Design Study of CEPC Booster Lattice

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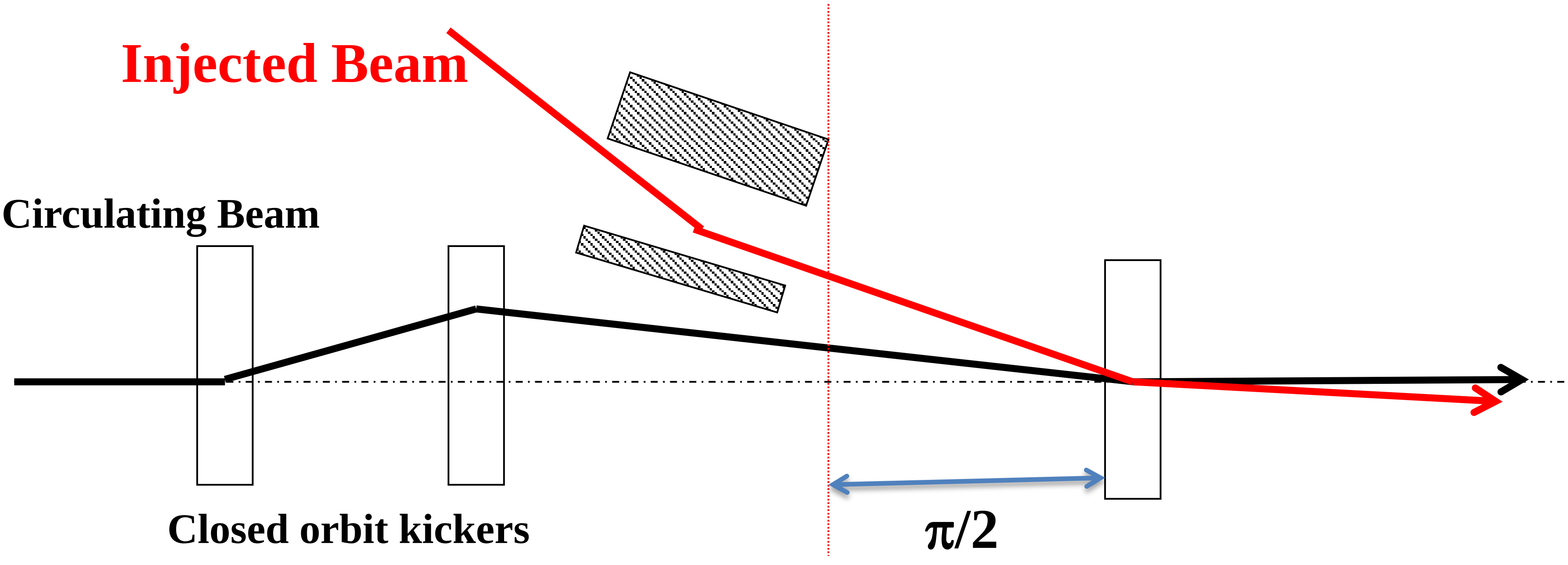
Outline

- **Design Goal of CEPC booster.**
- **Possible Options:**
  - **Normal Bend Scheme.**
  - **Wiggling Bend Scheme.**
- **Optimization Code Preparation**
  - **Moola：Modular&parallel Optics Optimization for LAttice**
- **Summary**

Design Goal

- **Consideration of injection**

➢ **Inject in X direction.**



Design Goal

Consideration of injection

- Emit in mainring is 2E-9 m*rad, asuming beta_x=590 meter in the injection point.
- Asuming DA_x=20 sigma@dp=0.5% in the mainring.
- Asuming beta_x=590 meter in the injection point.
- The total space for injection:

$$\sqrt{2.0\times10^{-9}\times590}\times20=0.0217(\mathrm{m})$$

- 8 sigma is retained for revolution beam to get enough quantum life time:

$$\sqrt{2.0\times10^{-9}\times590}\times8=\ 0.0087(\mathrm{m})$$

- 6 sigma is retained for injection beam to loss less particles:

$$\sqrt{3.5\times10^{-9}\times590}\times6=\ 0.0086(\mathrm{m})$$

- 3.2mm is lefted for septum and emit of booster@120Gev is 3.5E-9 m*rad.

Design Goal

Design Goal

- For injection, emit of booster@120Gev should be about 3.5E-9 m*rad.
- 1 percent energy acceptance for enough quantum lifetime.
- DA_x and DA_y should bigger than 5~6 sigma for injection.

Linac parameters

- From : Li Xiaoping, Pei Guoxi, etc, "*Conceptual Design of CEPC Linac and Source*".

Parameter	Symbol	Unit	Value
E^- beam energy	E_{e-}	GeV	6
E^+ beam energy	E_{e+}	GeV	6
Repetition rate	f_{rep}	Hz	50
E^- bunch population	N_{e-}		2×10^{10}
E^+ bunch population	N_{e+}		2×10^{10}
Energy spread (E^+/E^-)	σ_E		$<1\times10^{-3}$
Emitance (E^-)			0.3 mm· mrad
Emitance (E^+)			0.3 mm· mrad

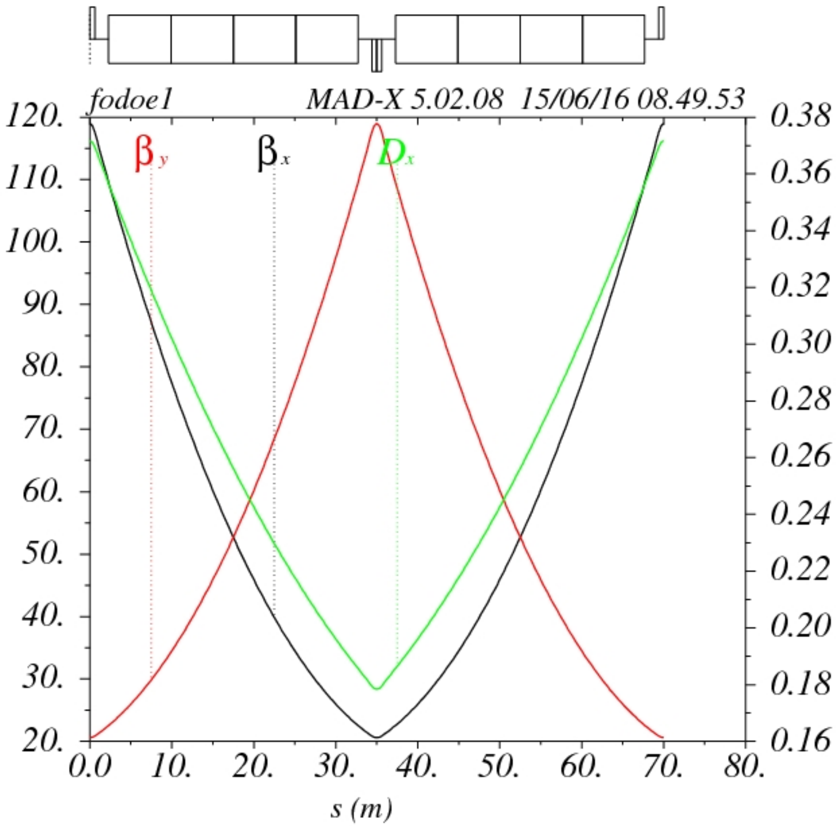
Normal Bend Scheme

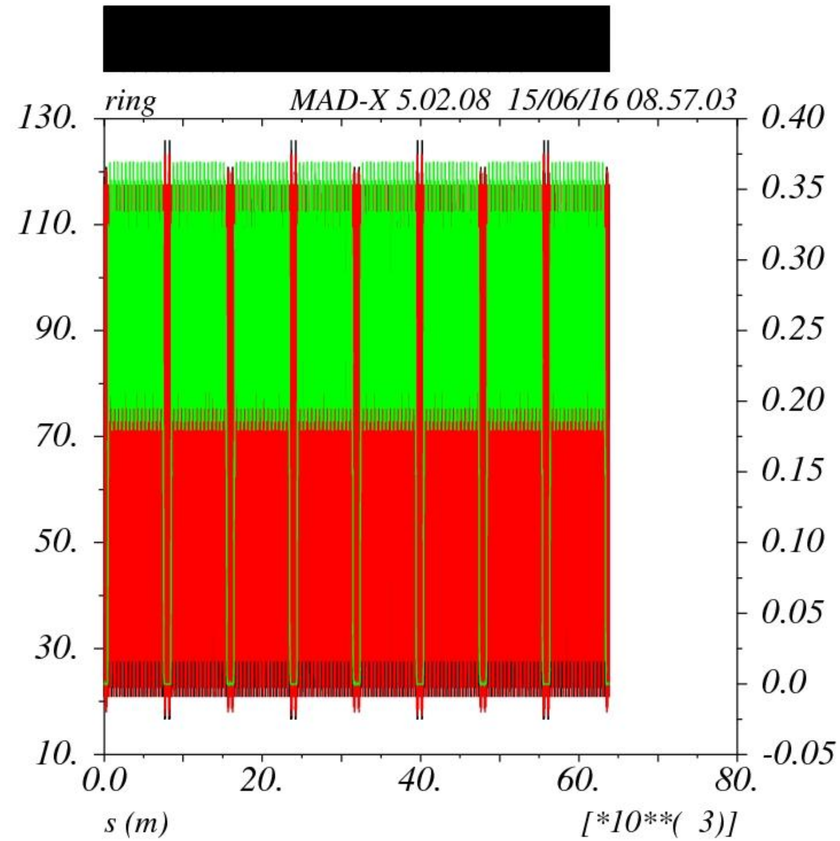
Introduction of Normal Bend Scheme

- The inject energy is 6GeV.
- The earth field is about 0.5Gs, so in the normal bend scheme start at 30Gs@6GeV may be difficult.
- Shielding and correcting are needed.
- With earth field, booster is a broken ring. So the first turn orbit correction is important. After the first turn orbit correction, the circular beam is existed and the closed orbit correction can be done.

Linear Optics

- **90 degree FODO**
- **FODO length:70 meter**





Chromaticity Optimization

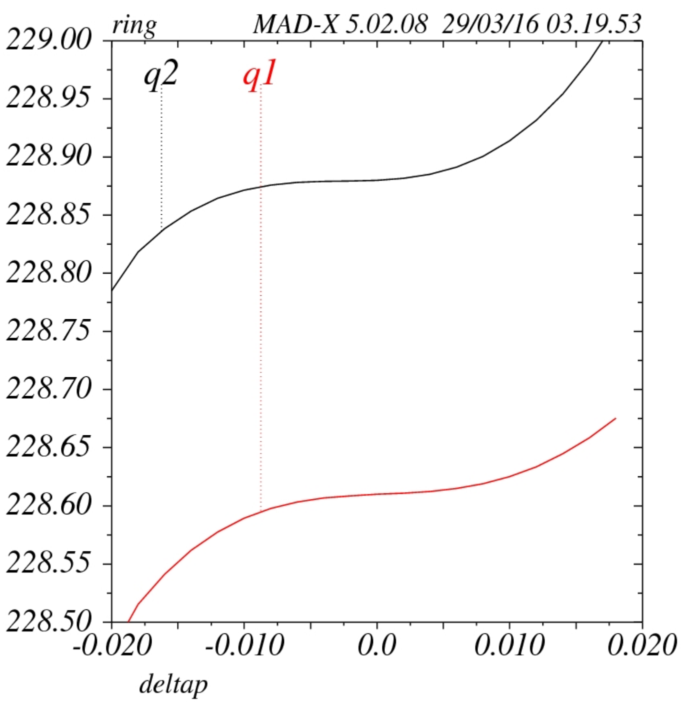
Sextupole scheme

- Non-interleaved sextupoles are used.
- Another pair of sextupole with the same strength apart by 90° phase advance for cancel the second order chromaticity automatically.
- 8 sextupole families, optimize using both symbolic differential algebra and numeric way.
- Only optimizing the 8 sextupole families is not enough.
- Appropriate phase advance between arcs is necessary.

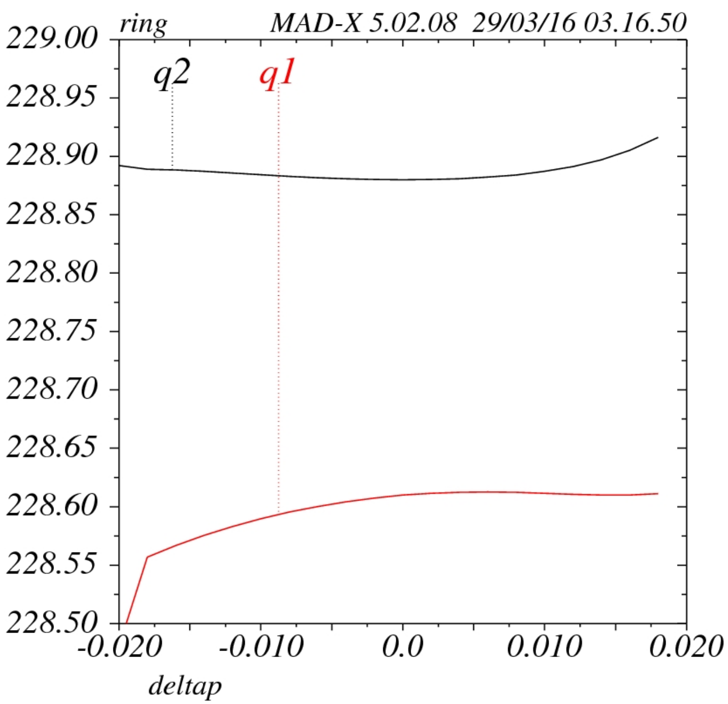
SF1	**SF1 SF2**	**SF2 SF3**	**SF3 SF4**	**SF4**
SD1	**SD1 SD2**	**SD2 SD3**	**SD3 SD4**	**SD4**

Chromaticity Optimization

- **Optimization result**



before optimization

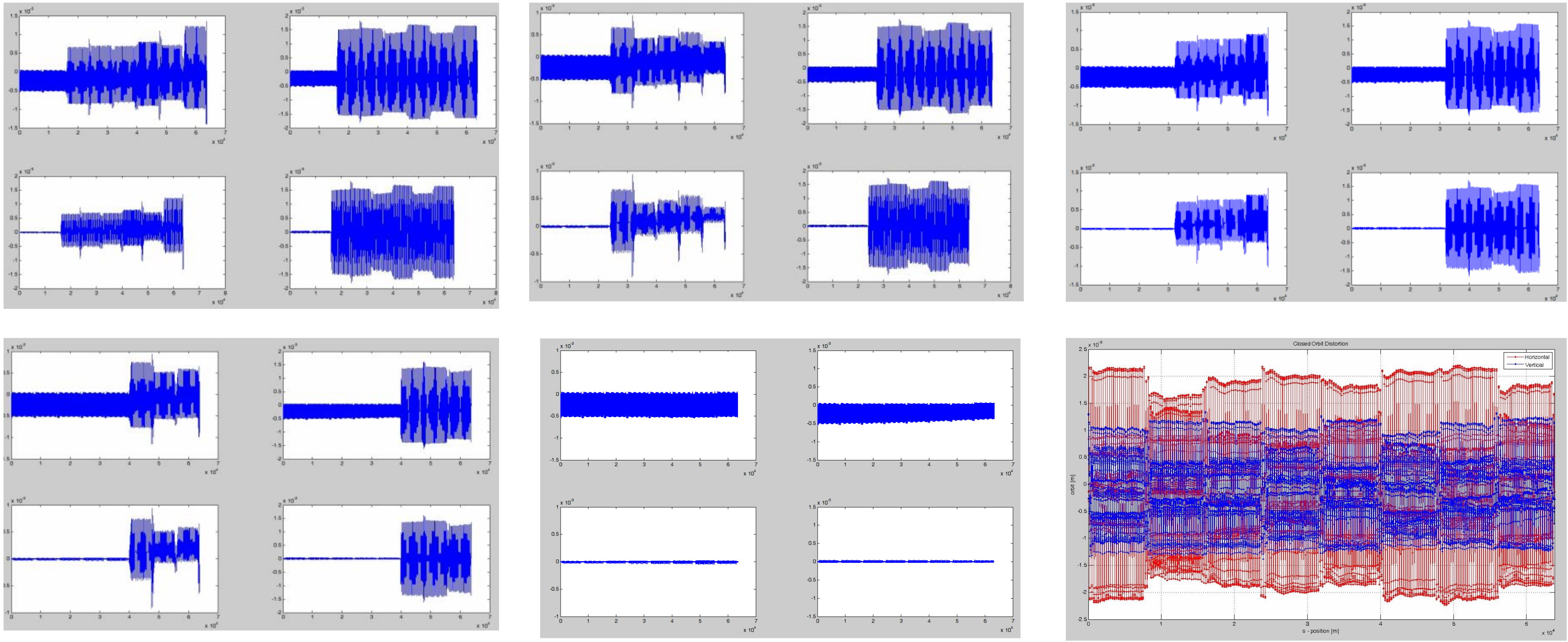


after optimization

Earth field Orbit Correction

■ First turn orbit correction

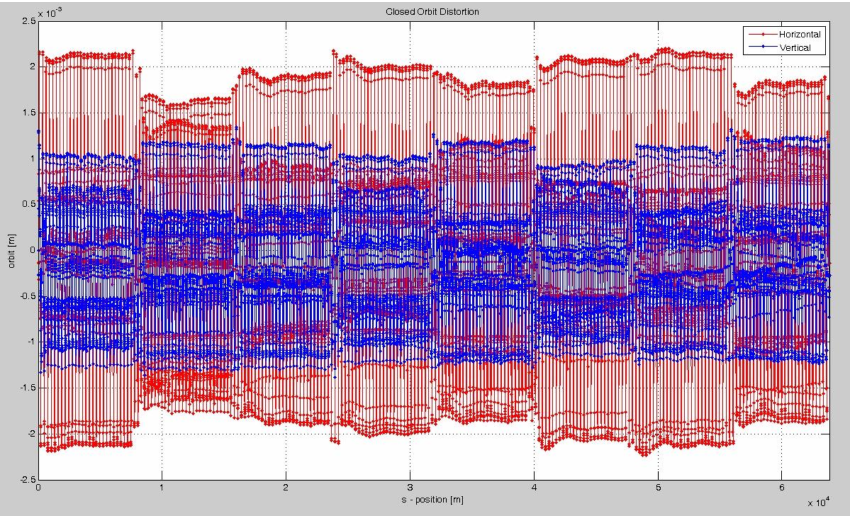
➢ **As we have said, the first turn orbit correction is important. It is similar to the closed orbit correction. This code is finished using Matlab.**



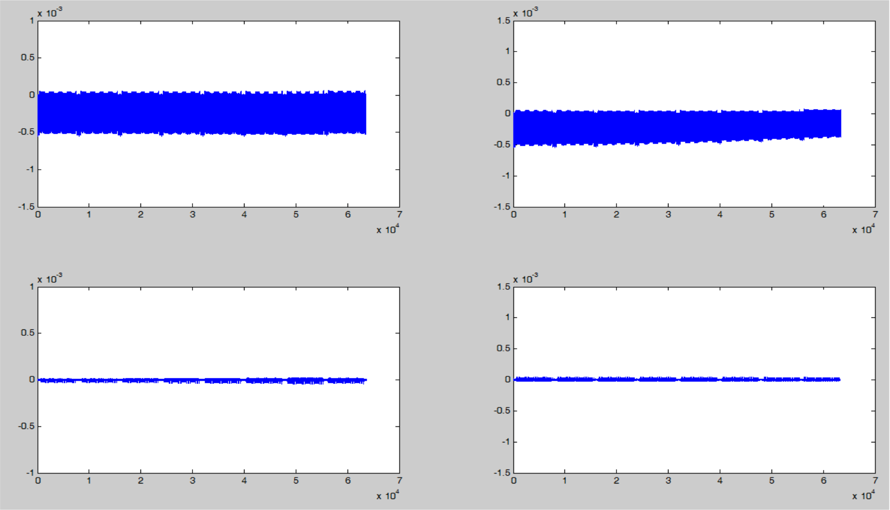
Earth field Orbit Correction

Closed orbit correction

- After the first turn orbit correction, the closed orbit is existed.



Closed orbit after first turn orbit correction



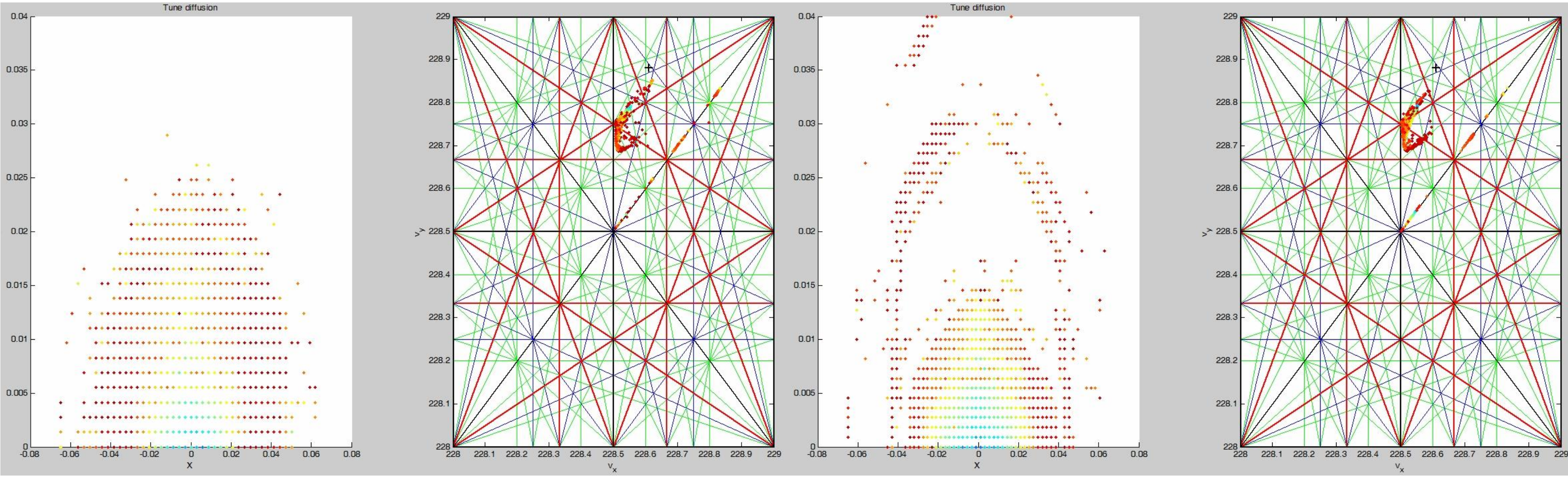
Closed orbit after first turn orbit correction and closed orbit correction

CEPC Booster Error Estimate

	BEPCII			CEPC		
	bend	quad	sext	bend	quad	sext
Dx(mm)	0.2	0.15	0.15	0.3	0.1	0.15
Dy(mm)	0.2	0.15	0.15	0.2	0.1	0.15
Tilt(mrad)	0.1	0.2	0.5	0.1	0.1	0.5
B*L	3e-4	3e-4	2e-3	5e-4	5e-4	4e-3
quadrupole (s)	3e-4			8e-4		
sextupole(s)	6e-4	5e-5		2e-4	6e-4	
Octupole(s)		7e-5	6e-4	7e-5	5e-4	1.7e-3
Decapole(s)	5e-4	9e-5	2e-4	1.3e-4	6.9e-4	3.4e-3
Dodecapole(s)		6e-4	5e-4	1.4e-4	1e-3	6.5e-3
Quadrupole(r)	1e-4	3e-4		2e-4		
Sextupole(r)	1e-4	1e-4	3e-3	2.9e-4	1.2e-3	
Multipole(r)	1e-4	1e-4	3e-4	2e-4	1e-3	2e-2

DA result

- **Tune:190.61/190.88 and cavity on**



With error and orbit correction,

dp=0.0

With error and orbit correction,

dp=0.01

Booster Parameters

■ Parameter List for Normal Bend Scheme.

Parameter	Unit	Value
Beam energy [E]	GeV	6
Circumference [C]	km	63.84
Revolutionfrequency[f_0]	kHz	4.69
SR power / beam [P]	MW	2.16
Beam off-set in bend	cm	0
Momentum compaction factor[α]		1.91E-05
Strength of dipole	Gs	25.8
n_B/beam		50
Lorentz factor [g]		11741.71
Magnetic rigidity [Br]	T·m	20
Beam current / beam [I]	mA	0.92
Bunchpopulation[N_e]		2.44E10
Bunch charge [Q_b]	nC	3.91681
emittance-horizontal[e_x] inequilibrium	m·rad	0.91E-11
injected from linac	m·rad	3E-7
emittance-vertical[e_y] inequilibrium	m·rad	0.046E-11
injected from linac	m·rad	3E-7

Parameter	Unit	Value
RF voltage [Vrf]	GV	0.2138
RF frequency [frf]	GHz	1.3
Harmonic number [h]		276831
Synchrotronoscillationtune[n_s]		0.21
Energy acceptance RF	%	4.995
SR loss / turn [U0]	GeV	1.47E-5
Energyspread[s_d] inequilibrium	%	7.47E-05
injected from linac	%	0.1
Bunch length[s_d] inequilibrium	mm	5.85E-05
injected from linac	mm	~1.5
Transversedampingtime[t_x]	s	174
	turns	
Longitudinaldampingtime[t_e]	s	174
	turns	

Booster Parameters

Parameter List for Normal Bend Scheme.

Parameter	Unit	Value
Beam energy [E]	GeV	120
Circumference [C]	km	63.84
Revolutionfrequency[f_0]	kHz	4.69
SR power / beam [P]	MW	2.16
Beam off-set in bend	cm	0
Momentum compaction factor[α]		2.54E-5
Strength of dipole	Gs	516.71
n_B/beam		50
Lorentz factor [g]		234834.15
Magnetic rigidity [Br]	T·m	400
Beam current / beam [I]	mA	0.92
Bunchpopulation[N_e]		2.44E10
Bunch charge [Q_b]	nC	3.91681
emittance-horizontal[e_x] inequilibrium	m·rad	3.61E-9
injected from linac	m·rad	3E-7
emittance-vertical[e_y] inequilibrium	m·rad	0.1083E-9
injected from linac	m·rad	3E-7

Parameter	Unit	Value
RF voltage [Vrf]	GV	6
RF frequency [frf]	GHz	1.3
Harmonic number [h]		276831
Synchrotronoscillationtune[n_s]		0.21
Energy acceptance RF	%	4.57
SR loss / turn [U0]	GeV	2.34
Energyspread[s_d] inequilibrium	%	0.12
injected from linac	%	0.1
Bunch length[s_d] inequilibrium	mm	1.36
injected from linac	mm	~1.5
Transversedampingtime[t_x]	ms	21.76
Longitudinaldampingtime[t_e]	ms	

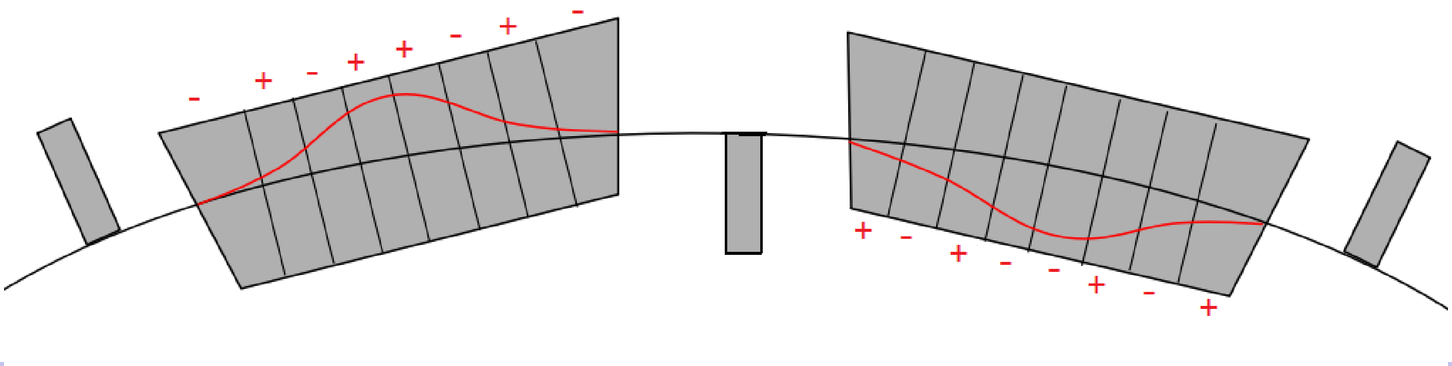
Conclusion

- **With error, orbit correction, cavities on and tune 0.61/0.88, DA_x=8.6sigma,DA_y=10.1sigma@dp=0%**
- **With error, orbit correction, cavities on and tune 0.61/0.88, DA_x=6.7,DA_y=6.5@dp=1%**
- **Contrast with the design goal we have proposed in previous section, this design is reasonable and meet requirements.**

Wiggling Bend Scheme

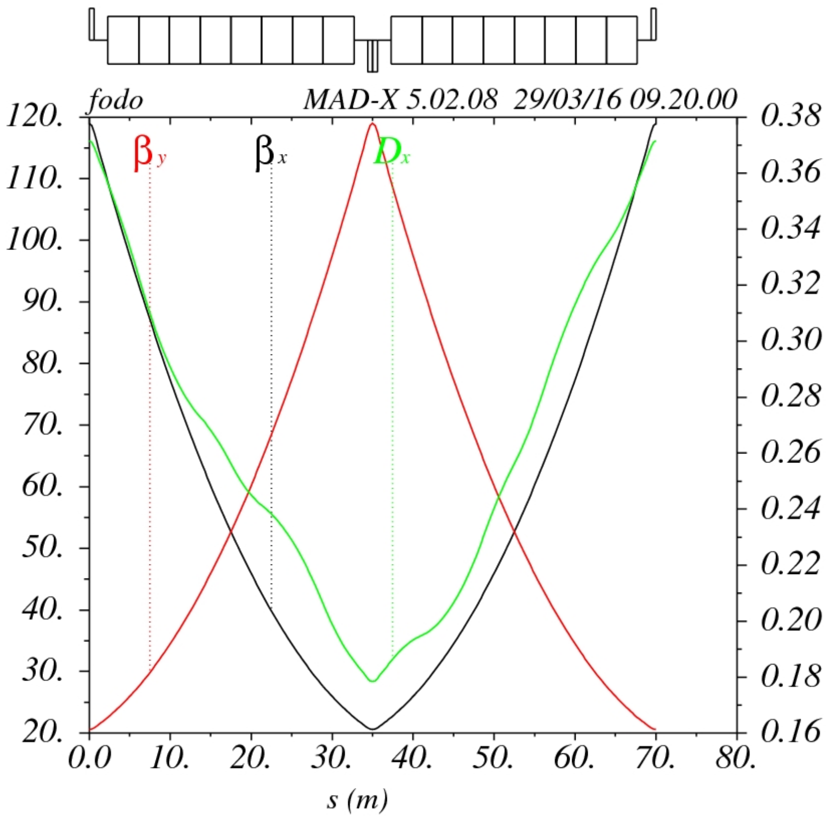
Introduction of Wiggling Bend Scheme

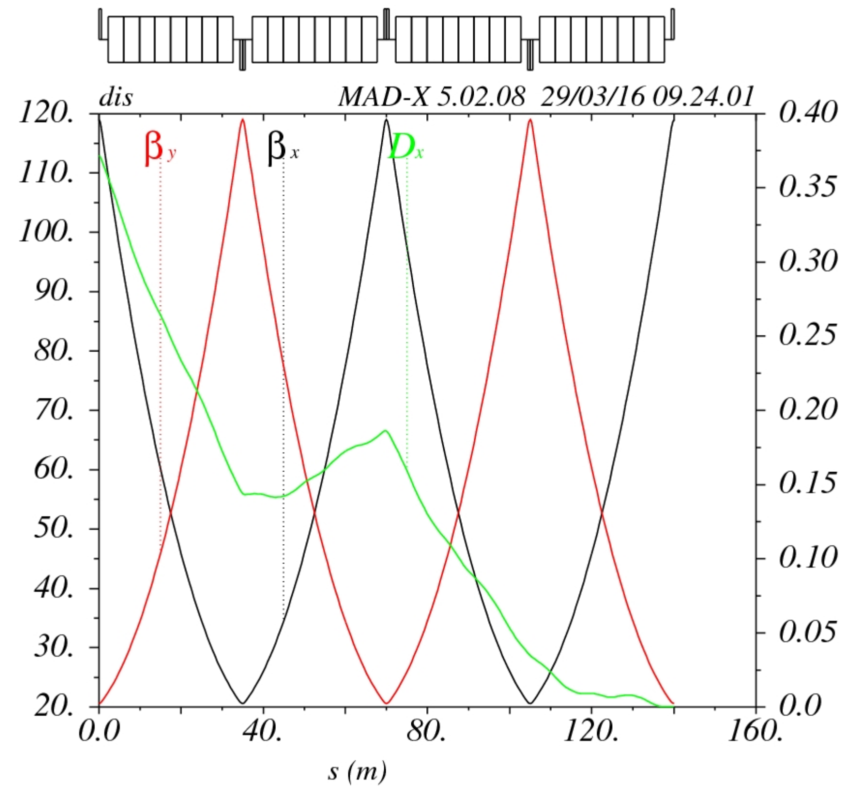
- The inject energy is 6GeV.
- If all the dipoles have the same sign, 33Gs@6GeV may cause problem.
- In wiggling bend scheme, adjoining dipoles have different sign to avoid the low field problem.
- The picture below shows the FODO structure.
- The wiggler scheme using the same sextupole scheme and magnet error and the wiggler scheme has little or no effect on dynamics.



Linear Optics

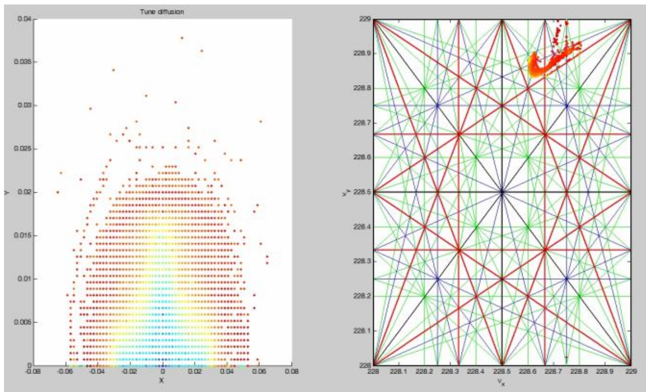
- **90 degree FODO**
- **FODO length:70 meter**



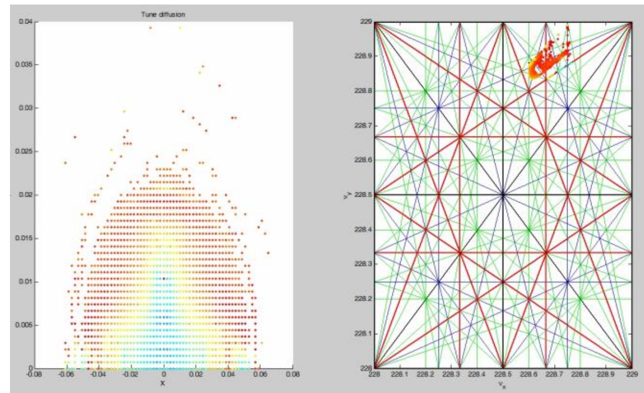


DA result

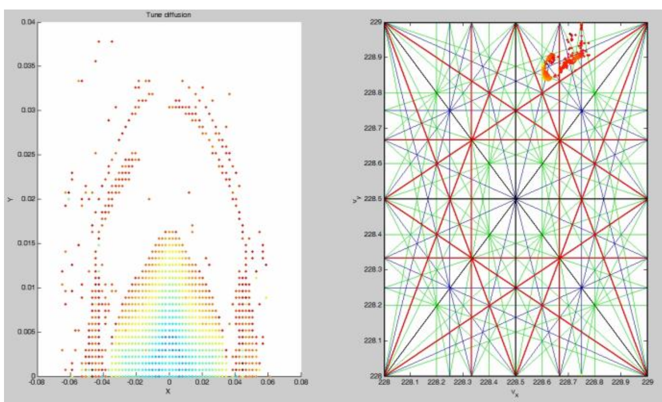
- **Tune:190.61/190.88 and cavity on**



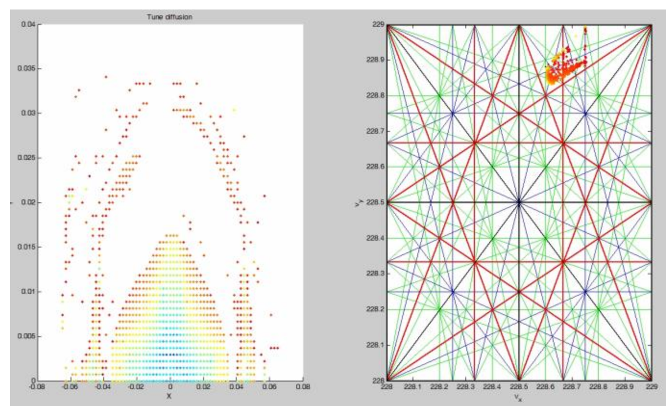
with error, dp=0



with error, dp=0.0



with error, dp=0.01



with error, dp=0.01

Booster Parameters

- **Parameter List for Alternating Magnetic Field Scheme.**

Parameter	Unit	Value
Beam energy [E]	GeV	6
Circumference [C]	km	63.84
Revolutionfrequency[f_0]	kHz	4.69
SR power / beam [P]	MW	2.16
Beam off-set in bend	cm	1.2
Momentum compaction factor[α]		2.33E-5
Strength of dipole	Gs	-129.18/+180.84
n_B/beam		50
Lorentz factor [g]		11741.71
Magnetic rigidity [Br]	T·m	20
Beam current / beam [I]	mA	0.92
Bunchpopulation[N_e]		2.44E10
Bunch charge [Q_b]	nC	3.91681
emittance-horizontal[e_x] inequilibrium	m·rad	6.38E-11
injected from linac	m·rad	3E-7
emittance-vertical[e_y] inequilibrium	m·rad	0.191E-11
injected from linac	m·rad	3E-7

Parameter	Unit	Value
RF voltage [Vrf]	GV	0.2138
RF frequency [frf]	GHz	1.3
Harmonic number [h]		276831
Synchrotronoscillationtune[n_s]		0.21
Energy acceptance RF	%	5.93
SR loss / turn [U0]	GeV	5.42E-4
Energyspread[s_d] inequilibrium	%	0.0147
injected from linac	%	0.1
Bunch length[s_d] inequilibrium	mm	0.18
injected from linac	mm	~1.5
Transversedampingtime[t_x]	ms	4.71
	turns	
Longitudinaldampingtime[t_e]	ms	4.71
	turns	

Booster Parameters

- Parameter List for Alternating Magnetic Field Scheme.

Parameter	Unit	Value
Beam energy [E]	GeV	120
Circumference [C]	km	63.84
Revolutionfrequency[f_0]	kHz	4.69
SR power / beam [P]	MW	2.16
Beam off-set in bend	cm	0
Momentum compaction factor[α]		2.54E-5
Strength of dipole	Gs	516.71
n_B/beam		50
Lorentz factor [g]		234834.15
Magnetic rigidity [Br]	T·m	400
Beam current / beam [I]	mA	0.92
Bunchpopulation[N_e]		2.44E10
Bunch charge [Q_b]	nC	3.91681
emittance-horizontal[e_x] inequilibrium	m·rad	3.61E-9
injected from linac	m·rad	3E-7
emittance-vertical[e_y] inequilibrium	m·rad	0.1083E-9
injected from linac	m·rad	3E-7

Parameter	Unit	Value
RF voltage [Vrf]	GV	6
RF frequency [frf]	GHz	1.3
Harmonic number [h]		276831
Synchrotronoscillationtune[n_s]		0.21
Energy acceptance RF	%	4.57
SR loss / turn [U0]	GeV	2.34
Energyspread[s_d] inequilibrium	%	0.12
injected from linac	%	0.1
Bunch length[s_d] inequilibrium	mm	1.36
injected from linac	mm	~1.5
Transversedampingtime[t_x]	ms	21.76
Longitudinaldampingtime[t_e]	ms	

Conclusion

- **In the wiggling bend scheme, strength of dipole increase from 30Gs to -129.18/+180.84 Gs.**
- **Shorter damping times are obtained, which is 4.7 seconds.**
- **A ramping method of is alternating magnetic field booster proposed.**
- **Serveal tunes has been test. Some tunes are sensitive to magnet errors, some are not. 0.61/0.88 seems good.**
- **With error, cavities on and tune 0.61/0.88, DA_x=9.2,DA_y=9.6@dp=0%**
- **With error, cavities on and tune 0.61/0.88, DA_x=6.6,DA_y=6.4@dp=1%**

Moola：Modular&parallel Optics Optimization for LAttice

Introduction of Moola

- **In the lattice design process, especially in the challenging project like CEPC, we want to control every thing(such as the twiss, high order nonlinear parameter and so on), and using them for optimization.**
- **Lattice design code like Mad and Sad can complete some thing very well, but they dont let us do what ever we want, beacuse we can't handle the code.**
- **Based on this requirement, we need own code.**
- **Modular**
- **Parallel**
- **Linked to Zlib.**

Moola: Modular&parallel Optics Optimization for LAttice

- **Main physics base**

➢ **Hamilton and canonical coordinates**

$$H = -(1+h\cdot x)\cdot\sqrt{(1+\delta^2)-{p_x}^2-{p_y}^2}+h\cdot x+\frac{h^2\cdot x^2}{2}-\frac{e}{p_0}A_s$$

$$\vec{v}=\begin{pmatrix} x \\ p_x \\ y \\ py \\ \delta \\ t \end{pmatrix}$$

$$\delta=\frac{p-p_0}{p_0}$$

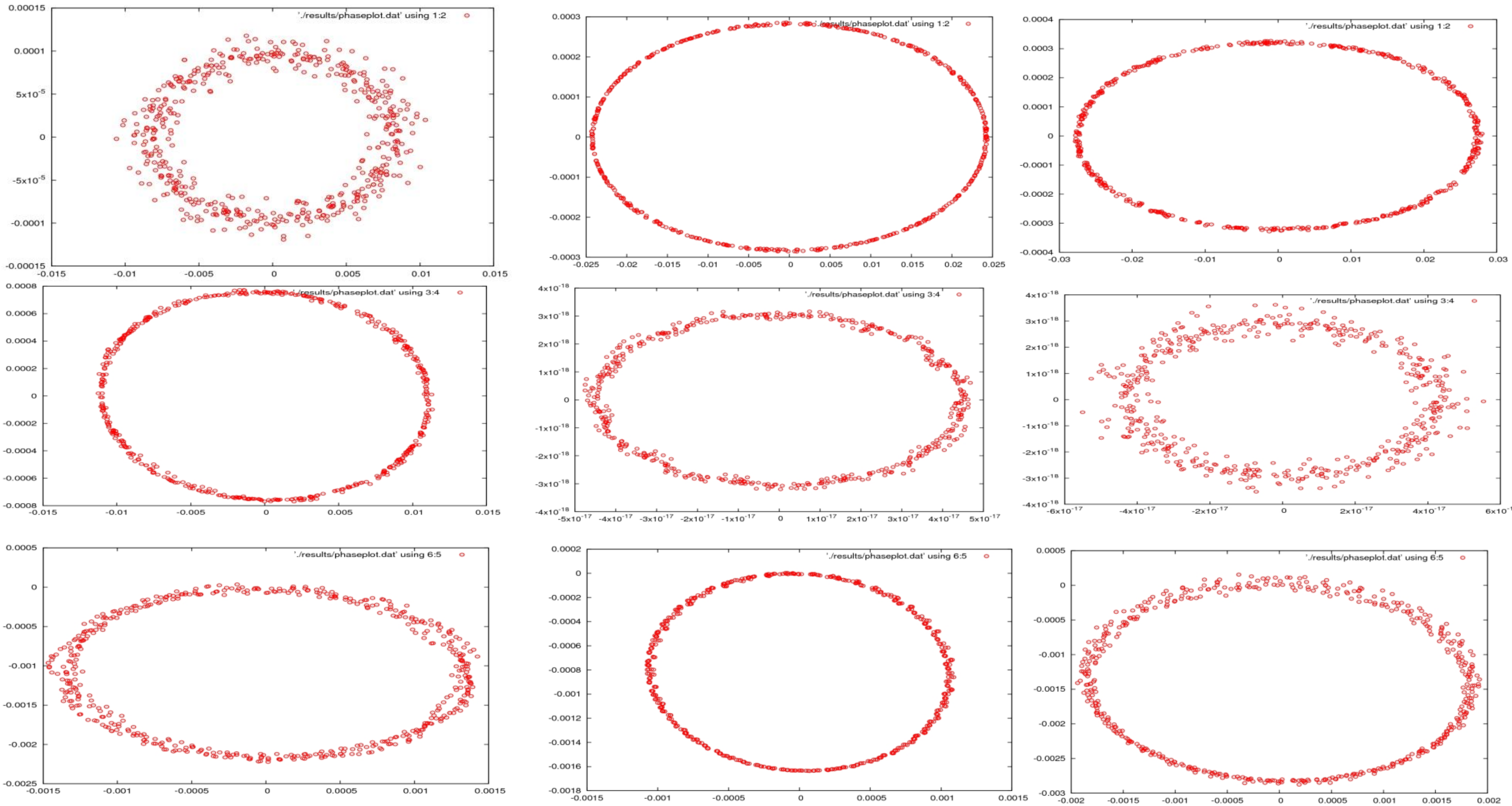
➢ **Fourth-order symplectic integrator**

$$M(s)=A\left(\frac{s}{2(2-\beta)}\right)B\left(\frac{s}{2-\beta}\right)A\left(\frac{s(1-\beta)}{2(2-\beta)}\right)B\left(\frac{-s\beta}{2-\beta}\right)A\left(\frac{s(1-\beta)}{2(2-\beta)}\right)B\left(\frac{s}{2-\beta}\right)A\left(\frac{s}{2(2-\beta)}\right)+O(s^5)$$

$$\beta=\frac{1}{2^3}$$

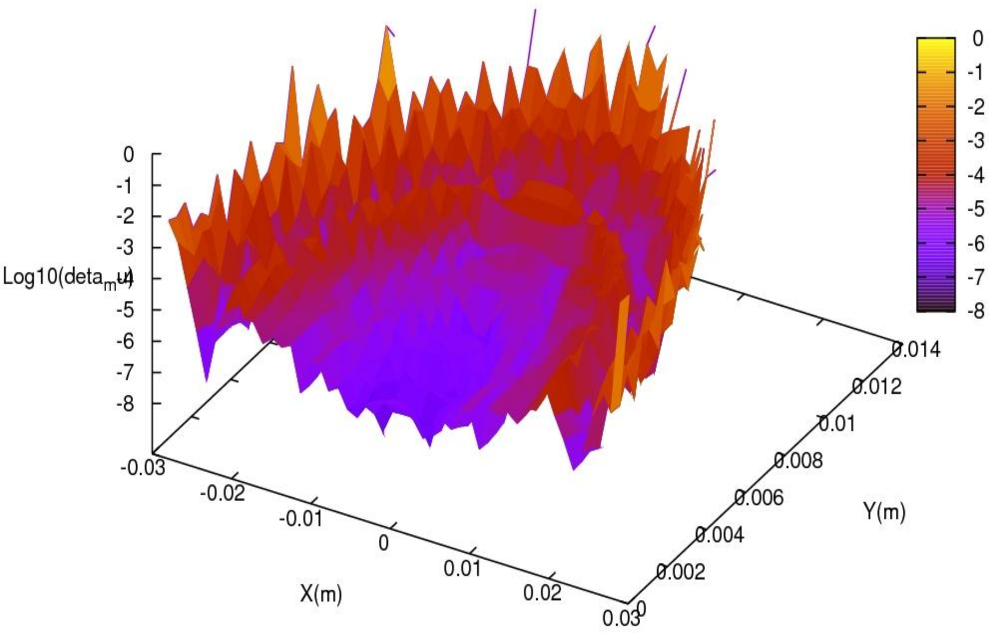
Moola：Modular&parallel Optics Optimization for LAttice

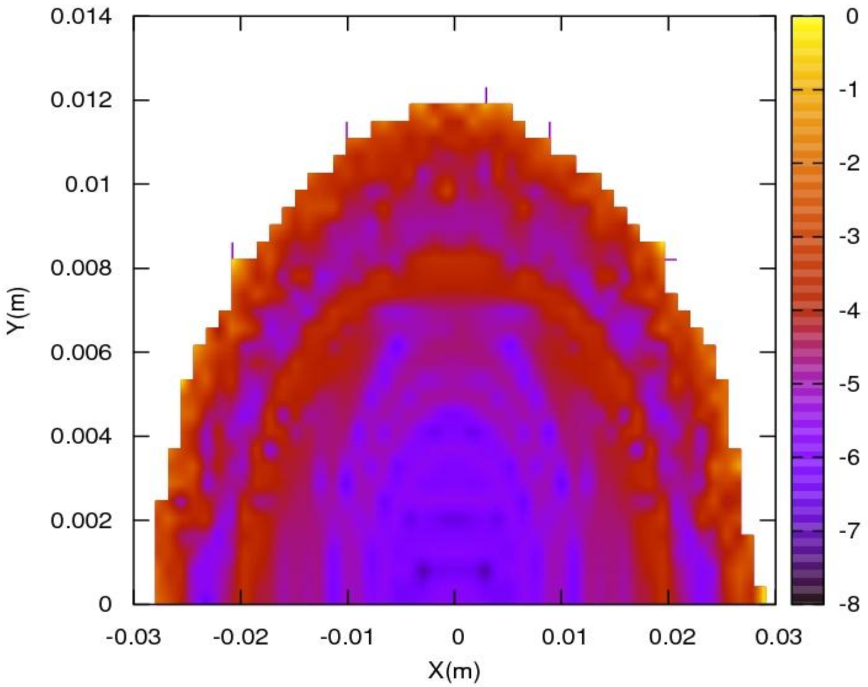
- **CEPC mainring results from Moola**



Moola：Modular&parallel Optics Optimization for LAttice

- CEPC mainring results from Moola

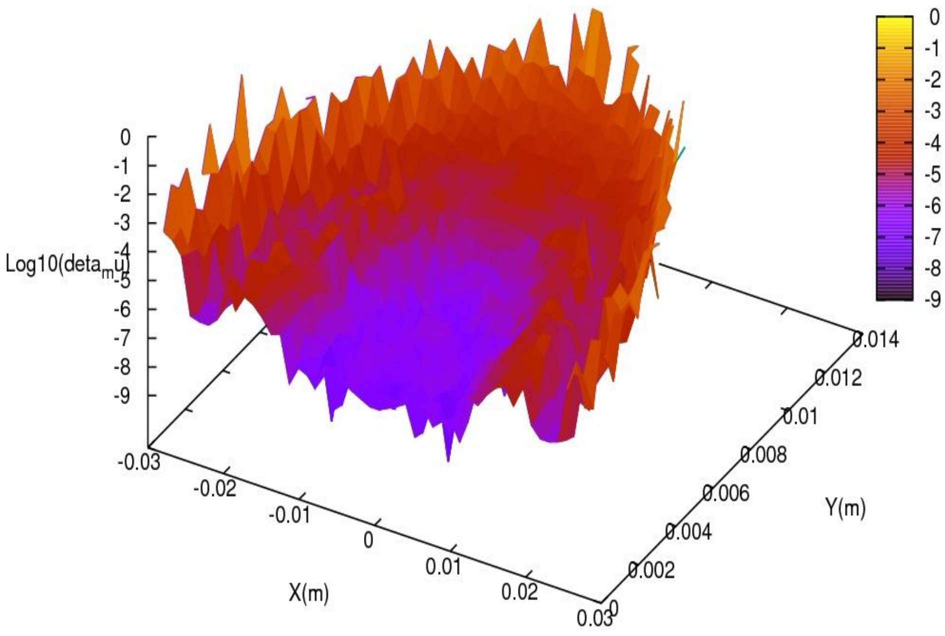


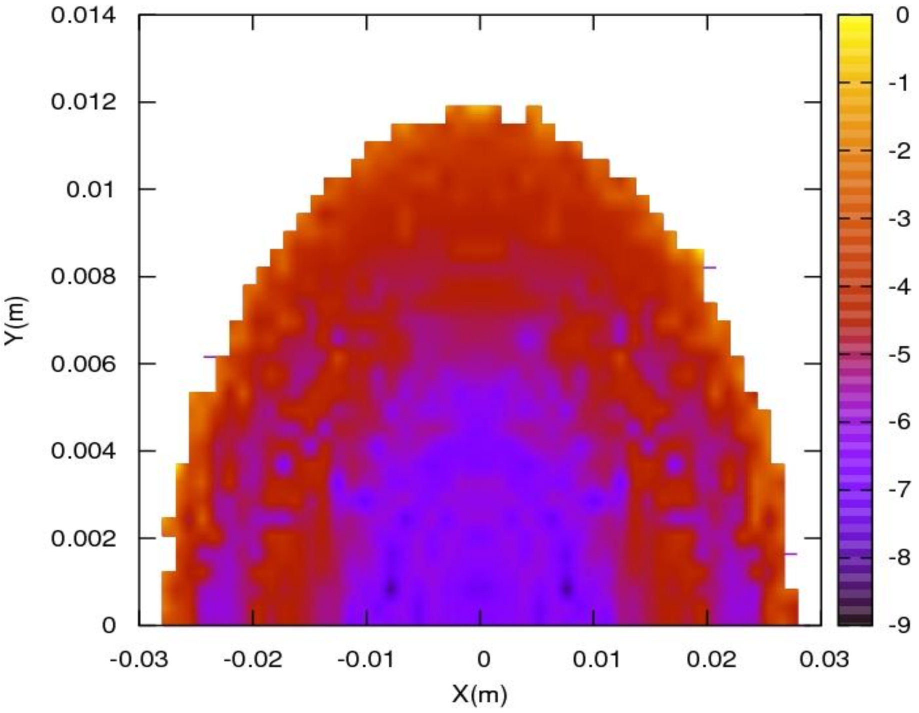


2500 particles, 256 turns in 109 seconds

Moola：Modular&parallel Optics Optimization for LAttice

- **CEPC mainring results from Moola**





2500 particles, 512 turns in 219 seconds

Moola：Modular&parallel Optics Optimization for LAttice

CEPC mainring results from Moola

Arbitrary order chromaticity

```
hhc in (2Jx)^m (2Jy)n (Delta)^p:
 -1.625581e+00 2 1 0 1
 -1.824465e+00 2 0 1 1
  3.060567e+00 3 1 0 2
 -2.925249e-01 3 0 1 2
  6.069474e+01 4 1 0 3
 -9.905047e+01 4 0 1 3
  1.709833e+07 5 1 0 4
  2.482804e+06 5 0 1 4
 -4.577566e+08 6 1 0 5
  1.982098e+09 6 0 1 5
```

Arbitrary order one-turn-map

```
x,  Max Order : 5,  5 Varibles
 *************************
 -2.181432e-01 1 1 0 0 0 0
  8.282591e+01 1 0 1 0 0 0
  6.140558e-06 1 0 0 0 0 1
 -2.584679e-13 2 2 0 0 0 0
  4.482296e-11 2 1 1 0 0 0
  9.182637e+00 2 1 0 0 0 1
  3.228498e-09 2 0 2 0 0 0
 -1.137751e+03 2 0 1 0 0 1
  1.972567e-14 2 0 0 2 0 0
  1.184135e-11 2 0 0 1 1 0
```

Detuning terms

```
hh in (2Jx)^m (2Jy)n (Delta)^p:
  7.975755e+03 2 2 0 0
  9.069602e+03 2 1 1 0
 -1.625581e+00 2 1 0 1
  2.805835e+04 2 0 2 0
 -1.824465e+00 2 0 1 1
  1.497153e+06 3 3 0 0
  1.037905e+07 3 2 1 0
  1.705424e+07 3 2 0 1
 -6.858572e+06 3 1 2 0
  2.882441e+07 3 1 1 1
  3.060567e+00 3 1 0 2
  7.577926e+06 3 0 3 0
  1.336103e+07 3 0 2 1
 -2.925249e-01 3 0 1 2
```

Linear optics

```
AI =
M 4 4
   1.085484e-01    0.000000e+00    0.000000e+00    0.000000e+00
  -1.952982e-15    9.212484e+00    0.000000e+00    0.000000e+00
   0.000000e+00    0.000000e+00    2.605808e-01   -2.524355e-29
   0.000000e+00    0.000000e+00   -1.043870e-14    3.837581e+00

RR =
M 4 4
  -9.048271e-01   -4.257792e-01    0.000000e+00    0.000000e+00
   4.257792e-01   -9.048271e-01    0.000000e+00    0.000000e+00
   0.000000e+00    0.000000e+00    7.289686e-01   -6.845471e-01
   0.000000e+00    0.000000e+00    6.845471e-01    7.289686e-01

AA =
M 4 4
   9.212484e+00    0.000000e+00    0.000000e+00    0.000000e+00
   1.952982e-15    1.085484e-01    0.000000e+00    0.000000e+00
   0.000000e+00    0.000000e+00    3.837581e+00    2.524355e-29
   0.000000e+00    0.000000e+00    1.043870e-14    2.605808e-01
```

Moola：Modular&parallel Optics Optimization for LAttice

Introduction of Moola

- **Moola is still preliminary, many functions is waiting to be added.**
- **With all the nonlinear parameters in my computer memory, we can call them in any optimization algorithm(like all kinds of evolution algorithm, "jMetalCpp" is linked).**
- **In the booster forther design and the mainring design, Moola will play a more important role.**

Summary

- **In this report, we proposed a design of both normal scheme and wiggler scheme.**
  - **Normal scheme:**
  - **With error, orbit correction, cavities on and tune 0.61/0.88, DA_x=8.6sigma,DA_y=10.1sigma@dp=0%**
  - **With error, orbit correction, cavities on and tune 0.61/0.88, DA_x=6.7,DA_y=6.5@dp=1%**
  - **Wiggler scheme:**
  - **With error, cavities on and tune 0.61/0.88, DA_x=9.2,DA_y=9.6@dp=0%**
  - **With error, cavities on and tune 0.61/0.88, DA_x=6.6,DA_y=6.4@dp=1%**
- **Contrast with the design goal we have proposed in previous section, both of the two design are reasonable and meet requirements.**
- **Moola, an optimization code is in process for further study.**