ILC Damping Ring Alternative Lattice Design**

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DR FODO LATTICE DESIGN CONSIDERATIONS

- To decrease the cost of the damping ring, use FODO arc cells to replace the original TME arc cells. The total number of quadrupoles has been decreased.
- To decrease the total construction expenses of the damping rings
  - The civil engineering (the number of shafts).
  - Cryogenic system.

  The number of wiggler sections has been decreased from 4 to **2** in the ILC DR lattice.
- Use 184 arc cells, two kinds of phase advance for two alpha case:
  - 72/72 arc cell for $\alpha_P = 4 \times 10^{-4}$.
  - 90/90 arc cell for $\alpha_P = 2 \times 10^{-4}$.

CONSIDERATIONS FOR THE ARC CELL

Scan some arc cell parameters.

- Arc cell number: from 120 to 240.
- Arc cell length: from 20 m to 40 m.
- The short drift length: from 1 m to 3 m.

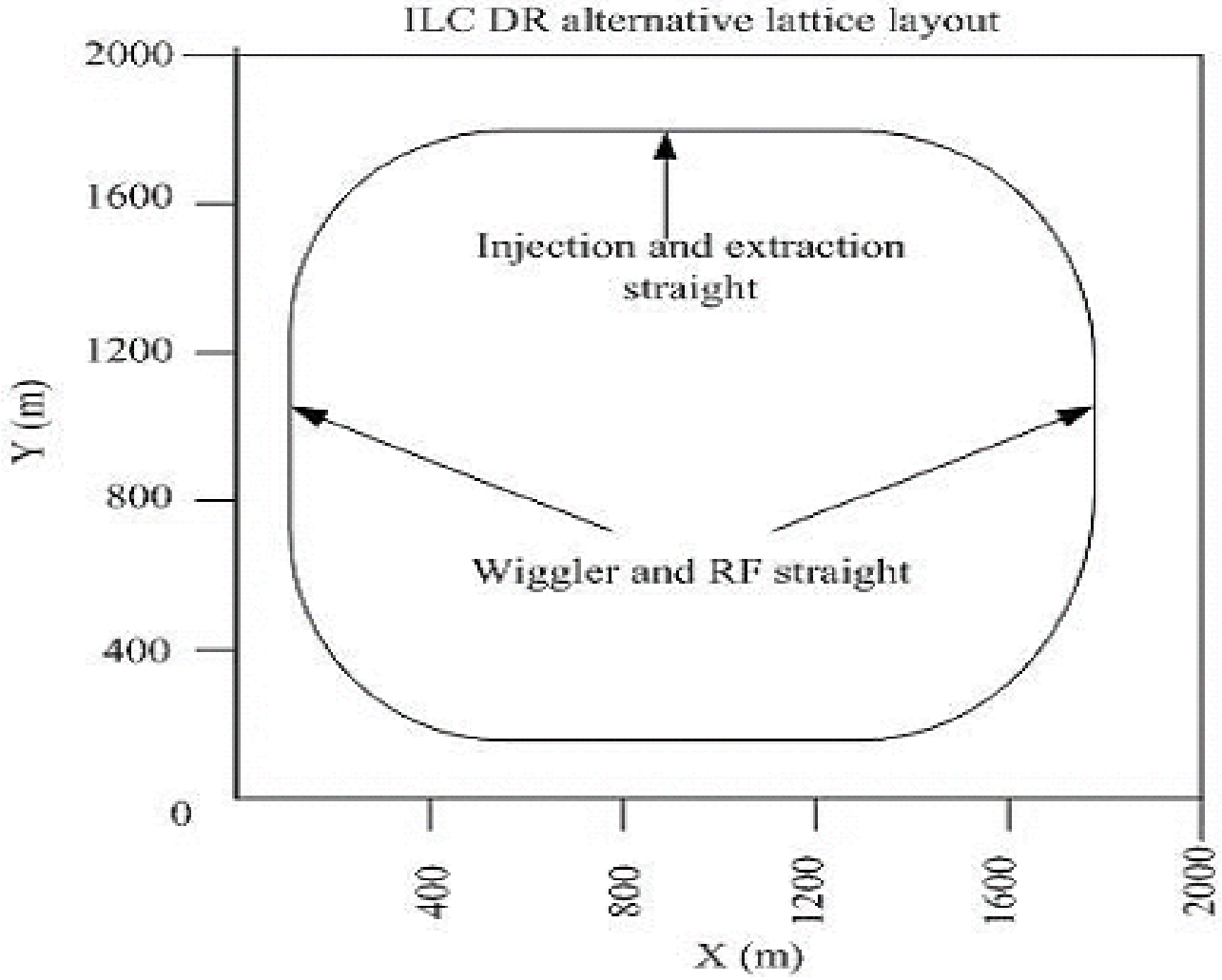
To get proper dispersion and beta functions at the sextupole location in a cell, suitable maximum beta function (less than 55 m), and two alpha case for two phase advance.

At last, we select the arc cell length to be 29.4 m, and the arc cell number to be 184.

COMPARISON WITH OCS6

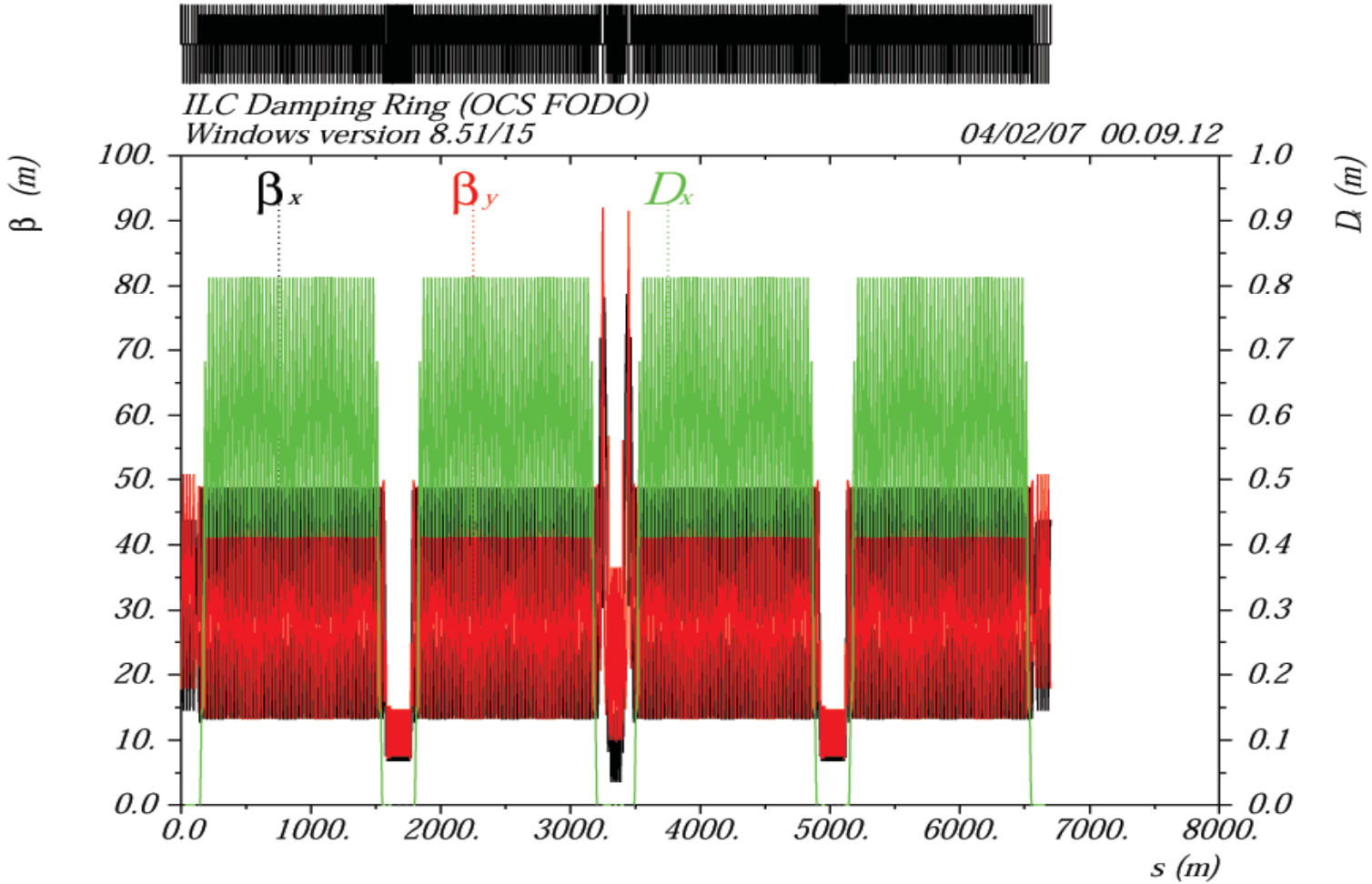
	OCS6	*FODO2*
Circumference [m]	6695	6695
Arc cell	TME	FODO
Phase advance of arc cell	90/90 (108/90)	72/72 (90/90)
Momentum compaction [10^{-4}]	4/2	4/2
Quadrupoles in all	**682**	**468**
Dipoles in all	114 × **6** m + 12 × **3** m	368 × **2** m
Sextupoles in all	**480**	**368**
Number of wiggler straights	**4**	**2**

LAYOUT



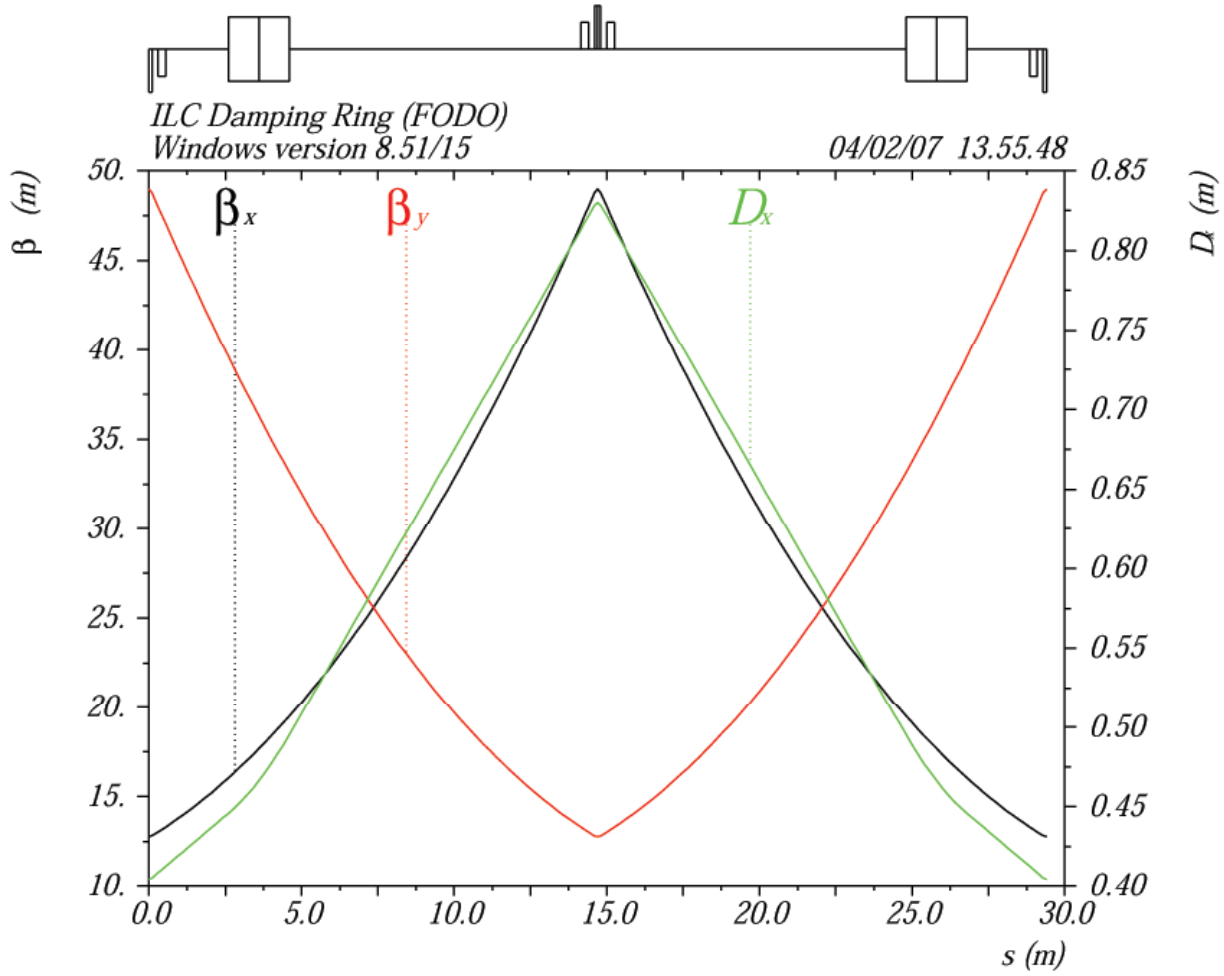
The number of wiggler and RF sections is decreased from 4 to **2**.

TWISS PARAMETERS



There are 184 arc cells in all, maintain the circumference of 6695.057 m.

ARC CELL OF HIGH ALPHA LATTICE

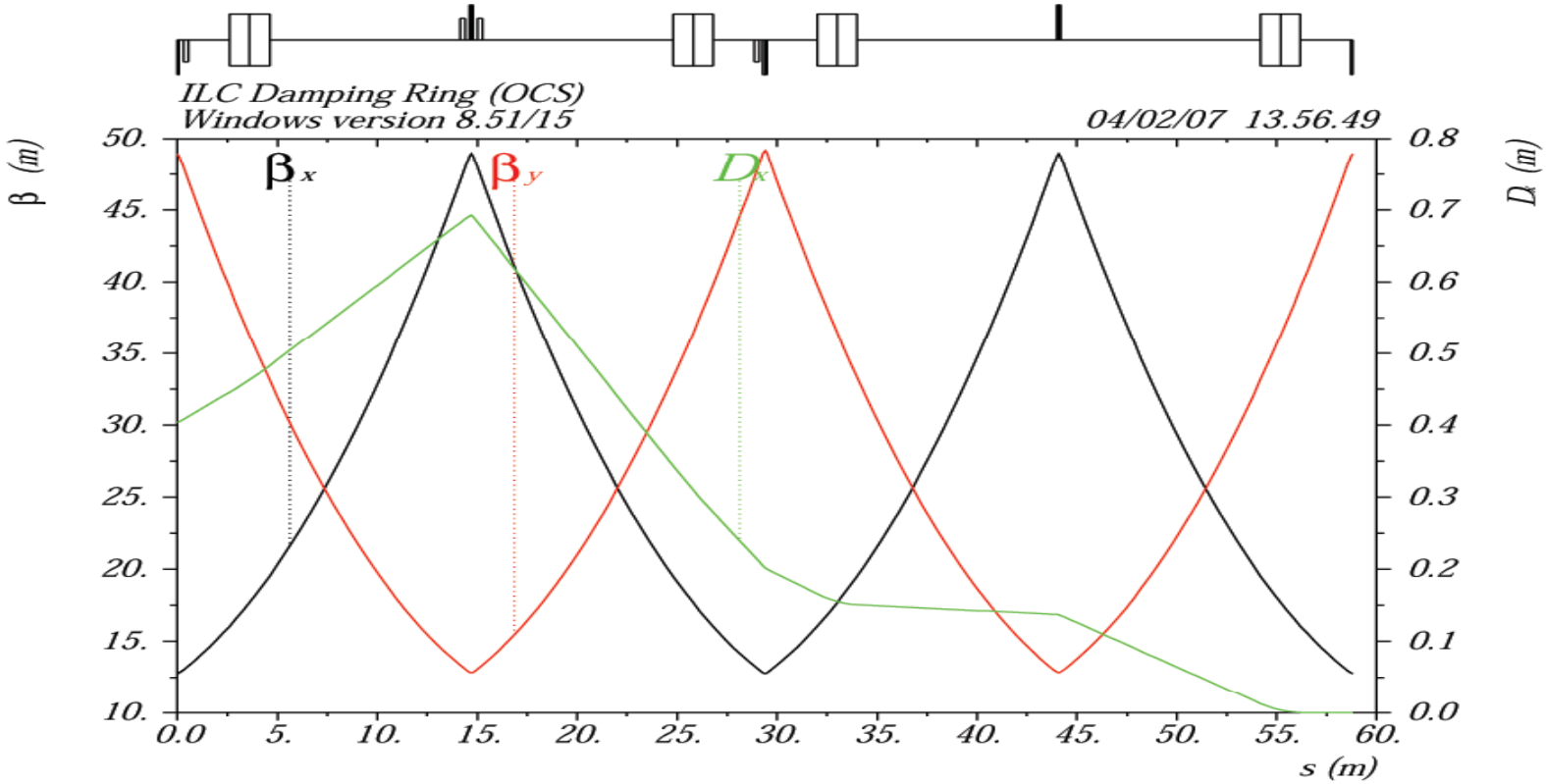


$$\beta^{\pm} = \frac{L_P(1 \pm \sin\frac{\mu}{2})}{\sin\mu}$$

$$D^{\pm} = \frac{L_P\phi(1 \pm \frac{1}{2}\sin\frac{\mu}{2})}{4\sin^2\frac{\mu}{2}}$$

The 72/72 degree modified FODO arc cell is chosen. The cell length is 29.4 m. Adjust the drift length to get suitable betas and dispersion functions.

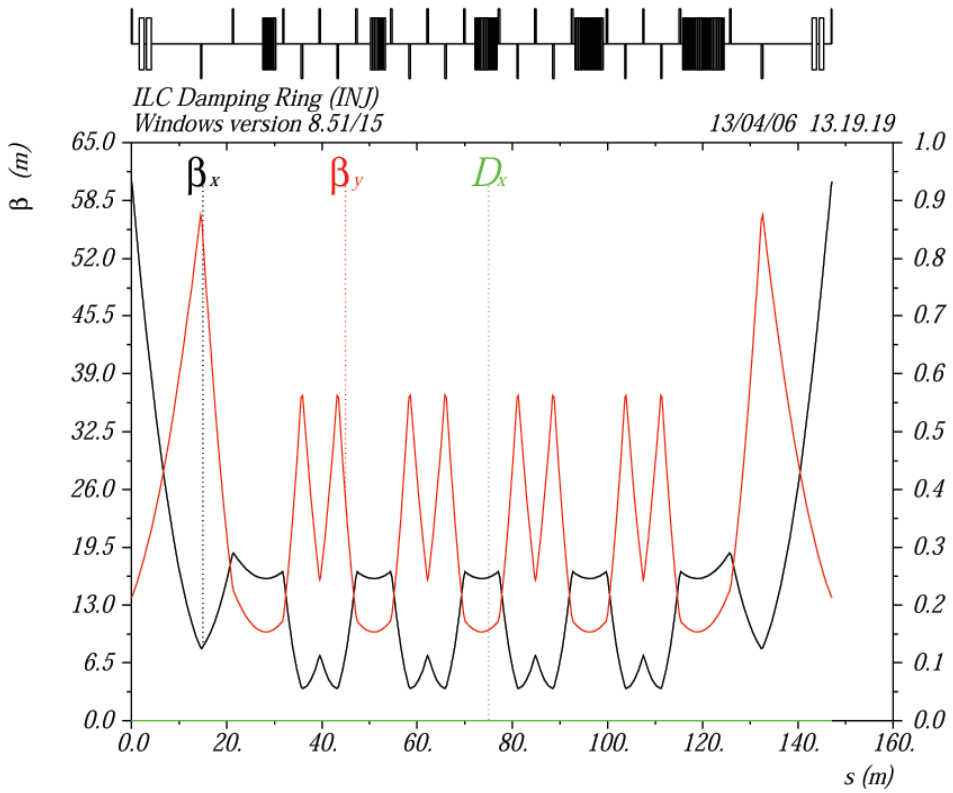
DISPERSION SUPPRESSOR



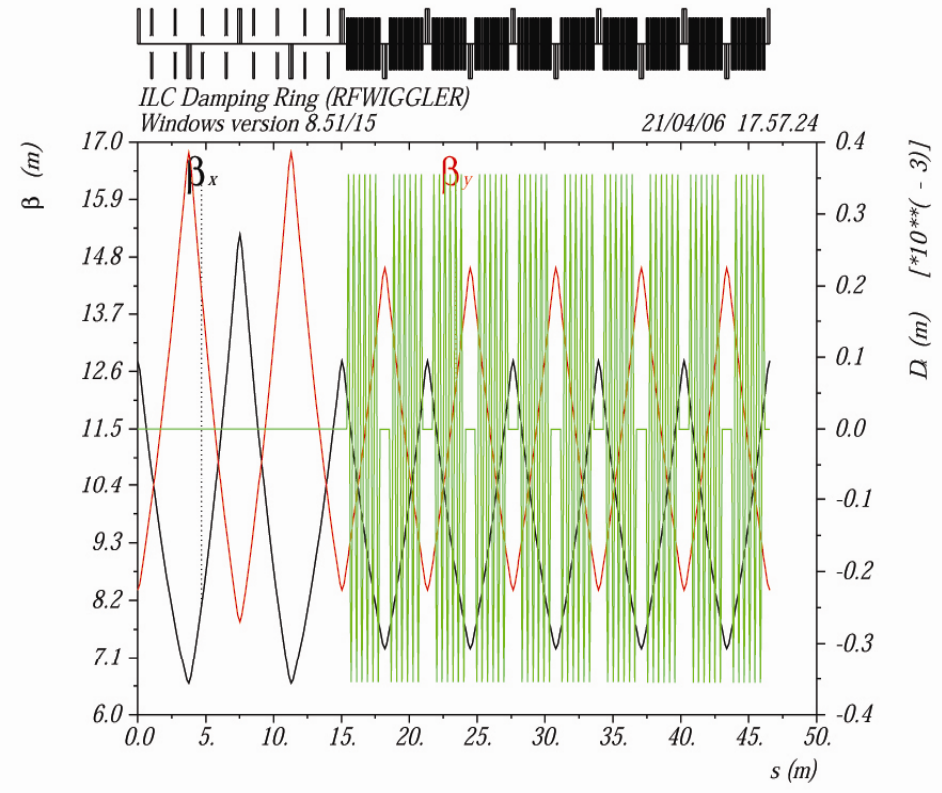
Add one arc cell after the last standard arc cell and **modify the bending angle** of these two cells according to the phase advance. The aim is to have undisturbed TWISS parameters in the dispersion suppressor.

$$\varphi_1 = \varphi \cdot \left(1 - \frac{1}{4\sin^2\frac{\mu}{2}}\right) \qquad \varphi_2 = \frac{\varphi}{4\sin^2\frac{\mu}{2}}$$

OTHER SECTIONS KEPT UNCHANGED

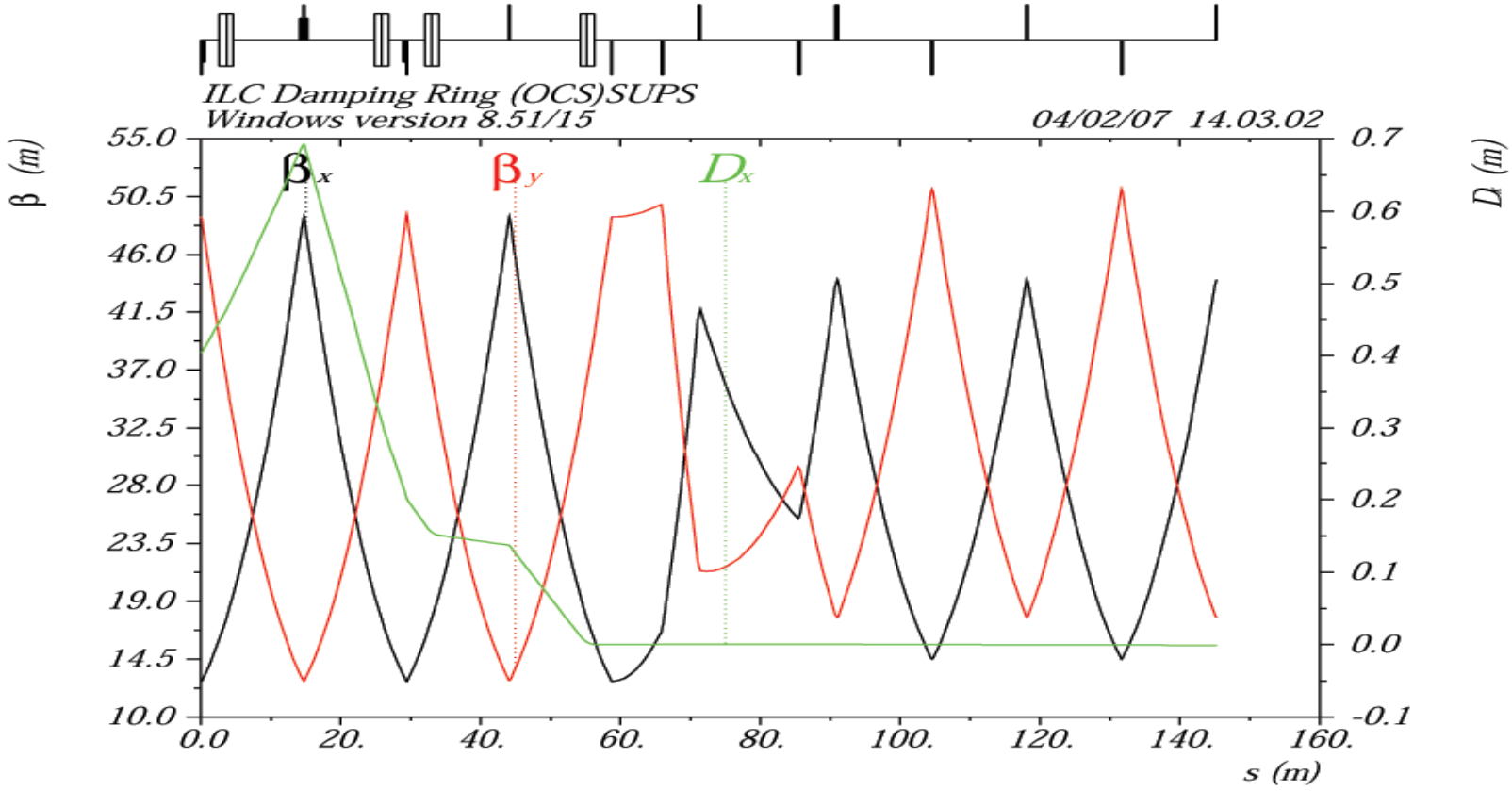


Injection (extraction) section.



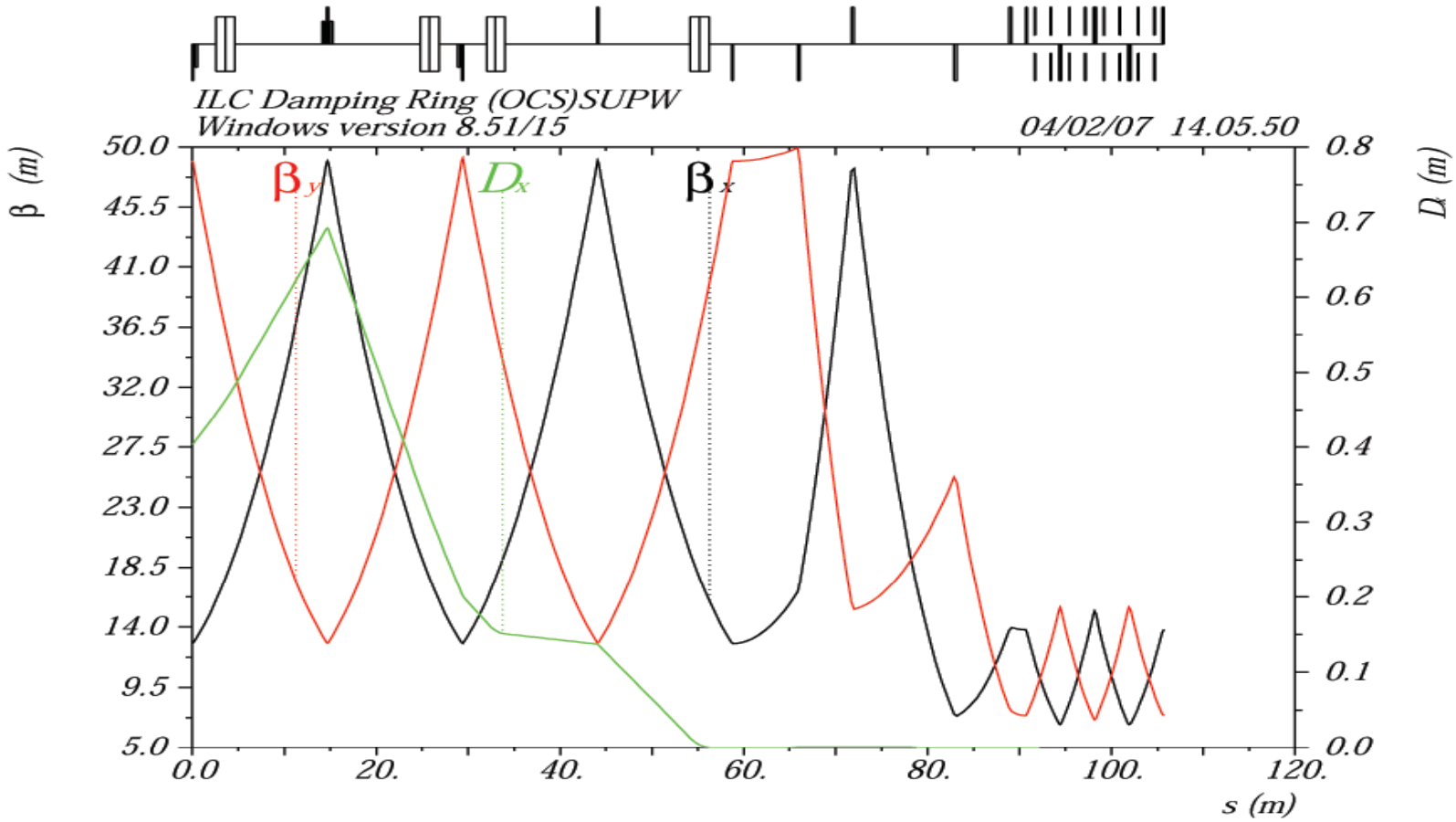
Wiggler and RF cell.

ARC TO EXTRACTION



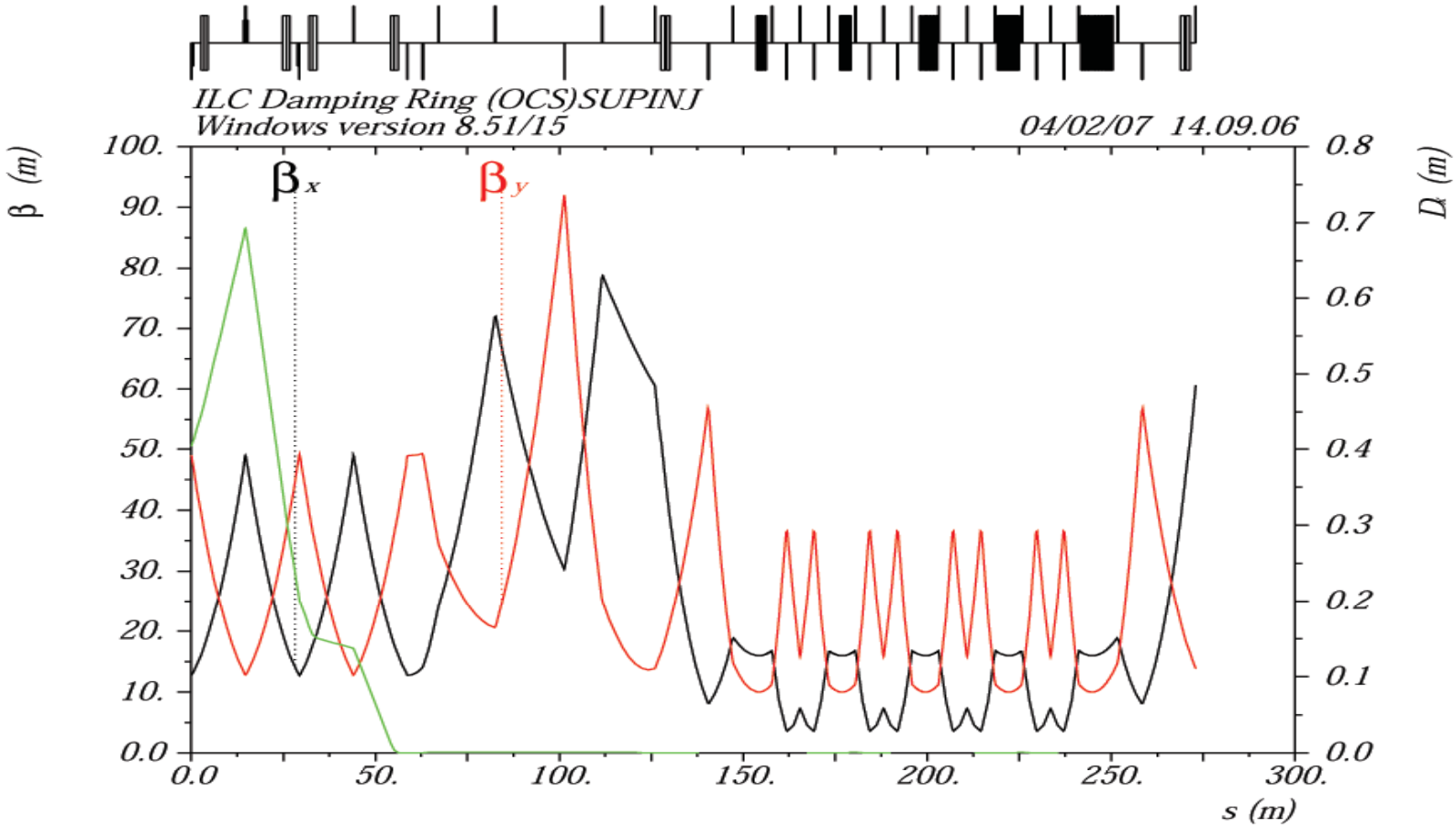
Four quadrupoles to match beta functions between arc and the extraction section.

ARC TO WIGGLER (RF)



Four quadrupoles to match beta functions between arc and wiggler straight.

ARC TO INJECTION

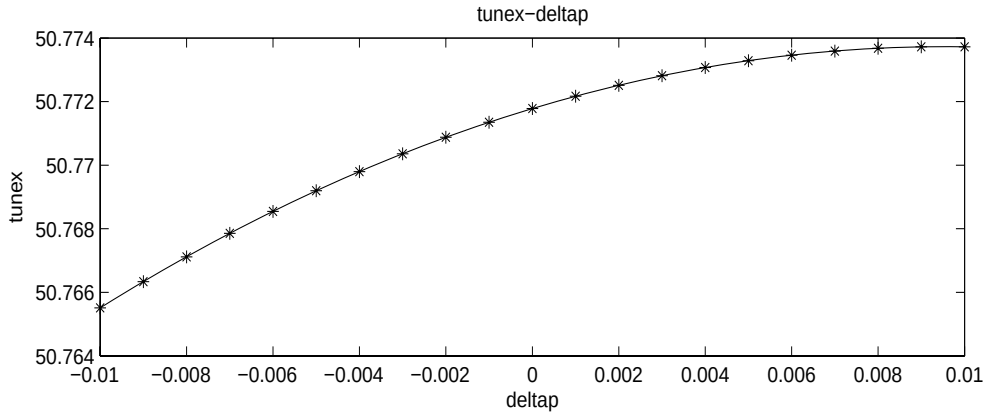


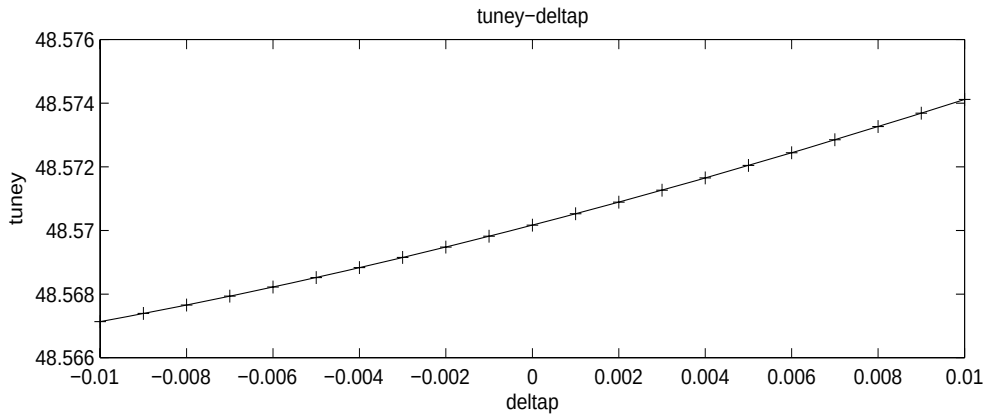
Six quadrupoles to match beta functions and alpha functions between arc and injection section.

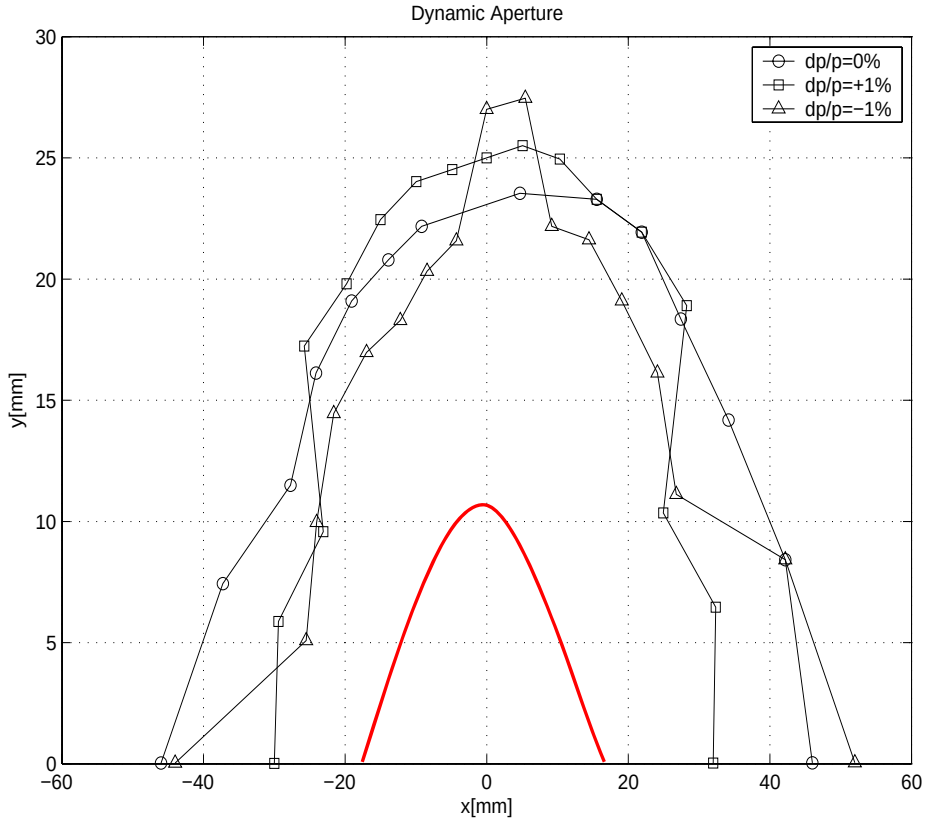
MAIN PARAMETERS OF THE HIGH ALPHA LATTICE

Circumference [m]	**6695**
Harmonic number	14516
Energy [GeV]	5
Arc cell	**FODO**
Tune	50.77 / 48.57
Natural chromaticity	-57 / -58
Momentum compaction [10^{-4}]	**4**
Transverse damping time [ms]	25 / 25
Norm. Natural emittance [μm-rad]	3.8
RF voltage [MV]	**22**
Synchrotron tune	0.062
Synchrotron phase [^{o}]	156.8
RF frequency [MHz]	650
RF acceptance [%]	1.466
Natural bunch length [mm]	**9.1**
Natural energy spread [10^{-3}]	1.28

CHROMATICITY CORRECTION AND DYNAMIC APERTURE







The chromaticity corrected to (0.3,0.31). The tune variation with momentum spread ±1% ; the dynamic aperture with momentum spread up to ±1% (with RF cavity, no errors).

With the same injection beam size as OCS. The red line is **3** times injected positron bunch size.

HIGH ORDER MAGNETS ERRORS

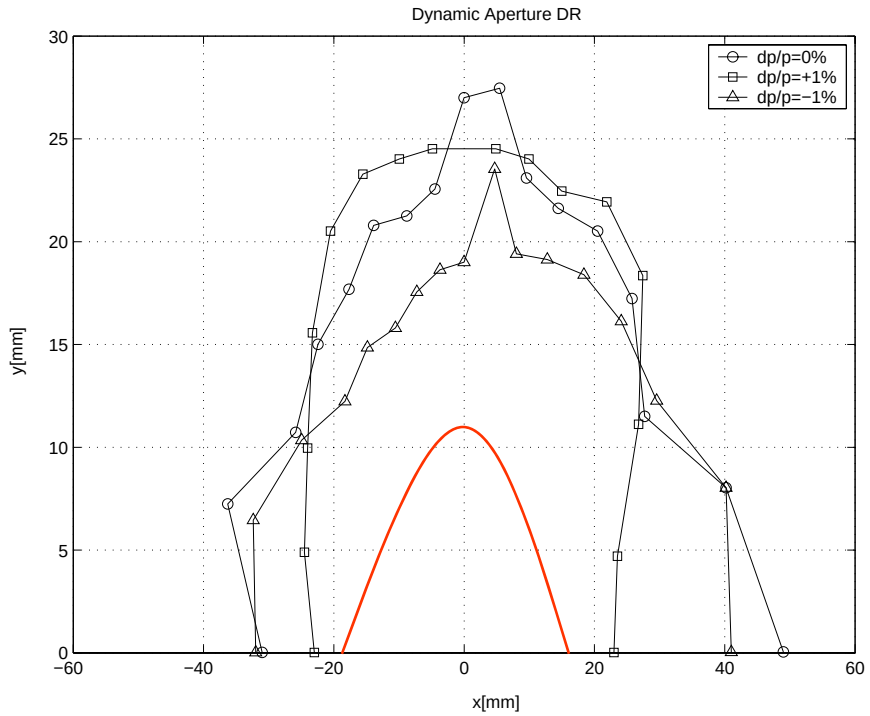
	Dipole (1×10^{-4})			Quadrupole (1×10^{-4})			Sextupole (1×10^{-4})		
Radius	30mm			30mm			30mm		
Error type	Sys	Ran	Φ (°)	Sys	Ran	Φ (°)	Sys	Ran	Φ (°)
1	0	0	0	0	0	0	0	0	0
2	0	1(3)	0	0	1(3)	0	0	0	0
3	1(3)	1	0	1	1	-80	0	10(20)	0
4	0	1	0	1	1	150	1	3	-85
5	1(3)	1	0	1	1	80	1	1	-130
6	0	1	0	1	1	0	1	1	-15
7	1(3)	1	0	1	1	180	1	1	66
8	0	0	0	1	1	5	1	1	203
9	0	0	0	1	1	75	1	1	1
10	0	0	0	1	1	180	1	1	-116
11	0	0	0	1	1	10	1	1	46
12	0	0	0	1	1	180	1	1	84
13	0	0	0	1	1	110	1	1	-291
14	0	0	0	1	1	25	1	1	-10
15	0	0	0	1	1	0	1	1	-182
16	0	0	0	1	1	0	1	1	0

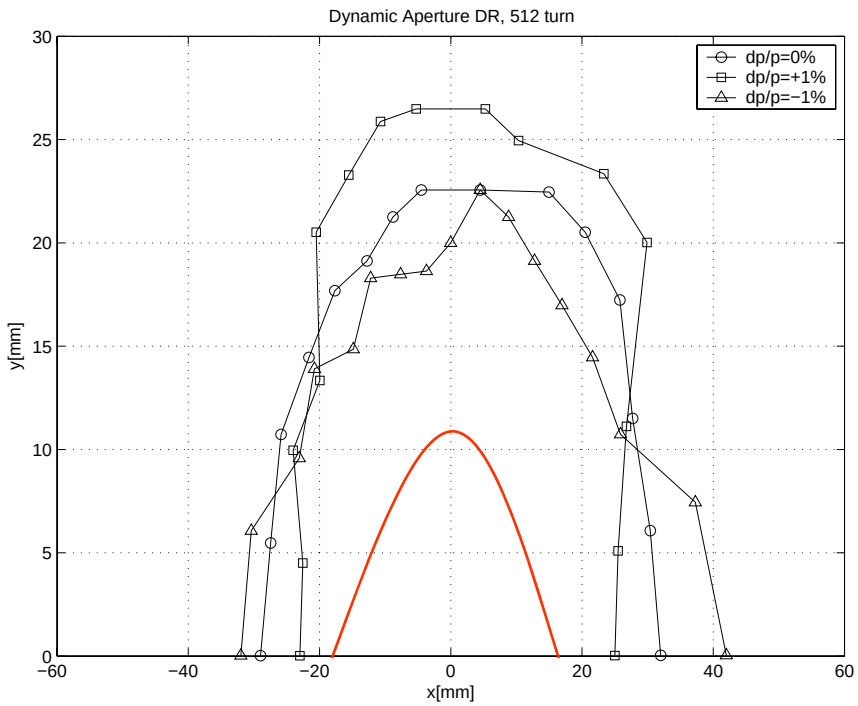
* Sys: system error; Ran: random error

MISALIGNMENT ERRORS

Element	Δx (mm)	Δy (mm)	Δz (mm)	$\Delta\theta_x$ (mrad)	$\Delta\theta_y$ (mrad)	$\Delta\theta_z$ (mrad)
Dipole	0.1	0.1	0.1	0.2	0.2	0.2
Quadrupole	0.1	0.1	0.1	0.2	0.2	0.2
Sextupole	0.1	0.1	0.1	0.2	0.2	0.2

DYNAMIC APERTURE WITH ERRORS

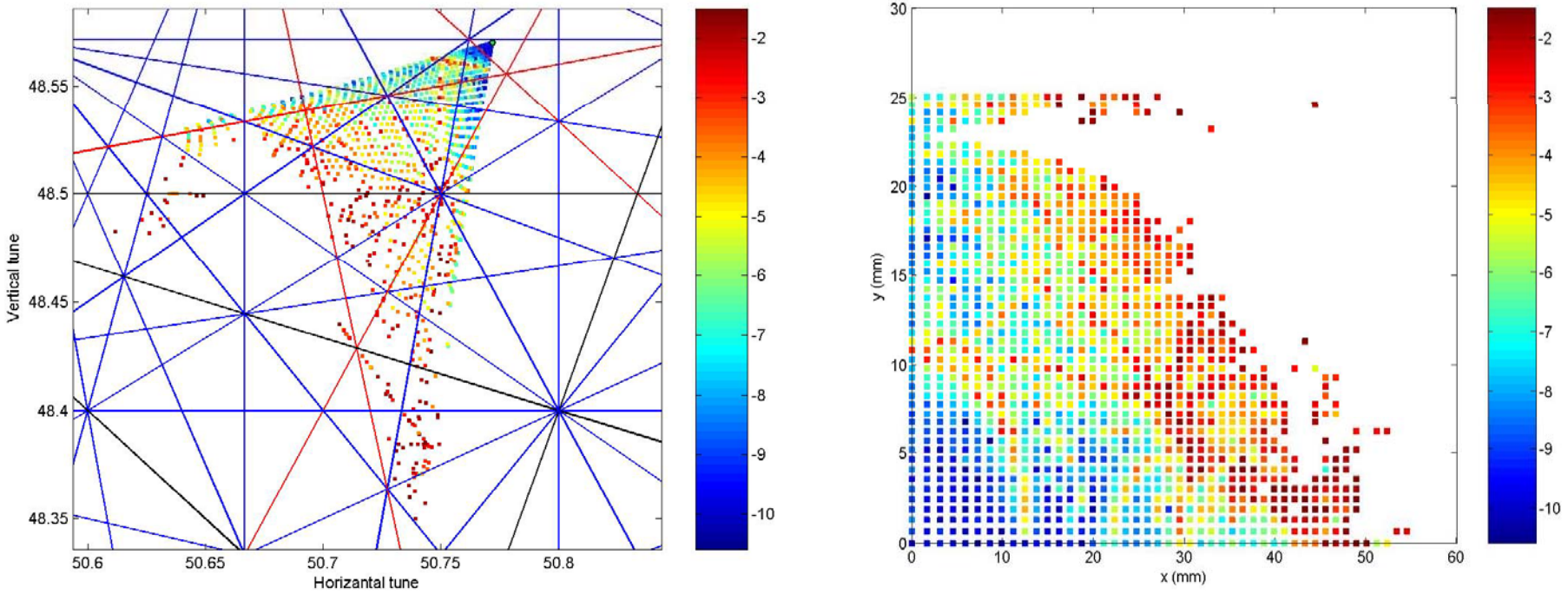




Left: only with high-order magnets errors; Right: with both high-order magnets errors and misalignment errors. 12 seeds averaged.

With the same injection beam size as OCS. The red line is **3** times injected positron bunch size.

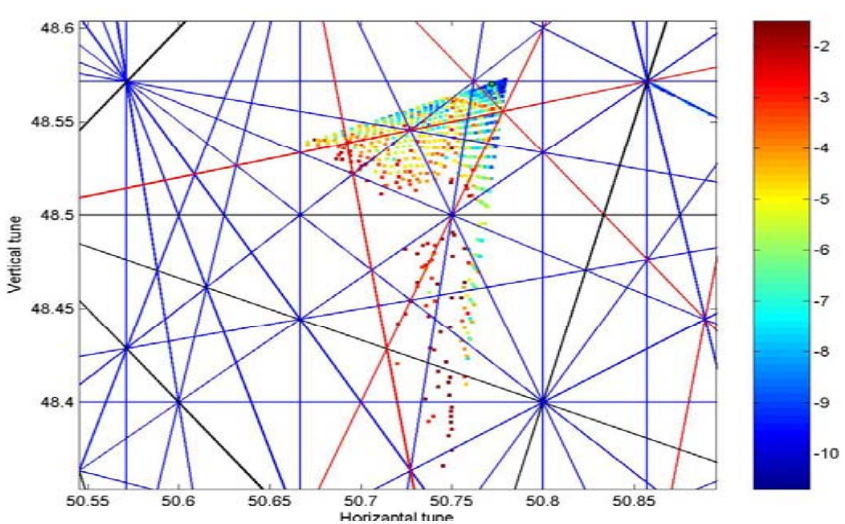
FREQUENCY MAP ANALYSIS (ON MOMENTUM)

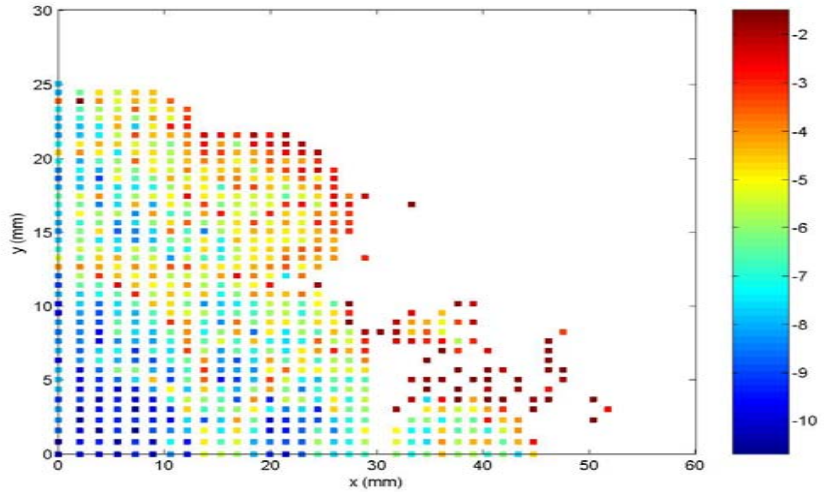


FMA analysis for on momentum particles: (Left) footprint; (Right) Dynamic aperture with FMA.

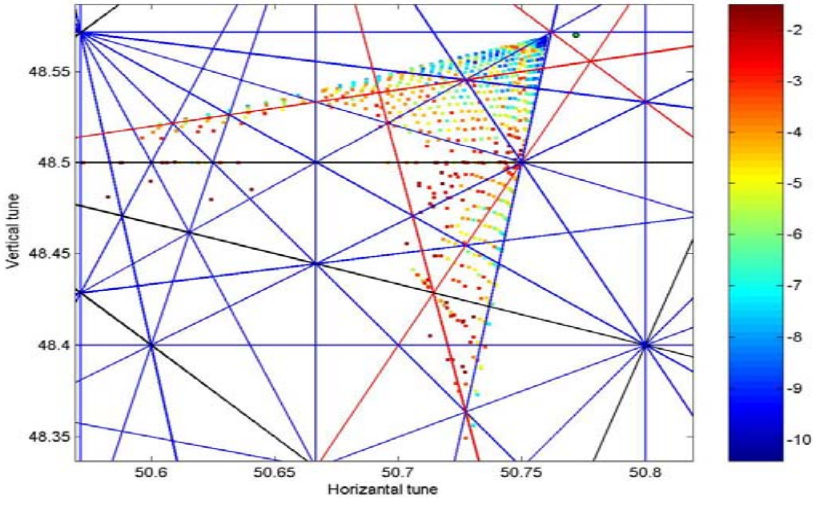
2500 particles distributed in the range of seven times the injected bunch size are tracked for 1024 turns.

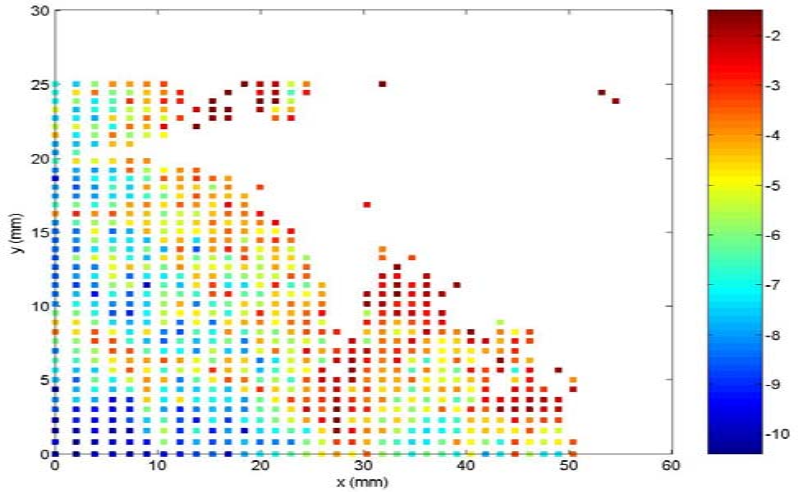
FREQUENCY MAP ANALYSIS (OFF MOMENTUM)





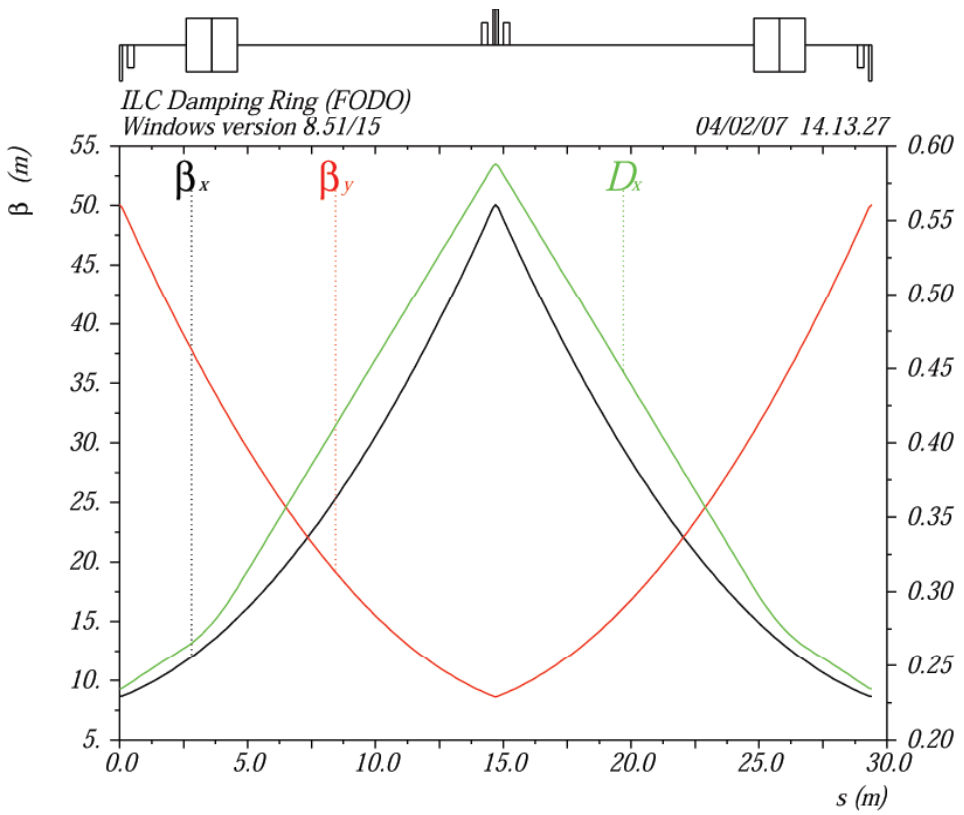
$\triangle p/p = 0.01$

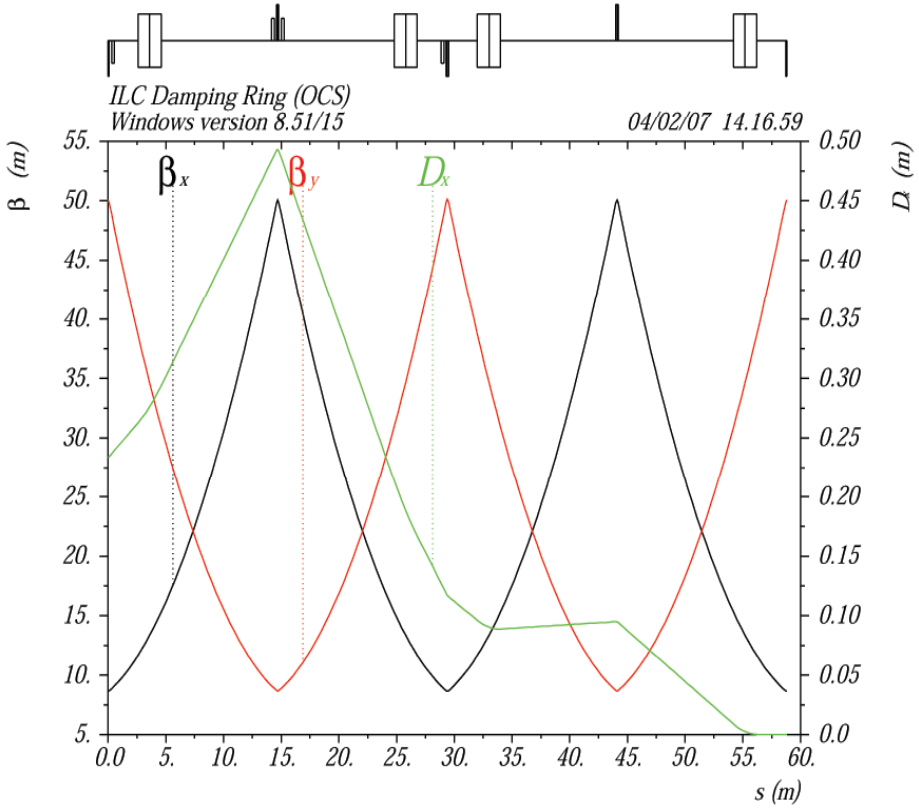




$\triangle p/p = -0.01$

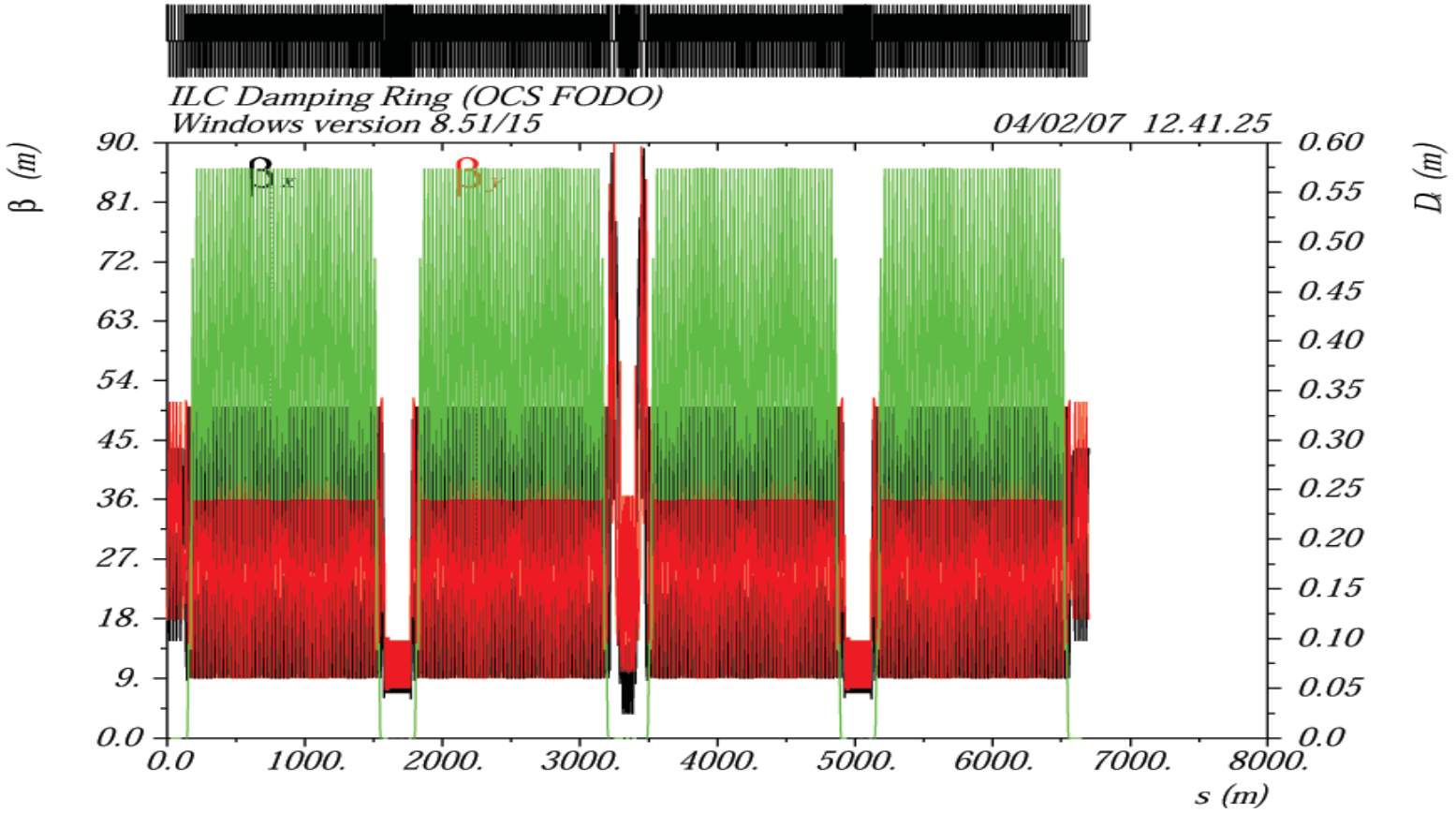
LOW ALPHA LATTICE (1)





The phase advance is adjusted from 72/72 to 90/90.

LOW ALPHA LATTICE (2)

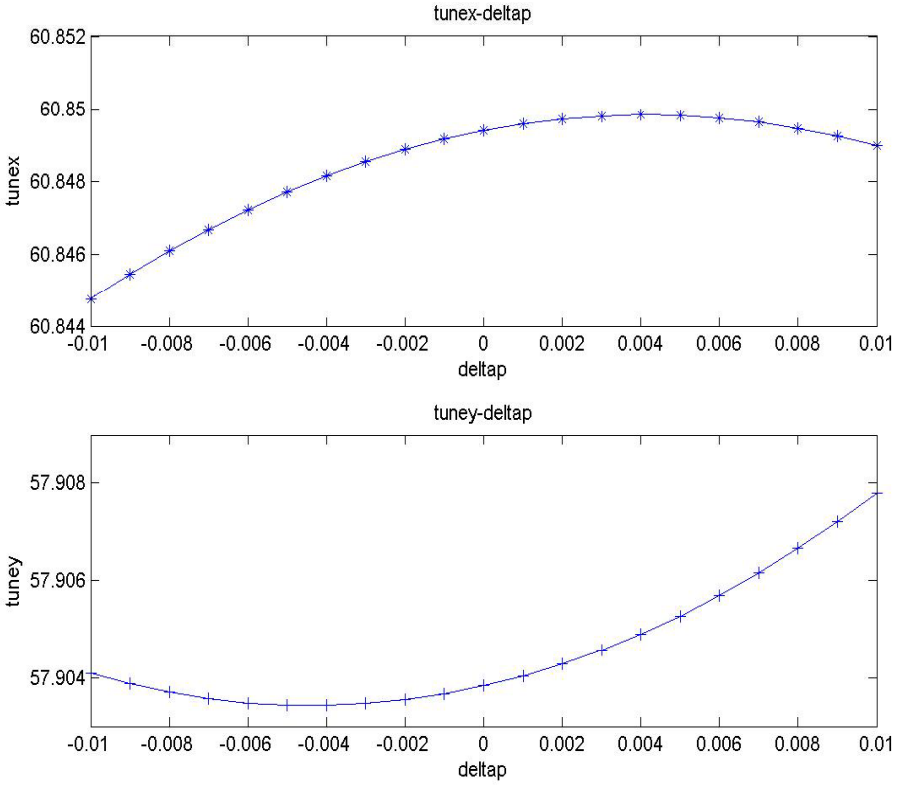


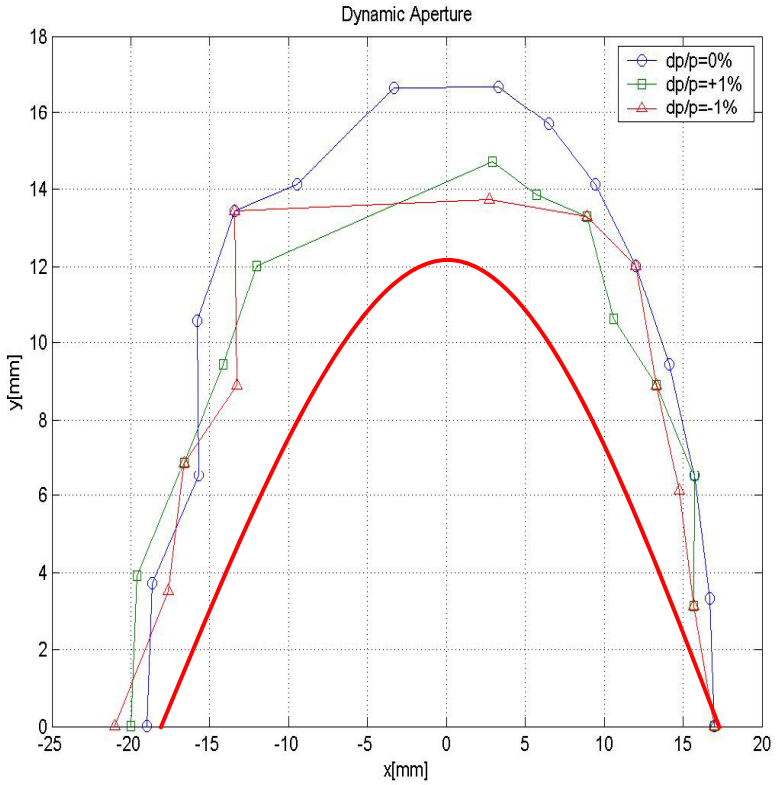
Adjusted the quadrupole strength in the match sections. There are 184 arc cells in all, maintain the circumference of 6695.057 m.

LOW ALPHA LATTICE (3)

Circumference [m]	**6695**
Harmonic number	14516
Energy [GeV]	5
Arc cell	**FODO**
Tune	60.85 / 57.9
Natural chromaticity	-74 / -75
Momentum compaction [10^{-4}]	**2.3**
Transverse damping time [ms]	25 / 25
Norm. Natural emittance [μm-rad]	3.3
RF voltage [MV]	**15**
Synchrotron tune	0.038
Synchrotron phase [^{o}]	144.7
RF frequency [MHz]	650
RF acceptance [%]	1.168
Natural bunch length [mm]	**9.2**
Natural energy spread [10^{-3}]	1.28

LOW ALPHA LATTICE (4)

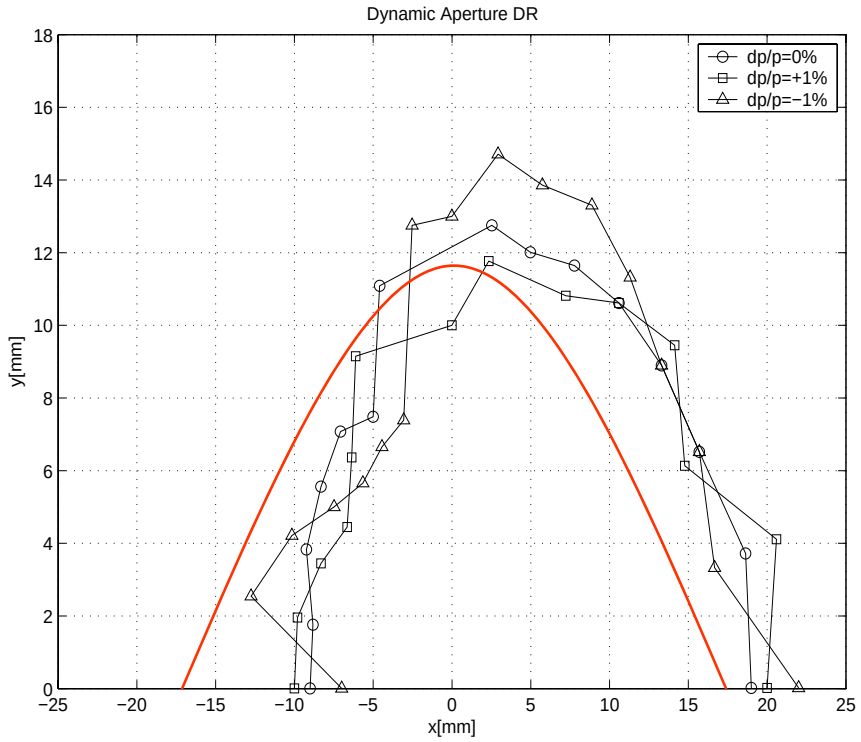


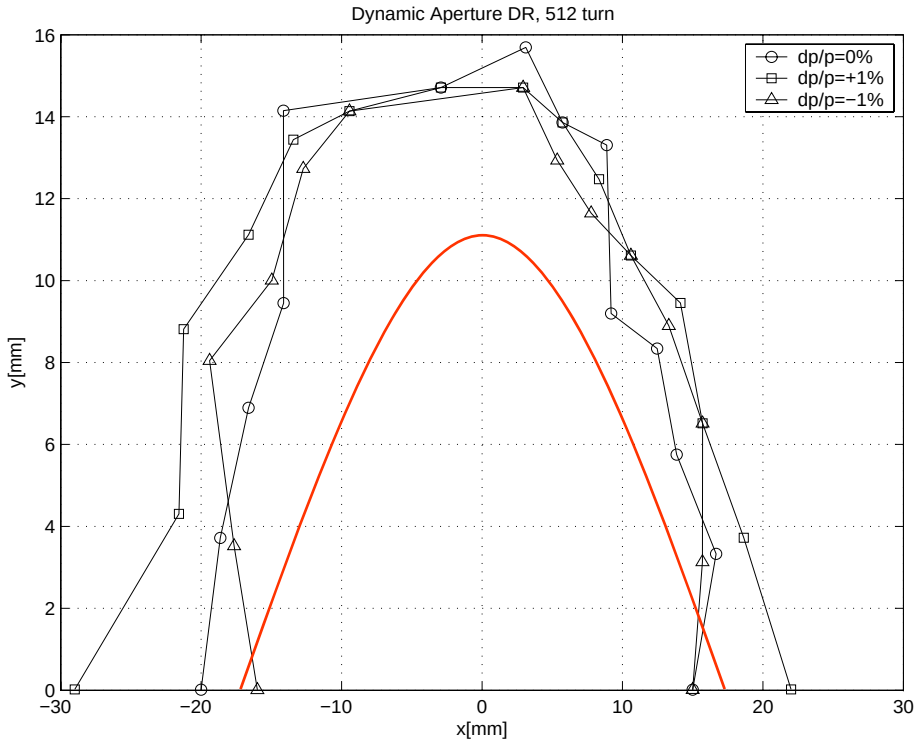


The chromaticity corrected to (0.15,0.15). The tune variation with momentum spread ±1% ; the dynamic aperture with momentum spread up to ±1% (with RF cavity, no errors).

With the same injection beam size as OCS. The red line is **3** times injected positron bunch size.

DYNAMIC APERTURE WITH ERRORS

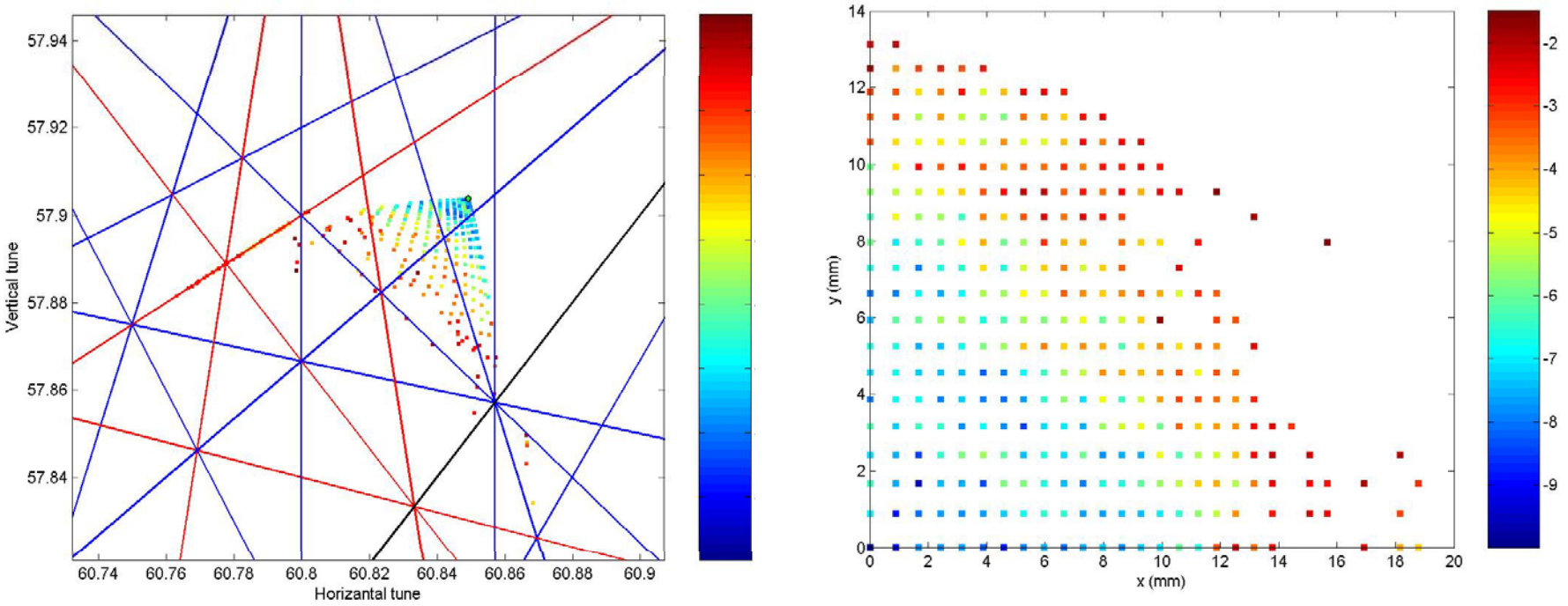




Left: with smaller high-order magnets errors and misalignment errors;
Right: with larger high-order magnets errors. 5 seeds averaged.

With the same injection beam size as OCS. The red line is **3** times injected positron bunch size.

LOW ALPHA LATTICE (5)



FMA for on-momentum particles.

2500 particles distributed in the range of seven times the injected bunch size are tracked for 1024 turns.

SOME CONCLUSIONS

- ILC DR alternative lattice design has been done with 72/72 degree FODO arc cells, with $\alpha_P = 4 \times 10^{-4}$.
  - The number of quadrupoles in the whole ring has been decreased by a factor of one third.
  - The number of access shafts needed to supply power, cryogenics etc. for the wigglers and other systems, is decreased from 4 to 2.
  - The circumference, the equilibrium emittance, the bunch length, the acceptance, the dynamic aperture without and with errors, and the damping time can fulfill the requirements for the ILC damping ring.
- Adjust the arc cell phase advance to 90/90 for $\alpha_P = 2 \times 10^{-4}$. The whole lattice is not changed. Just change the quadrupole strength in arc cell and matching sections.
- The lattice can be tuned with alpha between 2×10^{-4} and 6×10^{-4}, by only changing the power supply of the quadrupoles.

WORK IN THE NEXT STEP

- Optimize the dynamic aperture further, to be larger than 3 times injected positron bunch size in the case with momentum compaction between 2×10^{-4} and 6×10^{-4}.
- Consider the technical issues about the synchrotron radiation power on wigglers (as the wiggler section number is decreased from 4 to 2).

ACKNOWLEDGEMENT

Thanks to other colleague in ANL et al. who designed the injection/extraction and RF/wiggler sections.

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Thanks for your attention.