New layout for alternative ring and wiggler magnet considerations of SPS

20th FCC-e^+e^- Injector Meeting

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Thank you to Fanouria Antoniou for her help on this study.

Outline

For alternative design:

- After FCC week, **new layout study**
- **Phase advance scanning** for optimum selection,
- **Optics functions** and general **parameters**,
- First calculations for DA.

For SPS:

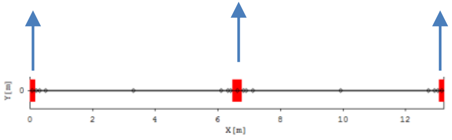
- **Robinson wiggler** for SPS to reduce the emittance.

New Layout

Straight sections:

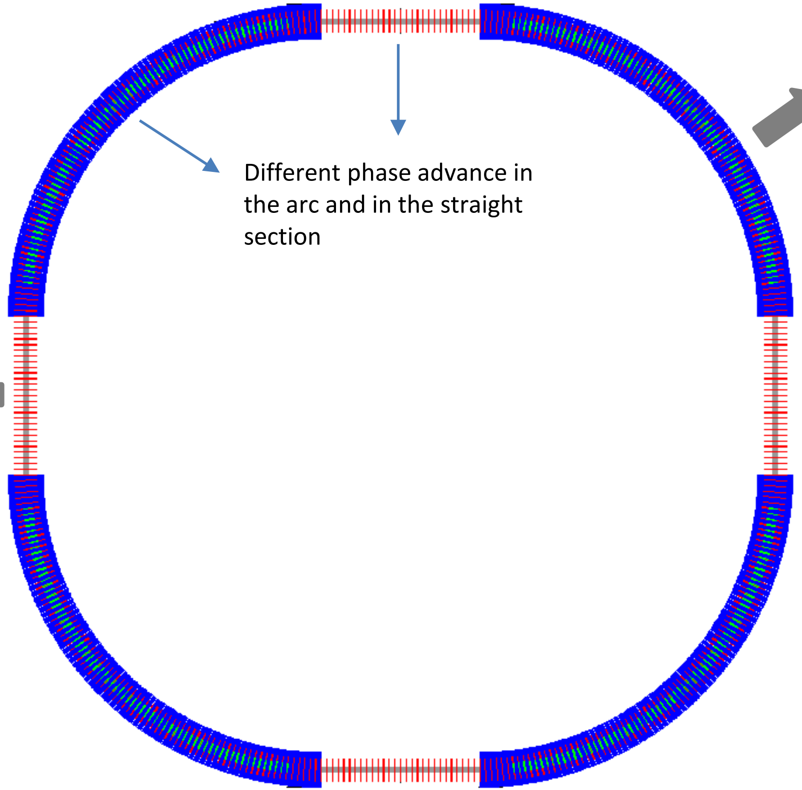
- 4 straight sections now instead of 2,
  - 2 for injection&extraction of electron and positron.
  - 1 for RF.
  - 1 for wiggler magnets.

qs2 qs1 qs2



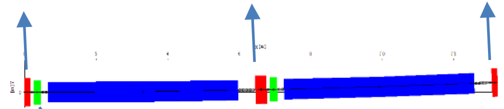
cell= 13.22 m

Straight section=10*cell



Different phase advance in the arc and in the straight section

q2 q1 q2



sx1 sx2

cell= 13.22 m

Arcs:

- 4 identical arcs,

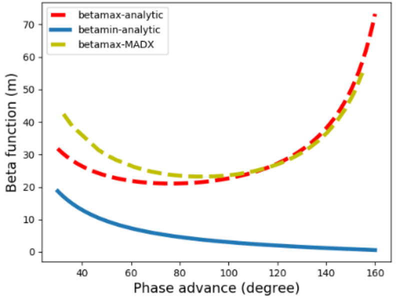
arc=35*cell + DS

- 2 families of sextupole in each cell in the arc (35 cell)

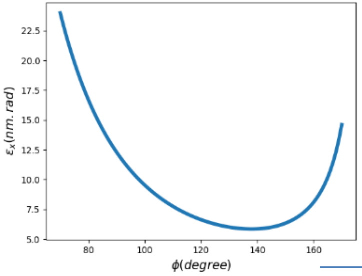
Blue: dipole magnet
Red: quadrupole magnet
Green: sextupole magnet

Layout and phase advances

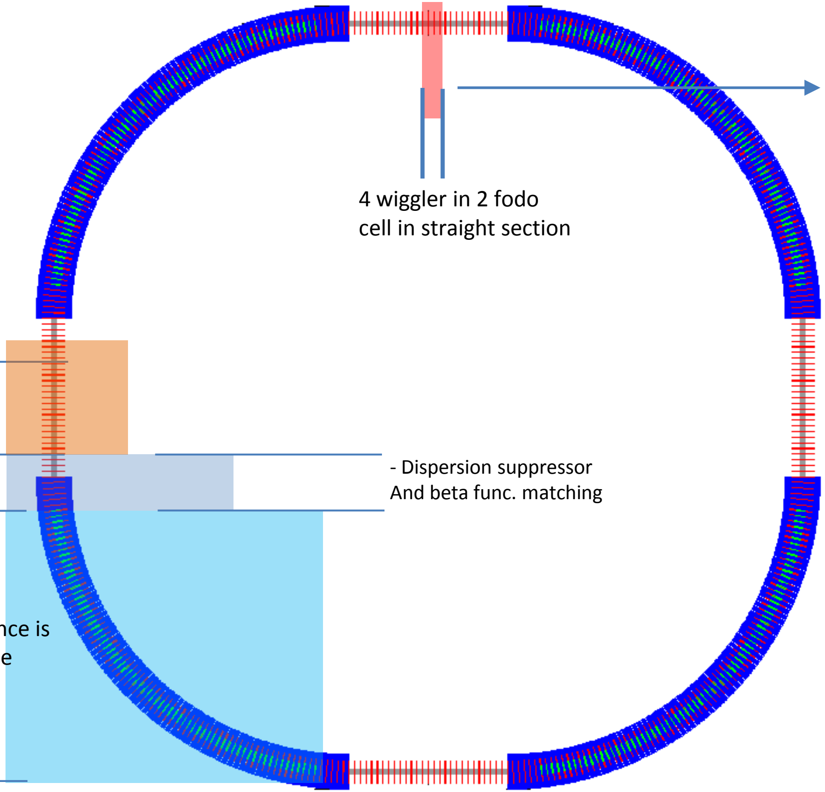
Different phase advances are chosen in the straight section and in the arcs. Wiggler magnets are located in one of the straight sections.



Straight section
10 (TBD) FODO cell
with close to 90 degree PA



Phase advance is
137.8 degree



4 wiggler in 2 fodo
cell in straight section

- Dispersion suppressor
And beta func. matching

Analytical calculation

$$\tau_x = \frac{3.E_0}{2\pi r_0 c^2} \frac{C}{B\gamma^2(J_x + F_w)}$$

τ_x = 0.281 s without wiggler @ 6 GeV
τ_x = 0.101 s with wiggler @ 6 GeV
$B_w = 2\,T$,
l_w= 8.1 m in total

MAD-X results

τ_x = 0.096 s
ε_x = 4.89 nm.rad (5.66 nm.rad Wout W)

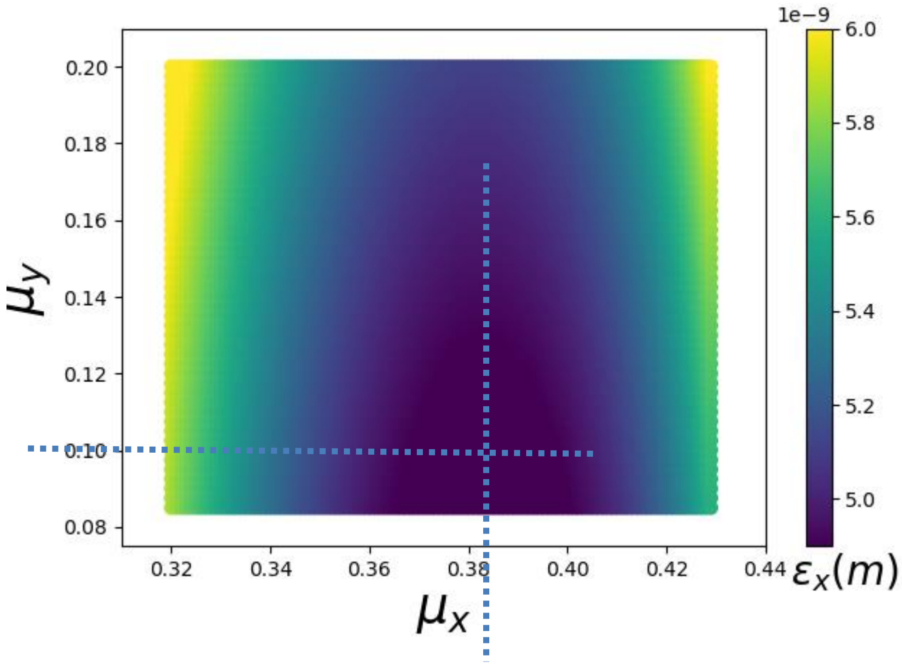
2 FODO with wiggler magnet is used to reduce the damping time at injection energy.

Same wiggler structure with CLIC DR:
$B_w = 2\,T$
$\lambda_w = 0.05\,m$
$l_w = 2.025\,m$ x 4 wiggler = 8.1 m in total

Blue: dipole magnet
Red: quadrupole magnet
Green: sextupole magnet

Phase advance in the arc

h/v emittance is mainly determined by arcs in the ring. Thus, FODO phase advance in the arc is scanned to observe the behavior of some important parameters like emittance, chromaticity, tune shift with amplitude, momentum compaction factor etc.

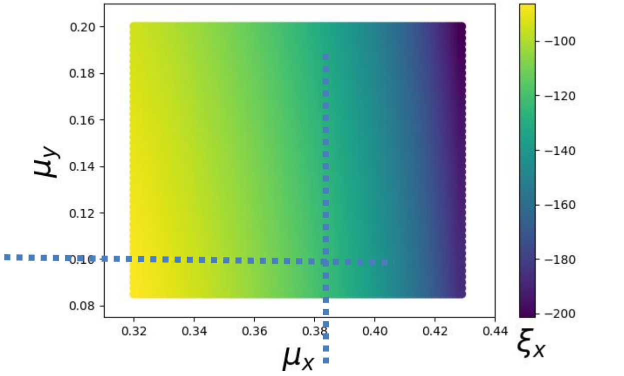


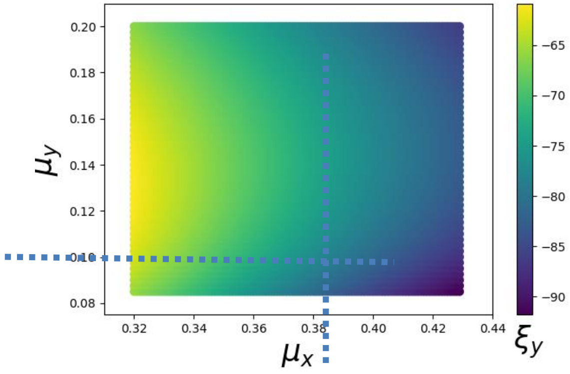
~137.8 degree

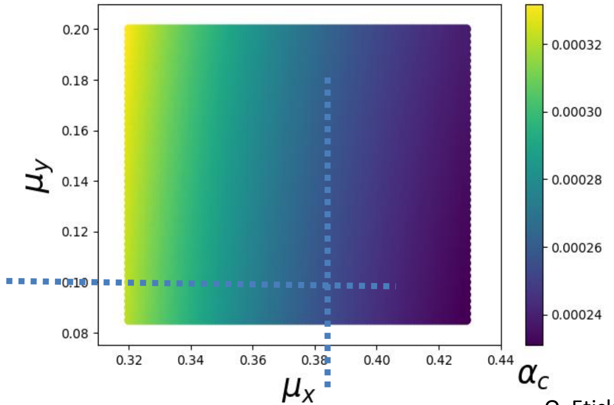
- Minimum emittance can be obtained with the horizontal phase advance ~ 0.383.
- Emittance is getting higher slightly while the vertical phase is getting higher.
- With the experience from CLIC damping ring, 0.1 is chosen for the vertical phase.

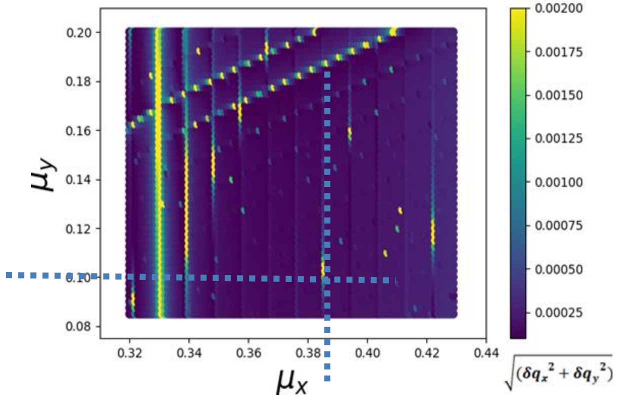
Phase advance in the arc

h/v emittance is mainly determined by arcs in the ring. Thus, FODO phase advance in the arc is scanned to observe the behavior of some important parameters like emittance, chromaticity, tune shift with amplitude, momentum compaction factor etc



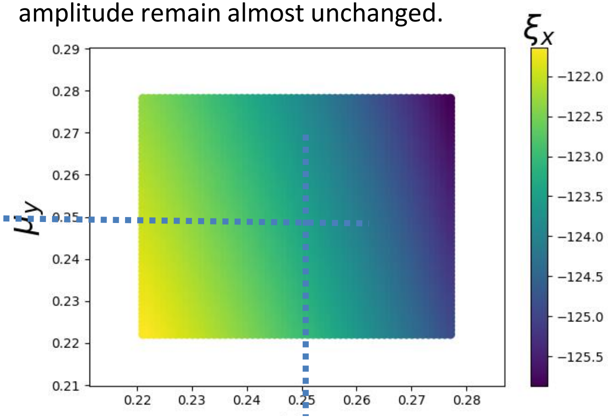


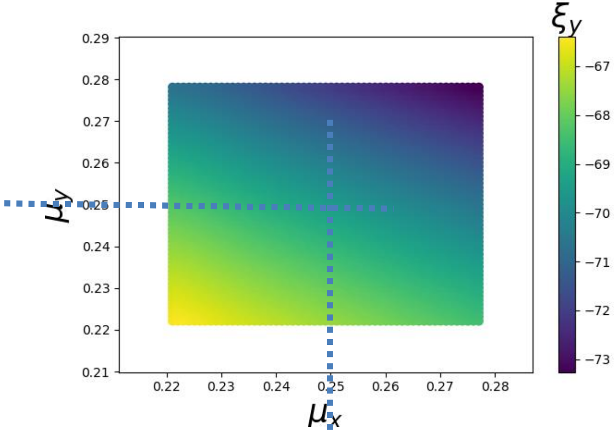


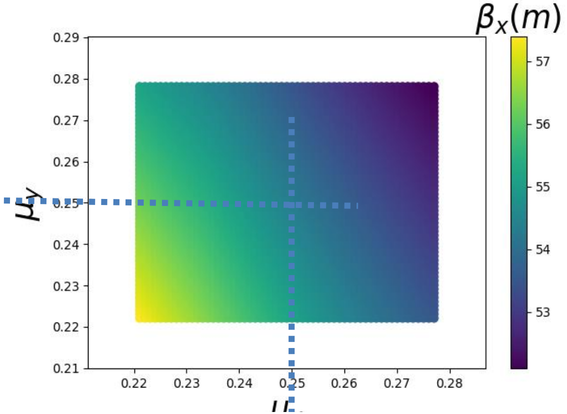


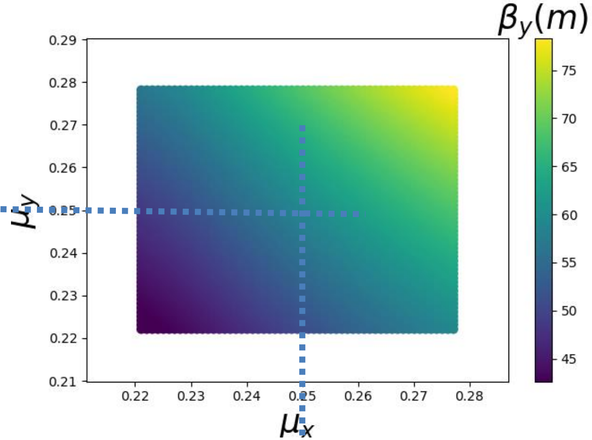
Phase advance in the straight section

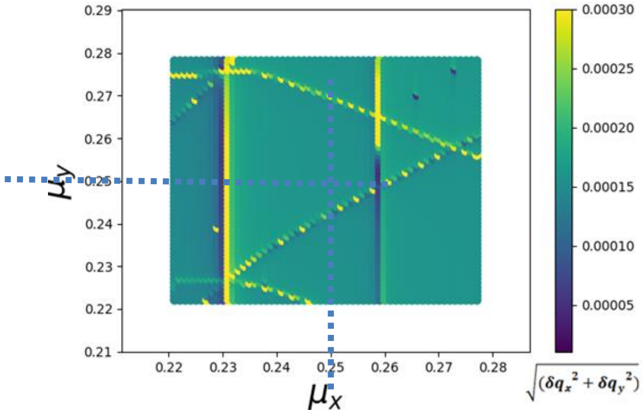
Having close to 90 degree phase advance in the straight section provides small beta functions and efficient injection/extraction scheme. But still, phase advance scanning can be done for 80-100 degree; exact phase advance to be decided for working point selection. As expected, emittance, chromaticity, tune shift with amplitude remain almost unchanged.

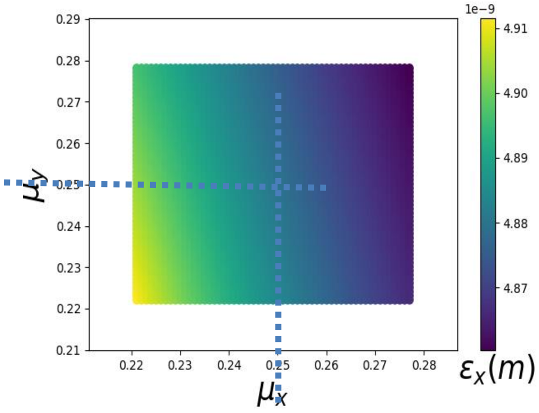




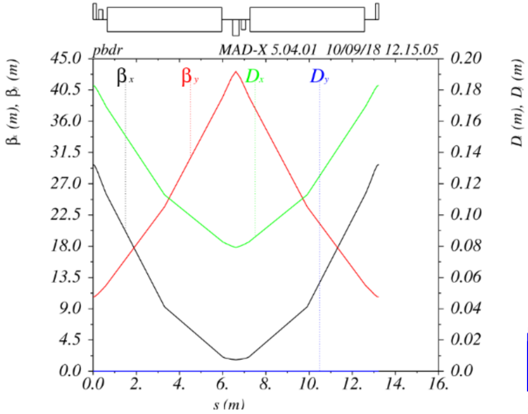


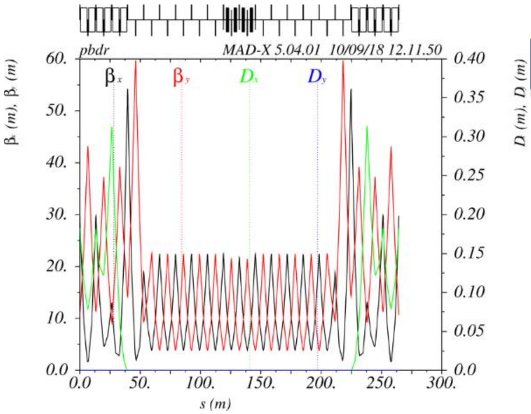


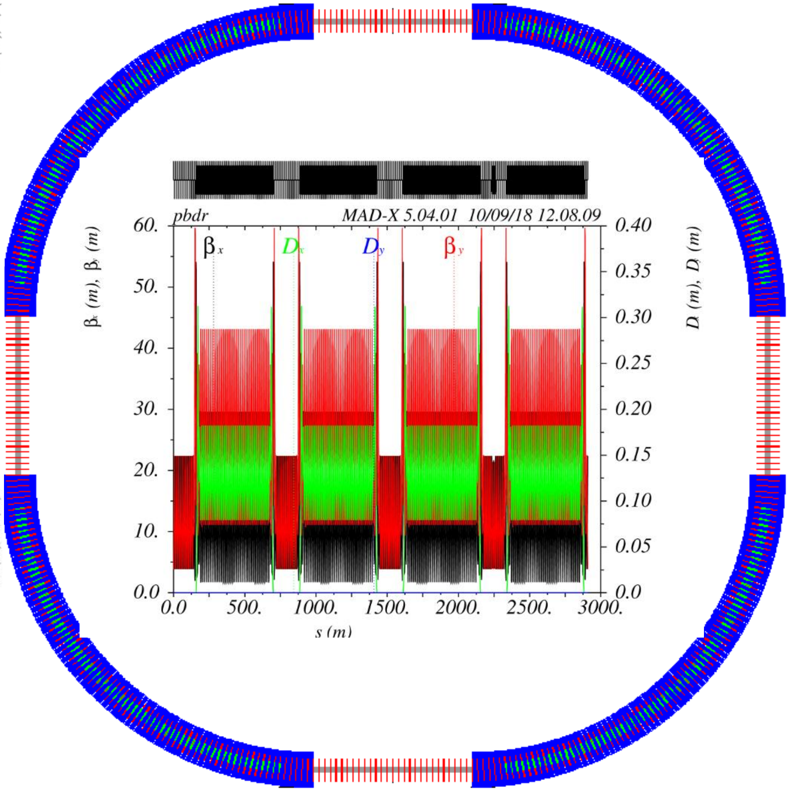


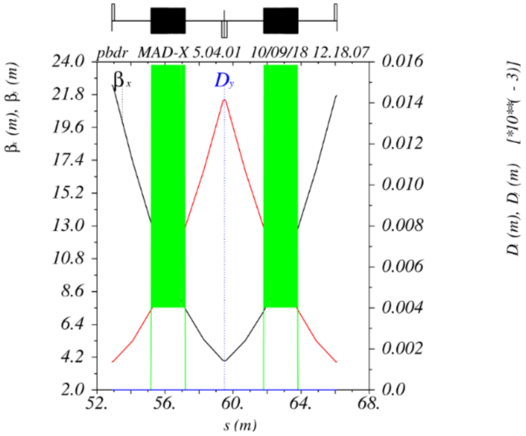


Optic functions and general parameters (0.25/0.25 at straight section)



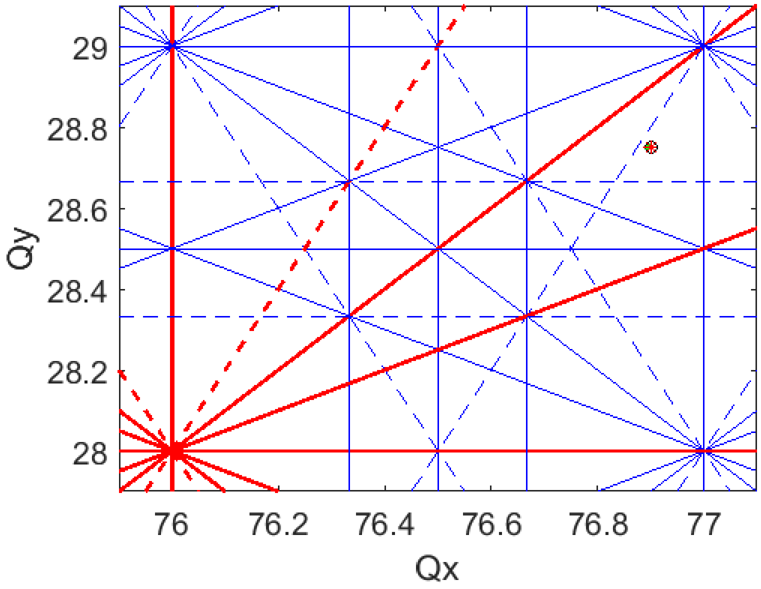


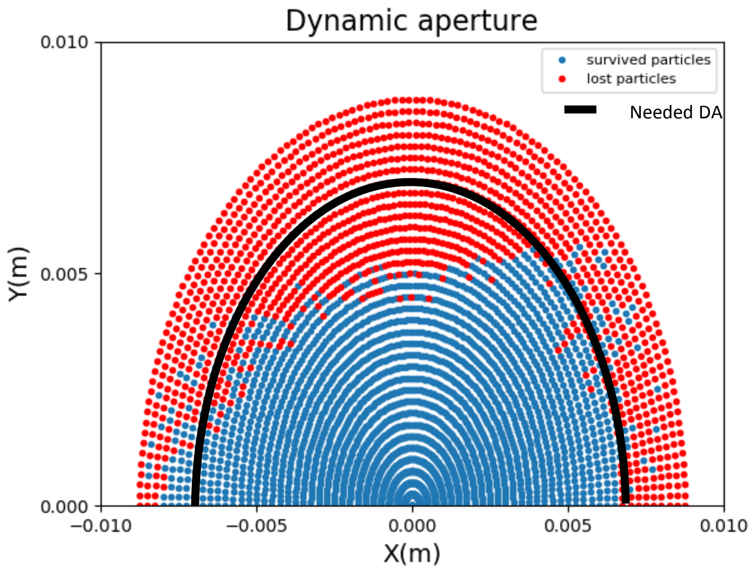




Parameters	Values	
Energy [GeV]	20	6
Circumference [m]	2908	
Emittance [nm.rad]	4.88	0.19
Energy loss / turn [MeV]	57.8	1.12
Natural h/v chromaticity	-123/-69	
Horizontal Damping times [ms]	0.006	0.096

Tune Shift and Dynamic Aperture (0.25/0.25 at straight section)



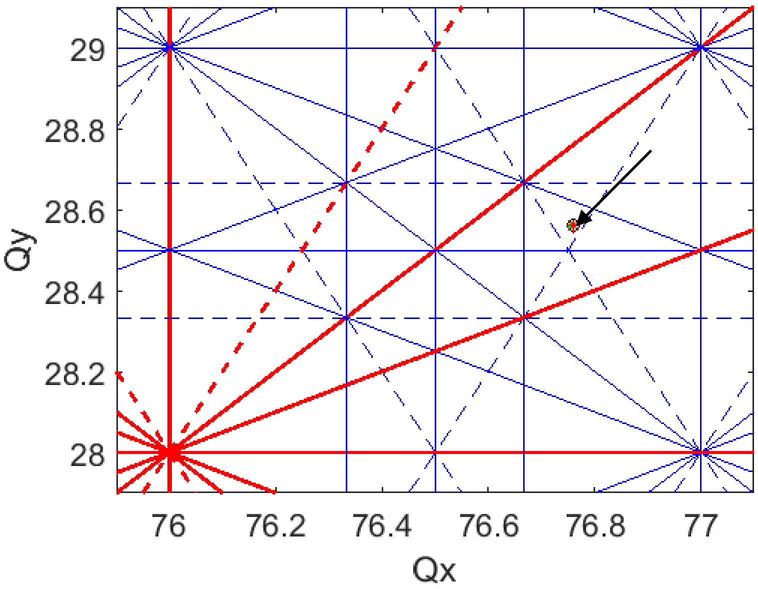


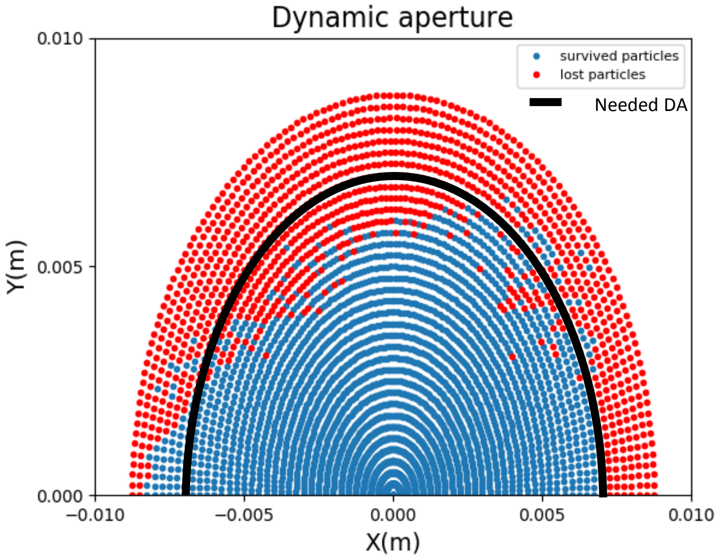
<u>First, I checked the ideal phase advance for straight section</u>

Phase advances is chosen to be (μ_x, μ_y) = (0.25/2π, 0.25/2π) for the straight section, corresponding to a tune working point of (Q_x, Q_y) = (76.90, 28.75) for the ring.

Dynamic aperture simulations were undertaken, the horizontal versus vertical DA for different momentum deviations using MADX-PTC.

Tune Shift and Dynamic Aperture (2)



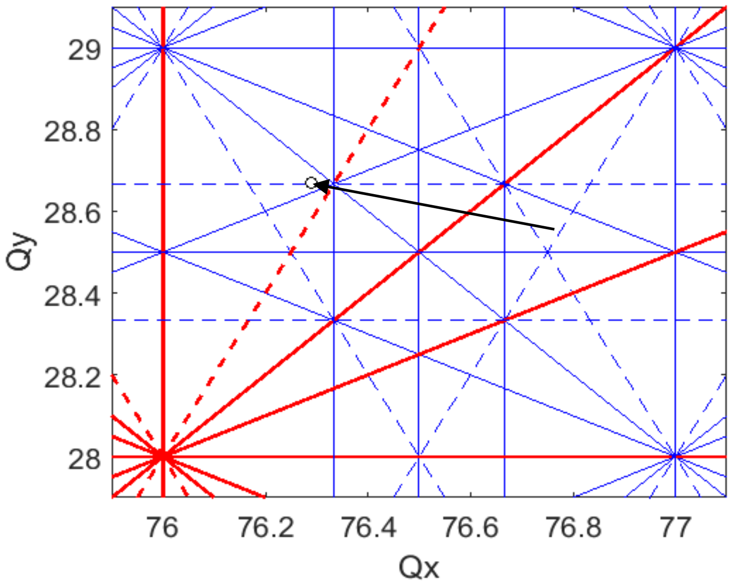


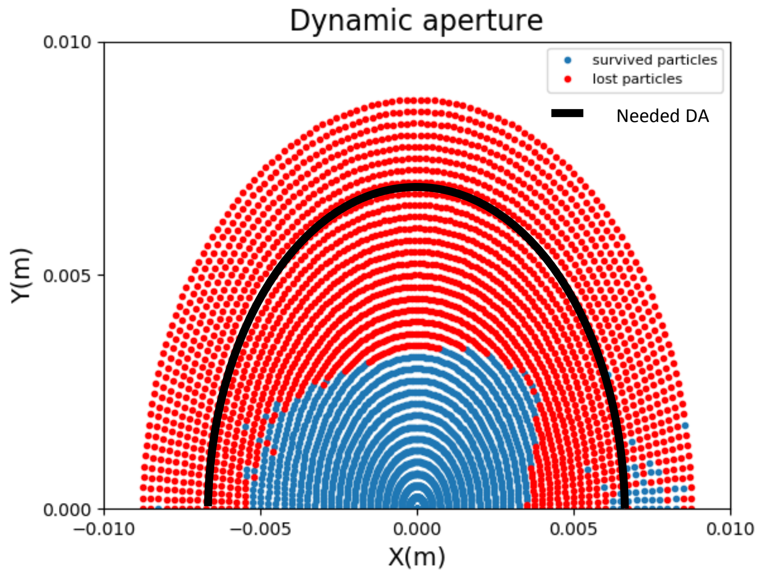
<u>And then, I moved the WP to have better DA.</u>

Phase advances is chosen to be **(μ_x, μ_y) = (0.247/2π, 0.245/2π)** for the straight section, corresponding to a tune working point of (Q_x, Q_y) = (76.76, 28.56) for the ring.

Dynamic aperture simulations were undertaken, the horizontal versus vertical DA for different momentum deviations using MADX-PTC.

Tune Shift and Dynamic Aperture (3)



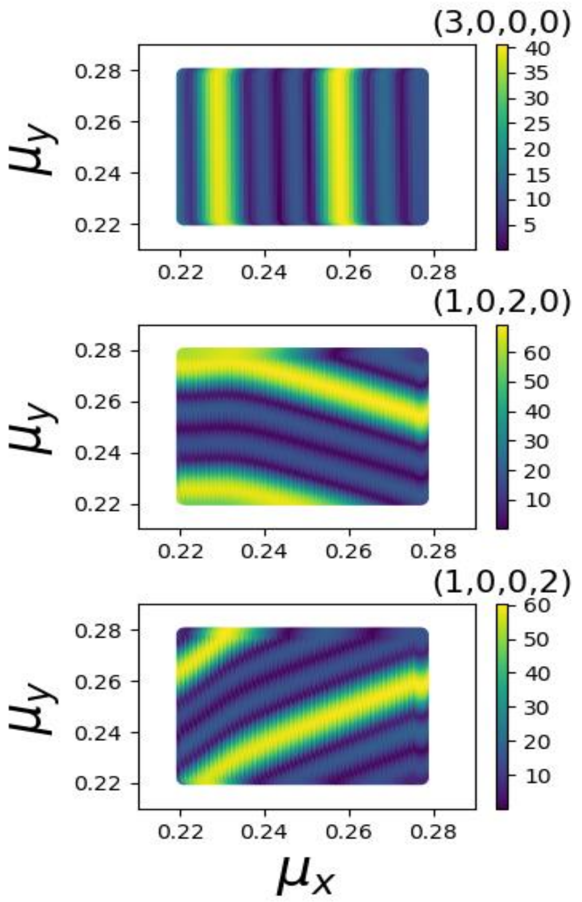


Phase advances is chosen to be **(μ_x, μ_y) = (0.237/2π, 0.246/2π)** for the straight section, corresponding to a tune working point of (Q_x, Q_y) = (76.29, 28.67) for the ring.

Dynamic aperture simulations were undertaken, the horizontal versus vertical DA for different momentum deviations using MADX-PTC.

This was an unexpected DA and it gave the idea to check out the higher order resonances.

Resonance driving terms

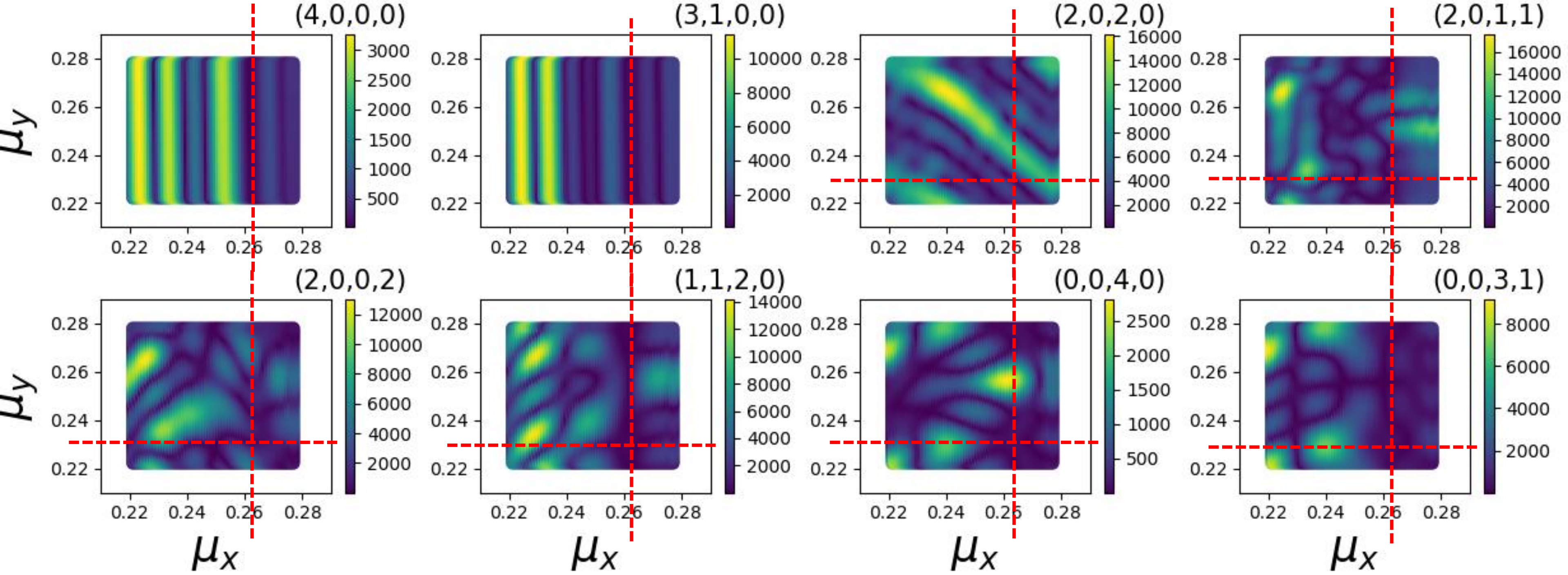


Figures shows the dependence of the third order resonance driving terms on the horizontal and vertical phase advances of a FODO cell.

Comparing to the 5 Hamiltonian modes, the (1,0,1,1) mode is excited at low horizontal phase advance.

The non-linear coupling terms (1,0,2,0) mode is excited at low and high vertical phase advance.
And for (1,0,0,2) suppressed area could be selected with horizontal and vertical phase advances.

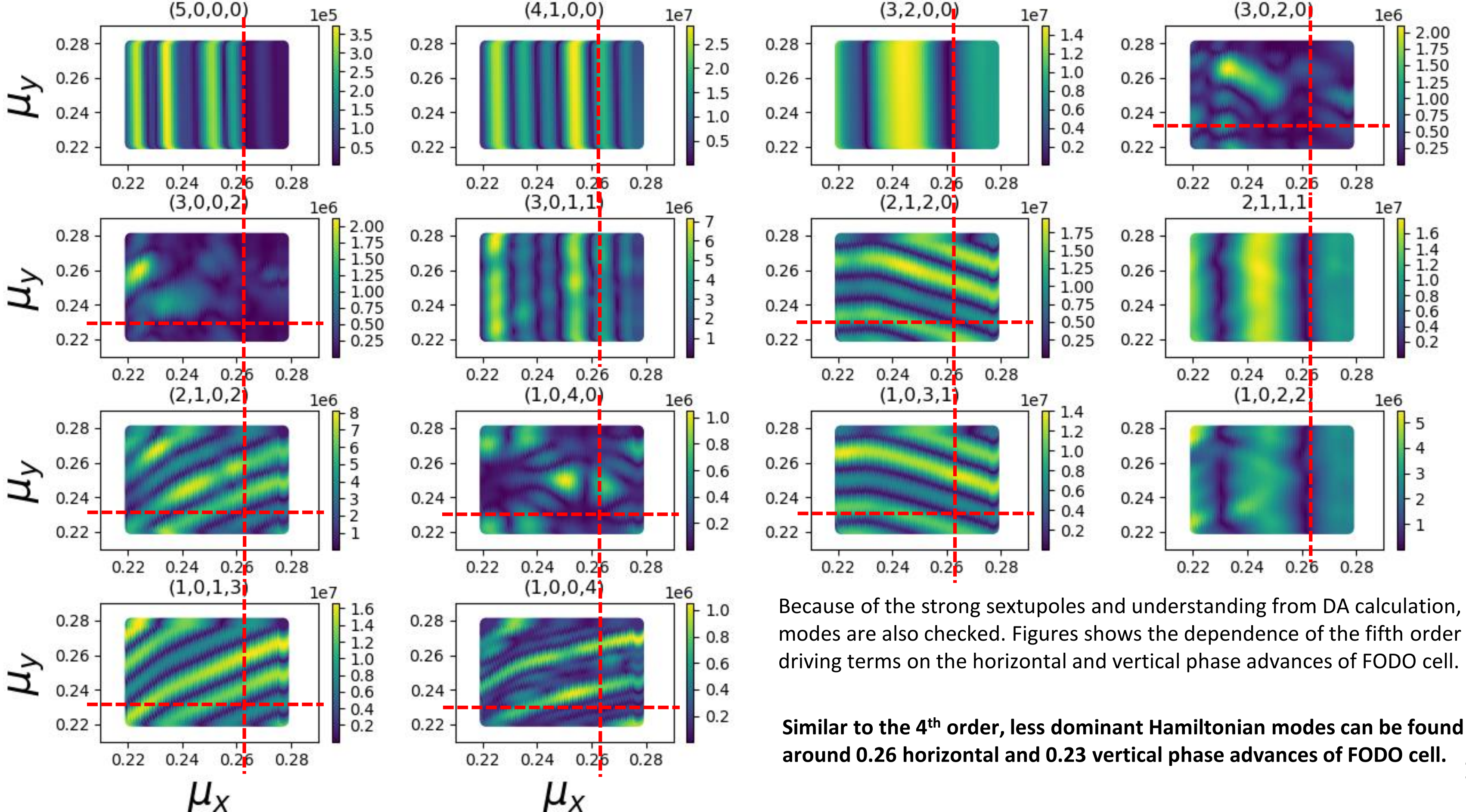
Resonance driving terms



Because of the strong sextupoles and understanding from DA calculation, higher modes are also checked. Figures shows the dependence of the fourth order resonance driving terms on the horizontal and vertical phase advances of FODO cell.

Hamiltonian modes can be suppressed with around 0.26 horizontal and 0.23 vertical phase advances of FODO cell.

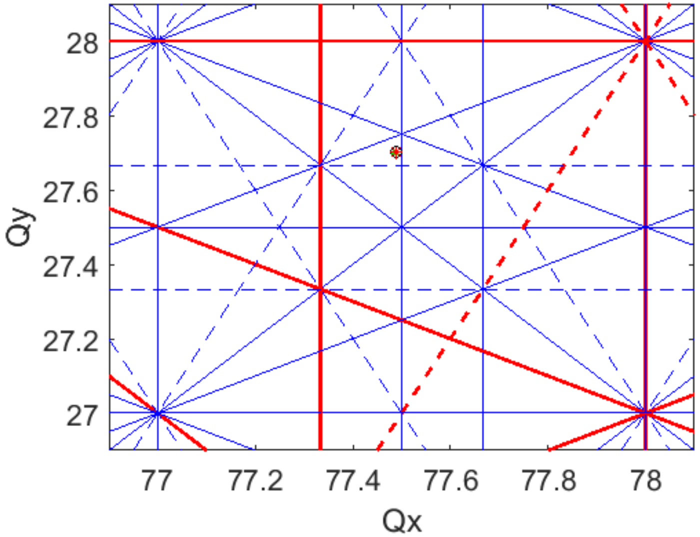
Resonance driving terms



Because of the strong sextupoles and understanding from DA calculation, higher modes are also checked. Figures shows the dependence of the fifth order resonance driving terms on the horizontal and vertical phase advances of FODO cell.

Similar to the 4th order, less dominant Hamiltonian modes can be found with around 0.26 horizontal and 0.23 vertical phase advances of FODO cell.

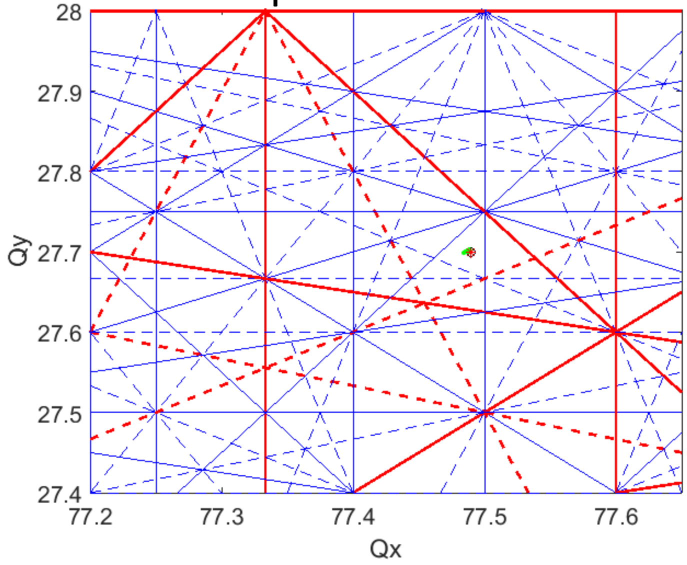
Up to 3rd order

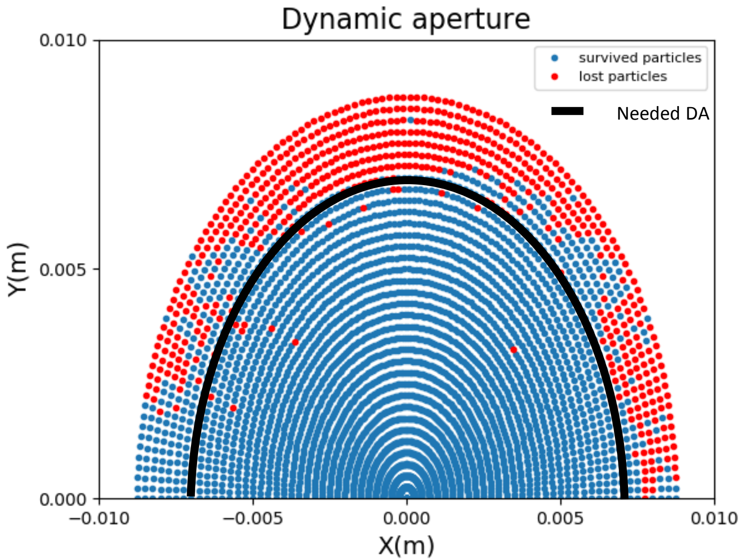


An optimal choice of phase advances is chosen to be **(μ_x, μ_y) = (0.263/2π, 0.225/2π)** for the straight section, corresponding to a tune working point of (Q_x, Q_y) = (77.49, 27.70) for the ring.

Tune Shift and Dynamic Aperture (Alternative)

Up to 5th order





An optimal choice of phase advances is chosen to be **(μ_x, μ_y) = (0.263/2π, 0.225/2π)** for the straight section, corresponding to a tune working point of (Q_x, Q_y) = (77.49, 27.70) for the ring.

Dynamic aperture simulations were undertaken, the horizontal versus vertical DA for different momentum deviations using MADX-PTC.

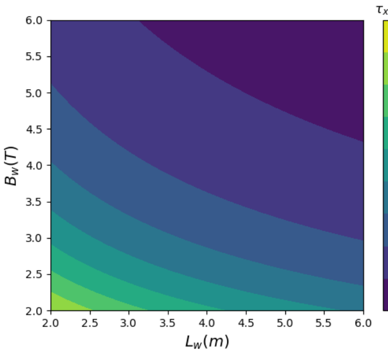
After the optimization by checking the resonance driving terms, we have better dynamic aperture. DA with errors should still be checked in the following days.

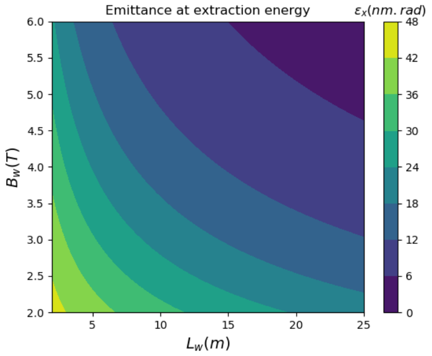
SPS (Reminder)

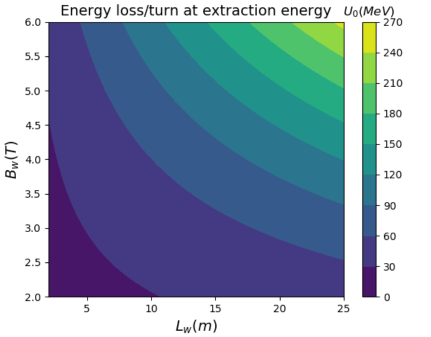
SPS Parameters * *phase advance is close to 135^0	
SPS Bending radius [m]	741.63
SPS injection energy [GeV]	6
SPS extraction energy [GeV]	20
Dipole length	6.26*4
Bending field @ injection [Gauss]	269.811
Bending field @ extraction [Gauss]	899.3703
Emittance @ injection (m.rad)	4.5×10^{-9}
Emittance @ extraction (m.rad)	51×10^{-9}
Energy Loss / turn @ injection [MeV]	0.154
Energy Loss / turn @ extraction [MeV]	19.094
Transverse Damping time @ injection [s]	1.79
Longitudinal Damping time @ injection [s]	0.894
Natural chromaticity h/v	-72/-40

Should be 0.1 s or less

Should be decreased to 5 nm.rad at least!







Parameter scaling are done for wiggler magnets in SPS to be able to determine the wiggler magnet characteristics to reduce the emittance to 5nm.rad.

Horizontal emittance, damping time and energy loss per turn are stated in the table with wiggler with the total length of 23 m and 5 T magnetic field.

	6 GeV		20 GeV	
	Wout W	With W	Wout W	With W
$\varepsilon_h\ (nm.rad)$	4.5	0.05	~50	~5
$\tau\ (s)$	1.7	0.02	0.005	0.002
$U_0(MeV)$	0.15	13.2	19	164

Can we find another solution to reduce this?

Robinson Wiggler for SPS

This is another option that we recently started to discuss after T. Tydecks' recommendation. Here, there are some first estimations for RW.

$J_x = 1 - \frac{I_4}{I_2}$, $J_y = 1$, $J_z = 2 + \frac{I_4}{I_2}$, $D = \frac{I_4}{I_2}$

$$\varepsilon_0 = c_q \gamma^2 \frac{I_5}{J_x I_2}$$

Emittance $\sim 1/(1-D)$

$$\sigma_\delta{}^2 = c_q \gamma^2 \frac{I_3}{J_z I_2}$$

Energy spread $\sim 1/(2+D)^{1/2}$

$$J_x \tau_x = J_y \tau_y = J_z \tau_z = 2\frac{E_0}{U_0} T_0$$

Damping time $\sim 1/(1-D)$

$$U_0 = \frac{C_\gamma}{2\pi} E^4 I_2,$$

Energy loss per turn $\sim I_2$

Synchrotron radiation integrals;

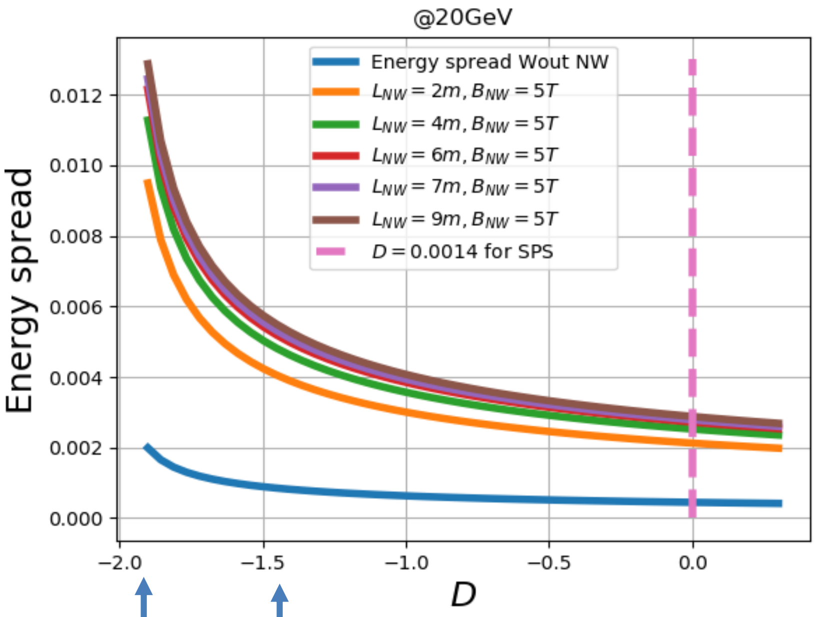
$$I_1 = \oint \frac{\eta_x}{\rho} ds \qquad I_4 = \oint \frac{\eta_x}{\rho^3}\left(\frac{1}{\rho^2} + 2k_1\right) ds$$

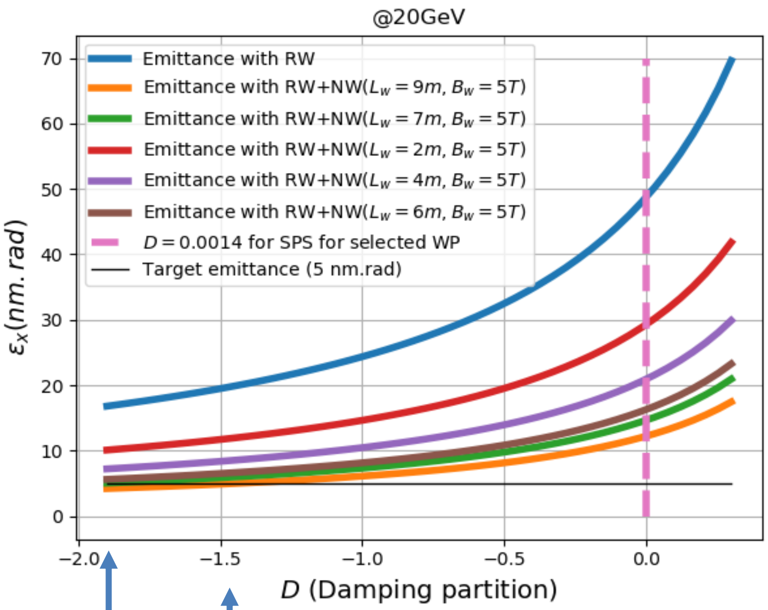
$$I_2 = \oint \frac{1}{\rho^2} ds \qquad I_5 = \oint \frac{\mathcal{H}_x}{\rho^3} ds$$

$$I_3 = \oint \frac{1}{\rho^3} ds$$

$$D = \frac{\rho_0 \eta_x}{\pi(\rho_0 B_0)^2} \left\langle B_w \frac{dB_{w,z}}{dx} \right\rangle L_w$$

Robinson Wiggler for SPS





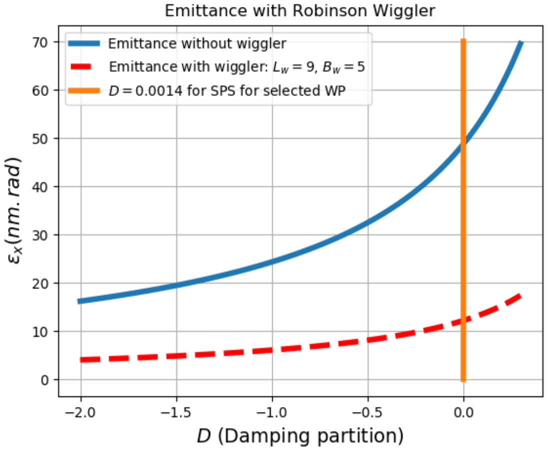
For D=-1.9
Energy spread~ %1

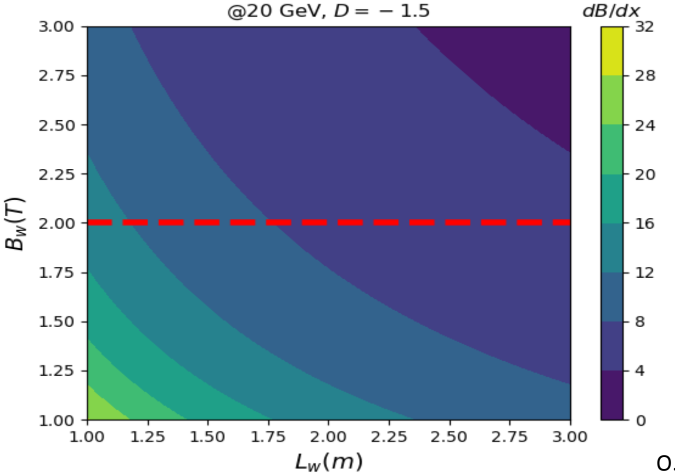
For D=-1.5
Energy spread~ %0.5

For D=-1.9
7 m normal wiggler for 5 nm.rad emittance

For D=-1.5
9 m normal wiggler for 5 nm.rad emittance

Robinson Wiggler for SPS





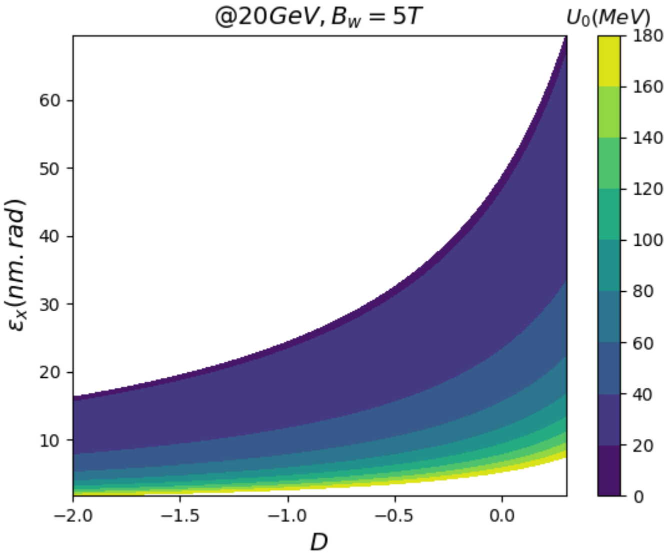
Since the emittance reduction is limited with only RW, we are working on a plan to include **both normal wigglers and Robinson wigglers** to the ring. Thus, the emittance can be reduced to 5 nm.rad from 50 nm.rad by keeping the energy loss per turn around 70 MeV. The left plot shows the D without RW, emittance without any wiggler, emittance with wiggler and emittance with RW.

$$D = \frac{\rho_0 \eta_x}{\pi (\rho_0 B_0)^2} \left\langle B_w \frac{dB_{w,z}}{dx} \right\rangle L_w$$

After first calculations, the emittance is estimated to reduce to 12 nm.rad from 50 nm.rad by using normal wiggler magnet with 9 m and 5 T, and it is reduced again to 5 nm.rad from 12 nm.rad by using 1-2 m, ~1 T Robinson wiggler.

Detail studies and simulations should still be done.

Energy Loss per Turn for SPS



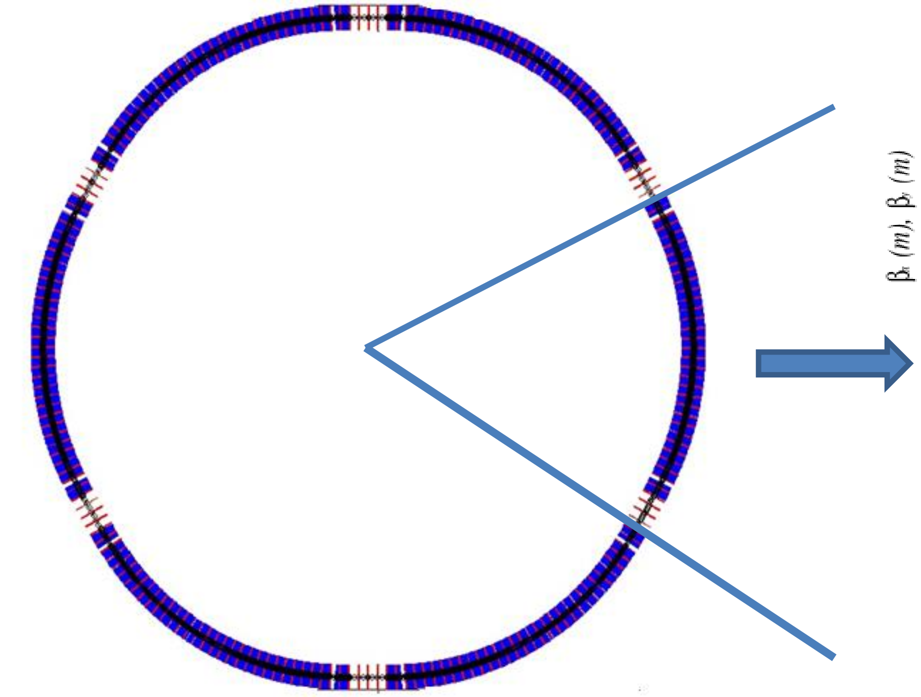
Since the emittance reduction is limited with only RW, we are working on a plan to include **both normal wigglers and Robinson wigglers** to the ring. Thus, the emittance can be reduced to 5 nm.rad from 50 nm.rad by keeping the energy loss per turn around 70 MeV.

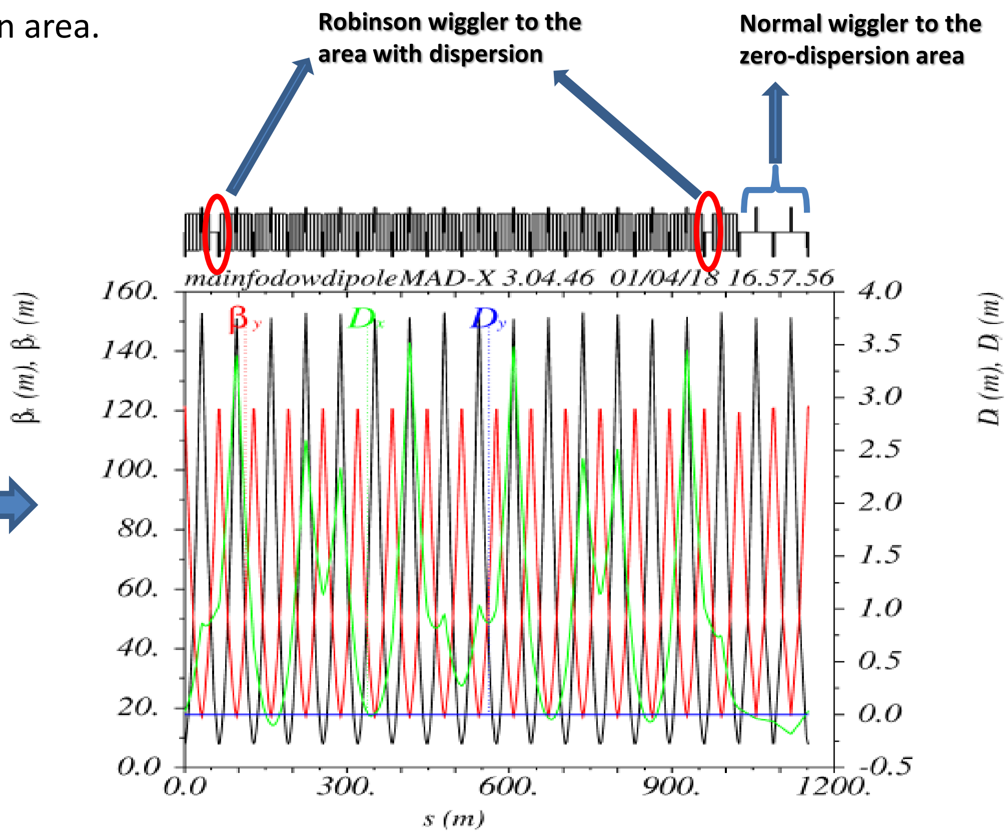
As it can be seen in the plot, when D is around zero (which means there is no Robinson wiggler), the energy loss per turn is around 160 MeV to be able to have an emittance around 5 nm.rad. However, the energy loss per turn reduces to around 70 MeV when D is around -1.5 (which means there is Robinson wiggler as changing the damping partition to -1.5 from 0).

Wiggler magnets in SPS

- For efficiency, RW should be located to high-dispersion area.

$$D = \frac{\rho_0 \eta_x}{\pi(\rho_0 B_0)^2}\left\langle B_w \frac{dB_{w,z}}{dx}\right\rangle L_w$$





Simulations for RW are not done yet for SPS

Summary&Next Steps

- New layout for alternative ring is provided;
    - DA studies with errors should be done,
    - Frequency map analysis should be done,

- Analytical calculations are done for planned wigglers of SPS;
    - RW simulations should be done for SPS.