

CEPC Booster, Damping Ring and Timing

Dou Wang (IHEP)

on behalf of CEPC AP group



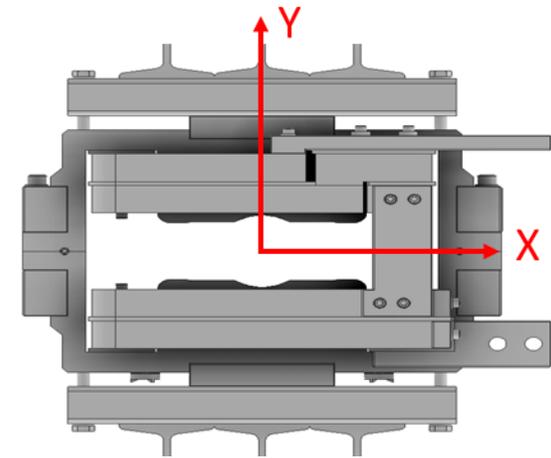
中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Content

- **EDR progress of CEPC Booster**
 - Feasibility study of the combined dipole magnets
 - Mini-review of the combined dipole magnets
 - Simulations of first turn injection commissioning
- **EDR progress of CEPC positron damping ring**
 - DR TDR design status
 - Polarized DR study
- **CEPC timing issue and detector performance**
- **Summary**

Booster error tolerance study in EDR

- The transverse offset error of the combined dipoles were scanned with 100um (RMS), 300um (RMS), 400um (RMS) and 500um (RMS) to see the tolerance from the view of beam dynamics, while all the other errors keep same as TDR error table.
- The combined dipole magnets were shifted Integrally without inner distortion.
- Both dynamic aperture and emittance growth are checked after error correction.
- Assume the error is Gaussian distribution, and are truncated at 3σ .
- Dynamic aperture was tracked by SAD.
- Emittance was calculated by both SAD and AT.



Error correction process

Daheng Ji

Orbit Correction + Horizontal dispersion

- ✓ Response Matrix(RM) Method: links corrector to beam orbit at BPM
- ✓ 2-level iteration:
- ✓ 1st Loop: 20%~100% Corrector
- ✓ 2nd Loop: 30%~80% Singular Value
- ✓ Dispersion correction
- ✓ Energy adjustment by corrector

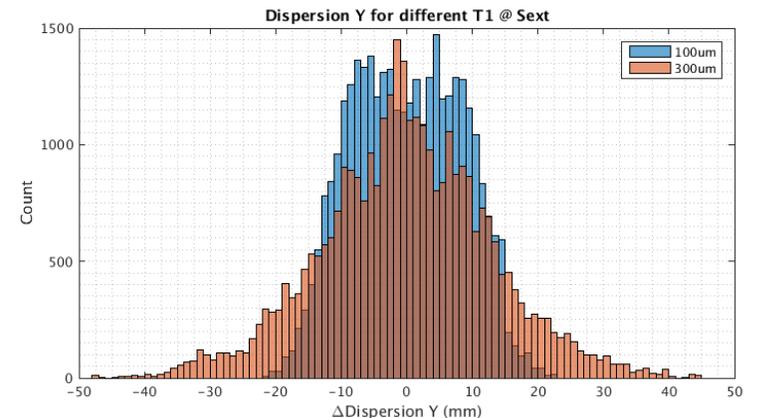
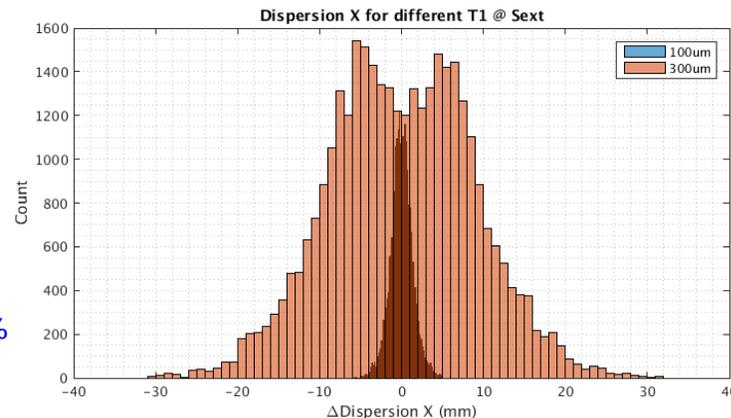
Optics correction

- ✓ RM + LOCO
- ✓ Based on 30GeV & 120GeV simulation
- ✓ All quadrupole independent
- ✓ Dispersion correction included

RMS@120GeV	100um	300um	400um	500um
Orbit (mm)	0.142/0.075	0.130/0.073	0.179/0.104	0.169/0.110
Betabeating(%)	0.67/0.17	0.98/0.64	2.571/1.442	4.862/2.663
Δ dispersion (mm)	1.3/8.3	8.8/13.332	19.267/11.42	23.445/13.05
Emittance(nm)	1.233/0.0086	1.241/0.0103	1.271/0.0114	1.280/0.0158
Coupling	0.599	0.57	0.899	1.1

Coupling and vertical dispersion correction

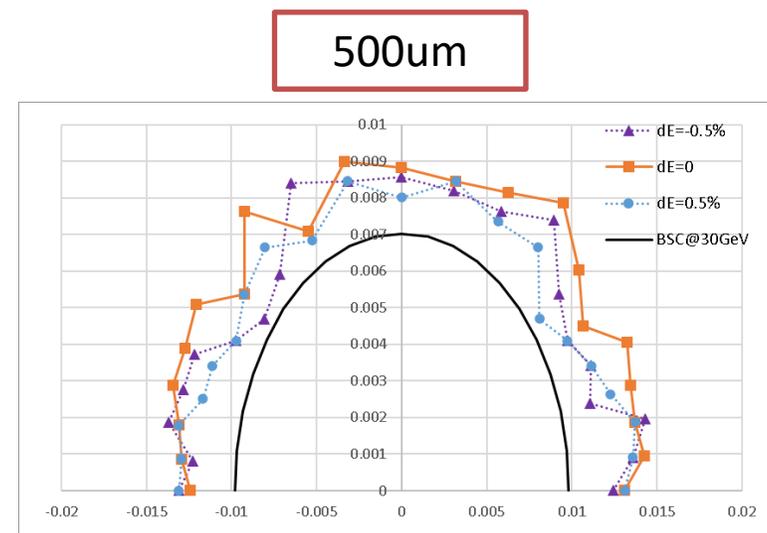
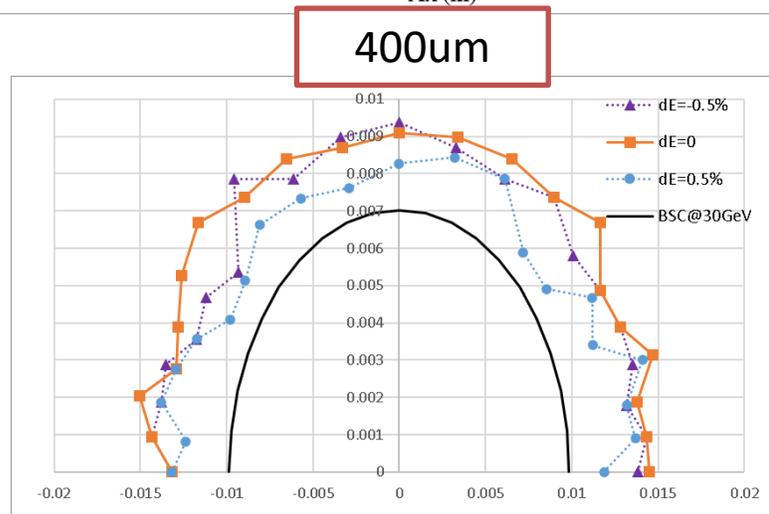
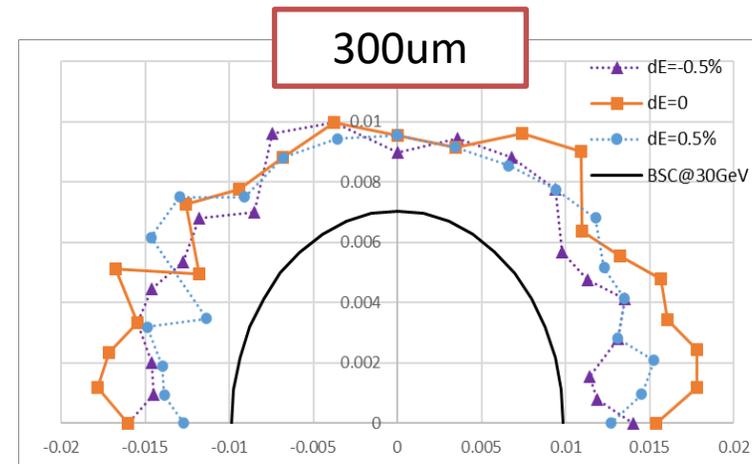
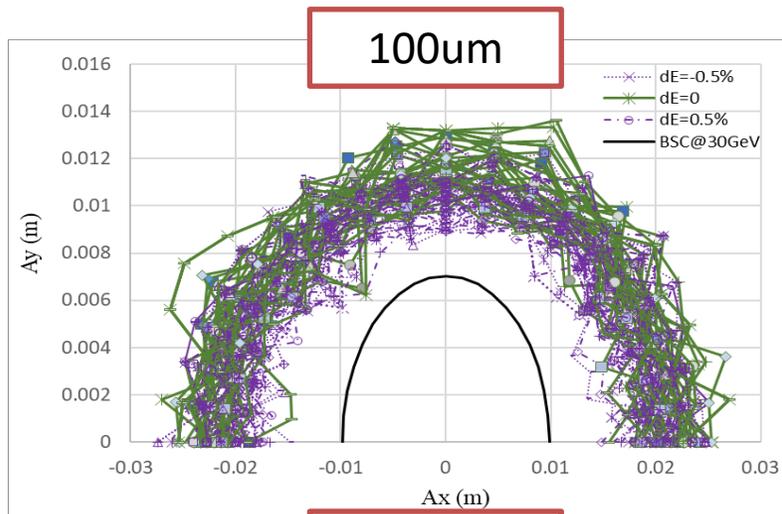
- ✓ 8 skew quadrupole skew quadrupole magnets are arranged in the dispersion free section to correct coupling
- ✓ the coupling control target being better than 1%



Booster DA results@30GeV

D. Wang, Daheng Ji

- 30 GeV is the most critical energy among other energy modes according to TDR study.



- Maximum integral transverse offset of whole magnet: 1.5mm (rms: 500um)

Emittance growth @120GeV

D. Wang, Daheng Ji

- Emittance growth at extraction energy should be controlled to make sure the injection efficiency to collider ring.
- Horizontal emittance growth is very small.
- Vertical emittance growth can be controlled by 8 skew quadrupoles and vertical dispersion correction.

- **Coupling design goal: $\leq 1\%$**

Trans. offset of com. Dipole (RMS)		100um	300um	400um	500um
Hor. Emit. growth (%)		<0.5	<0.8	<1.5	<2
Coupling (%)	w/o coupling correction	0.59	0.98	1.24	1.30
	w coupling correction		0.57	0.89	1.08

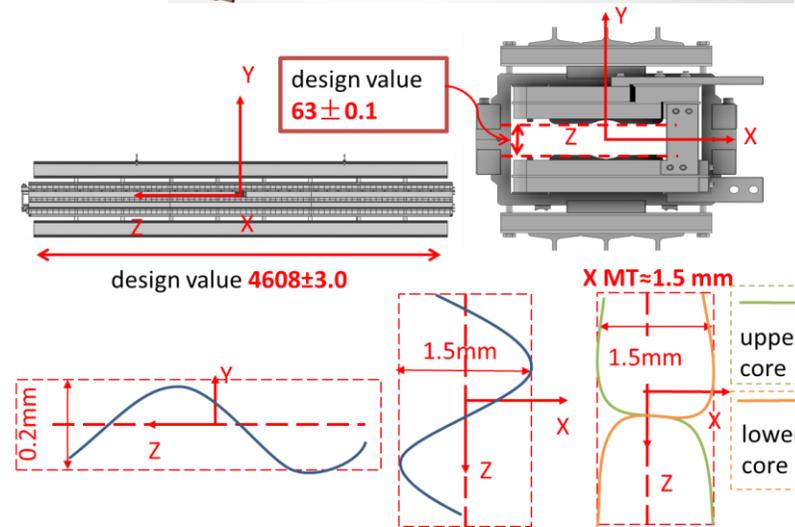
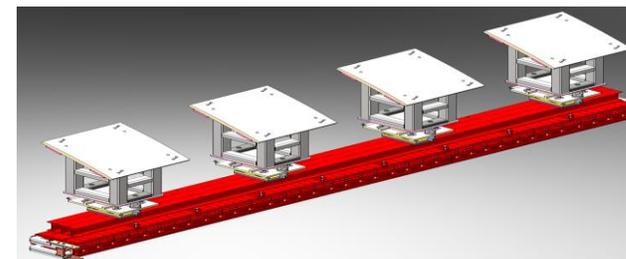
Booster dipole mass production preparation in EDR

- All the booster dipole magnets including the combined dipoles will be produced by the automatic fabrication lines in order to reduce the cost.
- Three fabrication lines will be required to produce the required 15,000 dipole magnets within 5 years (4 dipole magnets per day).
- Production error: combining machining error, assembly error, welding deformation, lifting deformation

Wen Kang, Zhihui Mu

Magnet name	BST-63B	BST-63B-SF	BST-63B-SD
Quantity	10832	2017	2017
Aperture [mm]	63	63	63
Max. Field [Gs T/m ²]	564 0	564 16.04	564 -19.14
Min. Field [Gs T/m ²]	95 0	95 2.67	95 -3.19
Turns per pole	2	2	2
Max. current[A]	714	791	764
Size of conductor [mm*mm]	30*40-Al	30*40-Al	30*40-Al
Core height [mm]	230	230	230
Core width [mm]	330	330	330
Core Length [mm]	4700	4700	4700

BST-63B: booster pure dipole; BST-63B-SF: dipole-SF combined magnet;
 BST-63B-SD: dipole-SD combined magnet.



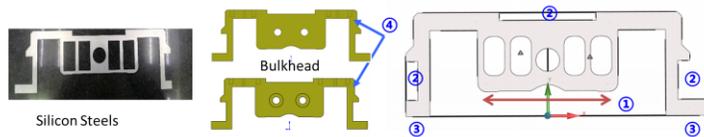
Production error tolerance analysis of combined magnets

Wen Kang, Zhihui Mu

Silicon Steels, Plates

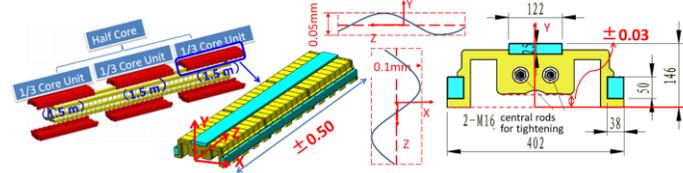
Steel laminations, Inserting plates and End Plates

- Steel laminations, inserting plates and end plates are ferromagnetic materials. They will be machined precisely to ensure the original accuracy of the magnet dimensions.
- Special attention is paid to the dimensional and form accuracy of the **pole face** (1) and the **three draw bar slots** (2) relative to the upper and lower **half-core base surfaces** (3).
- The sides of the inserting plates and end plates are **collimated measuring surfaces** (4) and should also be noted.
- Tolerance for critical positions: $\pm 0.02\text{mm}$; Tolerance for other positions: $\pm 0.05\text{mm}$**



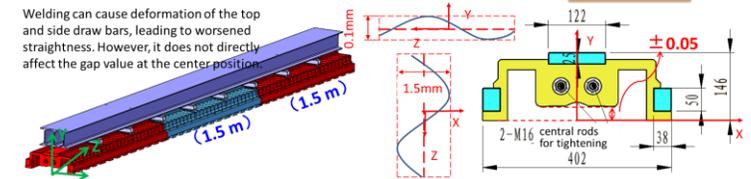
1/3 of the Half-Core

- We have manufactured many 1.5 meter long magnets in a single stack. We can use these experiences to evaluate the production errors of **one-third of the half-core**:
**Length Tolerance = $\pm 0.50\text{ mm}$, 1/2 Gap Tolerance = $\pm 0.03\text{ mm}$,
 Y straightness along Z = 0.05 mm , X straightness along Z = 0.3 mm**
- We lacked the experience of assembling and welding together three short ones (1.5 m).
- Therefore, we developed a special welding positioning platform for the process of combining three components into a single half iron core.



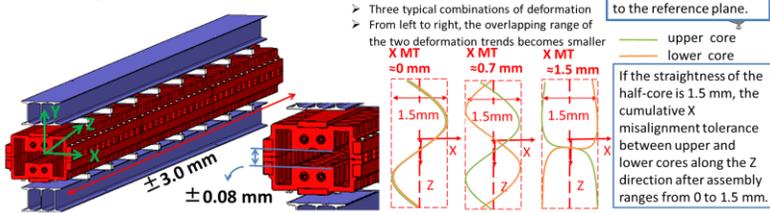
Half-Core

- The welding deformation caused by the three-stage integration is difficult to predict, and there is no use of physical experiments to get the actual data.
- After welding, the half-core is fixed to the hanger/holder to enhance the overall structural strength and to correct any deformation that may have occurred in the Y-direction.
- After comprehensive analysis, the estimated tolerance of the **half-core** is:
**Length Tolerance = $\pm 2.0\text{ mm}$, 1/2 Gap Tolerance = $\pm 0.05\text{ mm}$,
 Y straightness along z = 0.1 mm , X straightness along z = 1.5 mm** (more difficult to control)



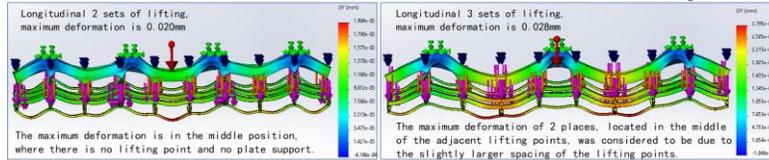
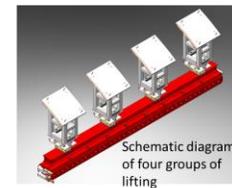
Core

- Taking one side ZY plane as the reference plane, the upper and lower cores are positioned close to the reference plane with the help of cylinders to ensure the straightness.
- The upper and lower iron cores are assembled using 36 sets of bolts (72 bolts), which helps to reduce the variation in gap.
- Length Tolerance = $\pm 3.0\text{ mm}$, Gap(Y) Tolerance = $\pm 0.08\text{ mm}$,
 X Misalignment Tolerance MAX = 1.5 mm**



Lifting

- The core is encircled by inserting plates and end plates, central and surrounding draw bars to form a stable support frame structure.
- Lifting beams + magnet support frame structure are simulated together to evaluate the magnet deformation.
- 4/3 lifting points are arranged along the length of the magnet.
- The maximum deformations for the 4/3-lifting-point configurations are $20\text{ }\mu\text{m}$ and $28\text{ }\mu\text{m}$, respectively.
- The magnetic gap changes are $10\text{ }\mu\text{m}$ and $15\text{ }\mu\text{m}$, respectively.



Overall

The final overall production tolerance, which is the combined effect of machining error, assembly error, welding deformation, and lifting deformation, is as follows:

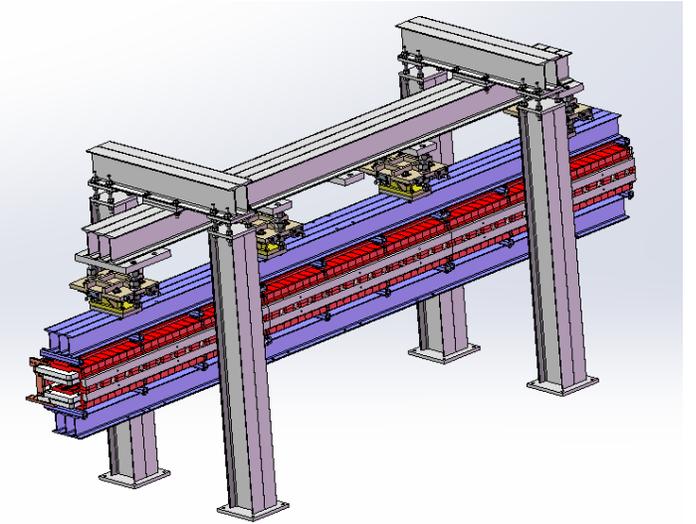
- Length Tolerance = $\pm 3.0\text{ mm}$, Gap(Y) Tolerance = $\pm 0.1\text{ mm}$,
 X Misalignment Tolerance MAX = 1.5 mm
 Y straightness along z = 0.2 mm , X straightness along z = 1.5 mm**

Prototype status of booster combined magnet

- A full size combined magnet prototype has been finished last October.
- Measurements and experiments were planned based on this prototype.



Tooling & Parts Preparation



* Refer to Zihui Mu's talk "CEPC Magnets Line, Booster Magnets, etc".

Summary from magnet system

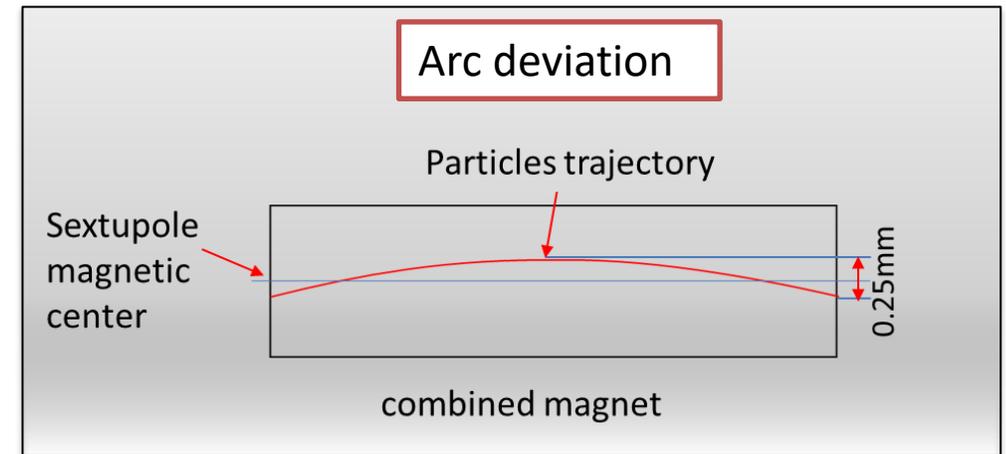
Wen Kang, Zihui Mu

1. Based on the magnetic design and mechanical design as well as material selection, a preliminary analysis of the production tolerance for the CEPC Booster dipole-sextuple combined magnet is presented.
2. The 4.7-meter-long dipole-sextuple combined magnets had never been fabricated before and its manufacture is extremely difficult.
3. We are actively working on the prototype of the dipole-sextuple combined magnet to verify the final machining accuracy.
4. The overall production tolerances evaluation will serve as the performance target for the automatic production line.

Alignment scheme for the combined dipole in EDR

Xiaolong Wang

- The booster dipole-sextupole combined magnet alignment will be based on its integrated sextupole center.
- Align the combined magnet to the position where the integral of the quadrupole magnetic field along the particle's trajectory is zero.
- The combined magnet final alignment error includes magnet fiducialisation error and magnet installation alignment error.
- **The alignment scheme based on mechanical center will be adopted.**
 - Rotating coil magnetic center measurement error is estimated to be 0.4mm
 - The mechanical structure of a magnet is highly correlated with the distribution of its magnetic field



- The integrated sextupole center is moved to outside of the beam inlet/outlet points (offset: ~ 180 μm).

Summary from alignment system

Xiaolong Wang

- Fiducialisation error

	Transversal X/mm	Vertical Y/mm	Roll θ_z /mrad	Pitch θ_x /mrad	Yaw θ_y /mrad
Based on mechanical center	0.071	0.071	0.14	0.011	0.011
Based on magnetic center	0.401	0.401	0.14	0.017	0.017

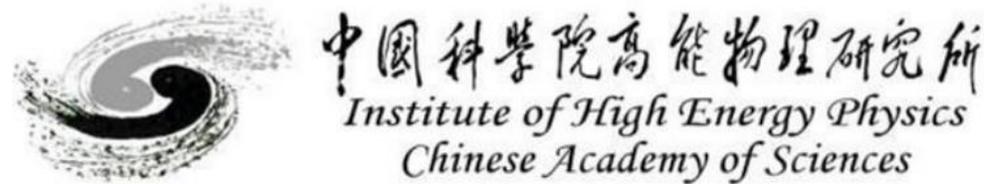
- Total alignment error

	Transversal X/mm	Vertical Y/mm	Roll θ_z /mrad	Pitch θ_x /mrad	Yaw θ_y /mrad
Based on mechanical center	0.1	0.102	0.29	0.019	0.019
Based on magnetic center	0.407	0.408	0.29	0.023	0.023

Mini-Review for CEPC EDR Combined Magnets

- The booster combined magnets mini-review was held on May 29th of 2025, as requested by the CEPC IARC.

- 7 foreign reviewers (online)
- 14 Chinese reviewers (on-site)



Mini-Review for CEPC EDR Combined Magnets

Brochure

Date & Time: Thursday, May 29th, 2025, 3:00 PM Beijing Time (UTC+8)

Format: Online Meeting & Onsite:

Topic: Mini-Review for CEPC EDR Combined Magnets

Meeting ID: 98353925325

Begin Time: 2025-05-29T15:00:00

Meeting URL: <https://zoom.us/j/98353925325?pwd=8tp7BHiM7USOb7ezfp0px07RtVcl8M.1>

Duration: 240 min

Password: 539795

Onsite meeting room: IHEP Main building A419

Review Committee:

No	Name	Institution	Email
1	<u>Mika Masuzawa</u> (Review committee chair)	KEK	mika.masuzawa@kek.jp
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3	Sidorin Anatoly	JINR	sidorin@jinr.ru
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21	Jianxin Zhou	IHEP	zhoujx@ihep.ac.cn

Mini-Review for CEPC EDR Combined Magnets



Institute of High Energy Physics of Chinese Academy of Sciences

I. Schedule of Review Meetings

Date & Time: Thursday, May 29th, 2025, 3:00 PM Beijing Time (UTC+8)

Format: Online Meeting & Onsite:

Topic: Mini-Review for CEPC EDR Combined Magnets

Meeting ID: 98353925325

Begin Time: 2025-05-29T15:00:00

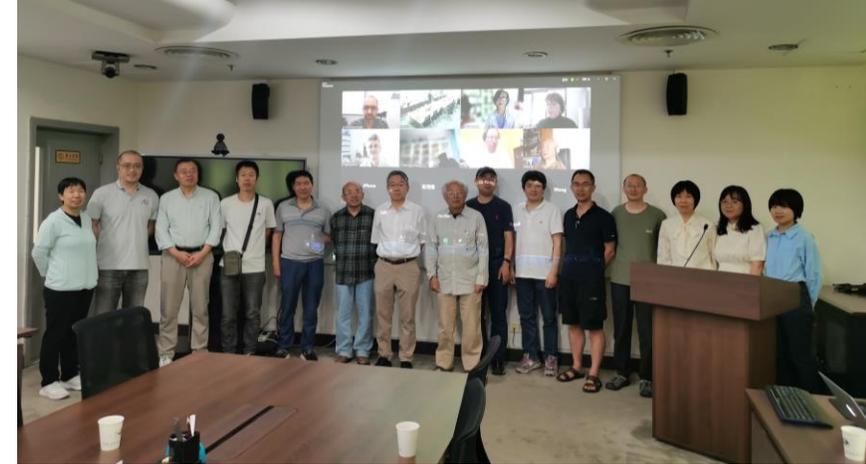
Meeting URL: <https://zoom.us/j/98353925325?pwd=8tp7BHiM7USOb7ezfp0px07RtVcl8M.1>

Duration: 240 min

Password: 539795

Onsite meeting room: IHEP Main building A419

Time	Content	Person	Host
15:00-15:05	Project Overview & Opening Remarks	Project Leader	Jie Gao
15:05-15:10	Introduction of Review Committees	Jie Gao	
15:10-15:30	CEPC booster design and philosophy of combined dipole magnets	Dou Wang	Mika Masuzawa
15:30-16:00	Design and production tolerance analysis of the CEPC Booster dipole-sextuple combined magnets	Wen Kang, Zhihui Mu	
16:00-16:30	Alignment scheme and accuracy analysis of the CEPC Booster dipole-sextuple combined magnets	Xiaolong Wang	
16:30-17:00	CEPC booster error analysis and corrections	Daheng Ji	
17:00-18:40	Q&A and Discussion	All Participants	
18:40-19:00	Closing Remarks & Group photos	Jie Gao	



II. Review Comments

Follow-up on Review Meeting

Dear Experts,

Following the review meeting, Dou Wang will send the final version of the four talks to all experts. Please kindly submit your review comments **by June 13th** to the Review Committee Chair, **Prof. Mika Masuzawa** (mika.masuzawa@kek.jp).

The Chair will compile all feedback, append her digital signature, and return the finalized document to **Jie Gao** (gaoj@ihep.ac.cn) and **Dou Wang** (wangd93@ihep.ac.cn) by **June 20th**.

Thank you for your attention and cooperation.

Best regards,

Dou Wang

Date: May 29th, 2025

Mini-review report



II. Review comments

1. Introduction

The CEPC Booster design includes combined functions dipole-sextupoles. On 29th May 2025, a review of the Booster Combined Magnets was held on-line and in presence at IHEP, as requested by the CEPC IARC. There were four presentations on the Booster combined dipole scheme and the evaluation of beam dynamics necessary to realize the scheme, combined dipole magnet design, magnetic field measurements, installation, and alignment.

The CEPC Booster Ring will require approximately 15,000 dipole magnets, of which 4,034 will be of the normal-conducting combined dipole-sextupole type. These magnets are designed to operate under relatively low magnetic fields. In response to technical and economic challenges, the CEPC team has made remarkable efforts to optimize the power consumption, manufacturing process, and cost efficiency of these magnets, leading to an estimated cost saving of approximately 280 million CNY. We commend the CEPC team's dedication in developing and implementing the combined dipole-sextupole magnet scheme.

2. Presentations

2-1 CEPC booster design and philosophy of combined dipole magnets

The Combined Dipole-Sextupole magnet scheme adopted in the CEPC Booster integrates bending and chromaticity correction functions into a single magnet, significantly reducing the number of components and simplifying the lattice structure. This design leads to a more compact and cost-effective accelerator, with estimated savings of approximately 280 million CNY. The approach also increases the bending

3. Recommendations for the Next IARC-EDR Meeting (September 16–19)

The committee suggests that at the next IARC-EDR meeting (16th-19th September) a few talks be presented:

- Control methods for the tunnel temperature
- Installation procedures of the Booster magnets beam pipe
- Studies of the tolerance to machine errors at all energies, with evaluation of the final emittances and energy spread for injection in the collider
- Simulation of injection at commissioning and orbit correction.

4. Conclusion

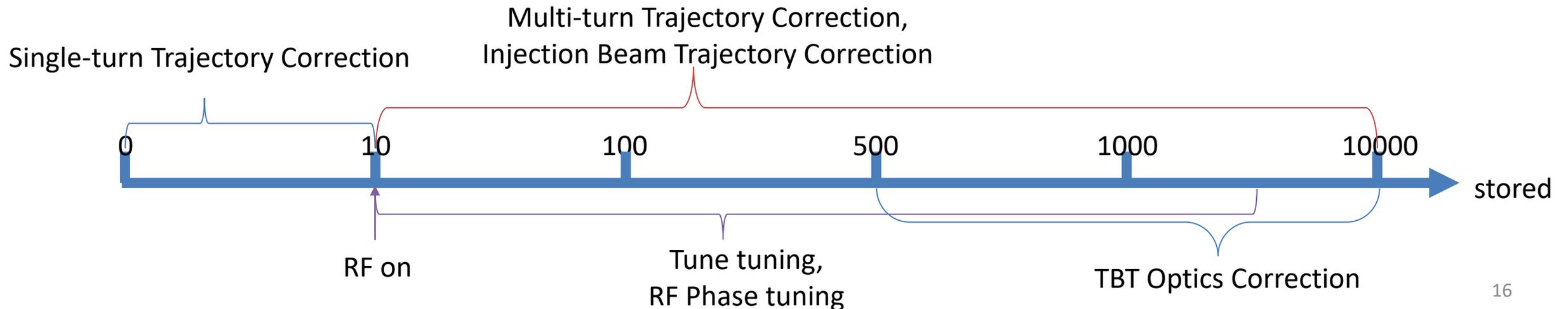
The CEPC team's decision to adopt the combined dipole-sextupole scheme was based on careful consideration of power consumption, manufacturing feasibility, and cost efficiency. Both the Review Committee and the CEPC team acknowledge the importance of continued validation through simulation, prototyping, and alignment studies to ensure the scheme's successful implementation in the Booster ring. The Committee commends the CEPC team for their commitment and dedicated technical efforts in advancing this technically promising approach.

Digital signature:	<i>Mika Masuzawa</i>
Date:	June 23, 2025

- Quick response was send to the review committee. All the recommendations will be addressed at the next meeting of the IARC.

First turn Injection Commissioning

- Recent simulation studies have been conducted on the initial beam commissioning of the CEPC Booster
 - These studies can also serve as a reference for related research on the CEPC storage ring.
- Simulation settings:
 - Physical aperture: 56mm
 - BPM Accuracy and offset: 300um
 - Other error settings are the same as those in ordinary error correction simulations.
 - The injection beam jitter and beam distribution are taken into account.
 - Based on the AT (Accelerator Toolbox) program.
 - Using the response matrices of orbit, trajectory, working point, and injection beam derived from theoretical models.
- A similar correction process has already been applied to the HEPS (High Energy Photon Source) booster and storage ring.

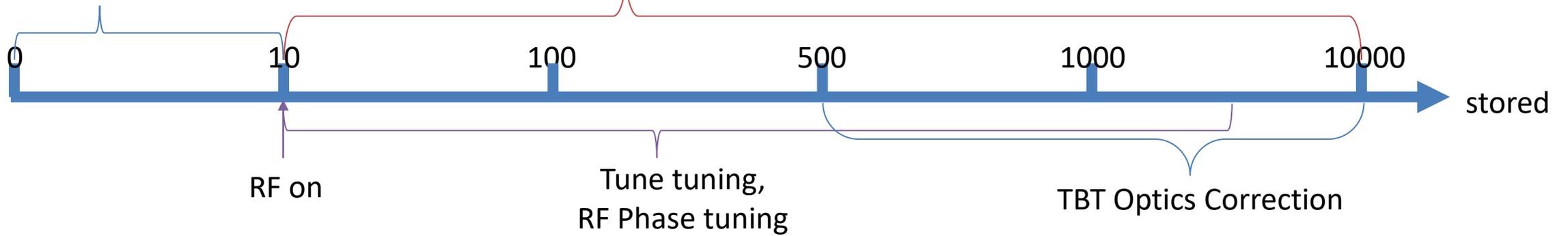


Single-turn and Multi-turn trajectory correction

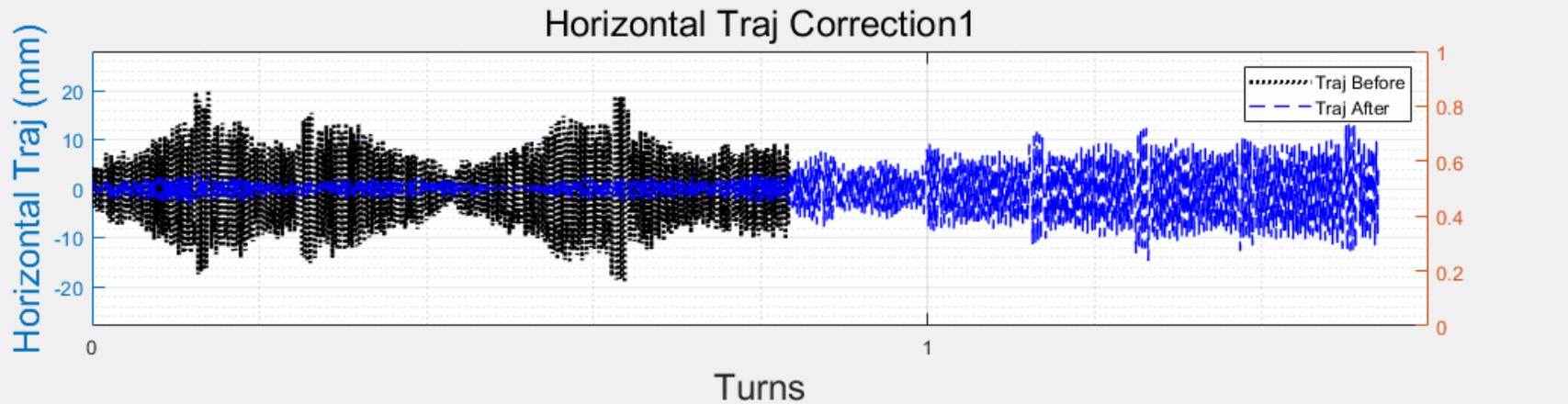
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Single-turn Trajectory Correction

Multi-turn Trajectory Correction,
Injection Beam Trajectory Correction



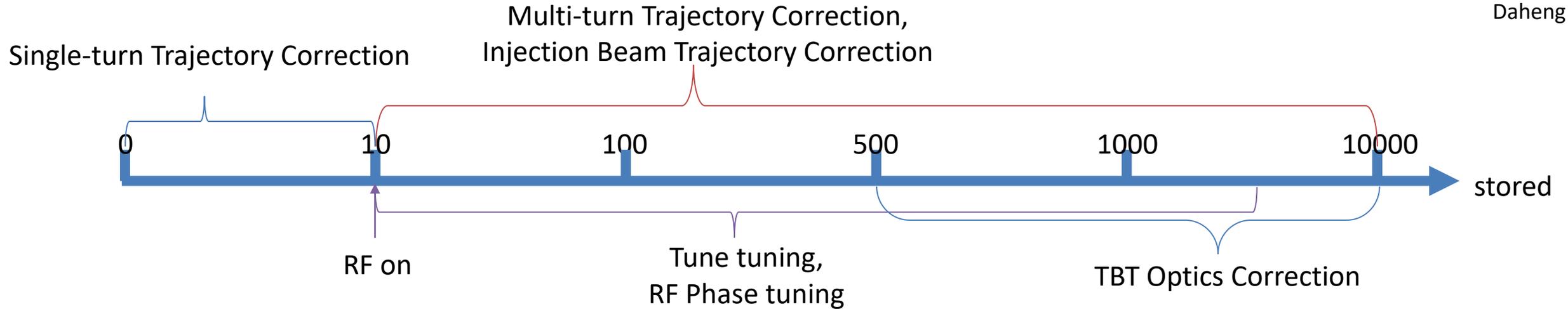
- **Single-turn trajectory correction:** Minimize the trajectory of the beam for the first 5 turns.
- **Multi-turn trajectory correction:** Average the beam trajectory over more than 5 turns to obtain an approximate closed orbit and correct it.



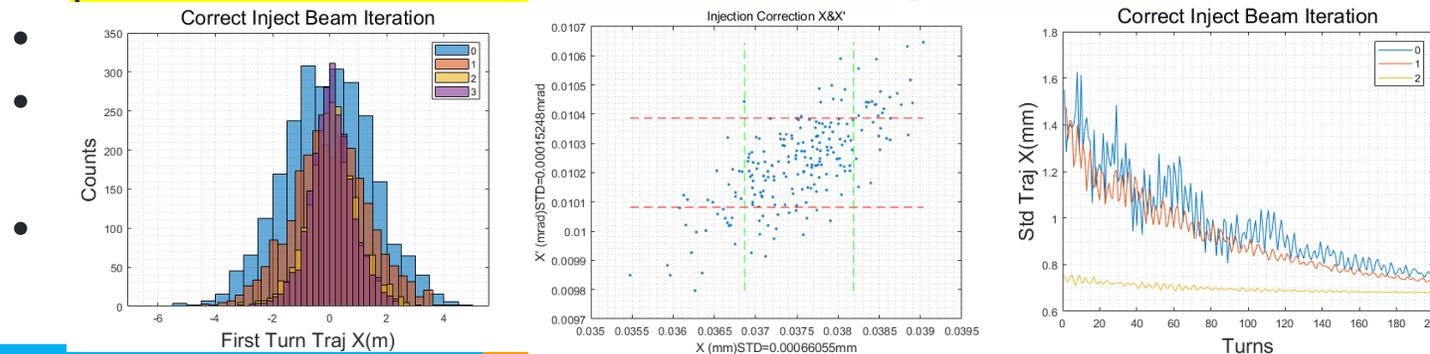
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m over 50 turns.
he horizontal

Injection beam trajectory correction

Daheng Ji



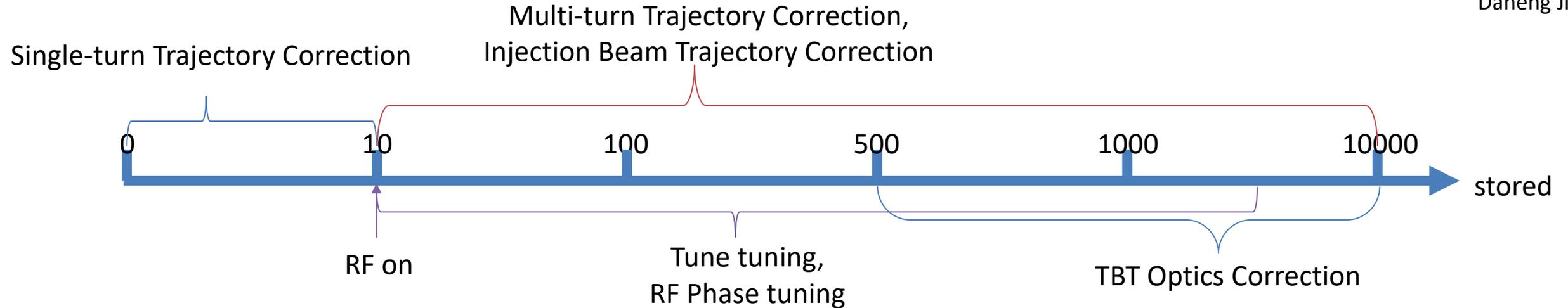
- **Single-turn trajectory correction:** Minimize the trajectory of the beam for the first 5 turns.
- **Multi-turn trajectory correction:** Average the beam trajectory over more than 5 turns to obtain an approximate closed orbit and correct it.
- **Injection beam trajectory correction:** Correct the coordinates of the injection beam at the injection point to reduce the oscillation of the injected beam.



point using the beam over 50 turns. with the average of the horizontal oscillation.

Injection beam trajectory correction

Daheng Ji



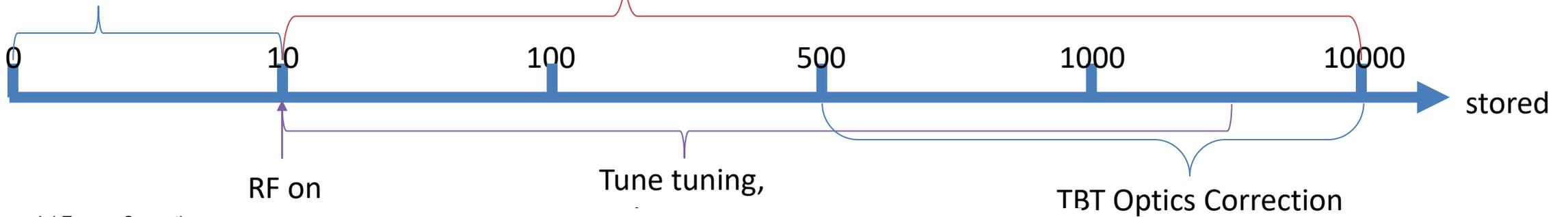
- **Single-turn trajectory correction:** Minimize the trajectory of the beam for the first 5 turns.
- **Multi-turn trajectory correction:** Average the beam trajectory over more than 5 turns to obtain an approximate closed orbit and correct it.
- **Injection beam trajectory correction:** Correct the coordinates of the injection beam at the injection point to reduce the oscillation of the injected beam.
- **Tune adjustment:** Calculate (Phased-CFT) and adjust the working point using the beam over 10 turns.
- **RF parameters adjustment:** Evaluate the beam energy variation with the average of the horizontal trajectory over each turn and adjust the RF parameters to reduce oscillation.
- **Optics correction:** Based on ICA, PCA.

RF parameters adjustment

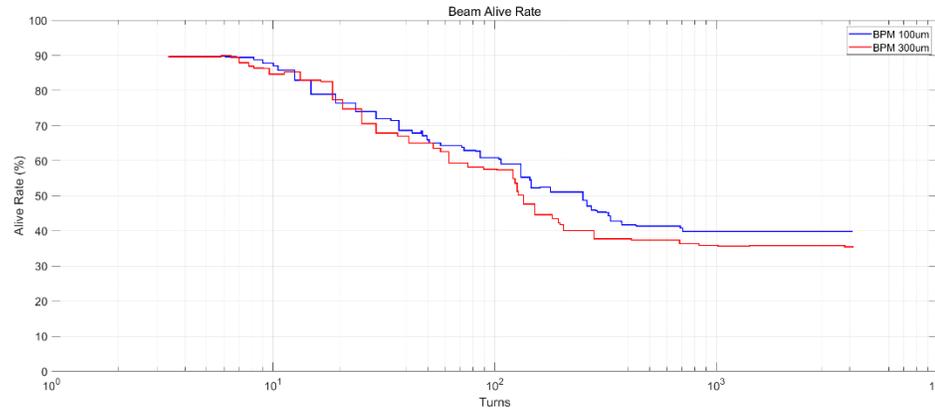
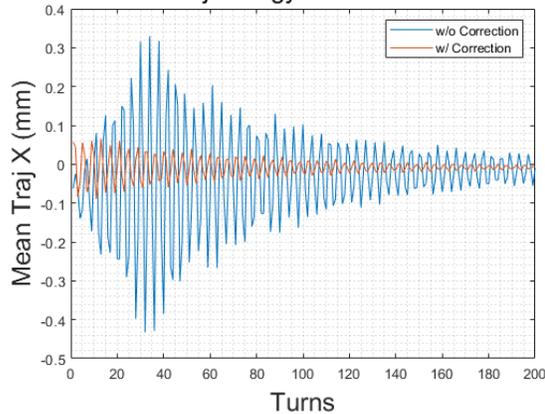
Daheng Ji

Single-turn Trajectory Correction

Multi-turn Trajectory Correction,
Injection Beam Trajectory Correction



Inj Energy Correction



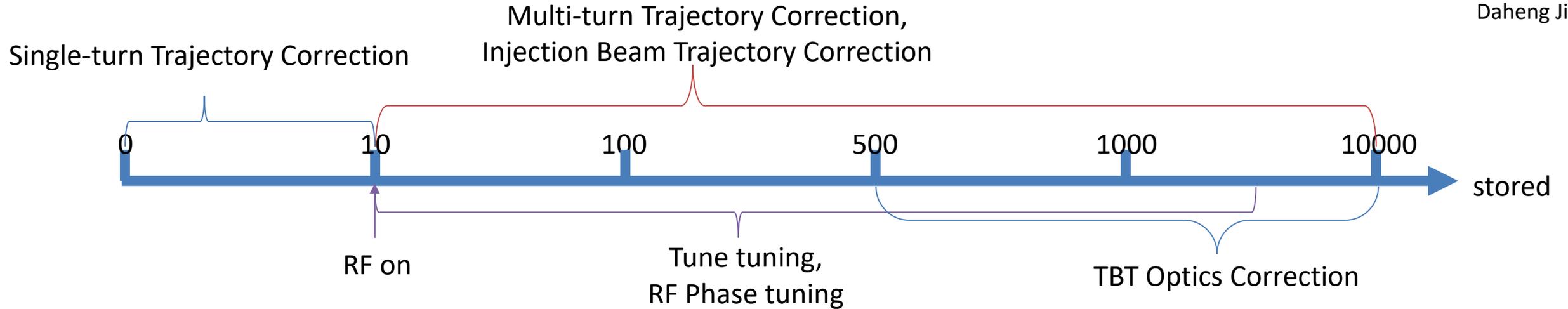
TBT Optics Correction

first 5 turns.
 5 turns to obtain an
 beam at the injection
 the beam over 50 turns.

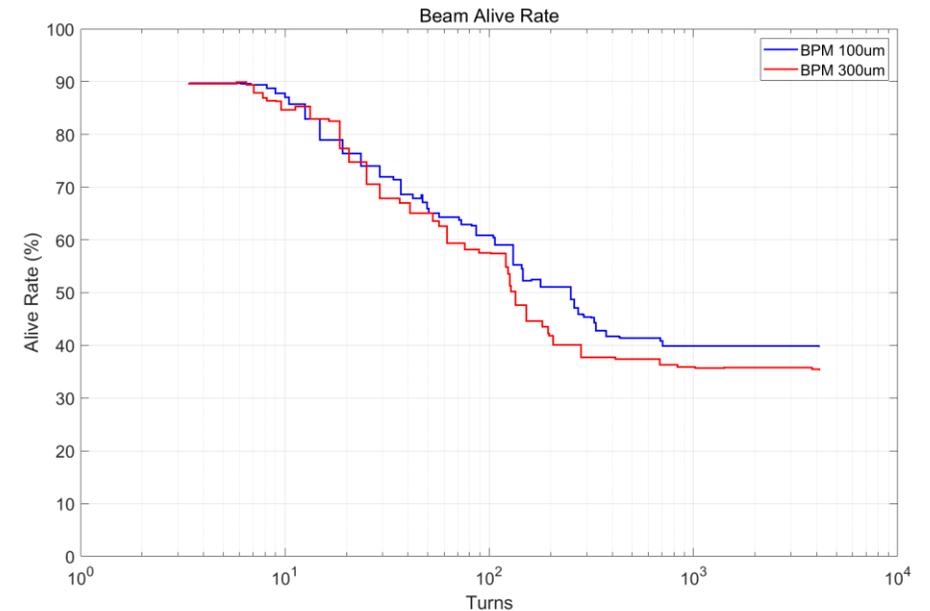
- **RF parameters adjustment:** Evaluate the beam energy variation with the average of the horizontal trajectory over each turn and adjust the RF parameters to reduce oscillation.
- **Optics correction:** Based on ICA, PCA.

Particles survive rate

Daheng Ji



- Results indicate that after correction, approximately 30% of the particles survive for more than 10,000 turns.
 - BPM Noise 300 μm and 100 μm has little impact on the results.
 - This can meet the needs of subsequent more detailed corrections
 - The algorithm is still undergoing optimization.
- The research still lacks many details, with some conditions such as more detailed physical apertures being updated and iterated.

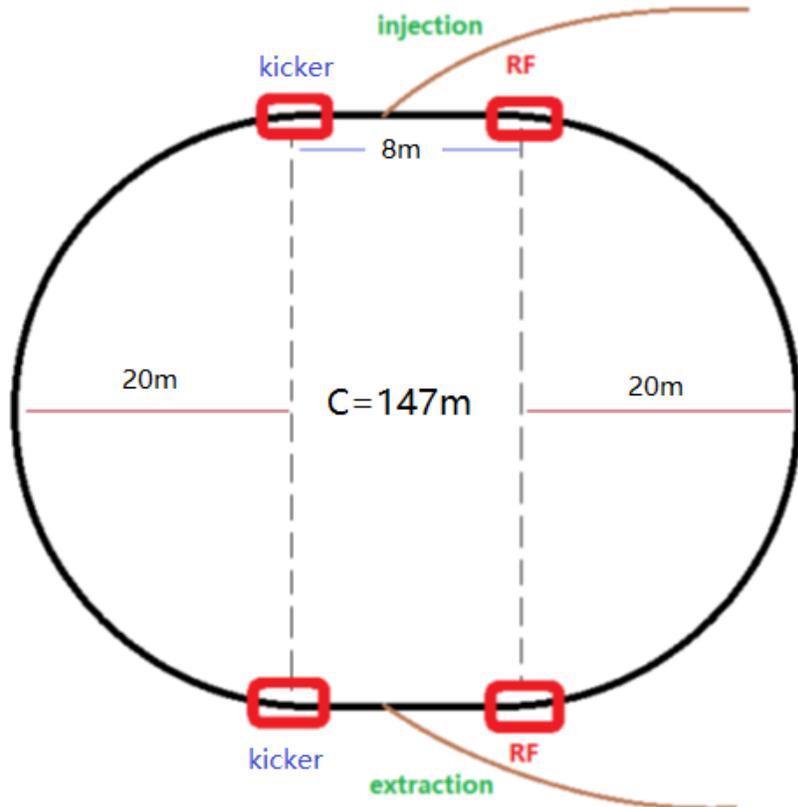


Content

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 - Feasibility evaluation of the combined dipole magnets
 - Mini-review of the combined dipole magnets
 - Simulations of first turn injection commissioning
- **EDR progress of CEPC positron damping ring**
 - DR TDR design status
 - Polarized DR study
- **CEPC timing issue and detector performance**
- **Summary**

DR parameters in TDR

- Damping with **reversed bending magnet**
- **4 (max. 8)-bunch** storage, storage time: **20 (40) ms**
- Emittance: 2500 → **166/75 (97/3) mm.mrad**
- Flexibility for extr. emittance

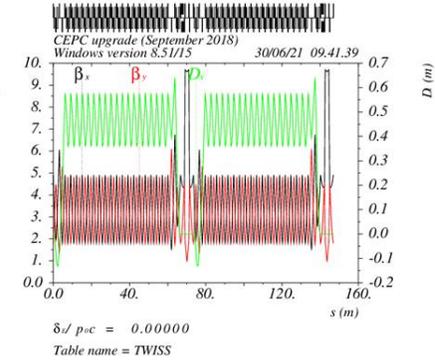
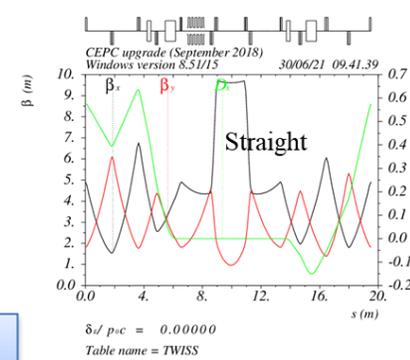
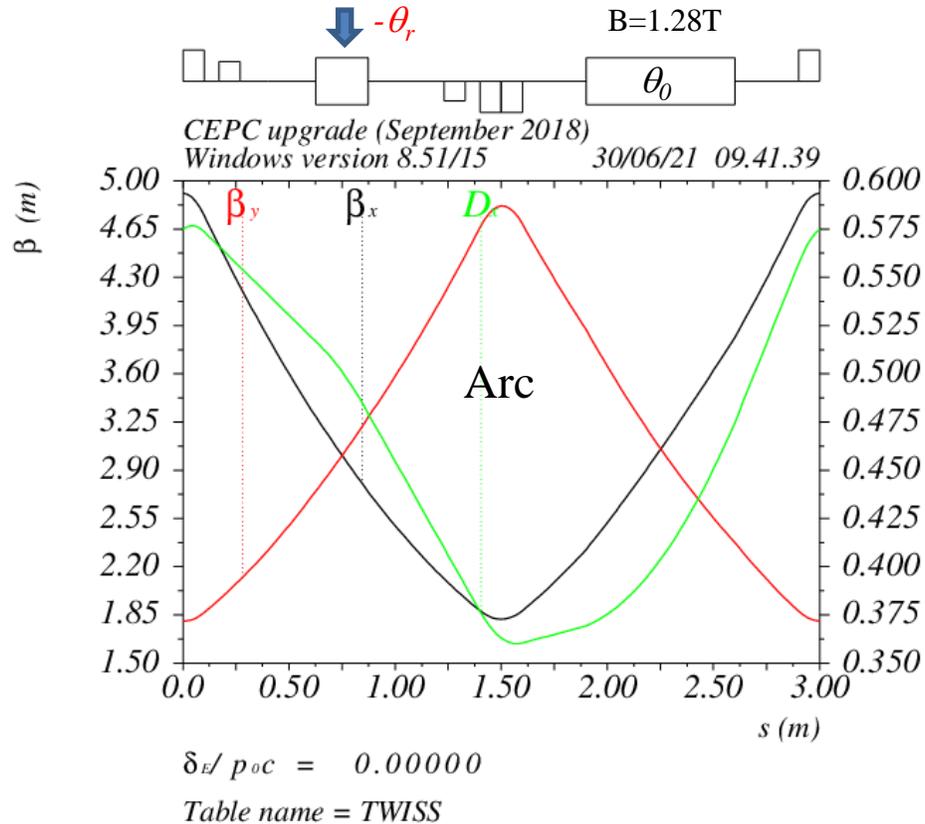


	DR V3.0
Energy (Gev)	1.1
Circumference (m)	147
Number of trains	2 (4)
Number of bunches/train	2
Total current (mA)	12.4 (24.8)
Bending radius (m)	2.87
Dipole strength B_0 (T)	1.28
U_0 (keV/turn)	94.6
Damping time x/y/z (ms)	11.4/11.4/5.7
Phase/cell (degree)	60/60
Momentum compaction	0.013
Storage time (ms)	20 (40)
δ_0 (%)	0.056
ϵ_0 (mm.mrad)	94.4
injection σ_z (mm)	4.4
Extract σ_z (mm)	4.4
ϵ_{inj} (mm.mrad)	2500
$\epsilon_{ext\ x/y}$ (mm.mrad)	166(97)/75(3)
$\delta_{inj}/\delta_{ext}$ (%)	0.18 /0.056
Energy acceptance by RF(%)	1.8
f_{RF} (MHz)	650
V_{RF} (MV)	2.5
Longitudinal tune	0.0387

DR optics and error study

- Phase/cell: $60^\circ/60^\circ$
- Interleave sextupole scheme
- 2 sex. families

- Cell length: 3m
- $B=1.28T$
- $\theta_r/\theta_0=0.355$



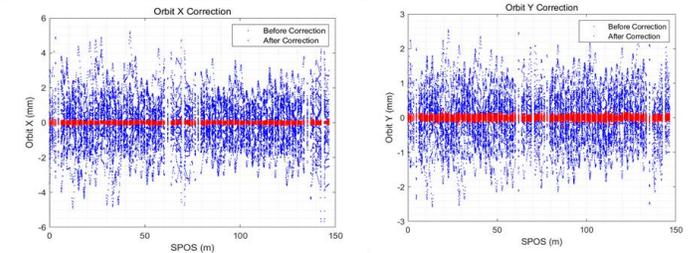
Error study

Parameters	Dipole	Quadrupole	Sextupole
Transverse shift X/Y (μm)	100	100	100
Longitudinal shift Z (μm)	100	150	100
Tilt about X/Y (mrad)	0.2	0.2	0.2
Tilt about Z (mrad)	0.1	0.2	0.1
Nominal field	1×10^{-3}	2×10^{-4}	3×10^{-4}

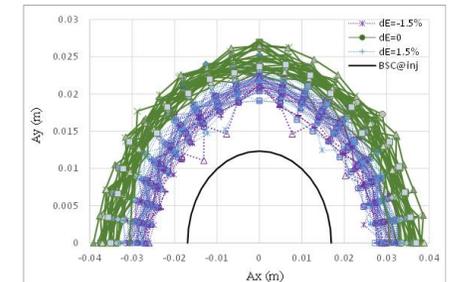
Parameters	BPM (10 Hz)
Accuracy (m)	1×10^{-7}
Tilt (mrad)	10
Gain	5%
Offset after beam based alignment (BBA) (mm)	30×10^{-3}

Dipole	Quadrupole	Sextupoles
$B_1 \leq 2$		
$B_2 \leq 3$	$B_2 \leq 3$	
$B_3 \leq 0.2$	$B_3 \leq 2$	$B_3 \leq 10$
$B_4 \leq 0.8$	$B_4 \leq 1$	$B_4 \leq 3$
$B_5 \leq 0.2$	$B_5 \leq 1$	$B_5 \leq 10$
$B_6 \leq 0.8$	$B_6 \leq 0.5$	$B_6 \leq 3$
$B_7 \leq 0.2$	$B_7 \leq 0.5$	$B_7 \leq 10$
$B_8 \leq 0.8$	$B_8 \leq 0.5$	$B_8 \leq 3$
$B_9 \leq 0.2$	$B_9 \leq 0.5$	$B_9 \leq 10$
$B_{10} \leq 0.8$	$B_{10} \leq 0.5$	$B_{10} \leq 3$

Orbit correction only



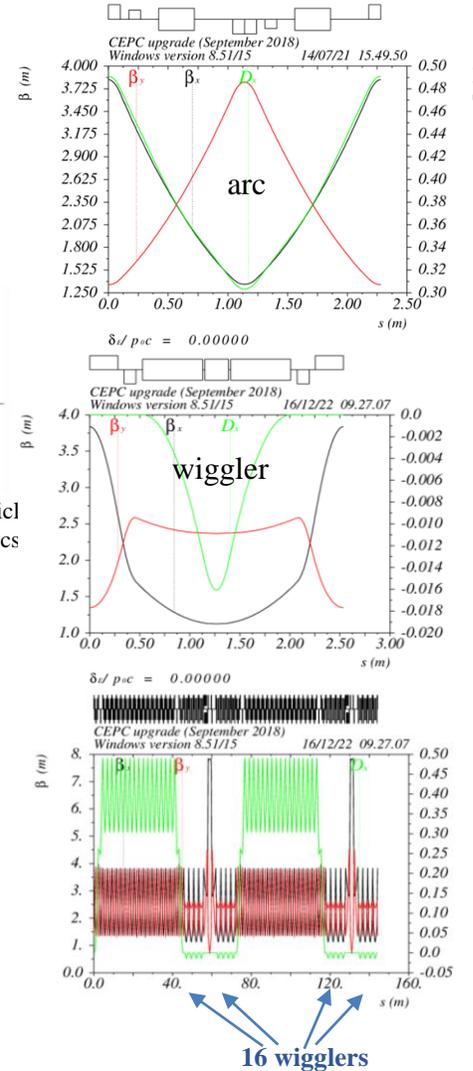
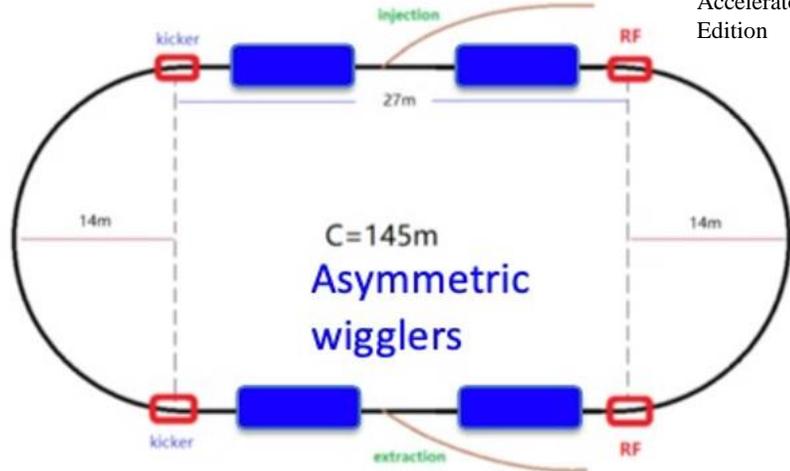
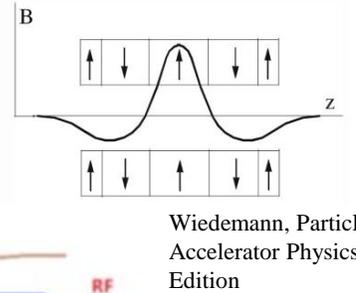
- $BSC_{x,y} = 5\sigma_{inj_{x,y}} + 5\text{mm}$
- Energy acceptance: $8.3\delta_{inj} = 1.5\%$



Alternative design for the DR with polarization

Z. Duan, D. Wang

- Produce polarized positron beam for the purpose of energy calibration @ Z & W*.
 - 10 min storage → ~20% polarization
- Compatible with standard top up operation
- Asymmetric wigglers
 - $B_+ = 1.8T = 5 B_-$
 - cell length = 1.5m

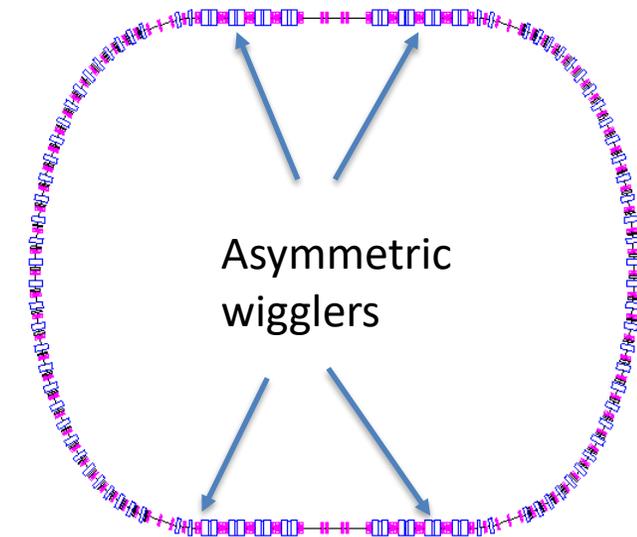
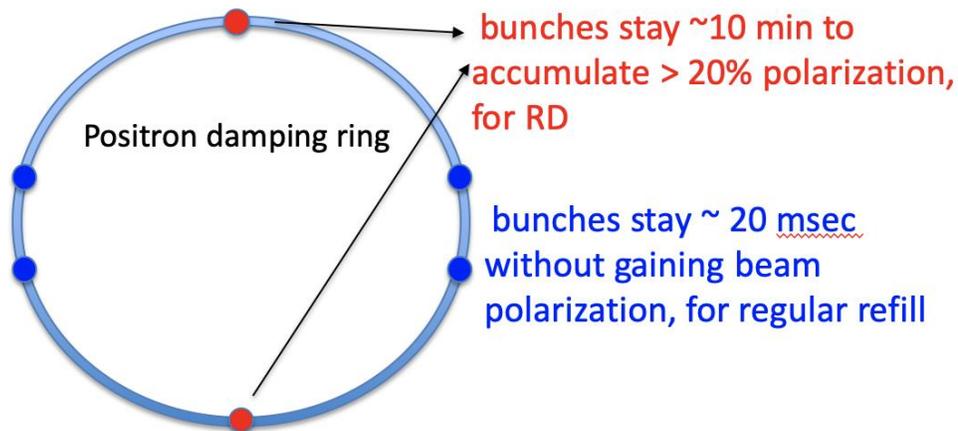


DR V4.0	unpolarized e+	polarized e+
Energy (Gev)	1.542	
Circumference (m)	145	
Number of trains	2(4)	
Number of bunches/train	1(2)	
Total current (mA)	12.4	
Bending radius (m)	3.44	
Dipole strength B_0 (T)	1.5	
Wiggler strength B_+ (T)	1.8	
Wiggler cell length (m)	1.5	
U_0 (kev/turn)	190.9	
Damping time x/y/z (ms)	7.77/7.77/3.89	
Momentum compaction	0.015	
Storage time	20 ms	10 min
δ_0 (%)	0.072	
ϵ_0 (mm.mrad)	138	
injection σ_z (mm)	6	
Extract σ_z (mm)	5.7	5.6
ϵ_{inj} (mm.mrad)	2500	
$\epsilon_{ext x/y}$ (mm.mrad)	150/15	138/14
$\delta_{inj}/\delta_{ext}$ (%)	0.18/0.072	
RF acceptance (%)	1.8	
f_{RF} (MHz)	650	
V_{RF} (MV)	3.95	
Longitudinal tune	0.044	

Positron damping/polarizing ring

Z. Duan

- Optimization of a dual-purpose design
 - Bunches stay ~ 20 msec for regular refill
 - Bunches stay ~ 10 min to accumulate > 20% polarization for resonant depolarization in the Colliders
- Cost and benefit comparison between two schemes
 - Higher beam energy without asymmetric wigglers
 - Lower beam energy with asymmetric wigglers



Content

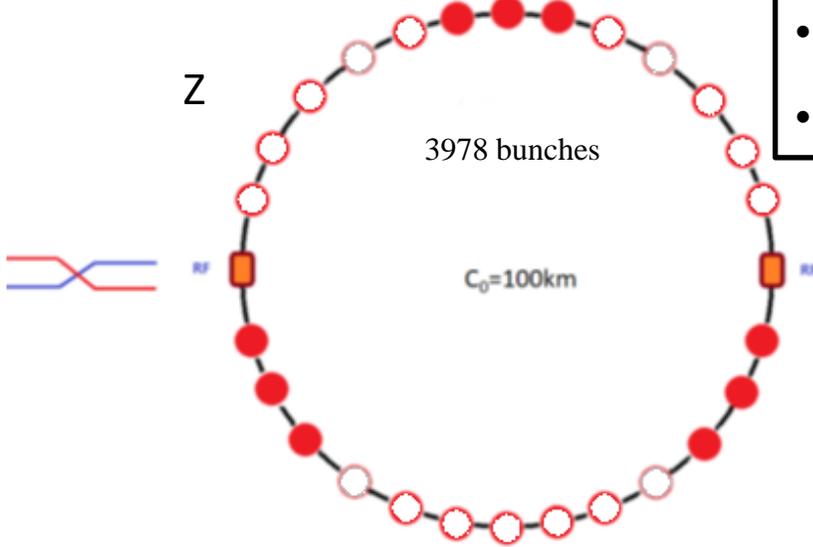
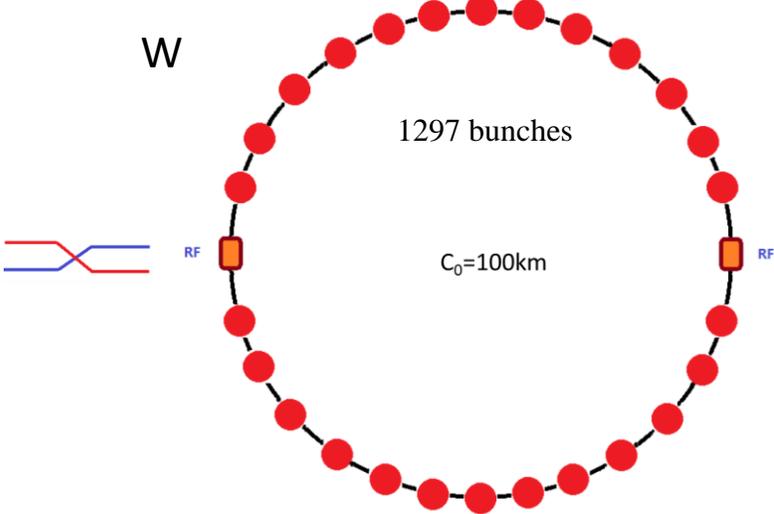
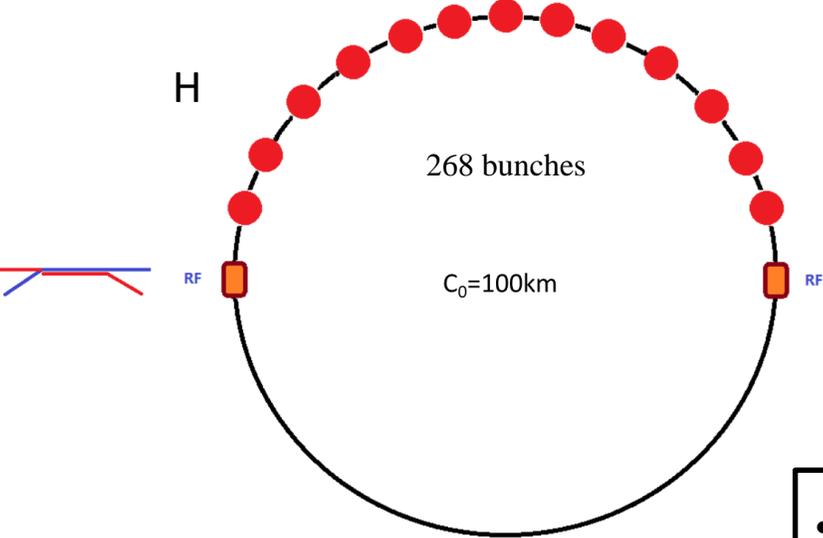
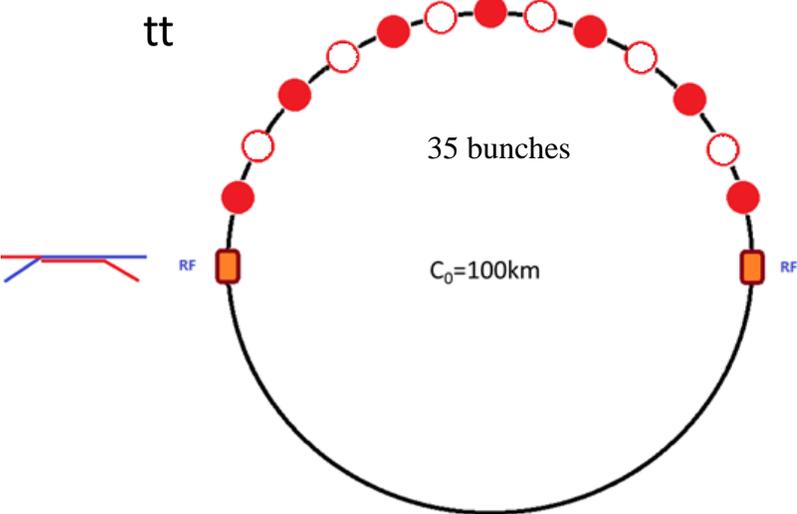
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CEPC frequency choice

f (MHz)		SHB1	SHB2	Linac_S	DR	Linac_C	Booster	Collider
CEPC	Baseline (thermal cathode gun)	158.89	476.76	2860	650	5720	1300	650
	Alternative (RF gun)	—	—	2860	650	5720	1300	650

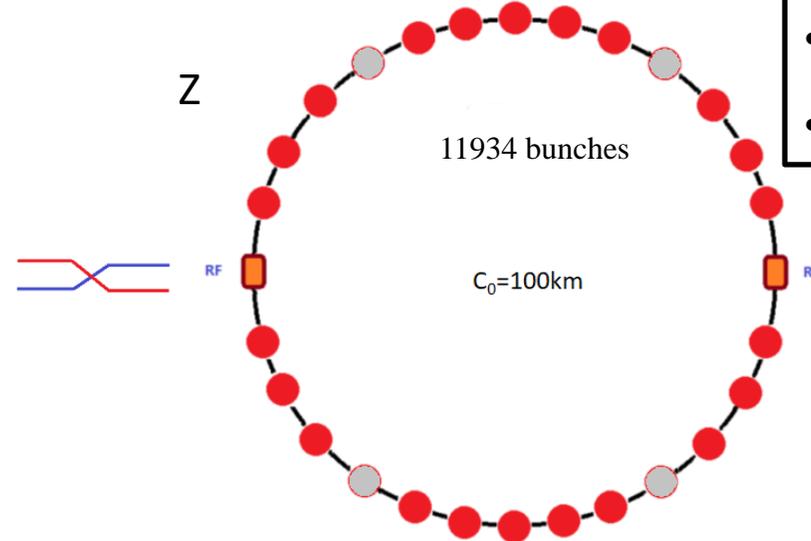
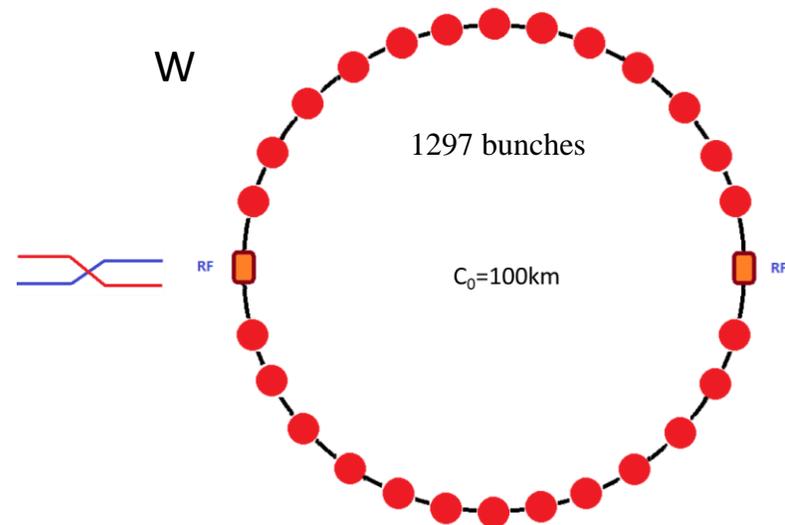
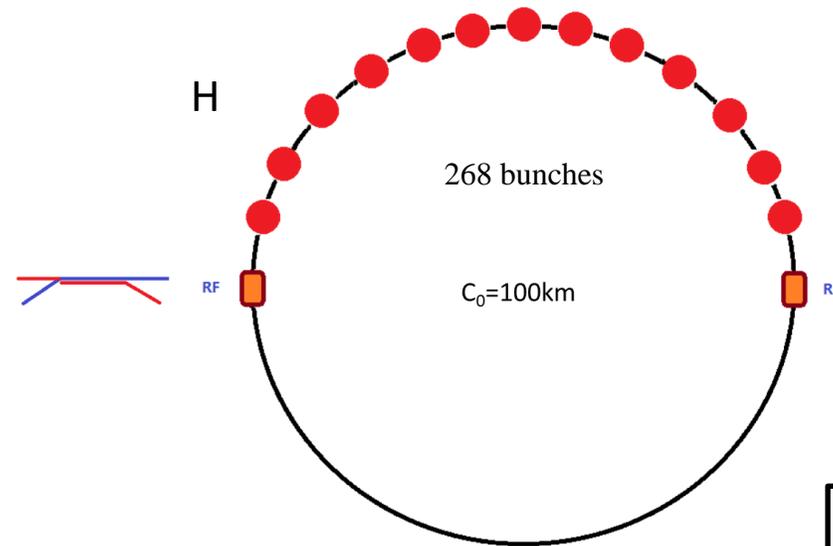
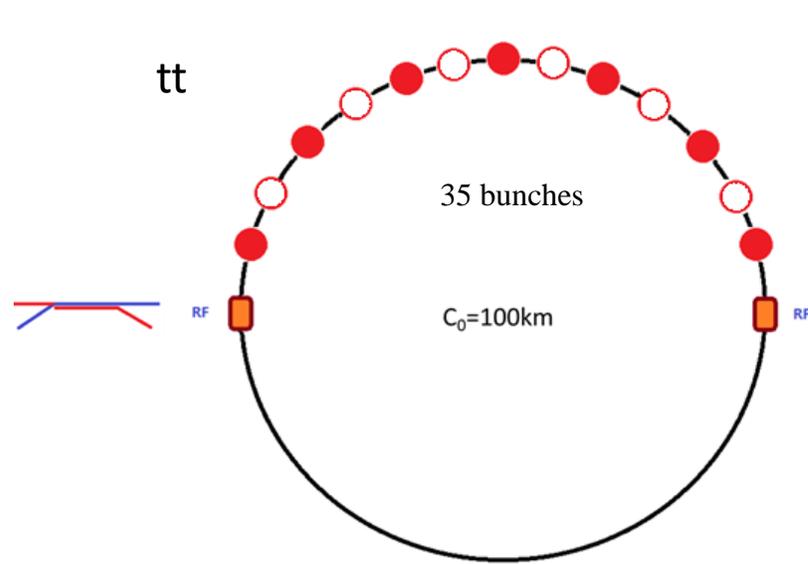
- **CEPC**: greatest common divisor=130 MHz \longrightarrow Min bunch spacing @ rings: 7.6923ns
- Bunch spacing @ Z: $7.6923 \times 3 = 23.0769$ ns
- **FCC**: greatest common divisor=400 MHz \longrightarrow Min bunch spacing @ rings: 2.5 ns

Bunch structure in Booster



- Train structure @Z
- 51 train
- 78 bunch/train

Bunch structure in Collider



- Train structure @Z
- 153 train
- 78 bunch/train

TDR Bunch Structures and Circumference

D. Wang, X. H. Cui, C. Meng, G. Lei, G. Li, J. H. Chen, J. C. Wang, W. Wei...

- The spacings between adjacent bunches in any CEPC operation mode are integer numbers of 23.08 ns..
- The master CEPC clock will be provided by the accelerator to the detector system(s), synchronous to the beam. The CEPC detector system relies on the clock to sample physics signal at the right time.
- It is agreed to have the detector frequency of 43.3 MHz = 130 MHz / 3 = 1 / 23.08 ns, which is reasonably good from the detector point of view.
- The CEPC collider ring have possible 14,442 bunch positions ($14,442 \times 23.0769 \text{ ns} \times c = 99.914 \text{ km}$).

$$14,442 = 2 \times 3 \times 29 \times 83$$

SR 30 / 10 MW	H	Z		W	t \bar{t}
SR power per beam [MW]	30	30	10	30	30
Bunch number	268	11,934	3,978	1,297	35
Bunch spacing* [ns]	576.9	23.1	69.2	253.8	4523.1
[$\times 23.08 \text{ ns}$]	25	1	3	11	196
Train gap [%]	54	17	17	1	53
Luminosity/IP [$\times 10^{34} \text{cm}^{-2} \text{s}^{-1}$]	5.0	115	38	16	0.5

SR 50 MW	H	Z	W	t \bar{t}
SR power per beam [MW]	50			
Bunch number	446	13,104	2,162	58
Bunch spacing* [ns]	346.2	23.1	138.5	2700.0
[$\times 23.08 \text{ ns}$]	15	1	6	117
Train gap [%]	54	9	10	53
Luminosity/IP [$\times 10^{34} \text{cm}^{-2} \text{s}^{-1}$]	8.3	192	26.7	0.8

It is important that **beam collisions are synchronized with a 43.33 MHz clock.**

Circumference finetuning and detector performance improvement

D. Wang, J. Gao, J. C. Wang, X. H. Cui, C. Meng, Y. W. Wang, D. P. Jin, G. Lei, J. H. Chen, Y. H. Li, W. Wei, J. B. Ye, J. Y. Zhai, S. S. Sun, ...

- ❑ CEPC will operate in the **Higgs** and the **LL Z** modes in the first 10 years.
- ❑ The bunch spacing for the **LL Z** mode is **3×23.08 ns**. If the bunching spacing for the Higgs mode is an integer number of 3×23.08 ns, e.g. **24×23.08 ns**, the detector system could benefit more.
- ❑ An estimation of the vertex detector using 65nm CMOS sensor shows that the power consumption per sensor chip is reduced from **310 to 165 mW**, about 47% reduction. This significantly reduces the material budget, hence improve the physics performance.

$$14,448 = 24 \times 3 \times 7 \times 43$$

$$14448 \times 23.08ns \times c = 99955.418m$$

SR 30 / 10 MW	H	Z		W	t \bar{t}
SR power per beam [MW]	30	30	10	30	30
Bunch number	268	11,934	3,978	1,297	35
Bunch spacing* [ns]	553.85	23.08	69.23	184.62	3969.23
Case 14448 [× 23.08 ns]	24	1	3	8	172

SR 50 MW	H	Z	W	t \bar{t}
SR power per beam [MW]	50			
Bunch number	446	13,104	2,162	58
Bunch spacing* [ns]	276.92	23.08	138.46	2584.62
Case 14448 [×23.08 ns]	12	1	6	112

Summary

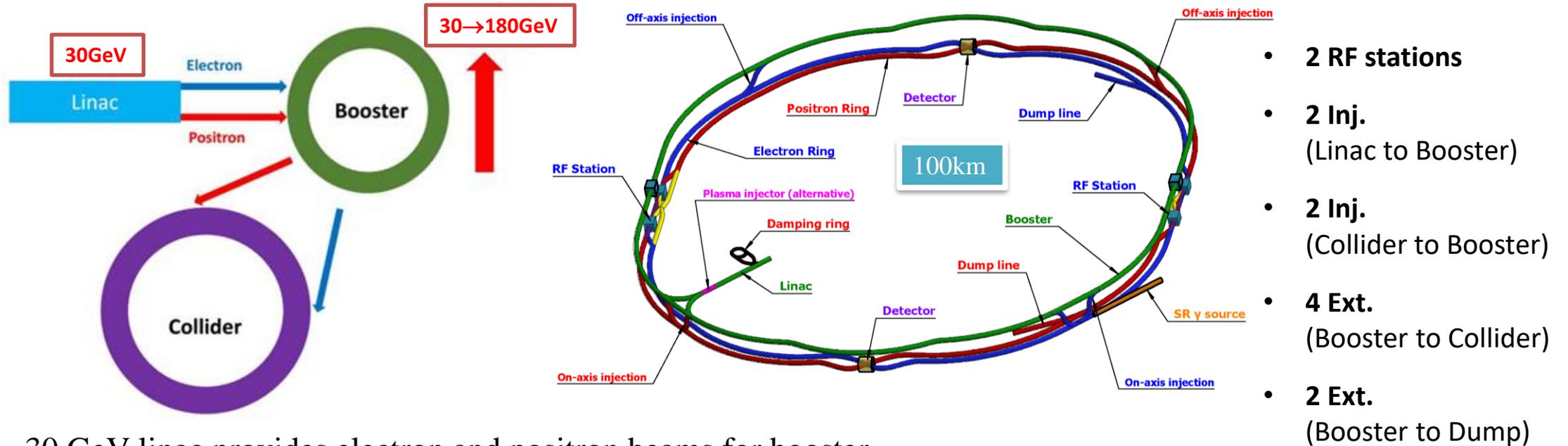
- Feasibility evaluation of the combined dipole magnets has been carried out in EDR. Mini-review finished (May 29th of 2025).
- So far, based on the evaluation of production error and misalignment error, the combined dipole scheme can fulfill the requirement of accelerator physics. Experience will be gradually accumulated through the development of prototype.
- The simulation work for first injection has been updated. The simulation results show that after correction, a beam survival rate of approximately 30% can be achieved after 10,000 turns, which meets the requirements for subsequent routine correction.
- The timing issue of CEPC has been studied between the accelerator team and the detector team. The circumference of CEPC is slightly changed to 99955.418m to improve the detector performance.

**Thanks for your
attention!**

Welcome to suggestions and comments!

Back up

CEPC injector chain



- 30 GeV linac provides electron and positron beams for booster.
- Top up injection for collider ring ~ 3% current decay
- Booster is in the same tunnel as collider ring, above the collider ring, bypass in IRs (same circumference).
- Budget for transfer efficiency **90%**: 95% for booster + 95% for transport lines (inj. to collider).
- Beam current threshold in booster is limited by RF system.
- Feedback systems (Transverse & longitudinal) are needed to damp the instability at low energy.

Booster TDR parameters

- Injection energy: 10GeV → 20GeV → 30GeV
- Max energy: 120GeV → 180GeV
- Lower emittance — new lattice (TME)

Injection		<i>t</i>	<i>H</i>	<i>W</i>	<i>Z</i>	
Beam energy	GeV			30		
Bunch number		35	268	1297	3978	5967
Threshold of single bunch current	μA	8.68	6.3	5.8		
Threshold of beam current (limited by coupled bunch instability)	mA	97	106	100	93	96
Bunch charge	nC	1.1	0.78	0.81	0.87	0.9
Single bunch current	μA	3.4	2.3	2.4	2.65	2.69
Beam current	mA	0.12	0.62	3.1	10.5	16.0
Growth time (coupled bunch instability)	ms	2530	530	100	29.1	18.7
Energy spread	%	0.025				
Synchrotron radiation loss/turn	MeV	6.5				
Momentum compaction factor	10 ⁻⁵	1.12				
Emittance	nm	0.076				
Natural chromaticity	H/V	-372/-269				
RF voltage	MV	761.0	346.0	300.0		
Betatron tune ν_x/ν_y		321.23/117.18				
Longitudinal tune		0.14	0.0943	0.0879		
RF energy acceptance	%	5.7	3.8	3.6		
Damping time	s	3.1				
Bunch length of linac beam	mm	0.4				
Energy spread of linac beam	%	0.15				
Emittance of linac beam	nm	6.5				

Extraction		<i>t</i>	<i>H</i>		<i>W</i>	<i>Z</i>	
		Off axis injection	Off axis injection	On axis injection	Off axis injection	Off axis injection	
Beam energy	GeV	180	120		80	45.5	
Bunch number		35	268	261+7	1297	3978	5967
Maximum bunch charge	nC	0.99	0.7	20.3	0.73	0.8	0.81
Maximum single bunch current	μA	3.0	2.1	61.2	2.2	2.4	2.42
Threshold of single bunch current	μA	91.5	70		22.16	9.57	
Threshold of beam current (limited by RF system)	mA	0.3	1		4	16	
Beam current	mA	0.11	0.56	0.98	2.85	9.5	14.4
Growth time (coupled bunch instability)	ms	16611	2359	1215	297.8	49.5	31.6
Bunches per pulse of Linac		1	1		1	2	
Time for ramping up	s	7.1	4.3		2.4	1.0	
Injection duration for top-up (Both beams)	s	29.2	23.1	31.8	38.1	132.4	
Injection interval for top-up	s	65	38		155	153.5	
Current decay during injection interval		3%					
Energy spread	%	0.15	0.099		0.066	0.037	
Synchrotron radiation loss/turn	GeV	8.45	1.69		0.33	0.034	
Momentum compaction factor	10 ⁻⁵	1.12					
Emittance	nm	2.83	1.26		0.56	0.19	
Natural chromaticity	H/V	-372/-269					
Betatron tune ν_x/ν_y		321.27/117.19					
RF voltage	GV	9.7	2.17		0.87	0.46	
Longitudinal tune		0.14	0.0943		0.0879	0.0879	
RF energy acceptance	%	1.78	1.59		2.6	3.4	
Damping time	ms	14.2	47.6		160.8	879	
Natural bunch length	mm	1.8	1.85		1.3	0.75	
Full injection from empty ring	h	0.1	0.14	0.16	0.27	1.8	0.8

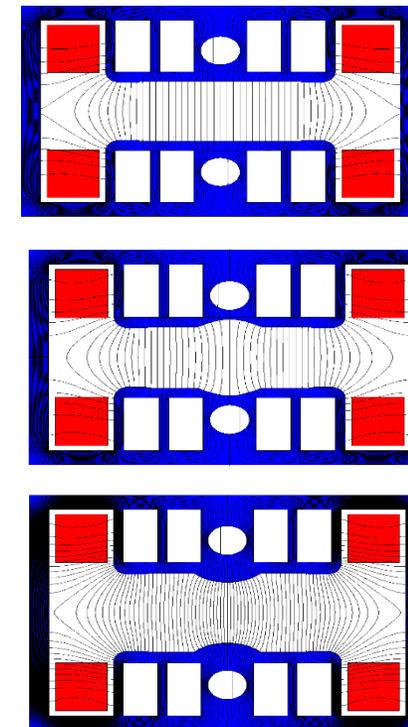
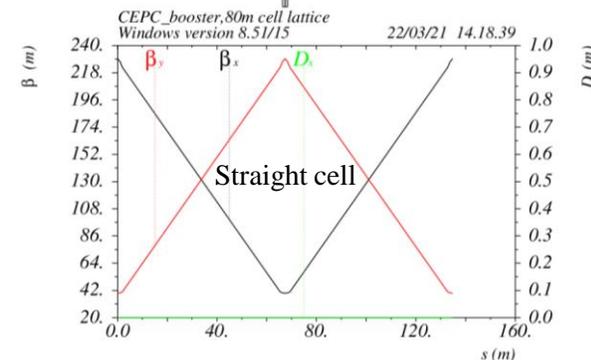
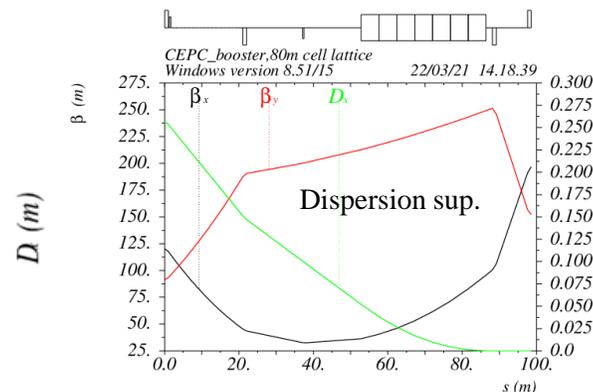
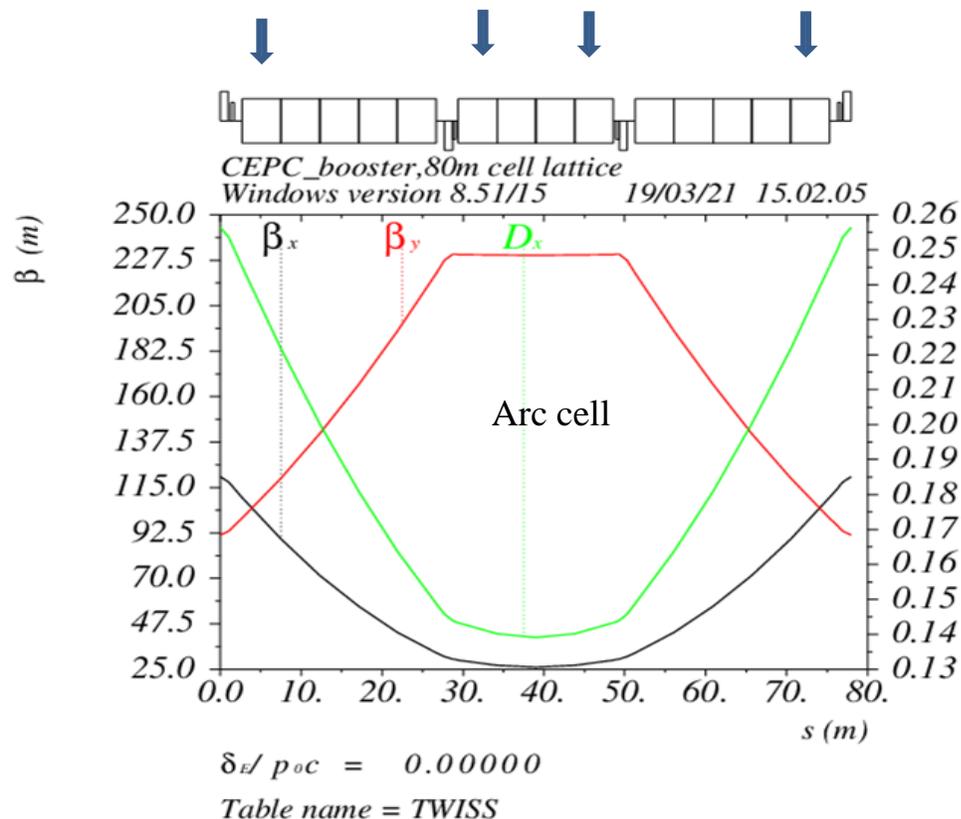
*Diameter of beam pipe is 56mm for re-injection with high single bunch current @120GeV.

Booster TDR optics

D. Wang, C. H. Yu, D. H. Ji,
Y. M. Peng, X. H. Cui,...

- Arc: TME like structure (cell length=78m)
- Interleave sextupole scheme
- Emittance@120GeV=1.26nm

- Overall idea: uniform distribution for the Q
- Combined magnet (B+S) scheme + 100 sextupoles
- Phase advance/cell: 100° (H) / 28° (V)



Main advantage of combined magnets (D+S)

- Cost saving (Unit: 10000 CNY): **280 Million CNY** (compared with independent sext. scheme)

-- Magnets : $3026 * 6 = 18156$

-- Power supply: 10000 (PS: 2000, cables: 8000)

✓ 8 groups sext. in each 1/8 arc

		number	Unit price (CNY)
Independent sextupole		3026	60000
Power supply	PS	64	300000
	Cables	1280 (km)	63 /m

- Increase the filling factor of dipoles to reduce the SR U0 as much as possible
 - Total Length of independent sextupoles : ~1.8 km
- Good synchronization for dynamics operation mode
- Small saving for the power consumption: 0.56~1.1MW

Error Set in Simulation

- Simulation based on Accelerator Toolbox(AT) Code.

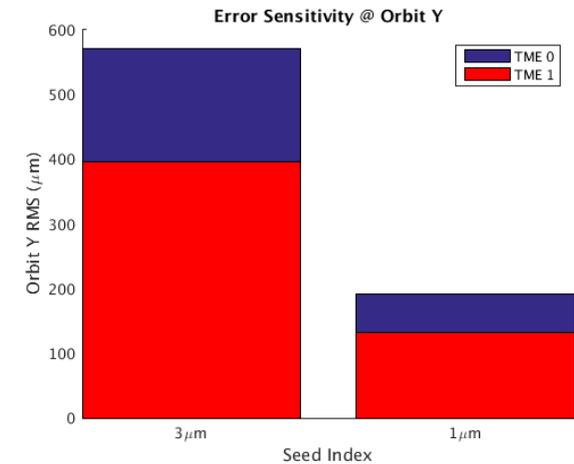
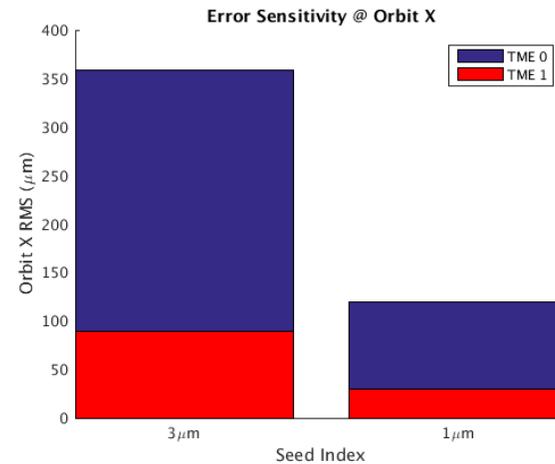
3σ cutoff	Dipole/Sextupole	Quadrupole
Transverse shift X/Y (μm)	300(old:100)	100
Longitudinal shift Z (μm)	100	150
Tilt about X/Y (mrad)	0.2	0.2
Tilt about Z (mrad)	0.2	0.2
Nominal field	1e-3/3e-4	2e-4

	Accuracy (μm)	Tilt (mrad)	Gain	Offset w/ BBA (μm)
BPM(10Hz)	0.1	10	5%	30
BPM(TBT@1 st Turn)	300	10	5%	300

#BPM: 2408

#Corrector: 2000

Dipole	Quadrupole
$B1/B0 \leq 2 \times 10^{-4}$	
$B2/B0 \leq 5 \times 10^{-4}$	$B2/B1 \leq 3 \times 10^{-4}$
$B3/B0 \leq 2 \times 10^{-5}$	$B3/B1 \leq 2 \times 10^{-4}$
$B4/B0 \leq 8 \times 10^{-5}$	$B4/B1 \leq 1 \times 10^{-4}$
$B5/B0 \leq 2 \times 10^{-5}$	$B5/B1 \leq 1 \times 10^{-4}$
$B6/B0 \leq 8 \times 10^{-5}$	$B6/B1 \leq 5 \times 10^{-5}$
$B7/B0 \leq 2 \times 10^{-5}$	$B7/B1 \leq 5 \times 10^{-5}$
$B8/B0 \leq 8 \times 10^{-5}$	$B8/B1 \leq 5 \times 10^{-5}$
$B9/B0 \leq 2 \times 10^{-5}$	$B9/B1 \leq 5 \times 10^{-5}$
$B10/B0 \leq 8 \times 10^{-5}$	$B10/B1 \leq 5 \times 10^{-5}$



Simulations show that due to the improved uniformity of quadrupole magnet strength, the sensitivity of the beam to errors in the new design has been significantly optimized.

Mini-Review for CEPC EDR Combined Magnets



- First CEPC IARC EDR Review (Sep. 18-20, 2024)
- Report of First CEPC IARC EDR Review

CEPC IARC EDR Review Committee

11 October 2024

A.3 CEPC Magnets (both collider and booster) (Wen Kang, Mei Yang)

A.3.1 Comments

For the booster magnet mass-production preparation, it is important to clarify the quantitative goal of automatic magnet-production lines to be demonstrated at an appropriate scale, during the EDR phase. Questions include how many magnets, in which level of production period and the yield. In this context the plans for setting up production and test facilities for magnets in the coming few years are important to achieve the EDR goals.

The combination of iron-steel lamination (1 mm) and aluminum lamination (2 mm) is a cost-effective selection. On the other hand, replacement of aluminum with plastic sheet should be carefully investigated and qualified in terms of long-term stability/sustainability and degradation caused by radiation damage.

The Committee notes with concern the choice of combined-function magnets (dipoles/sextupoles) for the booster ring, driven by economy in capital costs (260 MCNY) and reduced power consumption. The Committee notes that combined-function systems are notoriously complex in commissioning and operation. This choice still needs to be carefully justified, balancing cost-effective production with operational complexity. The Committee encourages further justification for the effectiveness of the combined-function dipoles.

The Committee also advises a thorough analysis of the alignment strategy with initial misalignment of 200 μm instead of the currently studied 100 μm , which the Committee finds too restrictive.

The Committee would appreciate summary tables with the key specifications of all magnet species, including power consumption of the magnets and their associated bus-bars.

The Committee notes that a lot of the 3D magnet-simulation work is still to be advanced and is eager to see the final results, notably on field-quality errors.

The unit length of 5m would be appropriate but the full length of 20 m might need to be further optimized, depending on the site optimization and the design of vertical shafts.

As a part of the magnet-production study, the field-measurement strategy should be clarified, to ensure that it covers wide ranges of the magnetic field strength and quality, as well as alignment.

A.3.2 Recommendations

1. Clarify the plan of the automatic magnet-production line, while satisfying the performance criteria, including the field qualification strategy at the appropriate time scale and production yield;
2. The pros and cons of the combined-function magnets shall be carefully evaluated with more information and advice from other machine's experience;
3. Provide summary tables for the collider and booster magnets specifications including the field quality.

Fiducialisation error based on magnetic center

■ Rotating coil magnetic center measurement error is estimated to be **0.4mm**.(from magnet engineer)

■ Measurement error of relating the rotation center of the coil to the fiducials of the magnet

- Laser tracker transversal and vertical measurement error 0.03mm
- Laser tracker pitch and yaw measurement error $0.03\text{mm} / 5\text{m} = 0.006 \text{ mrad}$

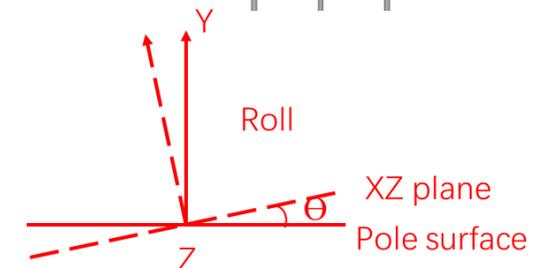
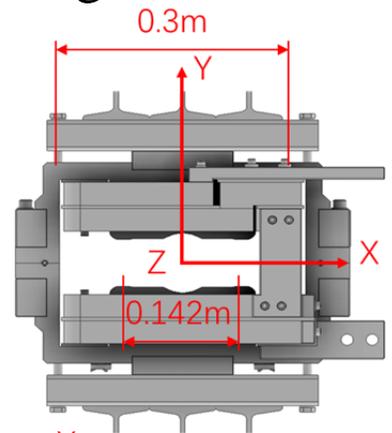
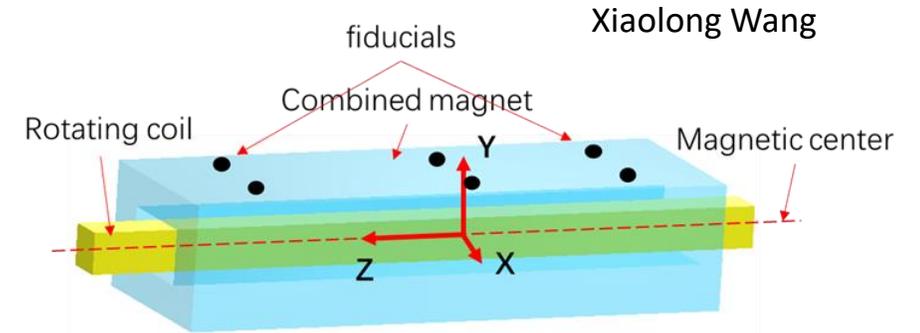
■ The total fiducialisation error based on integral magnetic center

1. Integral magnetic center transversal and vertical fiducialisation error

$$\sqrt{0.4^2 + 0.03^2} = 0.401\text{mm}$$

2. Roll (θ_Z) fiducialisation error $0.02\text{mm}/0.142\text{m}=0.14 \text{ mrad}$

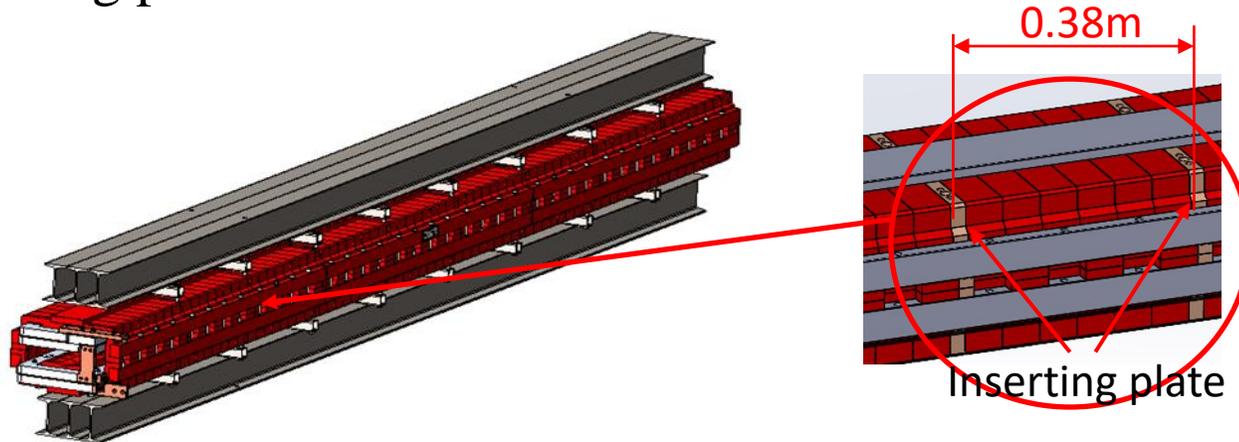
3. Pitch and yaw fiducialisation error $\sqrt{0.016^2 + 0.006^2} = 0.017\text{mrad}$



Alignment method based on mechanical center

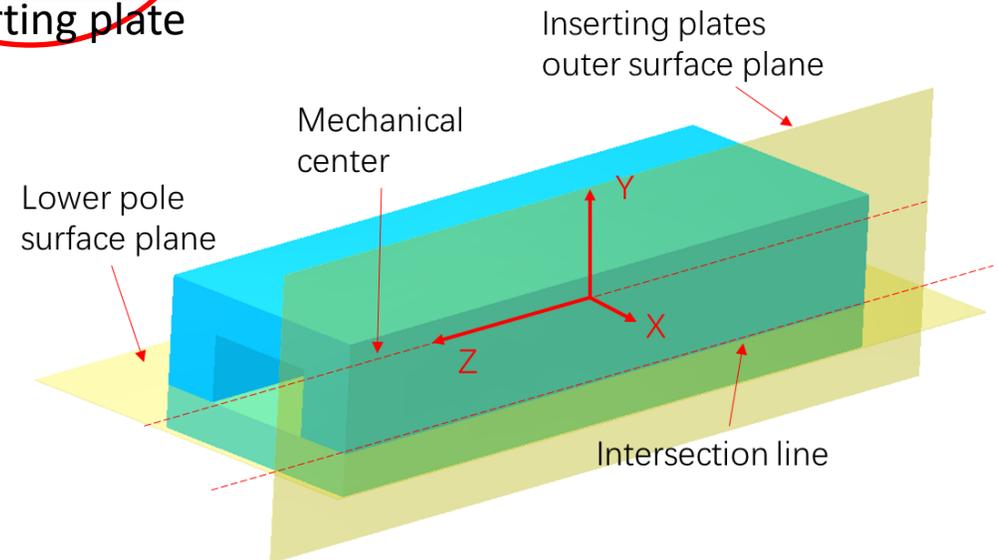
Xiaolong Wang

- Using a laser tracker to perform the measurement. By measuring the lower pole surface and the inserting plate outer surface to determine the mechanical center position.



There are 13 inserting plates along the magnet longitudinal direction.

- Using the measurement points best-fit two planes, obtain the intersection line of the two planes.
- Move the intersection line to the magnet center according to the design dimensions, obtain the mechanical center.



Fiducialisation error based on mechanical center

Xiaolong Wang

- Taking into account laser tracker measurement error and the inserting plates machining error (0.03mm), we estimate **the transversal and vertical measurement error of the mechanical center is about 0.05mm.**
- The mechanical structure of a magnet is highly correlated with the distribution of its magnetic field, so we can determine the integral magnetic center by the mechanical center. HEPS: transversal and vertical difference between magnetic center and mechanical center is 0.02mm(1 σ). Considering the combined magnet has a more complex magnetic field, longer dimension and a larger aperture than HEPS magnets, we estimate **the difference between integral magnetic center and mechanical center in transversal and vertical is about 0.05mm(1 σ) for the combined magnet.**
- The integral magnetic center fiducialisation error in transversal and vertical include the mechanical center measurement error and the difference between the mechanical center and the integral magnetic center, the total error is about $\sqrt{0.05^2 + 0.05^2} = 0.071mm$

Comparison between requirements and achievement

	Requirements	Achievements
Offset of integrated sextupole center (RMS)	$\leq 150\mu\text{m}$ (Horizontal) / $150\mu\text{m}$ (Vertical)	$100\mu\text{m}$ (Horizontal) / $102\mu\text{m}$ (Vertical) *
Magnet straightness along z (MAX)	$\leq 1.5\text{mm}$ (Horizontal) / 1.0mm (Vertical)	1.5mm (Horizontal) / 0.2mm (Vertical)

* Alignment based on mechanical center measurement