Institute of High Energy Physics
Chinese Academy of Sciences

CEPC Circular Electron Positron Collider

CEPC booster lattice design

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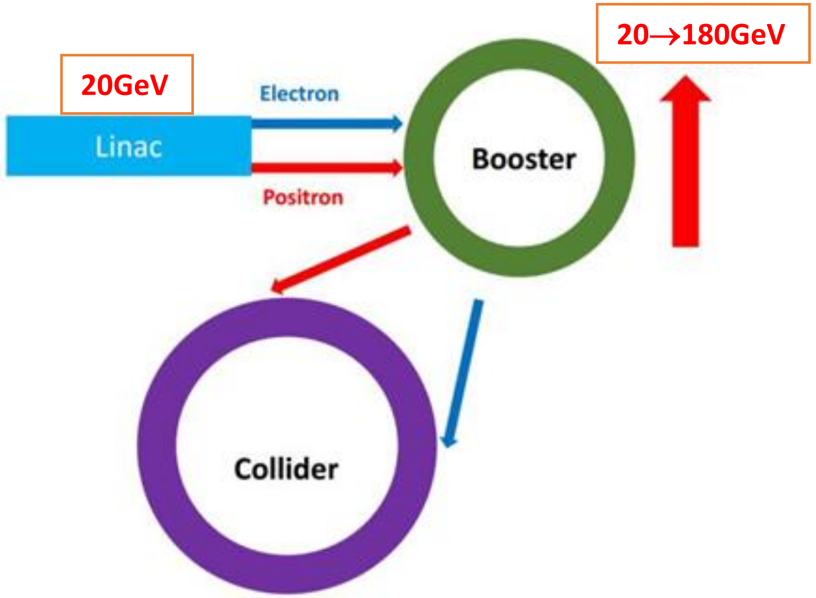
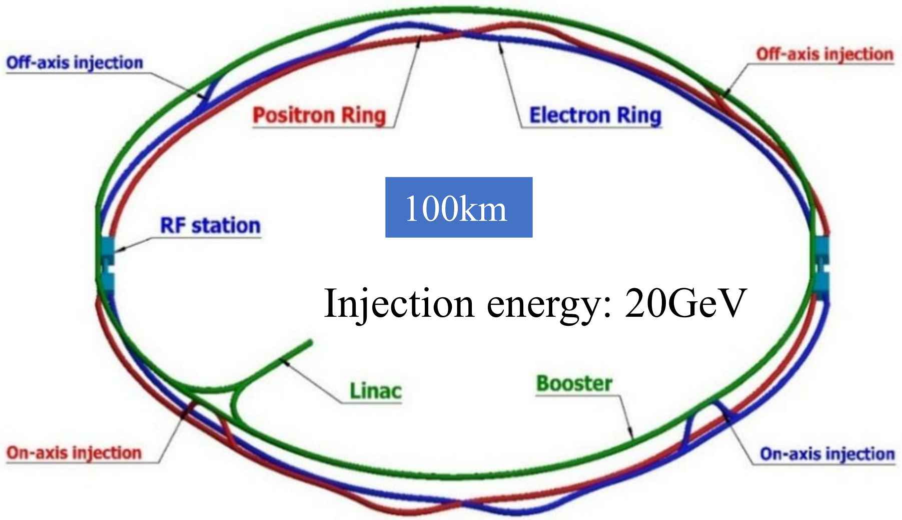
on behalf of CEPC AP group

The 65th Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022), Sep. 12-16, 2022. INFN-LNF.

CEPC injector chain



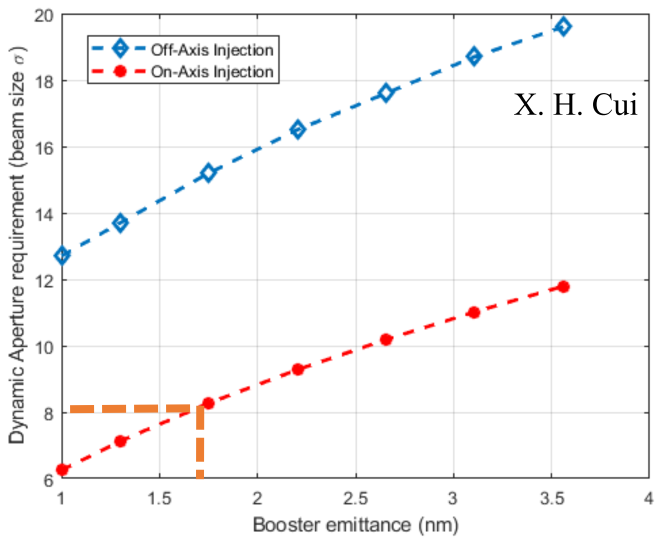


- 20 GeV linac provides electron and positron beams for booster.
- Top up injection for collider ring ~ 3% current decay
- Booster is in the same tunnel as collider ring, above the collider ring, bypass in IR.
- Budget for transfer efficiency **90%**: 95% for booster + 95% for transport lines.
- Beam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

Requirement update for booster

Collider ring	*Higgs (CDR)*	*Higgs (TDR)*
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	5.94
N_e/bunch (10^{10})	15.0	13.0
Bunch number	242	268
Beam current (mA)	17.4	16.7
SR power /beam (MW)	30	30
Bending radius (km)	10.7	10.2
Momentum compaction (10^{-6})	11.1	7.1
β_{IP} x/y (m)	0.36/0.0015	0.3/0.001
Emittance x/y (nm)	1.21/0.0024	0.64/0.0013
Transverse σ_{IP} (um)	20.9/0.06	14.0/0.036
ξ_x/ξ_y/IP	0.018/0.109	0.015/0.11
V_{RF} (GV)	2.17	2.20
f_{RF} (MHz) (harmonic)	650 (216820)	
Nature bunch length σ_z (mm)	2.72	2.3
Bunch length σ_z (mm)	4.4	4.1
Energy spread (%) (SR/BS)	0.1/0.134	0.1/0.17
Energy acceptance requirement (%)	1.35	1.6
Energy acceptance by RF (%)	2.06	2.2
Lifetime due to beamstrahlung (min)	80	40
Lifetime (min)	25	20
F (hour glass)	0.89	0.9
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	**2.93**	**5.0**

- Horizontal DA requirement of collider ring due to injection

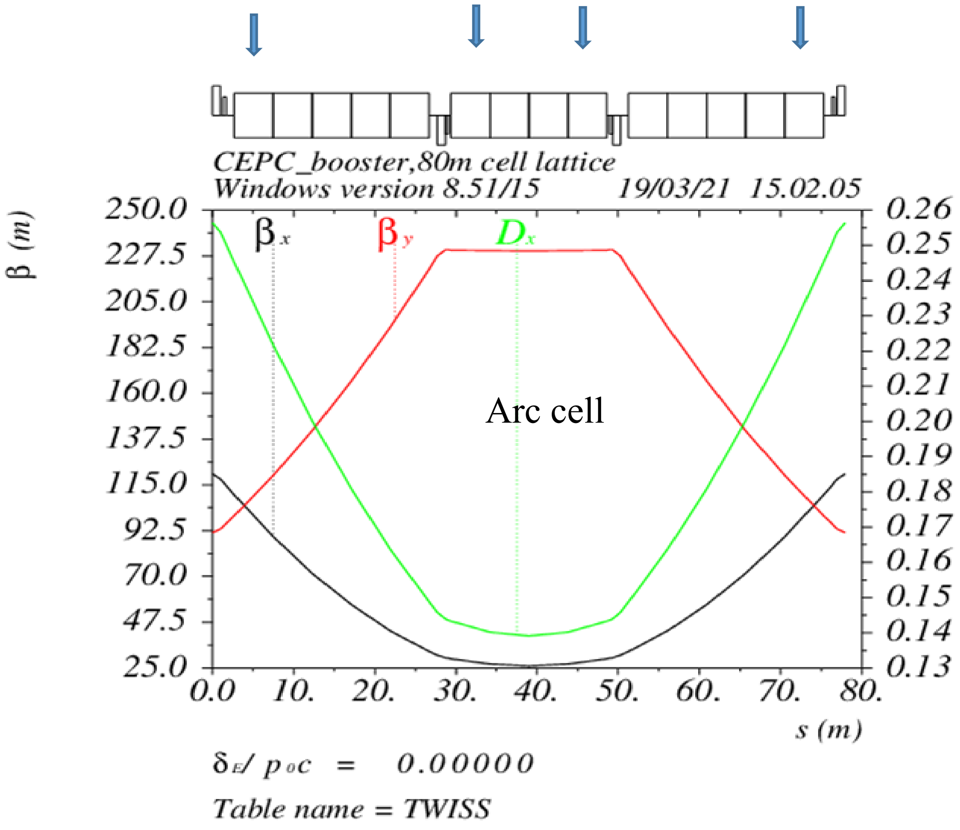


- Booster emittance @120 GeV <1.7nm (3.6nm in CDR)

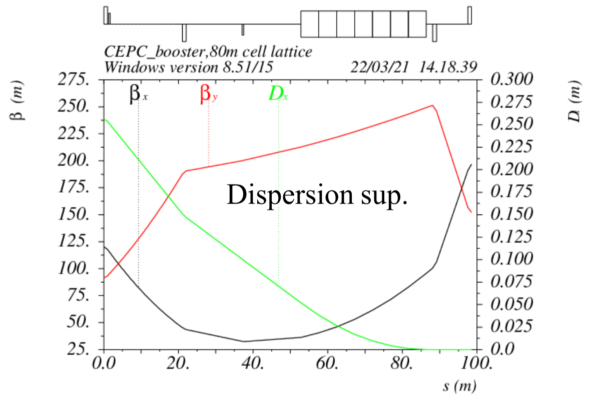
Booster TDR optics

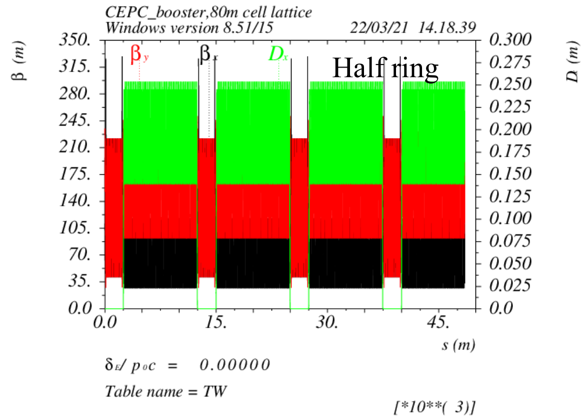
D. Wang, C. H. Yu, Y. M. Peng…

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



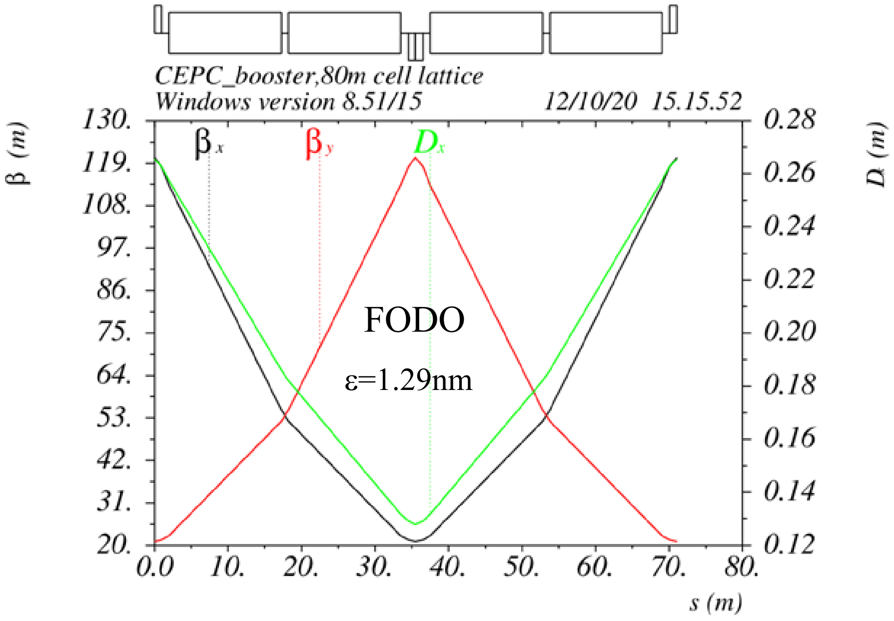
- Overall idea: uniform distribution for the Q
- Combined magnet (B+S) scheme possible
- Phase advance/cell: 100° (H) / 28° (V)



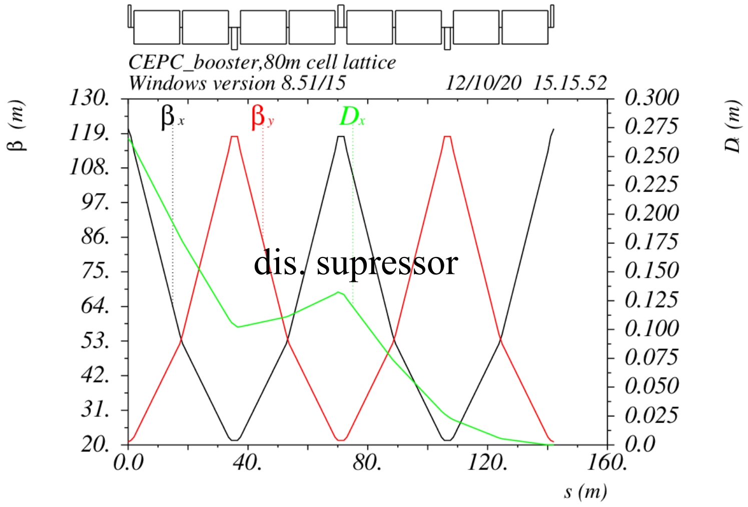


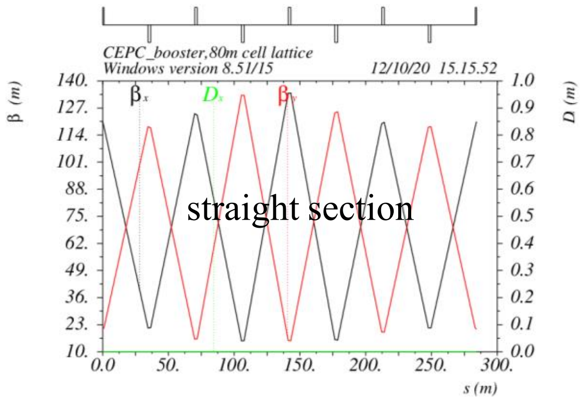
Booster alternative optics

- FODO structure (cell length=70m)
- 90°/90° phase advance
- Non-interleave sextupole scheme
- Similar structure as CDR



- Emittance@120GeV=1.29nm

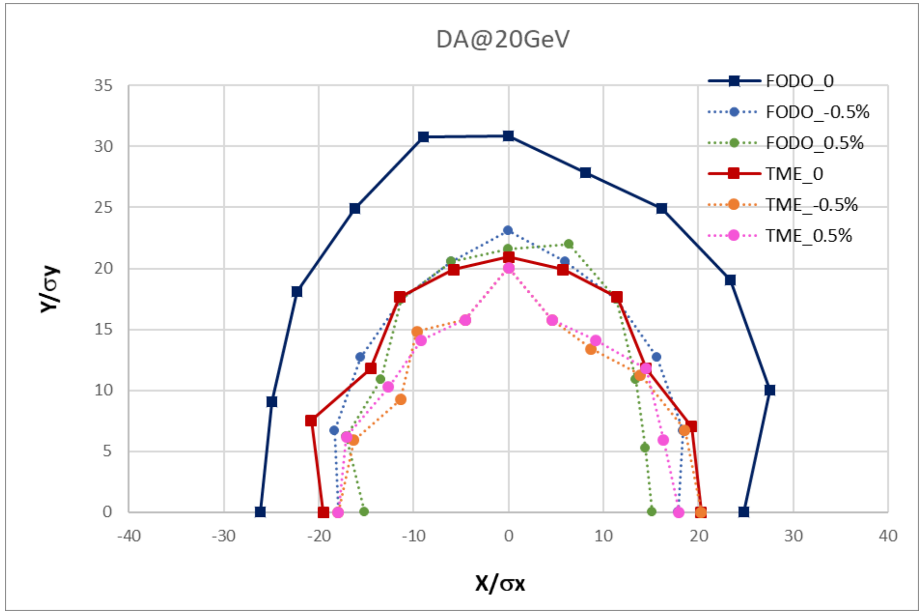


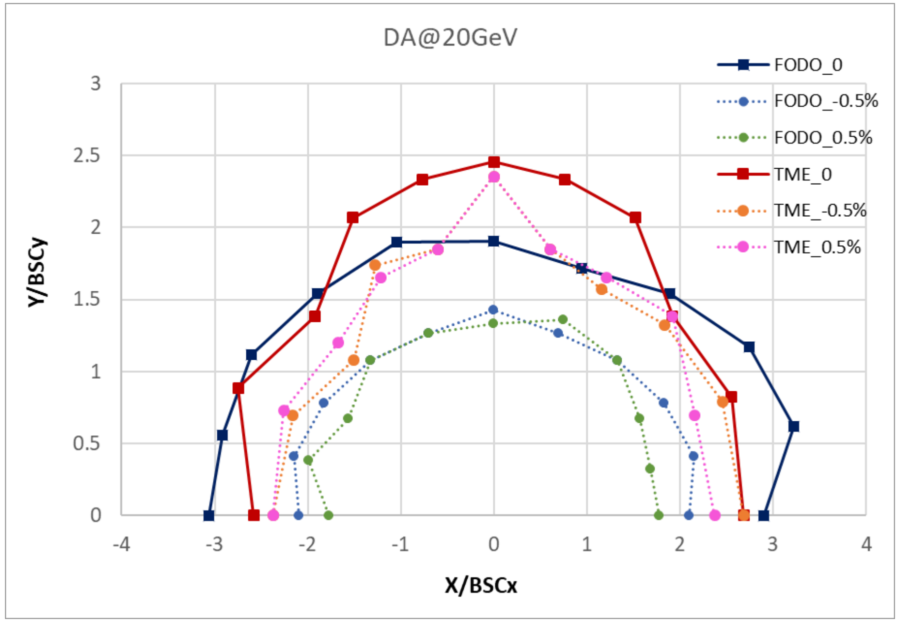


DA results @ 20GeV

- Booster energy: 20GeV~180GeV
- 20GeV: $BSC_{xy}=(4\sigma_{xy}+5mm)*2$

- Inj. emittance from Linac:10nm
- Energy spread from Linac: 0.16%





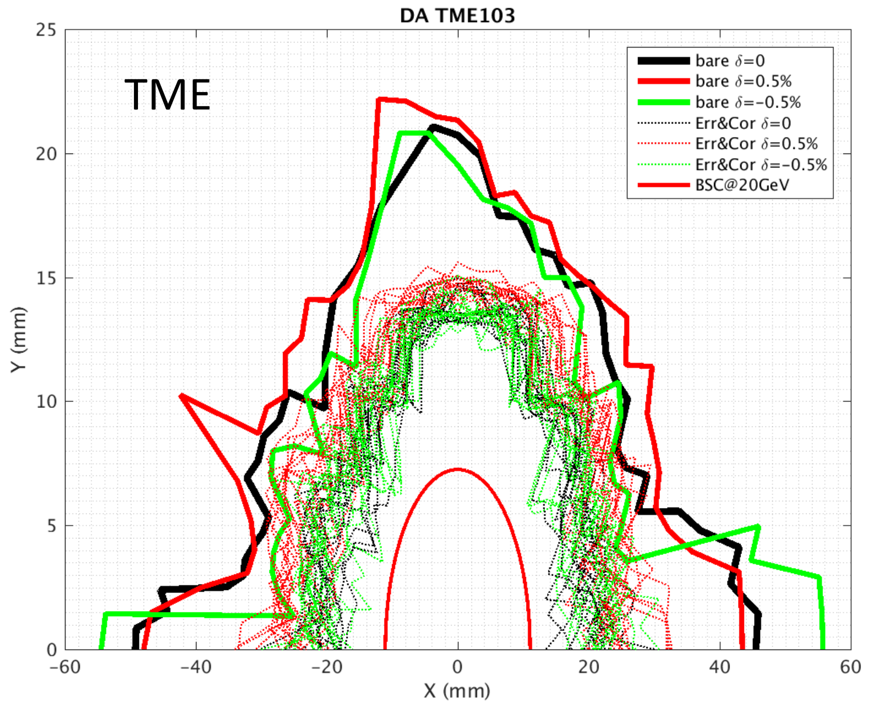
DA results with errors and correction (w/o multipoles)

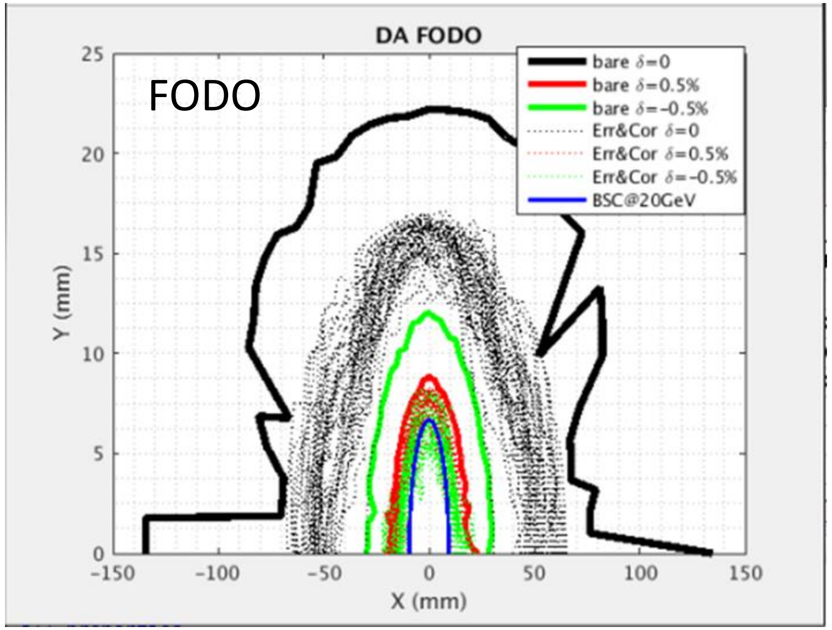
D. H. Ji

	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 correction (w/o SR effect)
  - Orbit correction
  - Optics correction



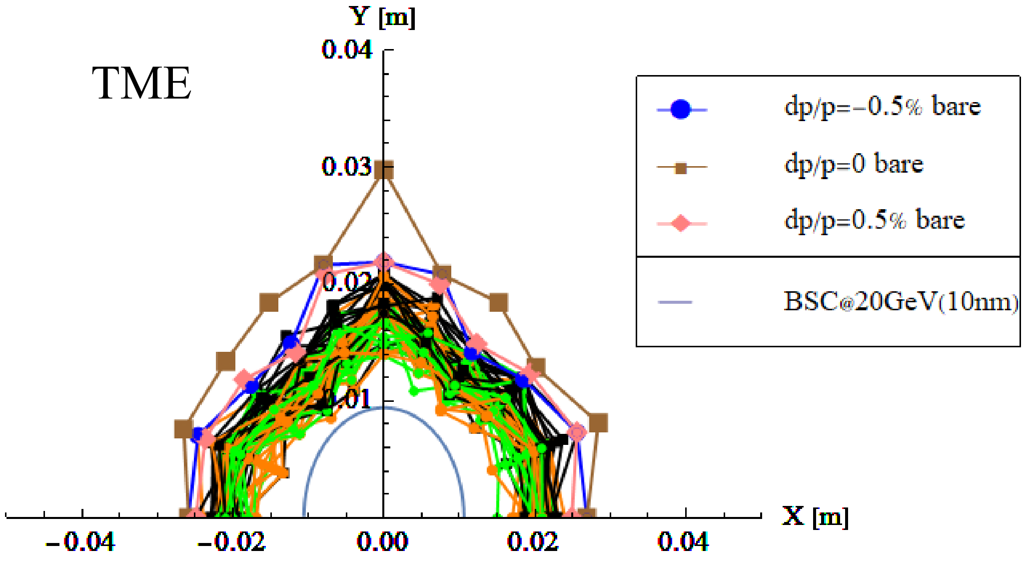


Multipole errors @ 20GeV

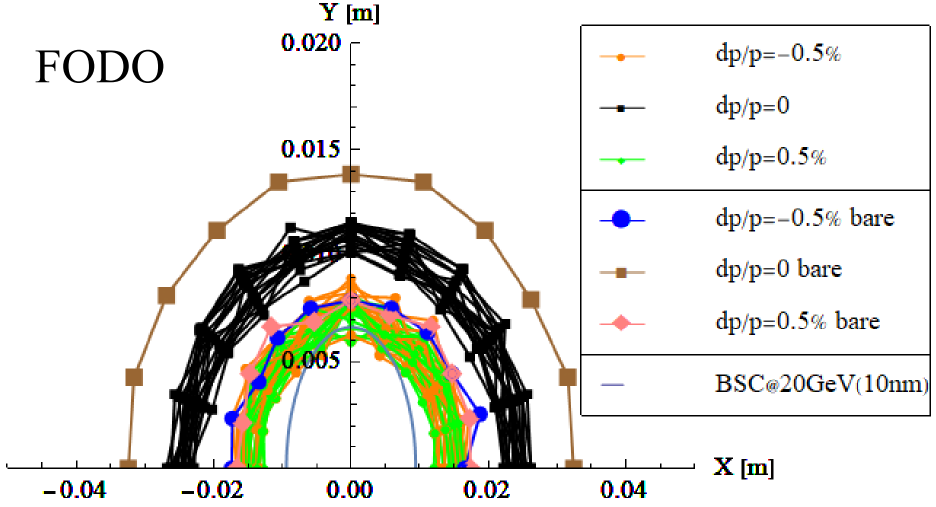
dipole	quadrupole	sextupole
$B1/B0 \leq 2\times10^{-4}$		
$B2/B0 \leq 3\times10^{-4}$	$B2/B1 \leq 3\times10^{-4}$	
$B3/B0 \leq 2\times10^{-5}$	$B3/B1 \leq 1\times10^{-4}$	$B3/B2 \leq 1\times10^{-3}$
$B4/B0 \leq 8\times10^{-5}$	$B4/B1 \leq 1\times10^{-4}$	$B4/B2 \leq 3\times10^{-4}$
$B5/B0 \leq 2\times10^{-5}$	$B5/B1 \leq 1\times10^{-4}$	$B5/B2 \leq 1\times10^{-3}$
$B6/B0 \leq 8\times10^{-5}$	$B6/B1 \leq 5\times10^{-5}$	$B6/B2 \leq 3\times10^{-4}$
$B7/B0 \leq 2\times10^{-5}$	$B7/B1 \leq 5\times10^{-5}$	$B7/B2 \leq 1\times10^{-3}$
$B8/B0 \leq 8\times10^{-5}$	$B8/B1 \leq 5\times10^{-5}$	$B8/B2 \leq 3\times10^{-4}$
$B9/B0 \leq 2\times10^{-5}$	$B9/B1 \leq 5\times10^{-5}$	$B9/B2 \leq 1\times10^{-3}$
$B10/B0 \leq 8\times10^{-5}$	$B10/B1 \leq 5\times10^{-5}$	$B10/B2 \leq 3\times10^{-4}$

- Multipole errors only
- Multipole errors can not be corrected
- TME is chosen as the baseline for TDR.

TME



FODO



DA results with errors and correction

D. H. Ji

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

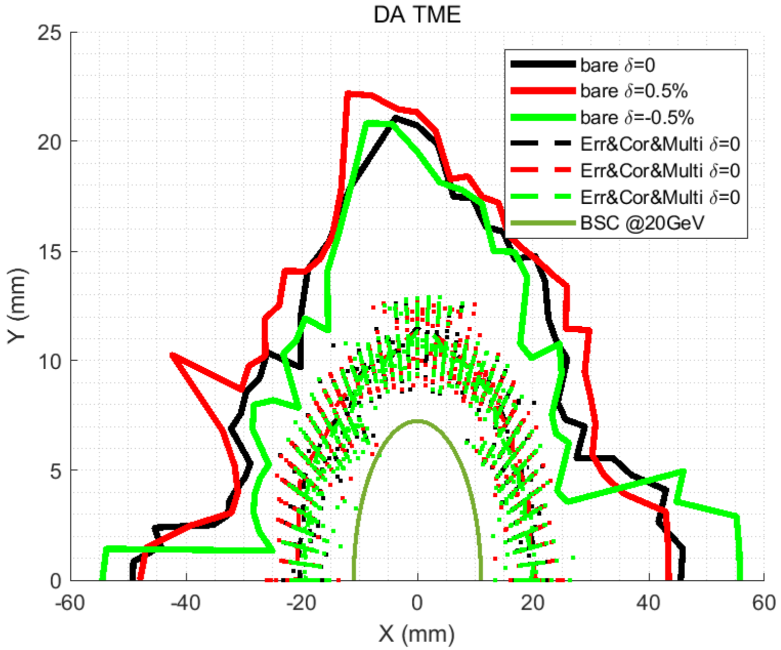
- Include multipole errors

dipole	quadrupole
$B1/B0 \leq 2\times10^{-4}$	
$B2/B0 \leq 5\times10^{-4}$	$B2/B1 \leq 3\times10^{-4}$
$B3/B0 \leq 2\times10^{-5}$	$B3/B1 \leq 2\times10^{-4}$
$B4/B0 \leq 8\times10^{-5}$	$B4/B1 \leq 1\times10^{-4}$
$B5/B0 \leq 2\times10^{-5}$	$B5/B1 \leq 1\times10^{-4}$
$B6/B0 \leq 8\times10^{-5}$	$B6/B1 \leq 5\times10^{-5}$
$B7/B0 \leq 2\times10^{-5}$	$B7/B1 \leq 5\times10^{-5}$
$B8/B0 \leq 8\times10^{-5}$	$B8/B1 \leq 5\times10^{-5}$
$B9/B0 \leq 2\times10^{-5}$	$B9/B1 \leq 5\times10^{-5}$
$B10/B0 \leq 8\times10^{-5}$	$B10/B1 \leq 5\times10^{-5}$

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

- Orbit & Dispersion Correction (100 seeds)
  - Response Matrix (RM)+SVD
- Optics Correction (93 seeds)
  - RM + LOCO
- DA track in AT @20GeV

RMS	TME
Orbit (mm)	0.062/0.071
Beta Beating(%)	0.16/0.1
Δ Dispersion(mm)	1.2/3.3



DA@20GeV

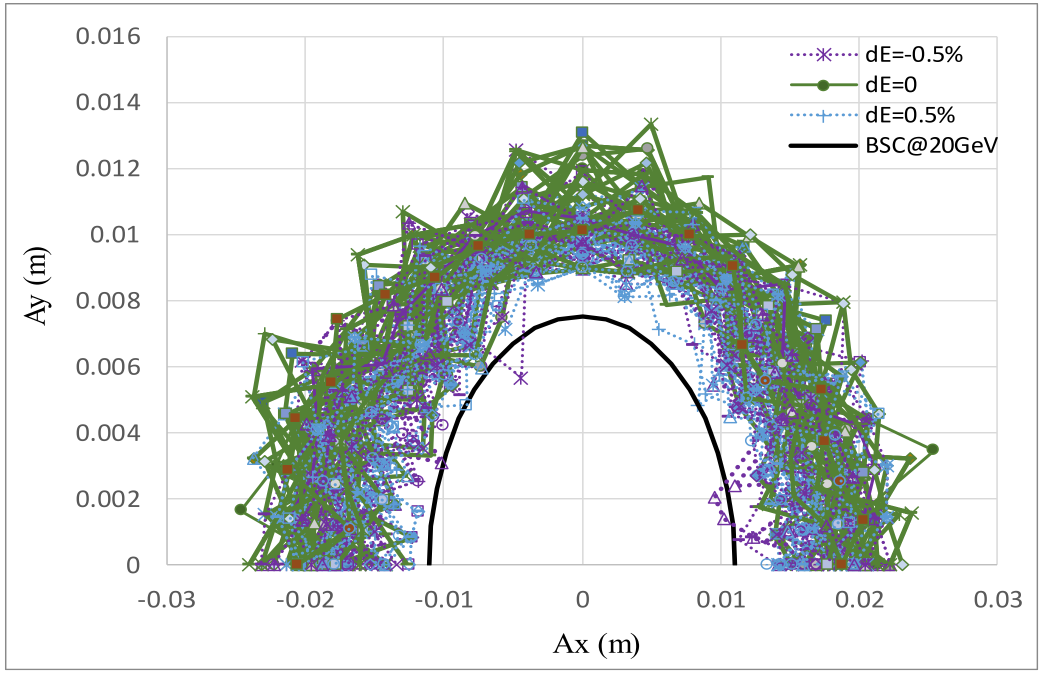
Dou Wang, Daheng Ji

- Tracking by **SAD** (2500 turns)
- include errors (w. multipole errors)
- Include SR sawtooth orbit (without taper)
- Include SR damping & fluctuation

- On axis injection from Linac to booster
- BSC definition (ε_{inj}=10nm):

$$BSC_{x,y} = 2\times(4\cdot\sigma_{x,y} + 5mm)$$

- Energy acceptance: $3*\delta_{inj}$=0.48%



DA@45GeV

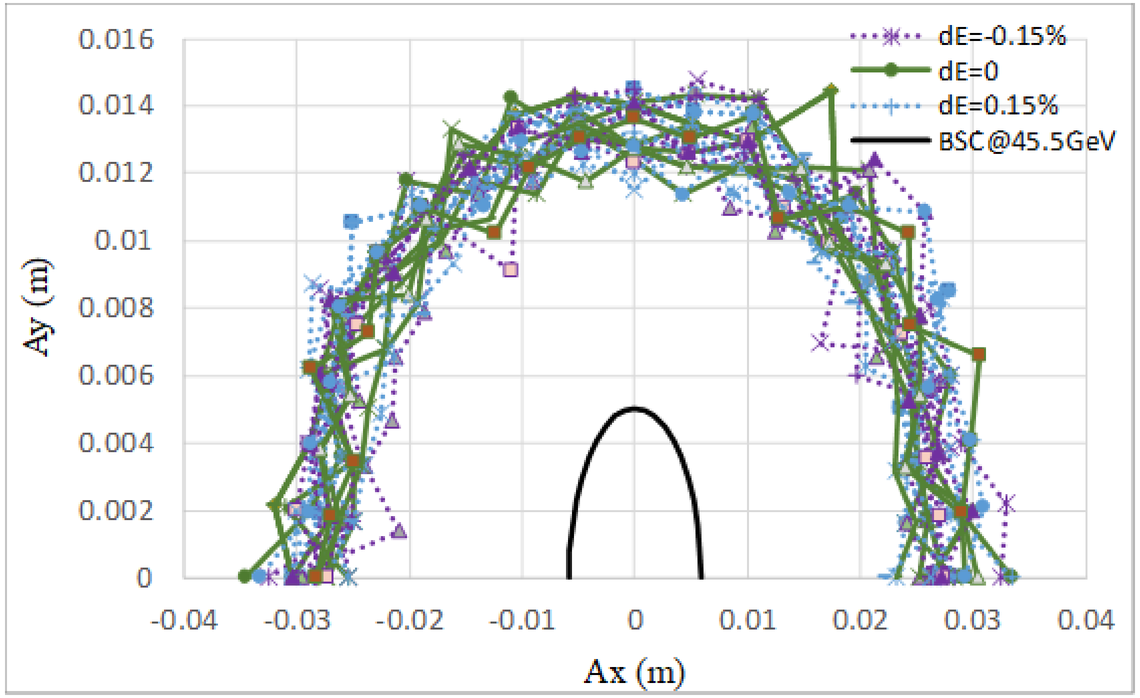
Dou Wang, Daheng Ji

- Tracking by **SAD** (1200 turns)
- include errors (w. multipole errors)
- Include SR sawtooth orbit (without taper)
- Include SR damping & fluctuation

- Off axis injection from booster to collider
- BSC definition (ε_x=0.18nm, $\varepsilon_y=\varepsilon_x$ *1%):

$$BSC_{x,y} = 2\times(4\cdot\sigma_{x,y} + 5mm)$$

- Energy acceptance: 4*δ=0.15%



DA@80GeV

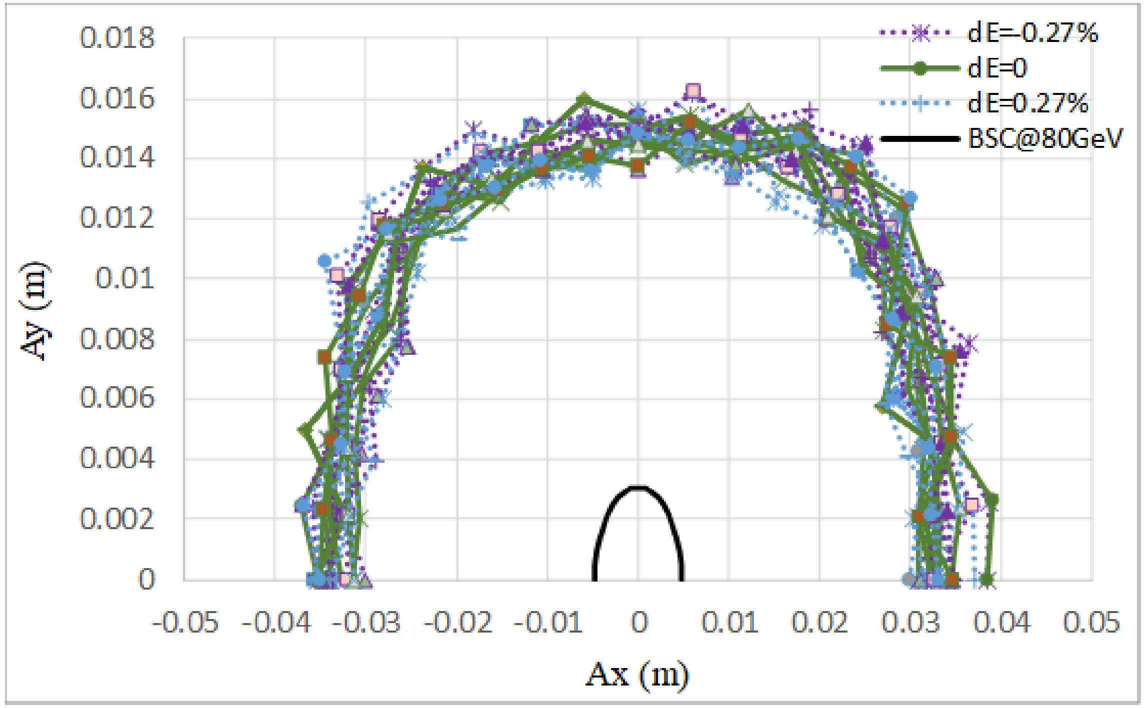
Dou Wang, Daheng Ji

- Tracking by **SAD** (500 turns)
- include errors (w. multipole errors)
- Include SR sawtooth orbit (without taper)
- Include SR damping & fluctuation

- Off axis injection from booster to collider
- BSC definition (ε_x=0.56nm, ε_y=ε_x *1%):

$$BSC_{x,y} = 2\times(5\cdot\sigma_{x,y} + 3mm)$$

- Energy acceptance: 4*δ=0.27%



DA@120GeV

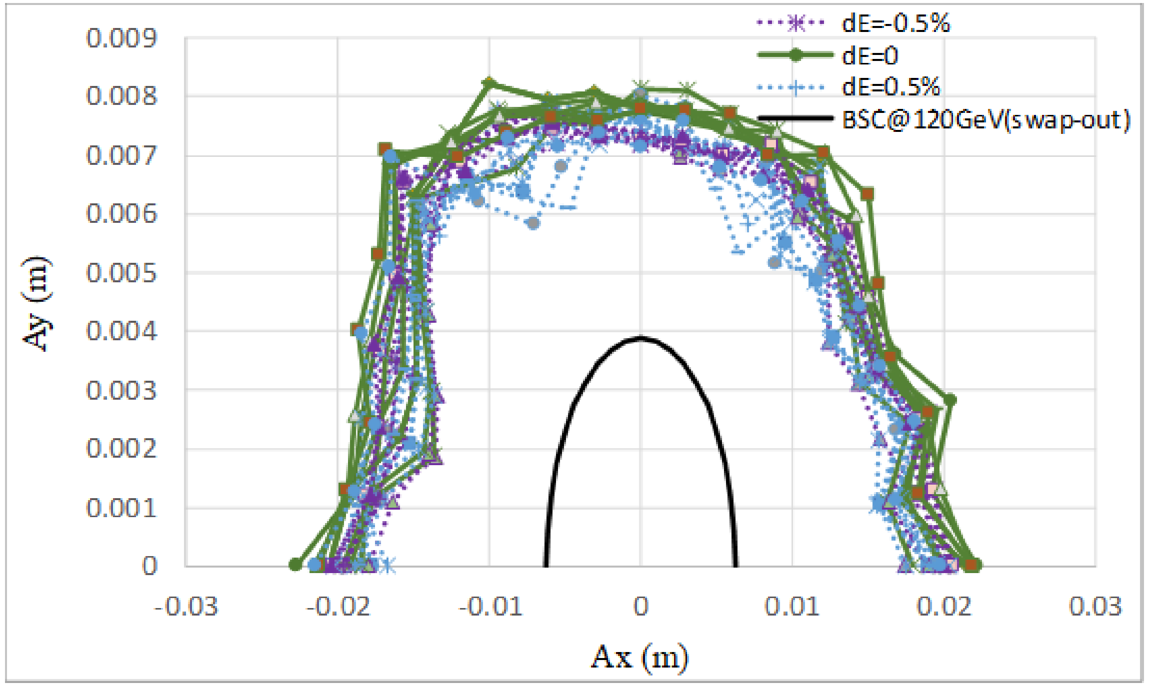
Dou Wang, Daheng Ji

- Tracking by **SAD** (250 turns)
- include errors (w. multipole errors)
- Include SR sawtooth orbit (without taper)
- Include SR damping & fluctuation

- On axis injection from booster to collider
- BSC definition (ε_x=1.26nm, ε_y=ε_x *1%):

$BSC_x = 2\times(6\cdot\sigma_x + 3mm)$ $\quad BSC_y = 2\times(39\cdot\sigma_y + 3mm)$

- Energy acceptance: 5*δ=0.5%

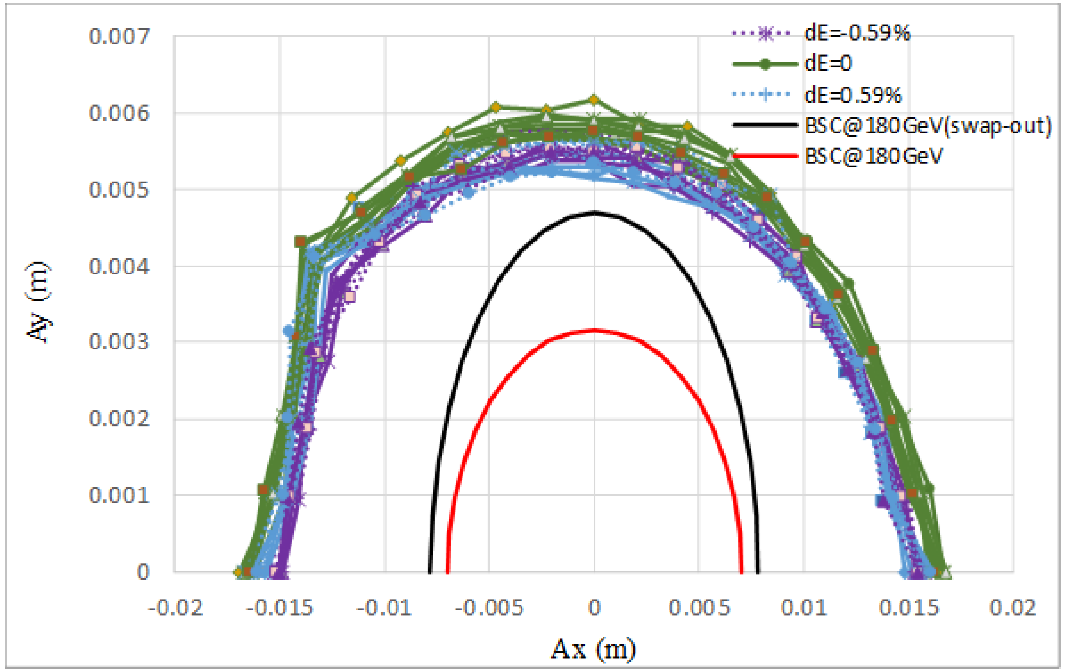


DA@180GeV

Dou Wang, Daheng Ji

- Tracking by **SAD** (150 turns)
- include errors (w. multipole errors)
- Include SR sawtooth orbit (**with taper**)
- Include SR damping & fluctuation

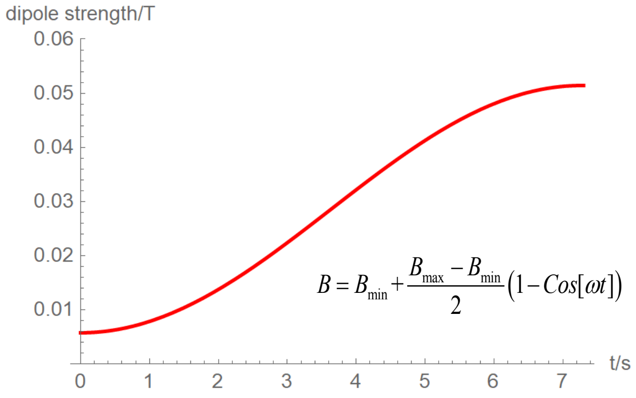
- Keep possibility for on axis injection to collider
- BSC definition (ε_x=2.84nm, ε_y=ε_x *1%):
  -- $BSC_x = 2\times(6\cdot\sigma_x + 3mm)$ $BSC_y = 2\times(50\cdot\sigma_y + 3mm)$
  -- $BSC_{x,y} = 2\times(5\cdot\sigma_{x,y} + 3mm)$
- Energy acceptance: 4*δ=0.59%



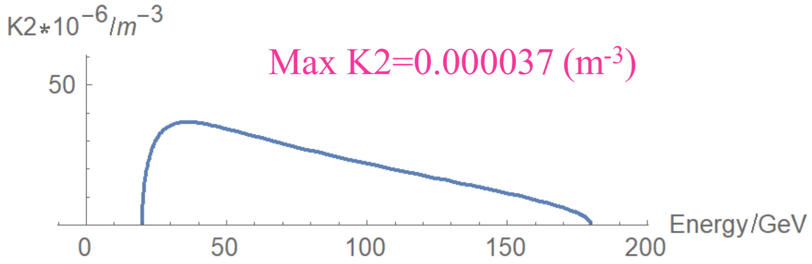
Eddy current effect

Dou Wang, Yuemei Peng, Daheng Ji

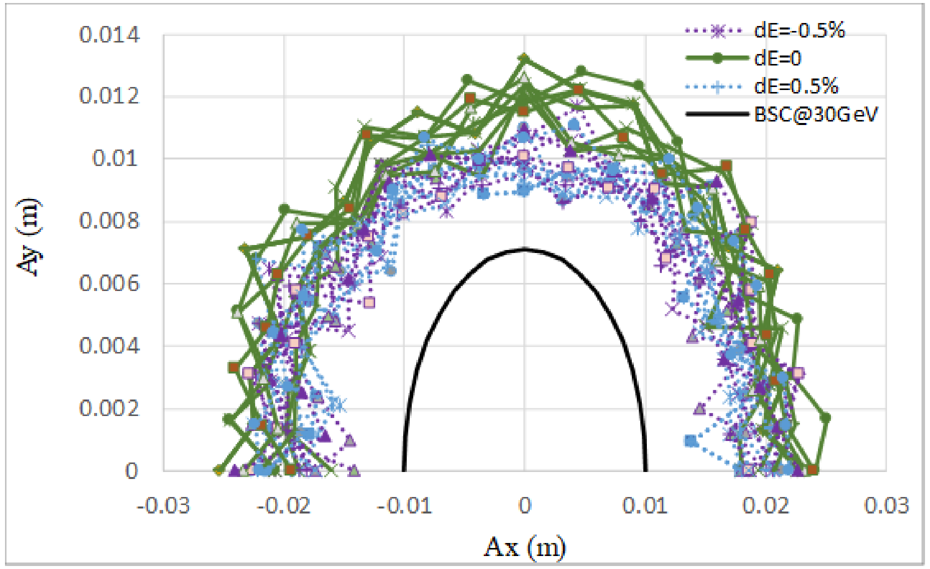
- Dedicated ramping curve to control the maximum K2.



- Analytical estimation for eddy effect*
- K2 reaches max at 30GeV.



- Al beam pipe (round shape)
  - inner diameter: 55mm, thickness: 2mm
- Dynamic chromaticity is not corrected.
  - Sextupole field is attached to dipole
- DA tracking including eddy effect and error effects
- Independent sext. (~100) — chromaticity adjustment

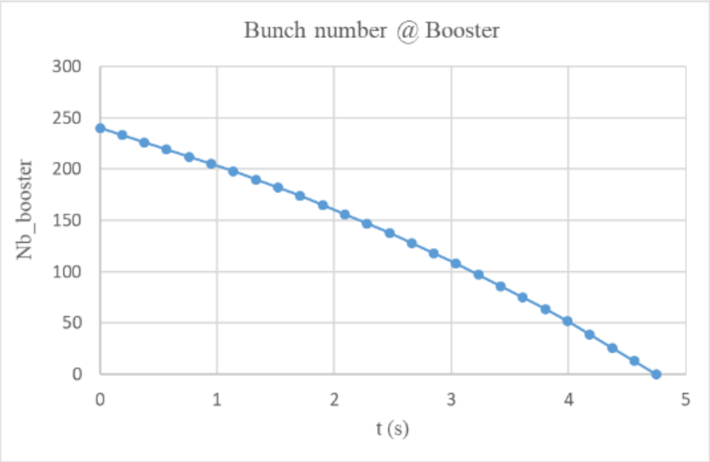


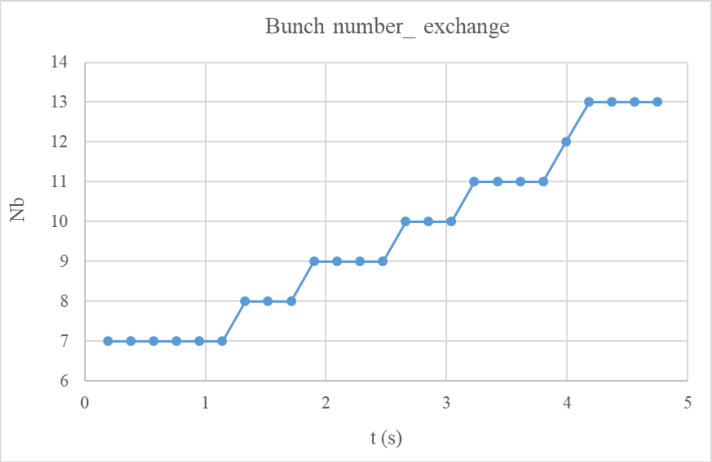
*Yuan Chen et al., Analytical expression development for eddy field and the beam dynamics effect on the CEPC booster, IJMPA, Vol. 36, No. 22 (2021) 2142010

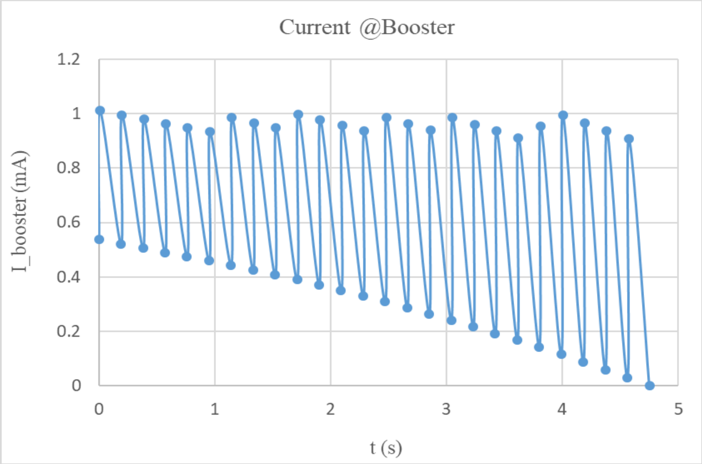
On-axis injection at Higgs energy

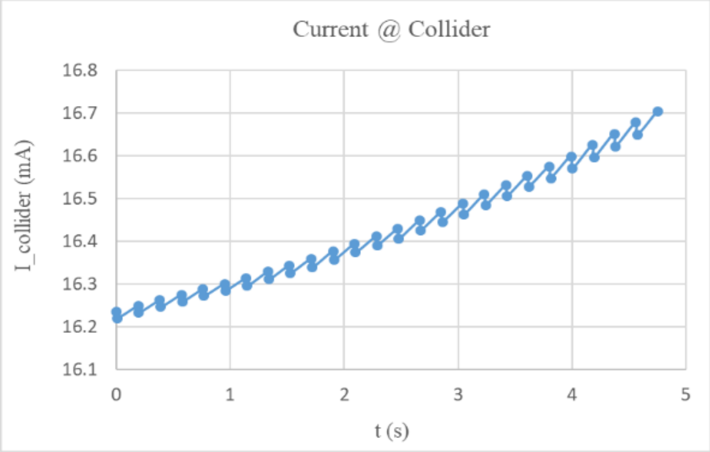
- Swap-out injection
- Current threshold in booster: 1A

- Current decay for collider: 3% (top up mode)
- 4 damping times to merge the bunches in booster





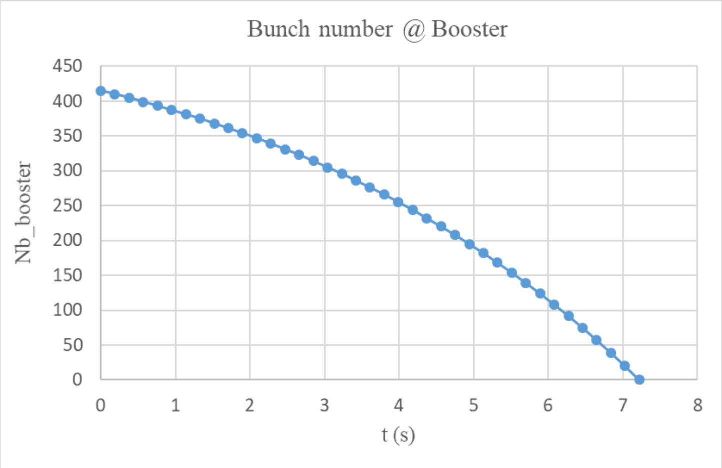


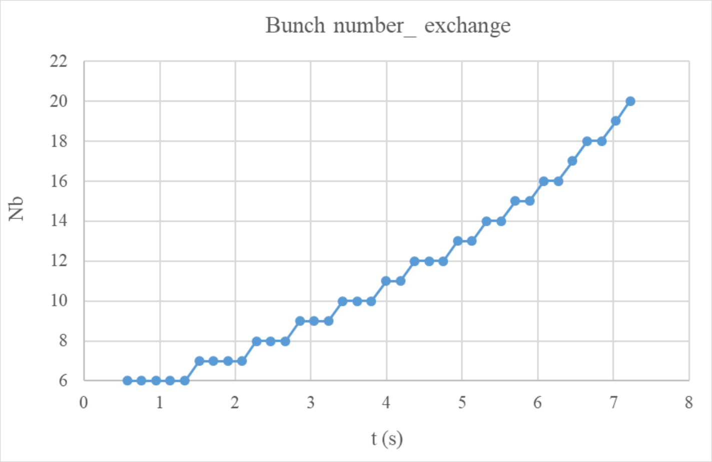


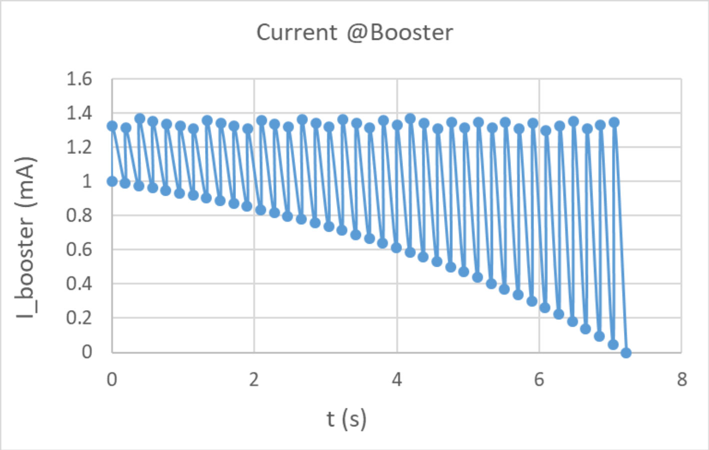
On-axis injection at Higgs energy (50MW upgrade)

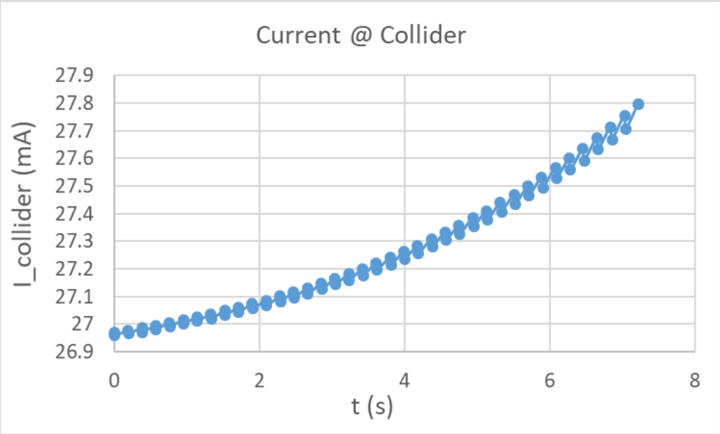
- Swap-out injection
- Current threshold in booster: 1.4 A

- Current decay for collider: 3% (top up mode)
- Small upgrade for the RF power source









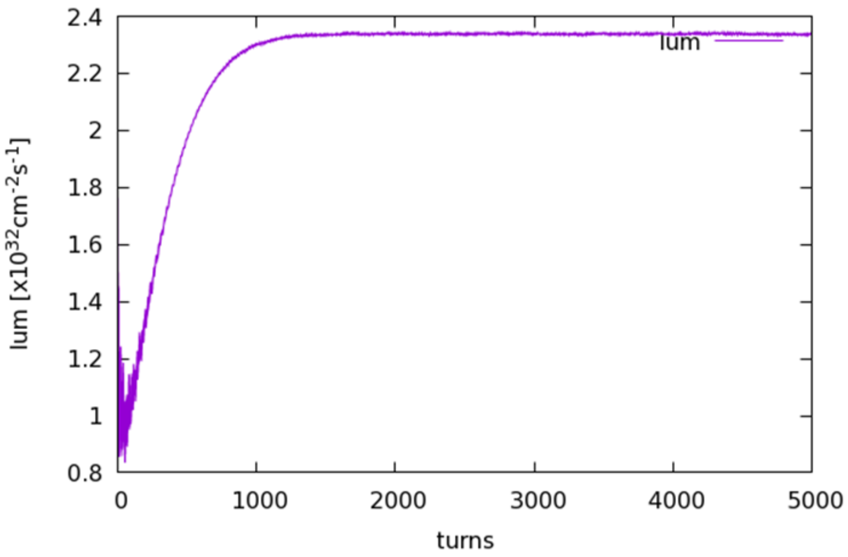
Beam beam instability for on-axis injection

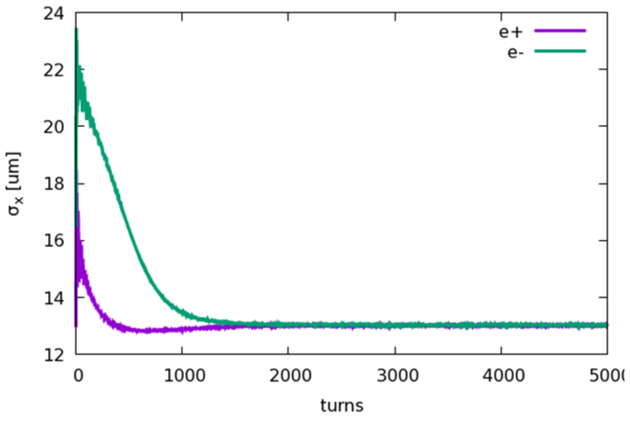
Yuan Zhang

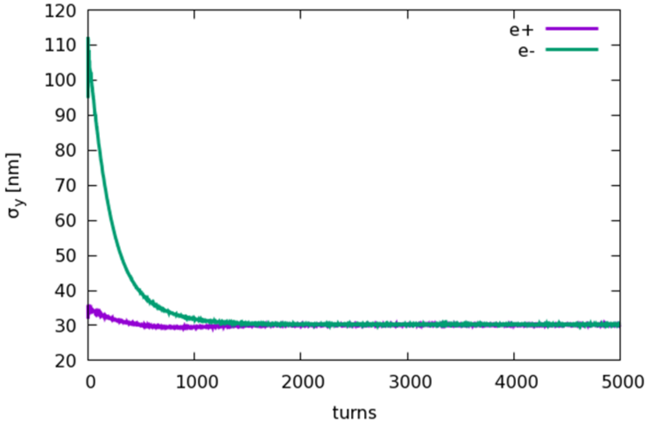
❖ Collision stability check for on-axis injection scheme at 120GeV

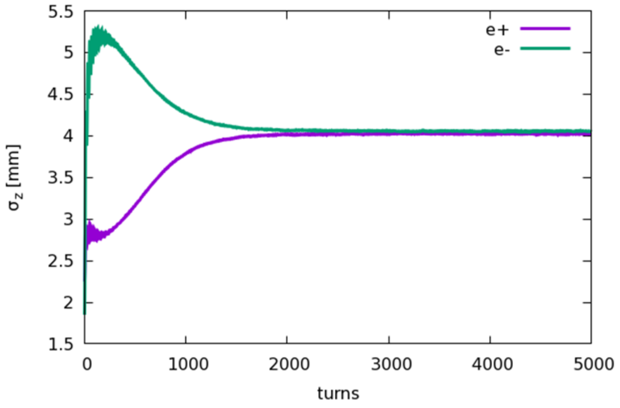
- e- (Ne=14×10^10)
- e+ (Ne=14×10^10)

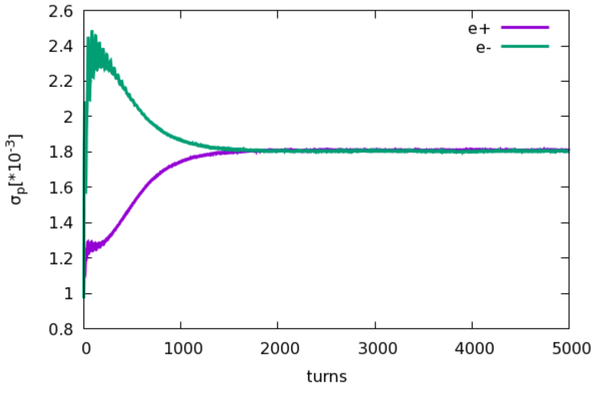
e-	e+
• Emittance X = 1.26nm • Energy spread = 0.1% • Bunch length=1.85mm • Coupling=1.0%	• Emittance X = 0.64nm • Energy spread = 0.1% • Bunch length=2.25mm • Coupling=0.2%











Dipole reproducibility requirement@20GeV

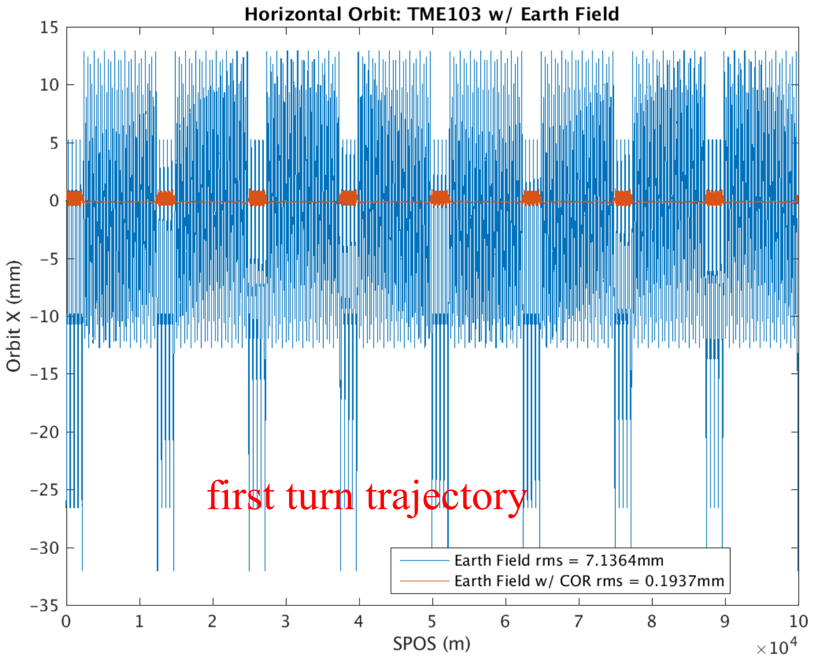
- Increase/decrease the strength of all the dipoles by the same amount.
- Evaluate the influence: working point, closed orbit, DA, energy acceptance
- Working point should not pass through the lower order resonance
- Small shrink for dynamic aperture
- Reproducibility requirement for dipoles: ~0.04%
- Stability requirement for power supply: ~0.01%
- **Dipole field error tolerance slightly loser than 10GeV.**

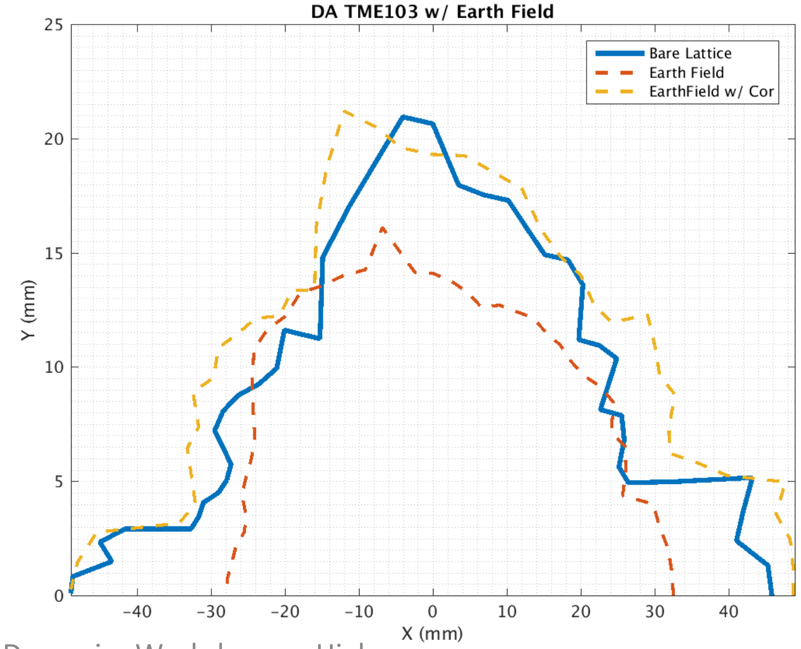
	original	+0.01%	-0.01%	+0.03%	-0.03%	+0.05%	-0.05%
nux	321.271	321.234	321.308	321.158	321.383	321.084	321.458
nuy	117.193	117.166	117.220	117.112	117.274	117.058	117.328
Δx (um)	0	-26	26	-77	77	-130	130
DA (%)	100	95	100	97	95	97	95

Effect of earthfield @20GeV

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: 0.6 gauss (simple model: perpendicular component only)
- Working point can be corrected by weaken the dipoles systematically (-0.07%)
- Earthfield problem can be solved by global orbit correction.





Booster ramping scheme

Dou Wang, Xiaohao Cui

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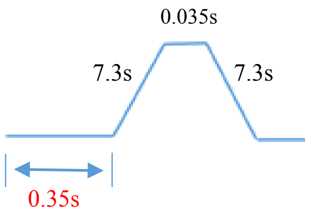
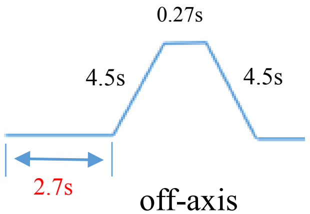


1 cycles/beam

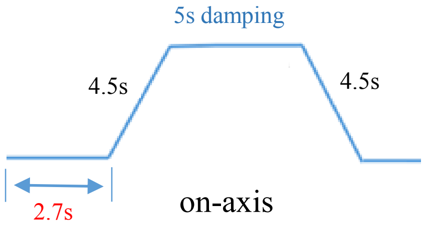
0.35s+7.3s+0.035s+7.3s=15.0s

Higgs



off-axis

1 cycles/beam



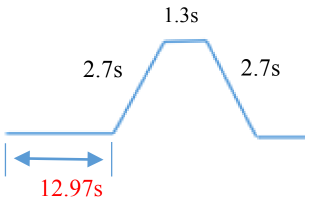
on-axis

2.7s+4.5s+5.0s+4.5s=16.5s

➤ On-axis injection @ Higgs

- Step 1: Linac→booster (240 small bunches)
- Step 2: Collider→booster (7 big bunches)
  off-axis injection
- Step 3: Mix in booster
  (233 small bunches + 7 big bunches)
- Step 4: Booster→collider (7 big bunches)
  on-axis injection
- → Step 2
- …

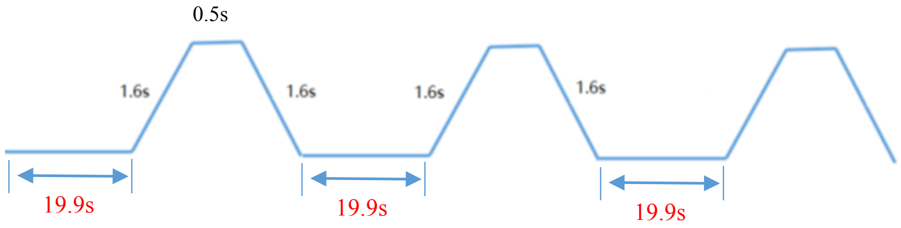
W



1 cycles/beam

12.97s+2.7s+1.3s+2.7s=19.7s

Z

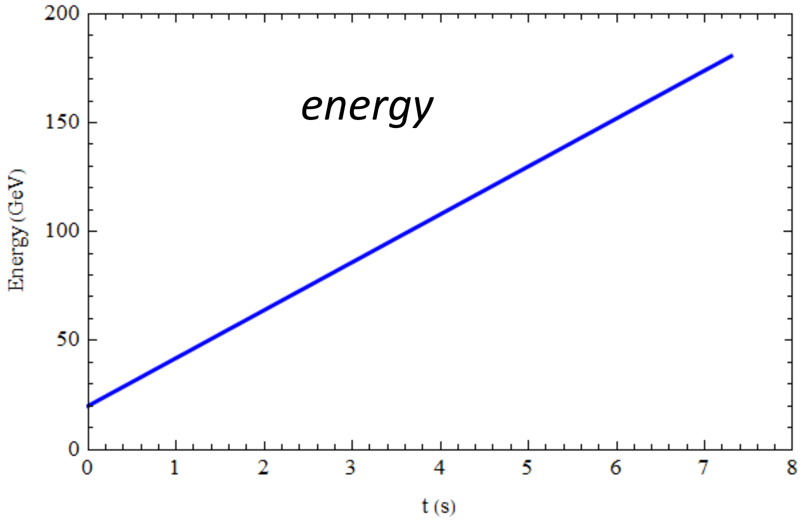


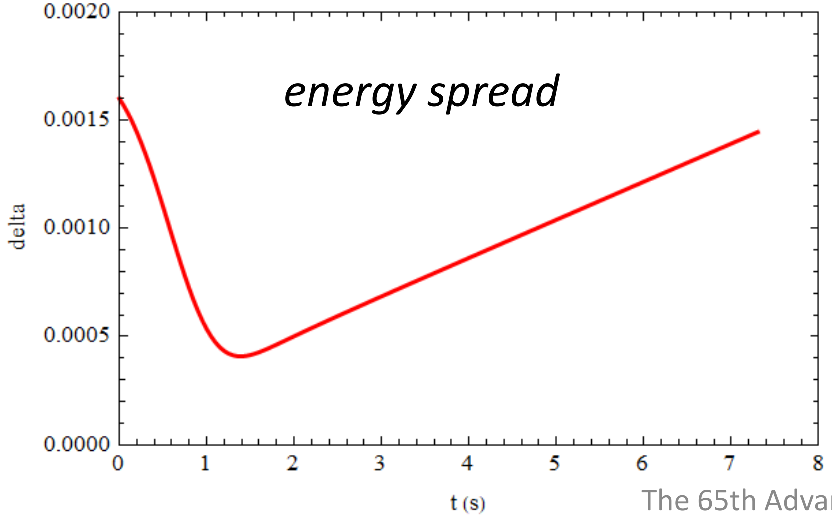
(19.9s+1.6s+0.5s+1.6s)*3=70.8s

3 cycles/beam

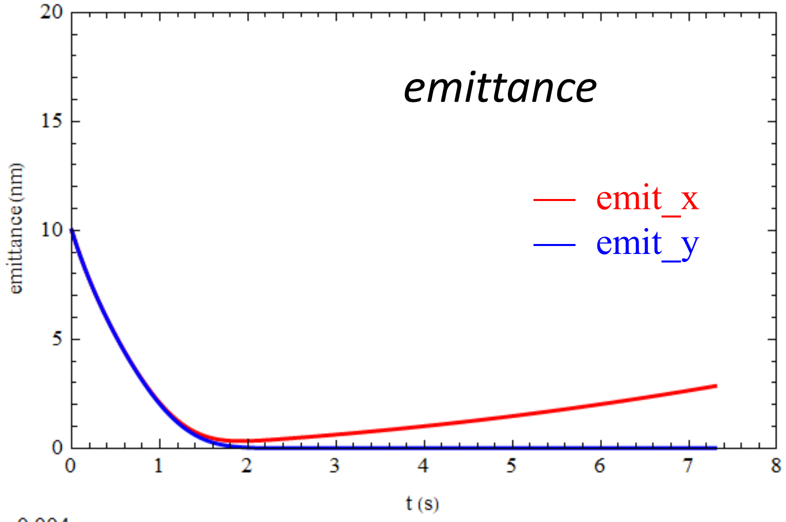
Beam parameter evolution

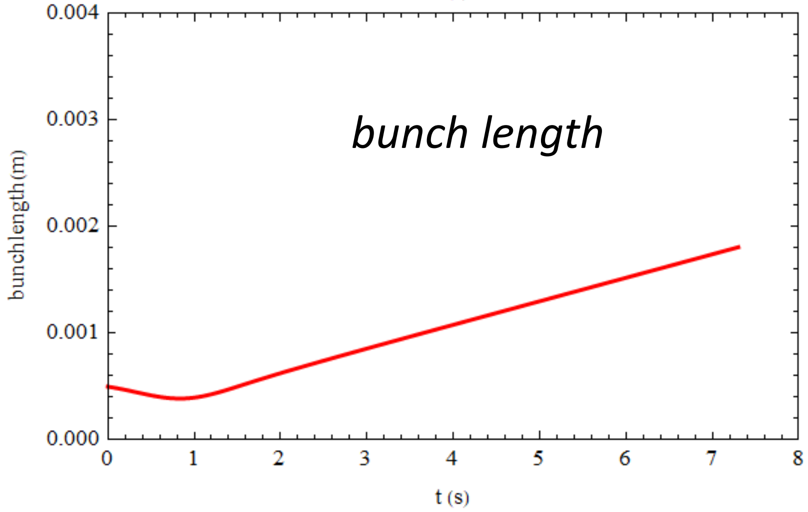
- Injection emittance: 10nm @20GeV





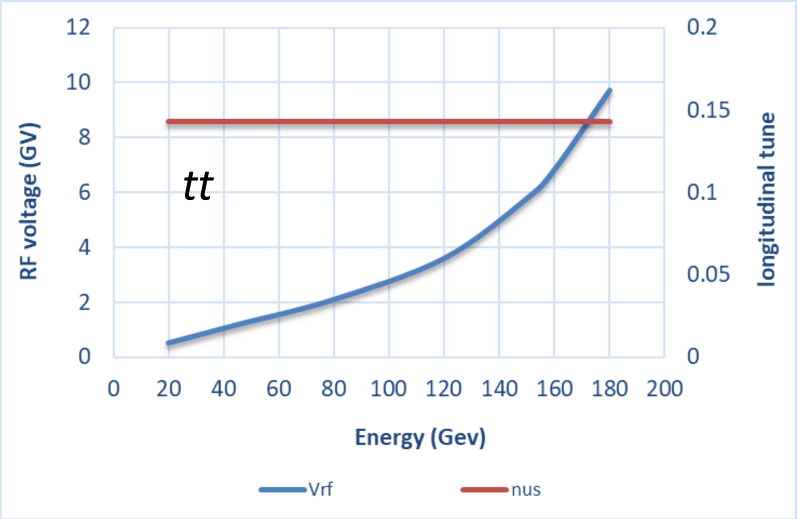
- Beam parameters reach balance after 60GeV.

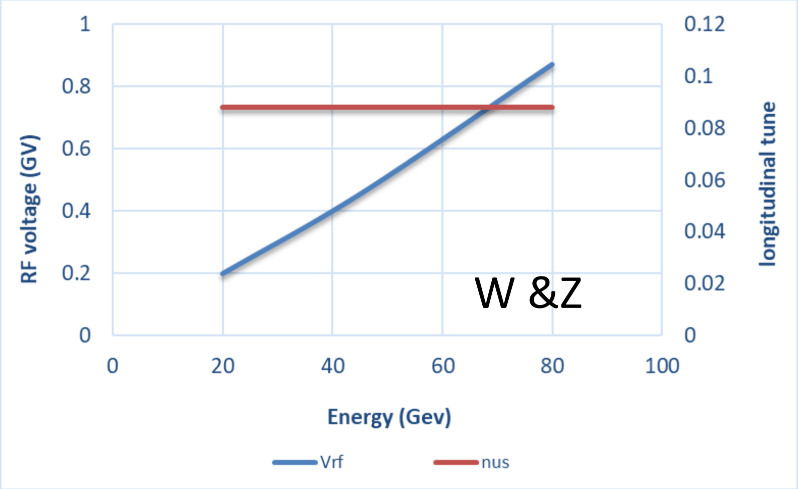


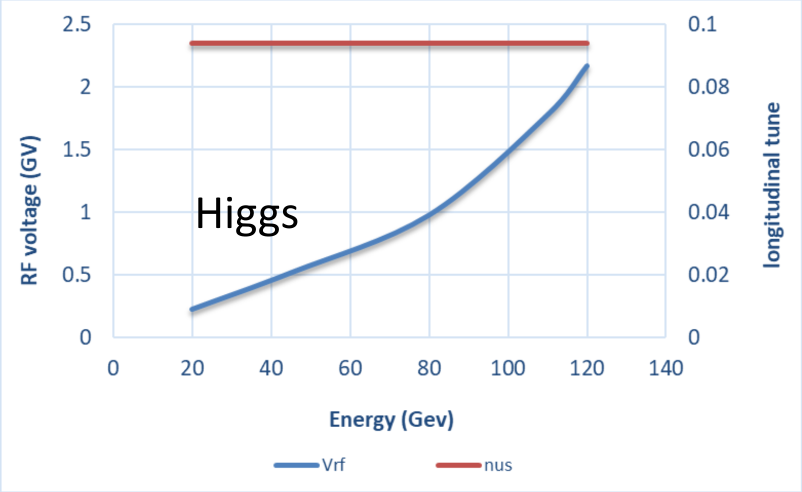


RF ramping curve

- Different RF ramping curve for each energy mode (constant νs)
  - νs for *tt*: 0.14
  - νs for Higgs: 0.094
  - νs for W & Z: 0.088
- Max RF voltage @*tt* determined by longitudinal quantum lifetime & DA.
  - η_{RF}: ~ 12 ×δ
  - VRF (180GeV)=9.8GV

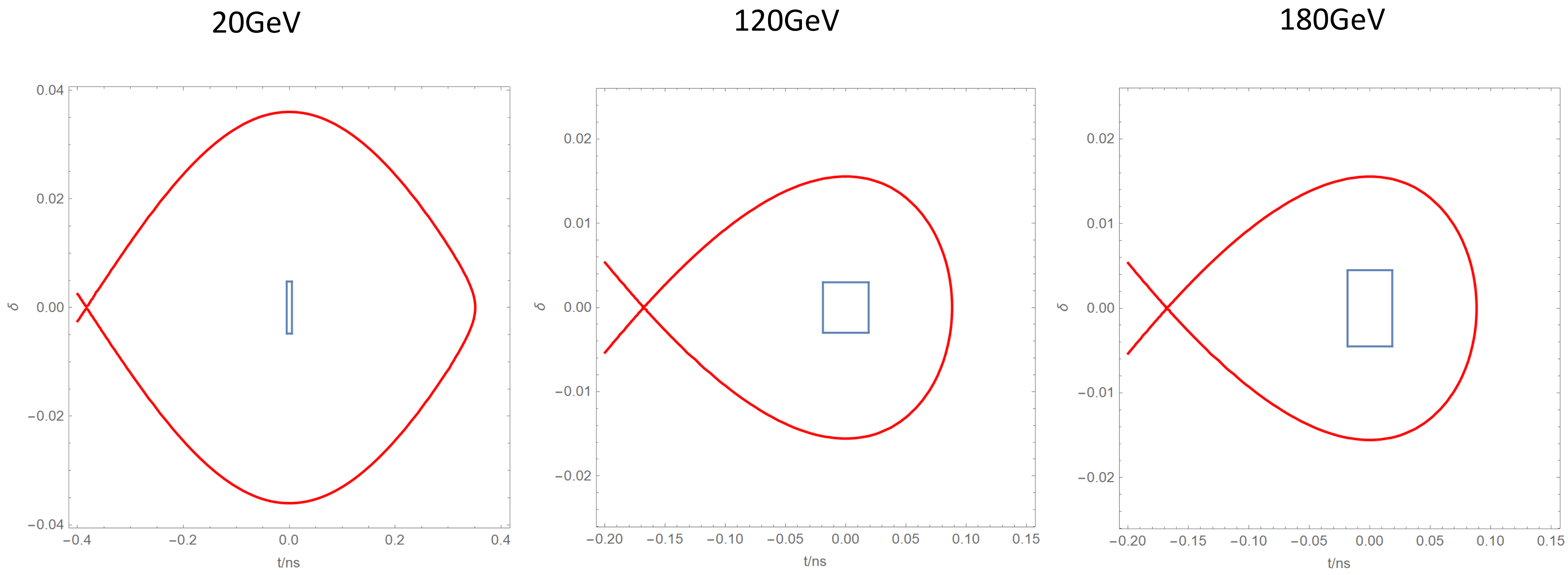






Longitudinal acceptance

- ±3 times of sigma for the longitudinal beam size



Optics parameter comparison

D. H. Ji, W. Kang

Lattice	FODO 0 （CDR）	FODO 1	TME (combine magnets)
Emittance X (nm) @120GeV	3.57	1.29	1.26
Momentum compaction ($\times 10^{-5}$)	2.44	1.18	1.12
Tunes	[263.201/261.219]	[353.180/353.280]	[321.271/117.193]
Quad amount	2110	2816	3458
Quad Strength (K1L rms)	0.0383	0.0407	0.0259
Sext amount	512	896	96
Sexts Strength (K2L rms)	0.179	0.4091	0.0492
H Corrector	1053	1408	1218
V Corrector	1054	1408	2240
BPM	2108	2816	3458
Power consumption of magnets@120GeV (MW) (max/average)	15/6		12.1/4.8

- Magnets' cost of TME is lower than FODO 1
  - Less independent sextupole for TME
  - Quadrupole strength of TME is lower
- TME is less sensitive to error effects
  - Weaker quad/sex strength
- TME has lower magnets' power consumption

Booster power consumption @Higgs

- The technical systems with changes are considered.
- The power consumption of TDR is lower than CDR with much lower emittance.

Technical system	CDR [MW]		TDR [MW]		Budget increment [MW]	
	max	average	max	average	max	average
Magnet system	15	6	12.1	4.8	-2.9	-1.2
Power supply	10.04	4.02	6.62	2.65	-3.42	-1.37
RF system						
RF power source	3.95	0.15	4.45	1.44	0.5	1.29
Beam Instrumentation	0.6	0.6	0.72	0.72	0.12	0.12
…						
total		20.97		19.81	-5.7	-1.16

Booster power consumption @Z

- The technical systems with changes are considered.
- The power consumption of TDR almost same as CDR with much lower emittance.

Technical system	CDR [MW]		TDR [MW]		Budget increment [MW]	
	max	average	max	average	max	average
Magnet system	2.14	1.28	1.72	0.69	-0.42	-0.59
Power supply	2.48	0.99	1.88	0.75	-0.6	-0.24
RF system						
RF power source	0.5	0.04	1.13	0.084	0.63	0.044
Beam Instrumentation	0.6	0.6	0.72	0.72	0.12	0.12
…						
total		9.7		9.034	-0.27	-0.666

Booster TDR parameters

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

Injection		*tt*	*H*	*W*	*Z*	
Beam energy	GeV	20				
Bunch number		35	268	1297	3978	5967
Threshold of single bunch current	μA	5.79	4.20	3.92		
Threshold of beam current (limited by coupled bunch instability)	mA	27				
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	1690	358	67	19.4	12.5
Energy spread	%	0.016				
Synchrotron radiation loss/turn	MeV	1.3				
Momentum compaction factor	10^{-5}	1.12				
Emittance	nm	0.035				
Natural chromaticity	H/V	-372/-269				
RF voltage	MV	531.0	230.2	200.0		
Betatron tune ν_x/ν_y		321.23/117.18				
Longitudinal tune		0.14	0.0943	0.0879		
RF energy acceptance	%	5.9	3.7	3.6		
Damping time	s	10.4				
Bunch length of linac beam	mm	0.5				
Energy spread of linac beam	%	0.16				
Emittance of linac beam	nm	10				

Extraction		*tt*	*H*		*W*	*Z*	
		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	7.3	4.5		2.7	1.6	
Injection duration for top-up (Both beams)	s	30. 0	23.3	32.8	39.4	141.6	
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 55mm for re-injection with high single bunch current @120GeV.

Summary

- Booster energy range is enlarged in TDR. (10GeV/120GeV → 20GeV/180GeV)

- Update booster design with smaller emittance in TDR— support for CEPC high lum. scheme

  - TME structure with combined magnets (B+S)
  - DA with error effects fulfill the requirements
  - Booster parameters update — consistent with CEPC TDR parameters at 4 energy

- 30GeV injection is under consideration for the cost saving.

  - The non-oriented silicon laminations for the iron dominated dipole magnet can be used at 30GeV.