Institute of High Energy Physics
Chinese Academy of Sciences

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THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

CEPC Booster and Damping Ring

Dou Wang

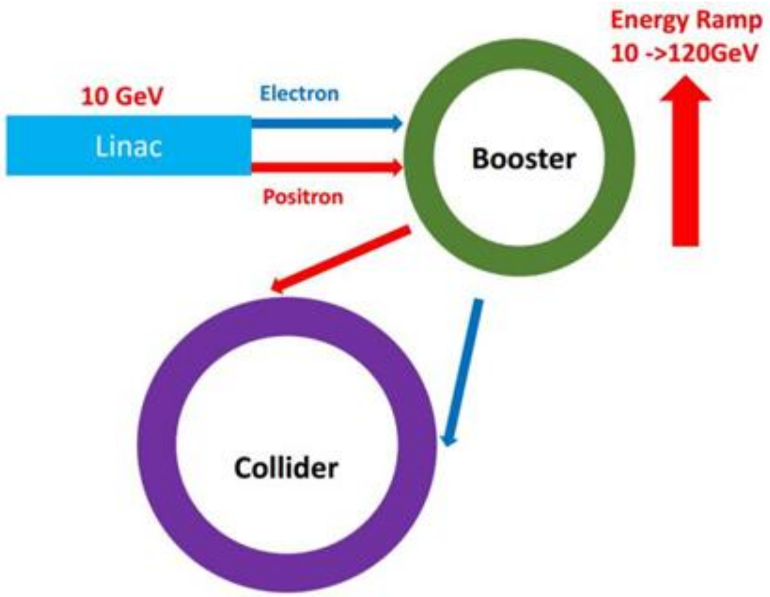
on behalf of CEPC AP group

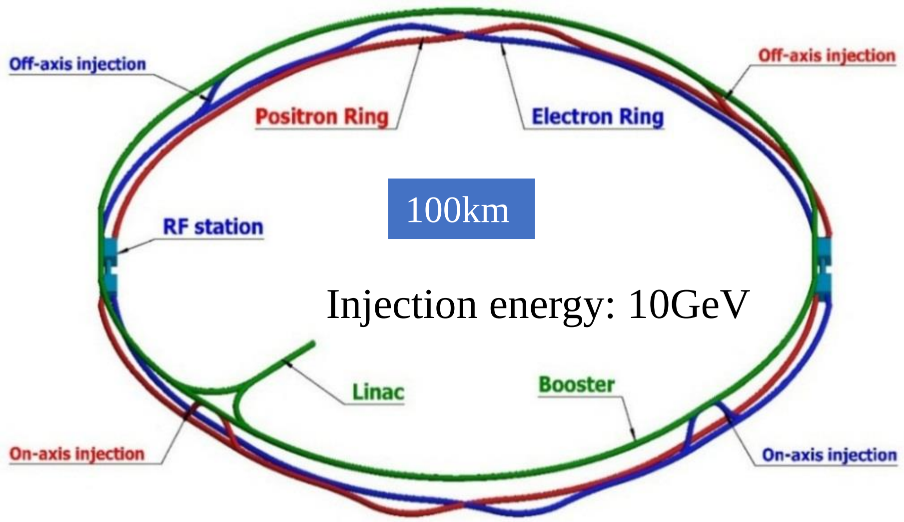
IAS Program on High Energy Physics, Jan. 14-21, 2020.

outline

- CEPC booster status
  - New booster design with lower emittance
    - TME & FODO
  - Injection scheme update
  - Impacts of Detector Stray Field
  - Table ramping scheme
- CEPC Damping Ring status
  - Damping ring
  - Transport lines between DR and Linac
- Summary

CEPC injector chain



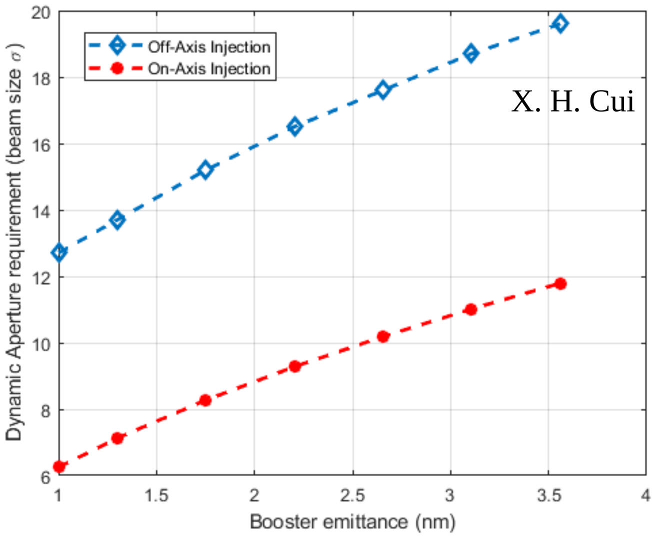


- 10 GeV linac provides electron and positron beams for booster.
- Top up injection for collider ring ~ 3% current decay
- Booster is in the same tunnel as collider ring, above the collider ring.
- Booster has the same geometry as collider ring except for the two IRs.
- Booster bypasses the collider ring from the outer side at two IPs.

CEPC high lum. Higgs parameters

	Higgs (CDR)	*Higgs*
Number of IPs	2	2
Energy (GeV)	120	120
Circumference (km)	100	100
SR loss/turn (GeV)	1.73	1.8
Half crossing angle (mrad)	16.5	
Piwinski angle	3.48	4.87
N_e/bunch (10^{10})	15.0	16.3
Bunch number	242	214
Beam current (mA)	17.4	16.8
SR power /beam (MW)	30	30
Bending radius (km)	10.7	10.2
Momentum compaction (10^{-6})	11.1	7.34
β_{IP} x/y (m)	0.36/0.0015	0.33/0.001
Emittance x/y (nm)	1.21/0.0024	0.68/0.0013
Transverse σ_{IP} (um)	20.9/0.06	15.0/0.037
ξ_x/ξ_y/IP	0.018/0.109	0.018/0.115
V_{RF} (GV)	2.17	2.27
f_{RF} (MHz) (harmonic)	650 (217500)	
Nature bunch length σ_z (mm)	2.72	2.25
Bunch length σ_z (mm)	4.4	4.42
Energy spread (%) (SR/BS)	0.1/0.134	0.1/0.19
Energy acceptance requirement (%)	1.35	1.7
Energy acceptance by RF (%)	2.06	2.5
Lifetime due to beamstrahlung (min)	80	41
Lifetime (min)	25	21
F (hour glass)	0.89	0.88
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	**2.93**	**5.0**

- Horizontal DA requirement of collider ring due to injection

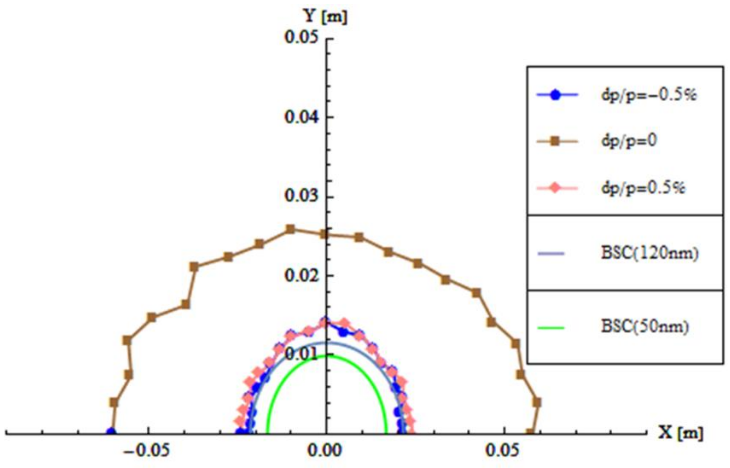


Lower emittance booster design

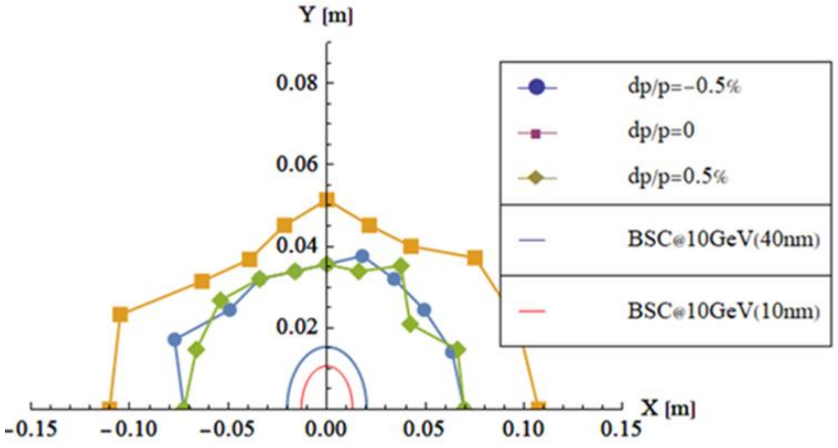
- Emittance: 3.57nm → (1.2nm~1.9nm)
- Coupling requirement: ~0.7%
- Injection for higher lum. H mode
- Off-axis injection for CDR H
- Difficulty transfer from Collider to booster

- Two kinds of low emittance lattice
  1. TME (cell length=110m)
  2. FODO (cell length=70m~80m)

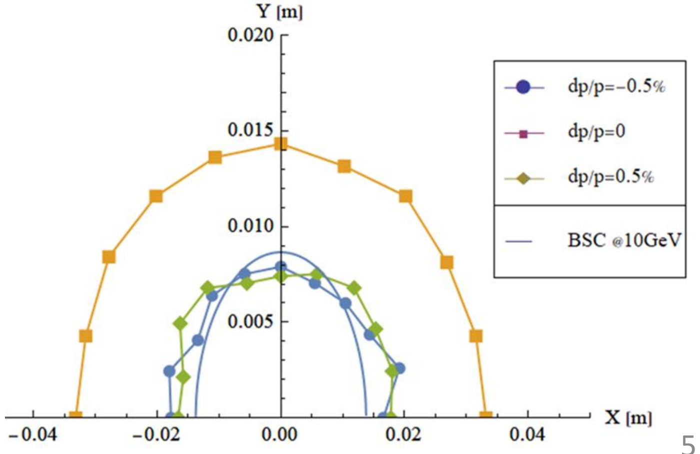
CDR



TME



FODO



TME design

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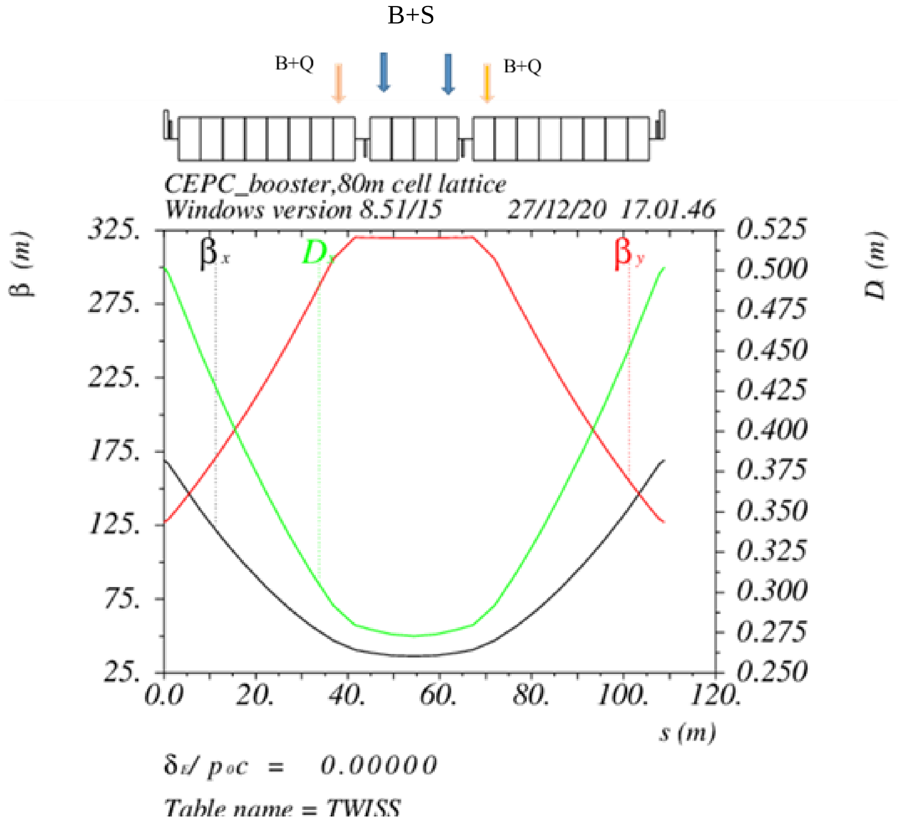
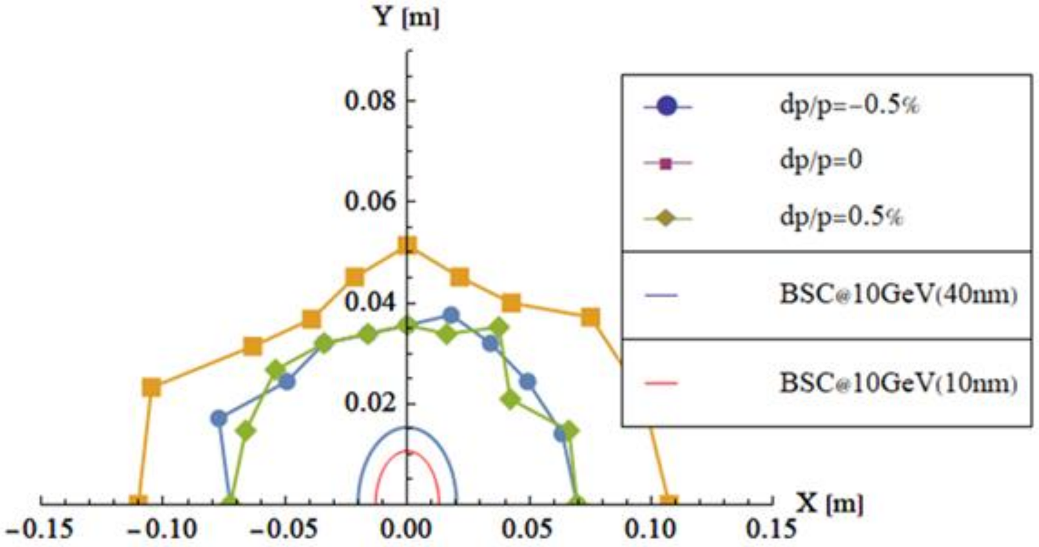
- Overall idea: uniform distribution of quadrupoles
- Combined magnet: B+Q, B+S
- Emittance = 1.45 nm@120GeV



- Energy spread = .00168
- $\alpha p = 2.21\times10^{-5}$
- Interleave sextupole scheme
- Phase advance/cell: 100°/28°



Error effect and correction (TME)

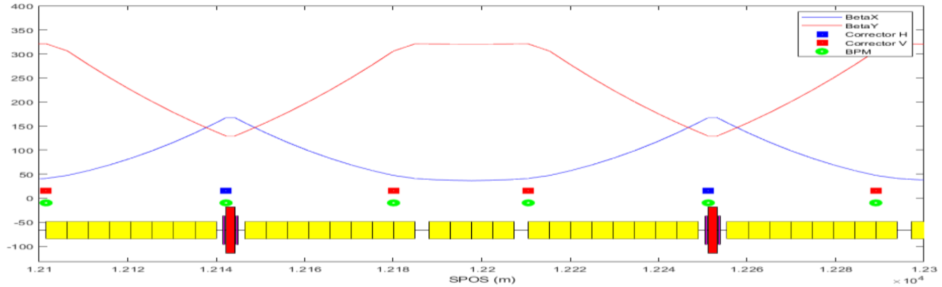
D. H. Ji

	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	0.2
Nominal field	1e-3	2e-4	3e-4

$$\text{Error Effect} \propto \sqrt{N} * KL$$

Lattice	FODO 0 (CDR)	FODO 1	TME1
Emittance X (nm)	3.57	1.29	1.44
Tunes	[263.201/261.219]	[353.180/353.280]	230.231/87.181
Quad amount	2110	2816	1090+(B+Q)
Quad Strength (K1L rms)	0.0383	0.0407	0.0190
Sext amount	512	896	1440+(B+S)
Sexts Strength (K2L rms)	0.18	0.41	0.02
H Corrector	1053	1408	898
V Corrector	1054	1408	1632
BPM	2108	2816	2530

	Accuracy (m)	Tilt (mrad)	Gain	Offset w/ BBA(mm)
BPM(10Hz)	1e-7	10	5%	30e-3



- Error correction process is almost same as CDR
  - Orbit correction
  - Optics correction with dispersion control
- So far, optics parameter recovery is good enough.
- on going

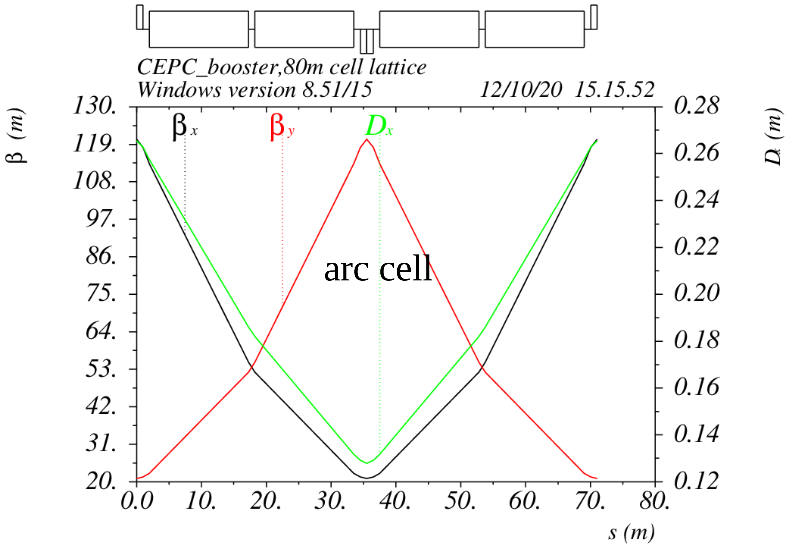
RMS	FODO 0 (CDR)	TME1
Orbit (mm)	0.0575/0.0525	0.156/0.077
Beta Beating(%)	0.294/0.353	0.0274/0.102
Delta Dispersion(m)	0.005/0.007	0.0008/0.011

Booster parameter update based on TME

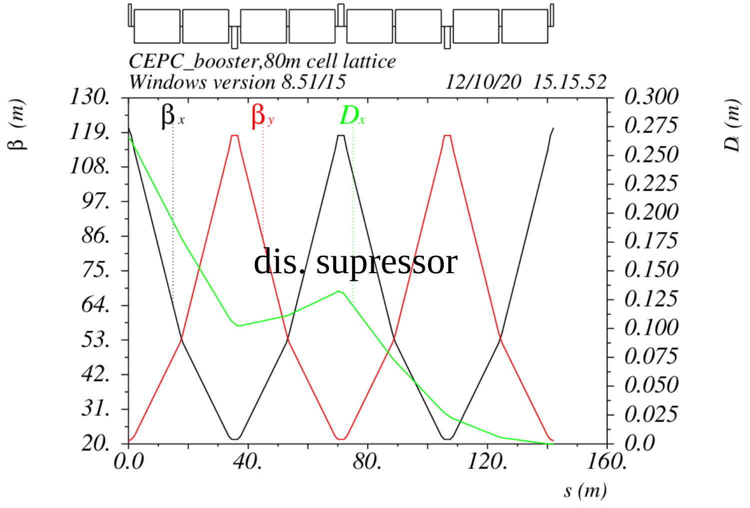
Injection		*tt*	*H*	*W*	*Z*
Beam energy	GeV	10			
Bunch number		37	214	1588	5750
Threshold of single bunch current	μA	6.82			
Threshold of beam current (limited by coupled bunch instability)	mA	44.6			
Bunch charge	nC	1.02	0.87	0.63	0.83
Single bunch current	μA	3.1	2.6	1.8	2.4
Beam current	mA	0.12	0.57	2.86	14.0
Energy spread	%	0.014			
Synchrotron radiation loss/turn	keV	79.5			
Momentum compaction factor	10^{-5}	2.21			
Emittance	nm	0.01			
Natural chromaticity	H/V	-271/-195			
RF voltage	MV	306.5	141.8	102.5	
Betatron tune ν_x/ν_y		230.23/87.18			
Longitudinal tune		0.216	0.147	0.125	
RF energy acceptance	%	4.5	3.1	2.6	
Damping time	s	36.3			
Bunch length of linac beam	mm	1.0			
Energy spread of linac beam	%	0.16			
Emittance of linac beam	nm	40			

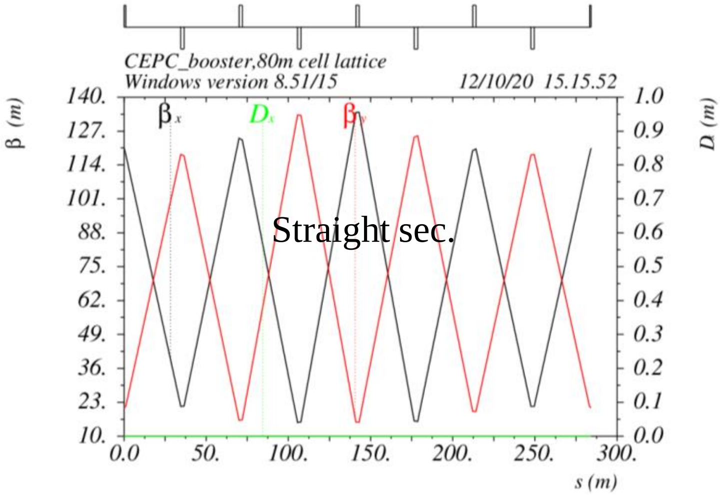
Extraction		*tt*		*H*		*W*	*Z*
		Off axis injection	On axis injection	Off axis injection	On axis injection	Off axis injection	Off axis injection
Beam energy	GeV	180		120		80	45.5
Bunch number		37	35+2	214	207+7	1588	5750
Maximum bunch charge	nC	0.92	30.7	0.78	26.1	0.58	0.75
Maximum single bunch current	μA	2.8	93.3	2.36	78.5	1.7	2.2
Threshold of single bunch current	μA	358.2		147.2			
Threshold of beam current (limited by RF power)	mA	0.3		1		4	13
Beam current	mA	0.105	0.29	0.51	1.0	2.69	12.6
Injection duration for top-up (Both beams)	s	31.7	32.6	24.3	30.8	51.9	150.2
Injection interval for top-up	s	65		38		153.0	153.5
Current decay during injection interval		3%					
Energy spread	%	0.25		0.168		0.112	0.064
Synchrotron radiation loss/turn	GeV	8.35		1.65		0.326	0.034
Momentum compaction factor	10^{-5}	2.21					
Emittance	nm	3.27		1.45		0.65	0.21
Natural chromaticity	H/V	-271/-195					
Betatron tune ν_x/ν_y		230.23/87.18					
RF voltage	GV	10.0		2.36		0.88	0.47
Longitudinal tune		0.216		0.147		0.125	0.125
RF energy acceptance	%	1.53		1.45		1.9	2.46
Damping time	ms	6.3		21.2		71.1	385.7
Natural bunch length	mm	4.1		3.88		3.15	1.8
Injection duration from empty ring	h	0.15		0.14		0.25	2.0

Alternative design based on FODO



- 90°/ 90° FODO cell
- FODO length: 70m~80m
- Noninterleave sextupole scheme
  - One Period = 5 FODO cell
- Similar structure as CDR

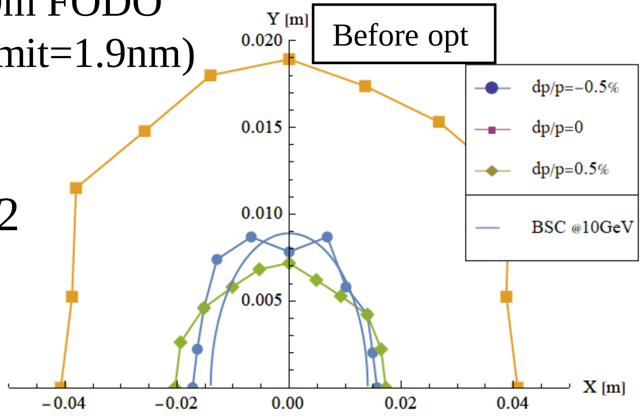




DA optimization for FODO lattice

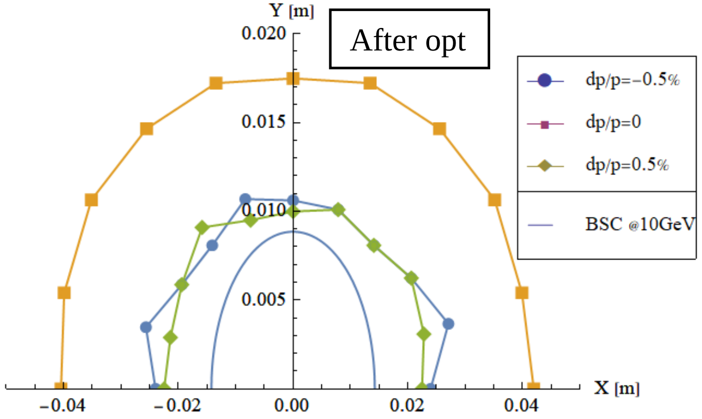
- Insert proper phase section to weaken/cancel some dispersive nonlinear term – enlarge off-momentum DA
  - 80m FODO (emit=1.9nm)

FODO 1.2



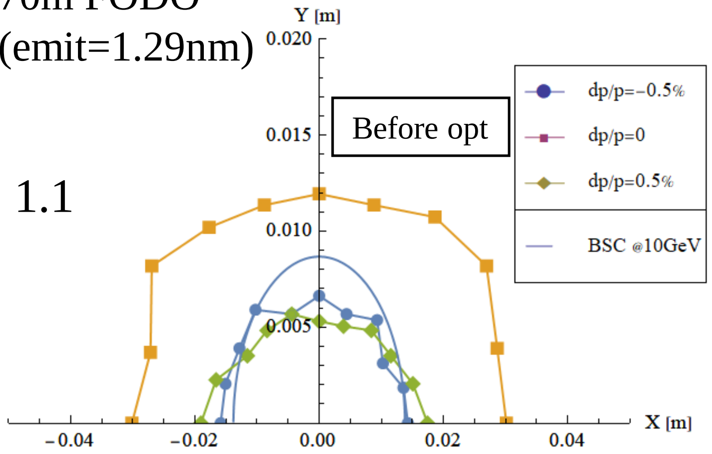
6*FODO5,
FODO,
6*FODO5,
FODO,
6*FODO5,
FODO,
6*FODO5

45° phase in short straight section



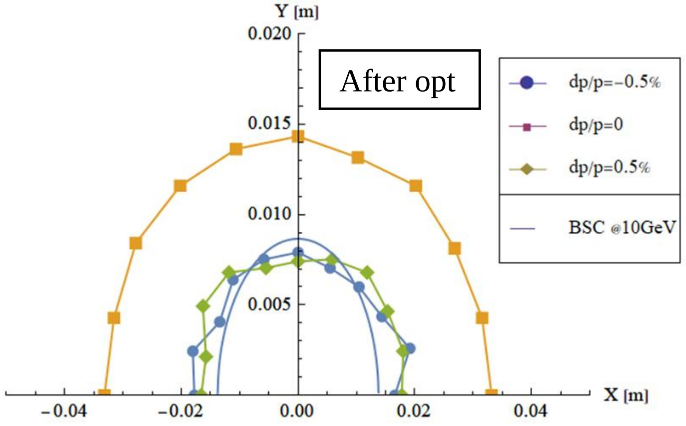
  - 70m FODO (emit=1.29nm)

FODO 1.1



7*FODO5,
7*FODO5,
7*FODO5,
7*FODO5

45° phase in short straight section



Error study based on FODO 1.1

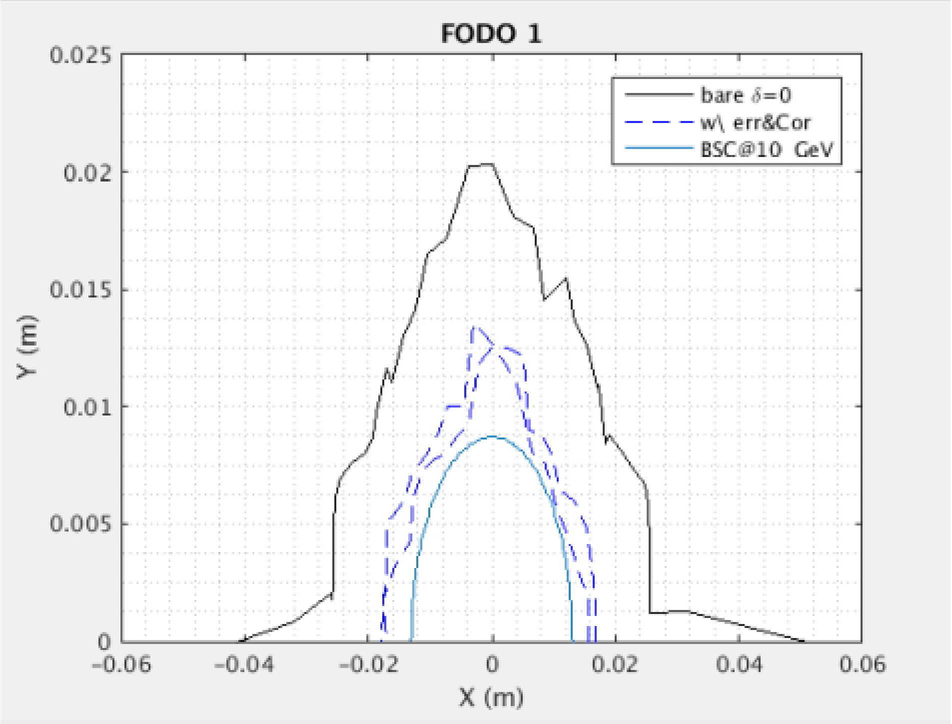
D. H. Ji

$$\text{Error Effect} \propto \sqrt{N} * KL$$

Lattice	FODO 0	FODO 1
Emittance X (nm)	3.57E-09	1.29E-9
Tunes	[263.201/261.219]	[353.180/353.280]
Quad amount	2110	2816
Quad Strength (K1L rms)	0.0383	0.0407
Sext amount	512	896
Sexts Strength (K2L rms)	0.1795	0.4091
H Corrector	1053	1408
V Corrector	1054	1408
BPM	2108	2816

w/ Correction	FODO 0	FODO 1
Orbit (mm)	0.0575/0.0525	**0.1693/0.1236**
Beta Beating(%)	0.294/0.353	**1.52/2.50**
Delta Dispersion(m)	0.005/0.007	**0.0045/0.0032**

- The sensitivity is stronger than FODO0 (CDR)
- The correction results are consistent with the sensitivity
- Linac emittance: 40nm →10nm



Injection time structure@ *tt*

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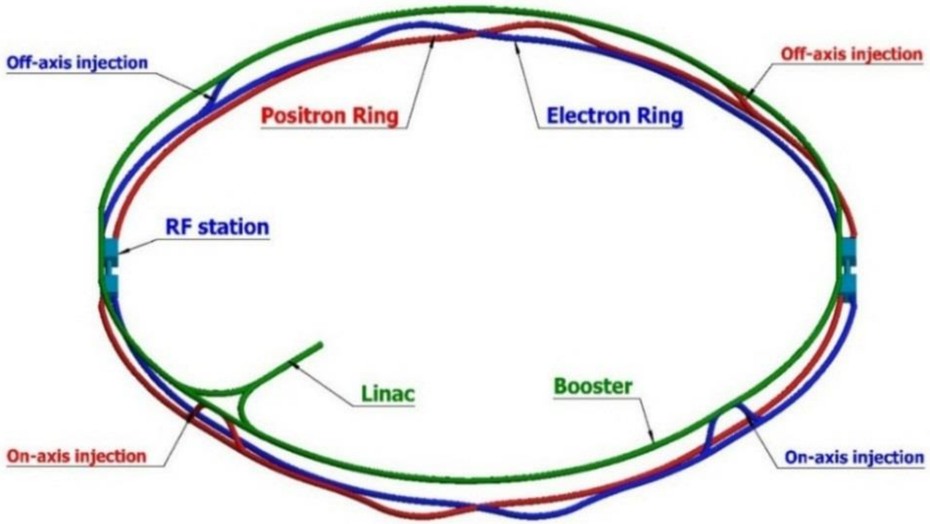
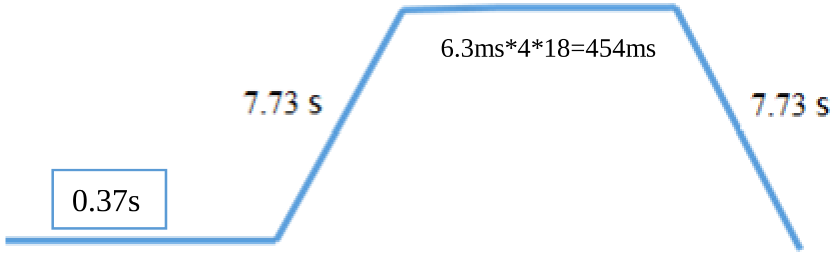
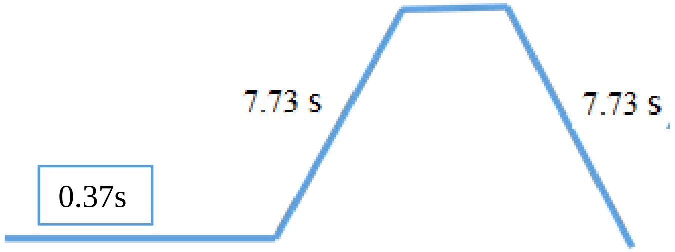
- On-axis injection in vertical plane with vertical local bump for booster
  - top up injection: 32.6s
- Off-axis injection with horizontal bump for collider
  - top up injection: 31.7s

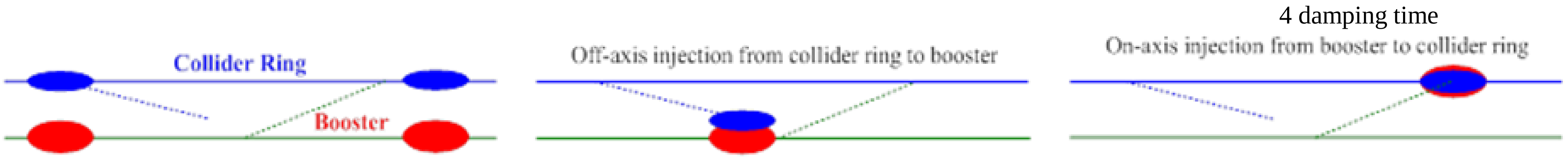


tt on-axis injection (baseline)



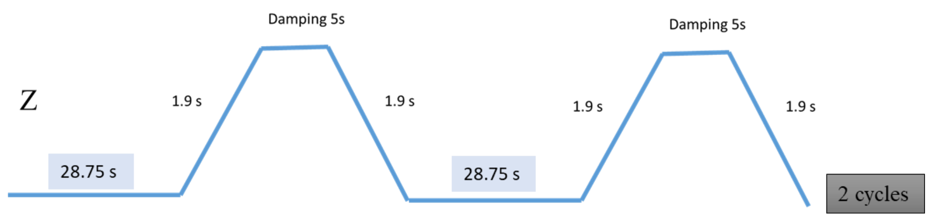
tt off-axis injection (alternative)





Injection time structure for high lum. Z

➢ Top up injection



- Interval requirement for top up injection: **153.5s**
- Top up injection time with CDR Linac:

  (57.5s+1.9s+5s+1.9s)×4=**265.2s**
- Injection time is dominated by the injection from Linac.
- Injection speed of Linac needs to be improved.
  - e.g., Linac speed×2, (28.75s+1.9s+5s+1.9s)×4=150.2s
  - 4 bunches in damping ring

➢ Linac injection must to speed up.

- Two bunches/pulse
- Double repetition: 200Hz

➢ Full injection

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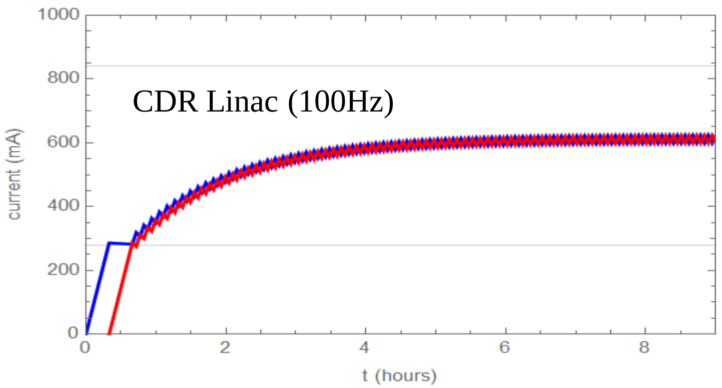
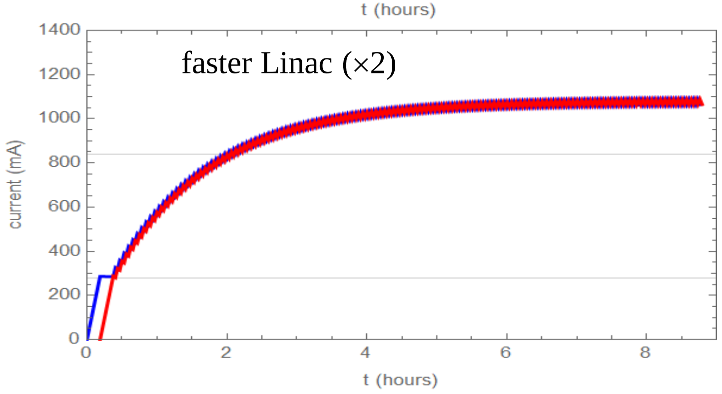
- Bootstrapping from 280mA





Injection scheme with faster Linac

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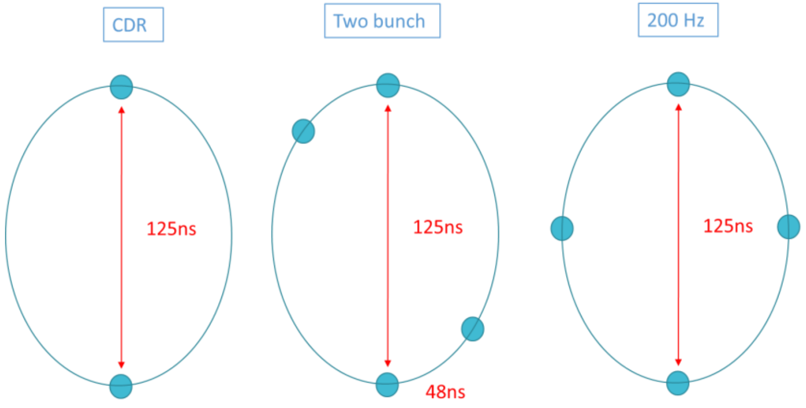
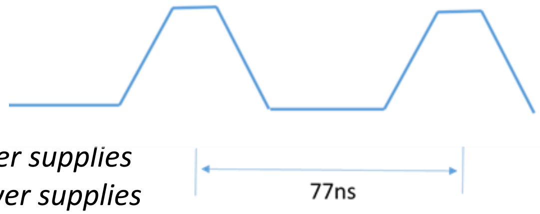
Damping ring inj./ext.



Booster LE inj.

- 200Hz — bunch by bunch
  - Kicker repetition: 200Hz
- Two bunch scheme — bunch by bunch
  - Bunch spacing: 77ns
  - Kicker repetition: 100Hz
  - Stagger trigger
    - *One kicker + two Pulse power supplies*
    - *two kickers + two Pulse power supplies*



	inj(Z_CDR)	inj(Z_new) 200Hz	inj(Z_new) Two bunch
Energy (GeV)	1.1	1.1	1.1
Bunch number	2	4	4
Bunch separation (ns)	125	62.5	20
Inj/ext scheme	Bunch by bunch	Bunch by bunch	Two by two
Bunch number/train			2
Train number			2
Train separation (ns)			48
Kicker repetition (Hz)	100	200	100
Kicker pulse duration (ns)	250	125	173
Kicker flat top (ns)			77
Kicker speed for rise up/down (ns)	<125	<62.5	<48
Timing delay (ns)	<125	<62.5	<125
Kicker angle (mrad)	1.5	1.5	1.5
Kicker integrated strength (T.m)	0.006	0.006	0.006

	inj(Z_CDR)	inj(Z_new) 200Hz	inj(Z_new) Two bunch
Energy (GeV)	10	10	10
Bunch number	6000	5750	5750
Bunch separation (ns)	25	20	20
Inj/ext scheme	Bunch by bunch	Bunch by bunch	Bunch by Bunch
Bunch number/train	80	77	77
Train number	75	75	75
Train separation (us)	2.46	2.46	2.46
Kicker repetition (Hz)	100	200	100
Kicker pulse duration (ns)	50	40	60
Kicker speed for rise up/down (ns)	25	20	38
Timing delay (us)	<2.46	<2.46	<2.46
Injection time (s)	60	28.75	28.75
Kicker angle (mrad)	0.11	0.11	0.11
Kicker integrated strength (T.m)	0.004	0.004	0.004

Uniformity requirement of injection kicker/LSM@10GeV

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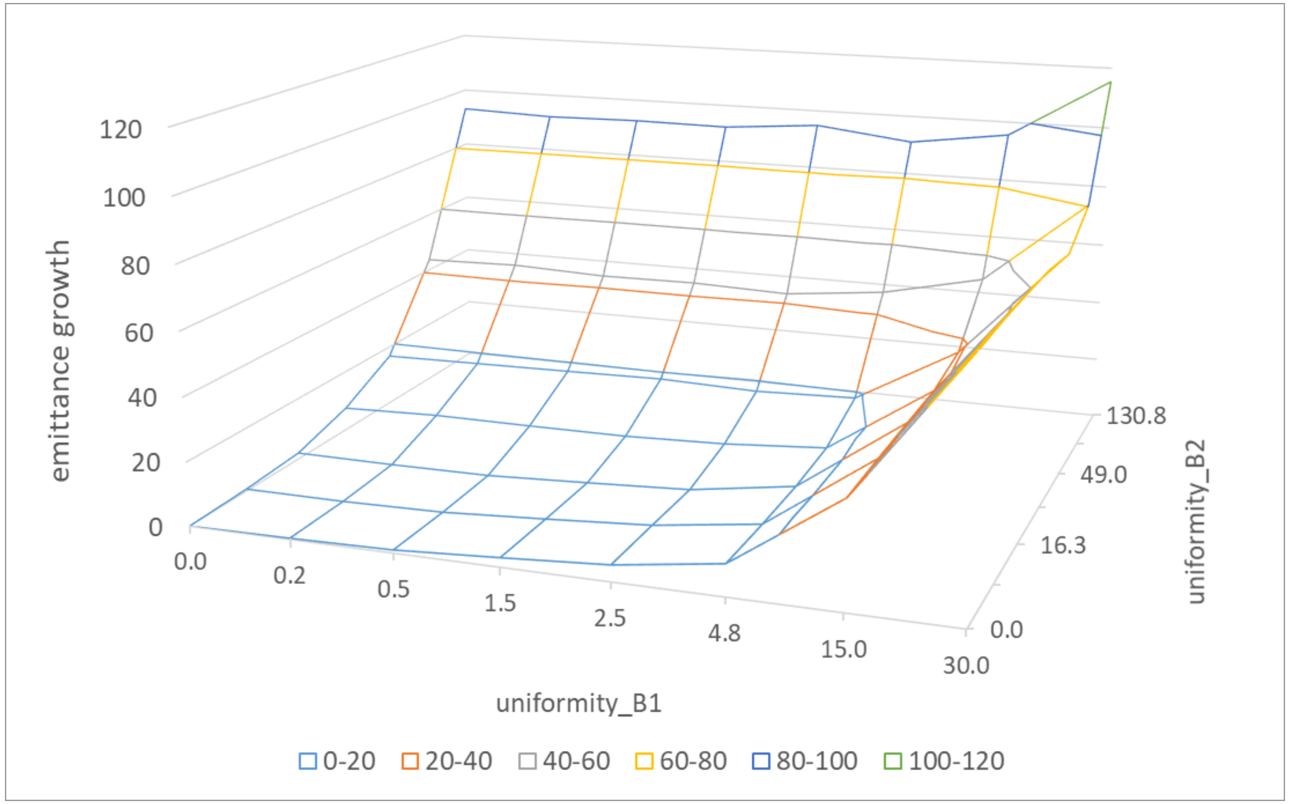
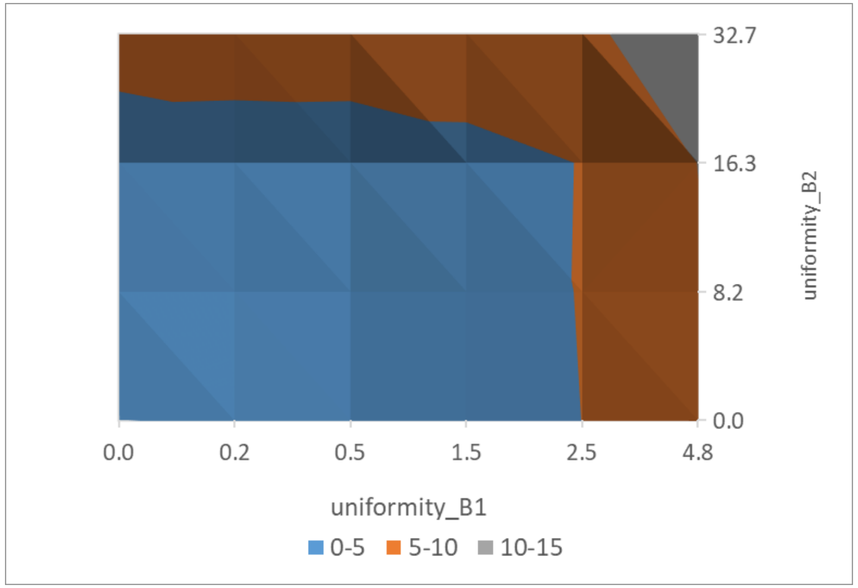
- Considering the combined effect of quadrupole field + skew quadrupole field
- Emittance growth of injection beam should be controlled (quadrupole field is dominant)
- Uniformity for kicker: $\leq \pm 2.5\%$,   uniformity for lambertson: $\leq \pm 0.02\%$



$$B_x = B_0 + B_1 y + B_2 x$$

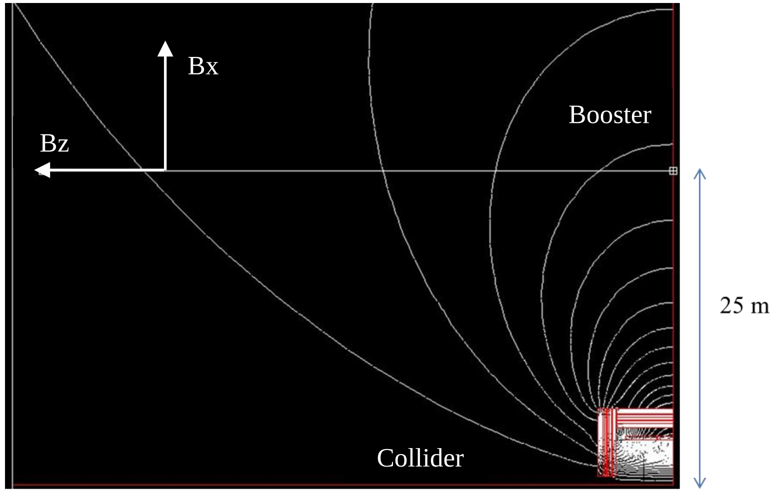
$$B_0 = 0.00367T$$

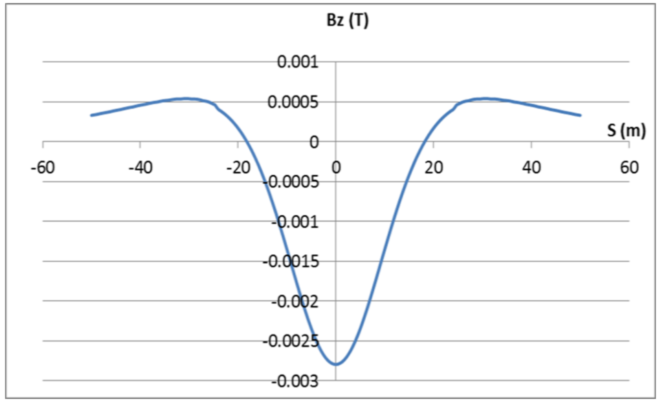


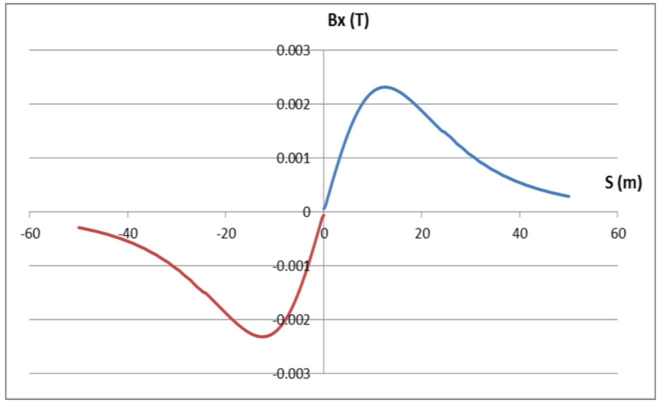
Impacts of Detector Stray Field

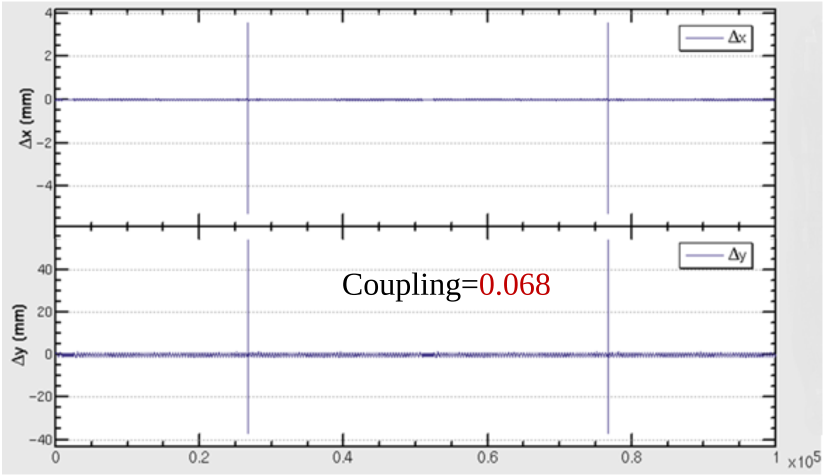
D. Wang, Y. Zhang, D. Ji

- Bz=28Gs Bx=23Gs By=2.3 Gs
  - Longitudinal field is modeled as solenoid.
  - Transverse field is modeled as dipoles.
  - 100 slices (-50m ~ 50m): simulate the real distribution of detector field.
- Beam dynamics effects of detector field is strongest at **10 GeV**.
- Vertical orbit distortion due to Bx is dominant effect.
- Orbit distortion: Δx ~ 5 mm, Δy ~ 50 mm (intolerable)
- Tolerance for detector stray field: ~ 1Gs (w/o correction)









Correction to Detector Stray Field

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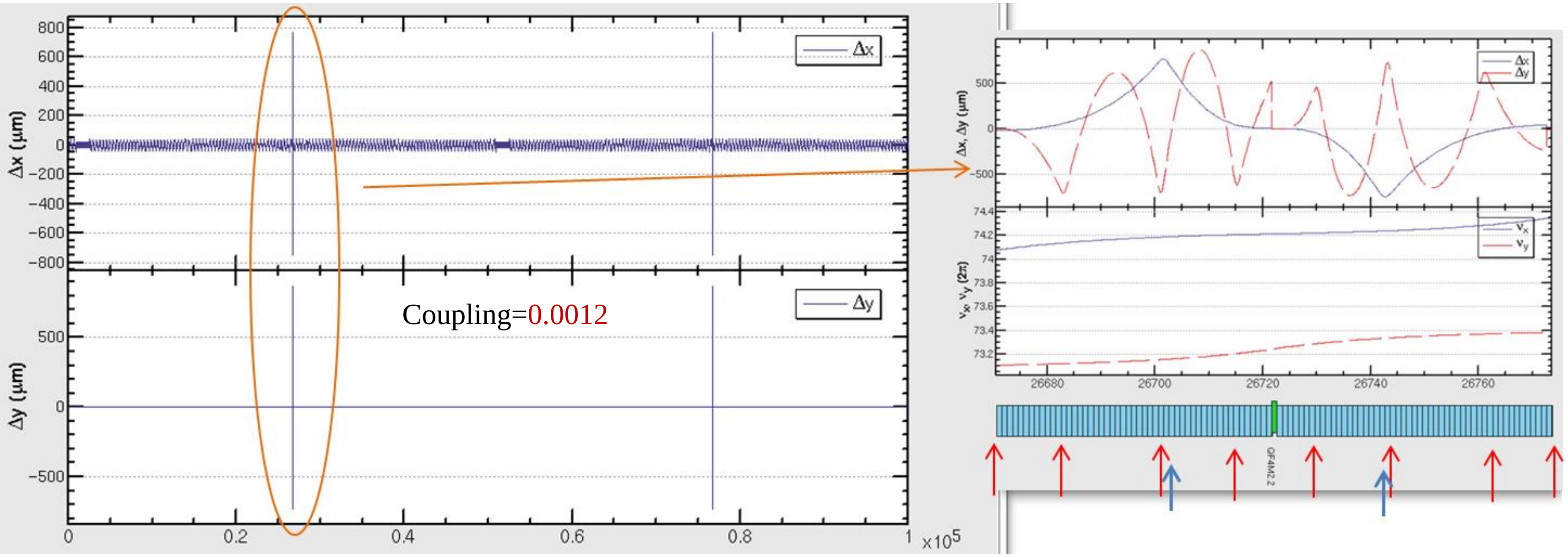
- Local orbit correction is essential (8 v correctors+ 2 h correctors)
- No influence to booster DA @10GeV after orbit correction
- Close orbit after correction: Δx ~ 0.8 mm, Δy ~ 0.8 mm
- Correction to the detector stray field is possible at low field level (<50Gs).



Dynamic simulation with errors during ramping

D. Wang, X. N. Wang, Z. Duan…

➢ Dynamic simulation with orbit correction

- Consistent simulation for orbit correction and ramping process (elegant)
- No close orbit before orbit correction
- Two steps of orbit correction
  - Sex off → sex open
- Transmission efficiency: 100%

parameters	Dipole	Quadrupole	Sextupole
Transverse shift x/y (um)	100	100	100
Longitudinal shift z (um)	100	100	100
Tilt about z (urad)	100	100	100
Nominal field	2×10^{-3}	2×10^{-4}	3×10^{-4}

	dipole	quadrupole	sextupole
n=1, N/S	$3\times10^{-4}/3\times10^{-4}$		
n=2, N/S	$1\times10^{-5}/1\times10^{-5}$	$4.5\times10^{-4}/4.5\times10^{-4}$	
n=3, N/S	$1\times10^{-6}/1\times10^{-6}$	$2.5\times10^{-5}/2.5\times10^{-5}$	$2\times10^{-3}/2\times10^{-3}$
n=4, N/S	$5\times10^{-7}/5\times10^{-7}$	$2.5\times10^{-5}/2.5\times10^{-5}$	$1\times10^{-4}/1\times10^{-4}$
n=5, N/S	$5\times10^{-7}/5\times10^{-7}$		$1\times10^{-4}/1\times10^{-4}$
n=6, N/S	$2\times10^{-7}/2\times10^{-7}$		$1\times10^{-4}/1\times10^{-4}$

➢ Study for track precision/synchronization tolerance

- Add random strength errors for dipoles, quadrupoles, sextupoles and correctors after COD correction at 10GeV
- Ramping simulation for first 200 turns
- 100 random seeds and 100 particles
- The worst 10% cases are rejected.
- Track precision/synchronization requirement: ~ 3×10^{-4} (RMS)

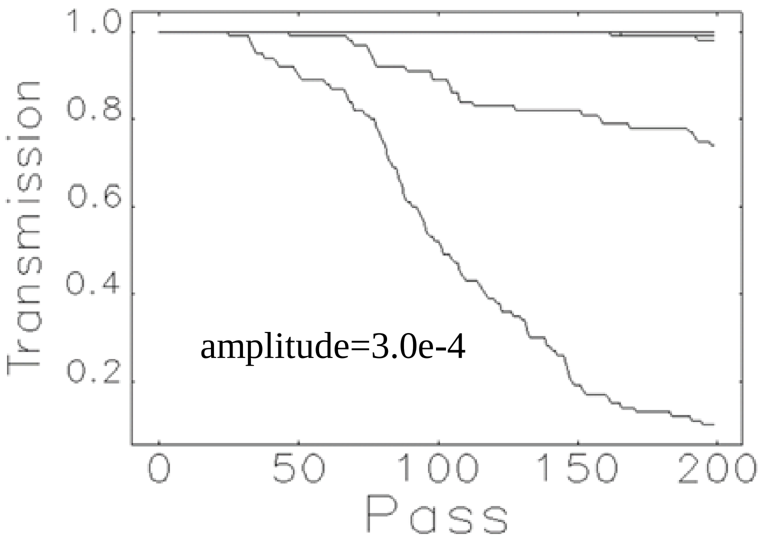


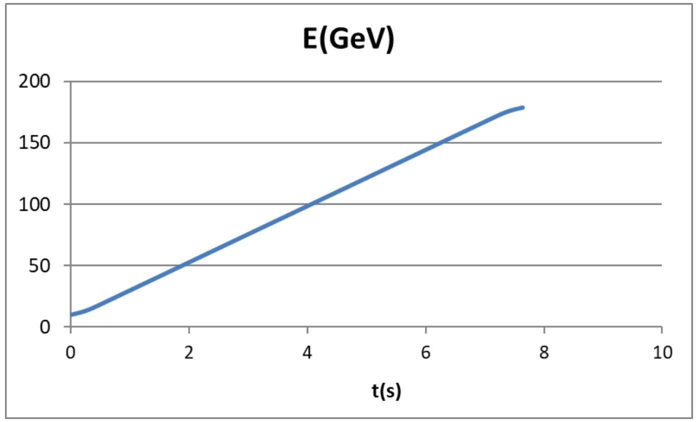
Table ramping scheme

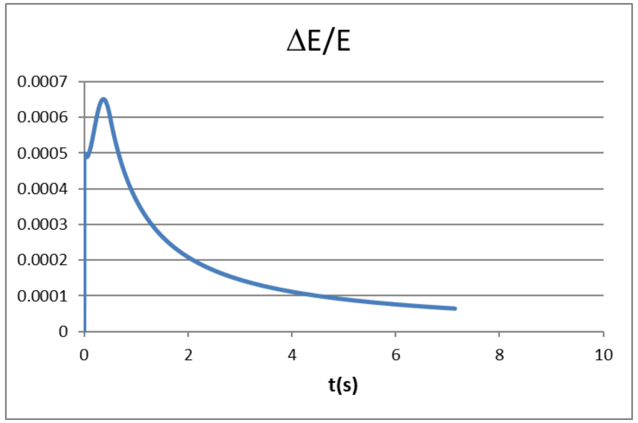
D. Wang, C. Meng

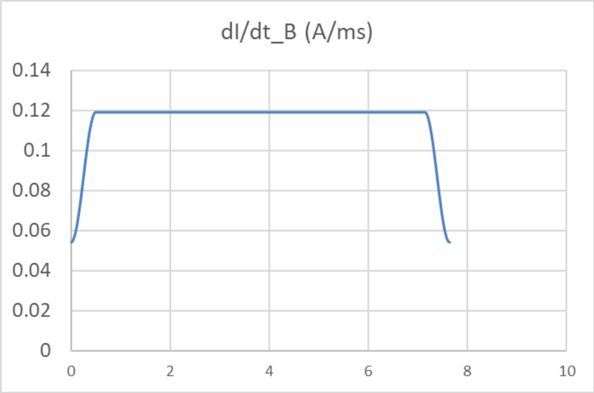
- There is some waiting time without ramping for CEPC booster and the duty factor is different for four energy modes.

- Tracking precision and synchronization of power supplies need to be controlled.

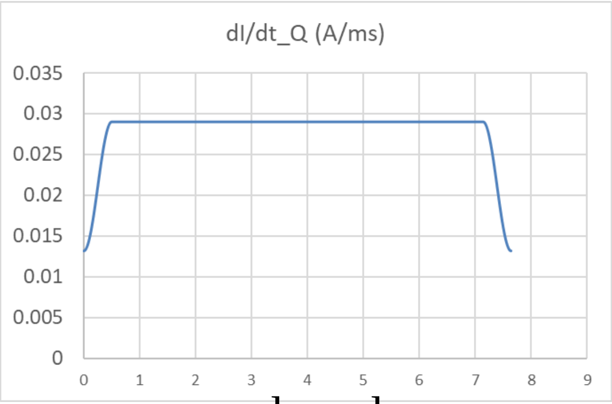
- Primary ramping table design is considered.
    - Ramping step : 0.5ms
    - Clock frequency: 2kHz
    - Points number: ~16000*2
    - Energy precision: < 0.07%



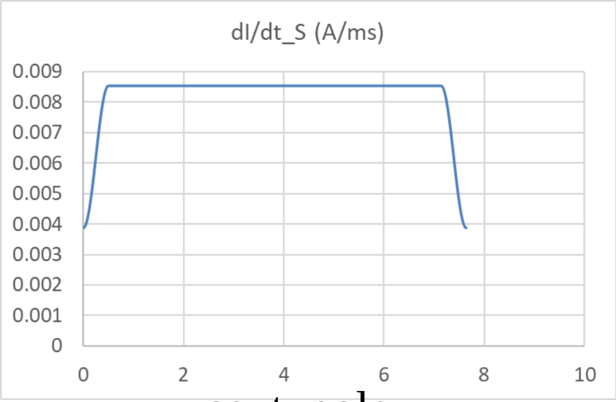




dipole



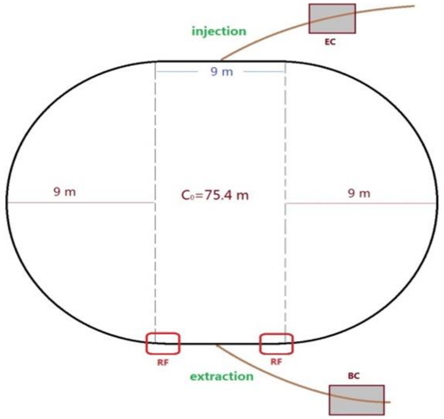
quadrupole



sextupole

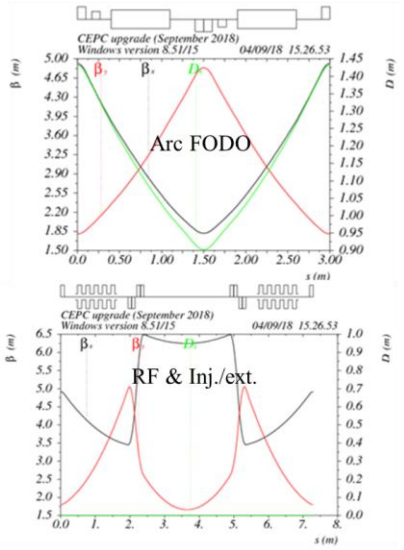
Damping ring design

- Linac repetition: 100Hz
- two-bunch storage scheme
- Storage time: 20 ms
- Emittance (norm.): 2500→ 530 mm.mrad
- Large trans. acceptance→ inj. efficiency

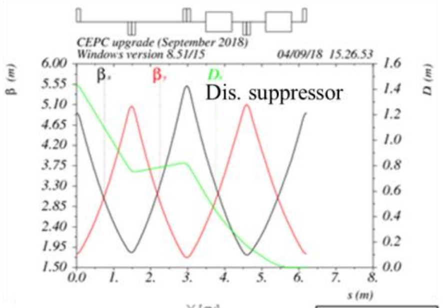


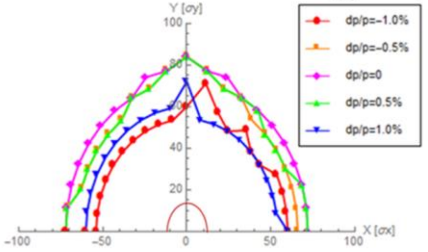
	DR V2.0
Energy (Gev)	1.1
Circumference (m)	75.4
Bending radius (m)	3.6
Dipole strength B_0 (T)	1.03
U_0 (kev/turn)	36.3
Damping time x/y/z (ms)	15.2/15.2/7.6
δ_0 (%)	0.05
ε_0 (mm.mrad)	376.7
injection σ_z (mm)	5
Extract σ_z (mm)	7.5
ε_{inj} (mm.mrad)	2500
$\varepsilon_{ext\ x/y}$ (mm.mrad)	530/180
δ_{inj} /δ_{ext} (%)	0.18 /0.05
Energy acceptance by RF(%)	1.0
f_{RF} (MHz)	650
V_{RF} (MV)	2.0

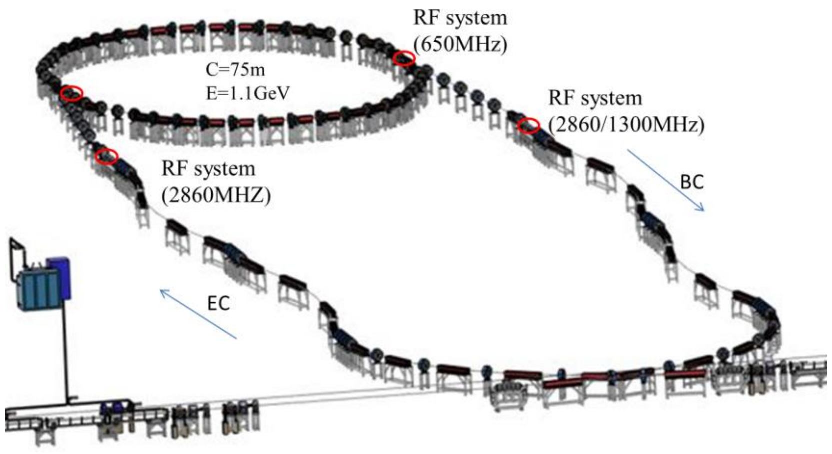
- 60°/60° FODO
- interleave sextupole scheme



- 2 sextupole families
- DA > 5×injection beam size





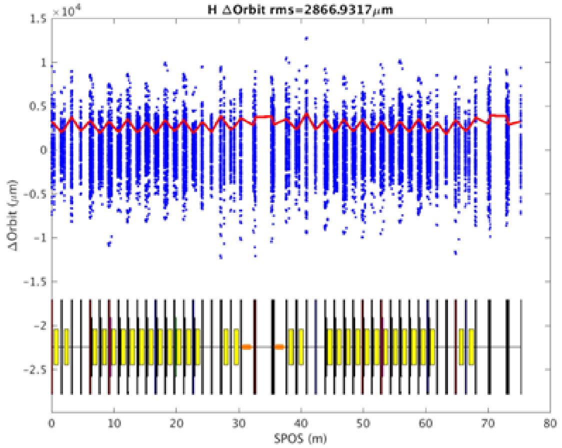


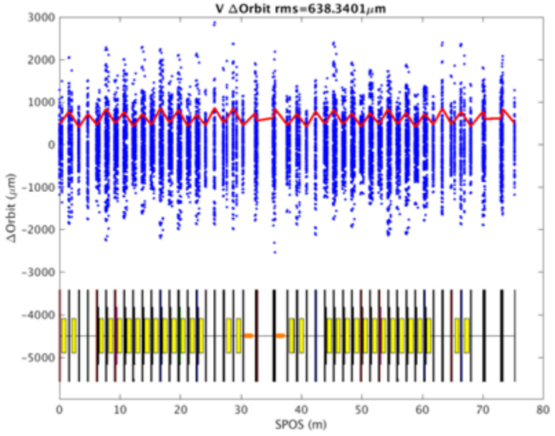
Damping ring error effect

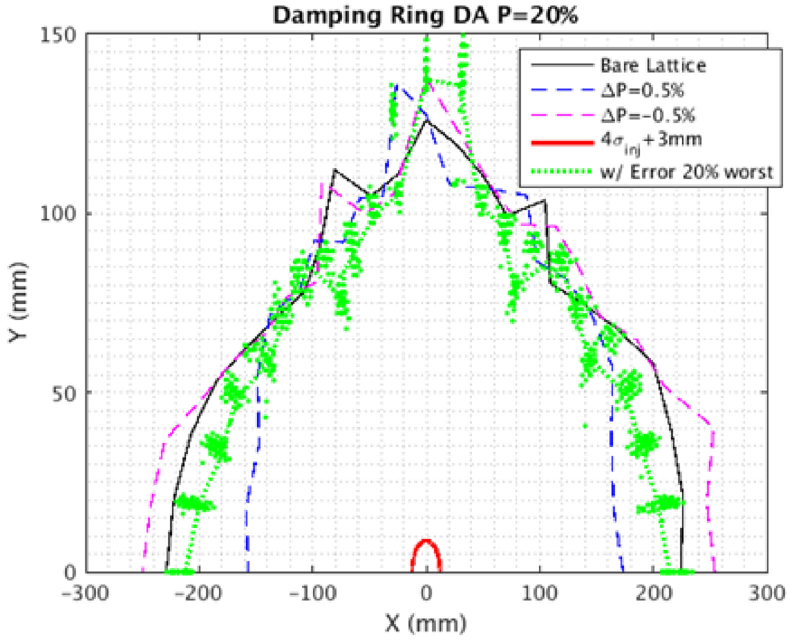
D. H. Ji

	Dipole	Quadrupole	Sextupole
Transverse shift X/Y (μm)	100	100	100
Longitudinal shift Z (μm)	100	150	150
Tilt about X/Y (mrad)	0.2	0.2	0.2
Tilt about Z (mrad)	0.1	0.2	0.2
Nominal field	3e-4	1e-3	2e-3

- 100 error seeds
- RMS closed orbit: 2.8mm (H) /0.6mm (V)
- Beta beating: 0.8%
- Without any correction, the DA can fulfill the requirement of injection of damping ring.





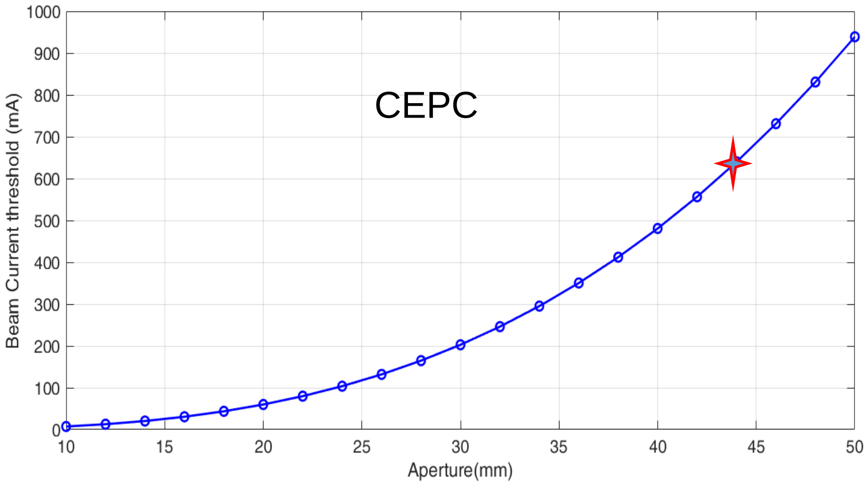


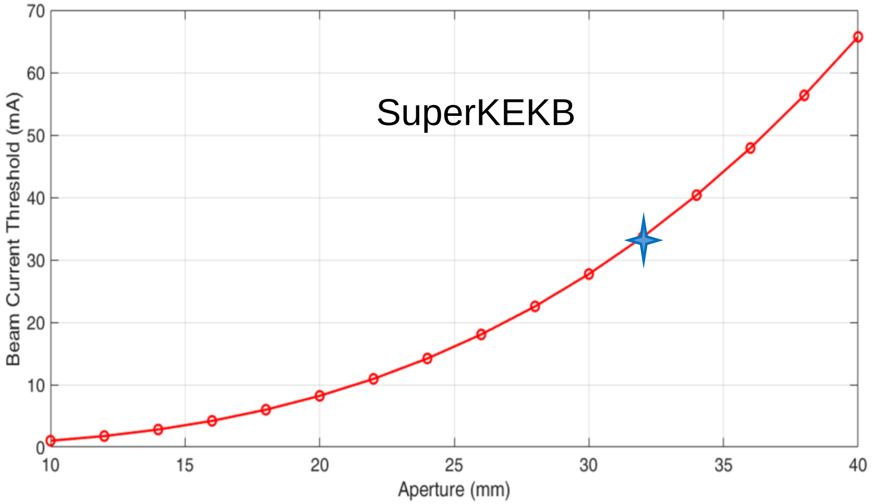
Impedance threshold

Y. D. Liu

- BSC: 4σ+5mm → d= 33mm (including dispersion effect)
- Size of beam pipe: 44mm, Al, 2mm thickness
- Circular beam pipe (SR power density=5W/m)

parameters	damping ring for SuperKEKB	damping ring for CEPC
Energy	1.1Gev	1.1Gev
circumference	135.5	75.4
Beta tune	8.24/7.265	3.84/4.81
Bunch lenght	11.12mm	5mm
Bunch number	4	2 → 4
synchtron tune	0.0153	0.062
Beam current	70 mA	10 mA → 20mA





CSR threshold

- The beam is assumed to be moving in a circle of radius ρ between two parallel plates at locations $y=\pm h$

- The threshold of bunch population for CSR is given by

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

- For CEPC DR, $\sigma_z \rho^{1/2}/h^{3/2}=4.4$ (=> CSR shielded)

  - Inner diameter of beam pipe: 44 mm

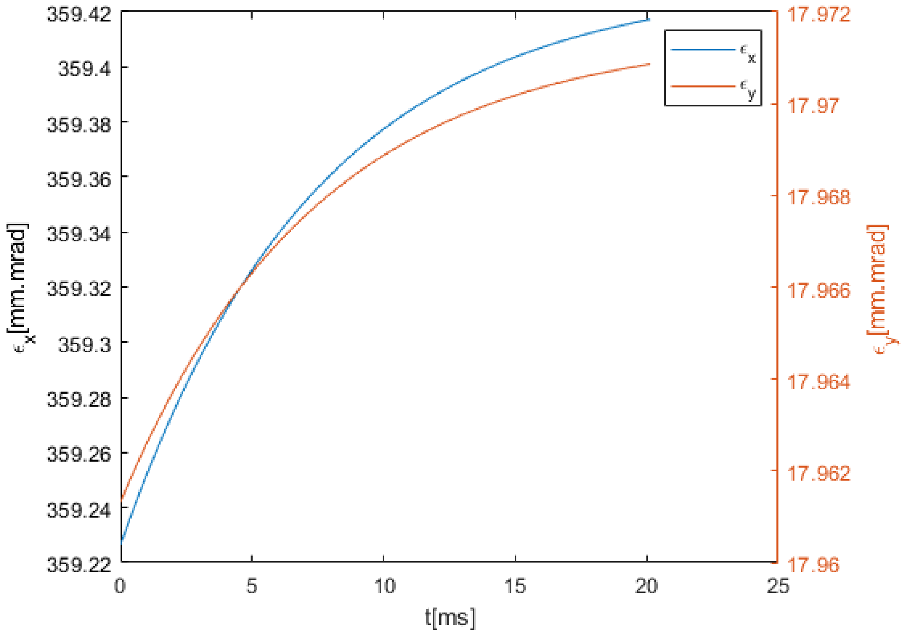
- The CSR threshold in CEPC DR is

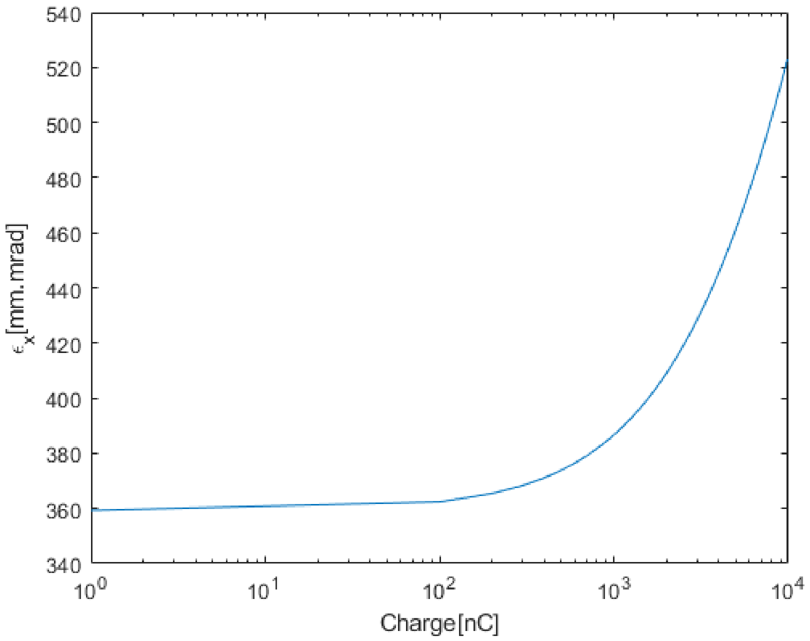
  $N_{b,Th} = 1.46\times10^{11} >> N_b = 9.36\times10^{9}$.

IBS effect

S. K. Tian

- Equilibrium emittance (H/V): 359/18 mm·mrad
- No emittance growth at design bunch current (1.5nC/bunch)
- IBS threshold: ~100nC/bunch
- IBS is not a concern in CEPC DR.





Transport lines between DR and Linac

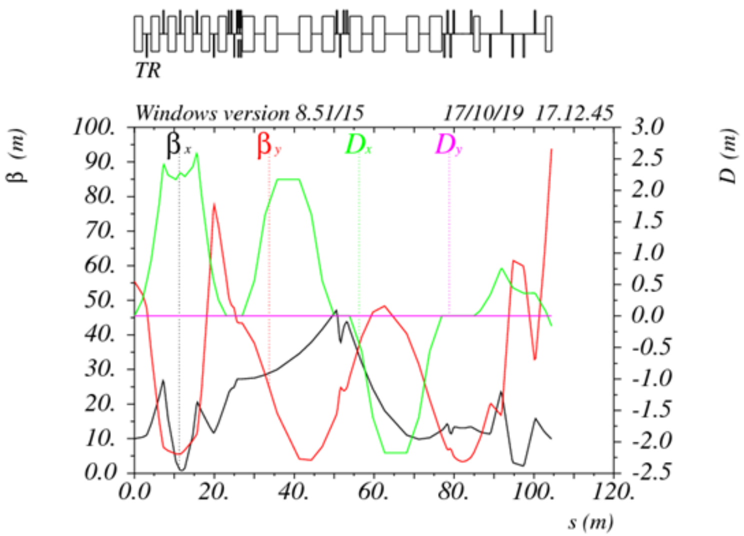
D. Wang, X. H. Cui

- Energy/bunch compressor

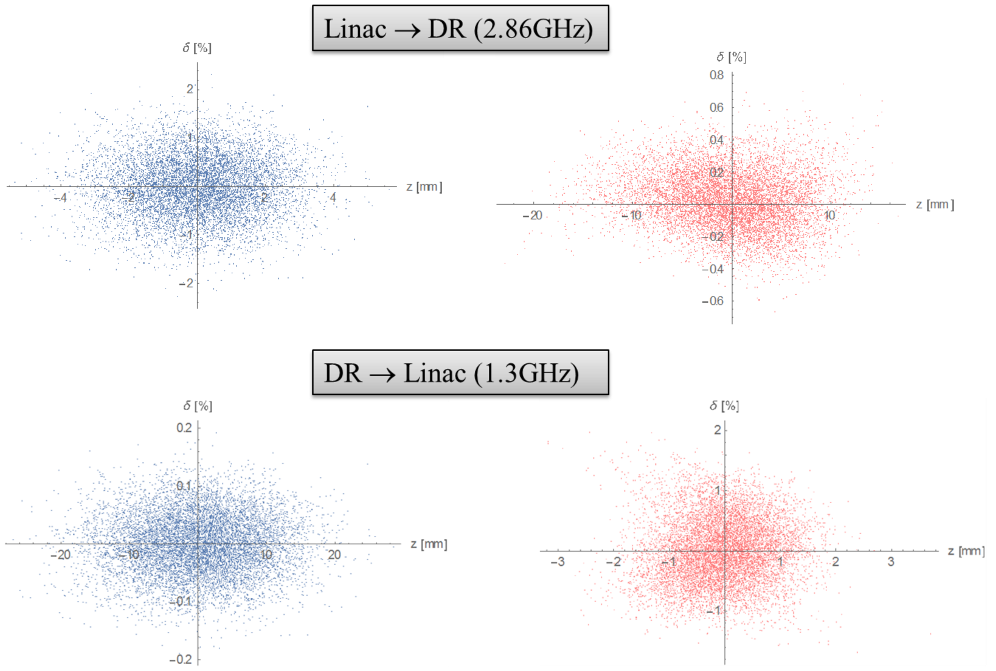
	EC
E_0 (Gev)	1.1
δ_0 (%)	0.6
σ_{z0} (mm)	1.5
f_{RF} (MHz)	2860
V_{RF} (MV)	22.0
Length of acc. Structure (m)	0.82
ϕ_{RF} (degree)	89.7
R_{56} (m)	-0.833
E_f (Gev)	1.1
δ_f (%)	0.18
σ_{zf} (mm)	5

	BC
E_0 (Gev)	1.1
δ_0 (%)	0.05
σ_{z0} (mm)	7.5
f_{RF} (MHz)	2860/1300
V_{RF} (MV)	13.1/29
Length of acc. Structure (m)	0.48/2.5
ϕ_{RF} (degree)	89.6
R_{56} (m)	-1.4
E_f (Gev)	1.1
δ_f (%)	0.54
σ_{zf} (mm)	0.7

- Beamline Optics



- Beam simulation



- CSR effect
  - Dipole strength for the chicane: 0.49T
  - No error included
  - No emittance growth due to radiation effect

Summary

- Explore new booster design with smaller emittance ─ prepare/support for CEPC new high lum. scheme
  - Two kinds of lattice: TME & FODO
  - DA of bare lattice is ok. Error study is going on…
  - Booster parameters update ─ consistent with CEPC new parameters at 4 energy
  - High lum. Z → Injection scheme update → Linac upgrade

- Impacts of detector stray field and correction methods are evaluated.

- Issues about booster dynamic operation was considered.
  - Dynamic simulation with errors and corrections
  - Table ramping scheme (preliminary)

- CDR damping ring system is reviewed.
  - A new damping ring design is expected ─ 10nm emittance @ end of Linac

Thanks!

Back up

CEPC high luminosity Parameters

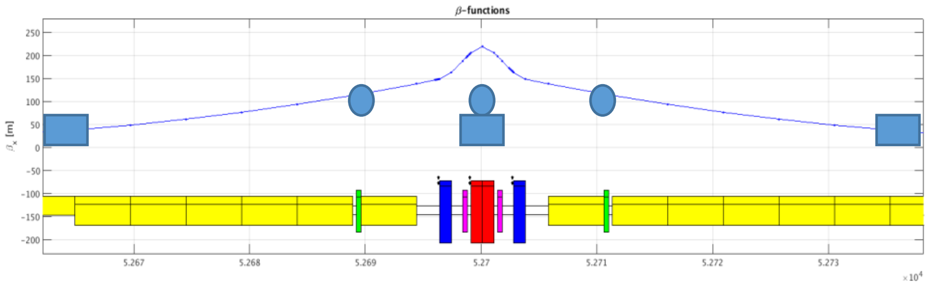
	tt	*Higgs*	*W*	*Z*	
Number of IPs	2	2	2	2	
Energy (GeV)	180	120	80	45.5	
Circumference (km)	100	100	100	100	
SR loss/turn (GeV)	8.53	1.73	0.33	0.036	
Half crossing angle (mrad)	16.5	16.5	16.5	16.5	
Piwinski angle	1.16	4.87	9.12	24.9	
N_e/bunch (10^{10})	20.1	16.3	11.6	15.2	
Bunch number (bunch spacing)	37 (4.45μs)	214 (0.7us)	1588 (0.2μs)	3816 (86ns)	11498 (26ns)
Beam current (mA)	3.5	16.8	88.5	278.8	839.9
SR power /beam (MW)	**30**	**30**	**30**	**10**	**30**
Bending radius (km)	10.7	10.7	10.7	10.7	
Phase advance of arc cell	90°/90°	90°/90°	90°/90°	60°/60°	
Momentum compaction (10^{-5})	0.73	0.73	0.73	1.48	
β_{IP} x/y (m)	1.0/0.0027	0.33/0.001	0.33/0.001	0.15/0.001	
Emittance x/y (nm)	1.45/0.0047	0.68/0.0014	0.28/0.00084	0.27/0.00135	
Transverse σ_{IP} (um)	37.9/0.11	15.0/0.037	9.6/0.029	6.36/0.037	
ξ_x/ξ_y/IP	0.076/0.106	0.018/0.115	0.014/0.13	0.0046/0.131	
V_{RF} (GV)	9.52	2.27	0.47	0.1	
f_{RF} (MHz) (harmonic)	650 (216816)	650 (216816)	650 (216816)	650 (216816)	
Nature bunch length σ_z (mm)	2.23	2.25	2.4	2.75	
Bunch length σ_z (mm)	2.66	4.42	5.3	9.6	
HOM power/cavity (kw)	**0.45 (5cell)**	**0.48 (2cell)**	**0.79 (2cell)**	**2.0 (2cell)**	**3.02 (1cell)**
Energy spread (%)	0.17	0.19	0.11	0.12	
Energy acceptance requirement (DA) (%)	2.0	1.7	1.2	1.3	
Energy acceptance by RF (%)	2.61	2.5	1.83	1.48	
Lifetime (hour)	0.59	0.35	1.3	1.7	1.4
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	**0.5**	**5.0**	**18.7**	**35.0**	**105.5**

Error effect and correction (TME 0)

D. H. Ji

	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	0.2
Nominal field	1e-3	2e-4	3e-4

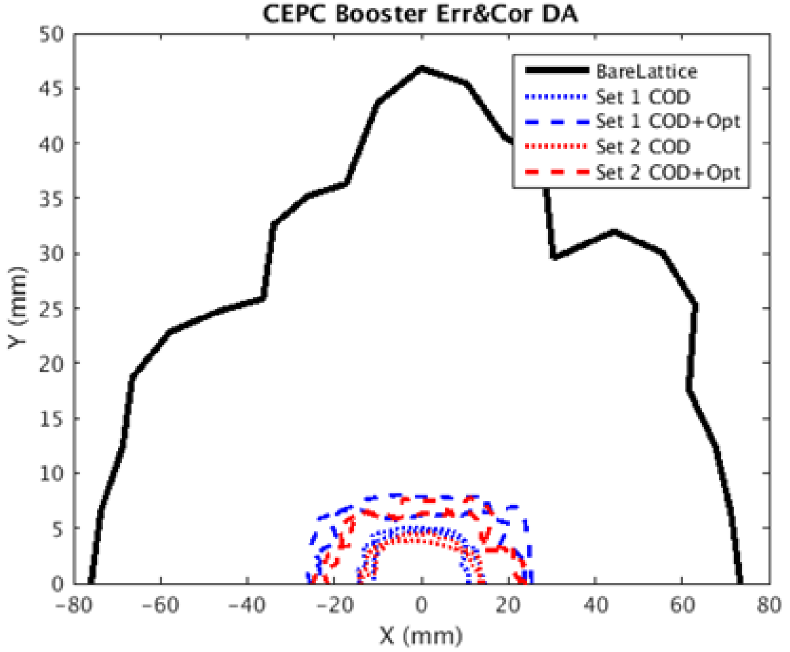
	Accuracy (m)	Tilt (mrad)	Gain	Offset w/ BBA(mm)
BPM(10Hz)	1e-7	10	5%	30e-3



Error Effect $\propto \sqrt{N} * KL$

	FODO 0 (CDR)	TME 0
Emittance X (nm)	3.57E-09	1.29E-9
Tunes	[263.2016/261.2193]	[319.2507/129.2806]
Quad amount	2110	2528
Quad Strength (K1L rms)	0.0383	0.0828
Sext amount	512	2912
Sexts Strength (K2L rms)	0.1795	0.1512
H Corrector	1053	896
V Corrector	1054	1632
BPM	2108	2528

RMS	FODO 0	TME 0	TME 0 opt.
Orbit (mm)	0.0575/0.0525	0.4065/0.2389	**0.2216/0.1784**
Beta Beating(%)	0.294/0.353	3.940/5.439	**2.79/3.833**
Delta Dispersion(m)	0.005/0.007	0.0156/0.0229	**0.0039/0.0052**

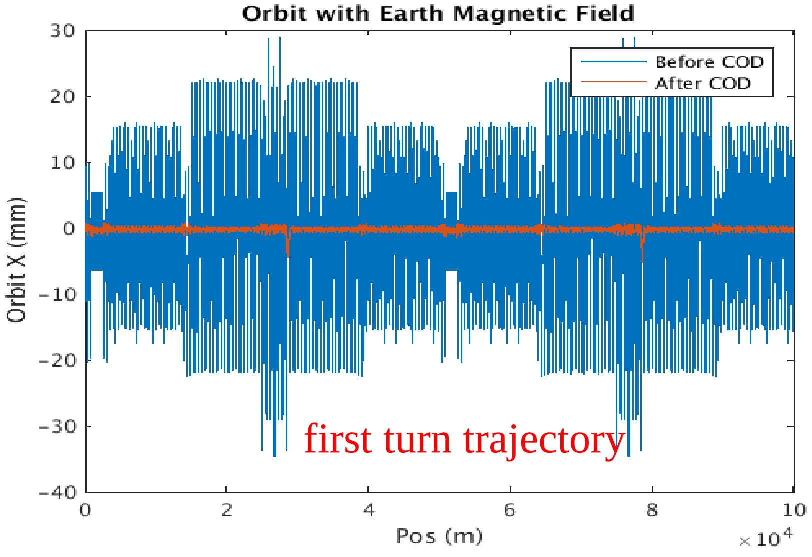


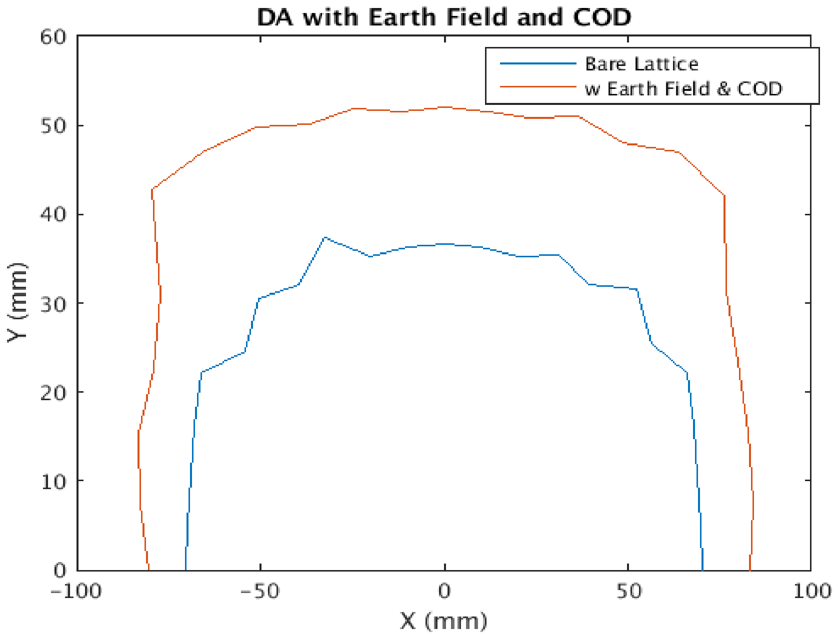
Effect of earthfield @10GeV

D. H. Ji, D. Wang

- ~20% vacuum pipe (drift) is exposed in earthfield directly.
- treat drifts as week dipole to simulate the effect of earthfield
- Assume earthfield: 0.3~0.6 gauss (simple model: perpendicular component only)
- Working point can be corrected by weaken the dipoles systematically (-0.07%)
- Global COD correction was tested for 0.3 gauss earthfield.
- DA is acceptable after COD correction.

0.3 gauss





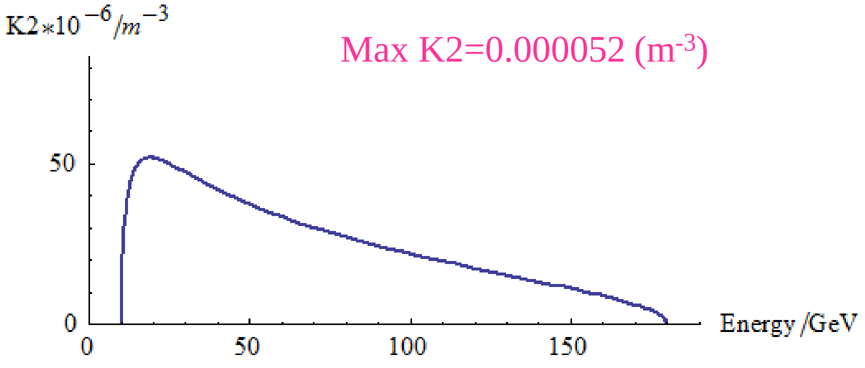
Eddy current effect and correction

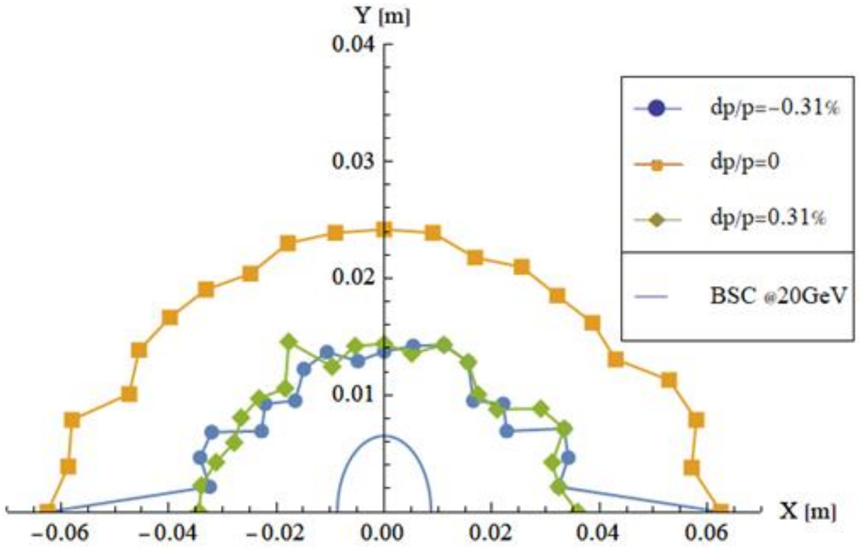
D. Wang, Y. Chen, Wen Kang

- Dedicated ramping curve to control the maximum K2.
- Analytical study was done – deeper understanding about eddy current
  - New formula created → agree with simu.
  - Dipole w core → multipole field
  - Dipole w/o core → No multipole field

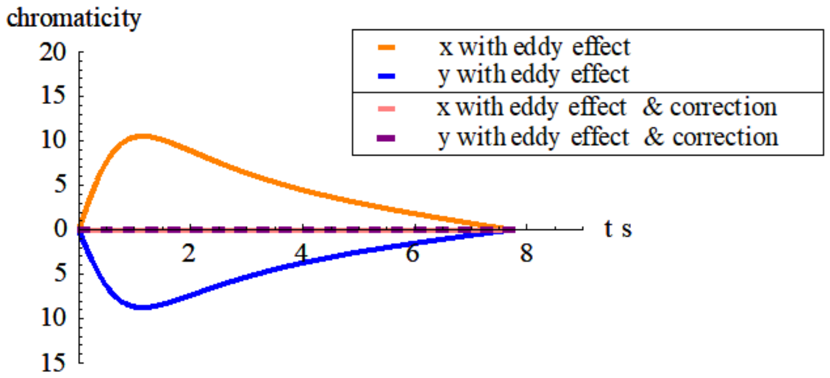
$$B_y(x,\, y\; =\; 0) \;=\; \frac{\mu_0 t B' R^2}{4 g \rho}\left(\frac{2g}{R} + \frac{2\pi^2 R}{3g} - \frac{2}{15}\frac{\pi^4 R}{g^3}x^2 + \cdots\right)\;*$$

- K2 reaches max at 20GeV.





- Small DA reduction @ 20GeV with dynamic chromaticity correction



* Yuan Chen, et al., https://arxiv.org/abs/1910.09781

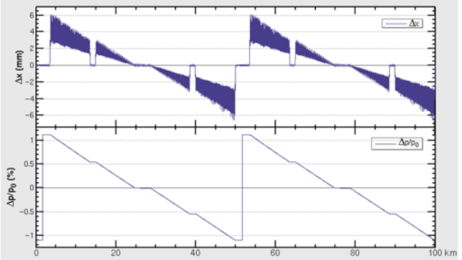
Sawtooth effect @180GeV

D. Wang, D. H. Ji

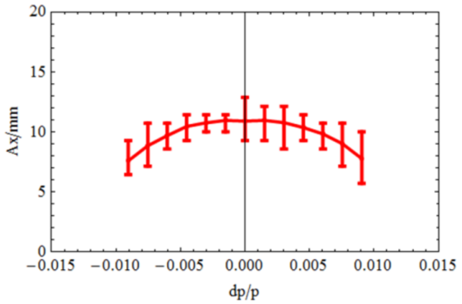
- 2 RF stations
- Maximum sawtooth orbit: 6 mm
- Energy deviation: 1.1%
- Emittance growth: ~3.6%
- Study of orbit correction with errors is going on.

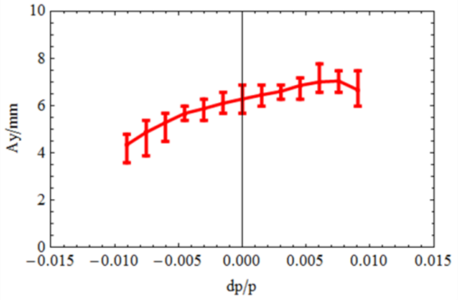
- Possible solutions:
  - Tapering for all the quad and sext
  - Taper dipoles in 8 sections
  - Orbit (optics) correction

W/O taper



- DA > requirement (BSC)
  - BSCX=4σx+3mm=7.7mm
  - BSCY=4σx+3mm=3.3mm
- Need careful error study





W taper

- sawtooth orbit was corrected by tapering
- DA tracking w/o errors (50 seeds, 100 turns)
- DA is good enough