Beam Dynamics of the CEPC Booster

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on behalf of CEPC AP group

Many Thanks to: K. Oide, Y. Cai, M. Koratzinos

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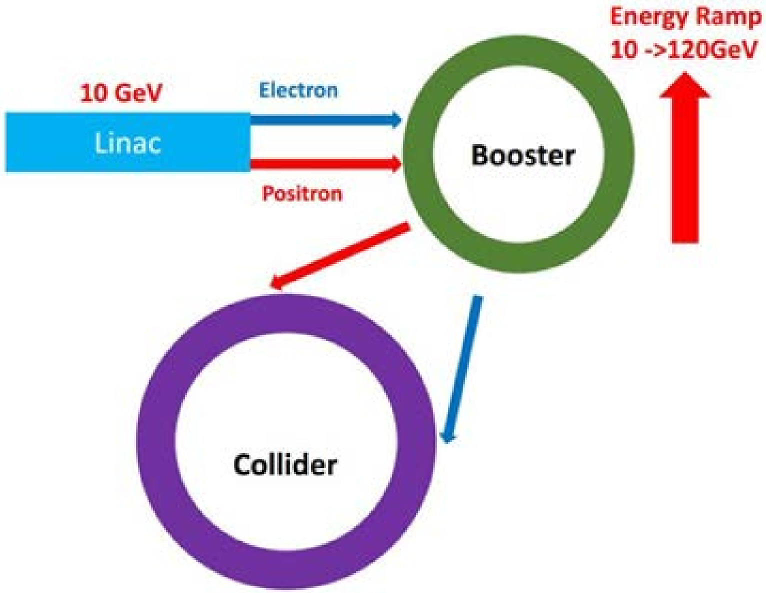
Outline

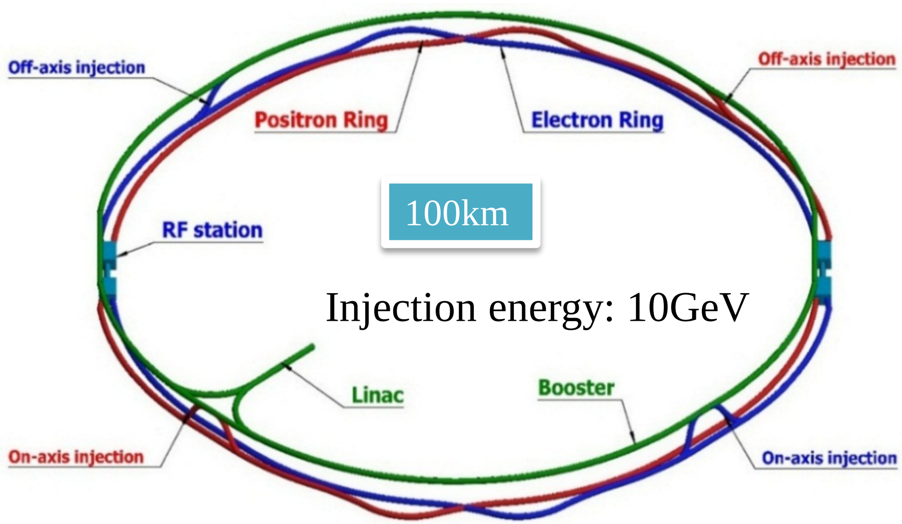
- Introduction
- Design requirements
- Geometry & optics
- Performance with errors
- Ramping curves & eddy current effect
- Summary

CEPC CDR Parameters

	Higgs	***W***	***Z（3T）***	***Z（2T）***
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	3.48	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	**242 (0.68μs)**	**1524 (0.21μs)**	**12000 (25ns+10%gap)**	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compact (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0024	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.06	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.018/0.109	0.013/0.123	0.004/0.06	0.004/0.079
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	4.4	5.9	8.5	
HOM power/cavity (2 cell) (kw)	0.46	0.75	1.94	
Energy spread (%)	0.134	0.098	0.080	
Energy acceptance requirement (%)	1.35	0.90	0.49	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.082	0.050	0.023	
Beamstruhlung lifetime /quantum lifetime* (min)	80/80	>400		
Lifetime (hour)	**0.43**	**1.4**	**4.6**	**2.5**
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP L (10^{34}cm^{-2}s^{-1})	2.93	10.1	16.6	32.1

CEPC injector chain





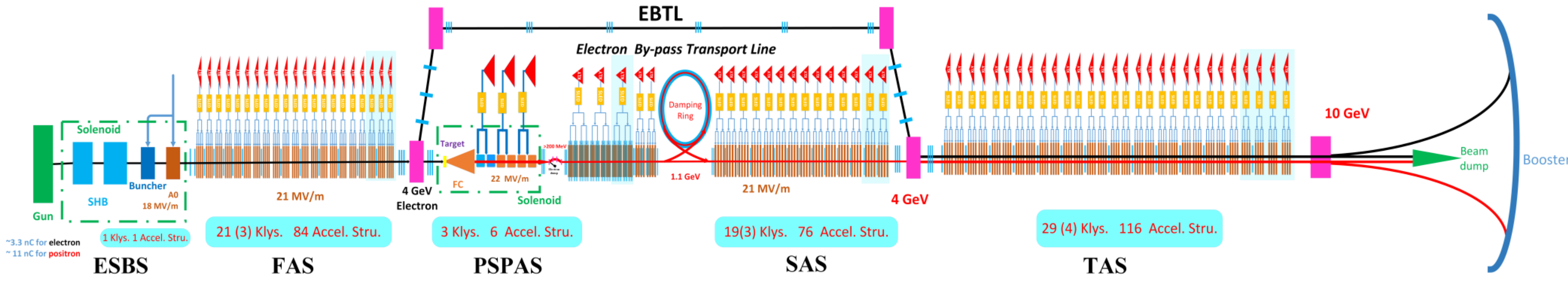
- 10 GeV linac provides electron and positron beams for booster.
- Top up injection for collider ring ~ 3% current decay
- Booster is in the same tunnel as collider ring, above the collider ring.
- Booster has the same geometry as collider ring except for the two IRs.
- Booster bypasses the collider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

Design requirements for CEPC booster

Parameters	***Design goals***
Beam current (mA)	<1.0 mA(Higgs), 4.0 mA (W), 10 mA(Z)
Emittance@ 120GeV (nm rad)	<3.6
Dynamic aperture @10GeV(σ, normalized by linac beam size)	>4σ+5mm
Dynamic aperture @120GeV	>6σx+3mm, 49σx+3mm
Energy acceptance	>1%
Coupling	<0.5%
Booster transfer efficiency	>92%
Total transfer efficiency (inc. inj. & ext.)	>90% (99%*92%*99%)
Timing	Meet the top-up injection requirements

- Beam current threshold in booster is limited by RF power.
- The diameter of the inner aperture is selected as **55mm** for high current injection.
- Assumption for total efficiency **90%**: 92% for booster+ 99% for transport lines.
- Emittance@120GeV <3.6nm, energy acceptance >1%
- Coupling <0.5%: requirement of Higgs on-axis injection scheme
- DA@10GeV: BSC region, DA@120GeV:on-axis injection (V) & quan. lifetime (H)

CEPC Linac



Parameter	Symbol	Unit	Baseline	Designed
e^- /e^+ beam energy	E_{e-}/E_{e+}	GeV	**10**	**10**
Repetition rate	f_{rep}	Hz	**100**	**100**
e^- /e^+ bunch population	N_{e-}/N_{e+}		> 9.4×10^9	**1.9×10^{10} / 1.9×10^{10}**
		nC	**> 1.5**	**3.0**
Energy spread (e^- /e^+)	σ_e		**< 2×10^{-3}**	**1.5×10^{-3} / 1.6×10^{-3}**
Emittance (e^- /e^+)	ε_r	nm· rad	**< 120**	**5 / 40 ~120**
Bunch length (e^- /e^+)	σ_l	mm		**1 / 1**
e^- beam energy on Target		GeV	4	**4**
e^- bunch charge on Target		nC	10	**10**

Booster parameters @ injection (10GeV)

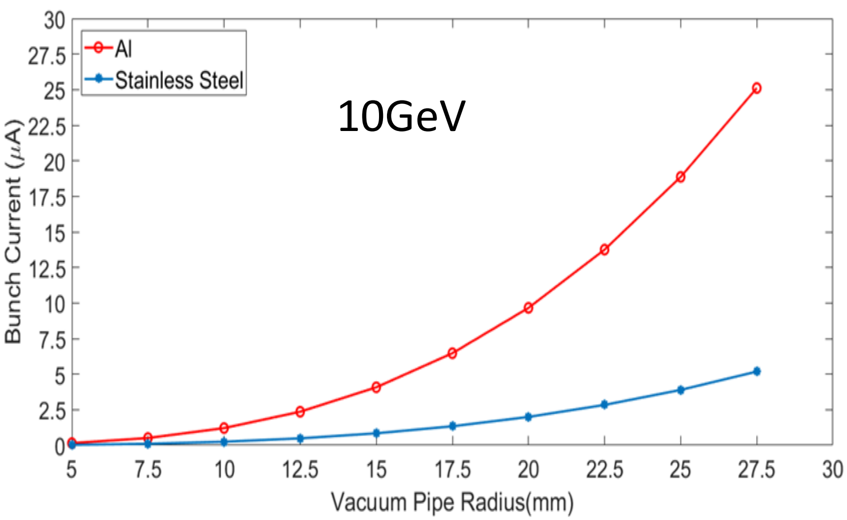
		H	*W*	*Z*
Beam energy	GeV	10		
Bunch number		242	1524	6000
Threshold of single bunch current	μA	25.7		
Threshold of beam current (limited by coupled bunch instability)	mA	100		
Bunch charge	nC	0.78	0.63	0.45
Single bunch current	μA	2.3	1.8	1.3
Beam current	mA	0.57	2.86	7.51
Natural Energy spread	%	0.0078		
Synchrotron radiation loss/turn	keV	73.5		
Momentum compaction factor	10^{-5}	2.44		
Natural emittance	nm	0.025		
Natural chromaticity	H/V	-336/-333		
RF voltage	MV	62.7		
Betatron tune $\nu_x/\nu_y/\nu_s$		263.2/261.2/0.1		
RF energy acceptance	%	1.9		
Damping time	s	90.7		
Bunch length of linac beam	mm	1.0		
Energy spread of linac beam	%	0.16		
Emittance of linac beam	nm	40~120		

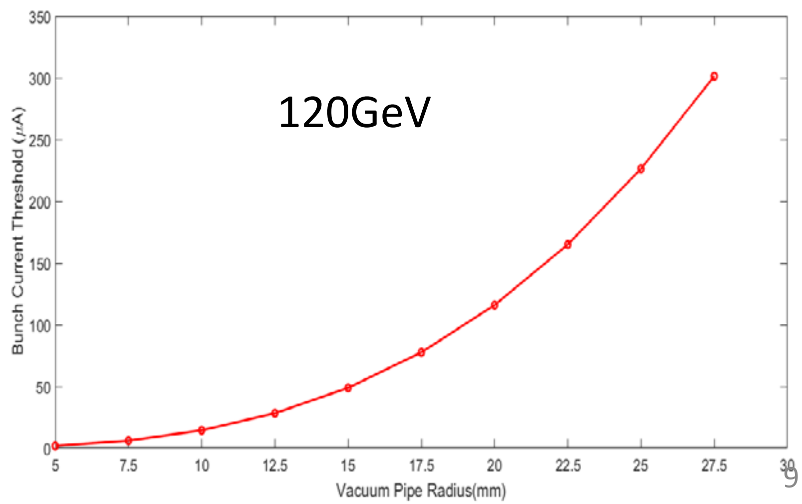
Booster parameters @ extraction

		H		*W*	*Z*
		Off axis injection	On axis injection	Off axis injection	Off axis injection
Beam energy	GeV	120		80	45.5
Bunch number		242	235+7	1524	6000
Maximum bunch charge	nC	0.72	24.0	0.58	0.41
Maximum single bunch current	μA	2.1	70	1.7	1.2
Threshold of single bunch current	μA	300			
Threshold of beam current (limited by RF power)	mA	1.0		4.0	10.0
Beam current	mA	0.52	1.0	2.63	6.91
Injection duration for top-up (Both beams)	s	25.8	35.4	45.8	275.2
Injection interval for top-up	s	47.0		153.0	504.0
Current decay during injection interval		3%			
Energy spread	%	0.094		0.062	0.036
Synchrotron radiation loss/turn	GeV	1.52		0.3	0.032
Momentum compaction factor	10^{-5}	2.44			
Emittance	nm	3.57		1.59	0.51
Natural chromaticity	H/V	-336/-333			
Betatron tune ν_x/ν_y		263.2/261.2			
RF voltage	GV	1.97		0.585	0.287
Longitudinal tune		0.13		0.10	0.10
RF energy acceptance	%	1.0		1.2	1.8
Damping time	ms	52		177	963
Natural bunch length	mm	2.8		2.4	1.3
Injection duration from empty ring	h	0.17		0.25	2.2

Beam instability

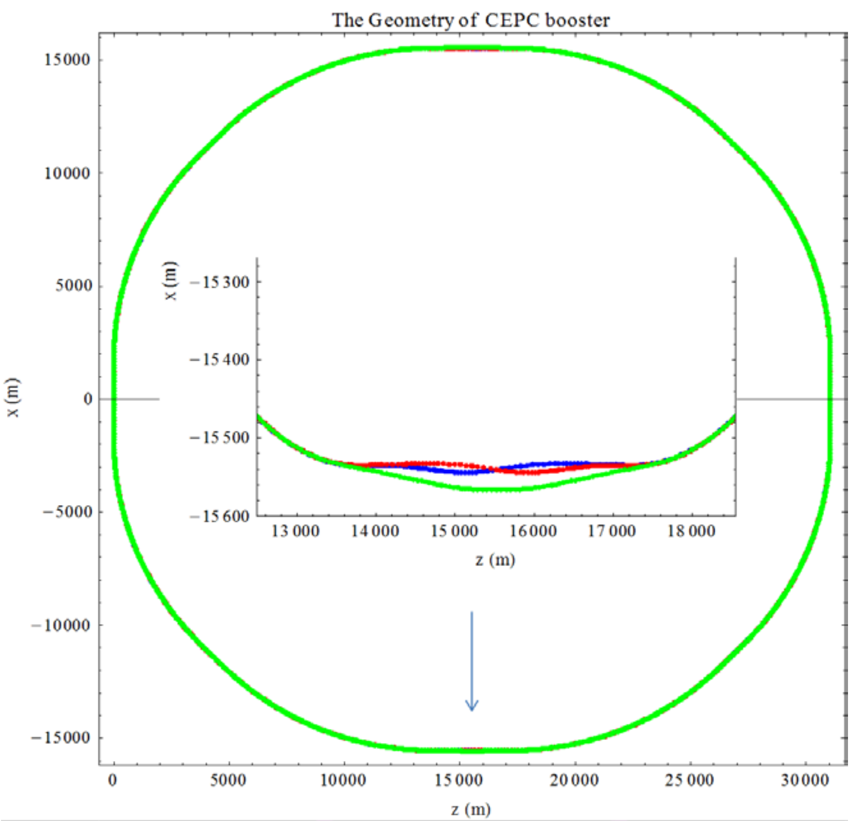
- Aluminum pipe with radius 27.5 mm is chosen
  - Higher threshold of beam current for reasonable injection time during z operation
  - Higher single bunch current threshold@120GeV (on-axis injection)
- Threshold of single bunch current (TMCI): 25.7uA (10GeV), 300 uA (120GeV)
- Threshold of beam current (resistive wall) w. FB: 127.5mA (10GeV)
  - Damping time of transverse feedback system: 1.67ms (~5 turns)
- Threshold of beam current (RF HOMs) w. FB: 100mA (10GeV)
- Total beam current limited by RF power: 1mA(H), 4mA(W), 10mA(Z)

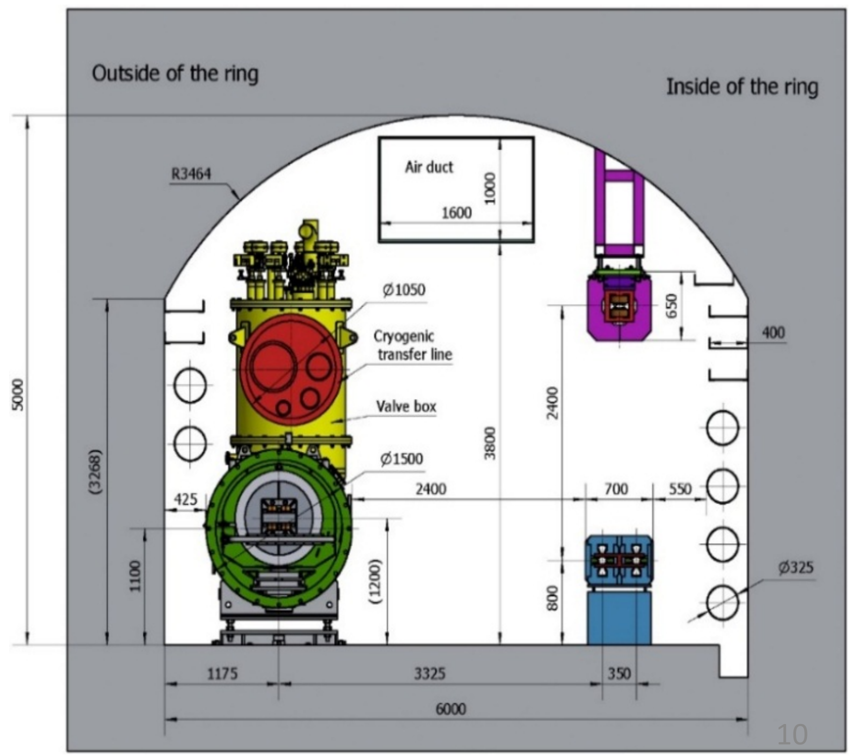




Booster geometry design

- Booster has almost same geometry as collider ring except for the two IRs.
- ARC: booster is in between the two beams of collider ring, error=±0.17m
  - -- precision of element length: ~10^{-5} m
  - -- precision of dipole angle: ~10^{-7} rad
- IR: separation between detector center and booster: ~25 m

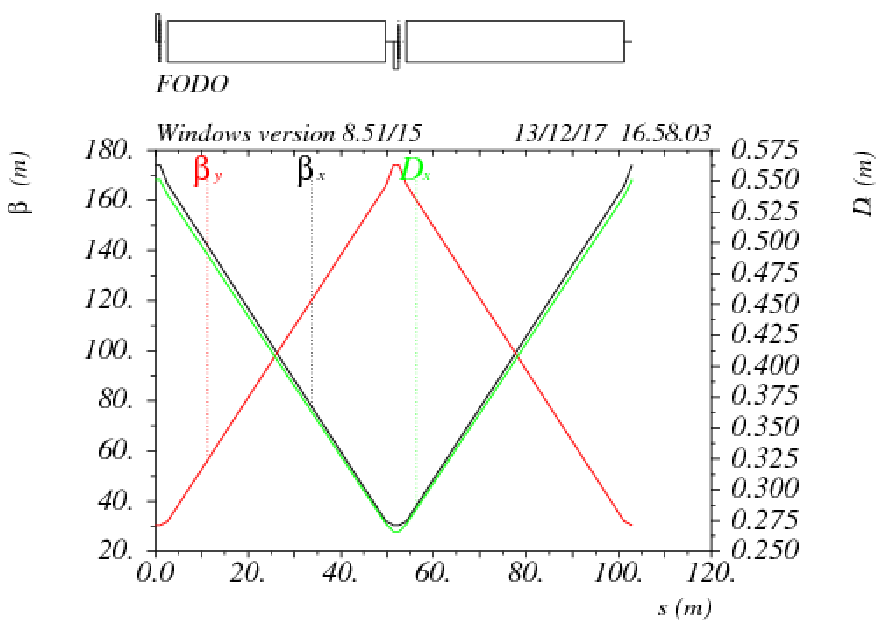




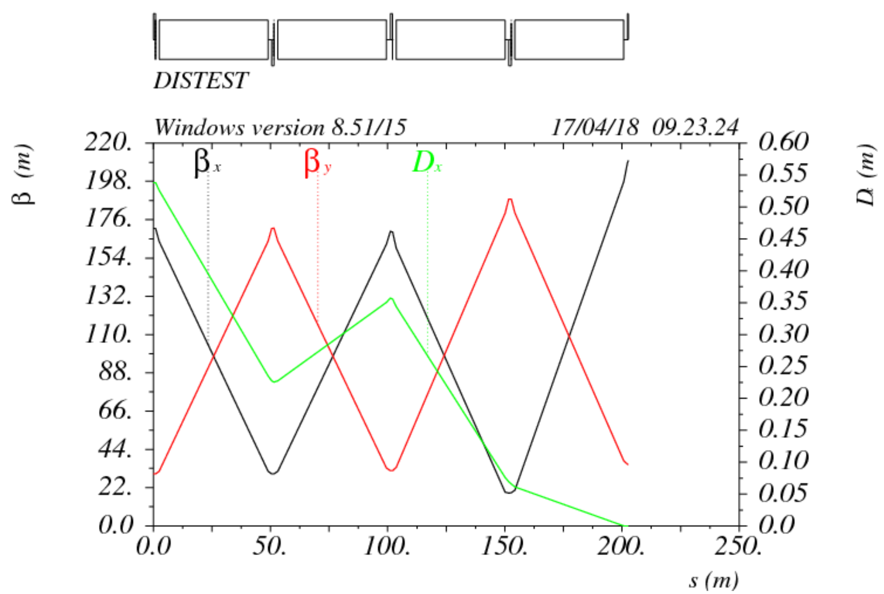
Booster optics - ARC

- 90°/ 90° FODO cell
- 2 cells @ booster = 3 cells @ collider
- FODO length: 101m
- Noninterleave sextupole scheme

- Dispersion suppressor
  - two standard FODO cell
  - adjust bend strength- match the geometry of collider ring



FODO cell

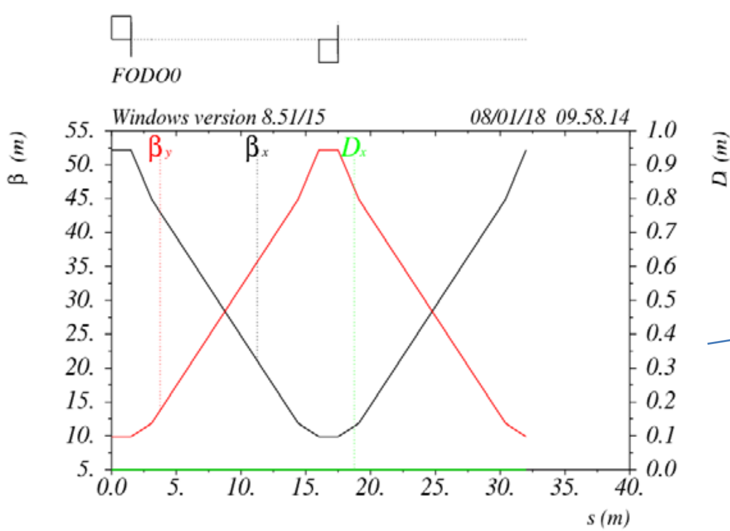


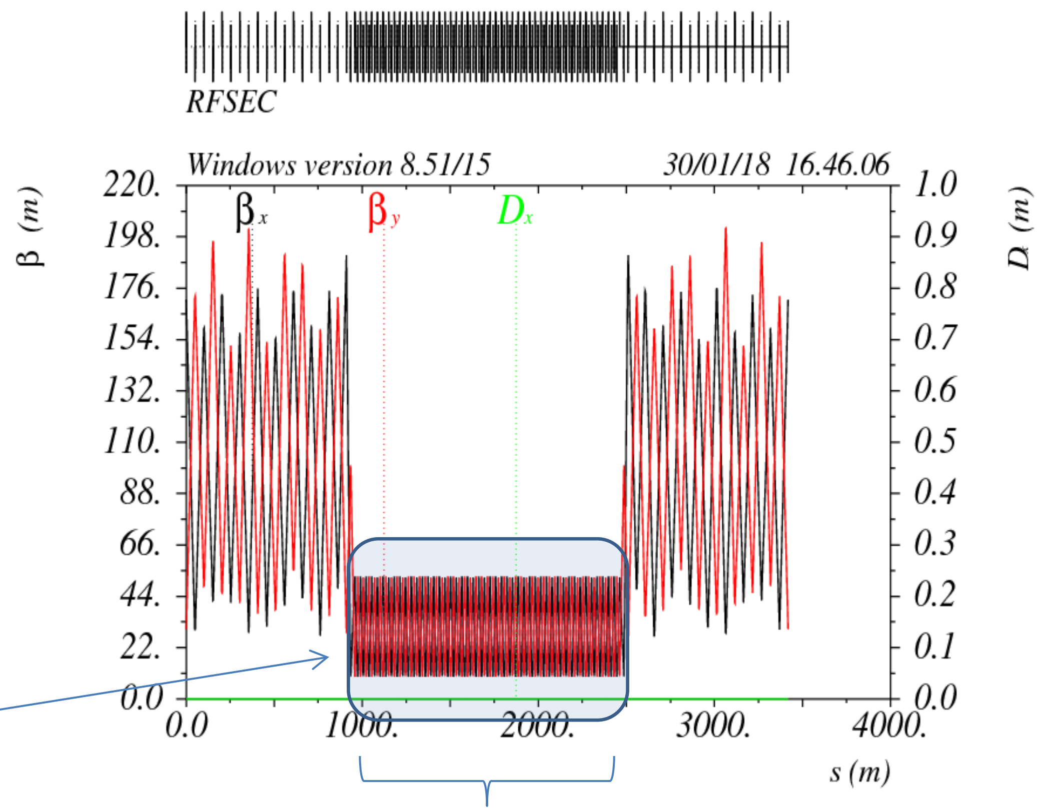
Dispersion suppressor

Booster optics - RF

- Booster RF straight section at the same location as collider ring -3.4km
- Low average beta to reduce the multi-bunch instability by RF cavities -1.6km

- 90°/ 90° FODO cell
- Average beta: 30 m
- Space between quadrupoles :14m

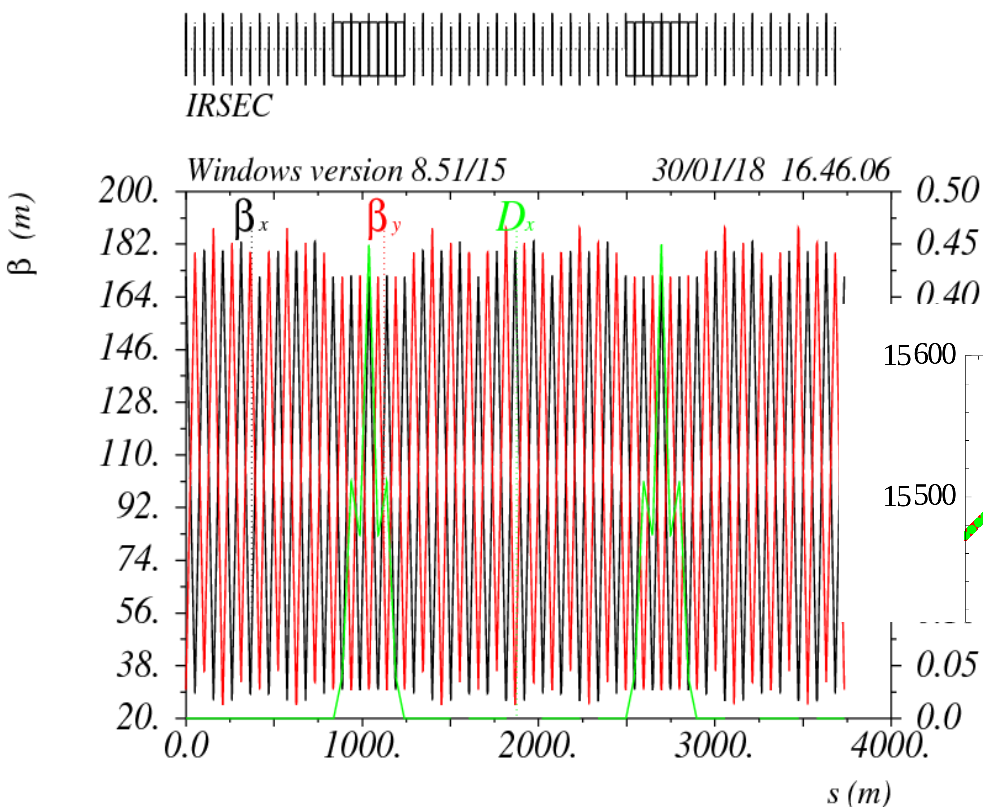


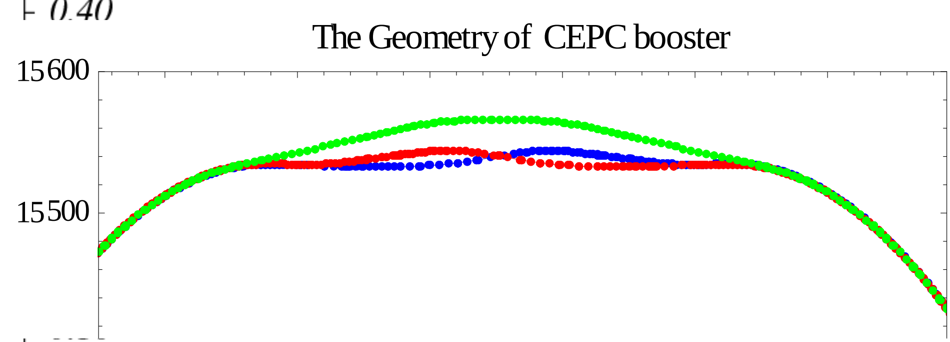


RF section

Booster optics – IR bypass

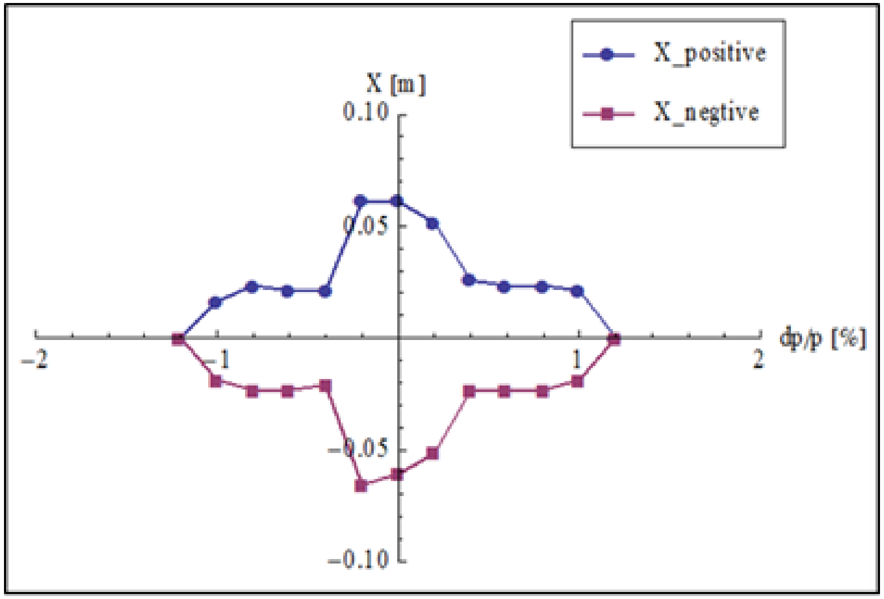
- In CEPC detector region, booster bypasses the collider ring from the outer side.
- 25m separation: requirements of civil engineering and the radiation protection

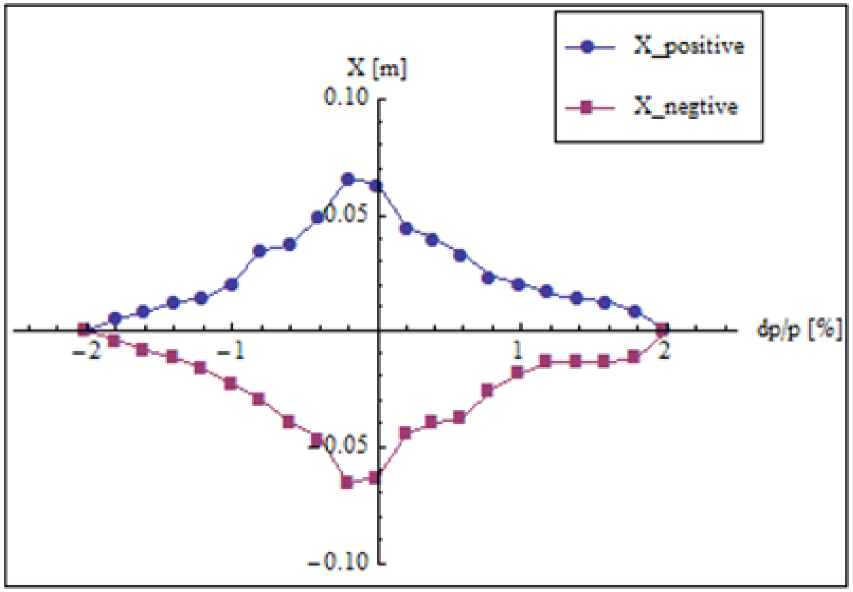




Off-momentum DA optimization

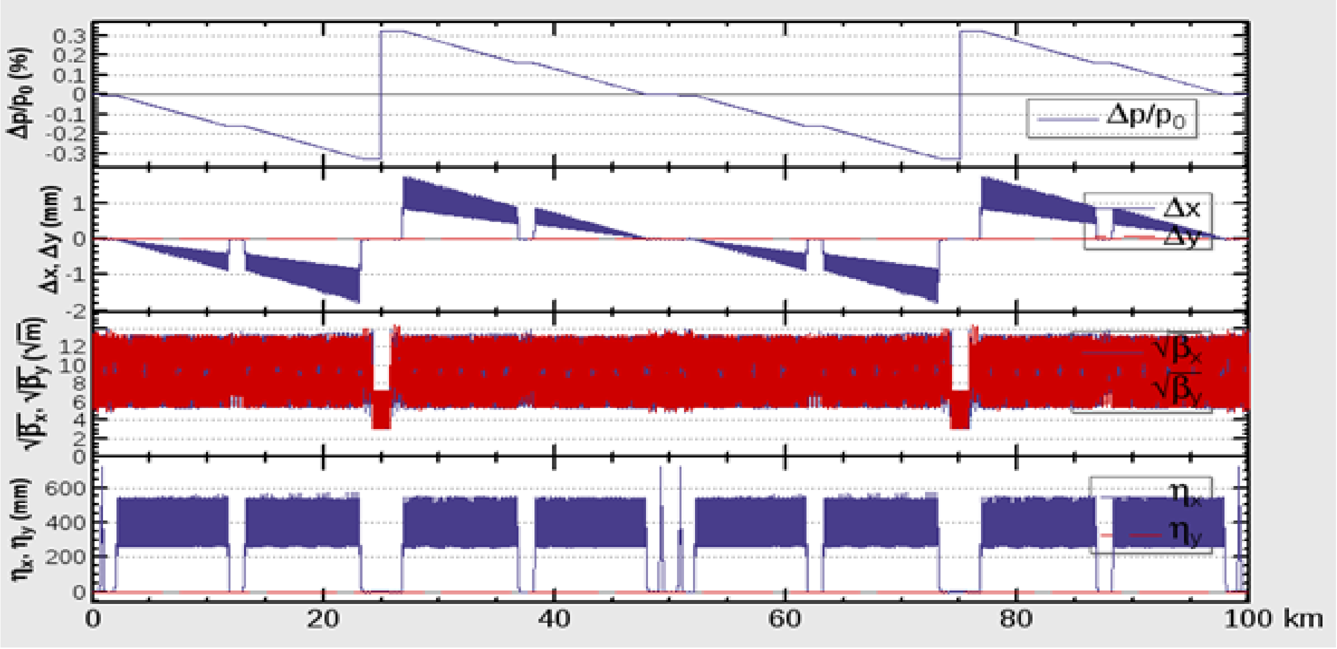
- Noninterleave sextupole scheme
- Two sext. families (SF, SD)
- Optimize the phase of the straight section between two octants automatically by downhill method
- Goal: reach 1% energy acceptance @ 120GeV including all kinds errors





Sawtooth effect @120GeV

- 2 RF stations
- Maximum sawtooth orbit: 1.7 mm
- Maximum optics distortion: ~2%, Maximum dispersion distortion: ~50 mm
- Emittance growth: ~0.3%
- No DA reduction due to sawtooth effect
- **Magnets energy tapering is unnecessary**



Booster error studies

- Gaussian distribution and cut-off at 3σ

Errors Setting

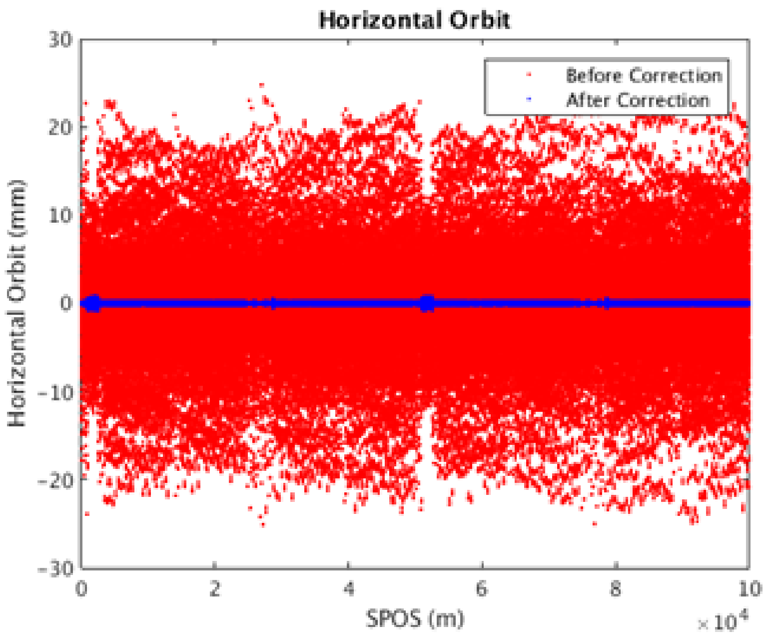
Parameters	Dipole	Quadrupole	Sextupole
Transverse shift x/y (μm)	50	70	70
Longitudinal shift z (μm)	100	150	100
Tilt about x/y (mrad)	0.2	0.2	0.2
Tilt about z (mrad)	0.1	0.2	0.2
Nominal field	3×10^{-4}	2×10^{-4}	3×10^{-4}

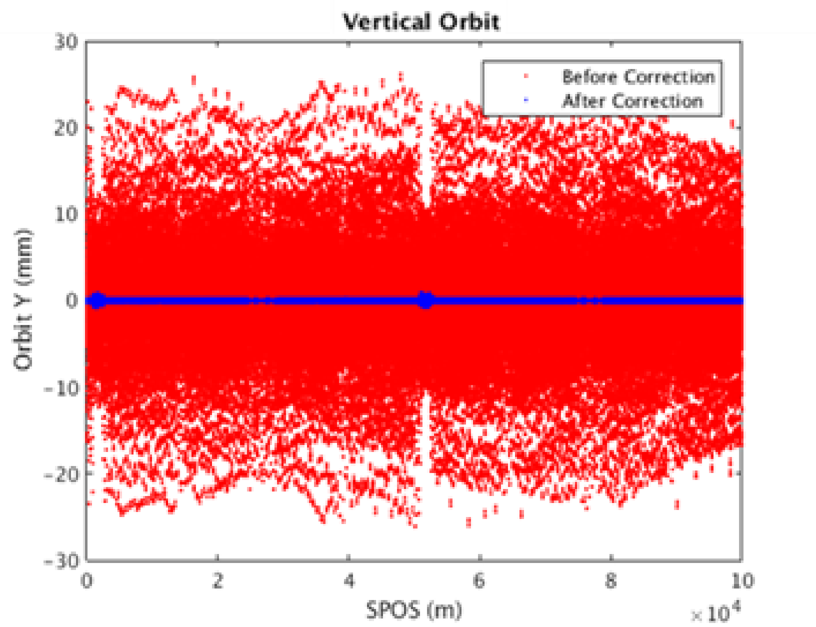
	Accuracy (m)	Tilt (mrad)	Gain	Offset after BBA(mm)
BPM	1×10^{-7}	10	5%	30×10^{-3}

Booster orbit with errors

- Beam pipe: 55mm (diameter)
- Orbit within the beam pipe
- "First turn trajectory" is not necessary

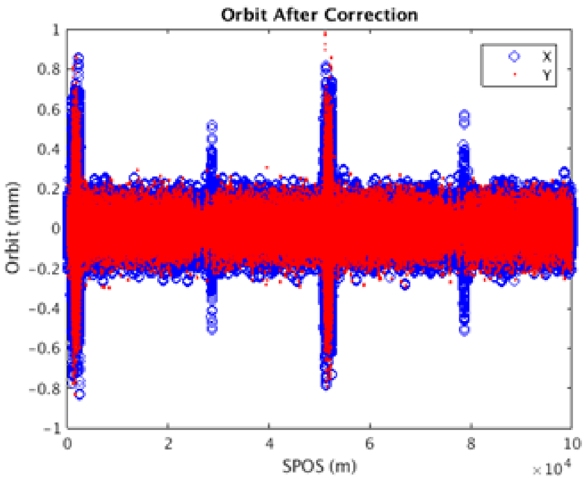
Horizontal Corrector: 1053
Vertical Corrector : 1054
BPM : 2108



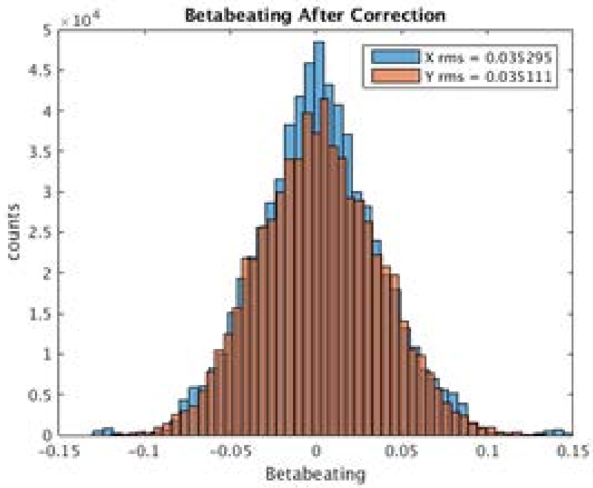


Booster orbit & optics with COD corrections

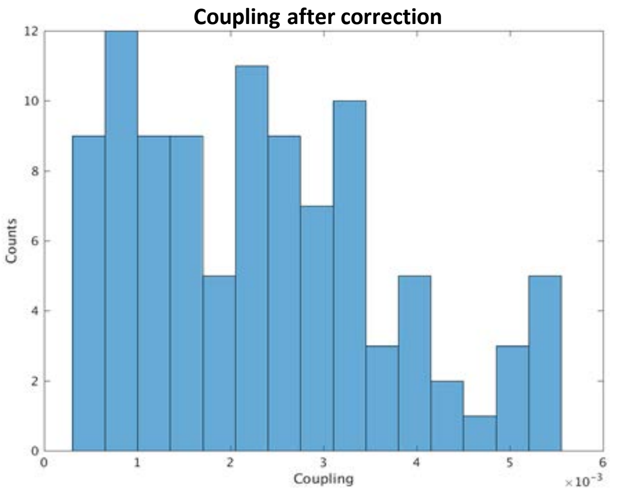
- Orbit correction: response matrix and SVD
- RMS Orbit ~ 80um, RMS betabeat ~3.5%, RMS disp. ~15mm
- Emittance growth < 10% for the simulation seeds
- Coupling <10% before coupling correction
- RMS coupling: 0.5% after coupling correction (512 Sextupoles)



Hor. 80um / Ver. 79um



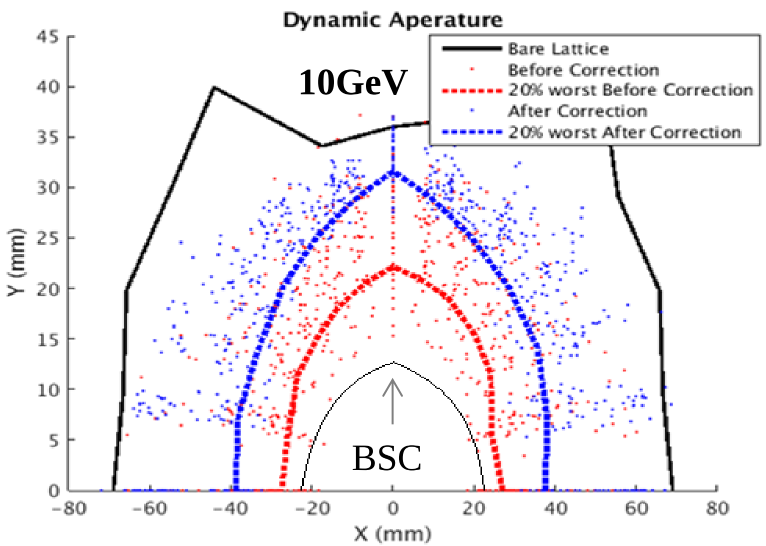
Hor. 3.5% / Ver. 3.5%

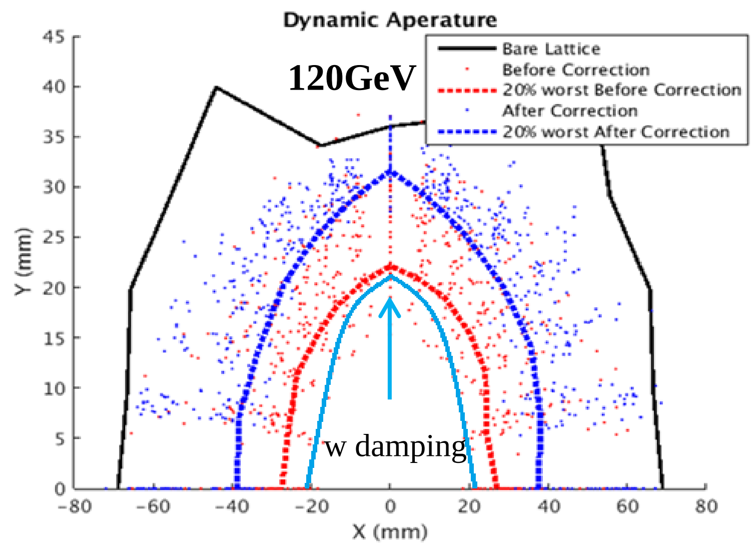


100 random seeds

Dynamic aperture with errors

- With only COD corrections, DA is nearly two thirds of bare lattice
- At 120GeV, radiative damping and sawtooth was considered.
- DA requirement @ 10GeV determined by the beam stay clear region
- DA requirement @ 120GeV: 1) H- quantum lifetime, 2) V- re-injection process from the collider in the on-axis injection scheme



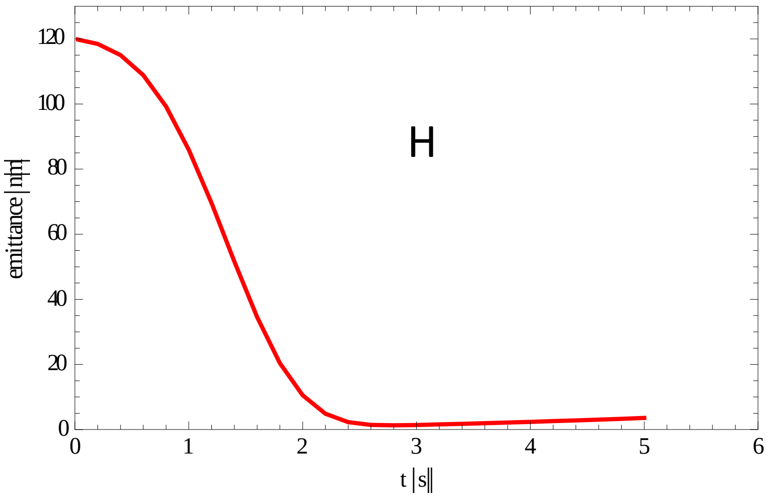


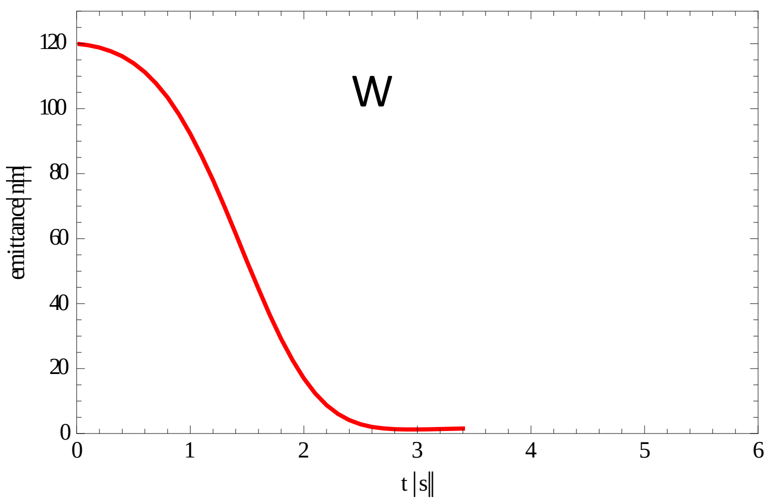
	DA requirement		DA results	
	H	V	H	V
10GeV ($\varepsilon_x = \varepsilon_y$ =120nm)	$4\sigma_x$ +5mm	$4\sigma_y$ +5mm	$7.7\sigma_x$ +5mm	$14.3\sigma_y$ +5mm
120GeV (ε_x=3.57nm, $\varepsilon_y = \varepsilon_x$*0.005)	$6\sigma_x$ +3mm	$49\sigma_y$ +3mm	$21.8\sigma_x$ +3mm	$779\sigma_y$ +3mm

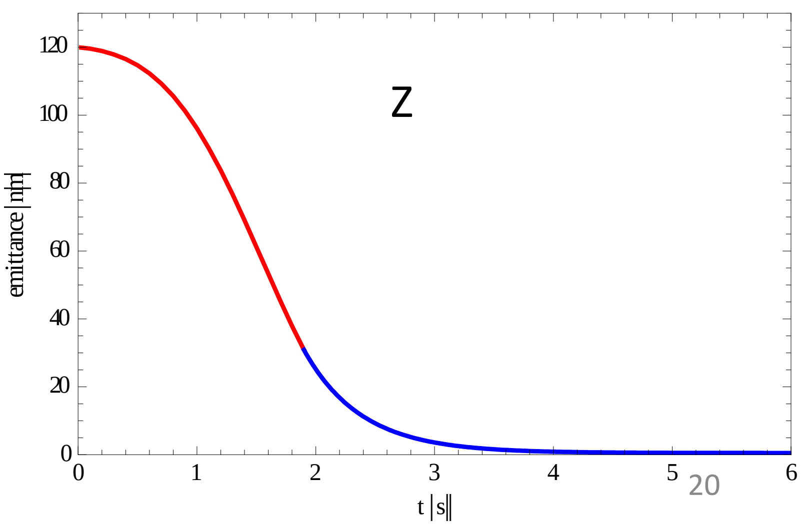
- Requirement for linac emittance: **< 150nm**, otherwise BSC > beam pipe

Emittance evolution

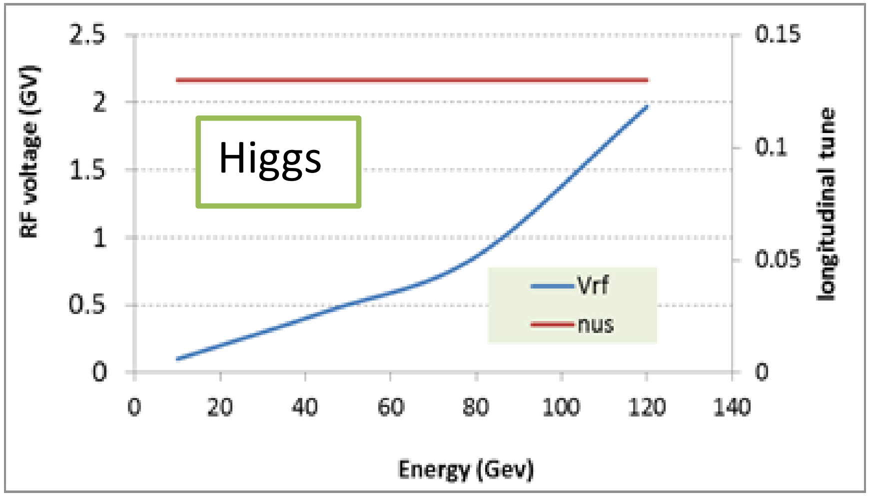
- Emittance @injection = 120nm
- Emittance is small enough for H &W after ramping, extra 5s damping for Z
- Beam loss due to lifetime at low energy determined by the emittance of Linac and the DA.

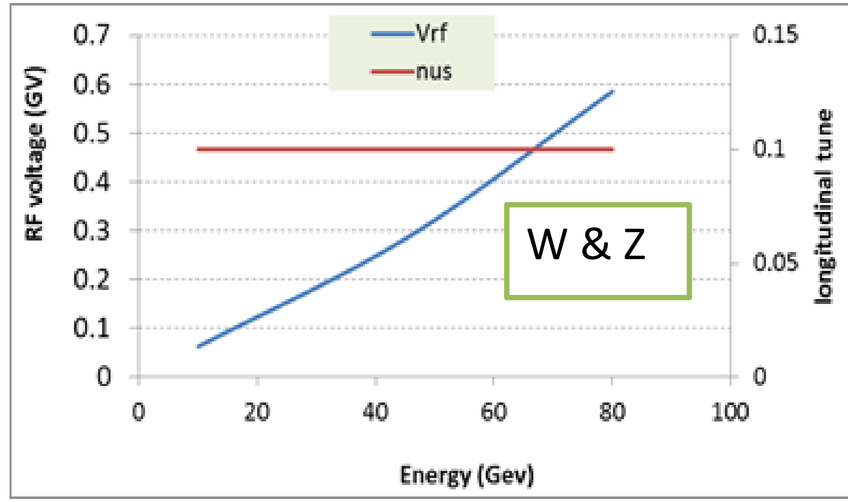


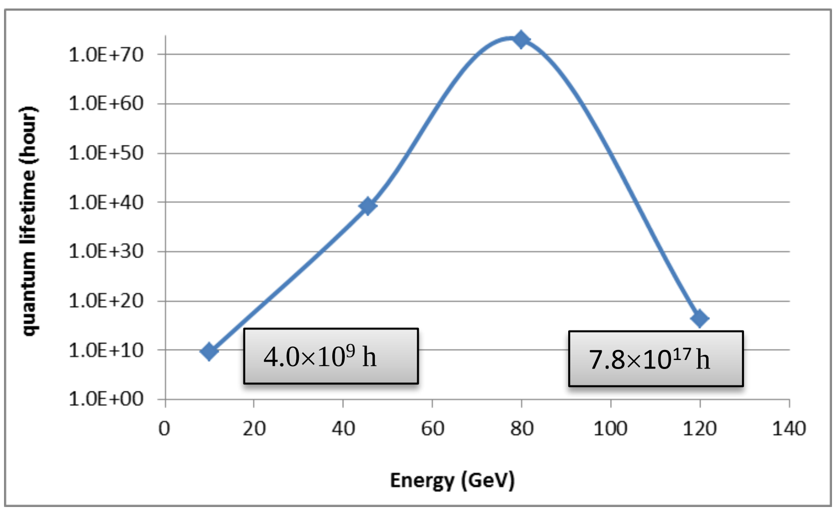




RF ramping curve

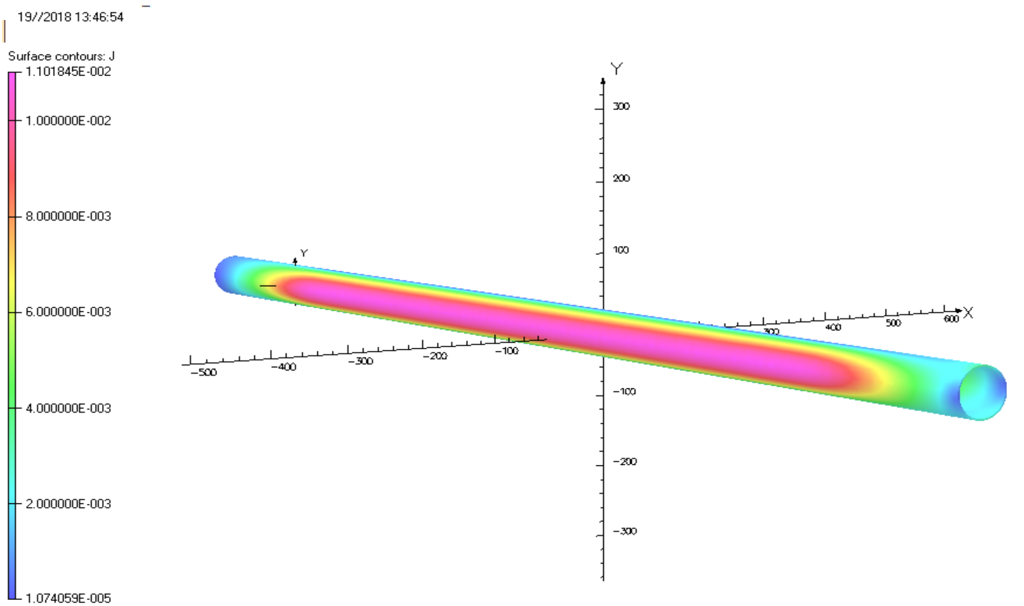






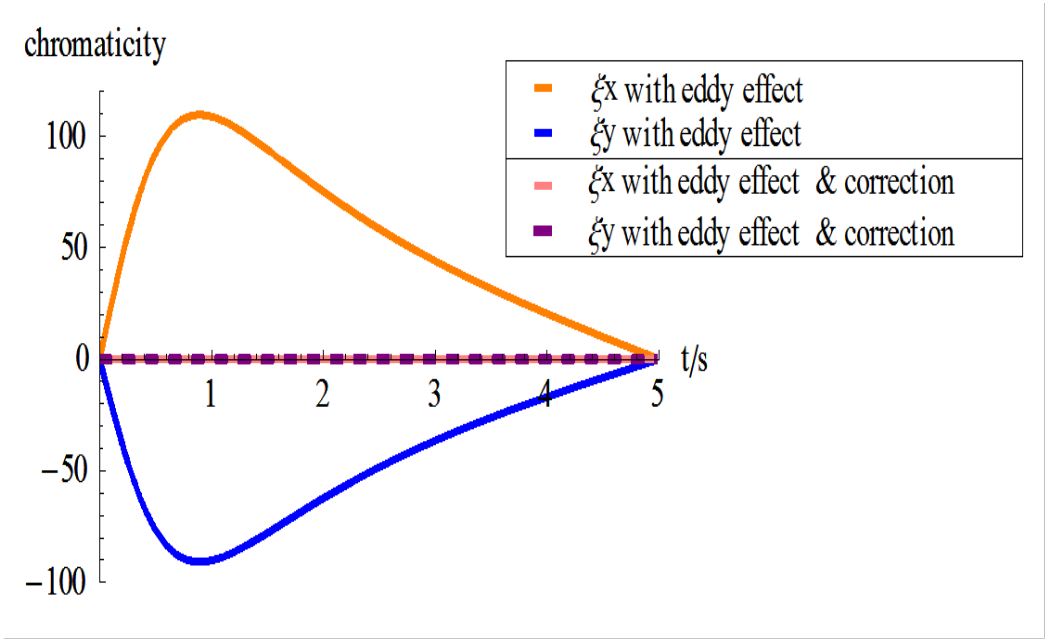
- nus=0.13 (Higgs), nus=0.1 (W&Z)
- 10 GeV & 45 GeV: transverse quantum lifetime
- 80GeV & 120 GeV: longitunidal quantum lifetime
- Beam loss during ramping due to lifetime << **1%**

Eddy current effect



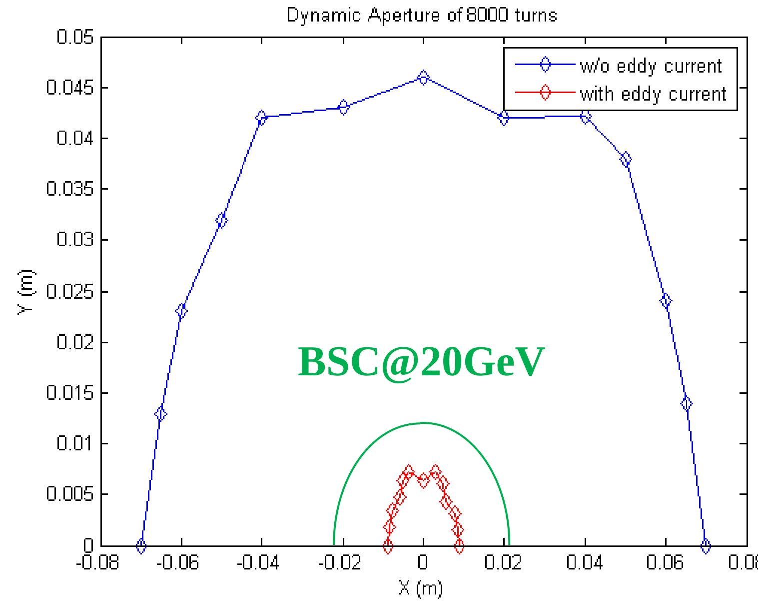
- During ramping, parasitic sextupole field is induced on beam pipe inside dipoles due to eddy current.
- Ramping rate is limited by eddy current effect.
- Dedicated ramping curve to control the maximum K2.

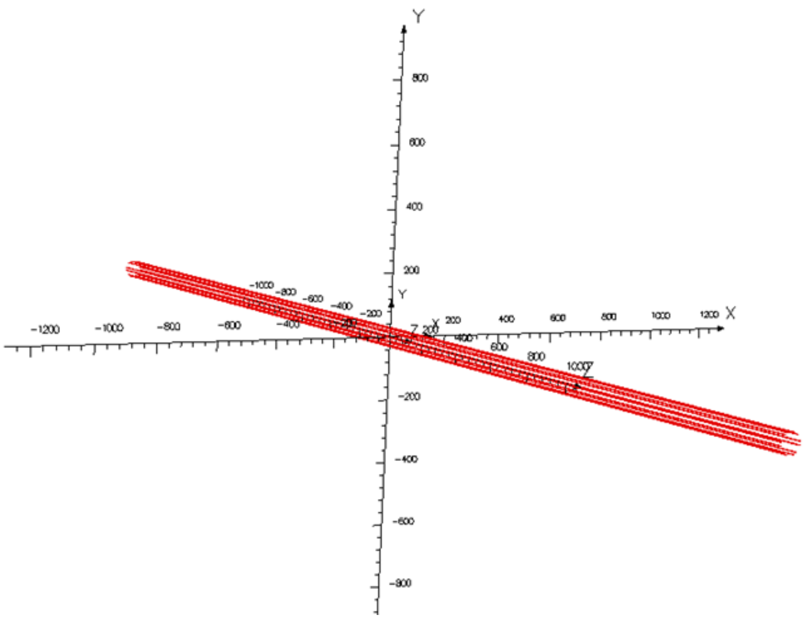
- Chromaticity distortion is corrected by 2 sext. families (SF, SD) during ramping.
- K2 reach maximum at 20GeV
- k2 curve is checked by dynamic magnetic 3D simulation

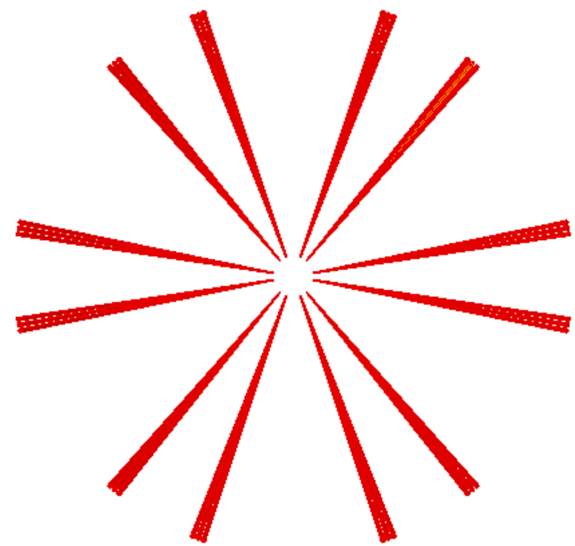


Booster DA with eddy current

- BSC @20GeV: 0.023m(H)×0.012m(V)
- Sextupole coils outside vacuum chamber are considered
  - Copper wire d=0.5mm
  - Current: 0.16A
  - Voltage: 2.5V
  - Current density: 0.8 A/mm^2
  - Fix with glue (epoxy), air cooling







Low field dipole magnets

➢ Challenges:

- Field error <29Gs*0.1%=0.029Gs
- Field reproducibility <29Gs*0.05%=0.015Gs
- The Earth field ~0.2-0.5 Gs, the remnant field of silicon steel lamination ~ 4-6 Gs.

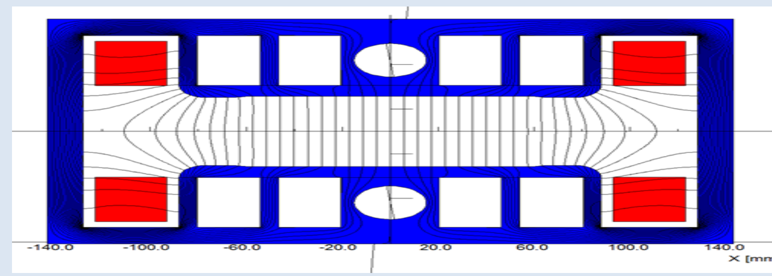
➢ Thinking beyond CDR

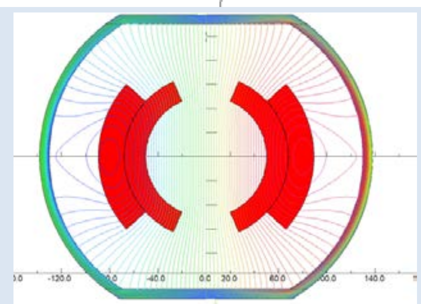
- Wiggler dipole scheme
- Combine the magnets with core and without core
- Combine CCT dipole with sextupole coils
- …

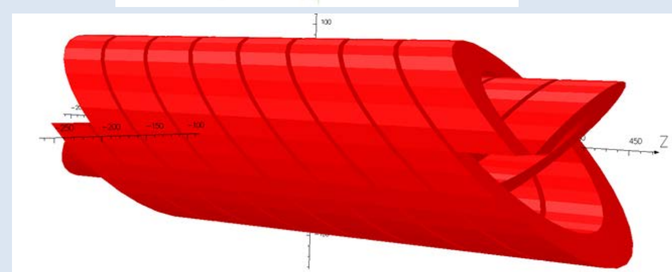
➢ Solutions by technical way

- With magnetic core - dilution (better material)
- Without magnetic core (higher power)

a) CT b) CCT







Summary

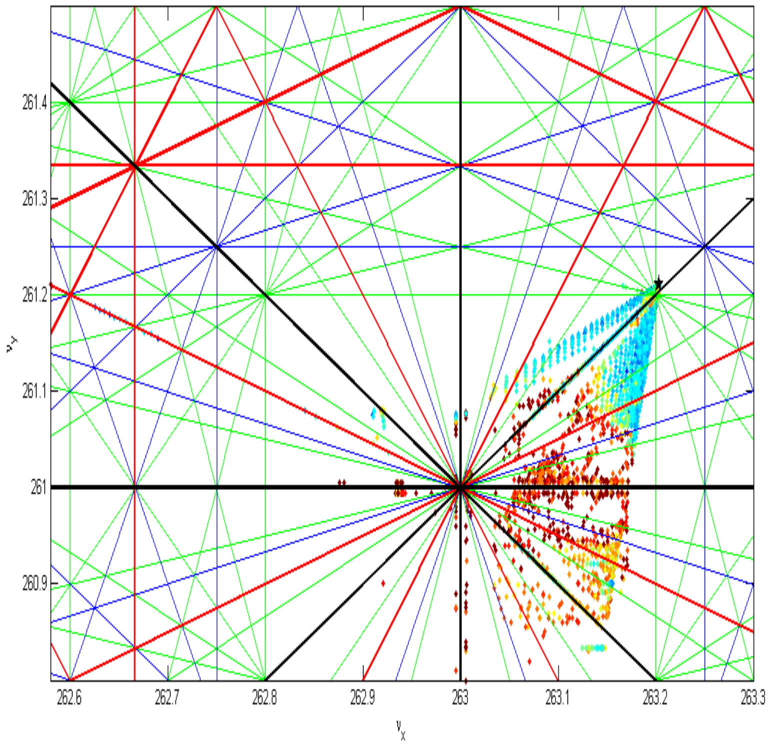
- The booster design can meet the injection requirements at three energy modes.
- Accelerator physics design satisfy the requirements of geometry, beam dynamics and key hardware.
- Error effects are studied. Errors in the booster are tolerable.
- DA reduction due to eddy current effect is serious and local correction with extra sextupole coils is designed.
- Low magnetic field in the booster is still a challenge. Both technical and physical solutions are studied continuously.

Thanks for your attention!

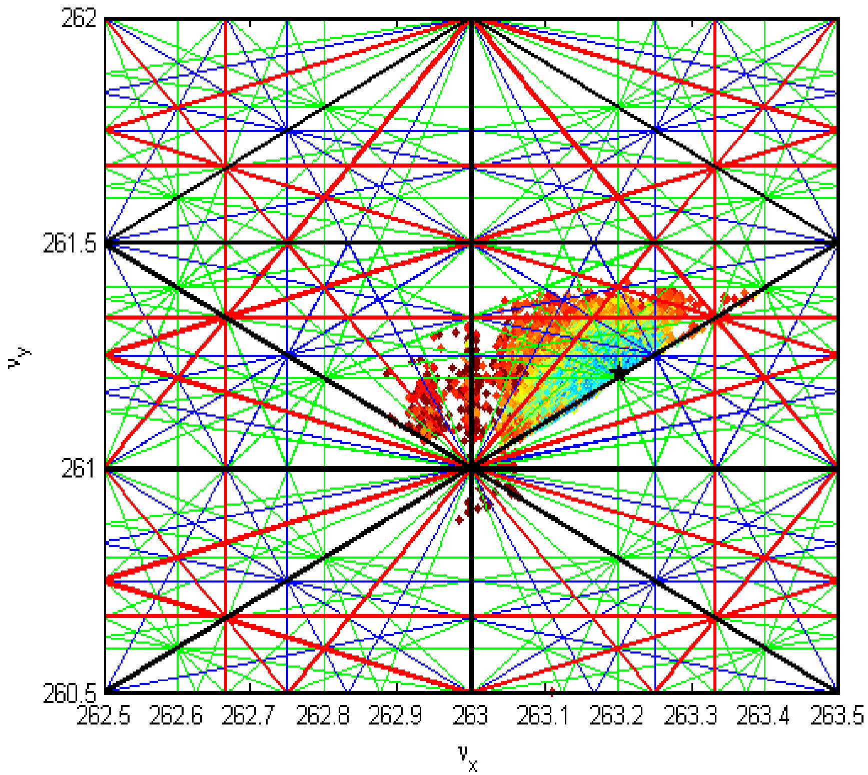
Back up

FMA @ booster

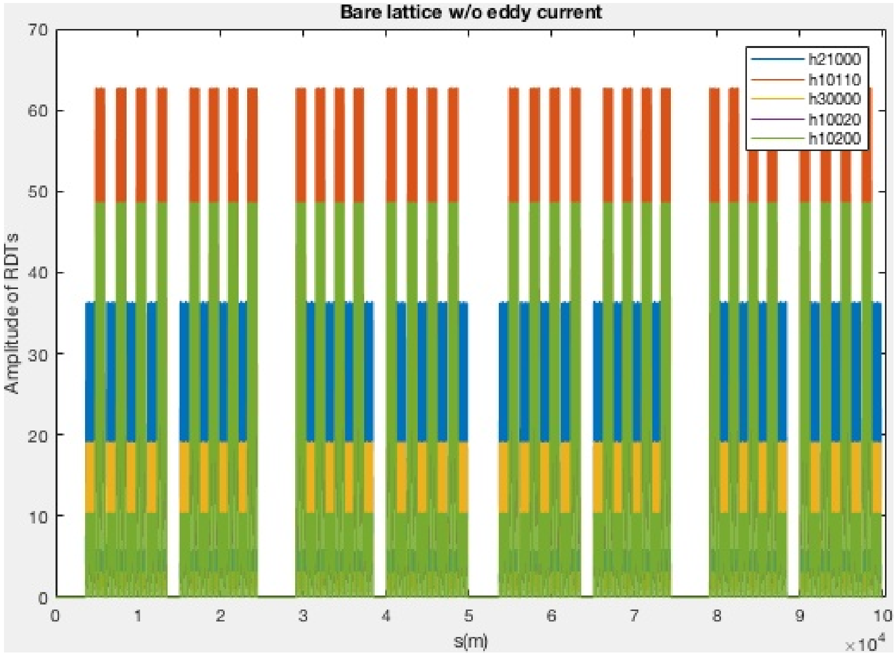
W/O eddy

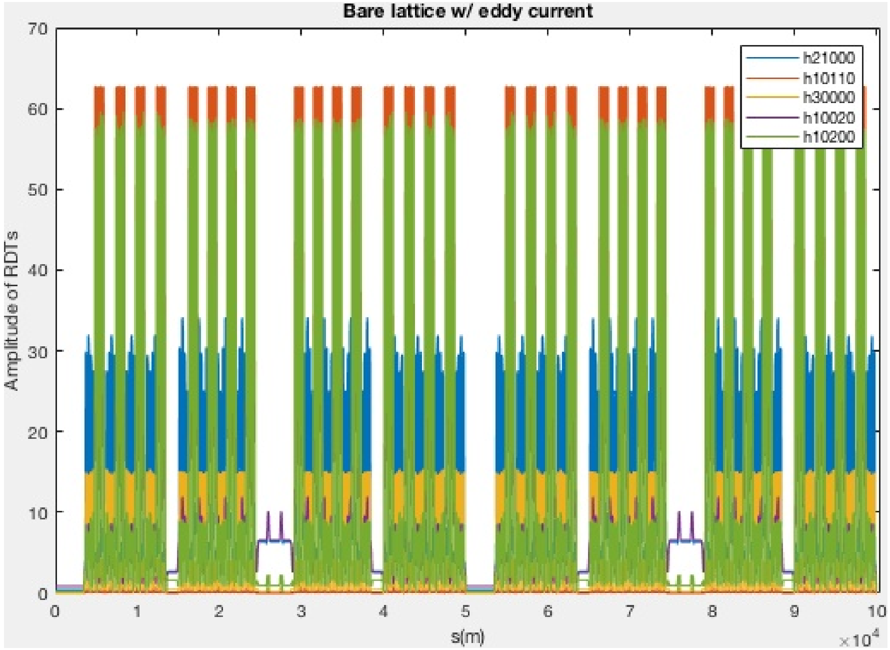


W eddy



Driven term @ booster

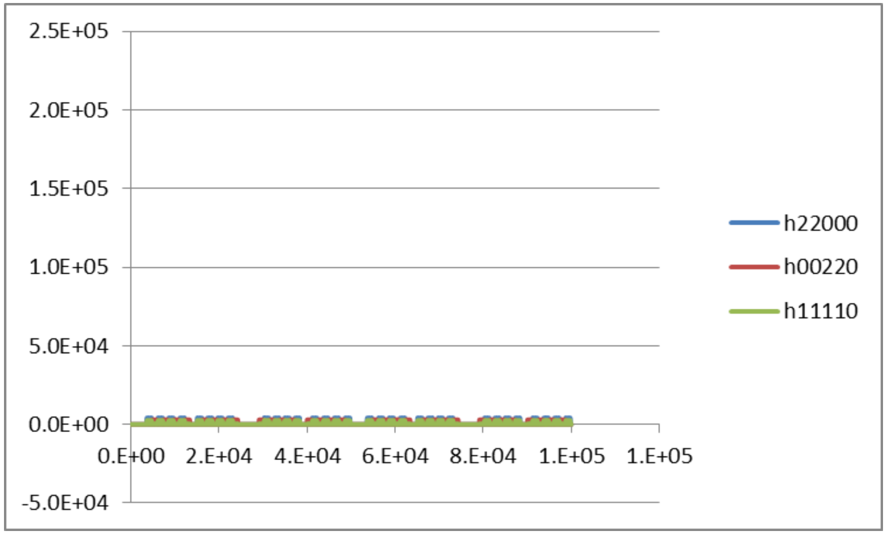




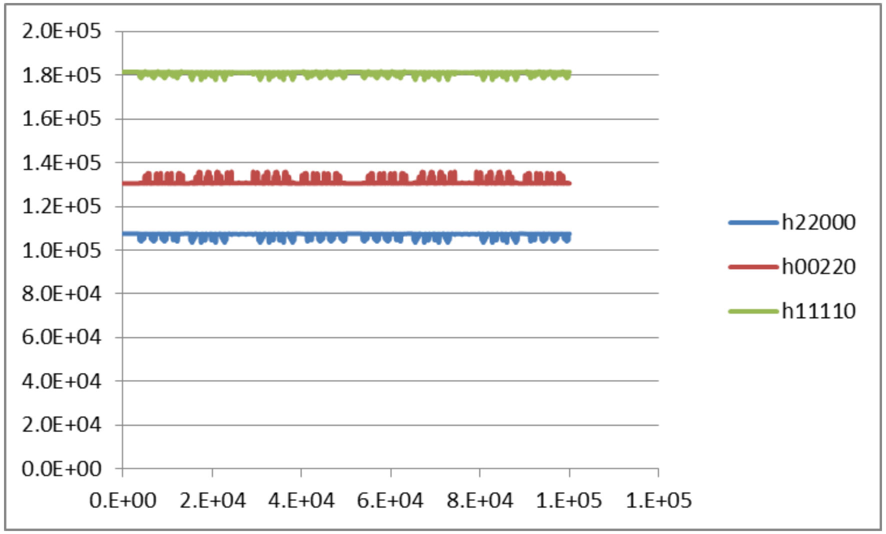
$(h_{21000}, h_{30000}, h_{10110}, h_{10020}, \text{ and } h_{10200})$

Driven term @ booster

w/o eddy

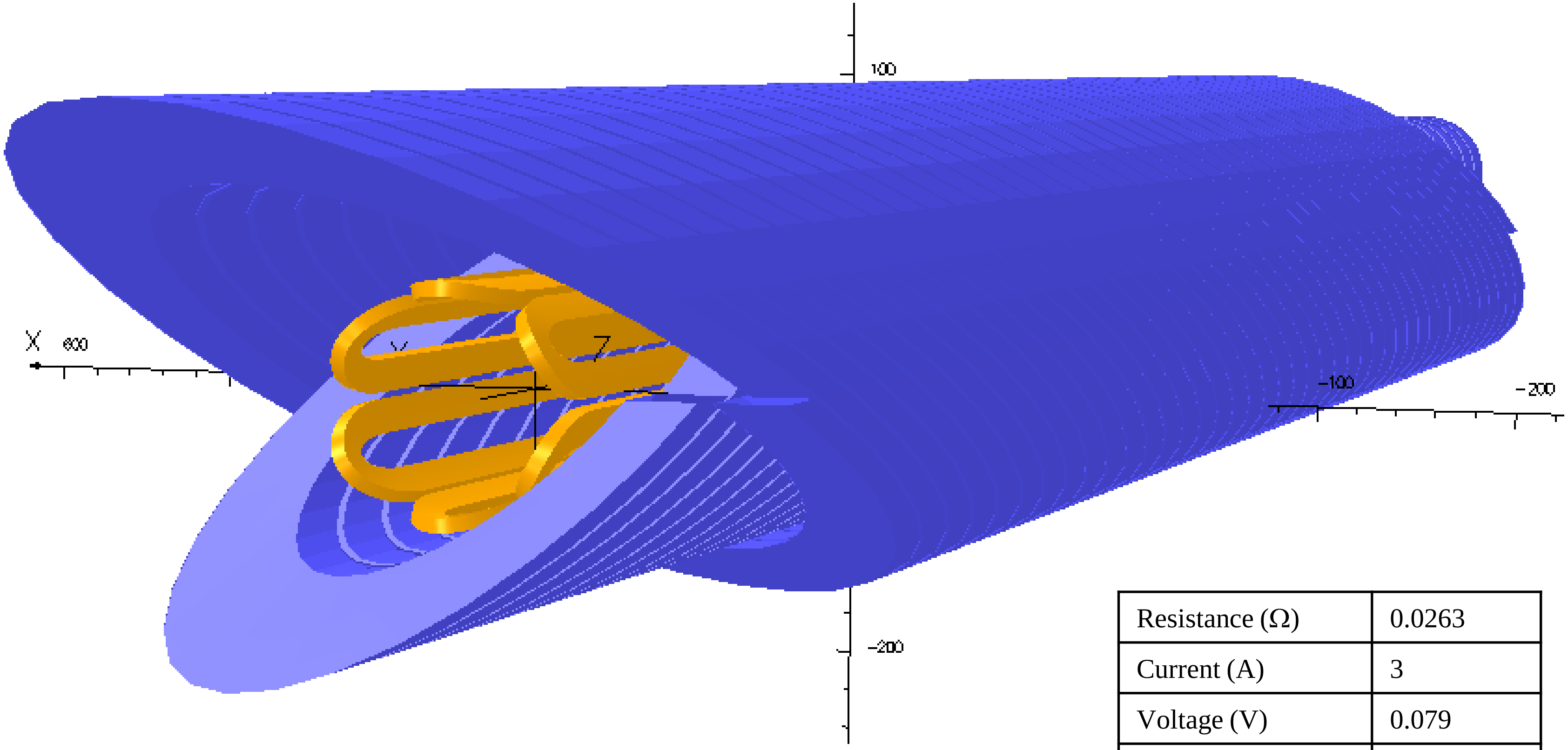


w eddy



$\boxed{h_{22000}，\ h_{00220} \text{ 和 } h_{11110}}$

CCT + sextupole coil



Resistance (Ω)	0.0263
Current (A)	3
Voltage (V)	0.079
Power (W)	0.237
Inductance (mH)	0.024
Stored energy (mJ)	0.11