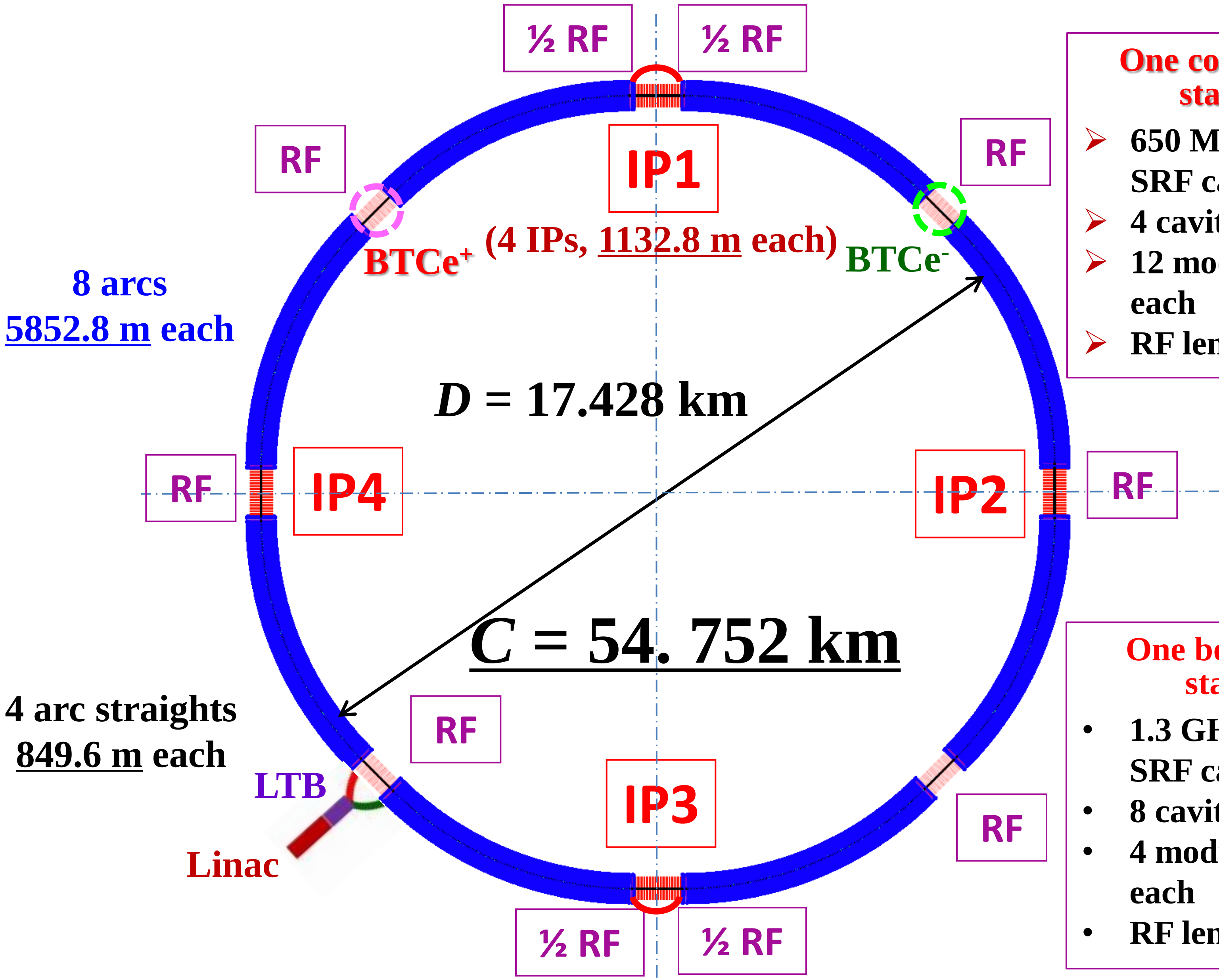
- General description
- Lattice
- Low injection energy issues
- Beam transfer
- Summary

1. General Description

Booster is in the same tunnel of the CEPC collider, and will be installed on its up-side with about the same circumference as the collider, while bypasses are arranged to keep away from detectors.

- **Providing beams for the collider with top-up frequency up to 0.1 Hz.**
- **Using 1.3 GHz RF system;**
- **The injection energy of the booster is 6 GeV;**
- **Magnetic Field is as low as 31 Gs at injection.**

The CEPC Layout



One collider RF station:

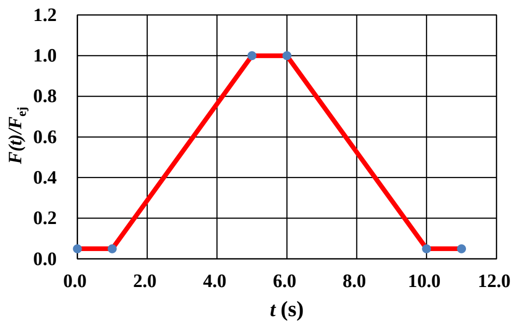
- 650 MHz five-cell SRF cavities;
- 4 cavities/module
- 12 modules, 8 m each
- RF length 120 m

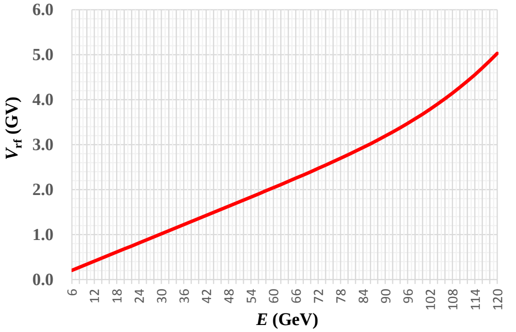
One booster RF station:

- 1.3 GHz 9-cell SRF cavities;
- 8 cavities/module
- 4 modules, 12 m each
- RF length 48 m

Main parameters of CEPC booster

Parameter	Symbol	Unit	Value
Injection energy	E_{inj}	GeV	6
Ejection energy	E_{ej}	GeV	120
Circumference	C	km	54.7528
Bending radius	ρ	km	6.519
Main bending field	B_{ej}/B_{inj}	T	0.0614/0.00307
SR loss/turn	U_0	GeV	2.814
Bunch number	n_b		50
Bunch population	N_b	10^{10}	2.0
Beam current	I_{beam}	mA	0.87
SR power @ 120GeV	P_{SR}	MW	2.46
SR Power density @120GeV	P_{SR}/C	W/m	45





- Single bunch injection from linac (E=6 GeV, I_p=3.2nC, f_{rep}=50 Hz, $\varepsilon_{x,y}$=0.1-0.3 mm·mrad) to booster;
- Assuming 5% of current decay in the collider between two top-ups ;
- Booster operates with repetition frequency of 0.1 Hz.
- Overall efficiency from linac to the collider is assumed as 90 %.
- SR power density of 45W/m is much lower than in BEPCII of 415W/m.

2. Lattice

- **Similar arc arrangement to the collider**
- **Simple structure:**

FODO cells + Disp. Suppr. + Straight / bypass

Arc straight	-DIS	78 FODO cells	DIS	IR2/IR4 straight
Arc straight	-DIS	75 FODO cells	DIS	Bypass

- **Cell length：**

To optimize cell number, emittance and aperture

- **Straight sections**

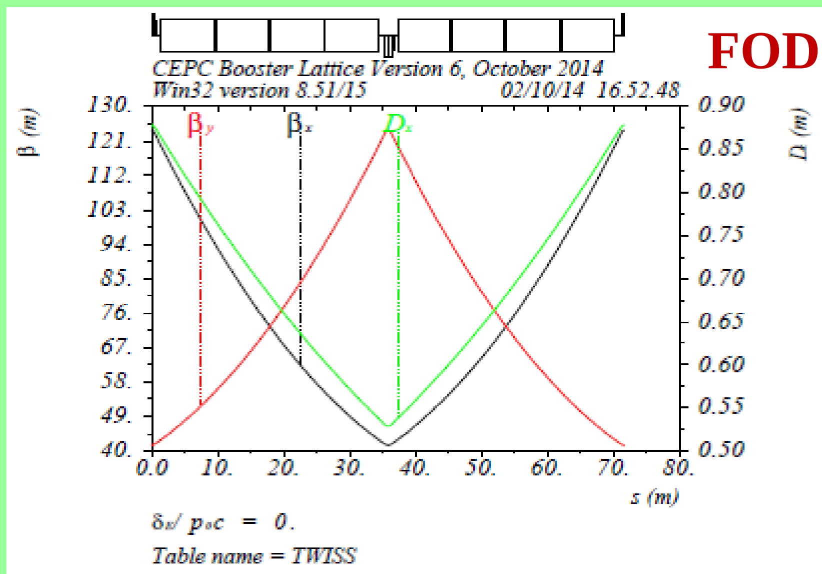
For RF cavities, injection, extraction, etc.

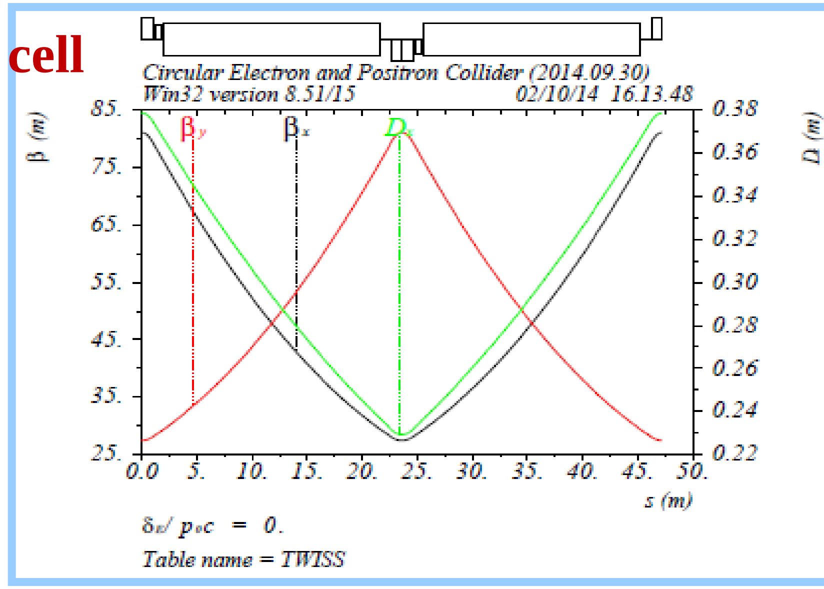
2.1. Choice of cell length

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	$\varepsilon_{x0} \propto L^3$	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

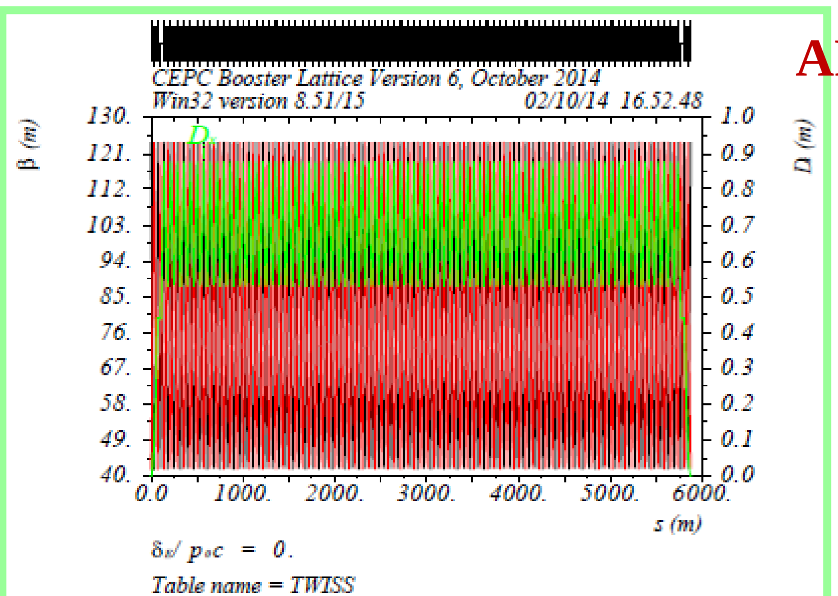
2.2 Lattice functions: booster vs. collider

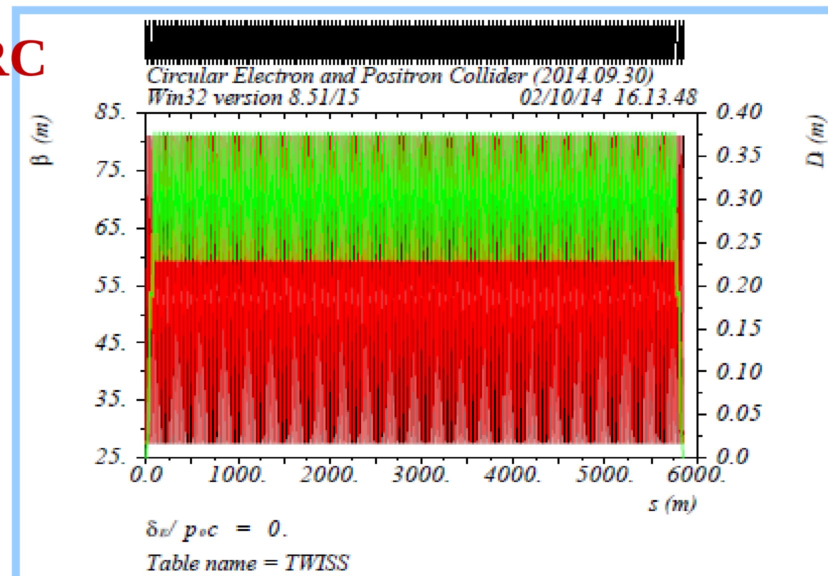
FODO cell





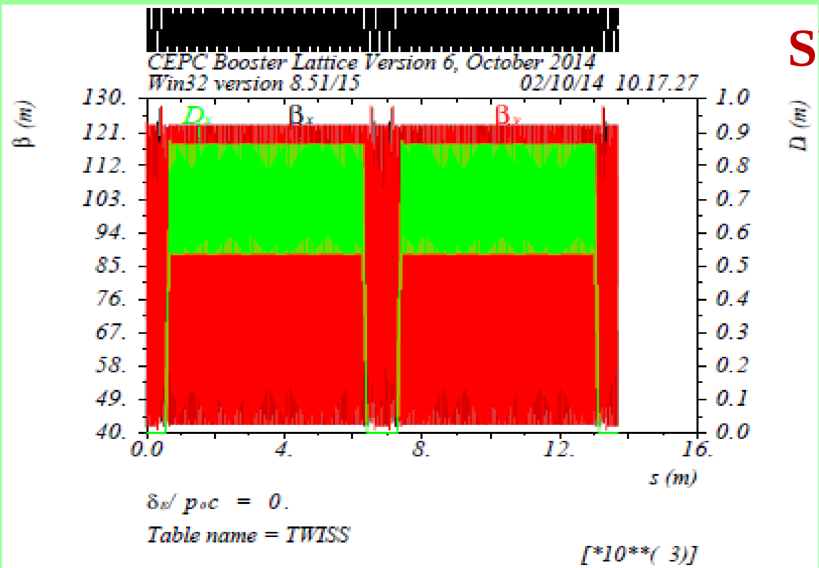
ARC

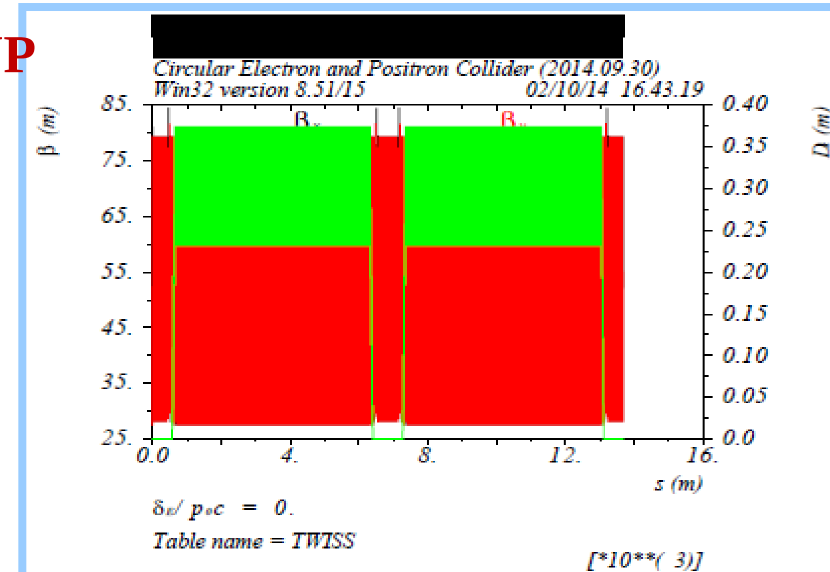




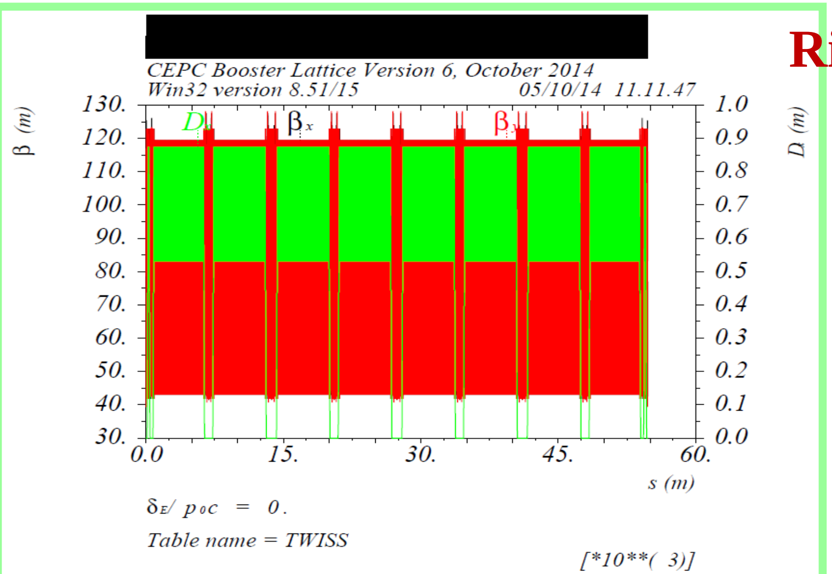
SUP and Ring Lattice: booster vs. collider

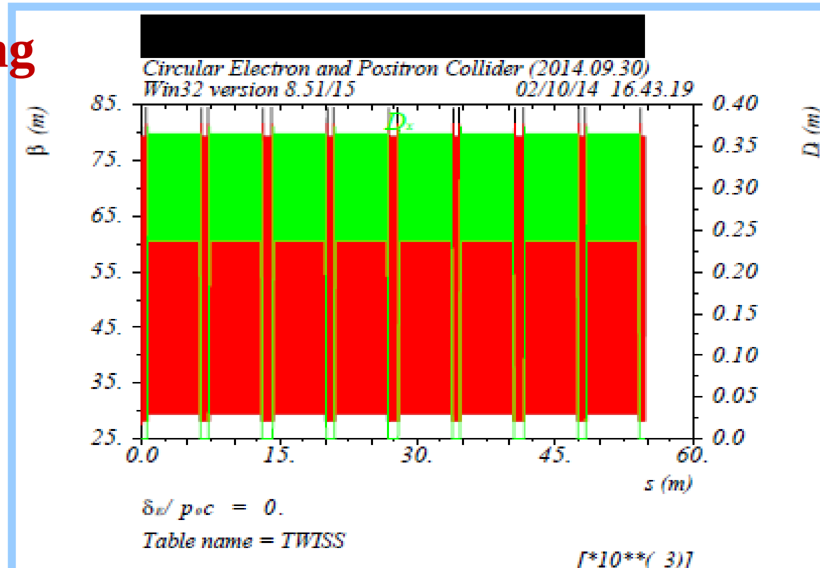
SUP





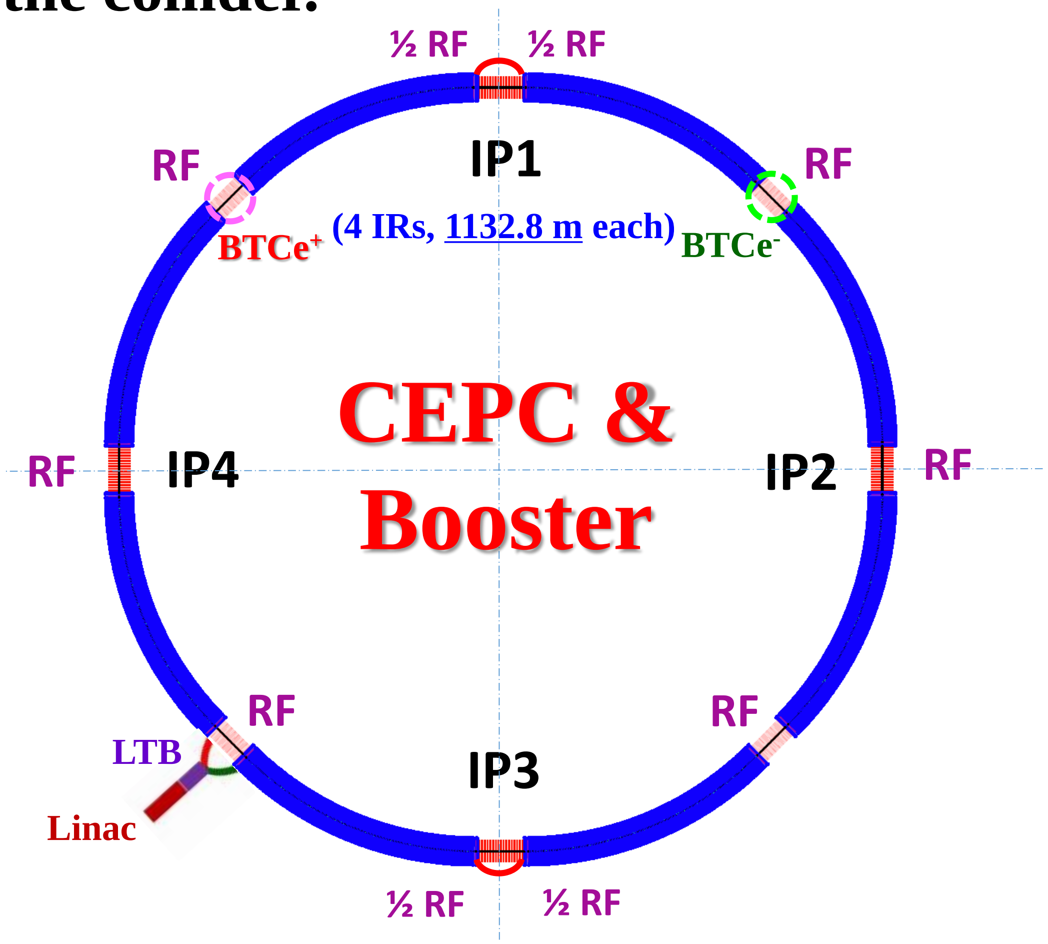
Ring





2.3 Bypasses

Two bypasses are arranged to skirt the detectors at IP1 and IP3 of the collider.

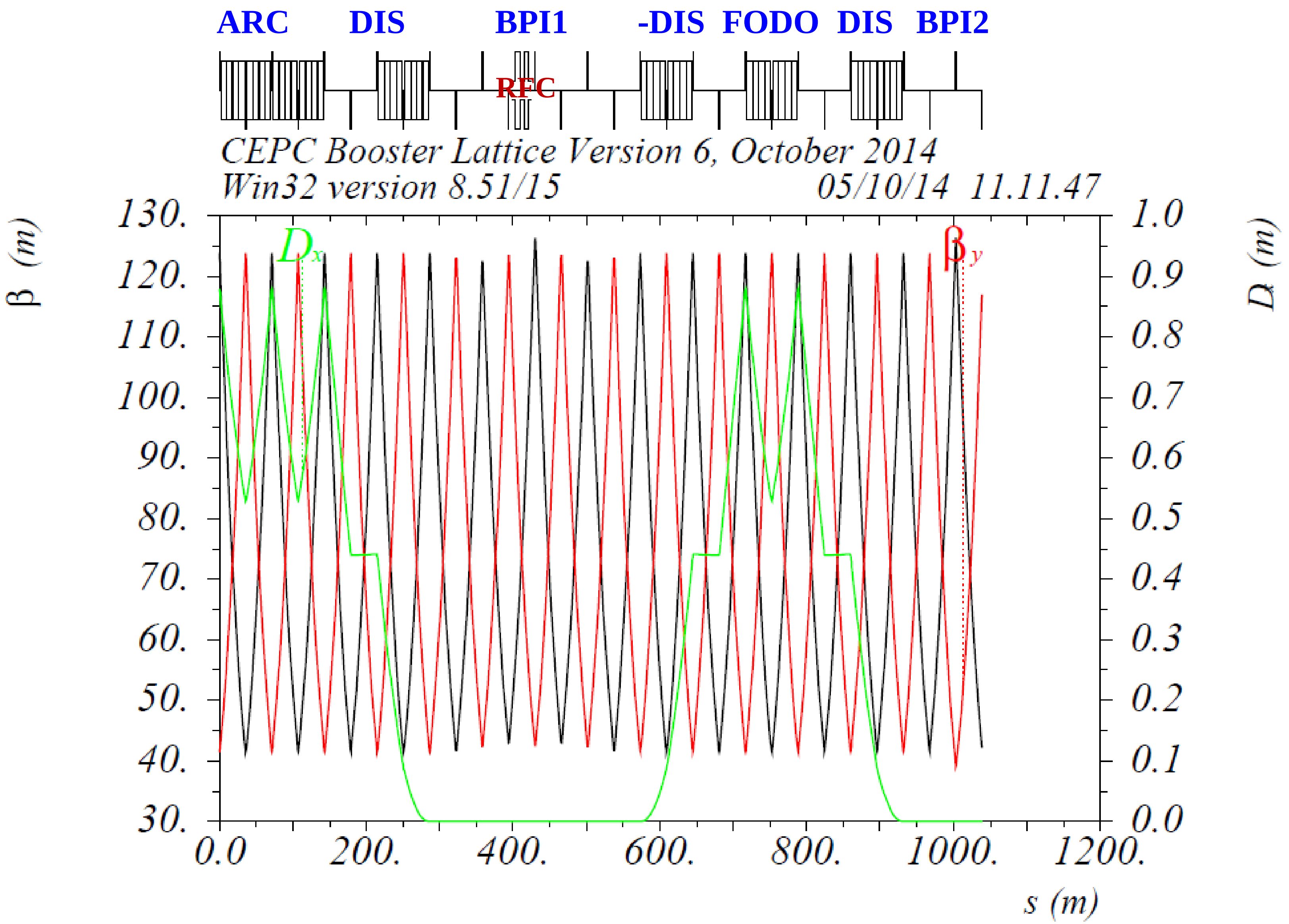


Bypasses

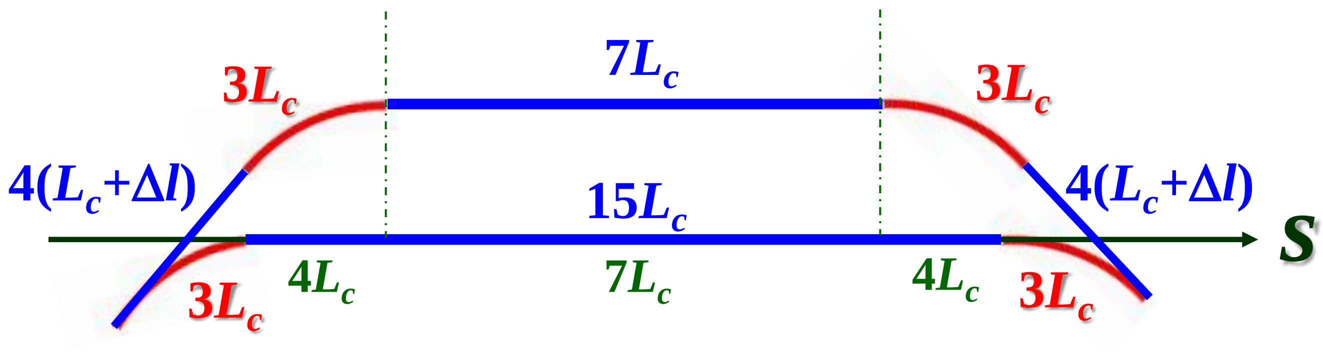
-3*FODO	DIS	BPI1	-DIS	FODO	DIS	BPI2
$-3L_c$	$2L_c$	$4f_1L_c$	$2L_c$	L_c	$2L_c$	$1.5f_2L_c$

- Length of half bypass: $L=(4+4f_1+1.5f_2)\cdot L_c$
- Width of the bypass: $W=(9.5+9f_1)\cdot\theta_c L_c$
- $L = 10.5L_c = 752.482$ m ($f_1=1.0$, $f_2=1.0$)
- $W \approx 18.5\cdot\theta_c L_c = 13.0$m ($f_1=1.0$) (MAD: 12.662 m)
- By adjusting f_1 and f_2, both length and width of bypass can be adjusted to fit the FFS length and detector width.
- No additional bending cell is required!

The bypass lattice



Orbit length change



$$L_{BP} = L_{AS+SS} + 8\Delta l = 21 L_C + \Delta L$$

$$\Delta L = 8\Delta l = L_C \cdot \delta = L_c(1/\cos 3\theta_C - 1) \qquad \Delta L = 0.25 \text{ m}$$

MAD calculation: $\Delta L = 2\times 0.1934 = 0.3868$ m

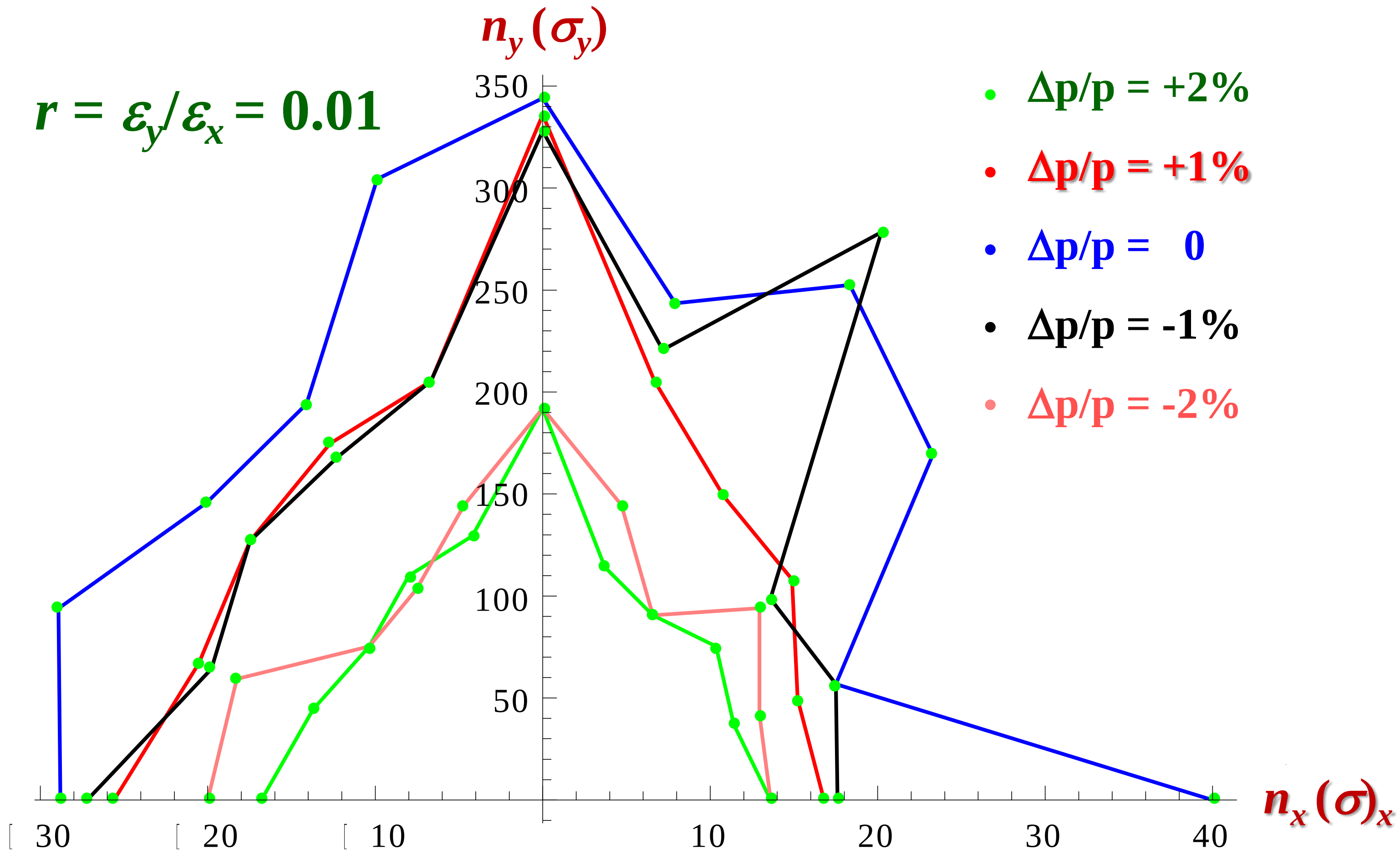
To increase the straight length from $7L_c$ to $7L_c + 2\Delta L$

$$L_{Booster} = C_{collider} + 2\,\Delta L = 54752.7936 \text{ m}$$

2.4 Dynamic aperture

With two family sextupoles, ξ_c=0.5

The dynamic aperture by tracking of 3 damping times



Lattice Parameters

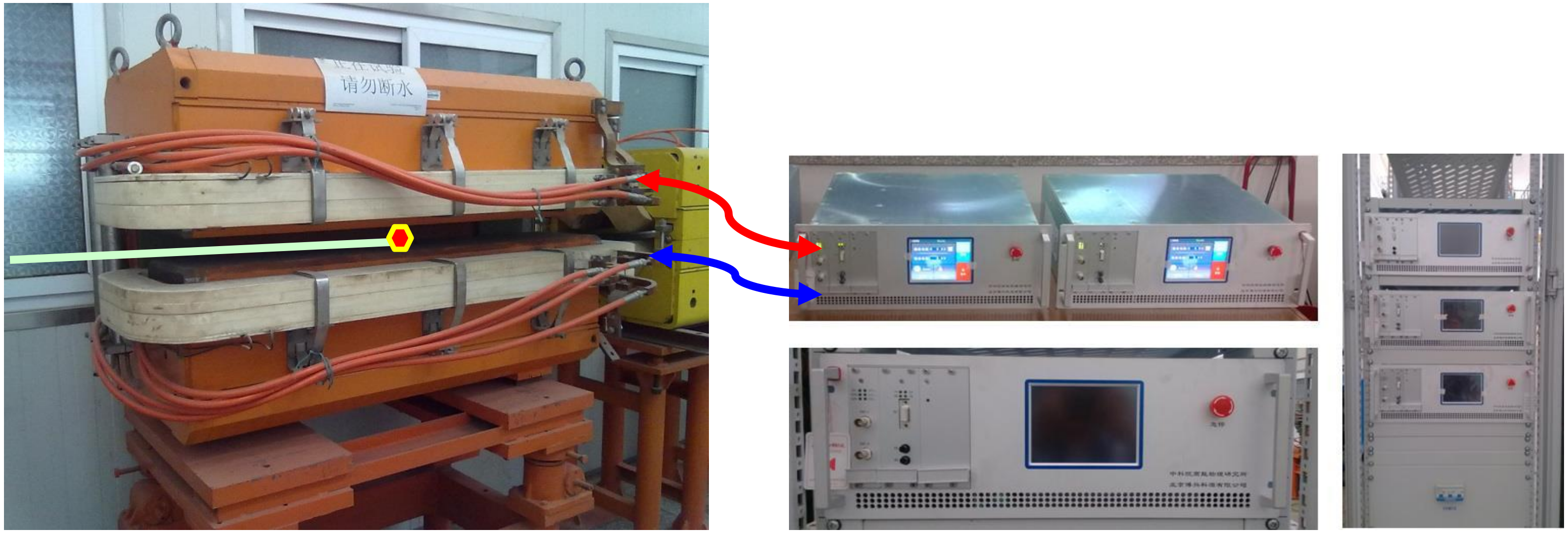
Parameter	Unit	Value
Circumference	m	54752.7936
Bending radius	m	6519
Horizontal/vertical tunes		127.18/127.28
Total FODO structures in a ring		768
FODO cell length	m	71.665
Phase advance in a cell (H/V)		60°/60°
Maximum horizontal/vertical β	m	123.84/122.97
Maximum dispersion function	m	0.879
Length of bypass	m	2×752.482
Width of bypass	m	13.0

3. Low injection energy and low field issue

The bending field of CEPC booster is 614Gs at 120 GeV; To reduce the cost of linac injector, the injection beam energy for booster is chosen as low as 6 GeV with the magnetic field of 30.7 Gs.

- It needs to be tested if the magnetic field could be stable enough at such a low field against the earth field of 0.5-0.6 Gs and its variation?
- Try to do magnetic measurement using existing magnet at low field strength.

3.1 Low field stability test

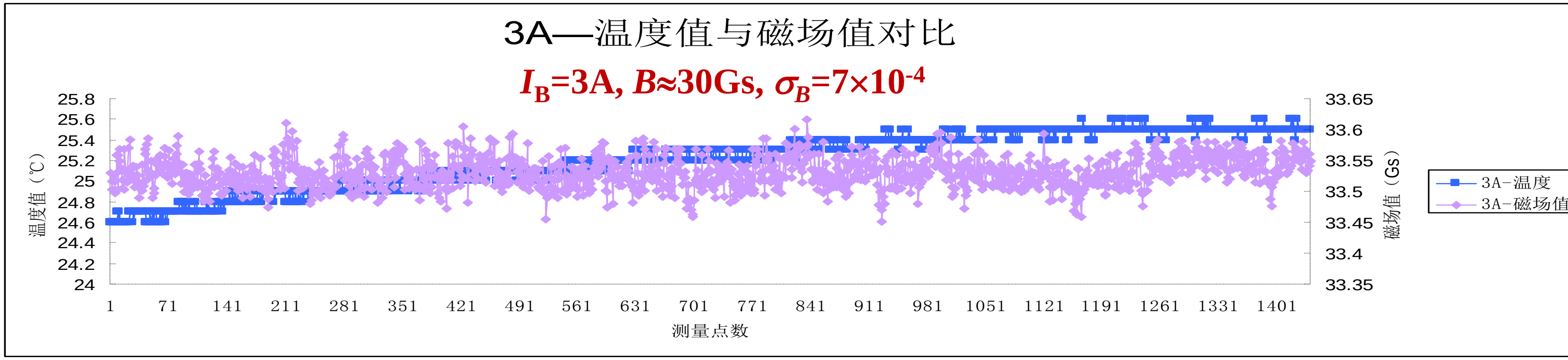


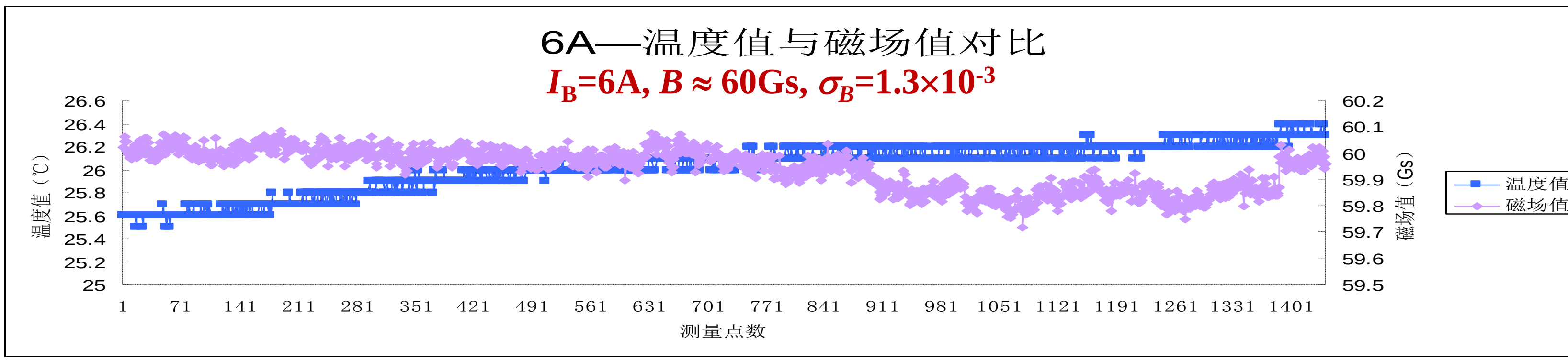
- A BEPC bending magnet:
- B_0=9028Gs @ I_B=1060A;
- B_0=30Gs @ I_B=3A 。

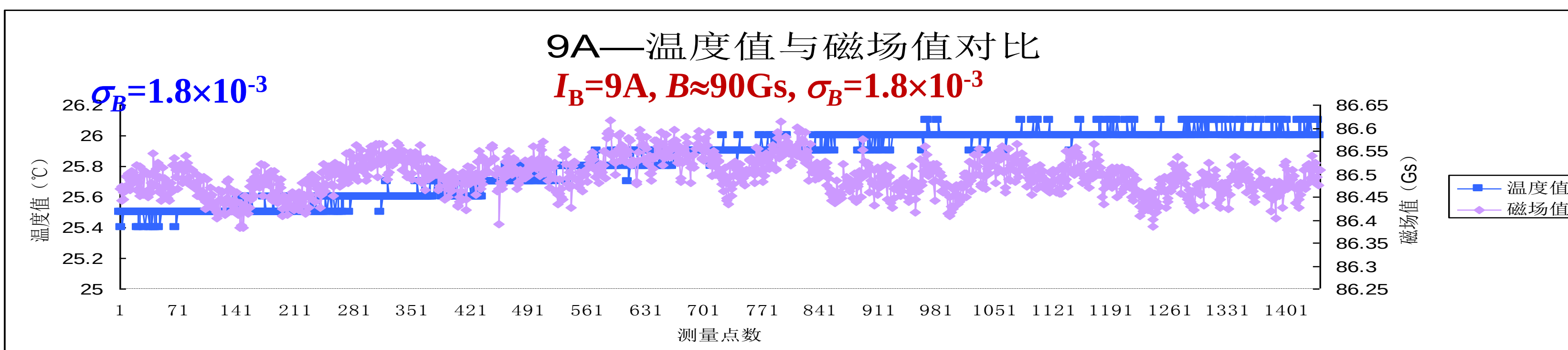
- Power supplies for ADS:
- 3A/5V, 15A/8V ;
- $\Delta I/I < 1\times10^{-4}$。

- Hall probe system will be used for field measurement;
- ΔB= 0.1 Gs ➡➡ $\Delta B/B_0 \sim 3\times10^{-3}$。

Magnetic field stability measured in 24 hours







Low field stability test

- The earth field outside the magnet: B_x=0.55±0.026Gs, B_y=0.45±0.027Gs, B_z=0.25±0.03 Gs ⇨⇨ B= 0.8±0.04Gs
- Inside the magnet, B_y=7.0±0.05Gs is dominated by residual field, B_x=0.4±0.04Gs reduced due to the shielding while B_z=0.25±0.03 Gs.
- The reason of the measured field variation (field itself or measurement error) is being investigated;
- The 24h field stability (σ_B) for 30 Gs-150 Gs is about (1-2)$\times 10^{-3}$;
- The magnet ramps smoothly around the low fields with accuracy better than 1×10^{-3};
- The field error $\Delta B_y/B_y \sim 10^{-4}$ for $x \in$(-60, 60) mm and $B_y \in$(30-150) Gs
- The injected beam energy for booster of 6 GeV could be feasible in view of magnetic field stability.

Mitigation

- Wiggling band scheme
- Increase linac energy ⇨

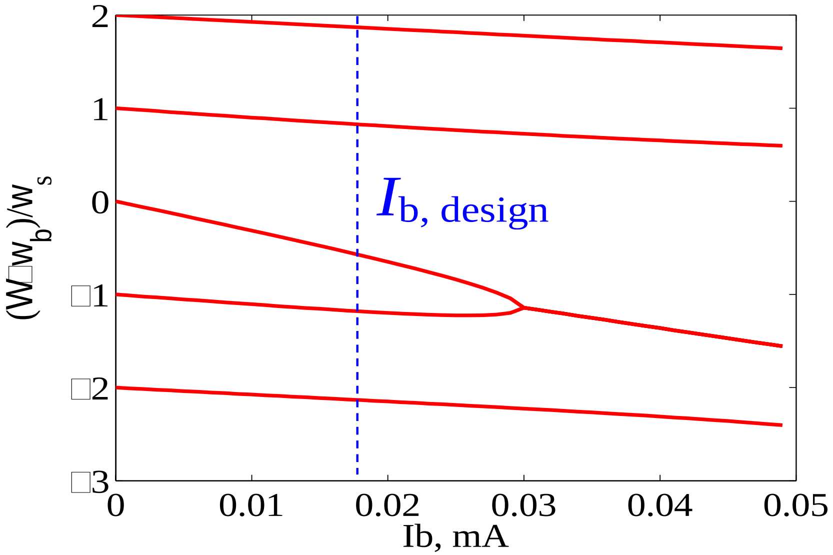
  10 GeV, 12 GeV…
- Accumulating pre-booster

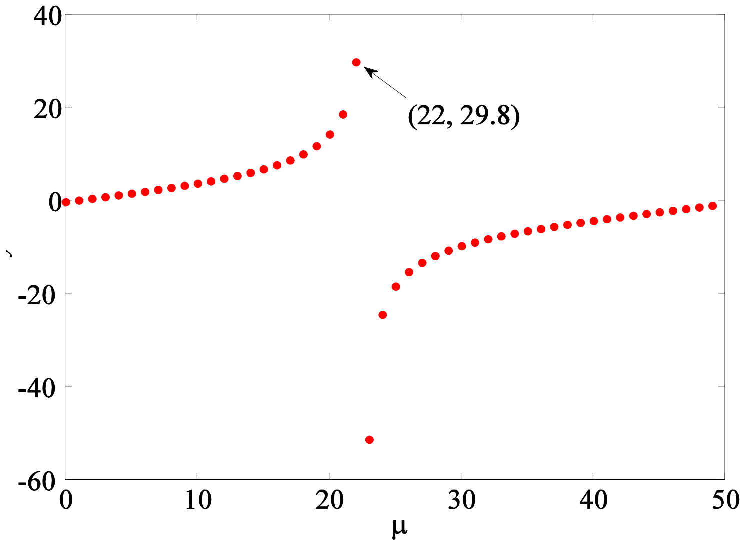
3.3 Instability issues

Beam stability at injection is concerned

- $E_{\text{booster, inj}}=0.05 \cdot E_{\text{collider}}$ **vs.** $I_{\text{booster,}}=0.05 \cdot I_{\text{collider;}}$
- **Almost no synchrotron radiation damping;**
- **HOM of 1.3 GHz SC cavities, CB instability;**
- **Resistive wall instability;**
- **Transverse mode coupling instability;**
- **ECI and ion effects?**
- **Bunch-by-bunch feedback to stabilize beams.**

Instability issues (*N. Wang*)





The transverse mode coupling

Considering the impedance generated from the resistive wall and the RF cavity, the single bunch threshold current of 27μA, higher than the design bunch current of 18μA, but doesn't leave much margin.

The resistive wall instability

The growth time for the most dangerous mode is 34 ms in the vertical plane. The growth rate is much shorter than the radiation damping time, transverse feedback system is needed to stabilize the beams.

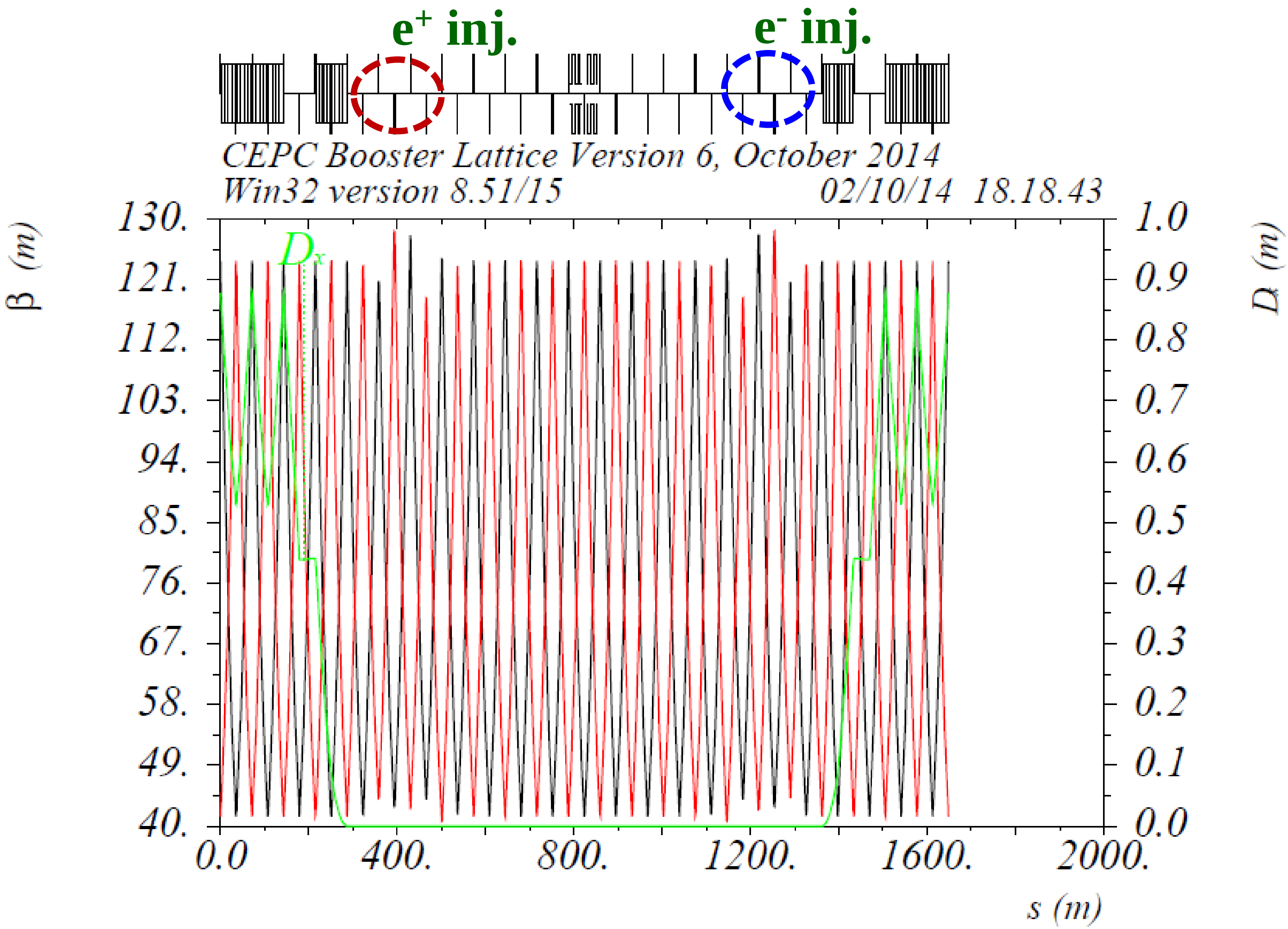
The growth rate of the first few HOM's

Monopole Mode	f (GHz)	R/Q (Ω)*	Q	σ_f (MHz)	τ (s)
TM011	2.450	156	58600	9	1.5
TM012	3.845	44	240000	1	0.5
Dipole Mode	**f (GHz)**	**R/Q (Ω/m)****	**Q**		**τ (ms)**
TE111	1.739	4283	3400	5	218
TM110	1.874	2293	50200	1	44
TM111	2.577	4336	50000	1	22
TE121	3.087	196	43700	1	497

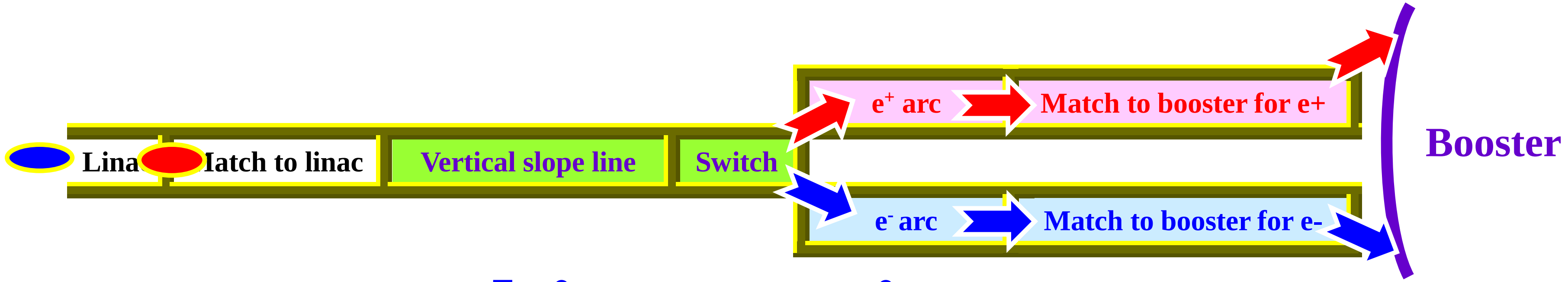
* $k_{\parallel}$ mode= $2\pi f\cdot(R/Q)/4$ [V/pC] ** $k_{\perp}$ mode = $2\pi f\cdot(R/Q)/4$ [V/(pC·m)]

- Longitudinal ($\tau_d < 0.5$ s) and transverse ($\tau_d < 20$ ms) feedback systems should be equipped to stabilize beams.

4. Beam transfer



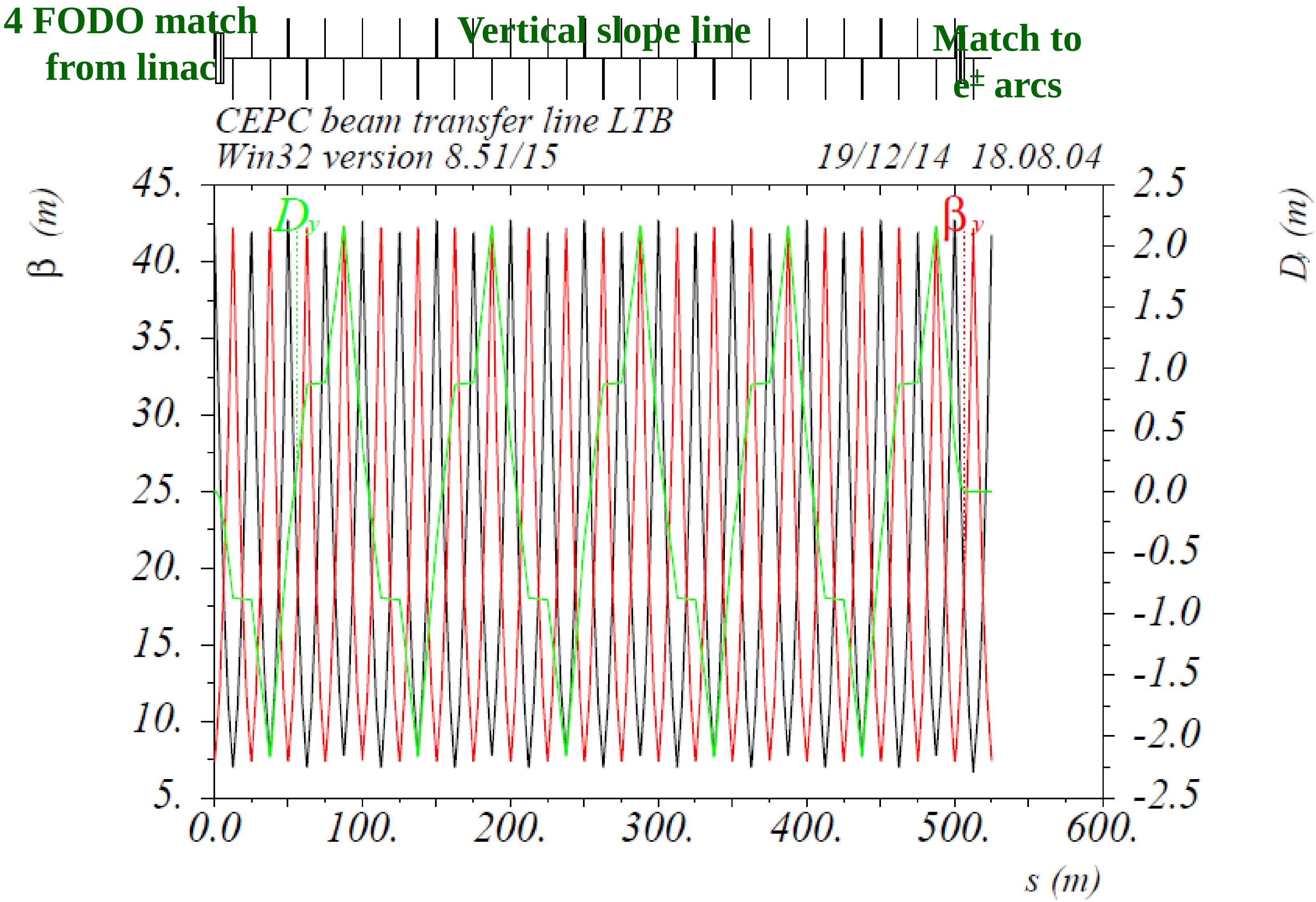
4.1 Transfer From Linac to Booster



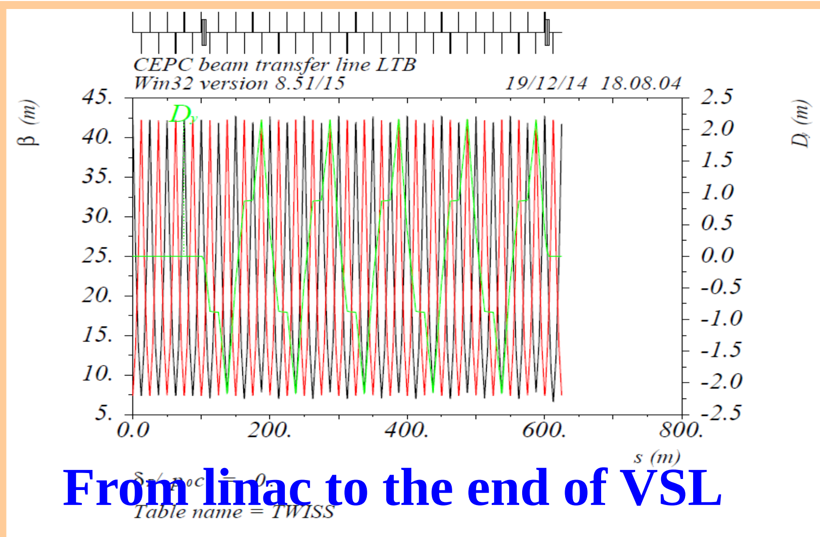
- Matching section
- Vertical slope line
- Match and Switch
- Arcs
- Match to the booster

Vertical slope line

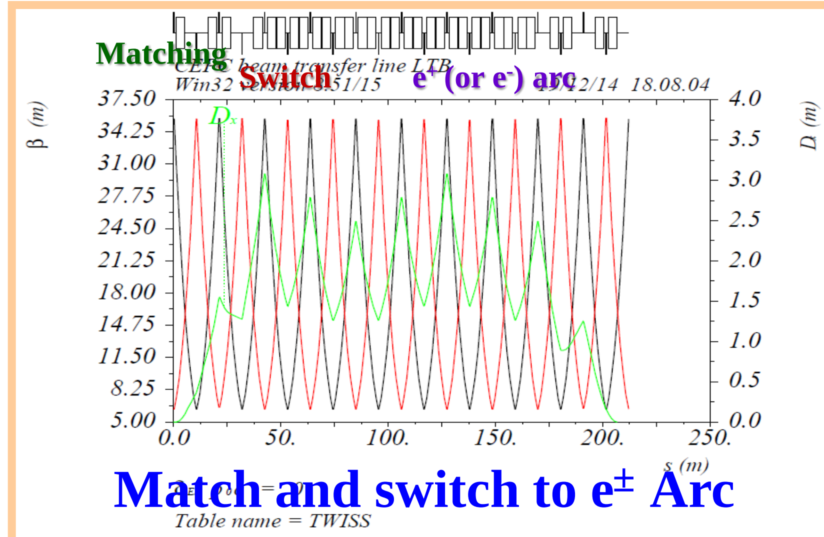
Slope = 1:10, L~500m, $D_{x,max}$~2m



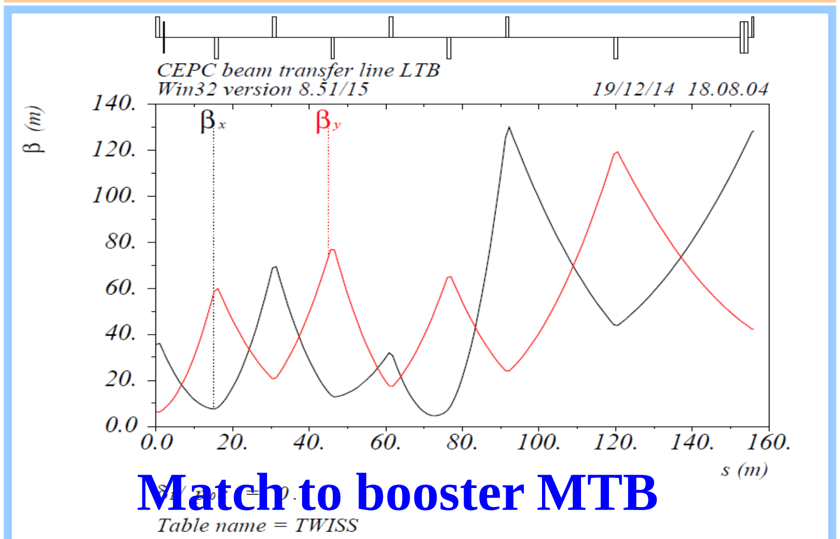
Match from linac to booster



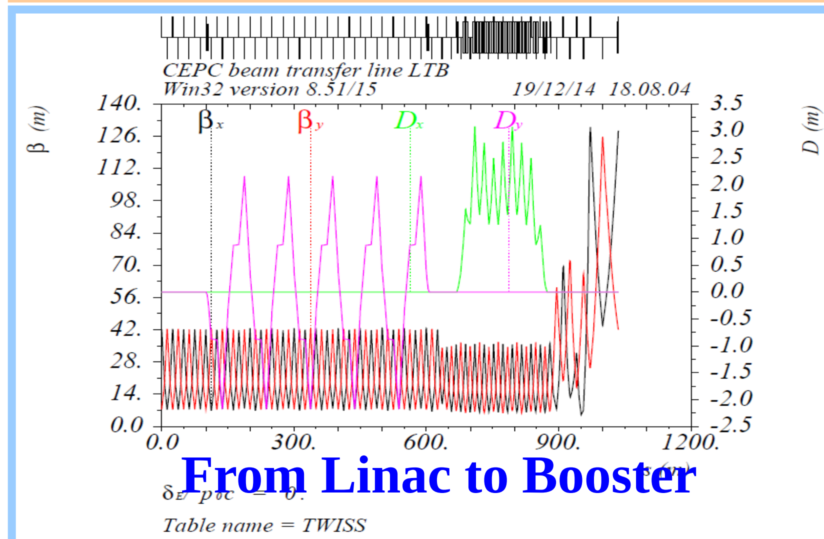
From linac to the end of VSL



Match and switch to e± Arc



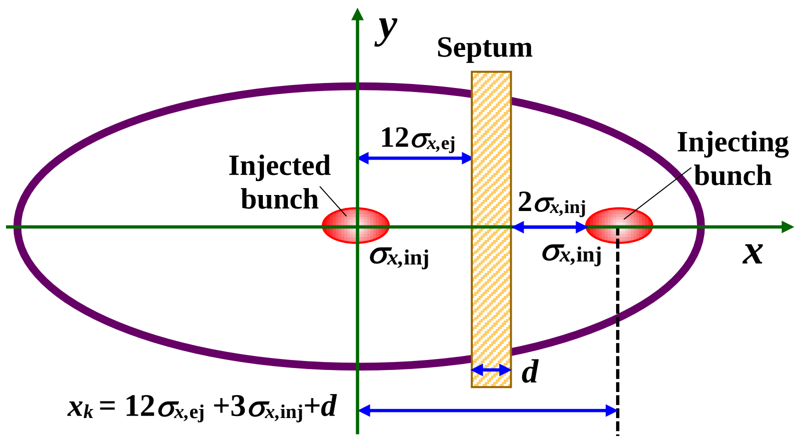
Match to booster MTB



From Linac to Booster

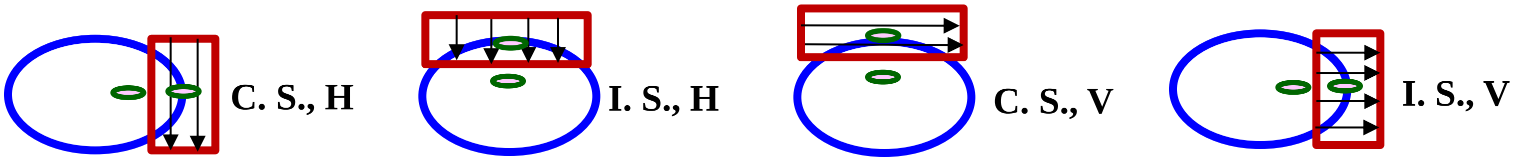
4.2. Beam injection to booster

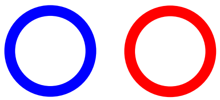
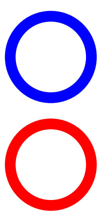
- $e^{\pm}$ beams are injected from outside of the booster ring;
- Horizontal septum is used to bend beams into the booster;
- A single kicker downstream of injected beams kick the beams into the booster orbit.



Component	Length (m)	Waveform	Deflection angle(mrad)	Field (T)	Aperture	
					H (mm)	V (mm)
Septum	2.0	DC	9.1	0.18	41.4	13.4
Kicker	0.5	1.5 μs half-sine wave	0.40	0.032	41.4	13.4

4.3 . Transfer from booster to collider



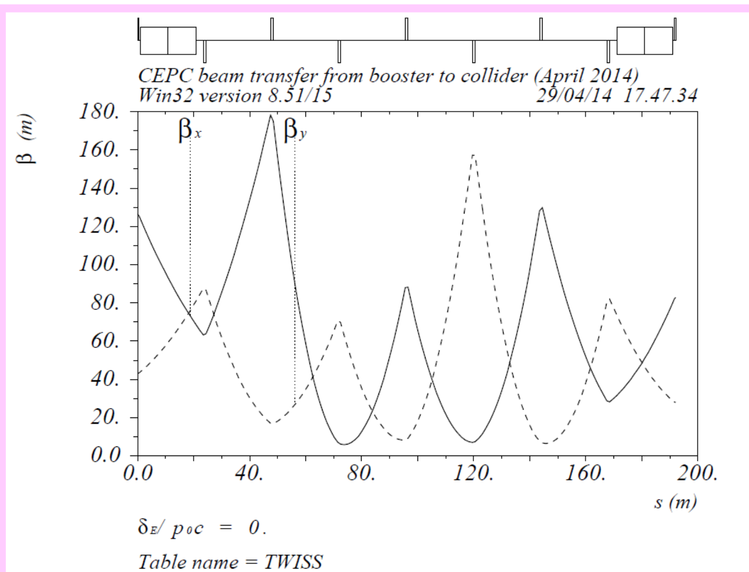
Tunnel Arrangement	Septum		Kicker	
	Booster	Collider	Booster	Collider
	Copper, H	Copper, H	H	H
	Iron, H	Iron, H	V	V or No
	Copper, V	Copper, V	V	V
	Iron, V	Iron, V	H	H

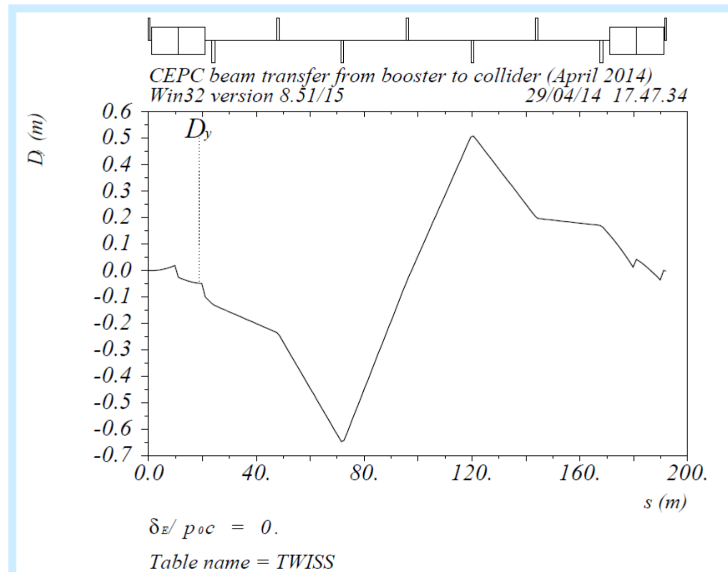
Booster ejection

- Single kicker + 4 orbit bumps are used for beam extraction vertically from the booster;
- Septum magnets are applied to bend beams vertically into BTC;
- Maximum extraction rate is 100 Hz.

Component	Length (m)	Waveform	Deflection angle(mrad)	Field (T)	Aperture	
					H (mm)	V (mm)
Lamberstson	10.0	DC	9.1	0.41	41.4	18.6
Kicker	2.0	1.5 μs half-sine wave	0.33	0.046	41.4	13.6

Vertical transfer





Summary

- Conceptual design study on CEPC-Booster has been carried out;
- There is no showstopper found in the design, from the point of view of lattice, bypasses, dynamic aperture, beam transfer and requirement to technical systems.
- The issues related to the low energy injection remain a central concern in the design. The schemes of extending the linac injection energy and/or adding a pre-booster are being considered.
- There are some technical challenges, such as the low HOM in 1.3 GHz SC cavities, supports & alignment etc.
- The design study will keep moving on.

Our Pre-CDR is available at:

- http://cepc.ihep.ac.cn/preCDR/volume.html

Thank you !