The Design of CSNS/RCS

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CSNS
CHINESE ACADEMY OF SCIENCES

Outline

- Introduction
- The Optics Design for RCS
- The Optics Correction
- Longitudinal Beam Dynamics Design
- Beam Loss & Control
- Space Charge Effects
- Impedance and Instability
- The Design of Injection
- The Design of Extraction
- Future Beam Power Upgrade

Why Was the RCS Chosen?

Rapid Cycling Synchrotron vs. Accumulate Ring

From the point view of budget,

- **For beam power above 1MW, prefer full energy linac+AR**
- **For several hundreds kW neutron source, prefer low energy linac+high energy RCS**

$$\langle P \rangle = E_k \langle I \rangle$$

$$\langle I \rangle = eN_p f_{\mathrm{rep}}$$

Space Charge Effects

Let two charged particles move parallel with same velocity, then electric field and magnetic field experienced by particles are

$$E = \frac{q}{4\pi\varepsilon_0 d^2}$$

$$B = \frac{\mu_0 q v}{4\pi d^2}$$

Where q is charge, ε_0 the dielectric constant, μ_0 the permeability, v the velocity.

The ratio of magnetic and electric forces is

$$\frac{F_m}{F_e} = \frac{v^2}{c^2} = \beta^2$$

For non-relativistic beam, $F_m \ll F_e$. Due to the signs of F_m and F_e are inverse, the space charge effects are decreased with the increase of the velocity.

Space-charge Tune Shift

Space charge is a fundamental limit to beam power in high intensity AR and synchrotron. The incoherent space-charge tune shift is

$$\Delta\nu_{x,y} = -\frac{f_{sc} N r_0 R}{2\pi B_f \nu_{0x,y} \beta^2 \gamma}\left[\frac{1}{\sigma_{x,y}(\sigma_x+\sigma_y)}\left(\frac{1}{\gamma^2}-\eta_e\right)+A_{im}^{e}\left(\frac{1}{\gamma^2}-\eta_e\right)+A_{im}^{m}\right]$$

The contribution from the electric and magnetic images of the beam are represented by the Laslett tune shifts A_{im}^{e} and A_{im}^{m}, respectively. For a round beam with no neutralization, the direct space-charge tune shift becomes

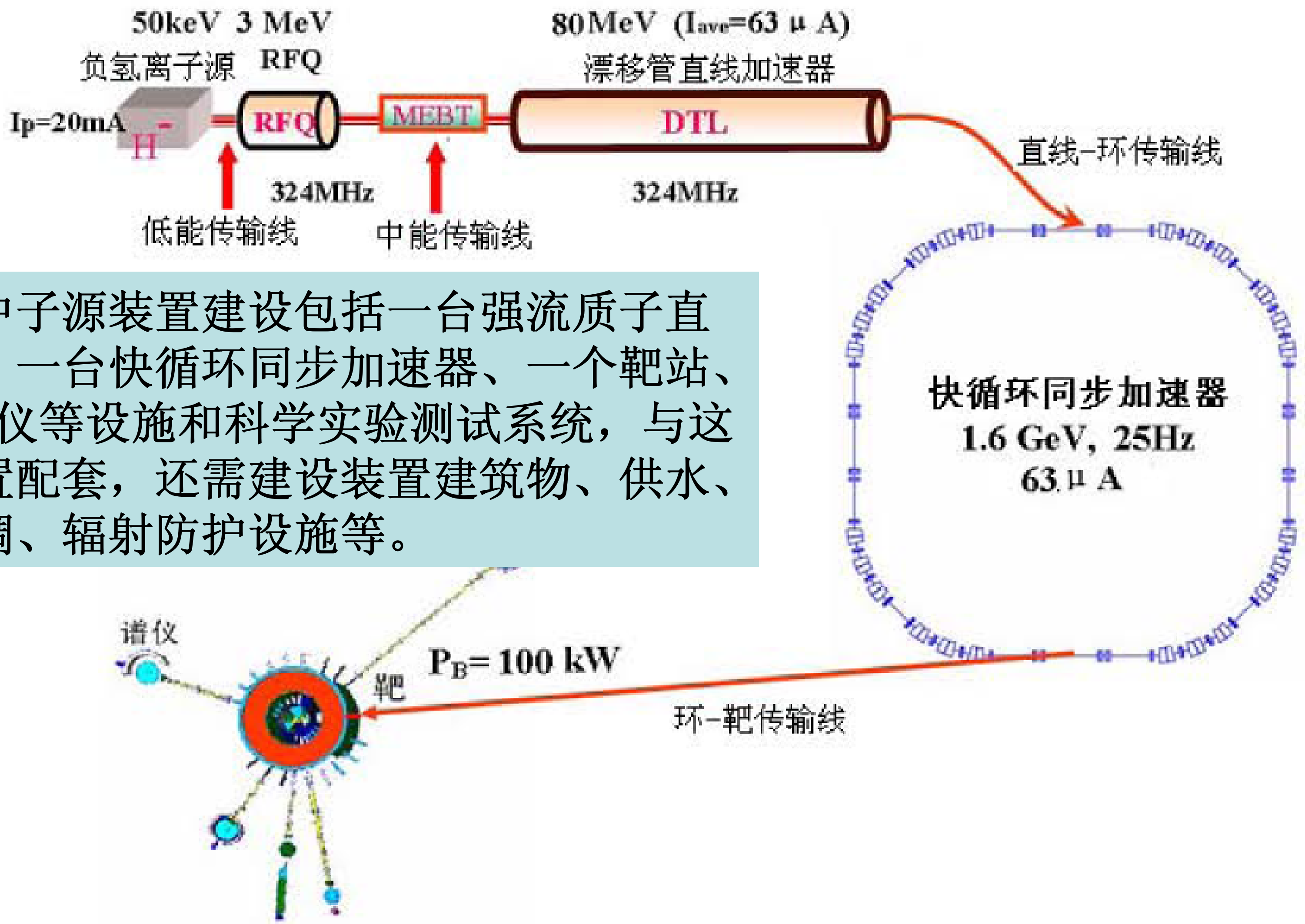
$$\Delta\nu_{x,y} \approx \frac{f_{sc} N r_0}{4\pi B_f \varepsilon_{rms} \beta^2 \gamma^3}$$

Where N is the proton number, r_0 is the classical radius of a proton, The bunch form factor *f*sc is equal to 1/2 for a uniform distribution, and to 1 for a Gaussian distribution. The B_f is bunching factor. ε rms= $\sigma_\perp^2/\beta_\perp^2$, $\beta_\perp = R_0/\nu_0$

Introduction

CSNS Schematic Layout

中国散裂中子源装置建设包括一台强流质子直线加速器、一台快循环同步加速器、一个靶站、3台中子谱仪等设施和科学实验测试系统，与这些主要装置配套，还需建设装置建筑物、供水、供电、空调、辐射防护设施等。



Primary Parameters of CSNS

Phase	I	II
Beam power on target [kW]	100	500
Beam energy on target [GeV]	1.6	1.6
Ave. beam current [μA]	62.5	315
Pulse repetition rate [Hz]	25	25
Protons per pulse [10^{13}]	1.56	7.8
Ion Source type	Penning	RF Volume
Linac energy [MeV]	81	250
Linac RF freq. [MHz]	324	324
Max. space charge tune shift	0.28	0.24
Target number	1	1
Number of spectrometers	3	18

Pulsed Spallation Neutron Sources

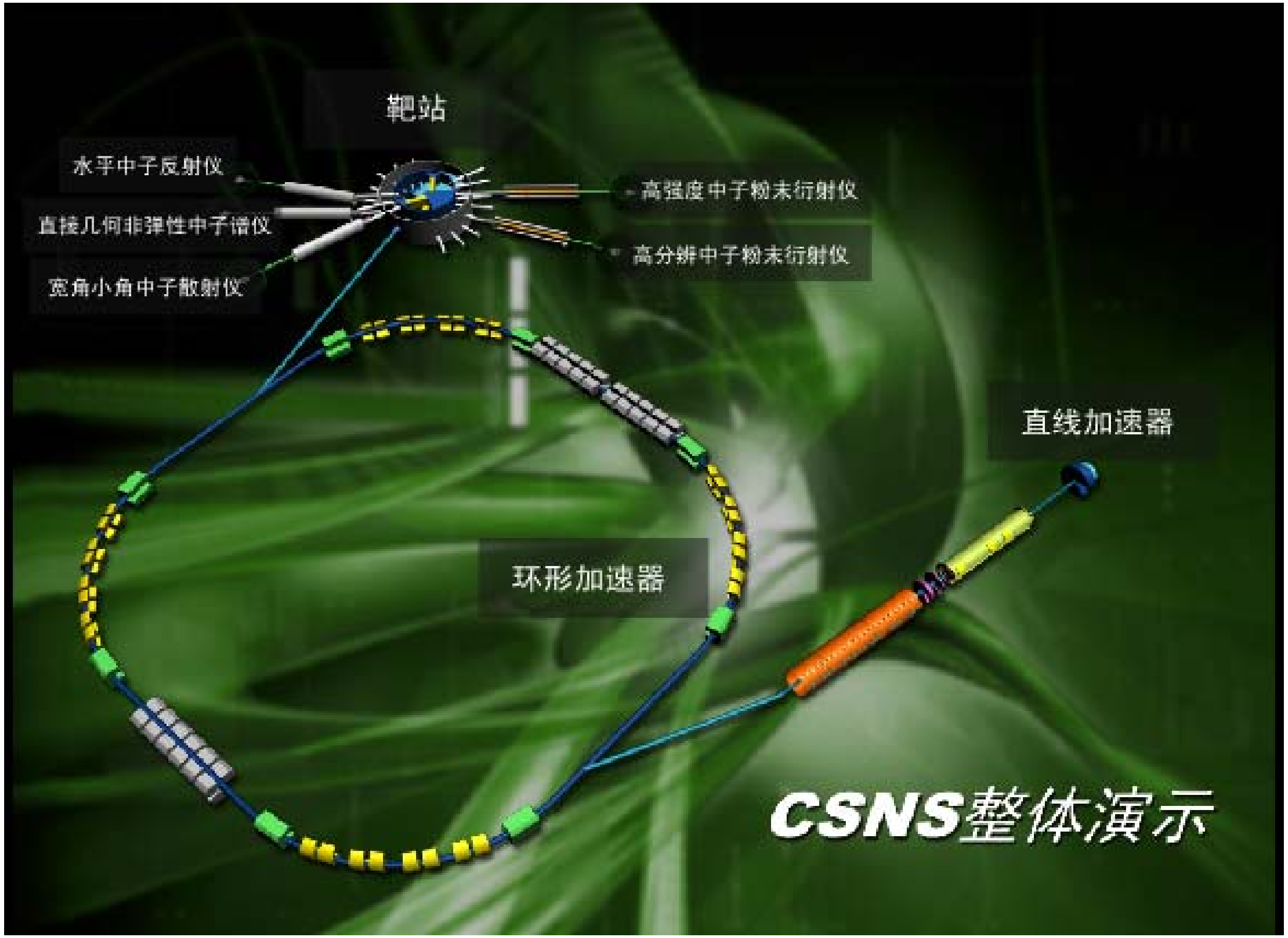
Machine	Energy [GeV]	Intensity [ppp]	Tune-shift	Rep-rate [Hz]	Power [MW]	Type
LANSCE	0.8	2.3×10^{13}		20	0.07	AR
ISIS	0.07-0.8	2.5×10^{13}	~0.4	50	0.2	RCS
J-PARC	0.4 - 3.0	0.8×10^{14}	0.15	25	1.0	RCS
SNS	1.0	1.6×10^{14}	0.1	60	1.0	AR
CSNS	0.08-1.6	1.56×10^{13}	0.28	25	0.1~0.5	RCS
ESS	1.334	2.3×10^{14}		50	2.5x2	AR

The Evolution of Beam in RCS

	Beam	Kinetic Energy (GeV)	Emittance/ Acceptance (π mmmrad)	Peak Current	Bunch Length	Beam Power (kW)
LRBT	H^-	0.08	4/25	15mA	~500μs	5
Injection	$H^- \rightarrow p$	0.08	300/540			5
RCS	p	0.08 →1.6	300 →80/540			5 →100
Extraction	p	1.6	~80/350	~3.5A	80ns+80ns	100
RTBT	p	1.6	~80/350	~3.5A	80ns+80ns	100

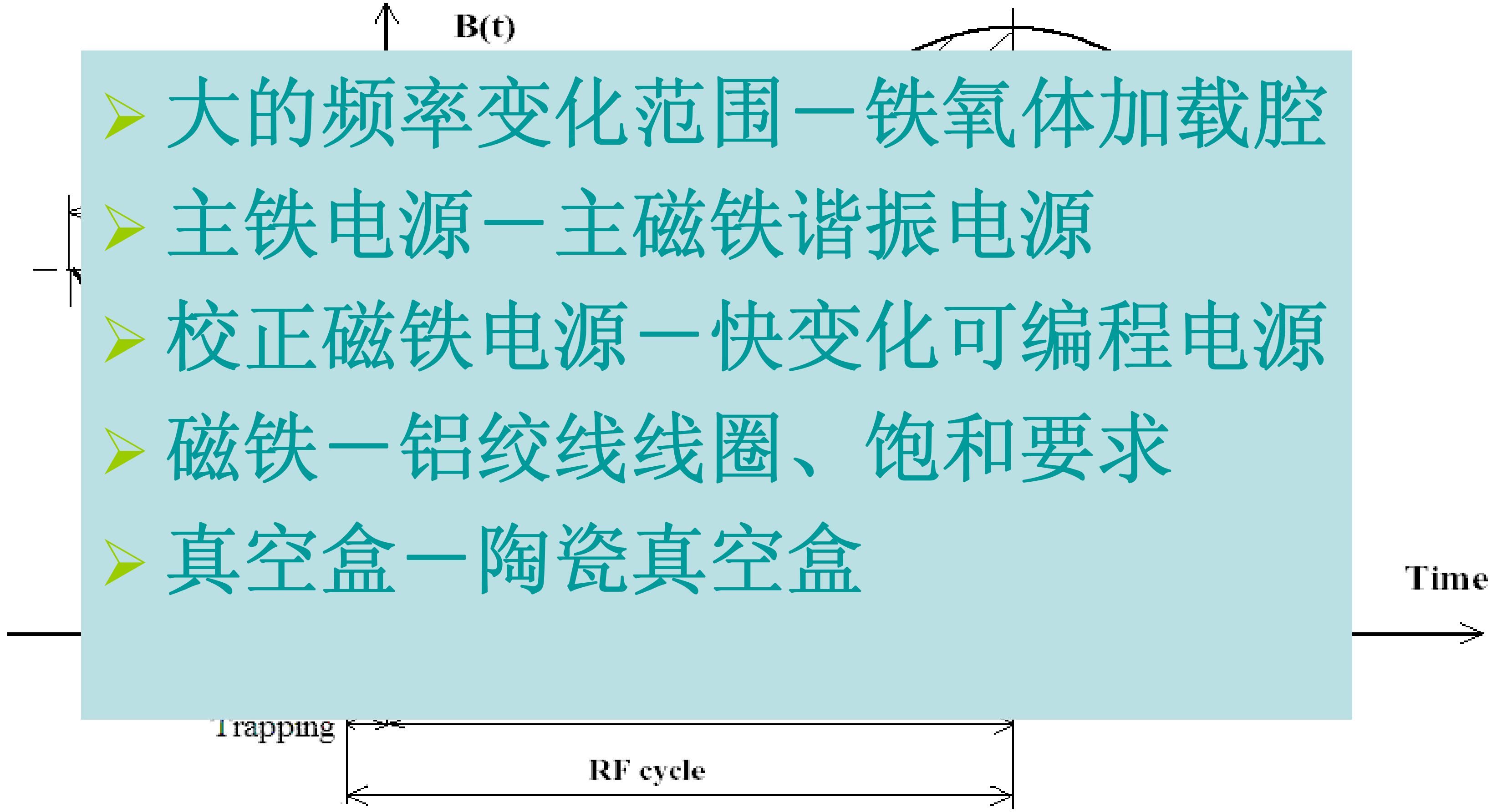
Average current 62.5 μA

Beam at the exit of Linac **Beam at the target**


靶站
水平中子反射仪
直接几何非弹性中子谱仪
宽角小角中子散射仪
高强度中子粉末衍射仪
高分辨中子粉末衍射仪
直线加速器
环形加速器
CSNS整体演示

The Optics Design for RCS

The resonant operating mode of RCS



- 大的频率变化范围—铁氧体加载腔
- 主铁电源—主磁铁谐振电源
- 校正磁铁电源—快变化可编程电源
- 磁铁—铝绞线线圈、饱和要求
- 真空盒—陶瓷真空盒

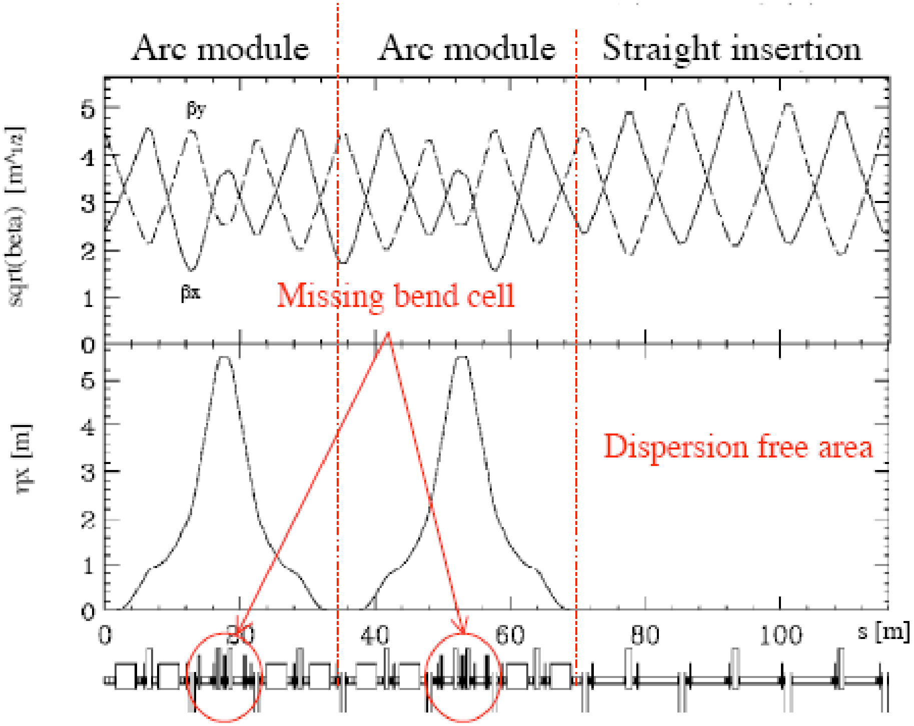
RCS design

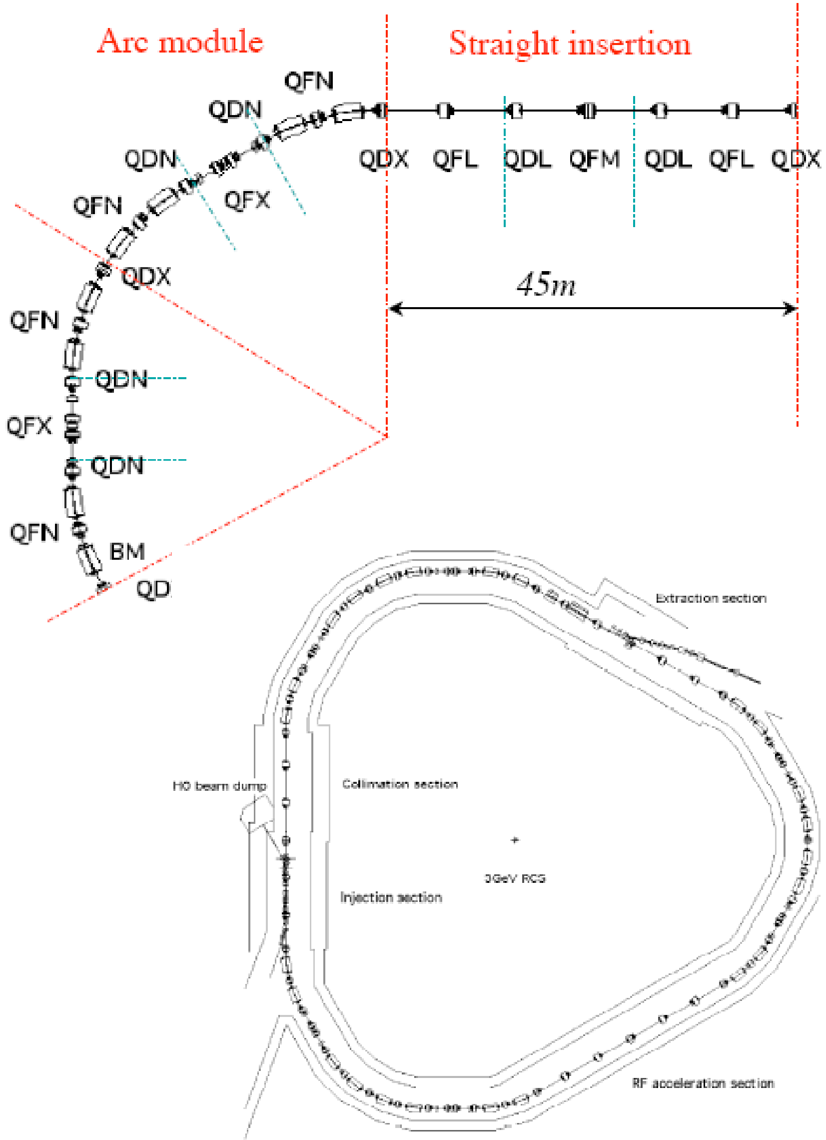
- RCS may be divided into various systems according to their beam-handling functions
  - Injection
  - Capture and acceleration
  - Extraction
  - Collimation, and transport
  - Beam instruments and correctors
- These systems are integrated by the ‘‘lattice’’ magnets, usually symmetrically arranged to alleviate the lower-order resonances

Lattice Design -Basic Requirement

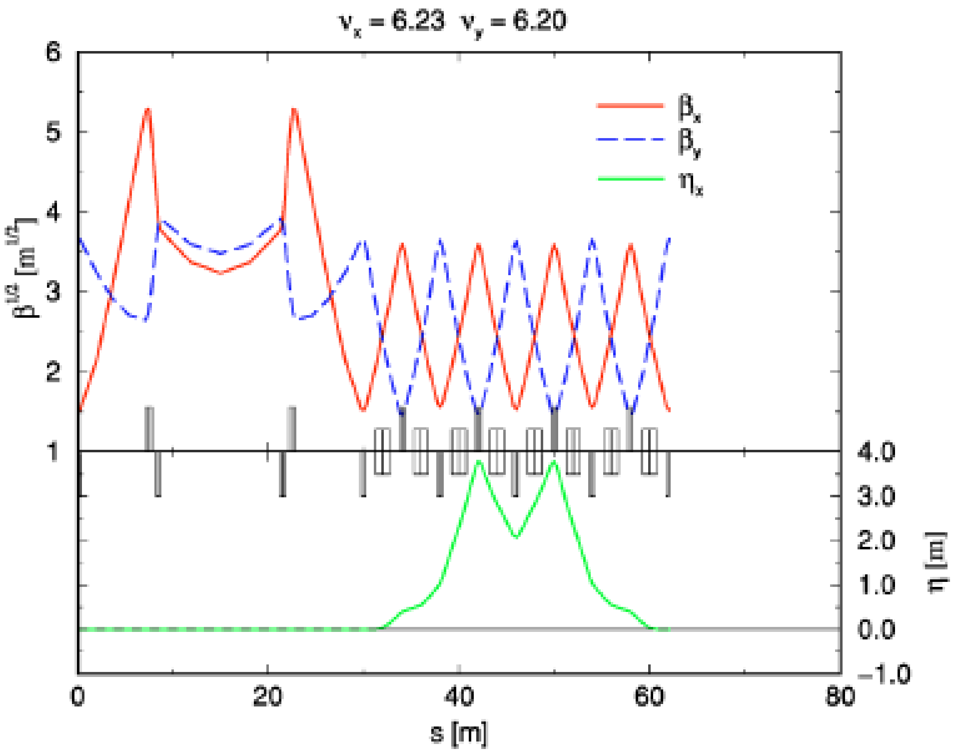
- The structure with proper super-periodicity
- Enough dispersion free straight section for accommodate injection, extraction, RF, beam collimation, and beam instrumentation
- Space with dispersion for momentum collimation
- Avoiding transition energy jump
- Tuning Flexibility
- Easy for optics correction
- Proper circumference
- Proper aperture of magnets
- Enough acceptance (both for transverse and momentum)

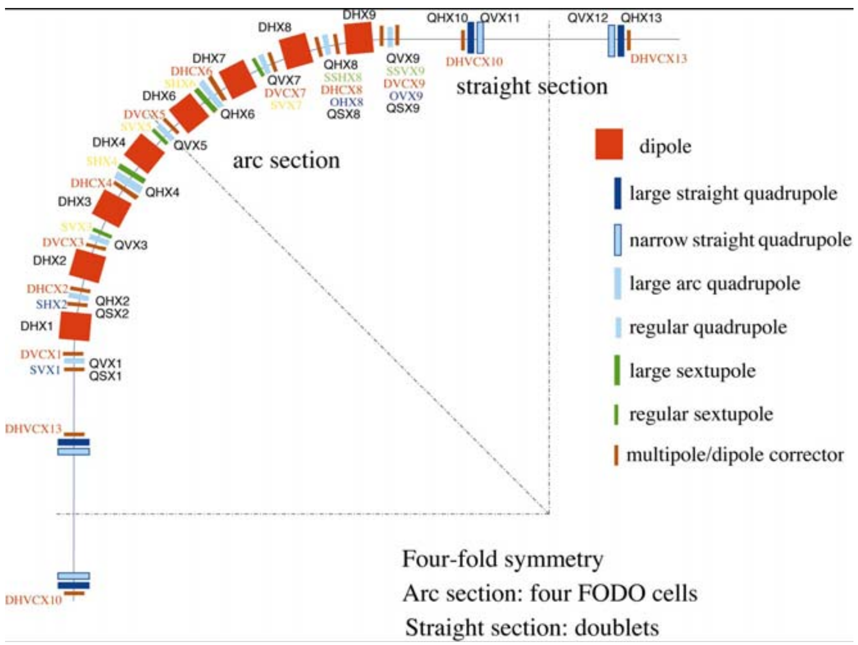
J-PARC/RCS lattice (3-fold, FODO)



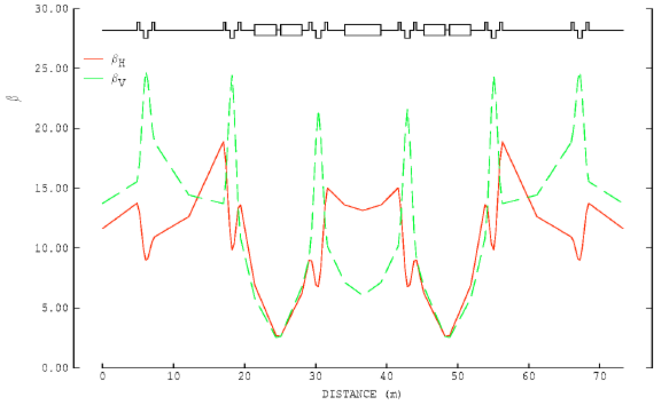


SNS Accumulator Lattice (4-fold, FODO+doublet)

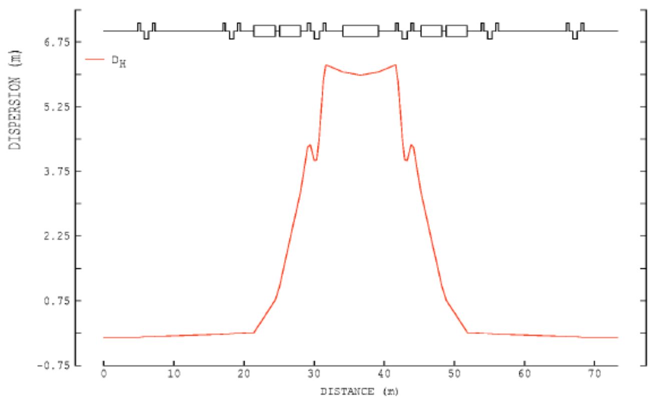




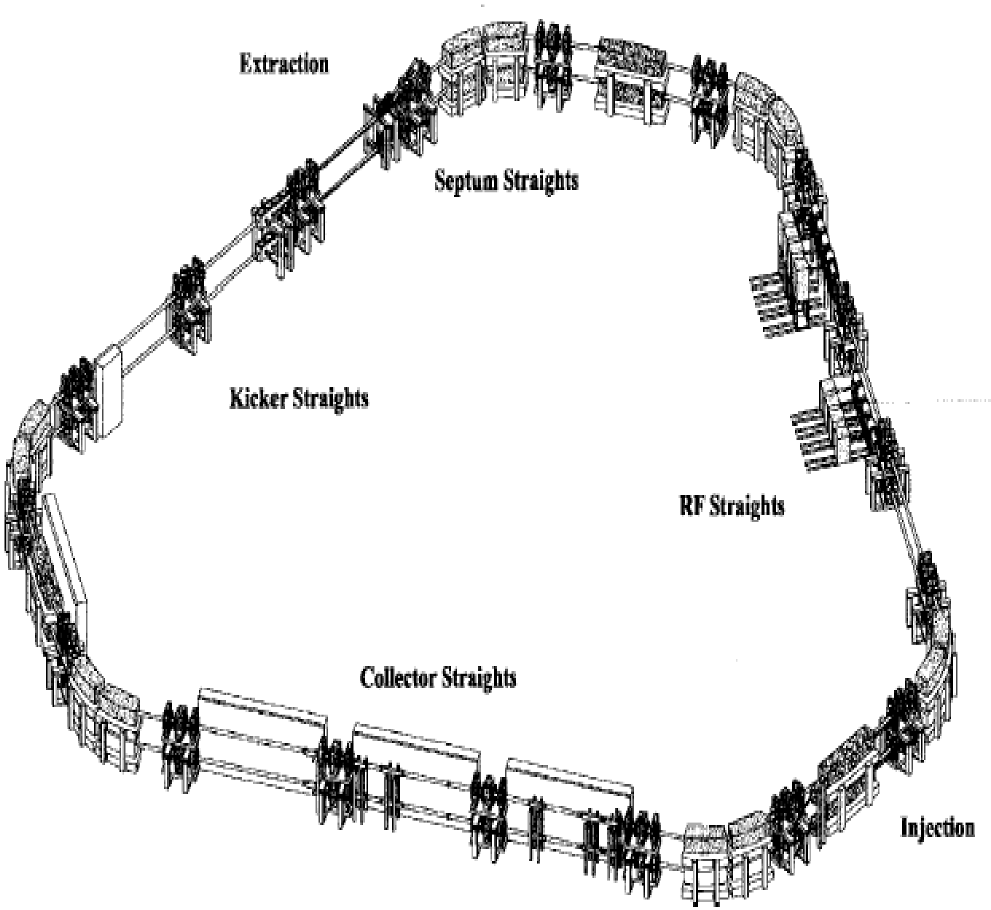
ESS Accumulator Lattice (3-fold, triplet)



(a) β-functions



(b) Dispersion function

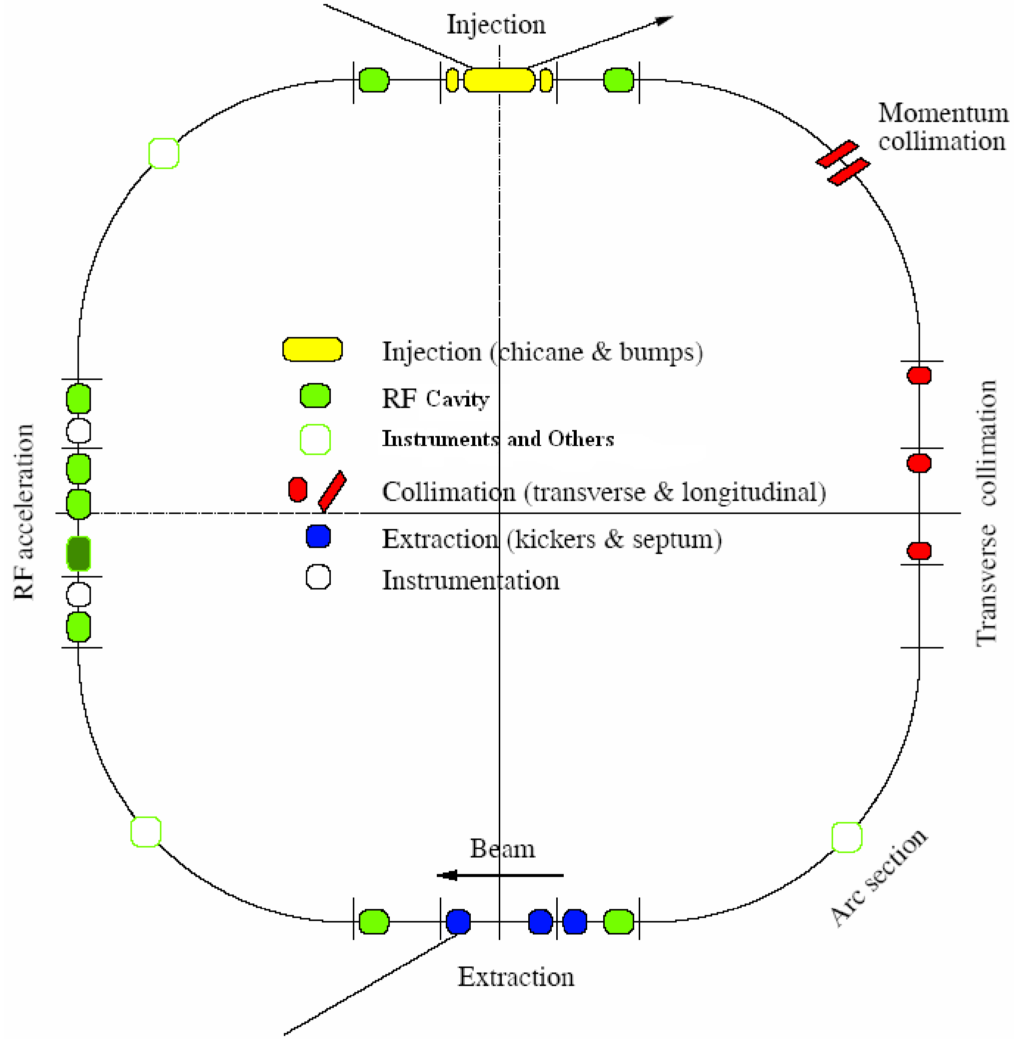


Lattice design procedure

- The choice of the number of super-periodicity
- The choice of focusing cell
- The choice of length and bending angle of dipole
- The circumference
- The dispersion depression
- The generation of long dispersion free straight section

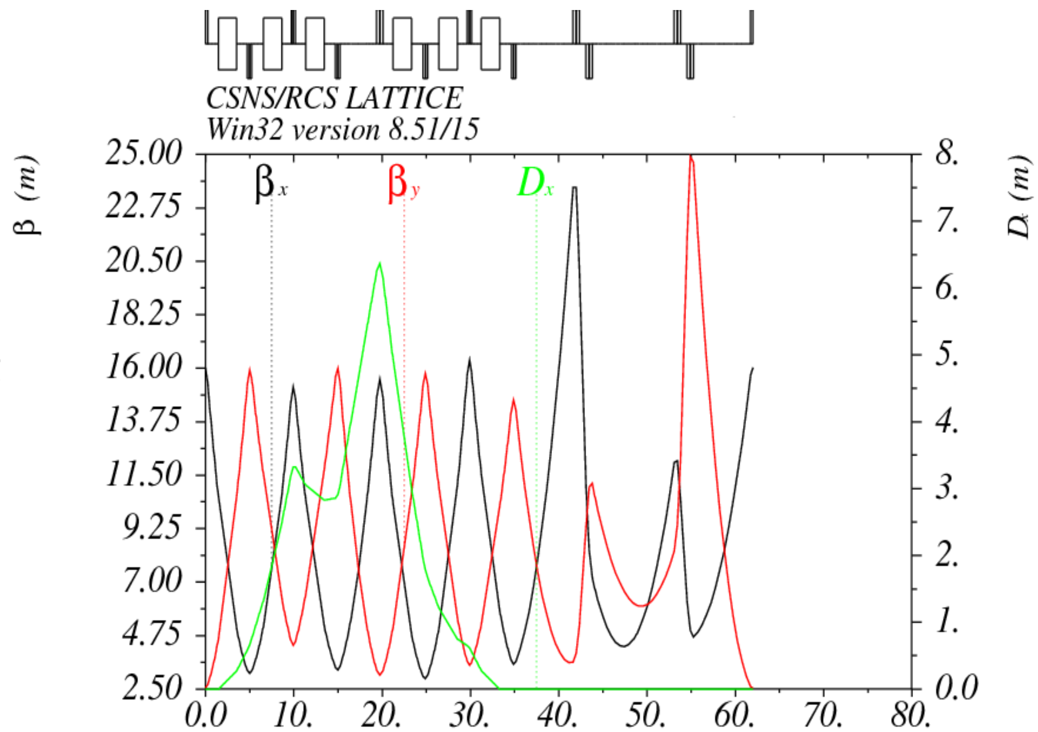
CSNS/RCS Lattice Design－4-fold Structure

- **Separated-function design**
- **The collimation be performed in a separate straight section.**
- **The superperiodicity of 4 is better for reducing the impact of low-order structure resonance than the superperiodicity of 3.**



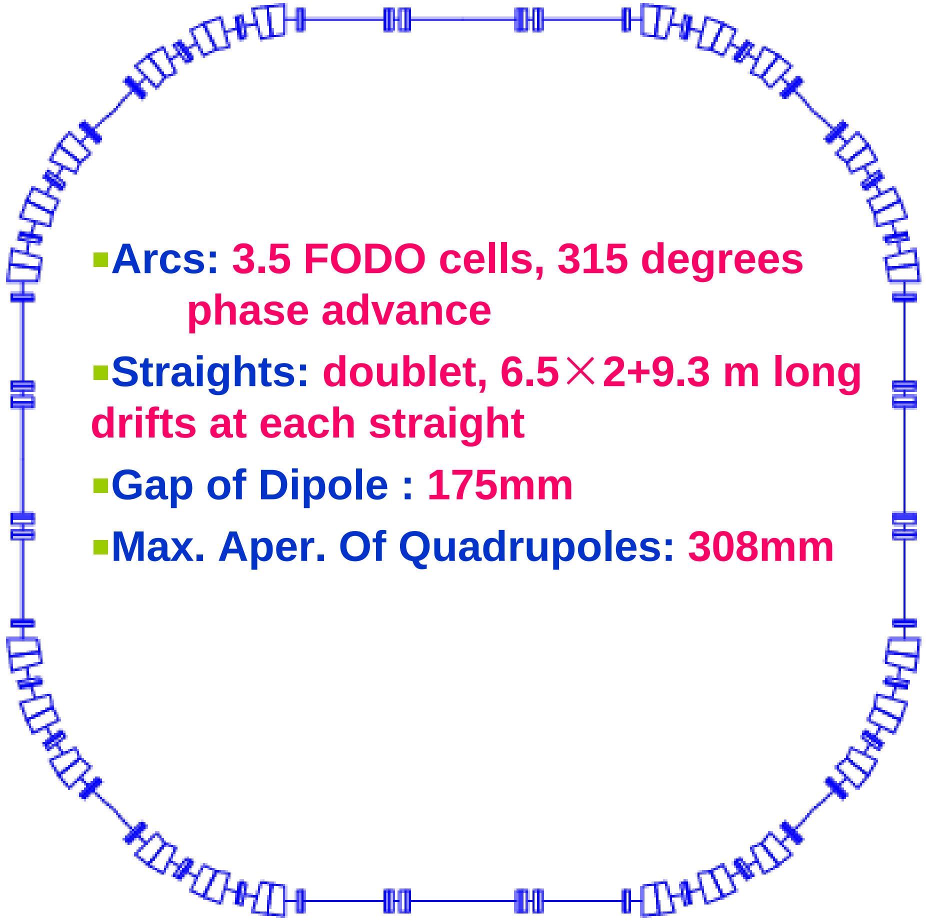
A Lattice with FODO Arc and Doublet straight

- **Four-fold symmetry**
  - **Separated functions**
- **FODO arc (3.5 cell at each arc)**
  - **Easy correction**
- **Dispersion-free doublet straight**
  - **long, uninterrupted straight for collimation & injection**
- **Missing-gap momentum collimation**
  - **Good for momentum collimation**
- **Larger B gap and Q aperture decided by intrinsic characteristic of FODO structure**



A Lattice with FODO Arc and Doublet straight

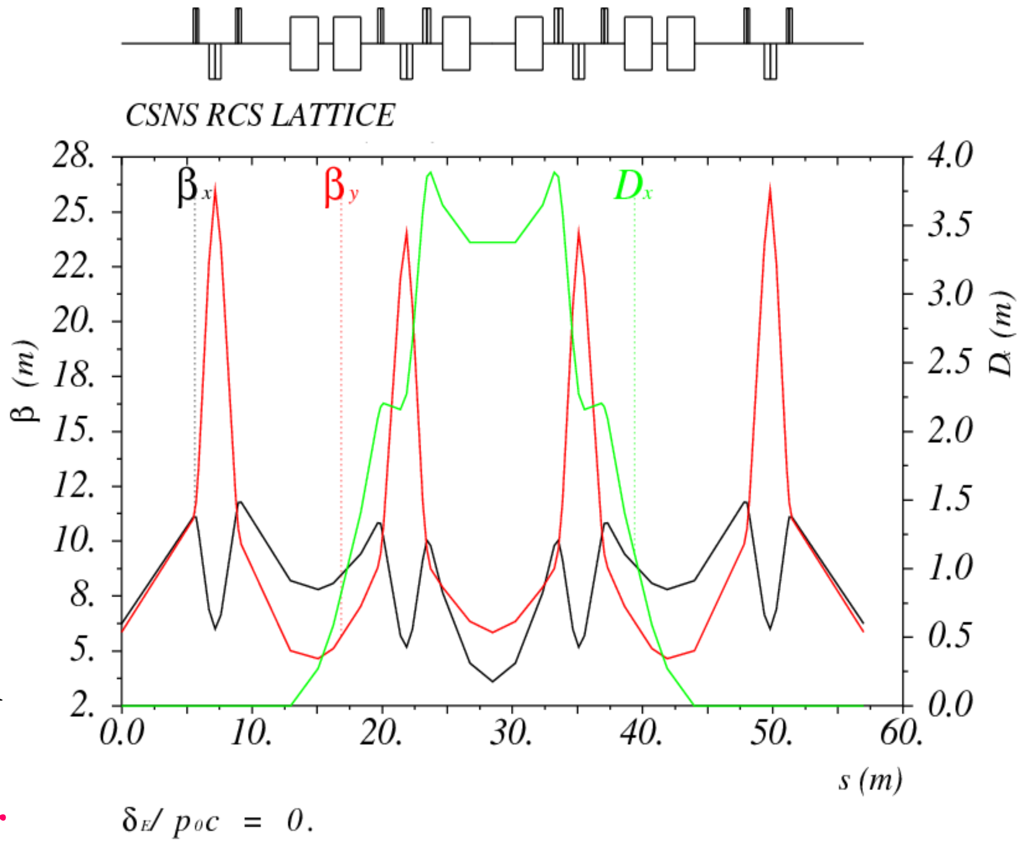
Lattice consists of FODO arc (with missing gap) and doublet dispersion free straight section



- Arcs: 3.5 FODO cells, 315 degrees phase advance
- Straights: doublet, 6.5×2+9.3 m long drifts at each straight
- Gap of Dipole : 175mm
- Max. Aper. Of Quadrupoles: 308mm

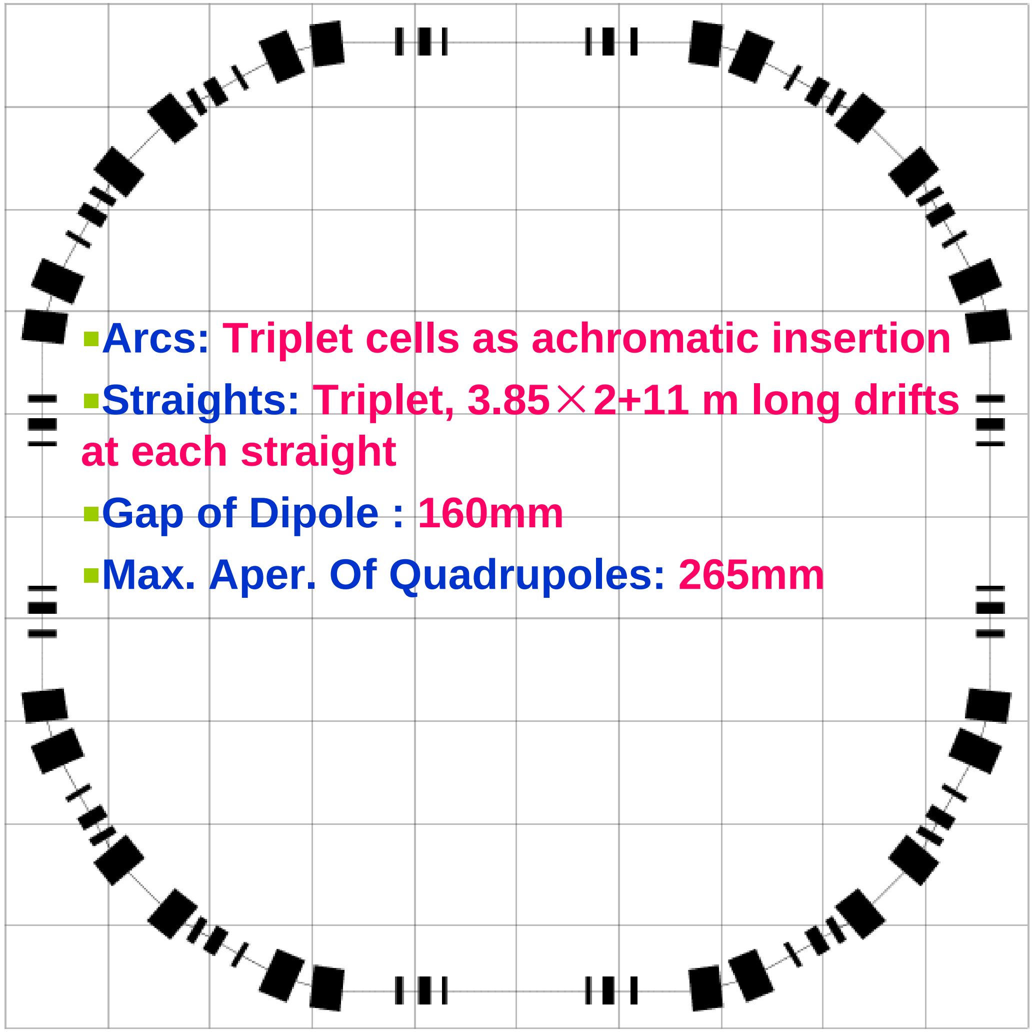
A Lattice with Triplet Cells

- Four-fold symmetry
  - Separated functions
- Triplet structure
  - Small magnet aperture
- Dispersion-free long uninterrupted straight
  - For collimation & injection/extraction
- Straight at arc with large dispersion
  - High efficiency momentum collimation
- The all-triplet structure is not good for chromaticity correction and dynamic aperture



A Lattice with Triplet Cells

Lattice consists of 16 triplet cells, with a gap in the middle of arc and dispersion free straight section .



- Arcs: Triplet cells as achromatic insertion
- Straights: Triplet, 3.85×2+11 m long drifts at each straight
- Gap of Dipole : 160mm
- Max. Aper. Of Quadrupoles: 265mm

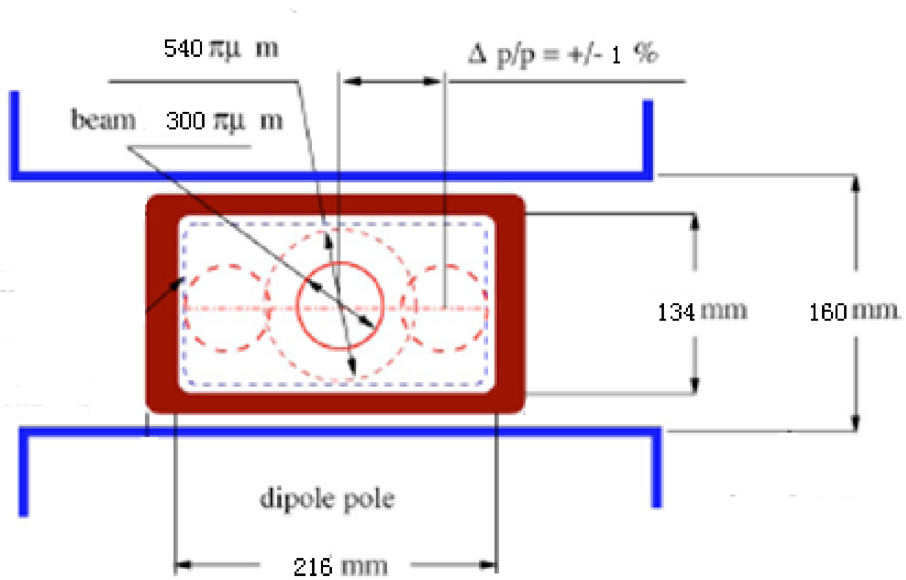
The primary parameters of two lattice schemes

Scheme	Triplet	FODO+Doublet
Circumference (m)	227.92	235
Superperiod	4	4
Number of dipoles	24	24
Number of quadrupoles	48	48
Lattice structure	Triplet	FODO+Doublet
Total Length of long drift (m)	3.85*8+11*4	6.5*8+9.3*4
Nominal Betatron tunes (h/v)	4.82/4.80	5.82/5.80
Chromaticity (h/v)	-4.3/-9.2	-6.6/-7.3
RF Freq. (MHz)	1.02~2.44	0.99~2.39
RF Voltage (kV)	165	165
Trans. acceptance (μπm.rad)	540	540
Momentum acceptance	1%	1%
Effective length of dipoles(m)	2.1	2.1
Dipole gap (mm)	160	175
Max. quadrupole aperture (mm)	265	308
Effective length of quadrupole(mm)	410, 450, 600, 900	500, 700
Number of dipole power supplies	1	1
Number of quadrupole power supplies	5	7

Emittance and Acceptance

Acceptance refers to the phase-space area within which particles oscillate stably. A large acceptance is essential to achieving a low-loss operation.

- betatron oscillations;
- the off-momentum closed orbit due to dispersion;
- closed-orbit deviation due to dipole field errors,
- β beating
- ……



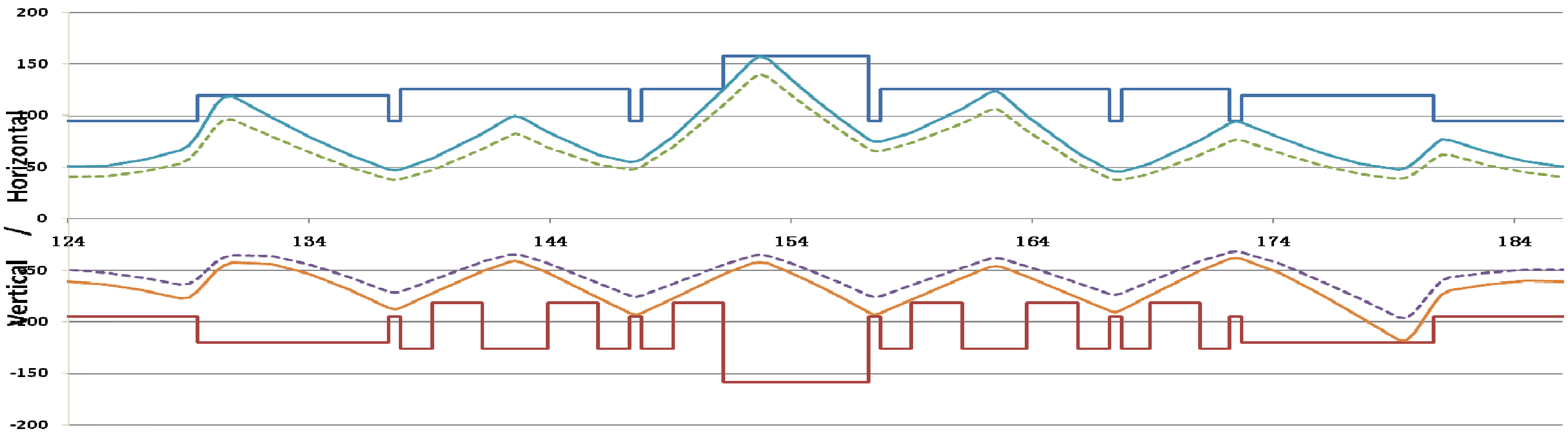
Aperture of magnet

Full aperture of magnet aperture:

$$\Phi_x = 2\times(\sqrt{\varepsilon_x\beta_x} + D_x\delta) + 26mm$$

$$\Phi_y = 2\times\sqrt{\varepsilon_y\beta_y} + 26mm$$

A momentum acceptance ±1%



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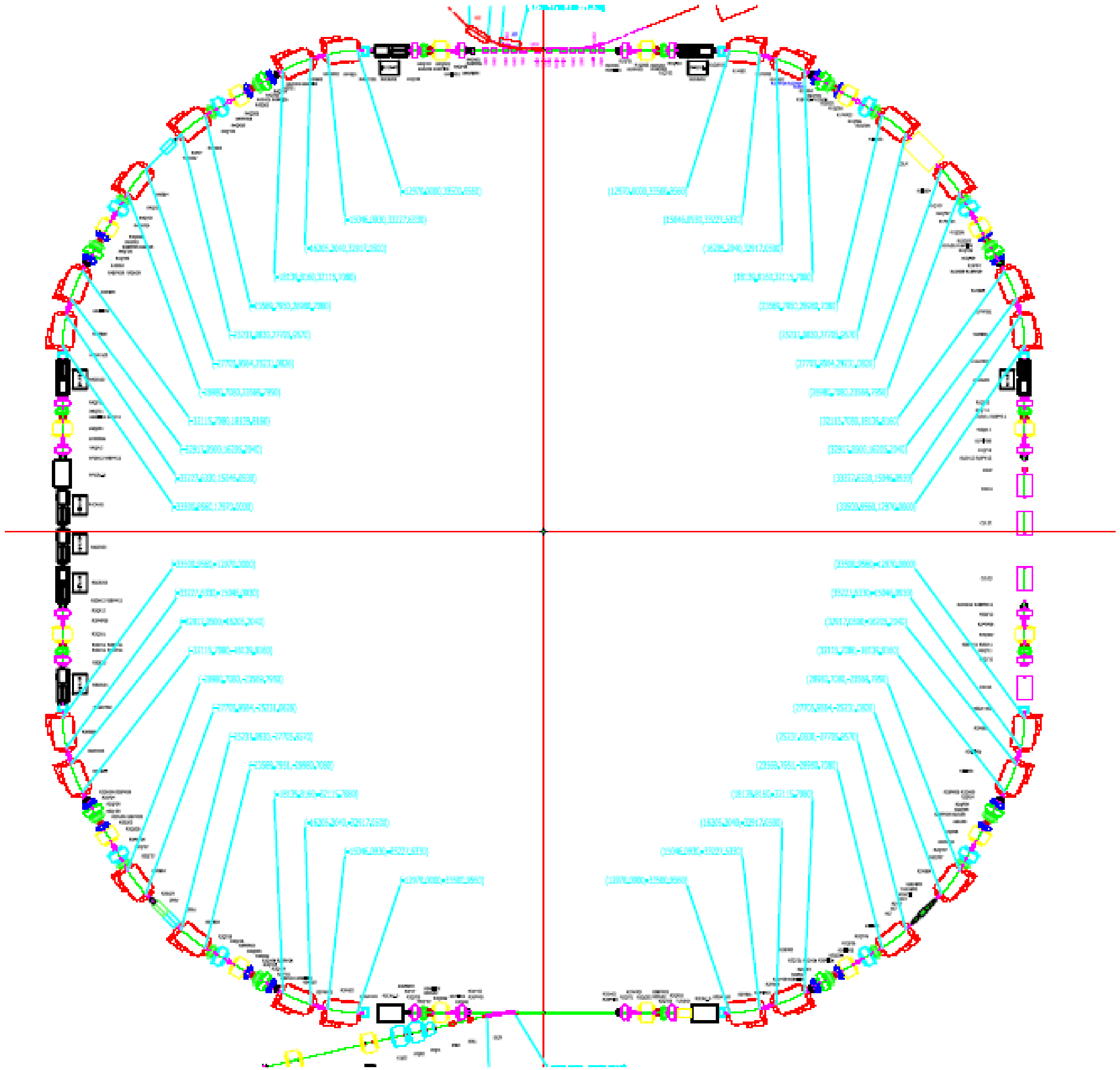
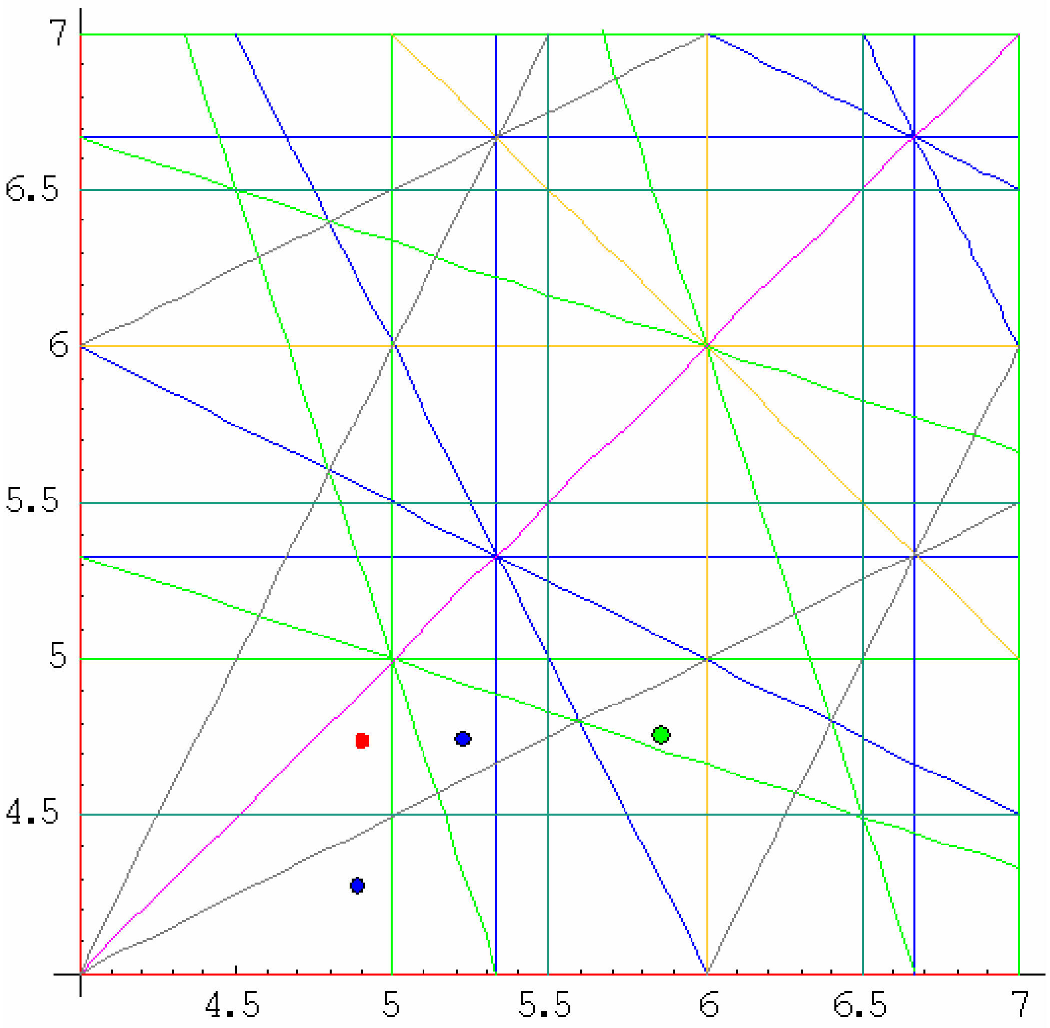
散裂中子源
China Spallation Neutron Source

RCS Components Layout



Tune Diagram for 4-fold Structure



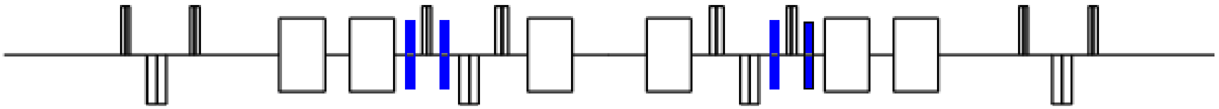
red: 1st order structure resonance
golden: 2nd order structure resonance
blue: 3rd order structure resonance
green: 4th order structure resonance
gray: 3rd deference structure resonance
pink: coupling resonance

$$mQ_x + nQ_y = 4l$$

m,n=0,±1,±2,±3,…

The Optics Correction

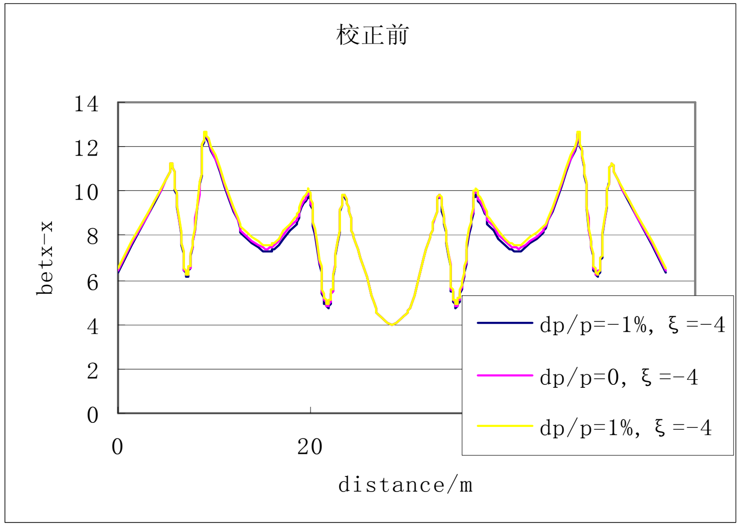
Chromaticity Correction

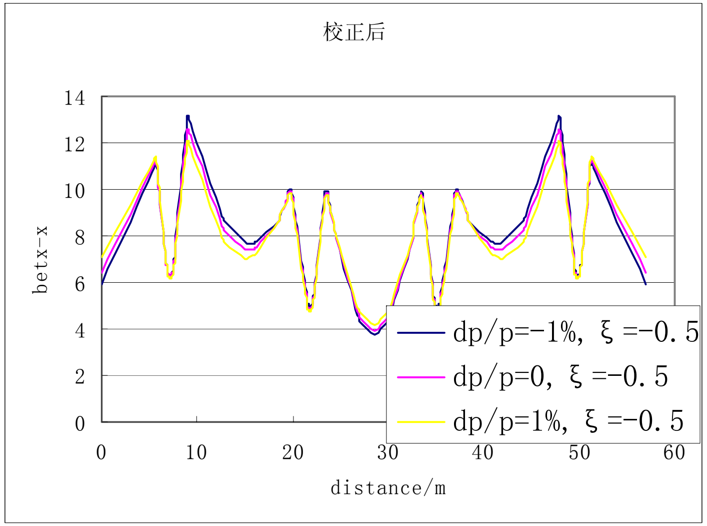


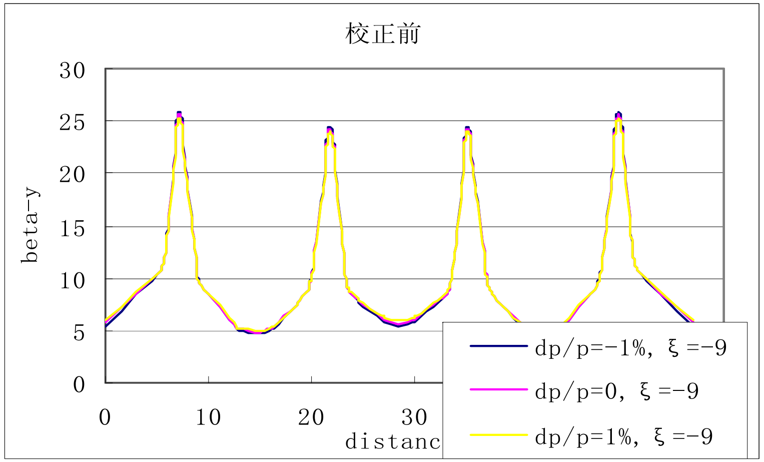
- Powered with DC power supply
- 2 families power supplies
- Designed for low beam density

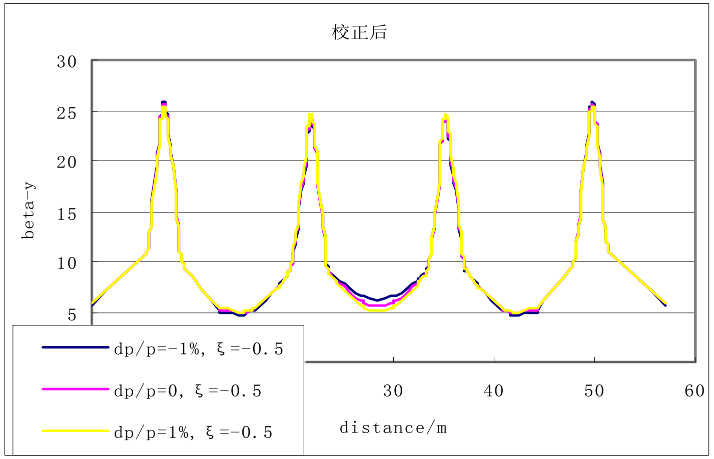
  - for commissioning

The twiss parameters for off-momentum particles with different chromaticity

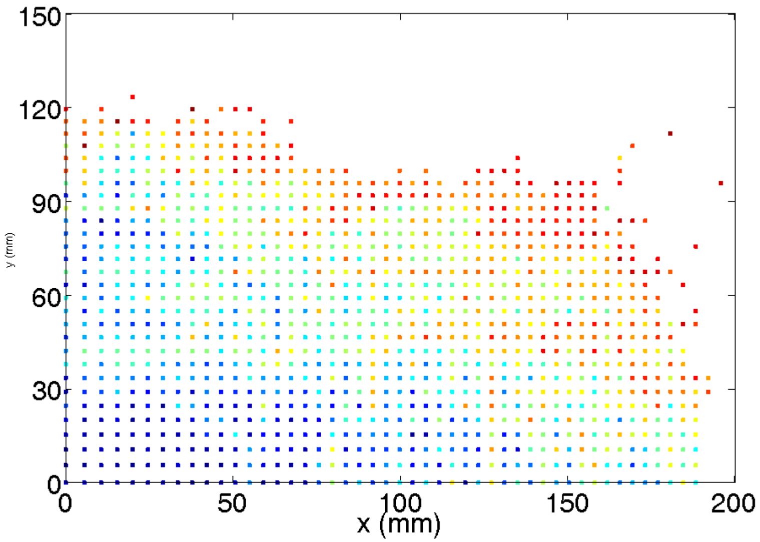


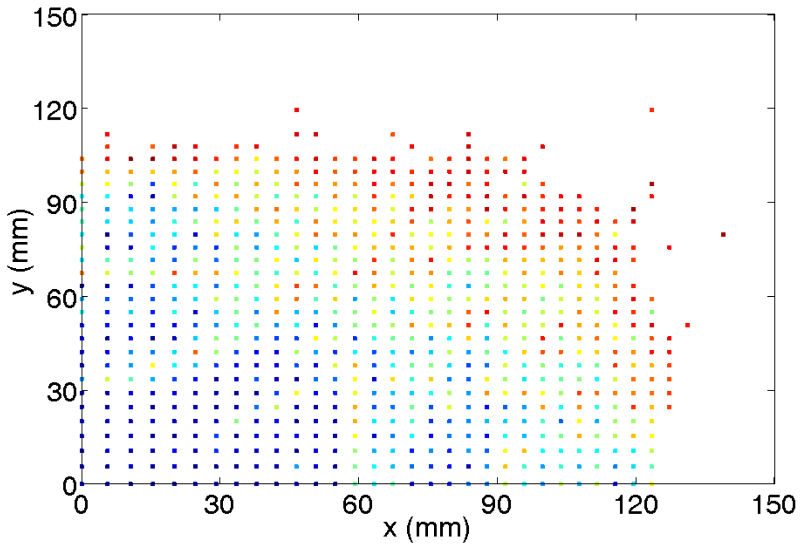






Dynamic Aperture



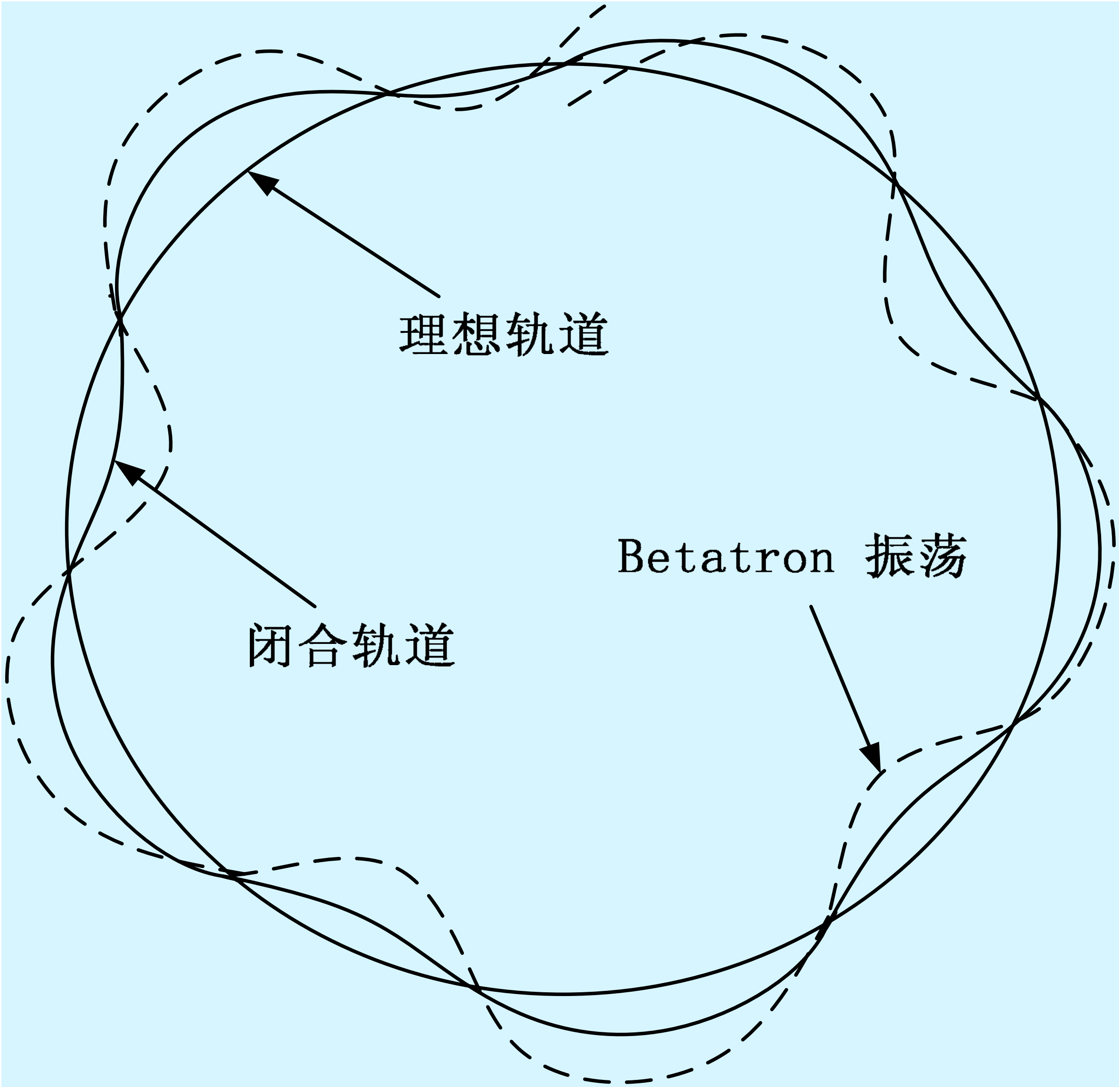


4.5 σ x×2.5 σ y, Δp/p=±1% with sextupoles

2.5 σ x×2 σ y, Δp/p=±1% with sextupoles and high order field of dipoles and quadrupoles

σ x and σ y are h and v beam size (320 π mm.mrad)

Closed orbit distortion and correction



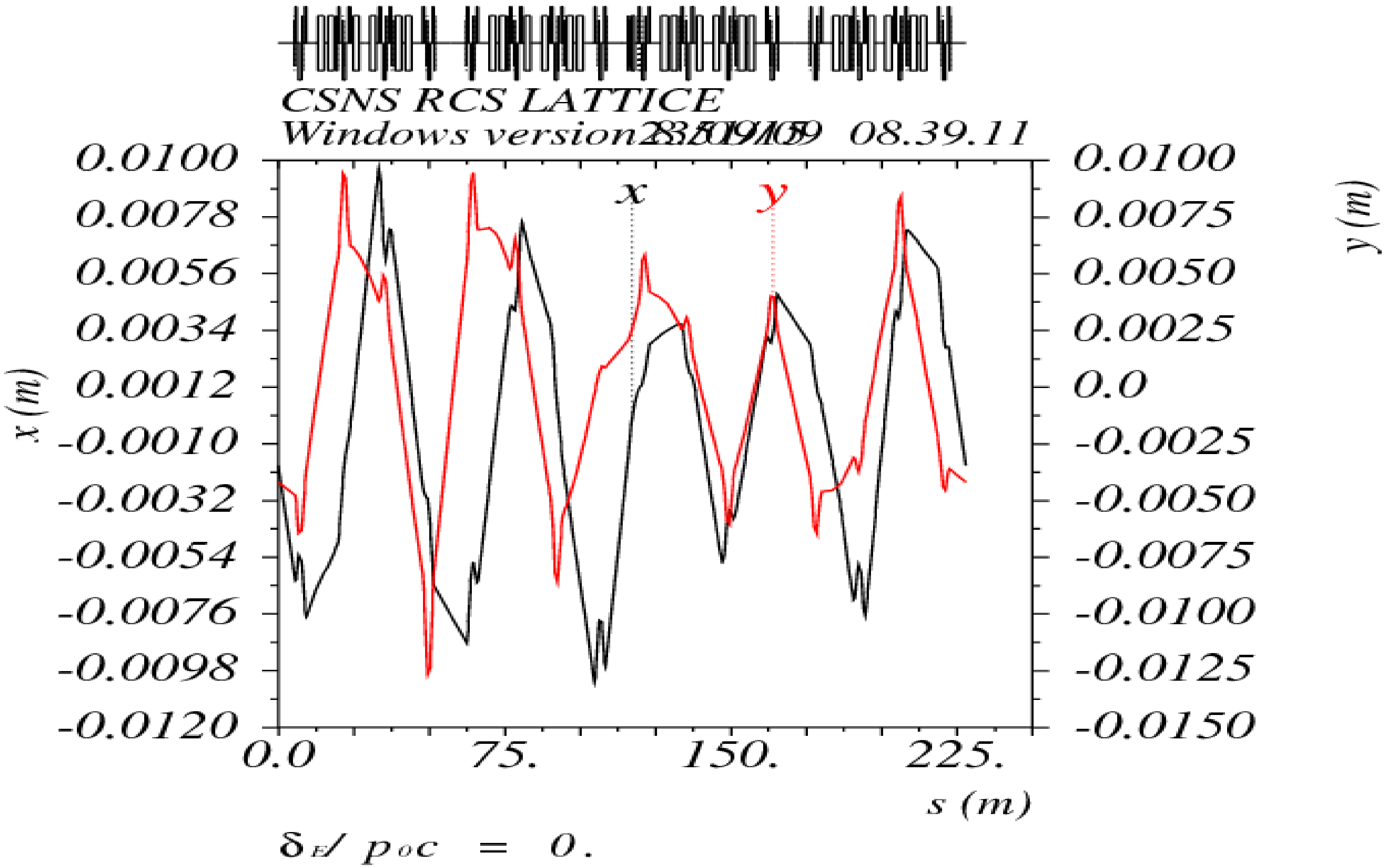
Closed Orbit Distortion and Correction

- **32 BPM for COD correction, two in each triplet cell**
- **34 dipole correctors , 17 for horizontal and 17 for vertical plane**
- **The power supply for dipole corrector is programmable**
- **The dipole corrector should be ramped from 10 to 20 steps during one RCS cycle**
- **The maximum correction ability of dipole corrector is 1mrad at 1.6GeV**

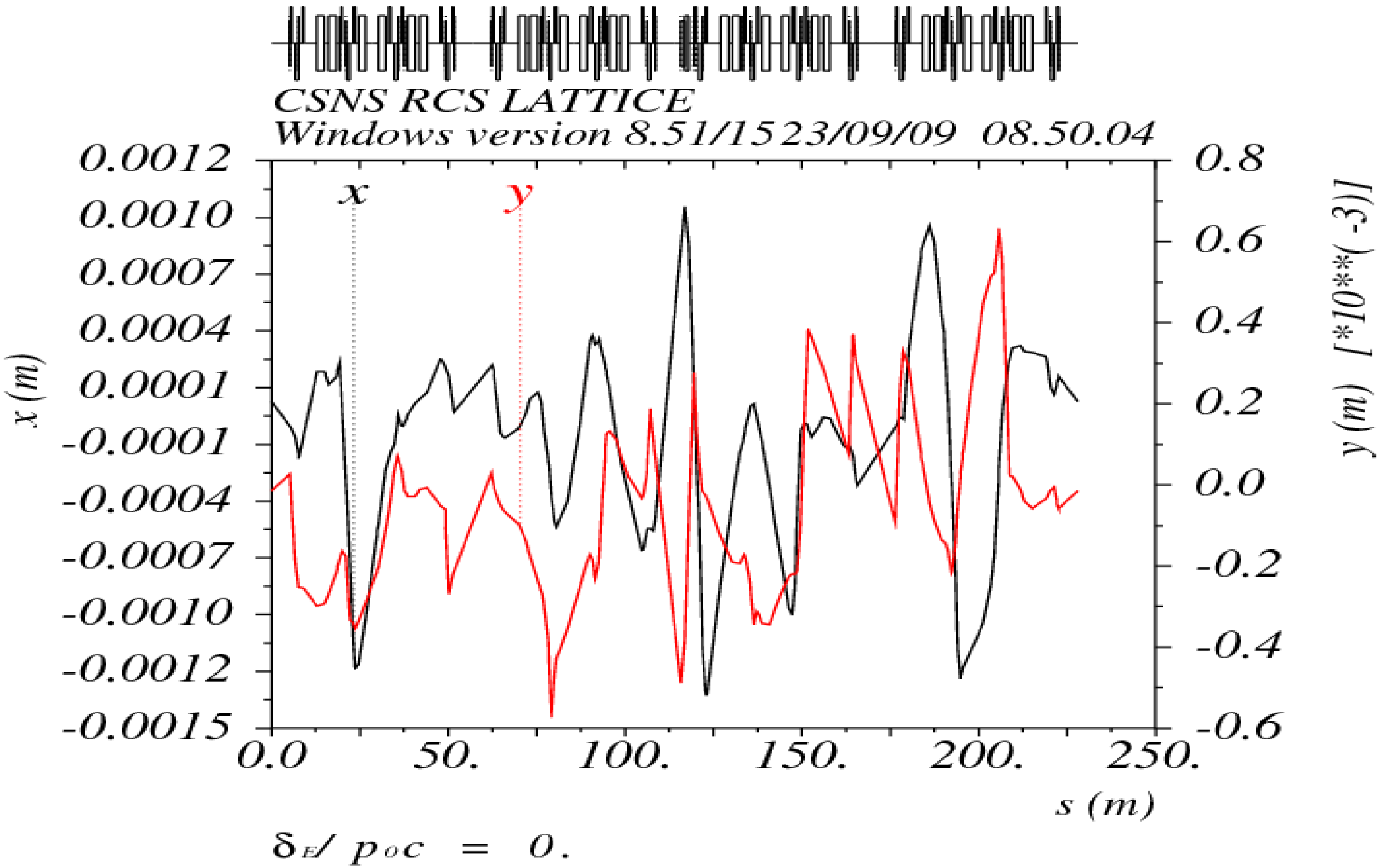
The Alignment Goal for RCS

Components	Δx (mm)	Δy (mm)	Δz (mm)	$\Delta\theta_x$ (mrad)	$\Delta\theta_y$ (mrad)	$\Delta\theta_z$ (mrad)
Dipoles	0.2	0.2	0.2	0.2	0.2	0.1
Quadrupoles	0.15	0.15	0.5	0.5	0.5	0.2
Sextupoles	0.15	0.15	0.5	0.5	0.5	0.5
Correctors	0.3	0.3	1.0	1.0	1.0	0.5
BPMs	0.15	0.15	0.5			

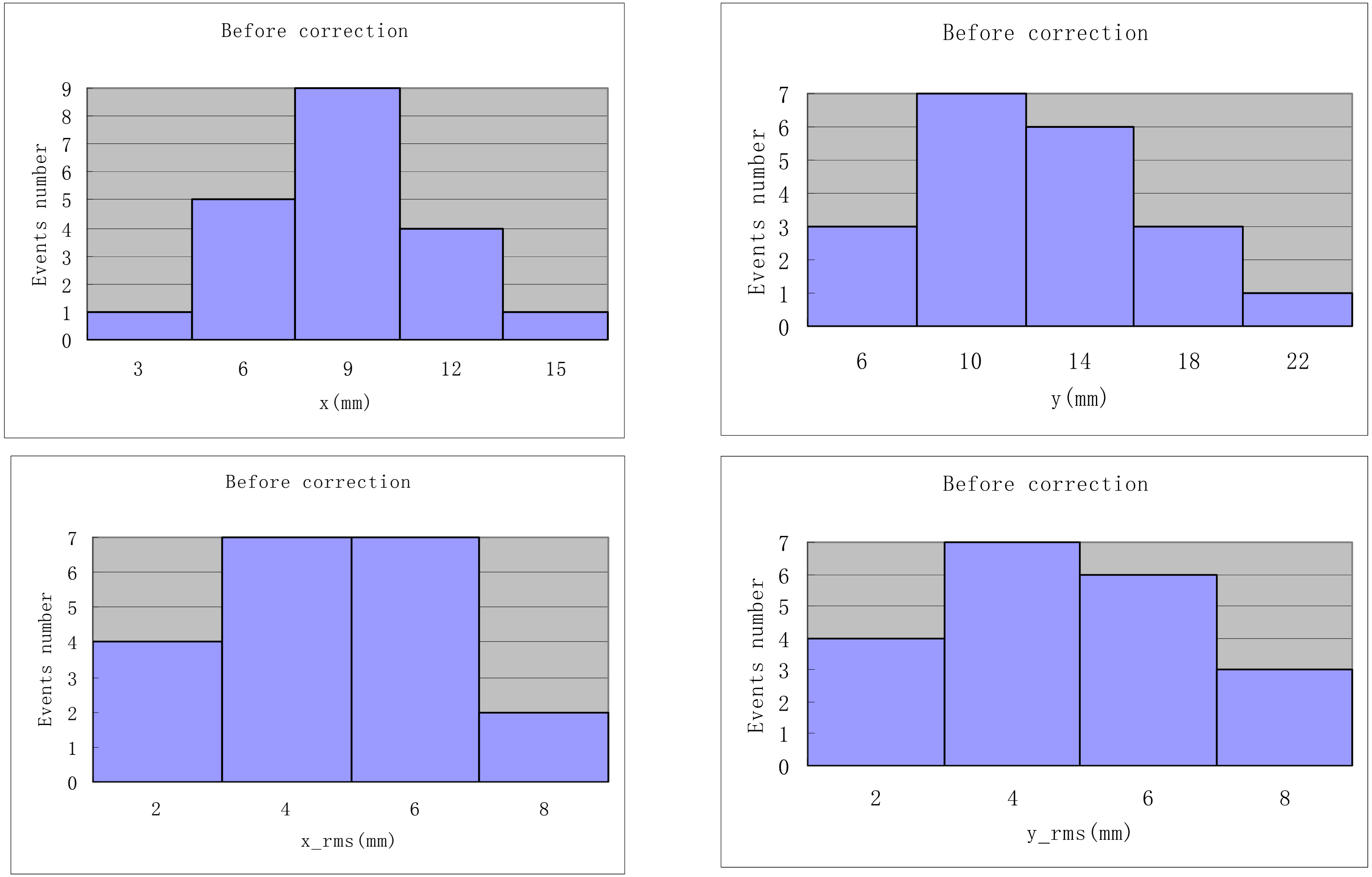
Closed orbit distortion



COD correction

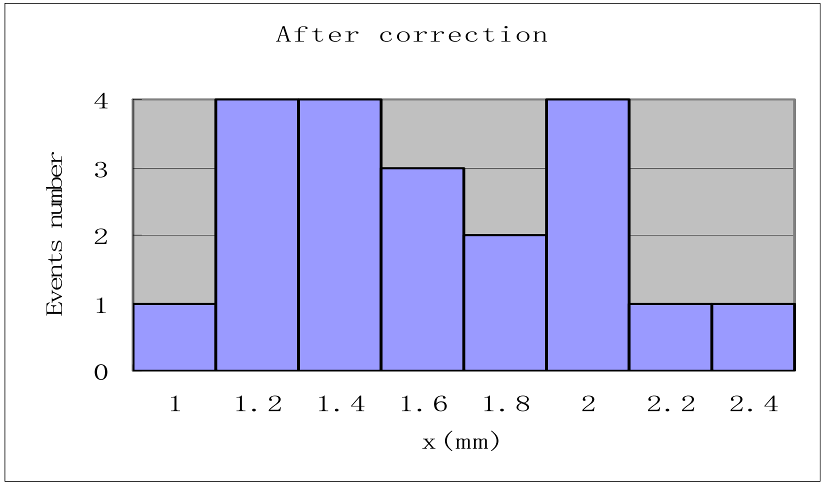


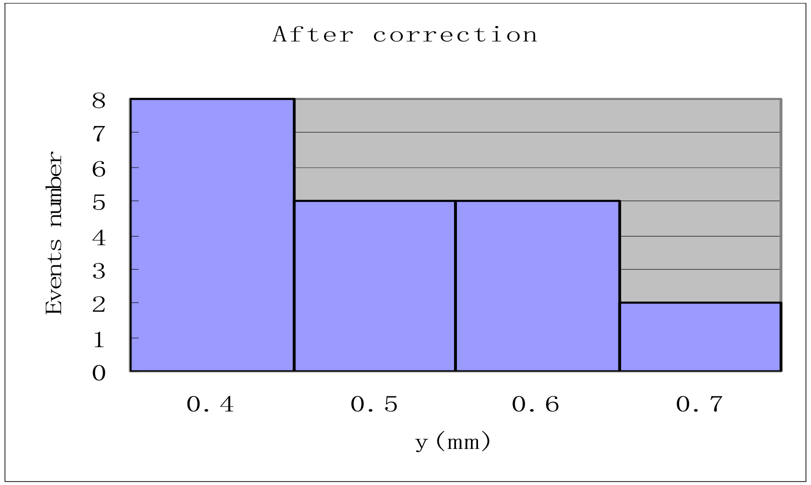
Closed orbit distortion with alignment and field errors

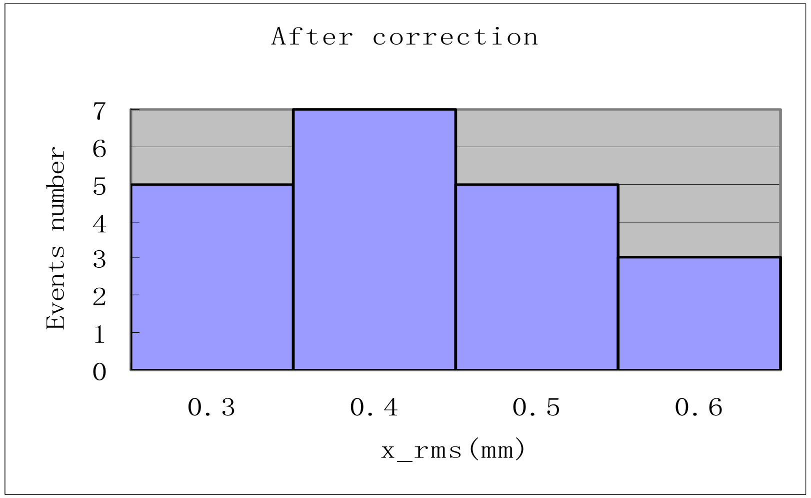


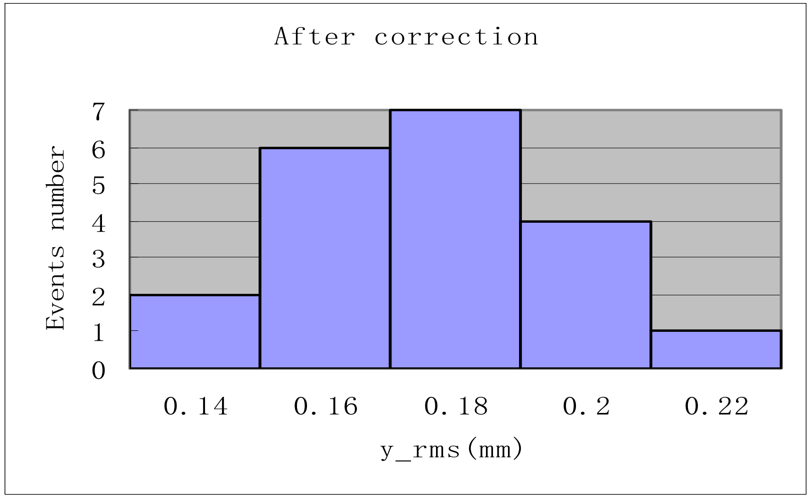
Statistics for 20 groups of random errors

COD Correction





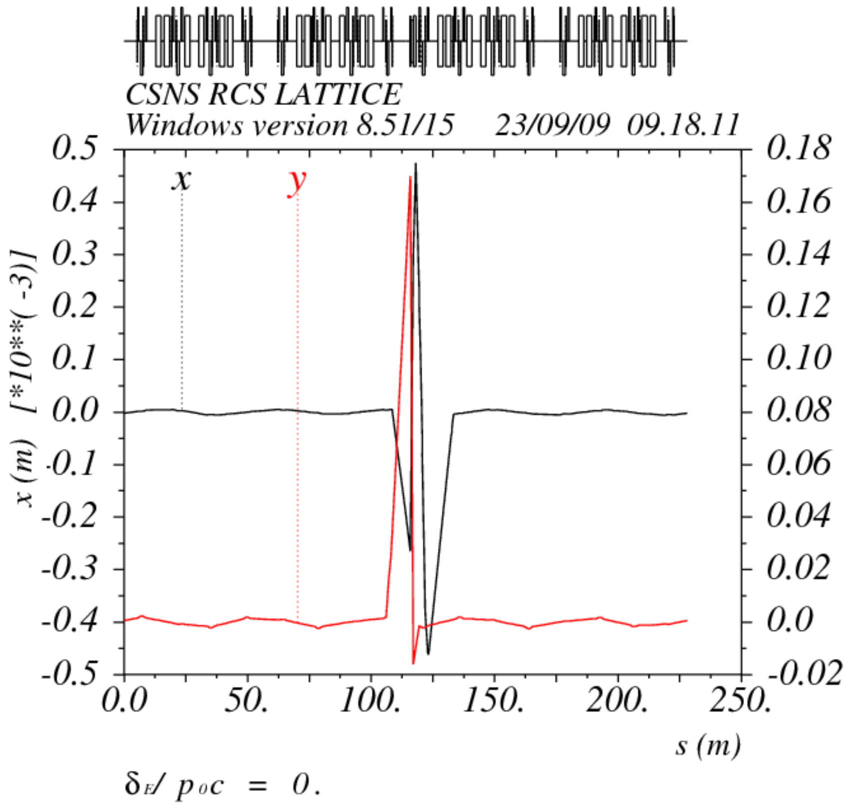




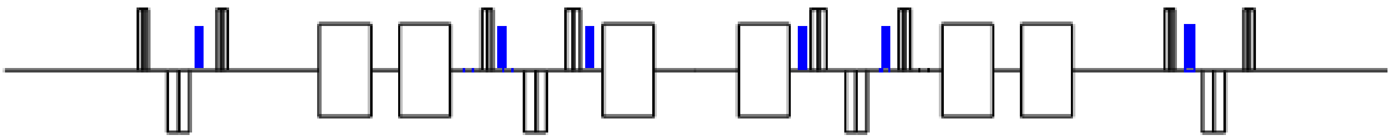
Statistics for 20 groups of random errors

Local COD Correction

- Distortion to closed orbit due to the stray field of Lambertson and correction
- The stray field of DC Lambertson make distortion to the circulating beam, especially to the beam in low energy stage;
- OPERA-3D simulation shows the vertical stray field yields 0.7mrad impact to the beam of 80MeV;
- A local 3-bump is design to locally correct this distortion.

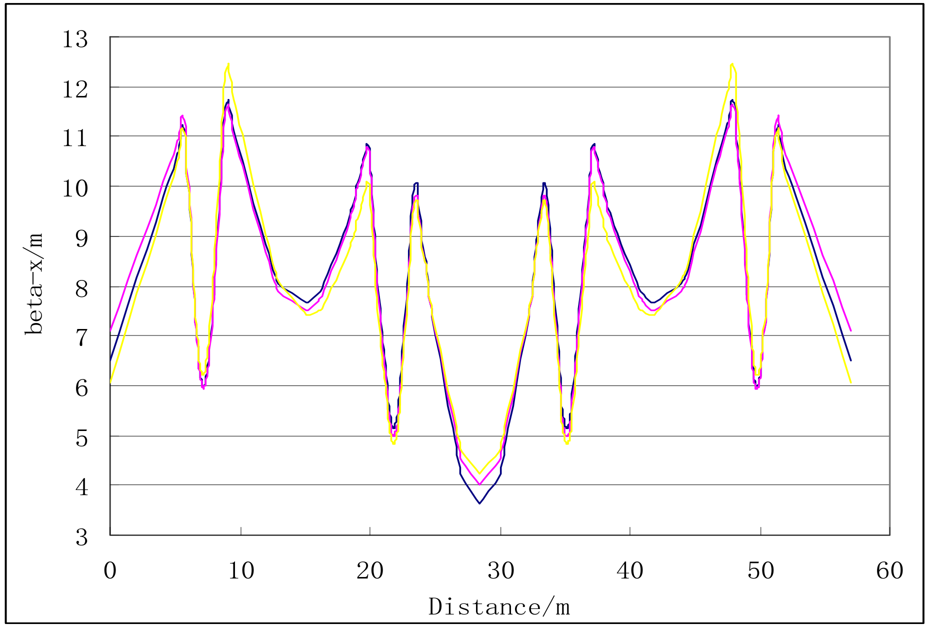


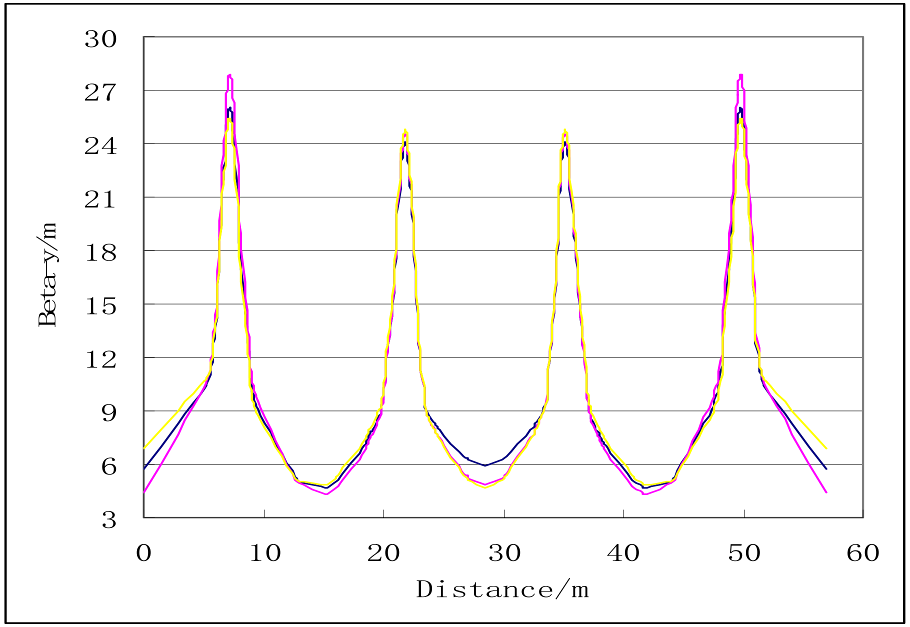
Tunes and Twiss parameter correction



- The saturation in high energy stage in an RCS cycle will lead to the mismatch between dipoles and quadrupoles, and make the deviation of twiss parameters and tunes. When the deviation is large, the correction is necessary.
- 24 trim quadrupoles are adopted in the optics design.
- Trim quadrupols are powered with programmable power supply.
- They also can be used to correct or compensate some of the space charge effect.
- The trim quadrupole also benefits to the response matrix beam measurement.

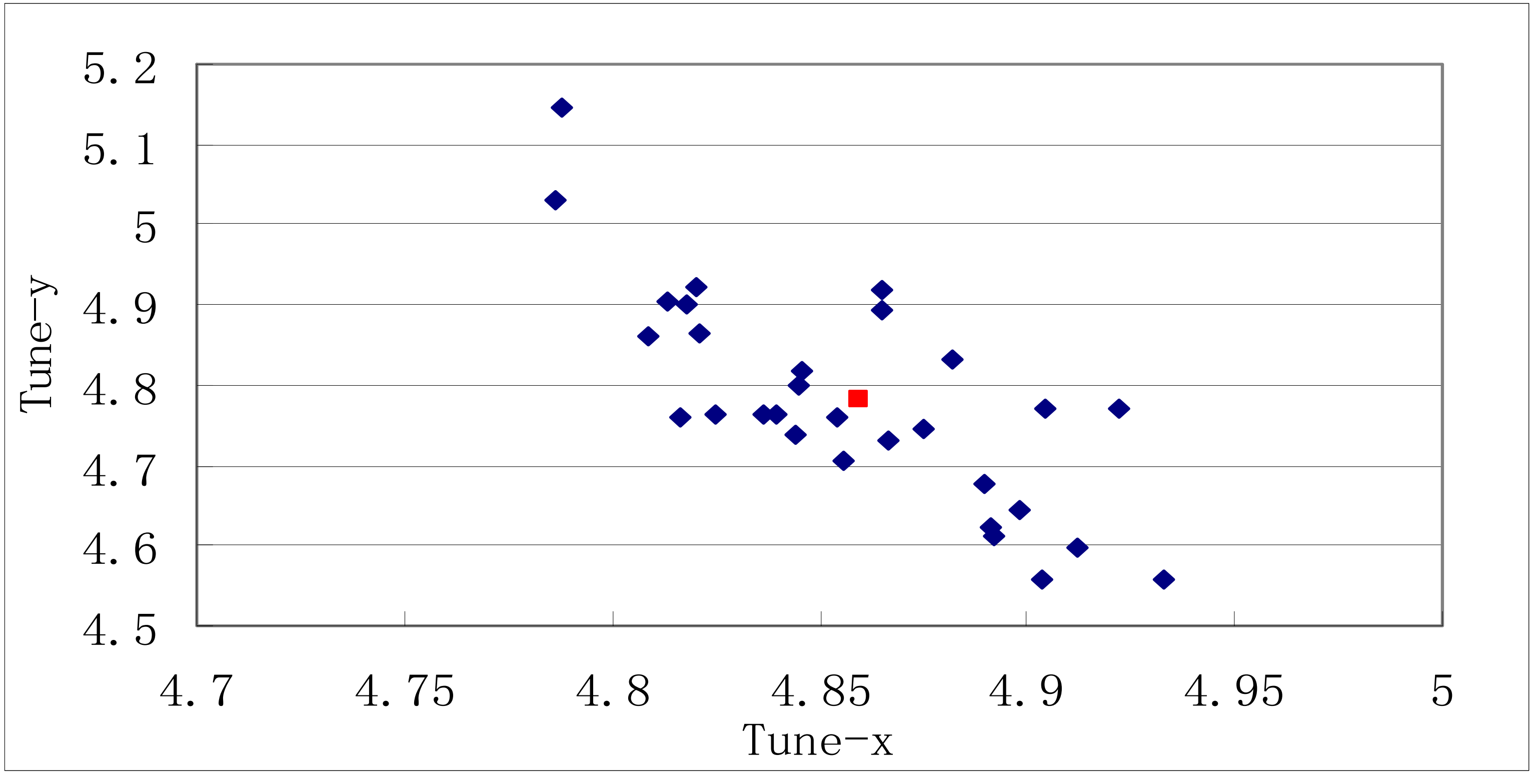
Twiss parameter distortion due to saturation errors



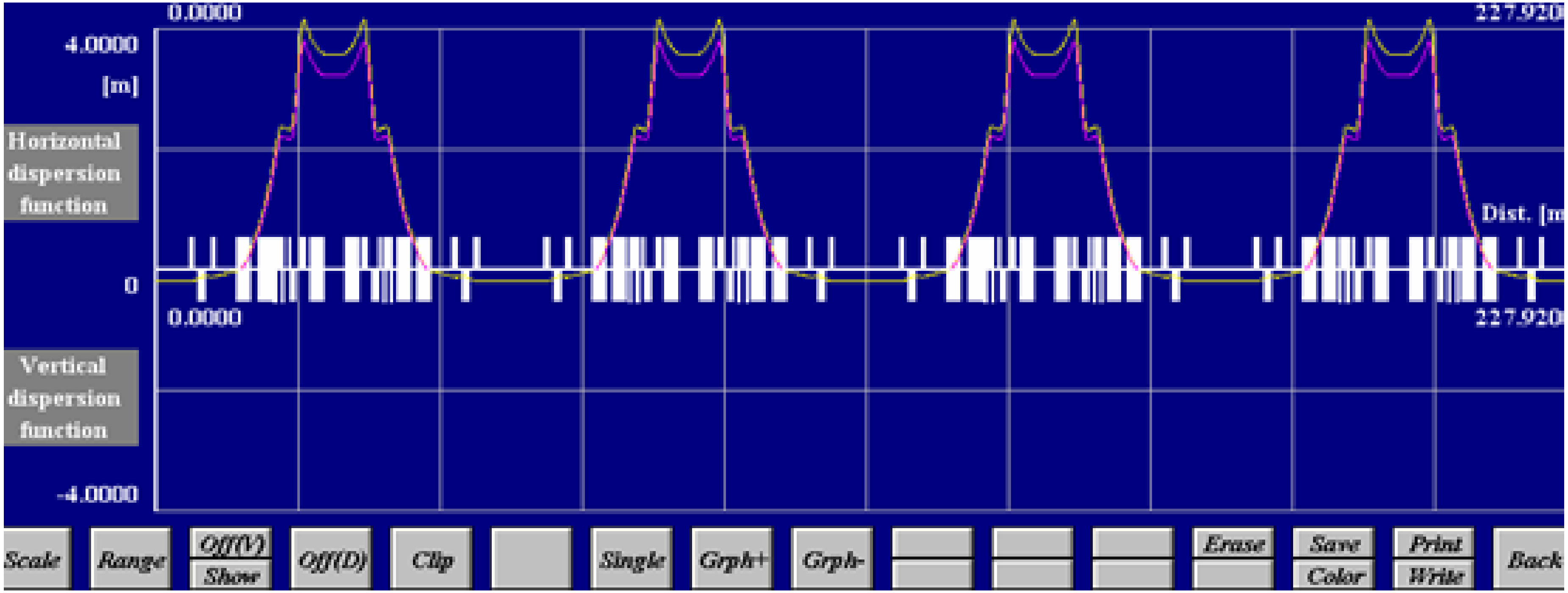


Blue represents nominal beta function, pink represents beta function with saturation errors (1%) and yellow represents beta function after correction

Tune shift due to saturation errors and correction



Compensation of space charge effects



Yellow: effected by space charge, pink: correction by trim Q

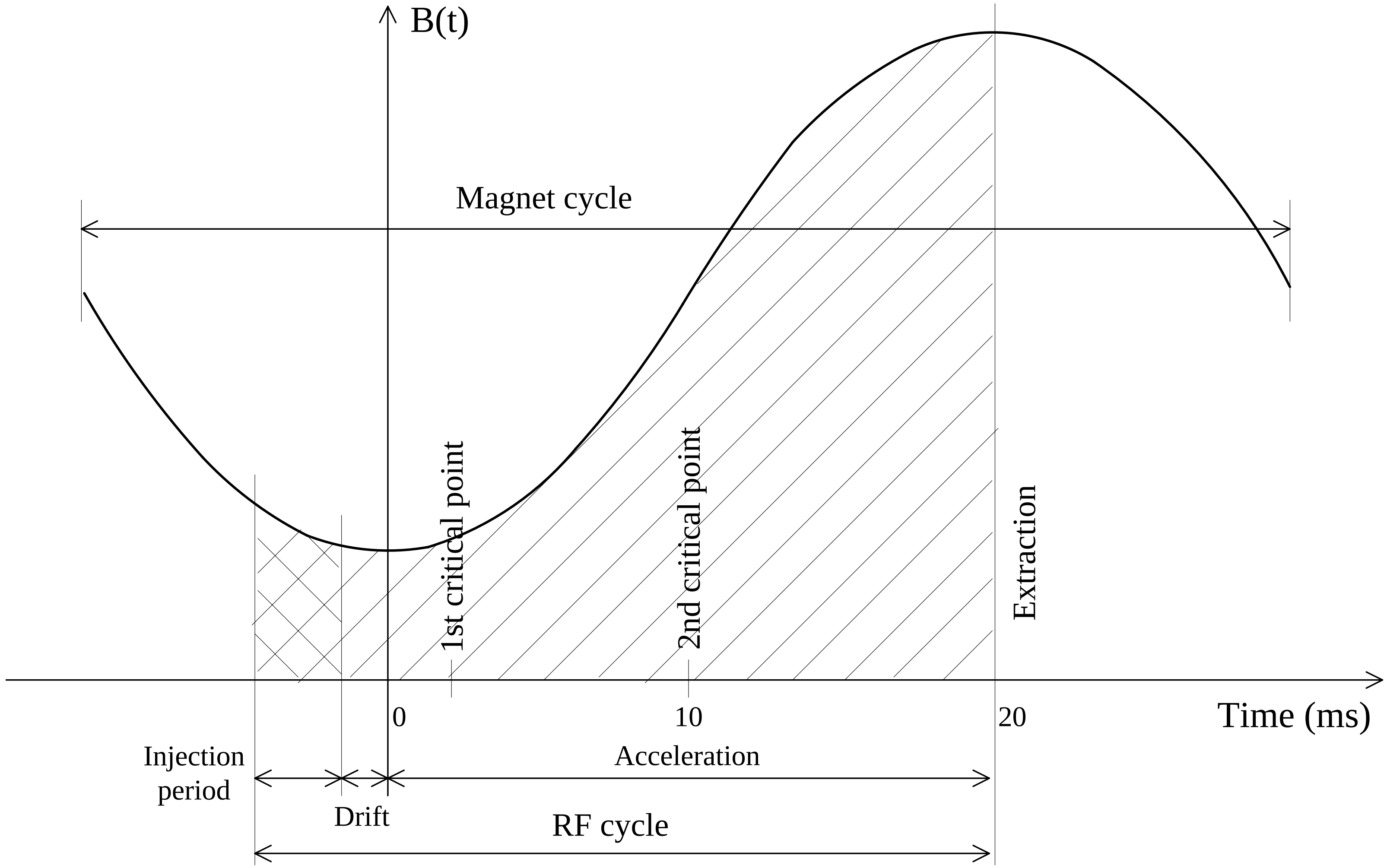
The tune by be changed by trim Q in different energy stage

Longitudinal Beam Dynamics Design

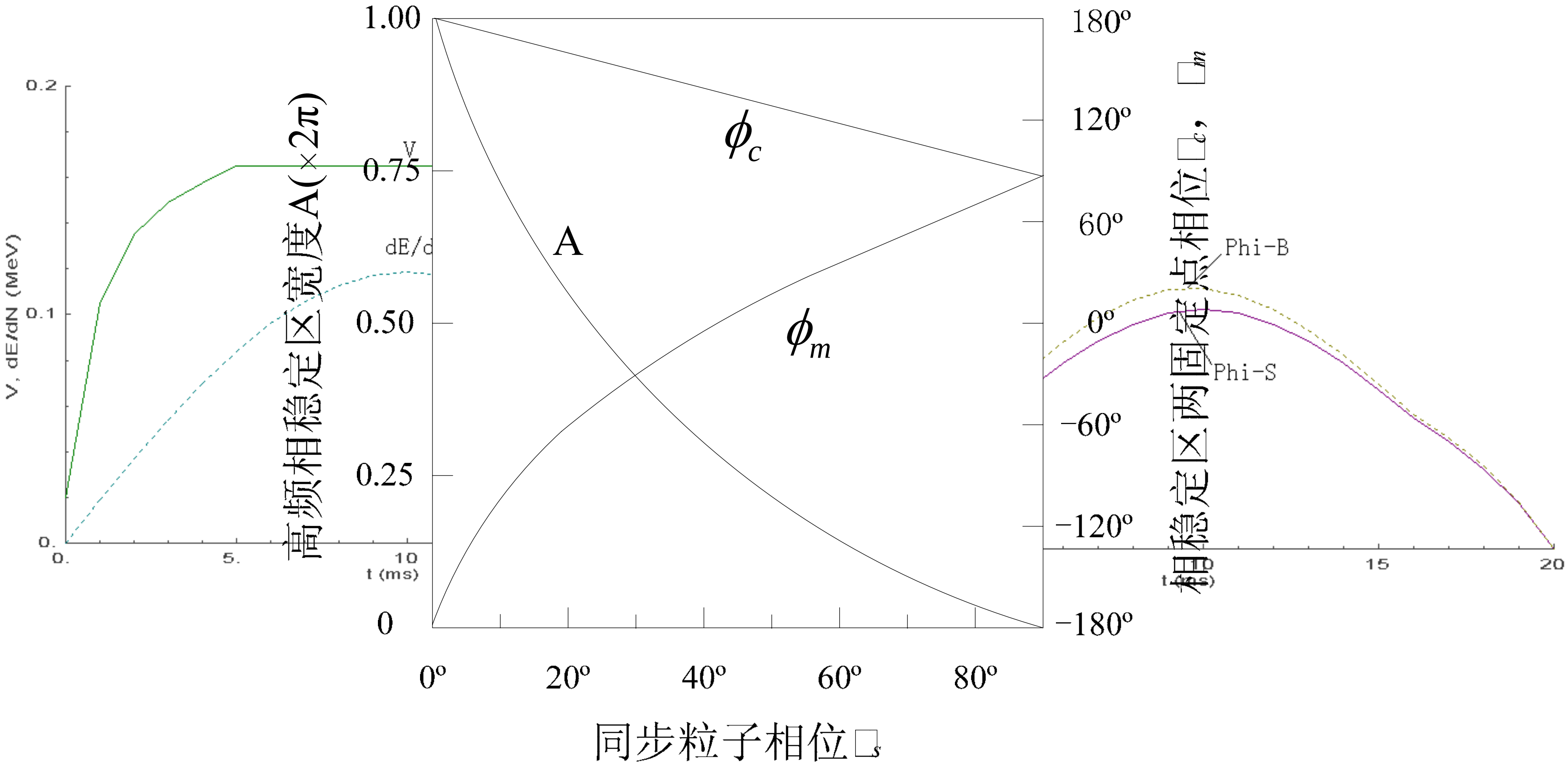
Longitudinal beam dynamics design

- **The RF cavities with harmonic number of 2 are adopted;**
- **Dual harmonic cavities will be added in the future upgrade for higher beam power;**
- **7 RF cavities provide total RF voltage of 165 kV, with one additional cavity for redundancy.**
- **The design of RF voltage and phase curves is an important issue to decrease the beam loss due to the space charge and phase changes**

An RF cycle

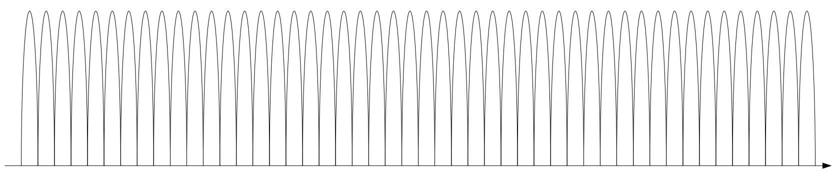

B(t)
Magnet cycle
1st critical point
2nd critical point
Extraction
0
10
20
Time (ms)
Injection
period
Acceleration
Drift
RF cycle

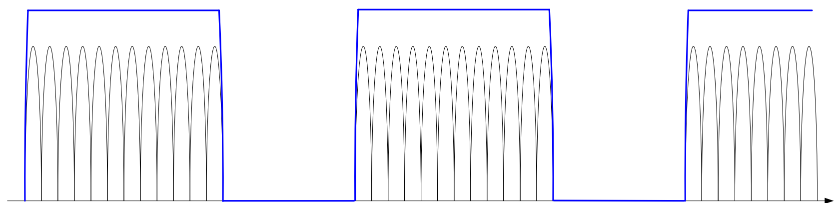
Voltage and Phase Curve

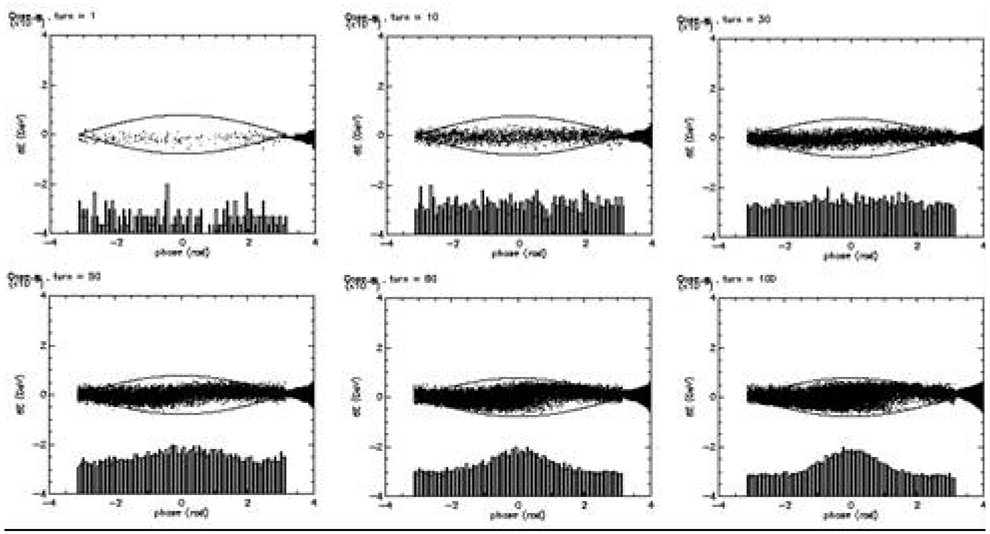


Chopping

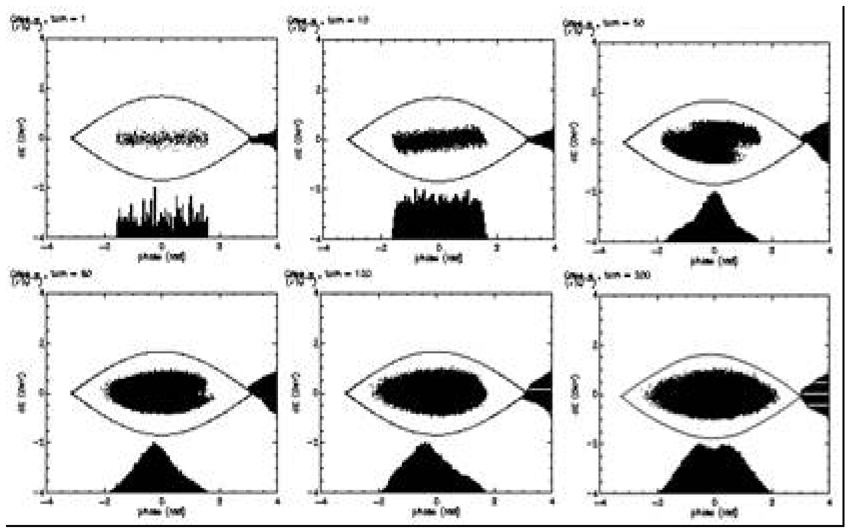
Chopper is located in the LEBT and/or MEBT of CSNS linac, for cleaning the particles out of the RF stable region. The voltage and phase curve need to be optimized according to different chopping rate.





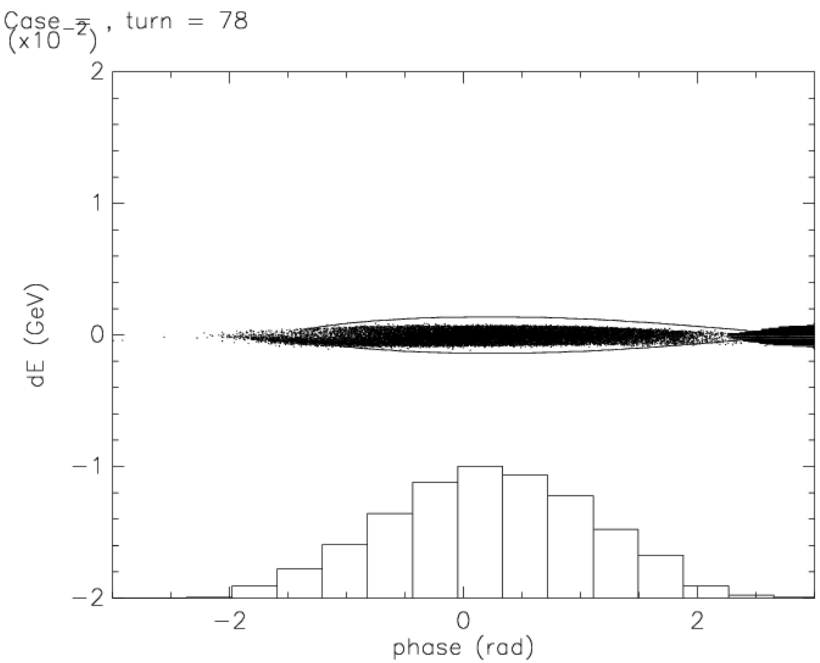


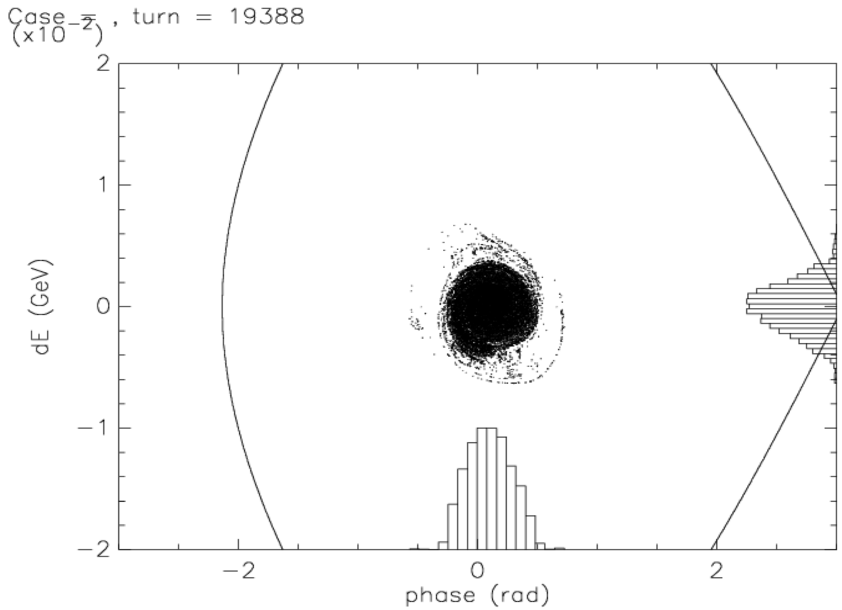
Without chopping



With chopping

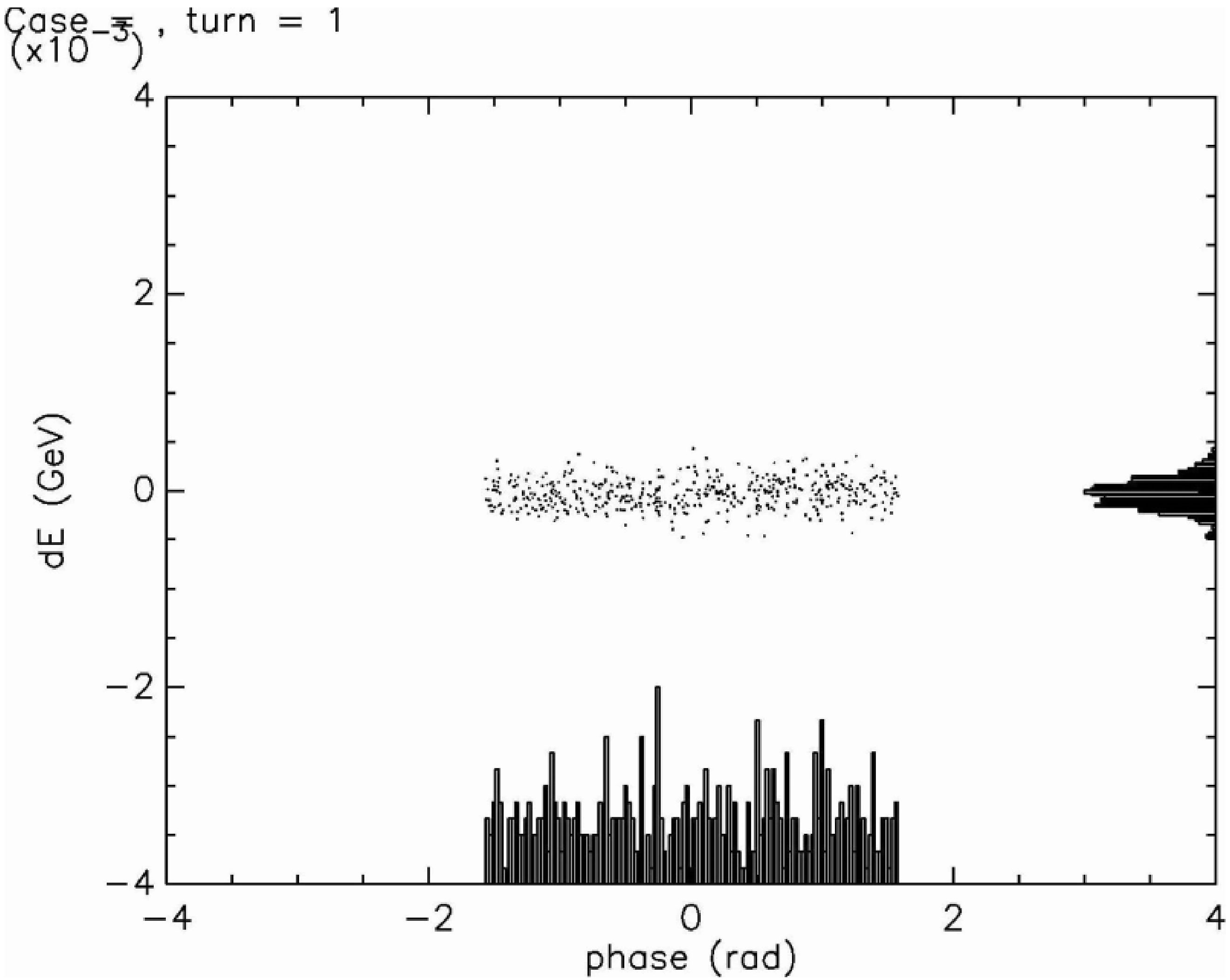
The Longitudinal Phase Space





Beginning of acceleration **End of acceleration**

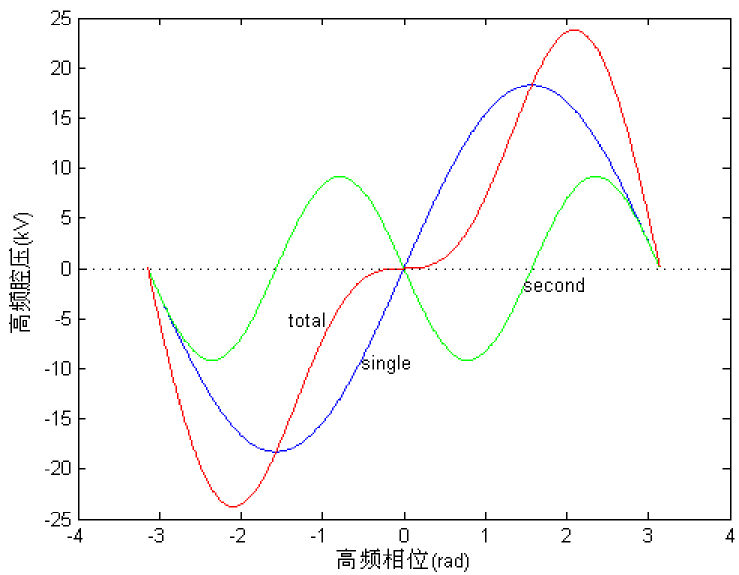
The Longitudinal Phase Space Evolution during a Cycle

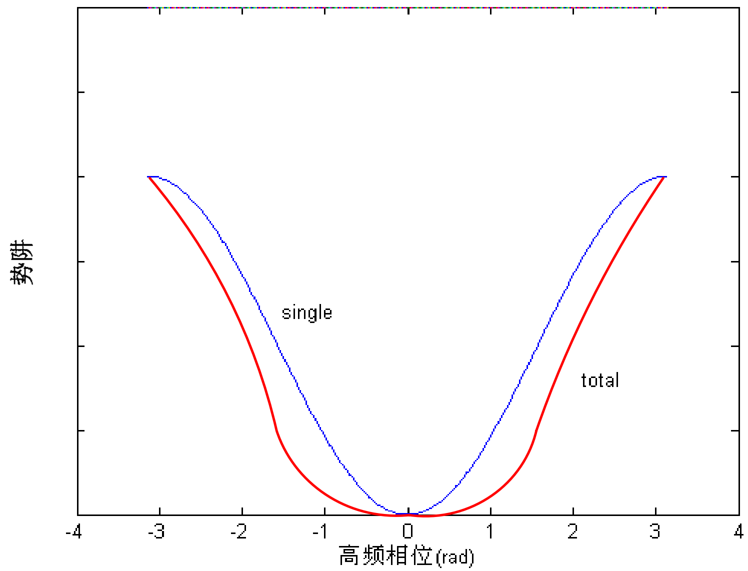


Dual Harmonic Acceleration

For getting more wide and flat potential well, to increase the bunch factor, so to decrease the transverse space charge effect

$$V = V1 \sin \varphi + V2 \sin (2\varphi - \theta)$$





Red line: the curve with dual harmonic acceleration; Blue line: curve for h=2, and green line for h=4

Beam Loss & Control

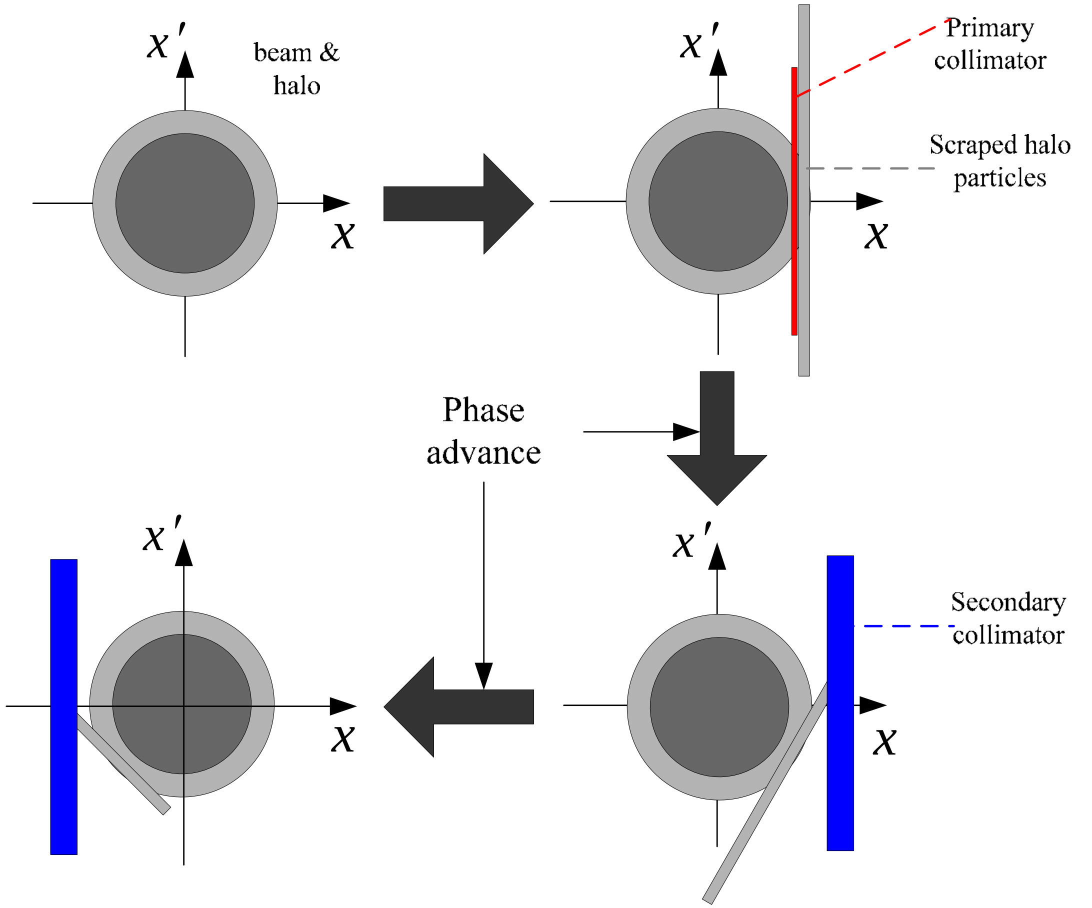
Beam loss limit

	损失束流能量	平均流强	最大束流损失功率	备注
	[MeV]	[μA]	[W/m, W]	
LEBT	0.05	400	4.0W	损失 20%
RFQ	1.5	220	150 W	Pre-chopping 束流损失
MEBT-chopper	3.0	156	190 W	30％束流损失在快 chopper 系统
DTL1	22	156	1 W/m	按手工维护要求
DTL2	42	156	1 W/m	按手工维护要求
DTL3	62	156	1 W/m	按手工维护要求
DTL4	81	156	1 W/m	按手工维护要求
DTL5	99	156	1 W/m	按手工维护要求
DTL6	116	156	1 W/m	按手工维护要求
DTL7	132	156	1 W/m	按手工维护要求
LRBT	130	156	1 W/m	按手工维护要求
LRBT collimator	130	155	20 W	动量尾巴切除，有局部屏蔽
Injection region	130	151	20 W	H-收集和切割磁铁损失
RCS	300	151	1.0 W/m	按手工维护要求
RCS collimatior x-y	300	151	4000 W	按横向 collimator 设计能力（90%准直效率）
RCS collimator z-	300	151	1000 W	按纵向 collimator 设计能力
Extraction region	1600	151	20 W	切割磁铁损失
RTBT	1600	151	1 W/m	按手工维护要求
RTBT collimator	1600	151	1000W*2	两段，都按最大值计算

Low-loss design philosophy

- A low-loss design
- Flexibility
- Localize beam loss to shielded area
- Engineering reliability: heat & radiation resistant
- Accidental prevention: Immune to front end, linac & kicker fault

Two-stage Collimation System

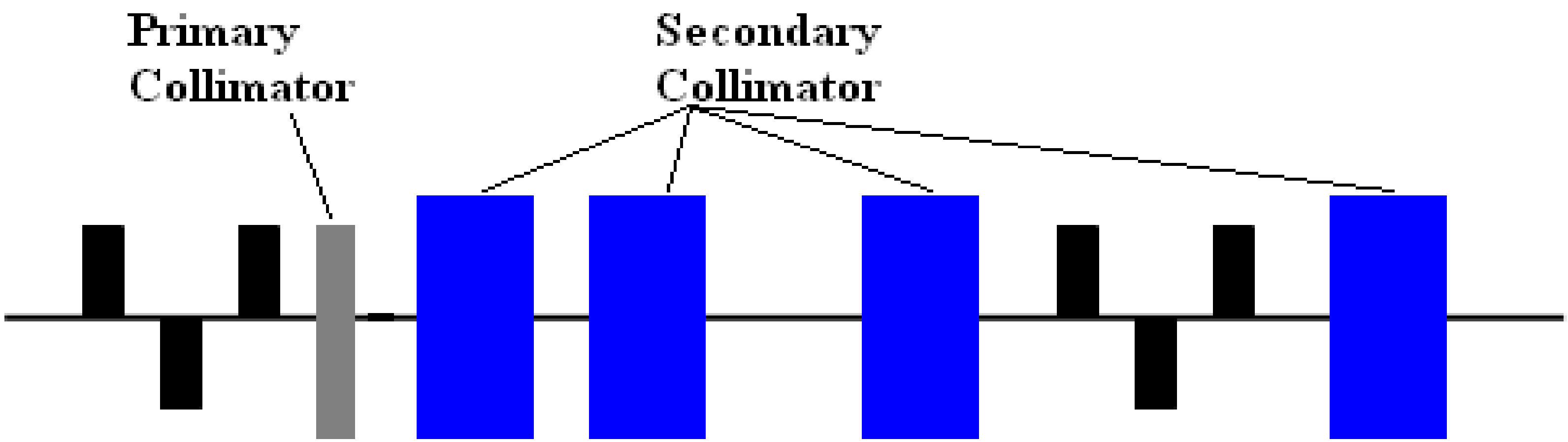


The beam and collimation in normalized phase space. The particles scatted by the primary collimator are absorbed by secondary collimators, which with certain phase advance from primary collimator.

Beam collimation

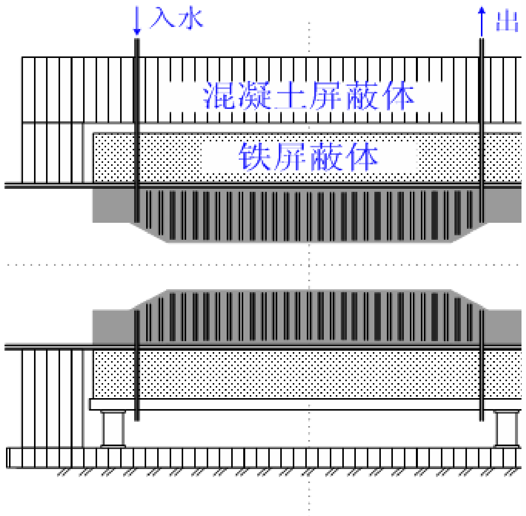
- The transverse collimation system adopts the two-stage collimation system. It consists of one primary collimator and four secondary collimators. It transverse collimation system takes a separate straight section, just downstream of the momentum collimators.
- One momentum collimator located in the gap of the arc, just after the injection straight, and the type of the momentum collimator is direct absorber made of graphite and copper.
- It is expected to have a collimation efficiency of over 95% for the whole collimation system.

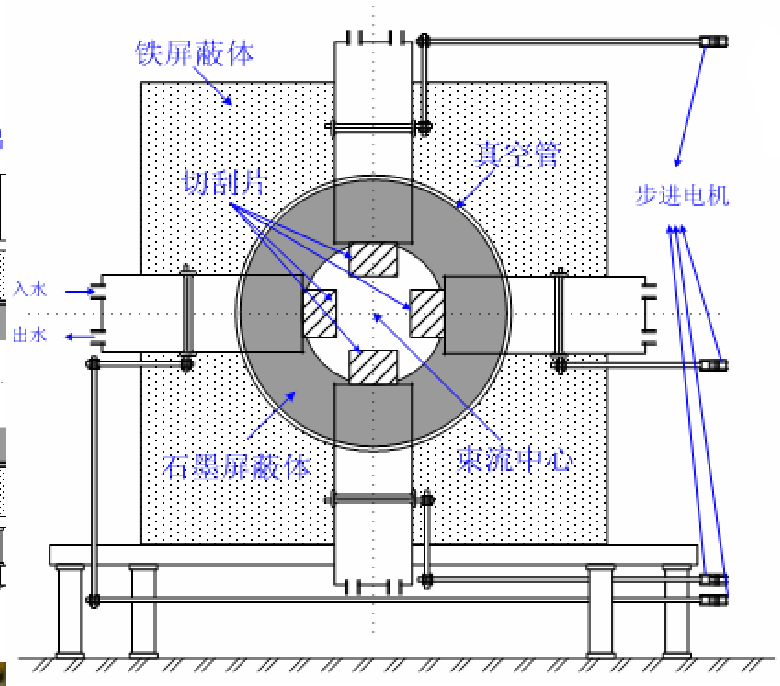
The layout of the transverse collimation system



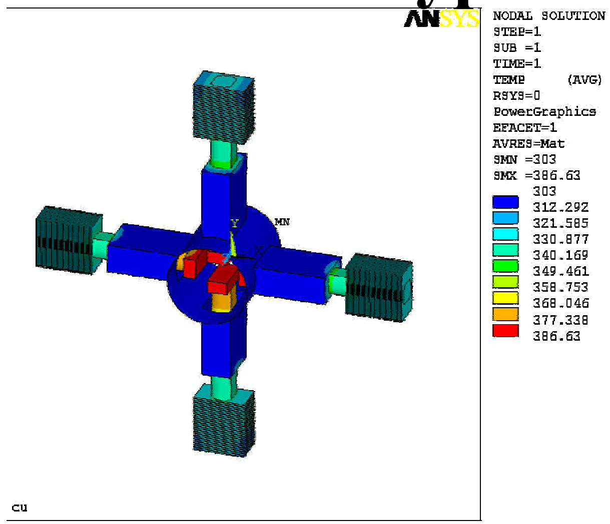
Collimator

SNS type





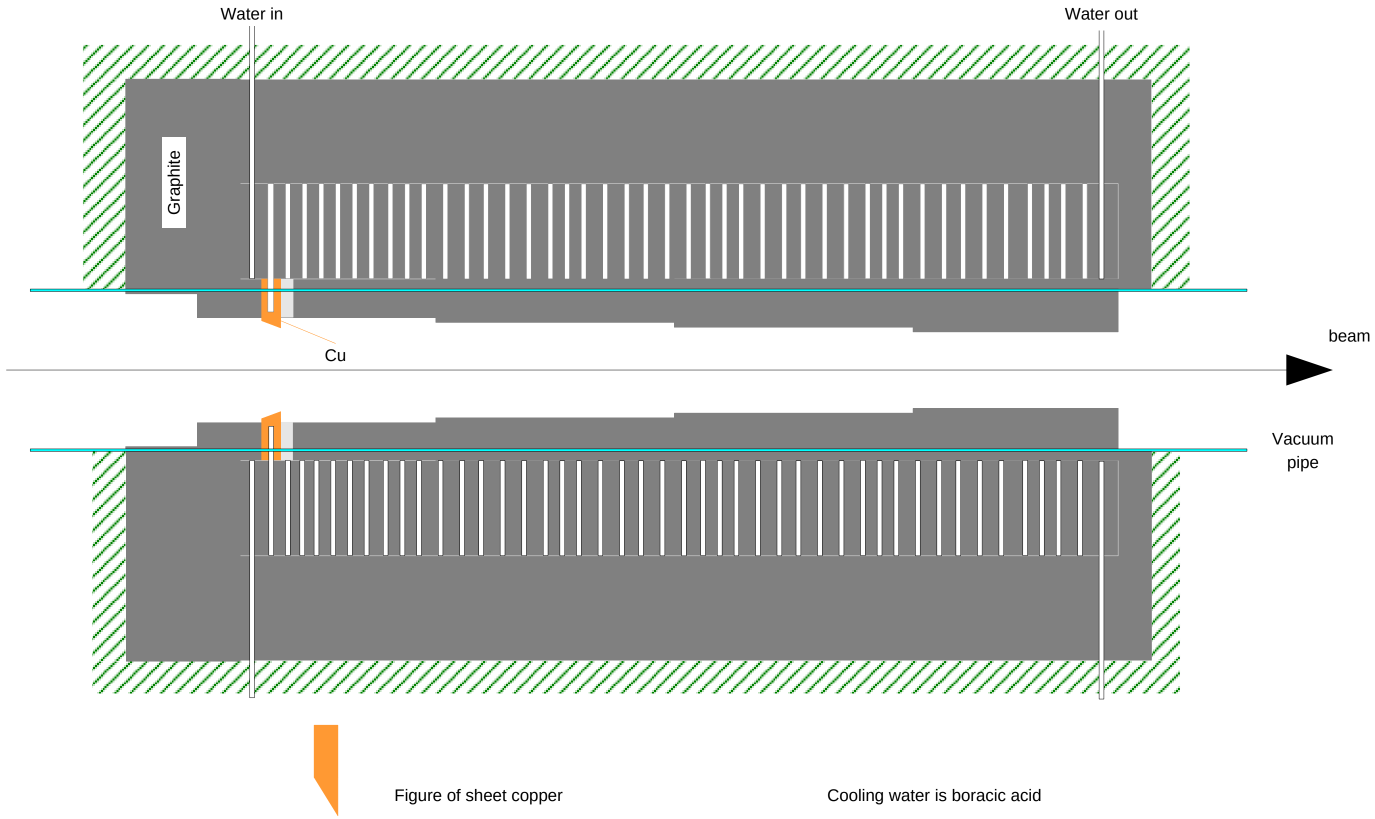
J-PARC type



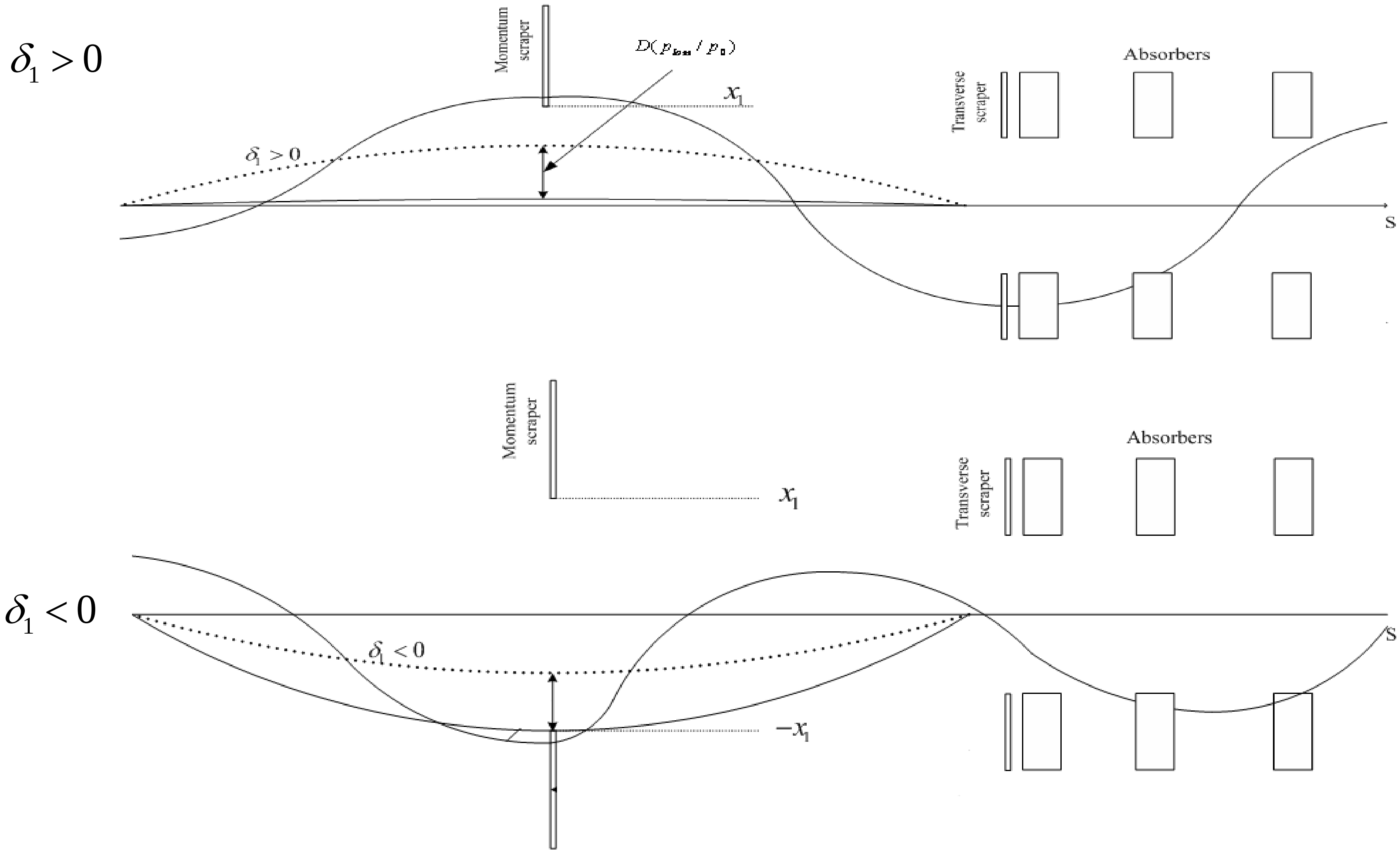
Sketch map of momentum collimation

Figure of longitudinal collimator

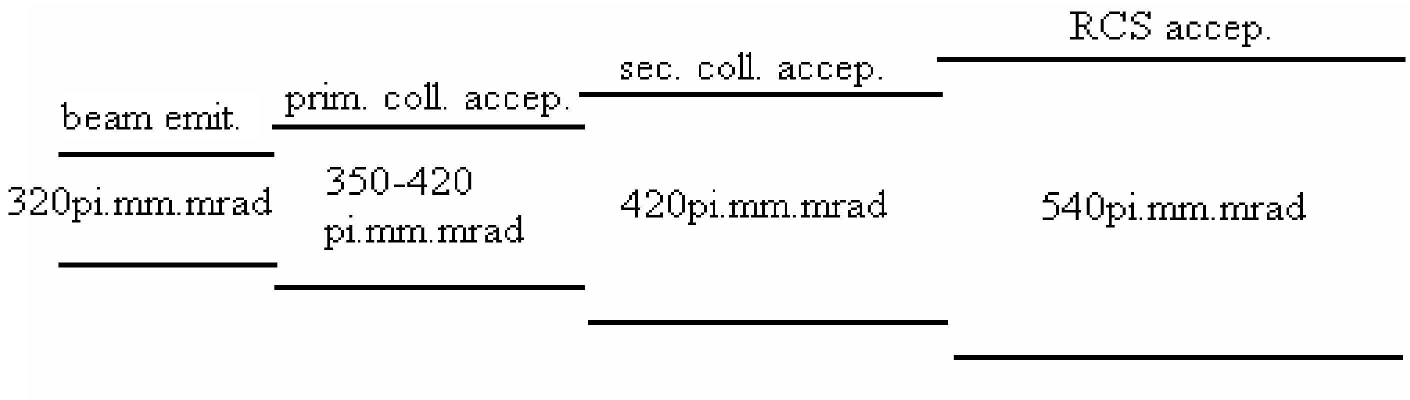
(top view)

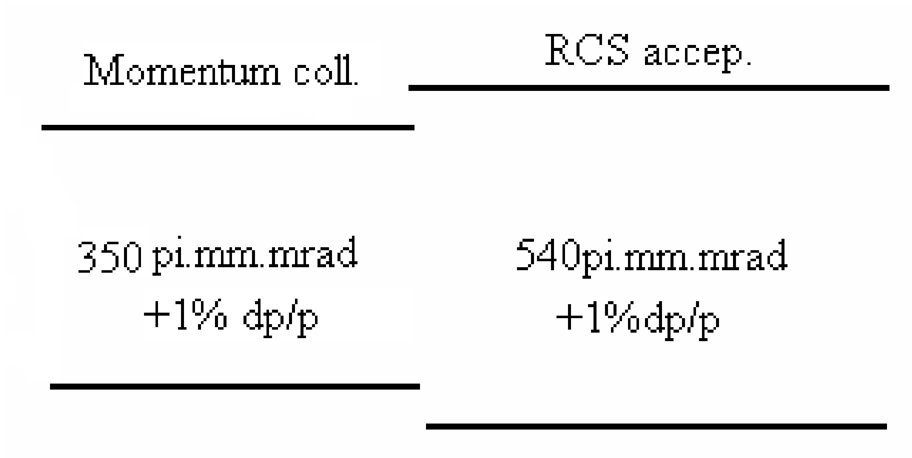


Momentum two-stage collimation

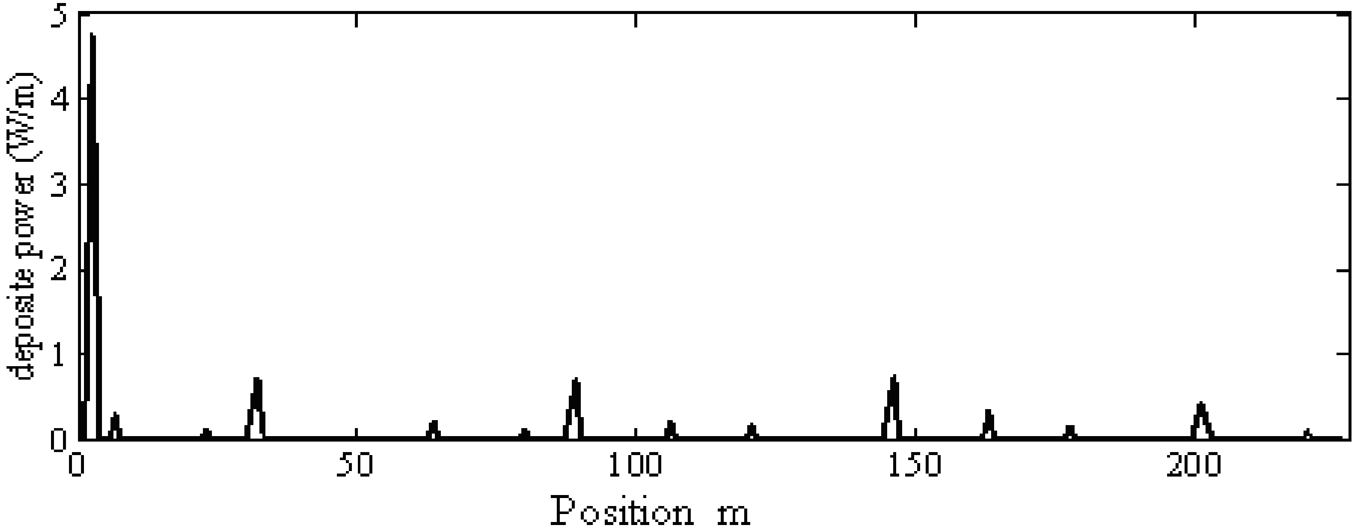


The emittance and acceptance in the RCS



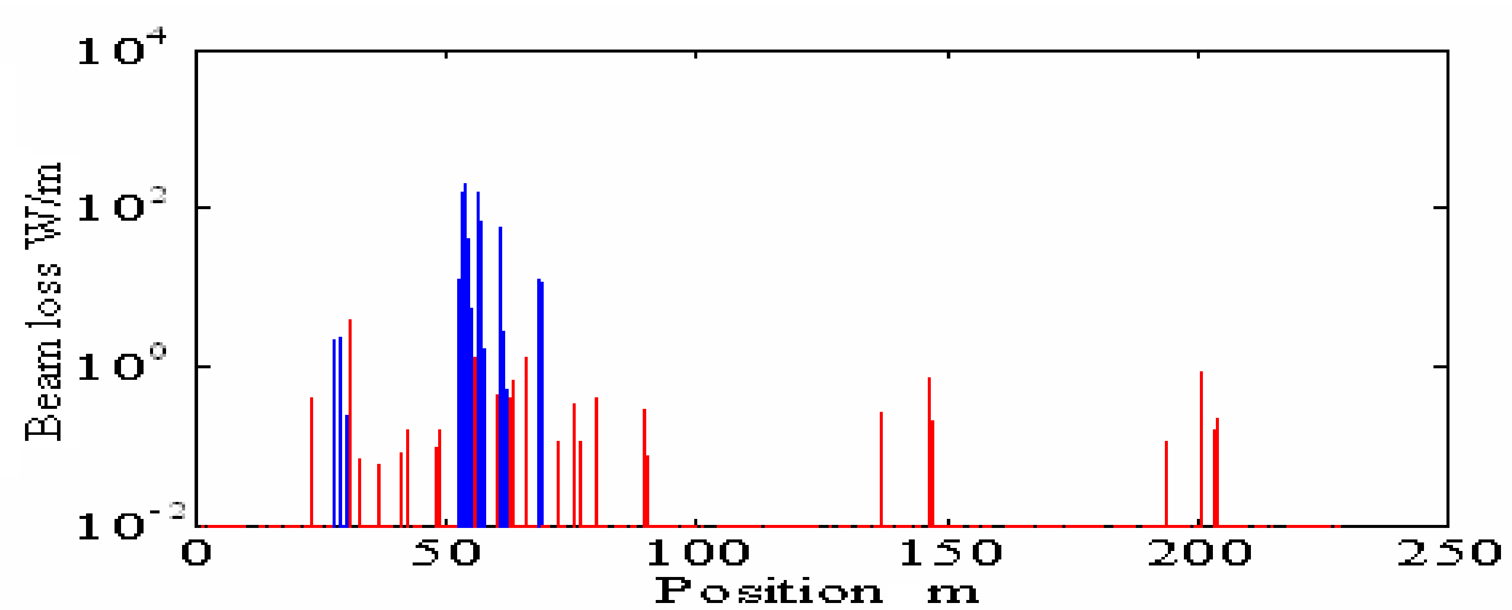


Beam loss without collimation



In case of no beam collimation, the total beam loss is small, but the maximum local beam loss is over 5W/m.

Beam loss with collimation



Beam loss distribution in the RCS with transverse and momentum beam collimation, total beam loss is about 5%, and the collimation efficiency is more than 96%

Space Charge Effects

Space charge effects

- Space charge effects set a fundamental limit to high intensity synchrotrons
- Due to beam length is much greater than its transverse beam size, the space charge effects in two directions can be considered separately
- In transverse direction, the dominant effects are the coupling of the transverse motions and the space charge induced resonant
- In the longitudinal direction, space charge contributes a defocusing force below the transition energy

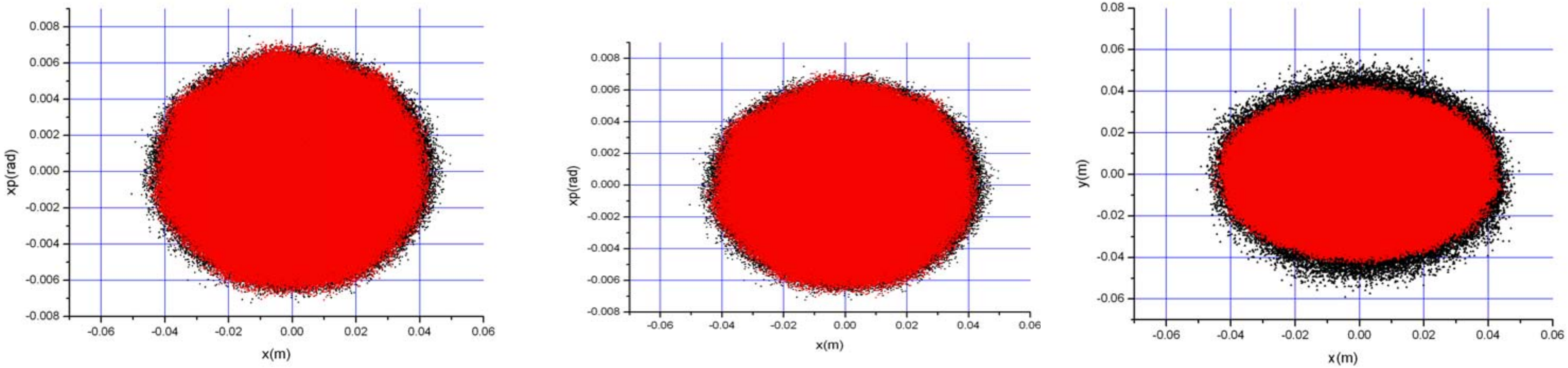
Cure:

- ✓ Flexible lattice design
- ✓ Painting
- ✓ Dual harmonic acceleration
- ✓ ……

Space charge effects simulation

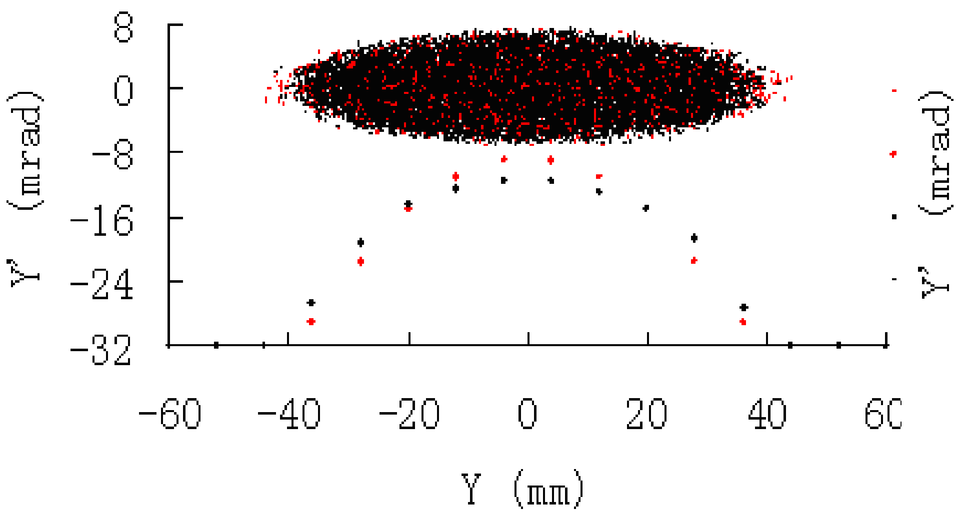
- The space charge effects limit the maximum beam density, as well as beam power.
- Many simulation works were done for the study of space charge effects by using code ORBIT and SIMPSONS.
- Various conditions, which may influence the space charge effects and beam loss, are considered, including the effects of different lattice structure, different tune, the combine effect of sextupole field and space charge, different painting beam distribution, etc. Some injection painting optimizations were made for decreasing halo formation and tune spread.
- The beam loss and emittance growth are compared for different conditions. The simulation results are the foundation of physics design and the choice of design parameters.

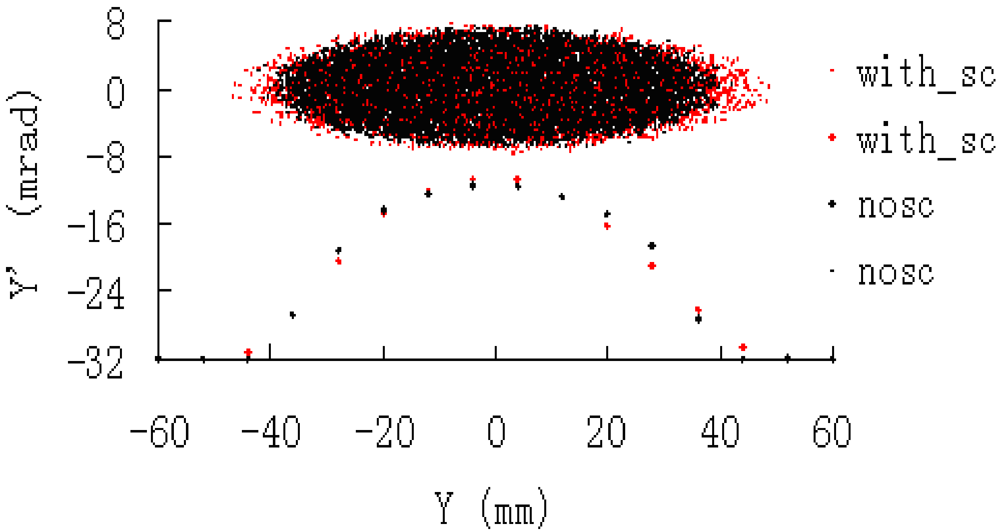
Emittance growth due to space charge effects



The emittance growth due to the space charge effects, red point represents the particles without space charge effects, and the black points represents the particles with space charge effects. The distribution is obtained at just finishing the correlated painting.

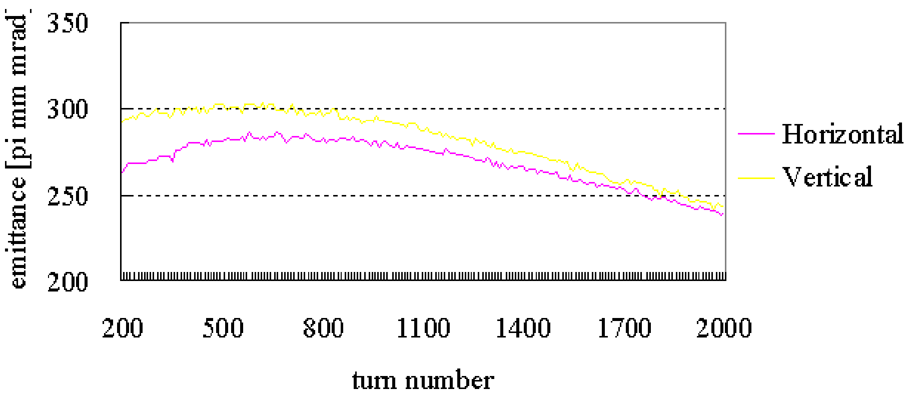
Injection optimization



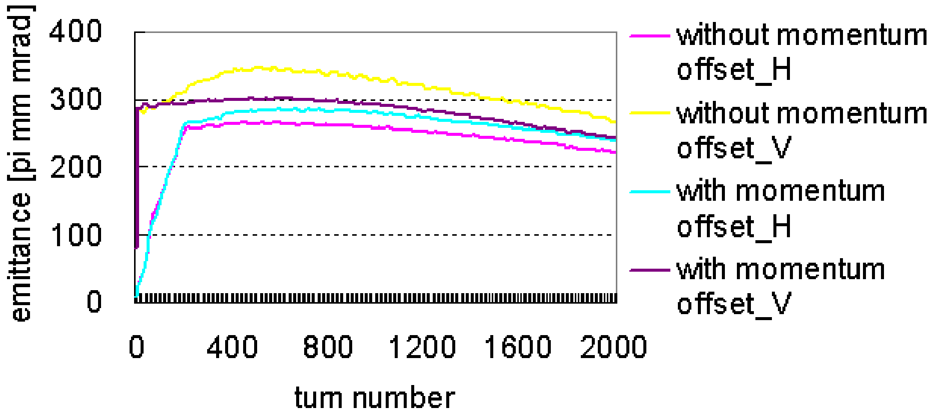


The beam distribution in y direction for correlated painting. With the space charge effect, the beam distribution is distorted from the painting result with no space charge effects (left). With the optimization of painting bump orbit, the beam distribution with space charge effects are optimized (right)

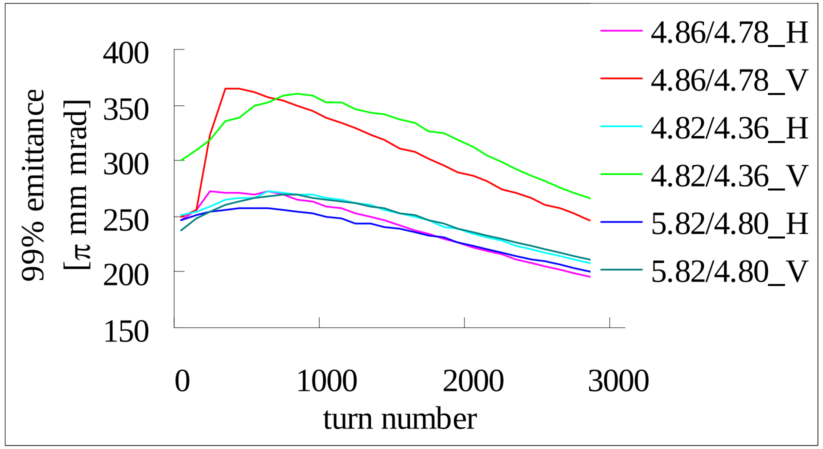
Space charge simulation



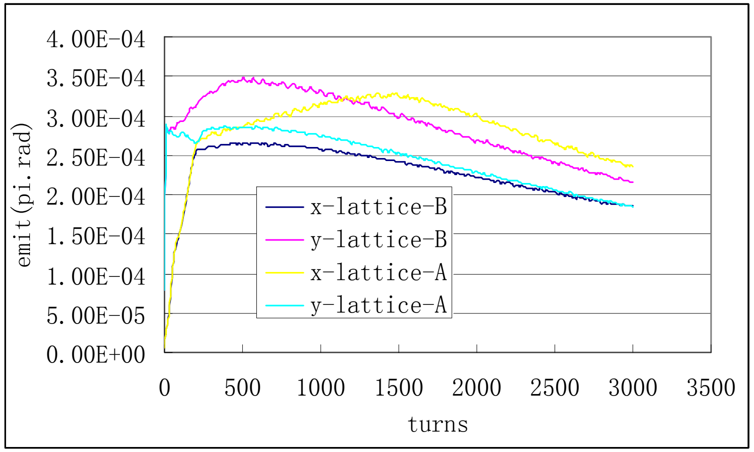
Emittance growth



With and without momentum offset



Emittance growth depends on tune



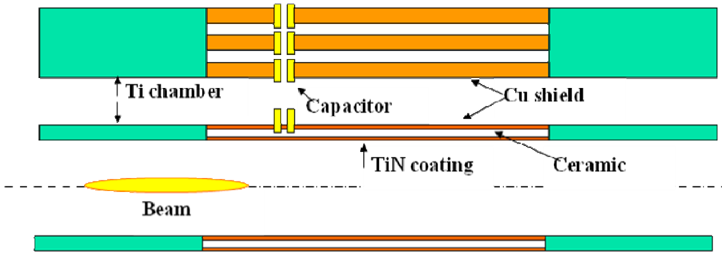
Emittance growth depends on lattice

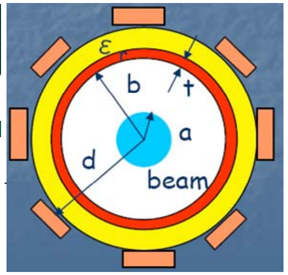
Impedance and Instabilities

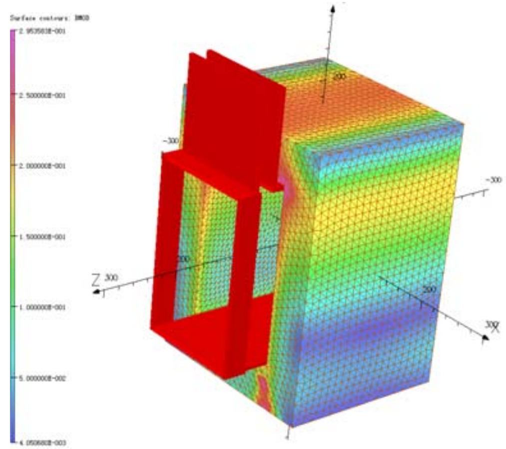
Impedance and instabilities

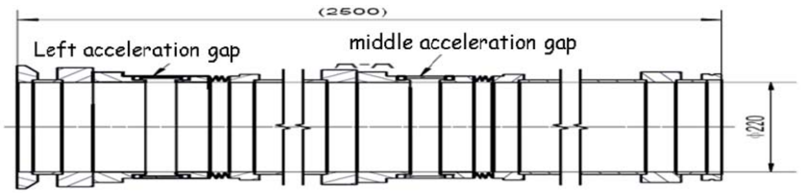
- The impedance of RCS comes from
  - the wall of chamber
  - bellows, kickers
  - RF cavities, BPM
  - collimators, steps
  - space charge
- The impedance of these components has been calculated both for injection energy and extraction energy
  - the space charge impedance dominates in the broad band impedance
  - wall impedance mainly comes from the stainless steel chamber

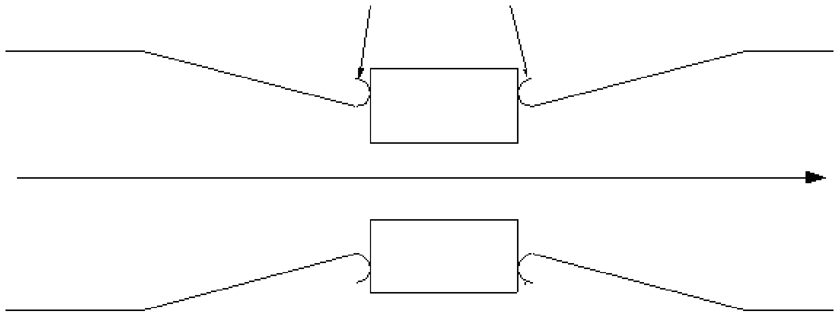
Some special impedance components











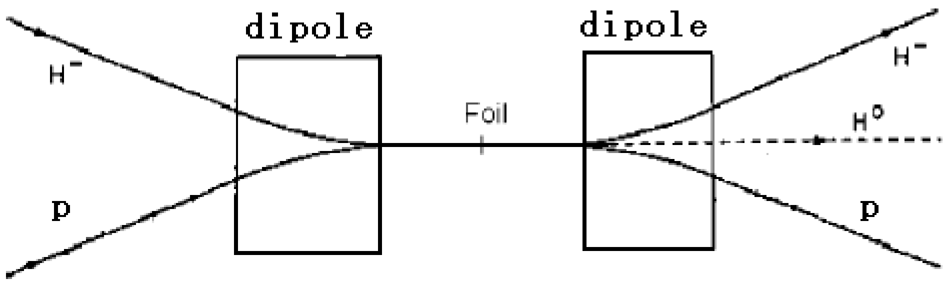
Beam instabilities assessment

- The primary calculation shows that there is no microwave instability occurred.
- The threshold of the impedance budget is larger than the threshold of transverse mode coupling instability, and there exists possible instability. But due to the damping effect of space charge, for synchrotron operates under transition energy, the theoretical calculation is always conservative. The details numerical simulation is needed for further study.
- The rise time of transverse wall impedance instability is less than a RCS cycle period, and this should be further studied.
- On e-p instability, the simulation shows that due to the long bunch space, electron cloud will not accumulate, and e-p instability is not a trouble.

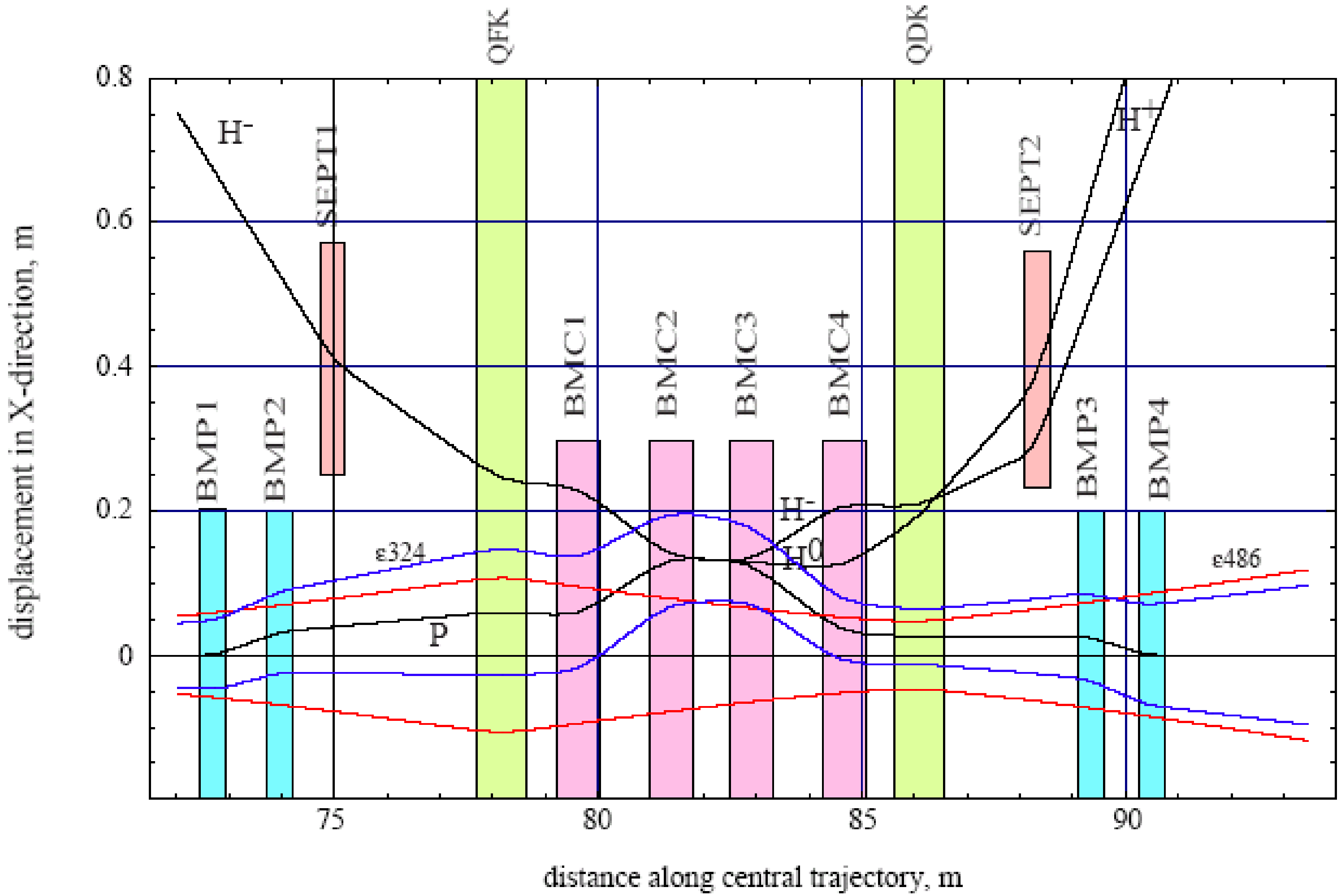
The Design of Injection

Multiturn charge-exchange injection

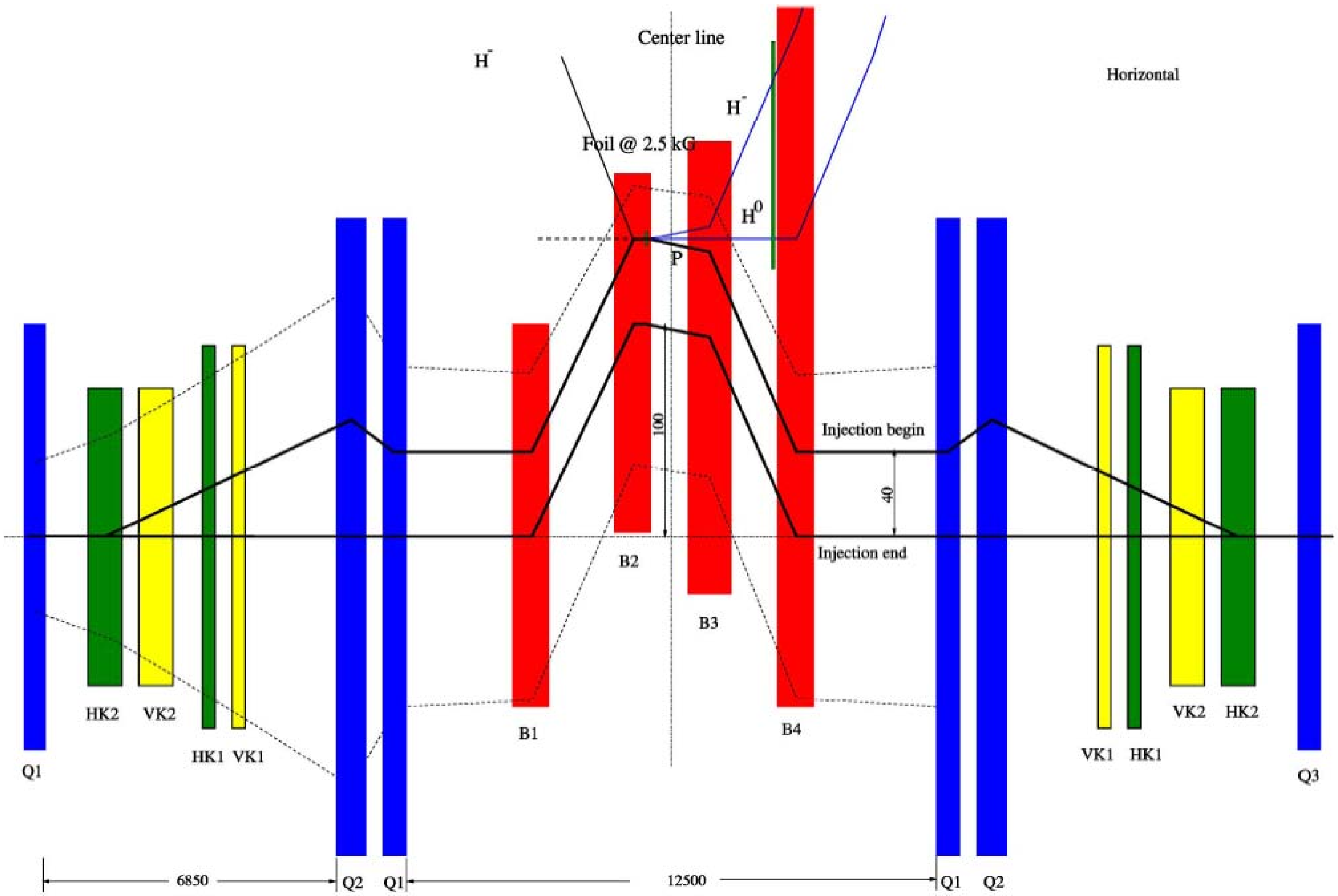
- Preferred for modern high-intensity rings
- It allows a large number of revolutions to be injected and controlled to realize a desired beam distribution. The constraints imposed by Liouville's theorem on conventional multiturn injection do not apply since the H- ions are stripped within the acceptance of the ring. With a programmed orbit bump, several hundreds of turns can be injected into the ring with tolerable foil scattering.



J-PARC/RCS injection scheme



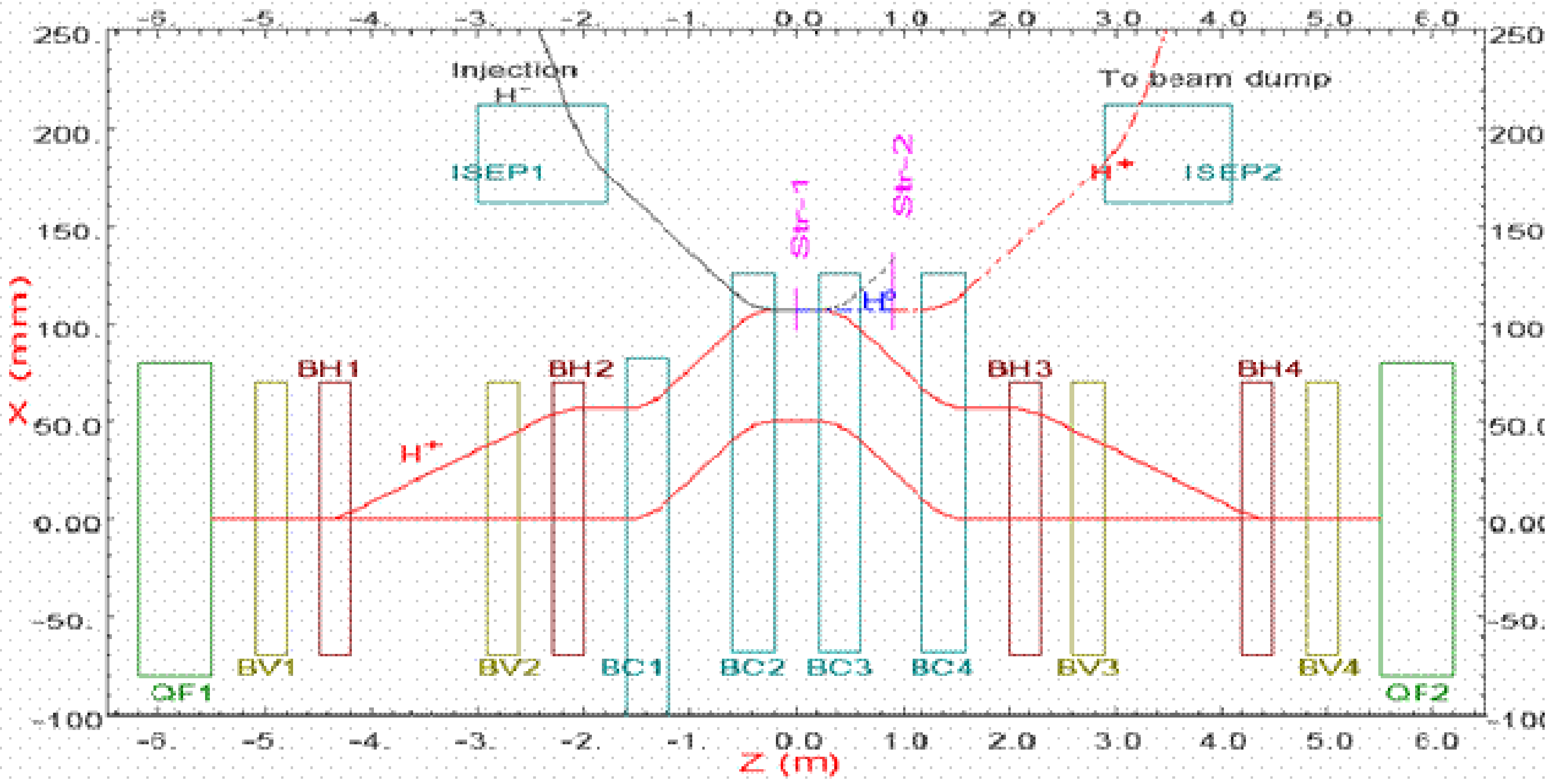
SNS/AR injection scheme



Beam injection

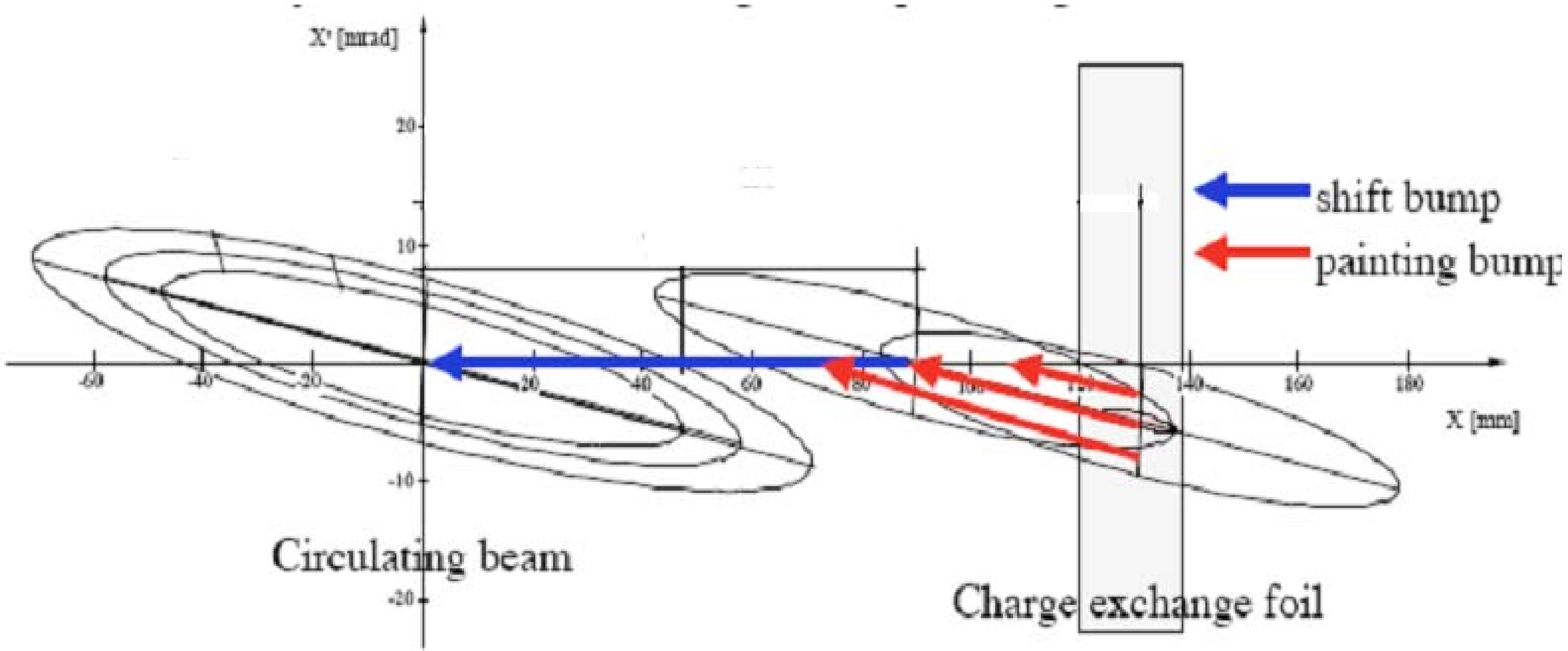
- H- stripping and painting method are used to match the small emittance beam from linac to large emittance beam in RCS.
- The injection is performed in a 11 m long straight section,
- Four horizontal painting magnets (BH), four vertical painting magnets (BV) , and four fixed orbit bump magnets (BC).
- BC magnets works in DC mode.

Beam injection

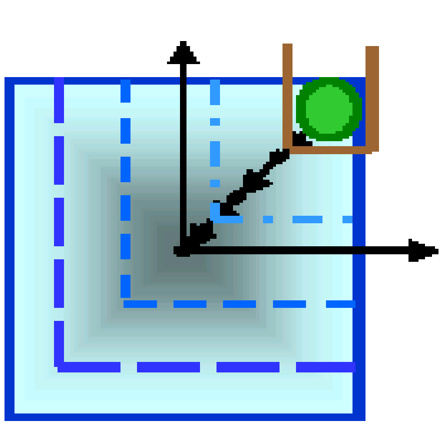


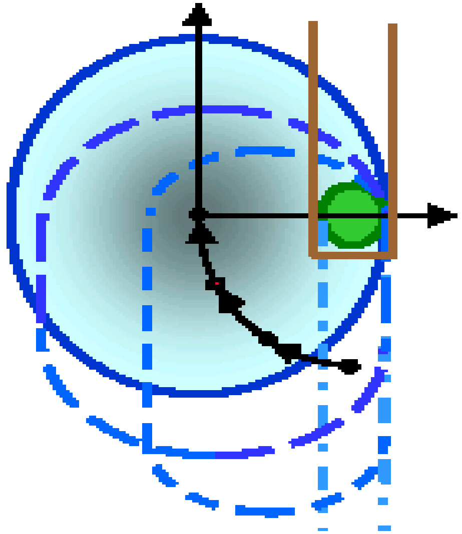
Injection component layout. BC1~BC4：Fixed orbit bump magnets，BH1~BH4：horizontal painting bumpers，BV1~BV4：vertical painting bumpers，ISEP1&2: septum

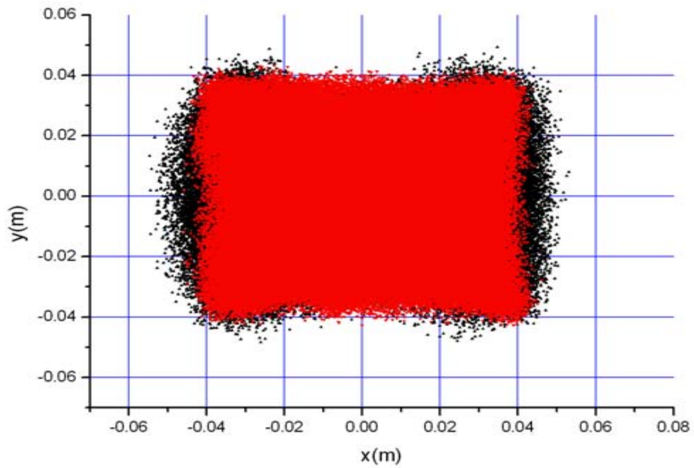
Schematic of shift bump and painting bump

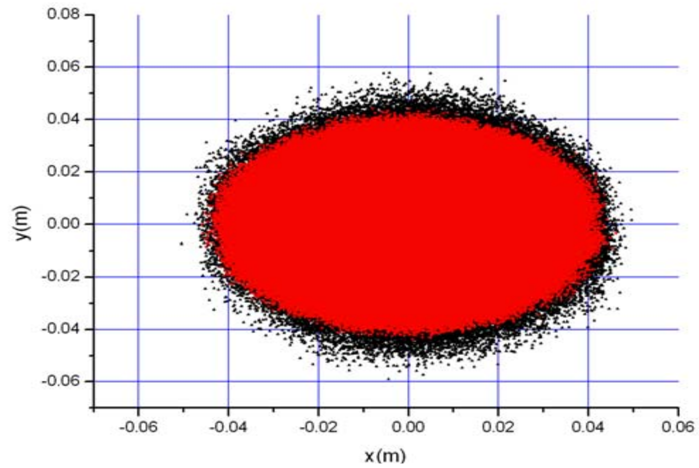


Injection painting scheme



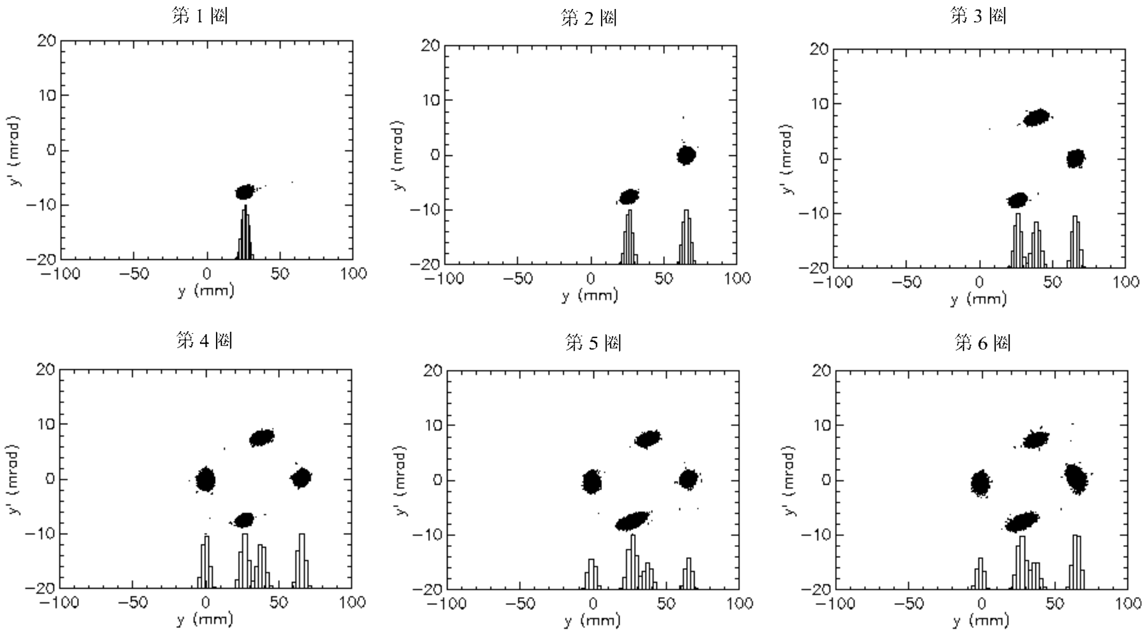




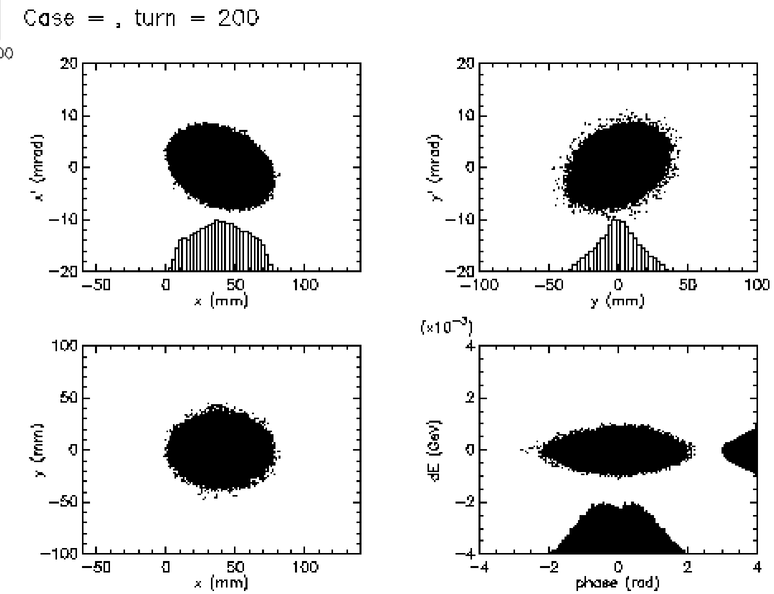


Finally, anti-correlated scheme was adopted

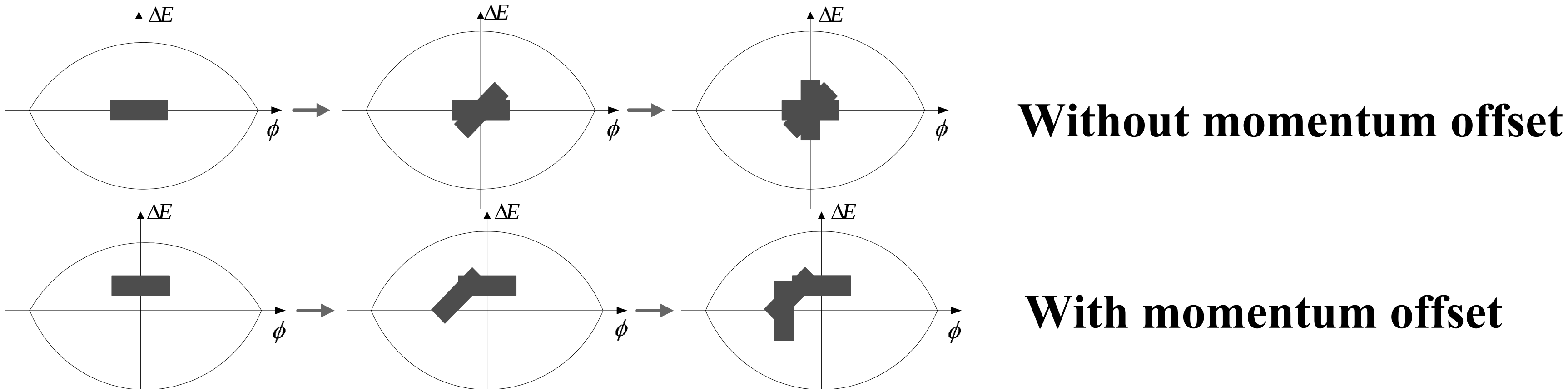
The painting procedure

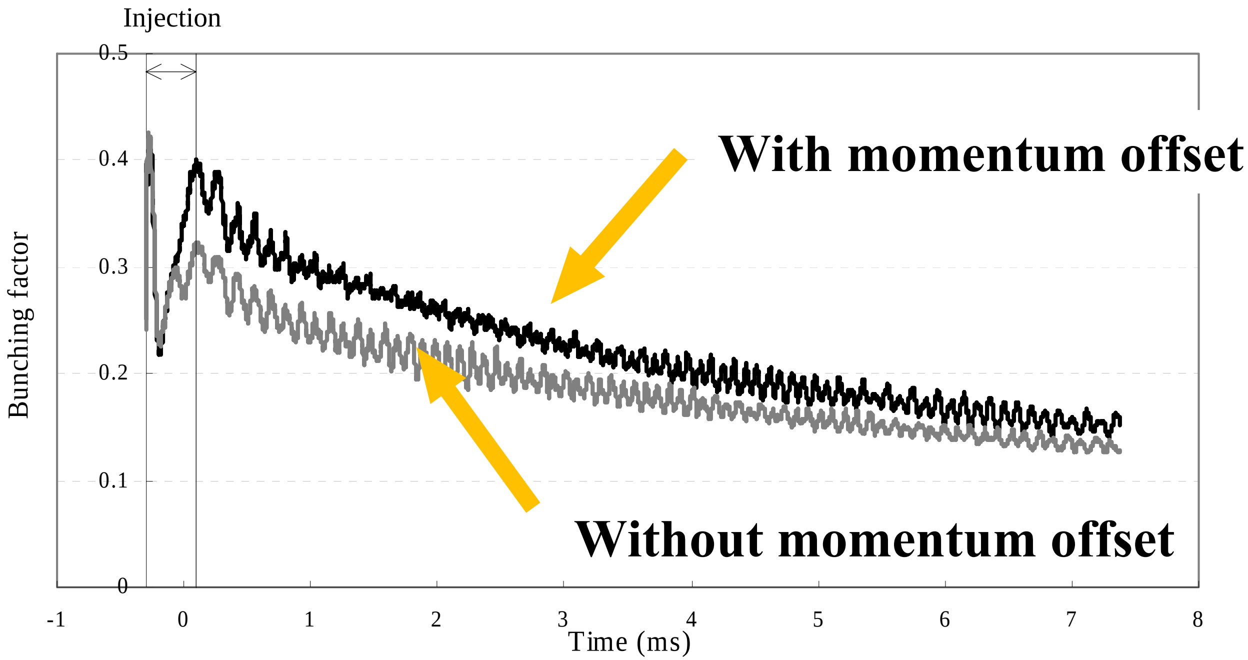


Injection finished



Injection with Momentum Offset



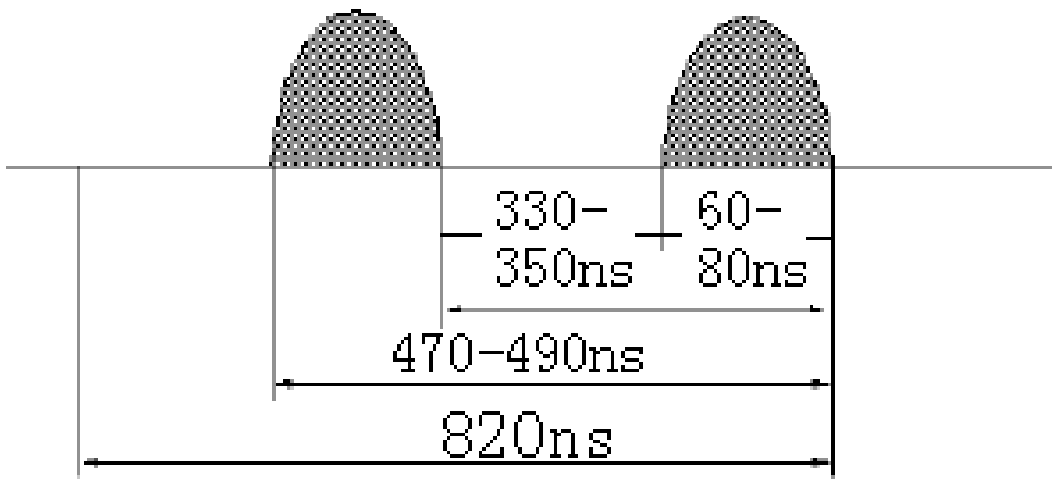


The Design of Extraction

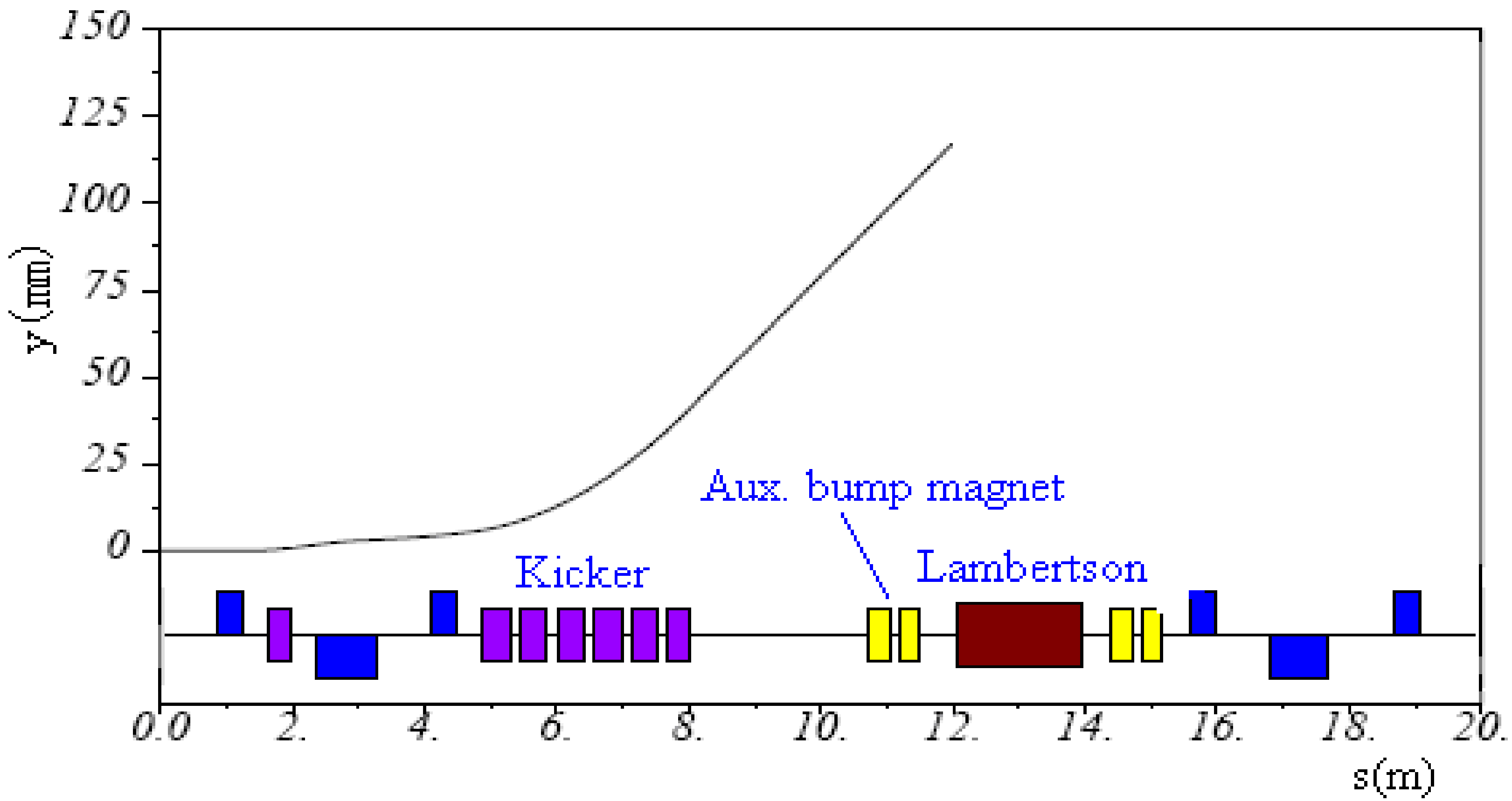
Extraction

- Two 1.6GeV proton bunches are extracted by one-turn extraction from RCS in each RCS cycle.
- The beam is vertically kicked by a series of kicker to a horizontal bending Lambertson type septum.
- The bunch length is about 60~80ns, and the space between two bunch is about 330~350ns. The rise time of kicker is required to be less than 250ns and flat top field need to be kept more than 550ns.
- The auxiliary bump magnets are adopted to provide additional extraction orbit and ease the kicker requirement.

The time structure of extraction beam



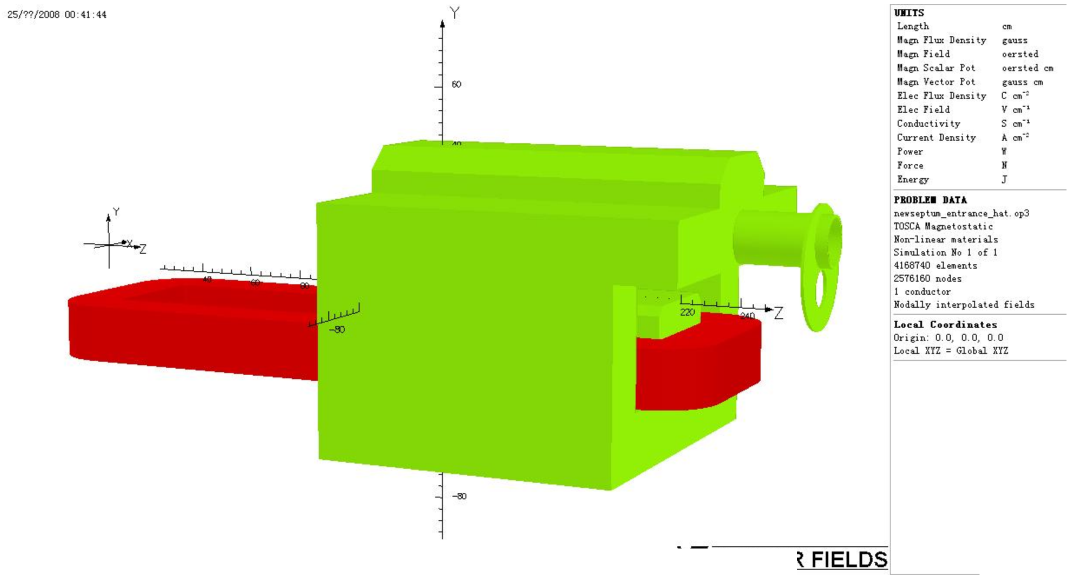
Extraction from RCS

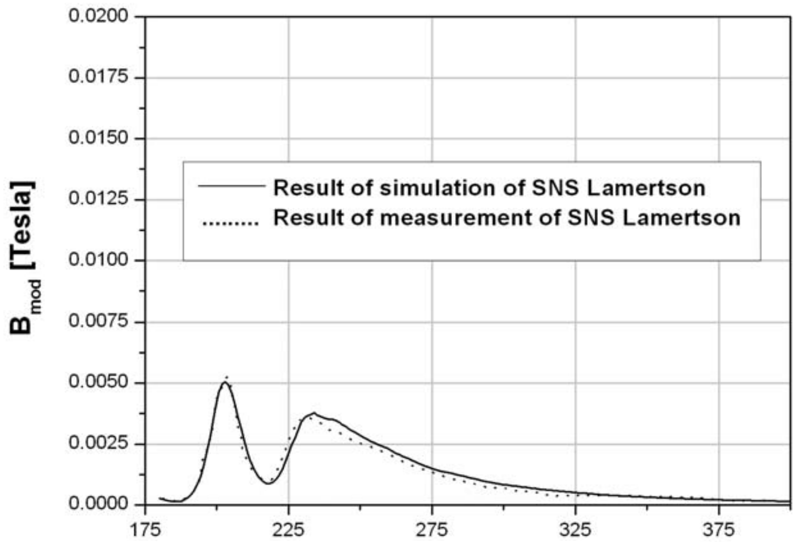


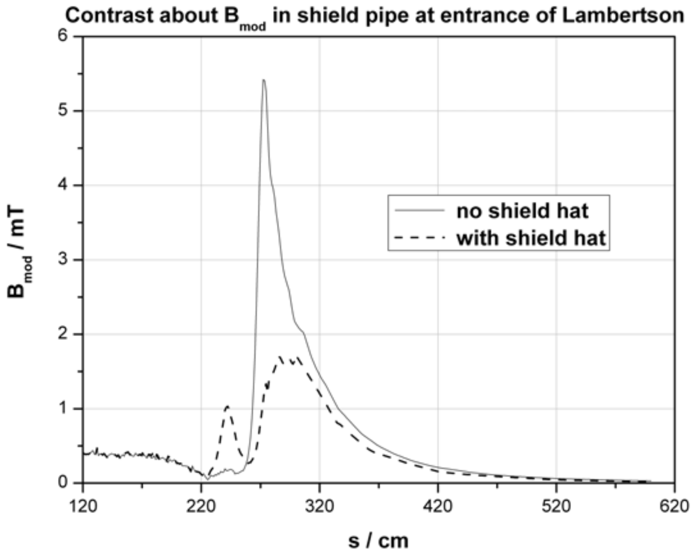
Main parameters of extraction components

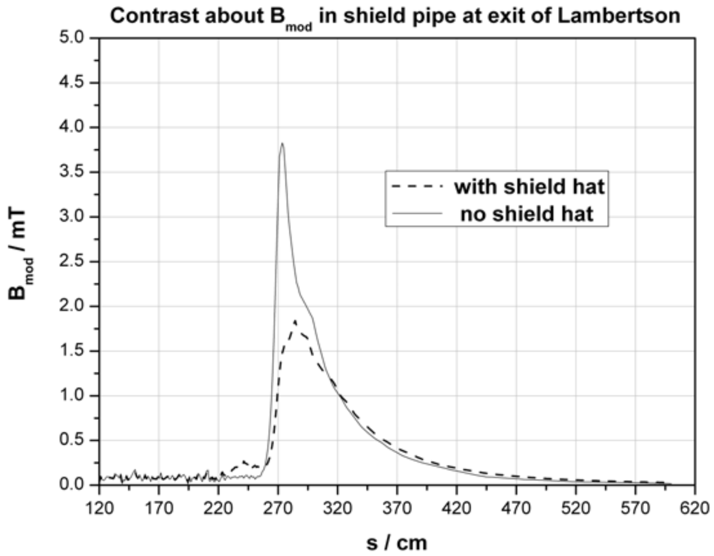
Components	Parameter	
General	Acceptance (πmm.mrad)	350
Kicker	Number	7
	Total strength (mrad)	19.05
	Rise time (ns)	≤250
	Pulse width (ns)	~600
	Magnetic field (G)	530~620
Lamberson	Number	1
	Effective length(m)	2.2
	Angle (°)	13
	Field strength (T)	0.9362

Stray field of Lambertson

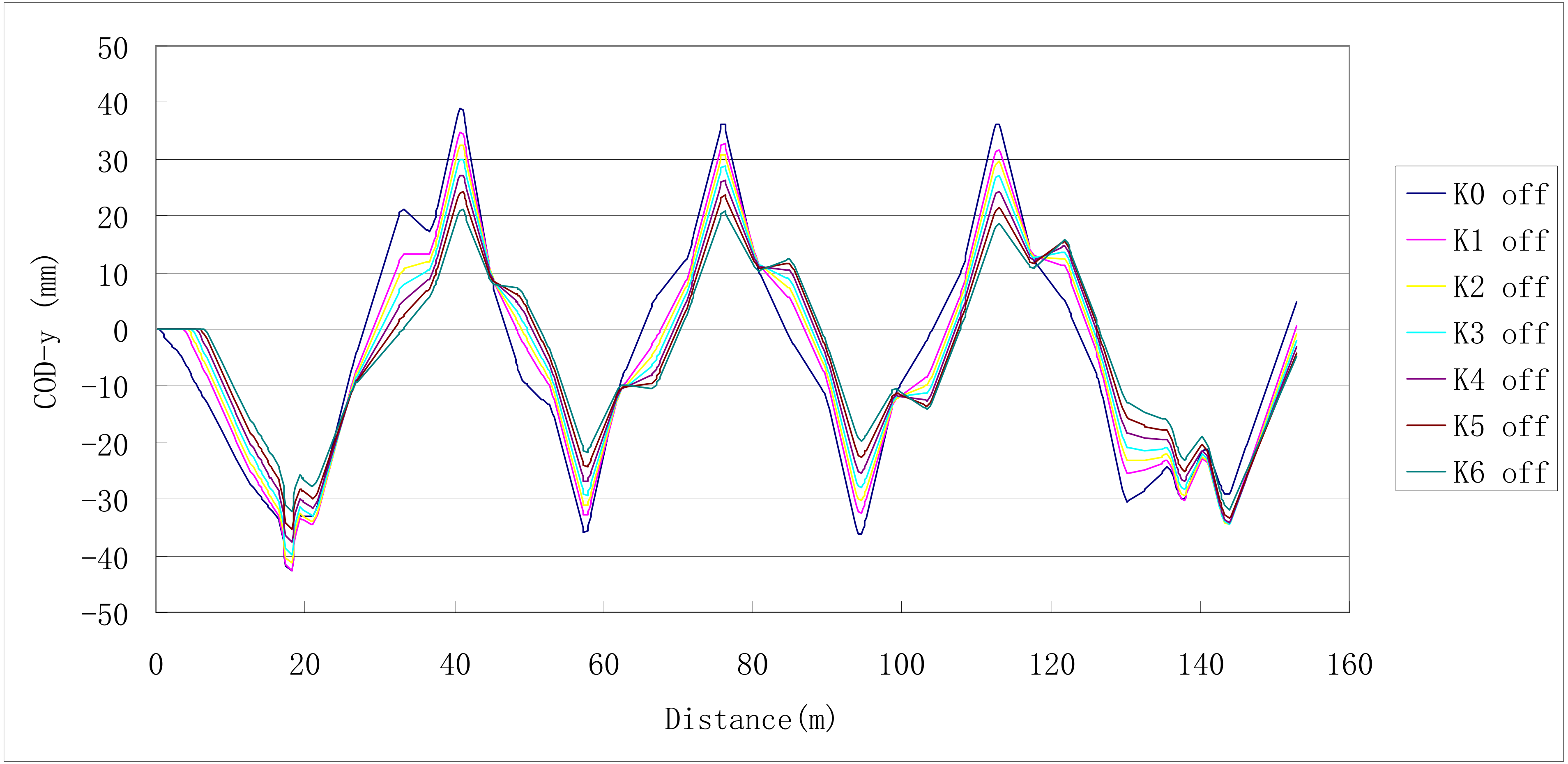






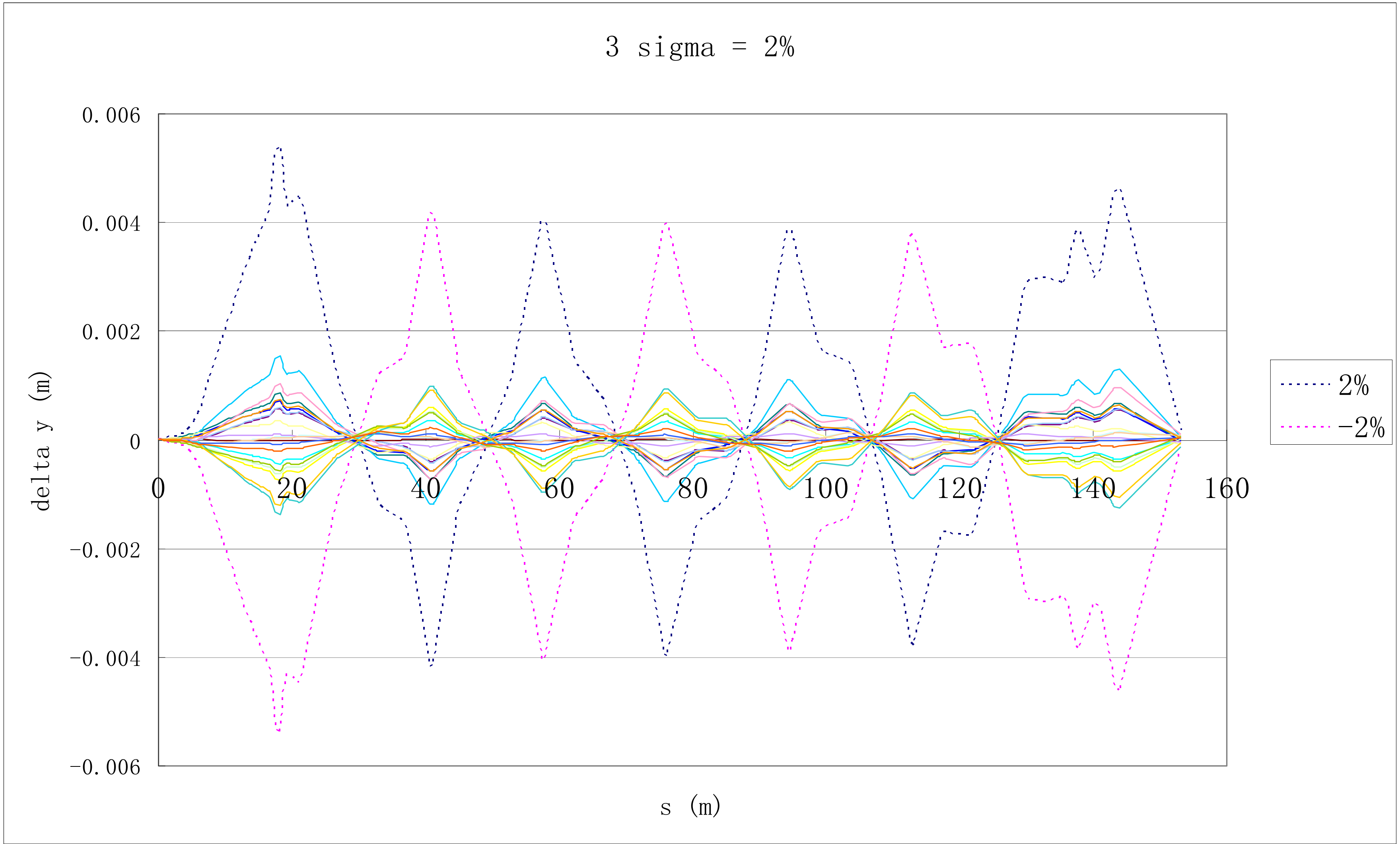


Effects of Malfunction of 1 kicker of 7



The acceptance is decreased to 100 πmm.mrad due to 40mm COD

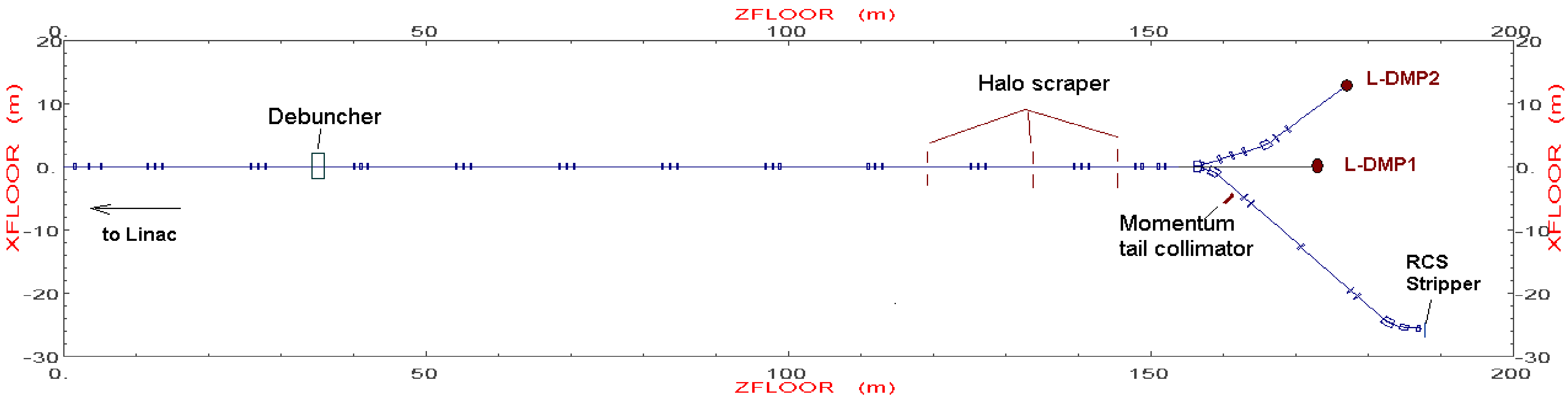
Effects of flat top field error of kickers



The statistics of 20 groups of random errors

Future beam power upgrade

- Necessary space for linac upgrade to 250MeV
- Necessary space left in RCS for Dual harmonic acceleration
- Beam loss and collimation
- Beam injection
- Beam dump
- …



Homework

1. 强流质子加速器中，控制束流损失的两个基本的设计原则是什么？在**CSNS RCS**设计上对束流损失的控制是如何考虑的？

2. 提高一台加速器的输出束流功率的途径有那些，**CSNS**未来功率升级的主要途径是什么？通过什么手段减弱空间电荷效应？

3. 试分析动量分散δ**>0**和δ**<0**的粒子，经过刮束器后的发射度的变化情况**(**参考**p57**）。

Thank you!

Have a good time at school!