Optimization of the BEPCII lattice with frequency map analysis*

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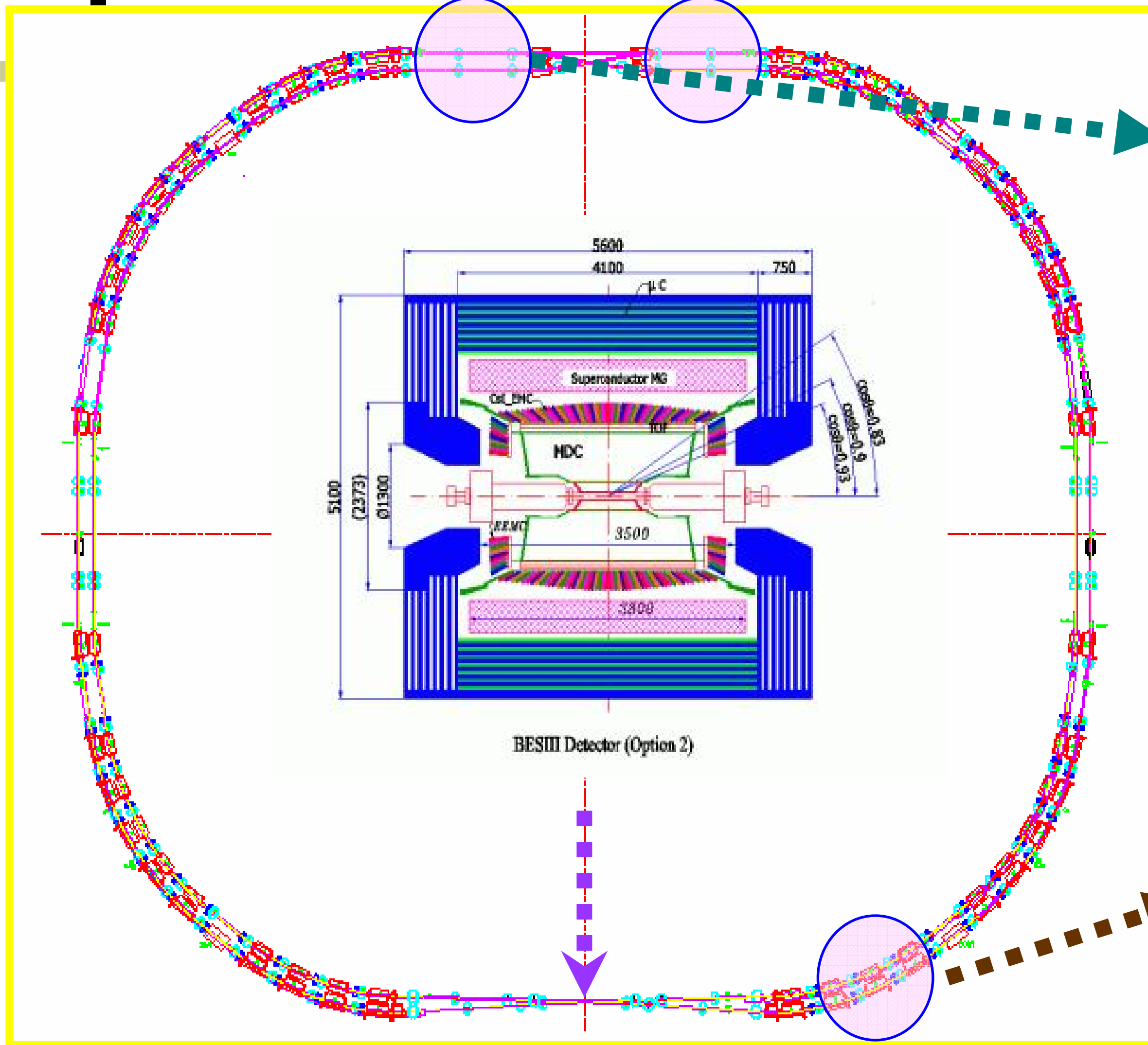
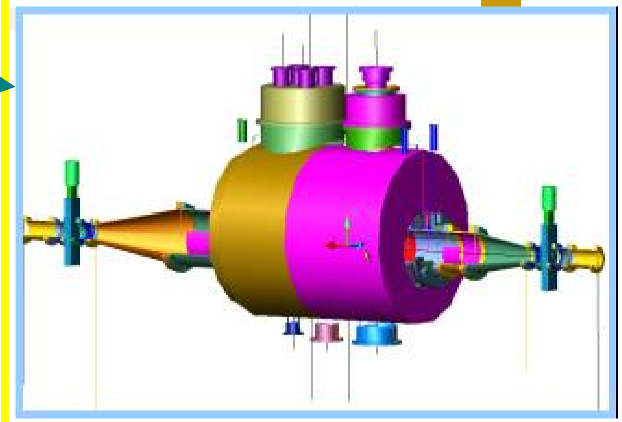
BEPCII: a high luminosity double–ring collider





BEPCII lattice

BEPCII is the upgrade project of the Beijing Electron Positron Collider (BEPC) being built at IHEP.

High luminosity

High beam current

multi-bunch collision

Double ring

Lattice

working point close to half integer

Low beta at IP

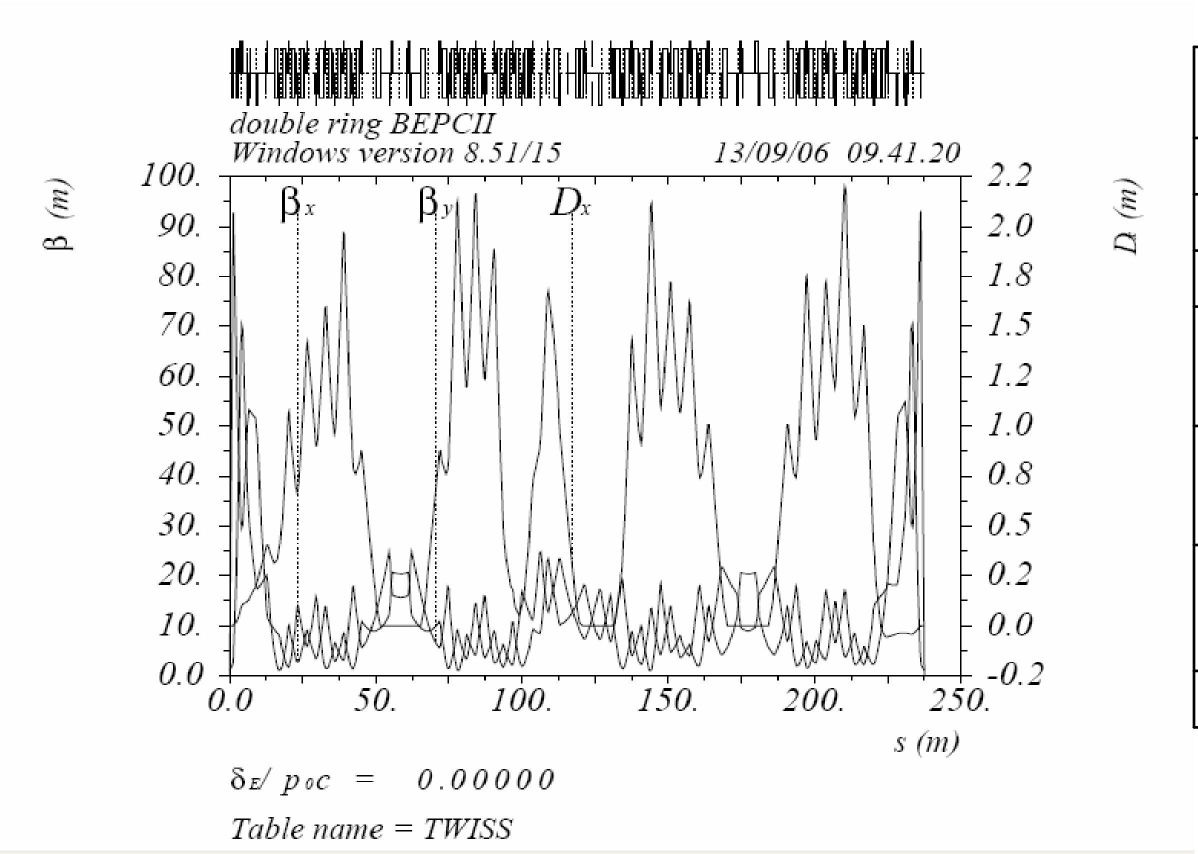
Elaborate analysis and optimization of the beam dynamics should be made

Frequency map analysis

- Frequency map analysis (FMA) is a very useful tool to study the single particle dynamics by constructing a one-to-one relationship between the space of initial conditions (x, y, $x' = y' = 0$) and the tune space (Q_x, Q_y).
- With this method, we can obtain the dynamic aperture (DA) and the corresponding frequency map (FM) at the same time, and study the effects and features of only one resonance out of others.
- This method has been used among many light sources (ALS, NSLS, SPEAR3, SOLEIL, ESRF, SSRF, etc) and other machines (LHC, SNS).
- It is the first time that we systematically apply the FMA to the lattice of the BEPCII storage ring.

BEPCII collision mode

- Main parameters and Twiss functions



Parameter	Unit	Collision mode
Beam energy	GeV	1.89
Circumference	m	237.53
RF voltage	MV	1.5
$Q_x/Q_y/Q_s$		<u>6.51</u>/5.58/ 0.034
Natural chromatity		–10.7/–21.0
Horizontal natural emittance	nm·rad	141
β_x / β_y (IP)	m	1 / <u>0.015</u>

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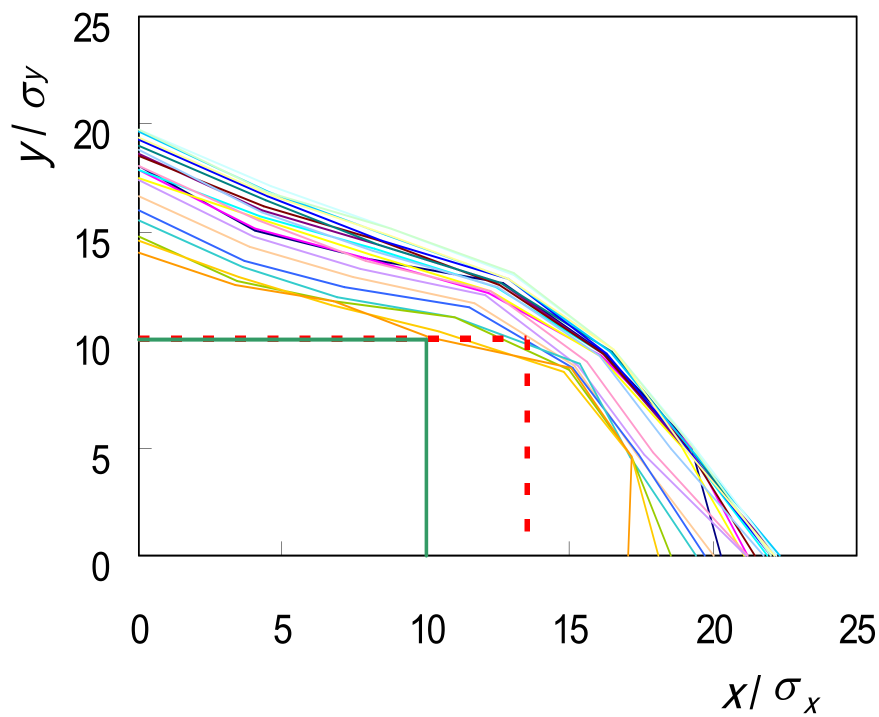
BEPCII collision mode

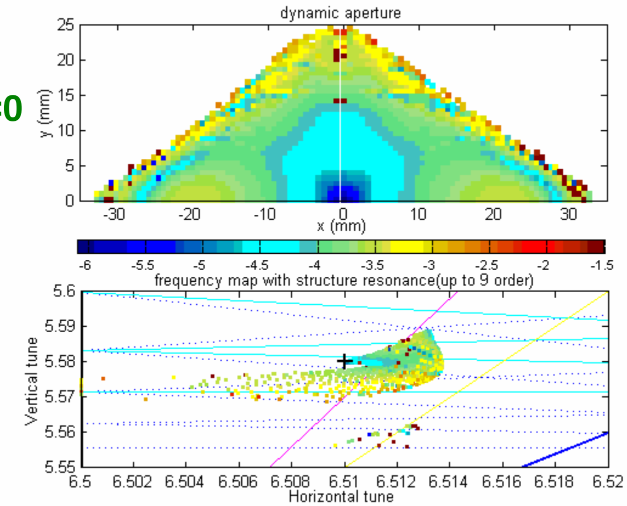
The nonlinear optimization of the lattice, i.e., 4 families of sextupoles being matched with MAD, is not perfect.

The average off-momentum DAs with errors (20 random seeds) are just bigger than the required aperture for collision, say $10\sigma_x \times 10\sigma_y$, the solid square, but smaller than the requirements for injection, i.e., $13.5\sigma_x \times 10\sigma_y$, the dashed square.

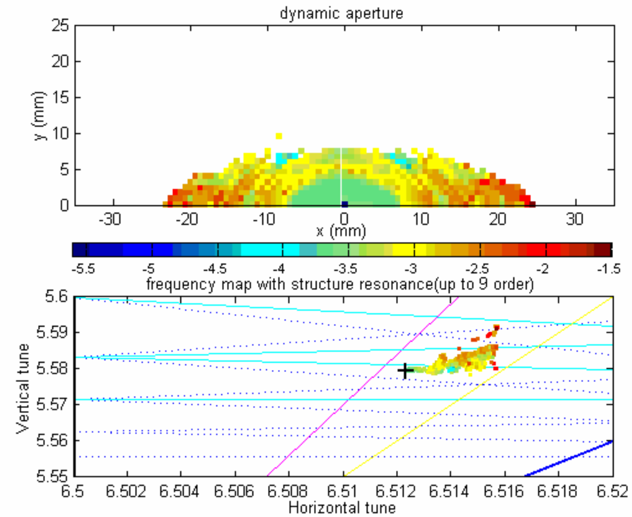


FMA on the collision mode

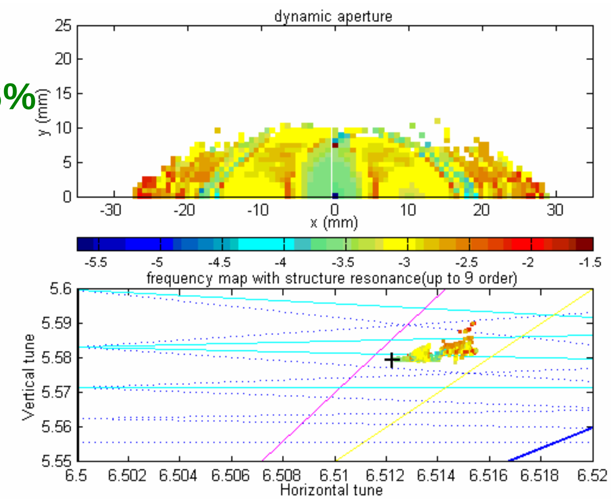
$\Delta p / p$=0

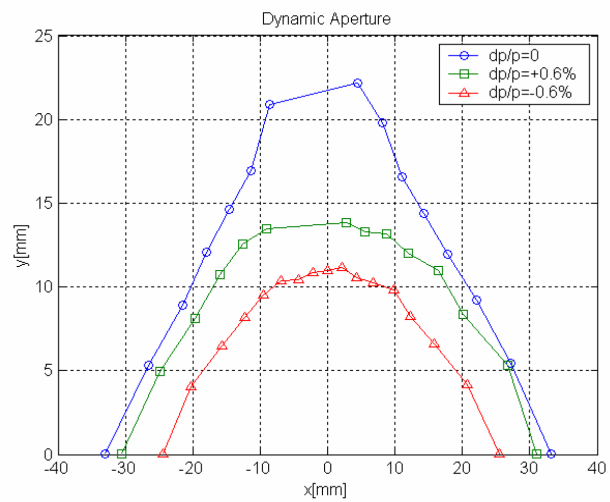


$\Delta p / p$= –0.6%



$\Delta p / p$= 0.6%





On- and off-momentum DAs

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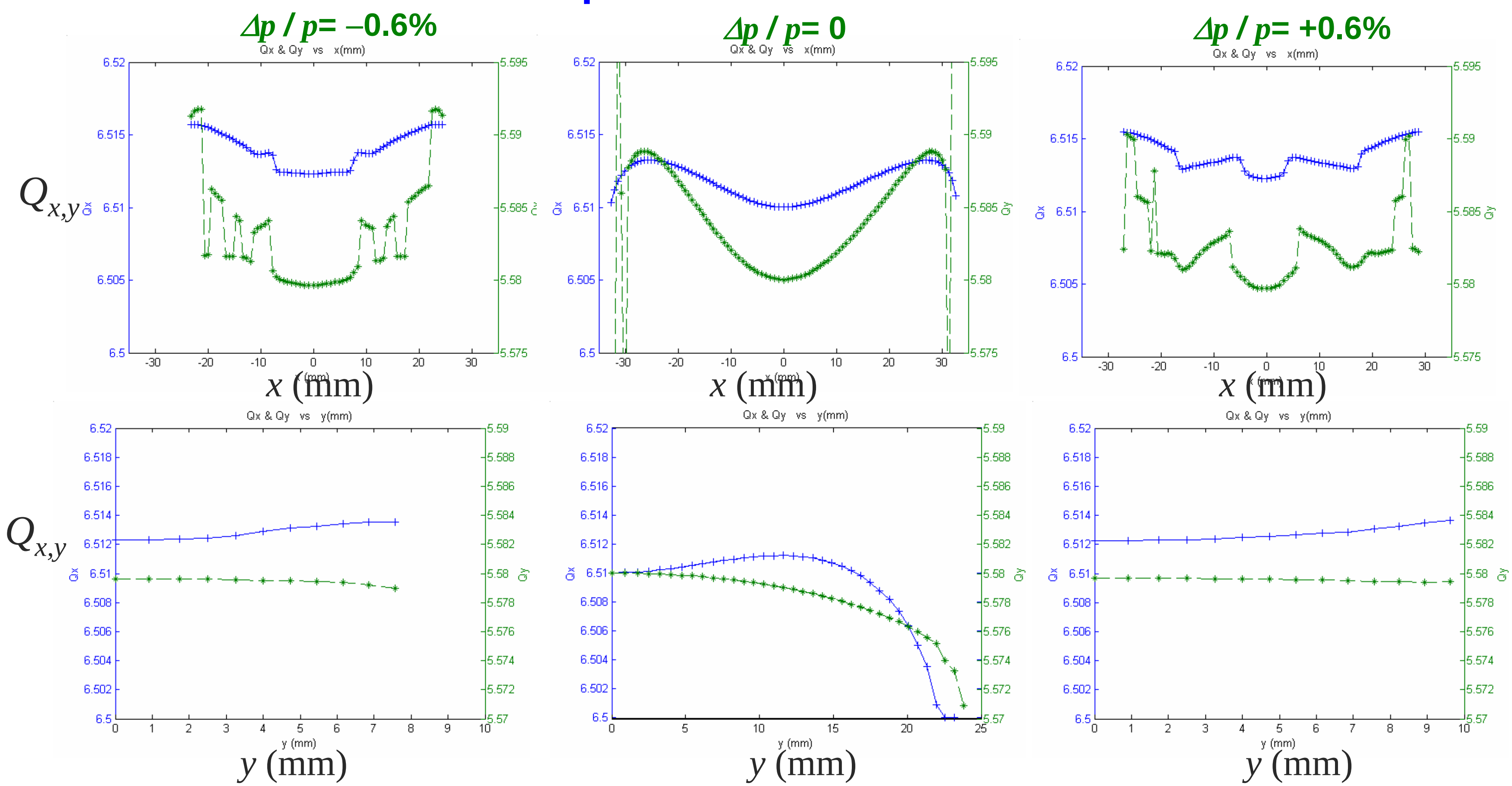
FMA on the collision mode

Tune variations with amplitude



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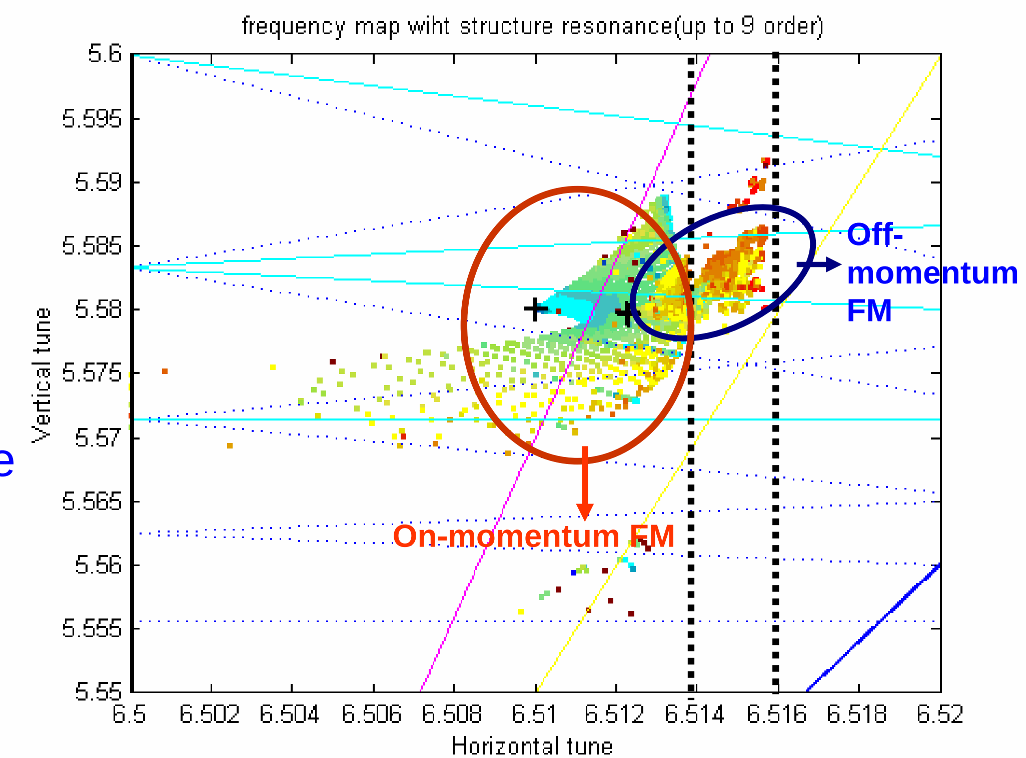
FMA on the collision mode

There exists great disparity between the on- and off-momentum DAs and FMs. That is, the off-momentum FMs are not folded like the on-momentum case and the tune footprints cover the range $Q_x \in (6.514, 6.516)$ with a high diffusion rate or even particle loss.



The FMs with $\Delta p/p$ =0, ±0.6% together

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FMA on the collision mode

The great disparity can be explained as follows.

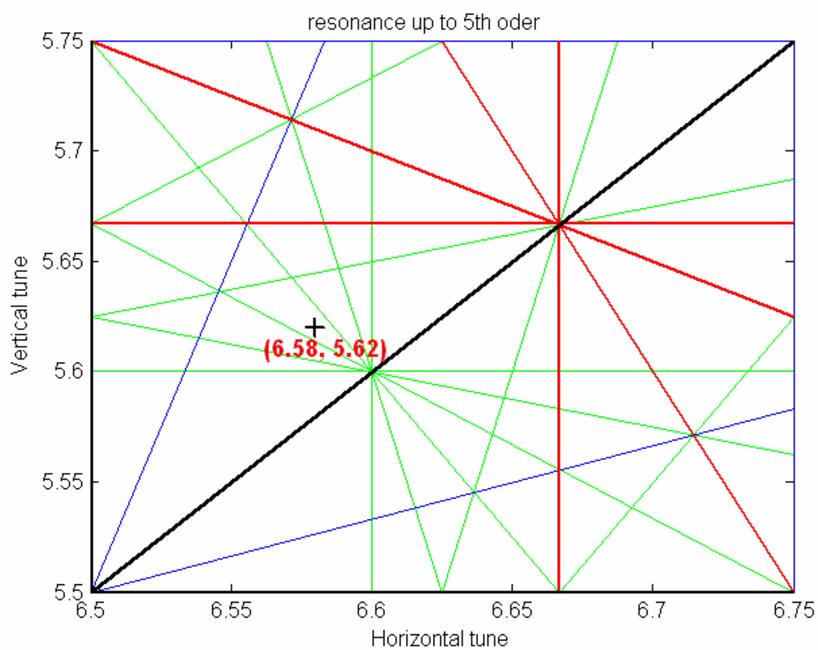
According to the theory of super-periodic structural resonances analysis (SSRA)*, the horizontal working point is very close to the half integer resonance, which is expected to be a second order super-periodic structural resonance with strong nonlinearity. The chromaticity correction of sextupoles does not have enough effective action range of momentum deviations, leading to a great difference between the on- and off-momentum beam dynamics. The off-momentum beam dynamics could be affected by the synchro-betatron resonance $2Q_x - Q_s = 13$, thus the DA is much smaller than the on-momentum DA, especially in vertical plane.

*1. S. X. Fang, Q. Qin. HEP & NP, 2006, 9: 880

2. Y. Jiao, S. X. Fang, Q. Qin, J. Q. Wang, NIM A 566 (2006) p.270

BEPCII injection mode

- The injection mode relaxes the constraints on the low vertical beta function at the IP and the working point close to half integer resonance, but calls for larger DA and better beam dynamics.
- We choose the working point as (6.58, 5.62), which is located in a relatively clean area in tune space.



Parameter	Unit	Collision mode
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RF voltage	MV	1.5
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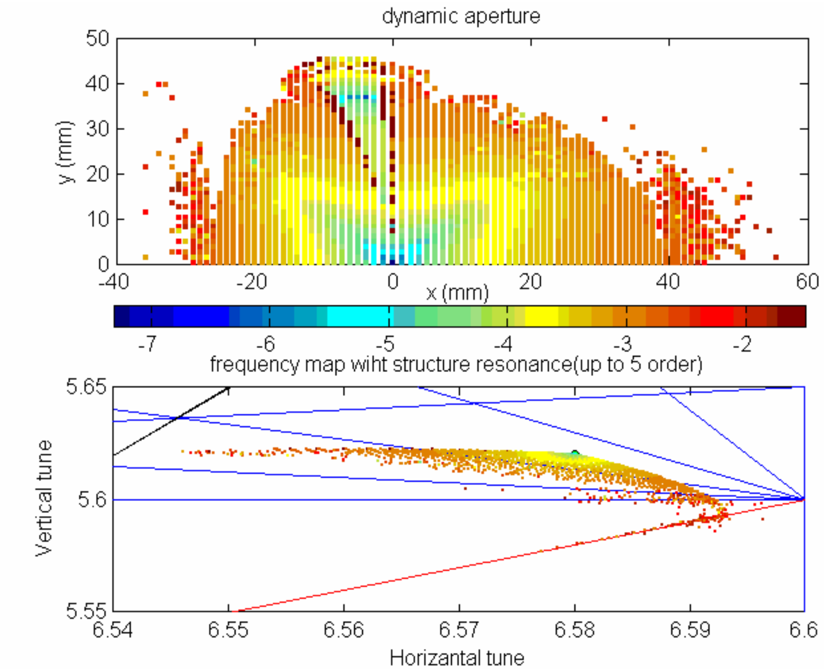
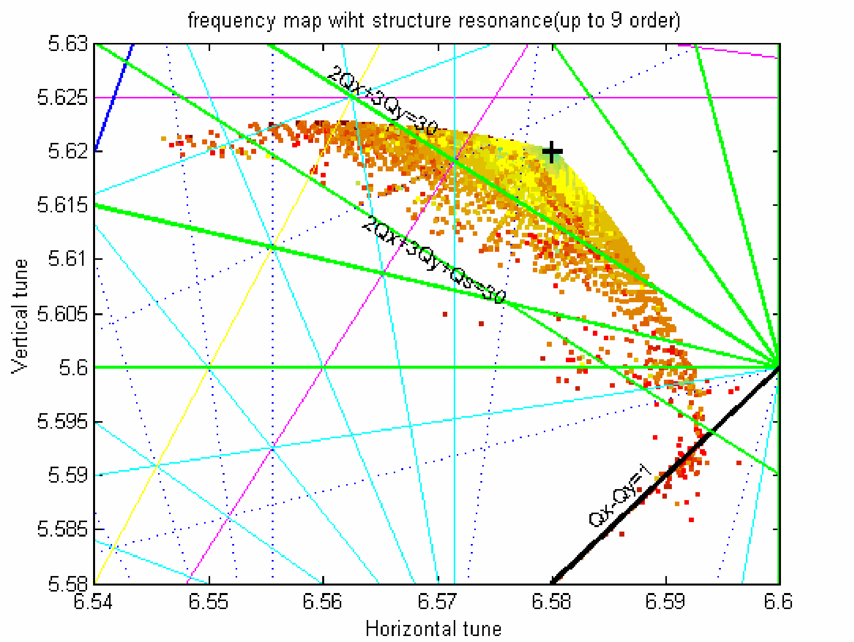
Natural chromatity		–10.5/–12.1
Horizontal natural emittance	nm· rad	135
β_x / β_y (IP)	m	4/0.028

FMA on the injection mode





DA and FM with $\Delta p / p = 0$

FMs with $\Delta p / p = 0$, ±0.6% together

The on- and off-momentum beam dynamics are similar, thus only the on-momentum DA and FM are shown.

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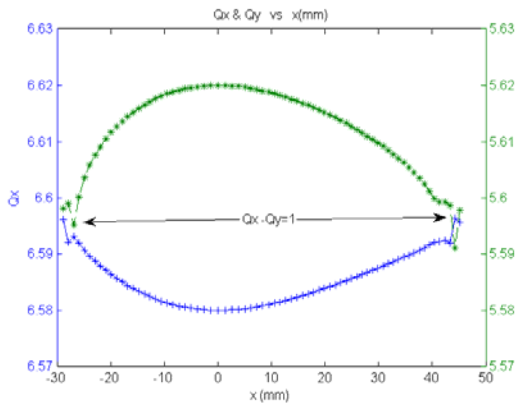
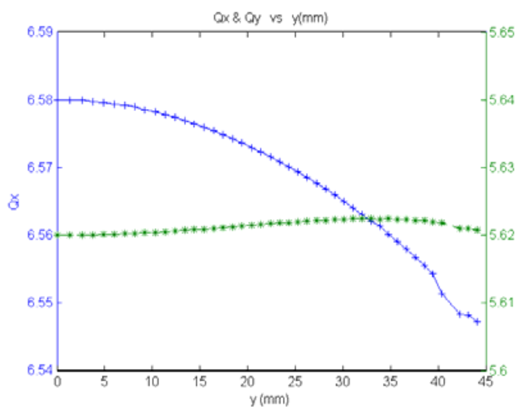
FMA on the injection mode

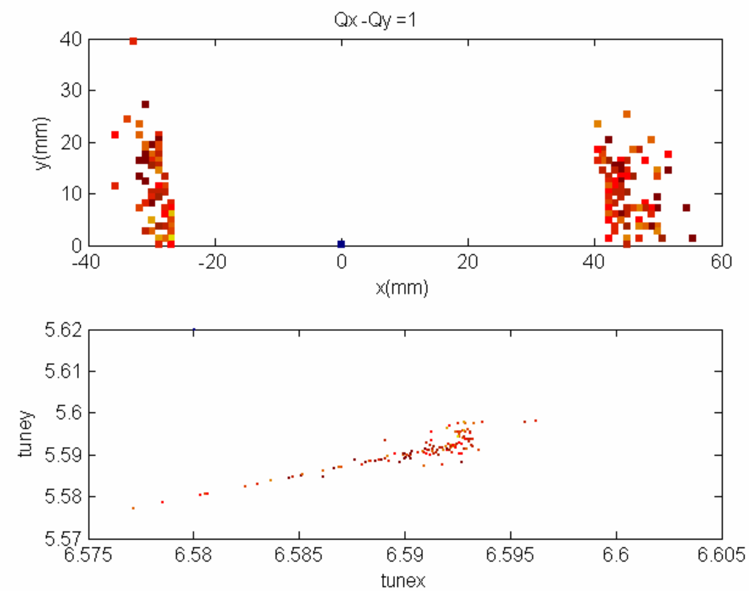
Tune variations with amplitude





Dominant resonances

Coupling resonance $Q_x - Q_y = 1$



The location of the coupling resonance in the DA and FM

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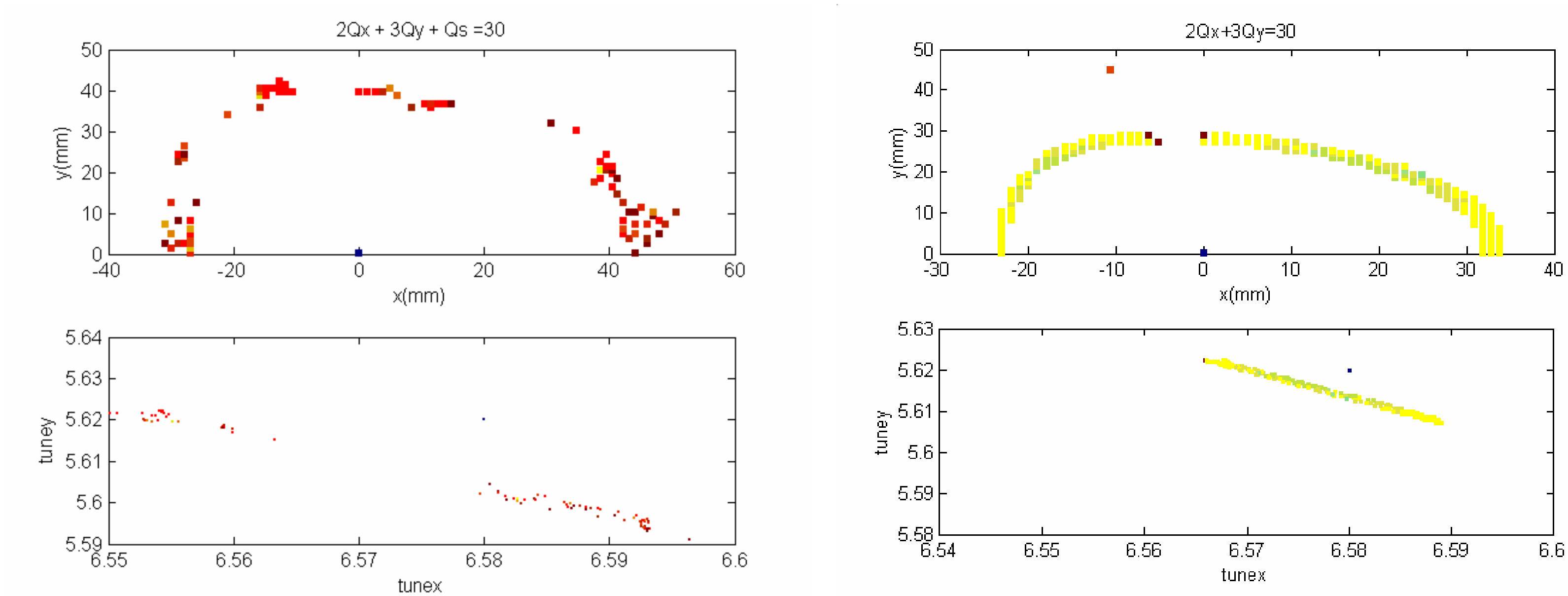
FMA on the injection mode

Dominant resonances

The synchro-betatron resonance $2Q_x + 3Q_y + Q_s = 30$ locates at the border of the DA, i.e., it limits the stability area. While the corresponding pure transverse resonance $2Q_x + 3Q_y = 30$ has much less effect on the beam dynamics.



The location of the resonances in the DA and FM.

FMA on the injection mode

Dominant resonances

To confirm the existence of the synchro-betatron resonance $2Q_x + 3Q_y + Q_s = 30$, a particle is launched with initial conditions $(x, x', y, y', \delta, l)$ = (30mm, 0, 15.5mm, 0, 0.3%, 0) and tracked with AT under three cases:

The voltage of the RF cavity Vrf =1.5 MV (the designed value)

1. Vrf =3.0 MV (change the Qs)
2. Turn off the RF cavity and radiation (excluding the longitudinal oscillation and damping)

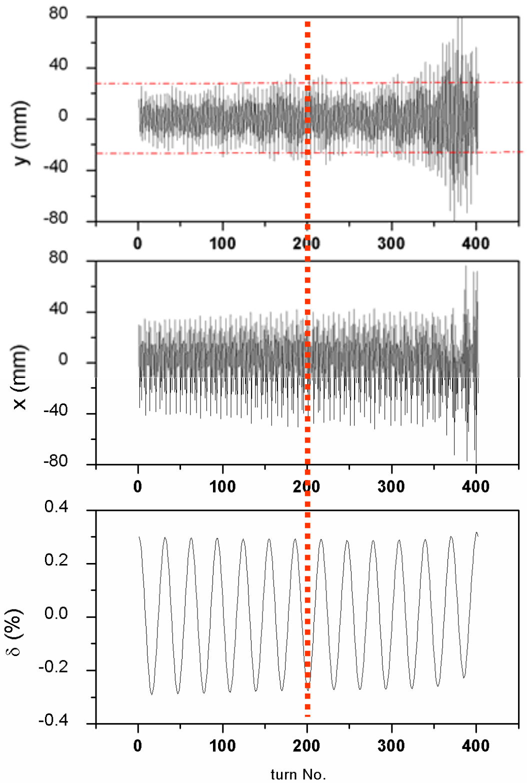
Simulation results:

Case 1, the particle gets lost in 400 turns due to the resonance $2Qx + 3Qy + Qs = 30$.

Case 2, the particle remains stable in 10000 turns.

Case 3, the particle is stable.

FMA on the injection mode



Tracking with longitudinal oscillations and damping. The dashed dot lines indicates the height of the vacuum chamber ±26mm.

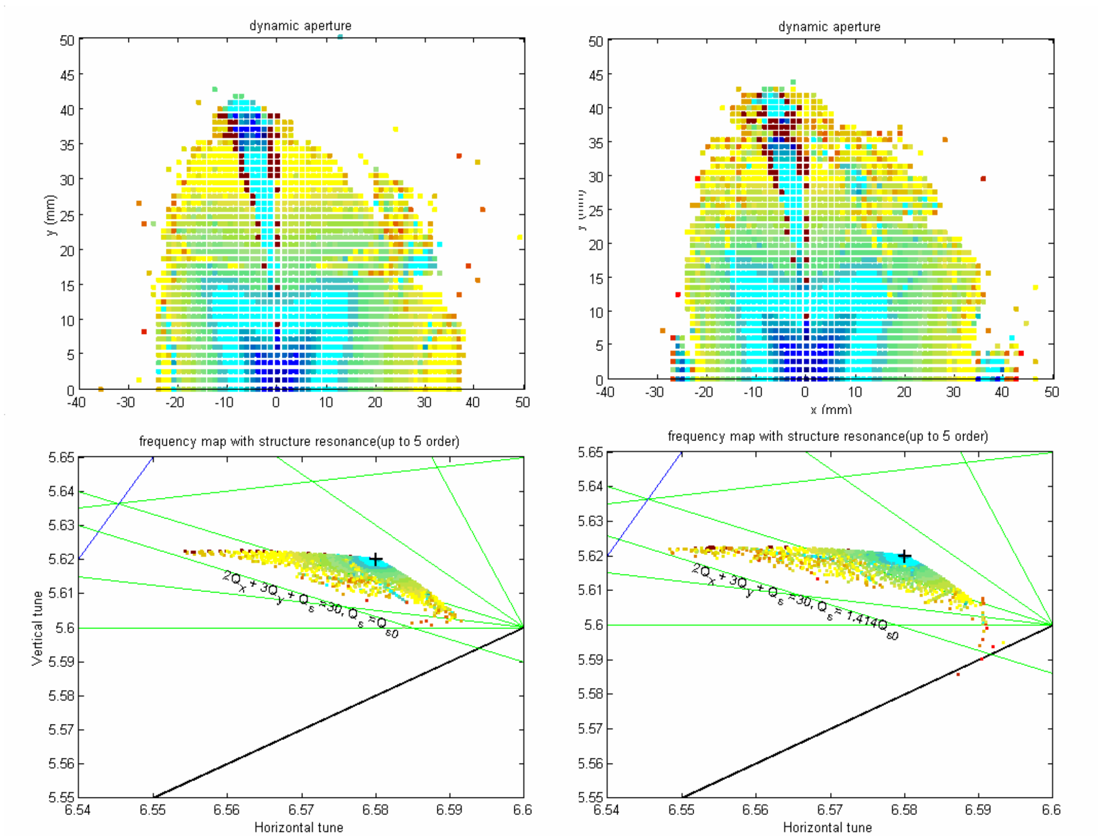
	First 200 turns	Last 200 turns
Q_x	6.5835	6.5807
Q_y	5.6078	5.6058
Q_s	0.0325	0.0327
$2Q_x + 3Q_y + Q_s$	30.0229	30.0115

The tunes are very close to the synchro-betatron resonance $2Q_x + 3Q_y + Q_s = 30$. The amplitudes increase rapidly and exceed the physical aperture in vertical plane.

FMA on the injection mode

Dominant resonances

the result of case 1 and case 2.



Both DAs are limited by the resonance $2Q_x+3Q_y+ Q_s=30$

but

in case 1,
$Q_s=Q_{s0}$~0.032,
in case 2,
$Q_s=1.414Q_{s0}$~0.045

The area for the tune spread of the survival particles becomes **larger.**

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Optimizing the collision mode

To reduce the anharmonicity terms and minimize the effect of the synchro-betatron resonance $2Q_x - Q_s = 13$, are used in the optimization.

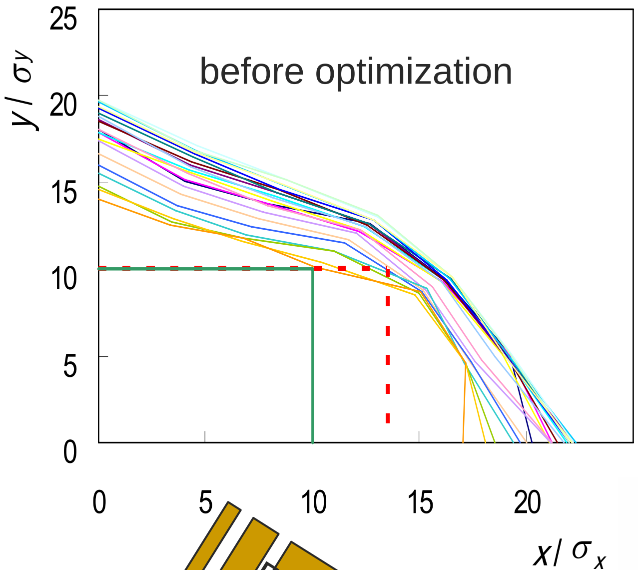
The anharmonicities terms are reduced from $(dQ_x/dx^2, dQ_x/dy^2, dQ_y/dy^2) = (73, 77, 208)$ to $(70, 68, 198)$.

The growth time of the resonance $2Q_x - Q_s = 13$ is:

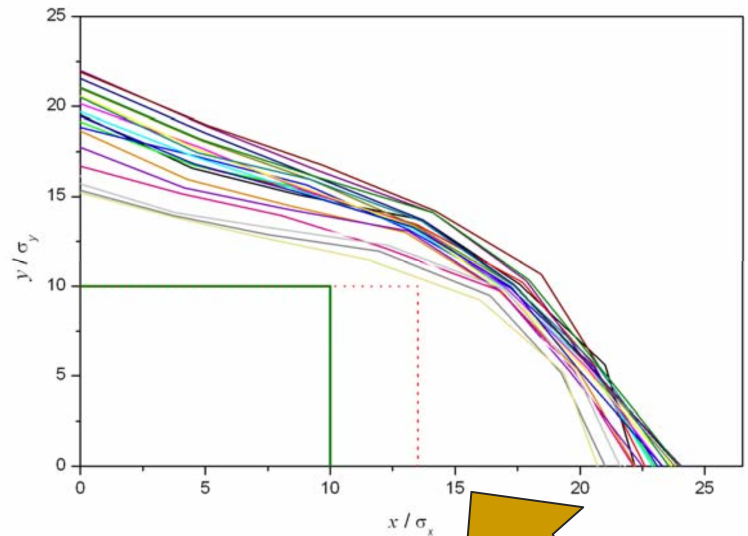
$$\frac{1}{\tau} = f_0\hat{\delta}\left|\sum_n k_{sn} D_{xn} \beta_{xn} e^{2i\phi_{xn}}\right| = f_0\hat{\delta}H$$

H along the whole ring is calculated and minimized by fine-tuning all the sextupole strengths. For example, we change the H from 19.7 to 3.1 for $\delta = 0.3\%$.

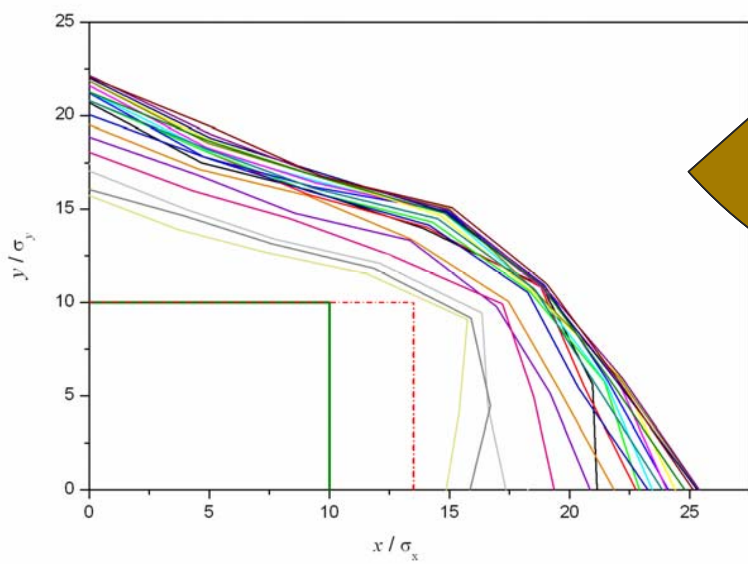
Optimizing the collision mode



The increase of size of DA with errors from SAD



Reduce anharmonicity

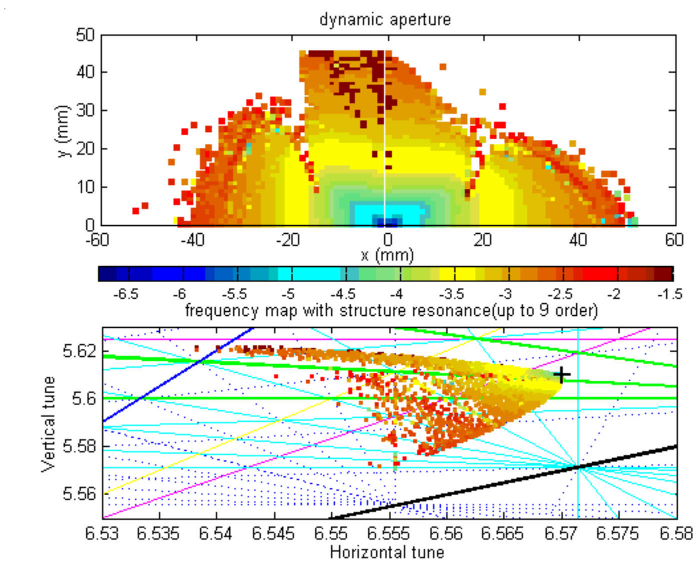


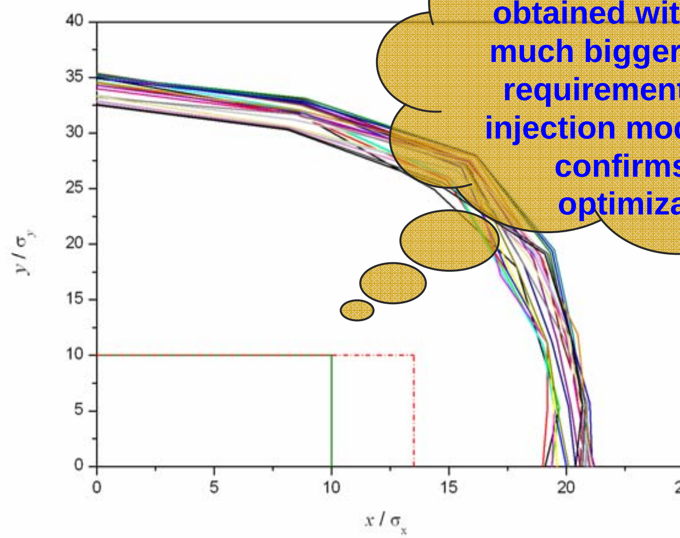
Minimize the growth time of resonance

Optimizing the injection mode

The working point of the lattice is moved to (6.57, 5.61), so as to keep the tunes away from the synchro-betatron resonance $2Q_x + 3Q_y + Q_s = 30$.

We change the the amplitude tune shift slope at origin $(dQ_x/dx^2)_{x=0}$ from 760 to 133, aiming to reduce the effect of coupling resonance $Q_x - Q_y = 1$.





The DA (with errors) obtained with SAD is much bigger than the requirements of the injection mode, which confirms our optimization

Conclusion

- FMA is used to analyze and optimize the BEPCII collision and injection mode lattice. The beam dynamics are reveal in a global way, the main resonances limiting the DA are studied in details. Several methods are used to further optimize the beam dynamics.

- When the longitudinal oscillation and the damping process are taken into account, the synchro-betatron resonances may be exited and affected the single particle dynamics. In the case of the BEPCII injection mode lattice with the working point of (6.58, 5.62), such a resonance is responsible for the limit of the DA. When we move the working point away from the resonance, the DA significantly increases.

- Compared to the injection mode, the limiting factor for the lattice is more severe, the optimization consequently becomes more complicated and difficult. Reducing the nonlinear anharmonicity terms and minimizing the effect of the synchro-betatron resonance $2Q_x - Q_s = 13$, are proved to be beneficial to the improvement of the beam dynamics.

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Thanks for your attention!