The High Energy Beam Transport and Expander Design at the China Spallation Neutron Source

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CSNS
CHINESE ACADEMY OF SCIENCES

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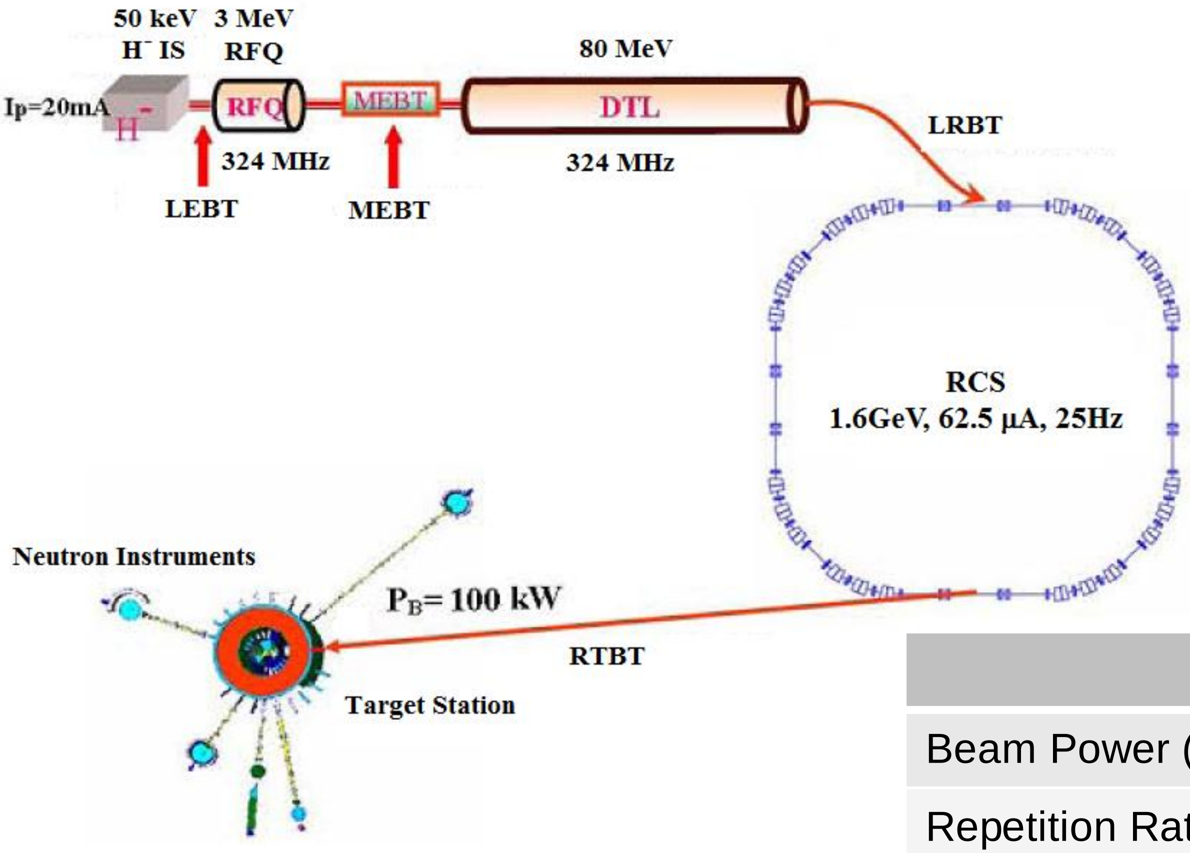
A Brief Introduction of CSNS

China Spallation Neutron Source (CSNS) is located in Dongguan, Guangdong province. The construction already started on October 20, 2011. The facility is intended to start commissioning in 2016, and operation in 2018.



	CSNS-I	CSNS-II
Beam Power (kW)	100	500
Repetition Rate (Hz)	25	25
Target Number	1	1
Average Current (μA)	62.5	312
Proton Energy(GeV)	1.6	1.6
Linac Energy (MeV)	80	250

RTBT Design

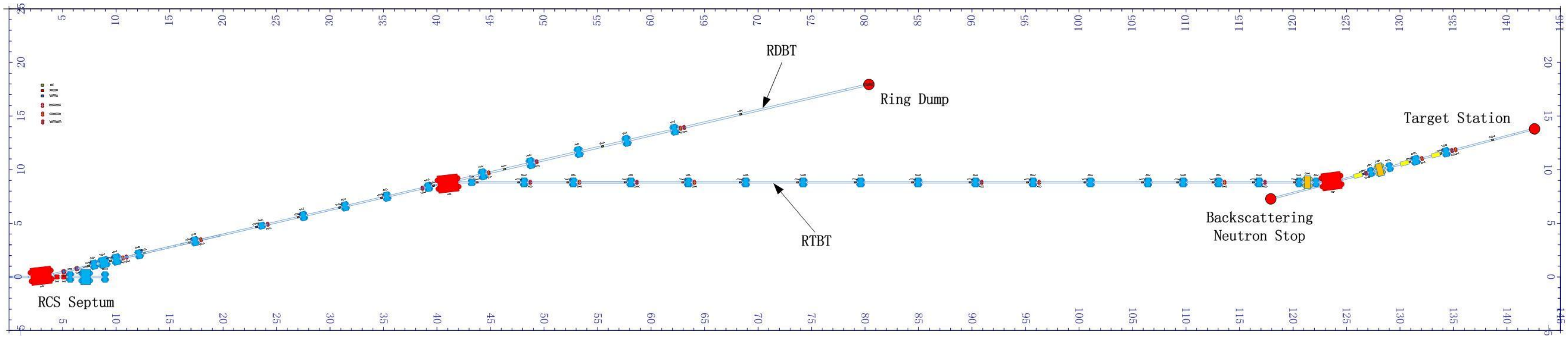
Transport Line

At CSNS the transport line transfers proton beam from the rapid cycling synchrotron (RCS) to the Tungsten target to generate neutrons is named as **RTBT**. The layout of CSNS changed a lot in the last two years. Then the RTBT lattice has been redesigned.

Now the trunk line of RTBT is about 144 m long. Two horizontal bending magnets (RTB01 and RTB02) divide RTBT into three parts.

A branch **RDBT** (Ring to the Dump Beam Transport line) of 41 m long attaches to the trunk line after RTB01, will be used for beam commissioning.

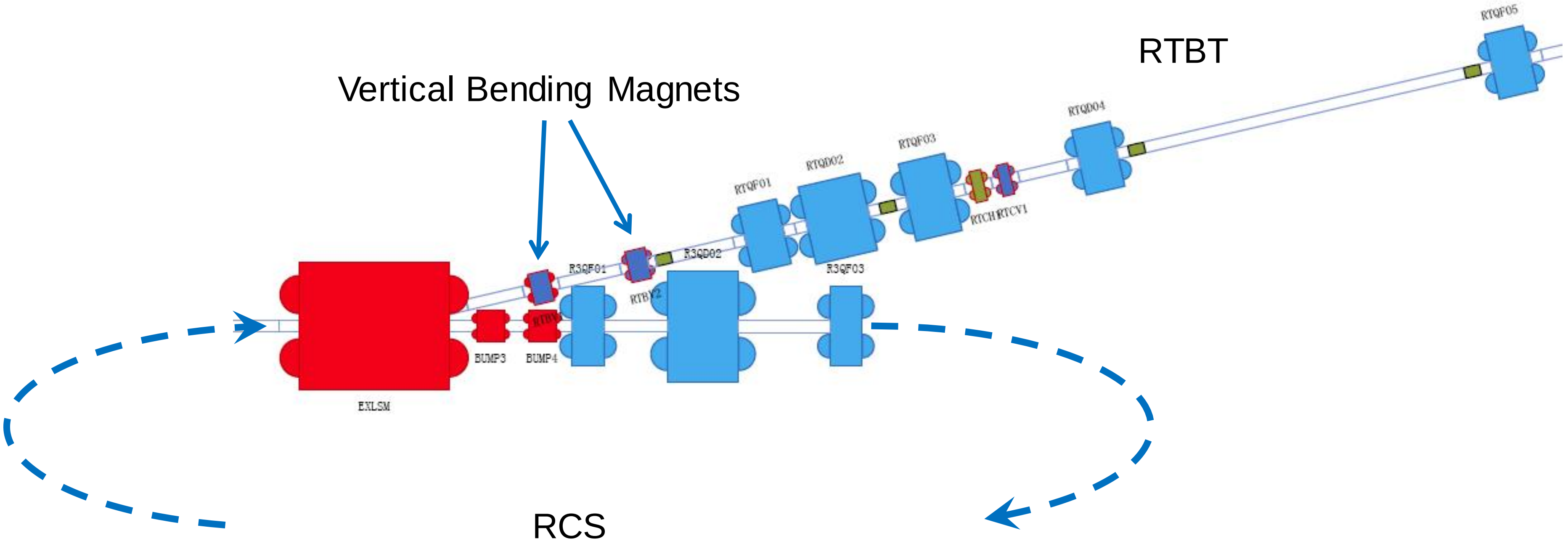
For the application of backscattering neutron, RTB02 is used to change the direction of RTBT. In the reverse direction of the final part, the backscattering neutron stop will be established.



General layout of the transport line for extraction beam

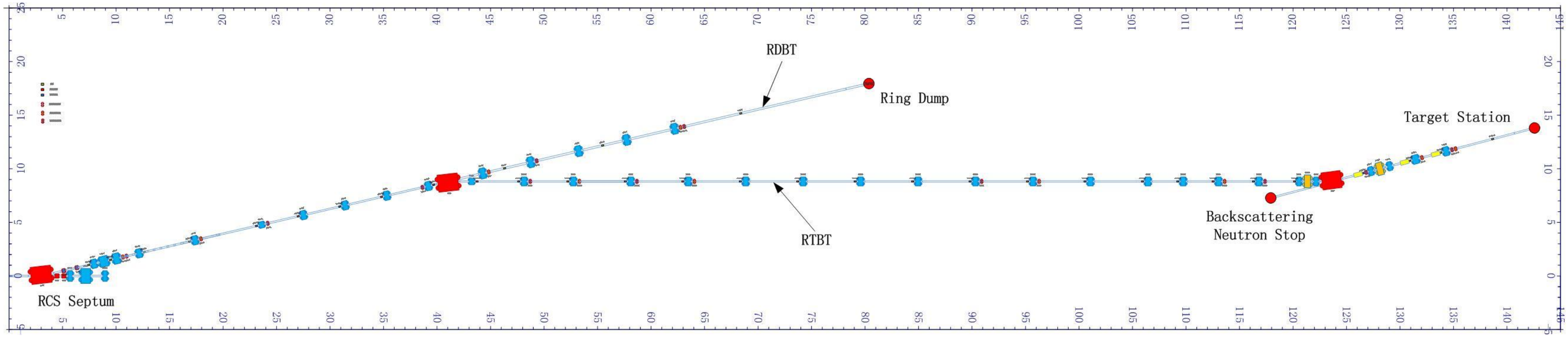
Beam Extraction

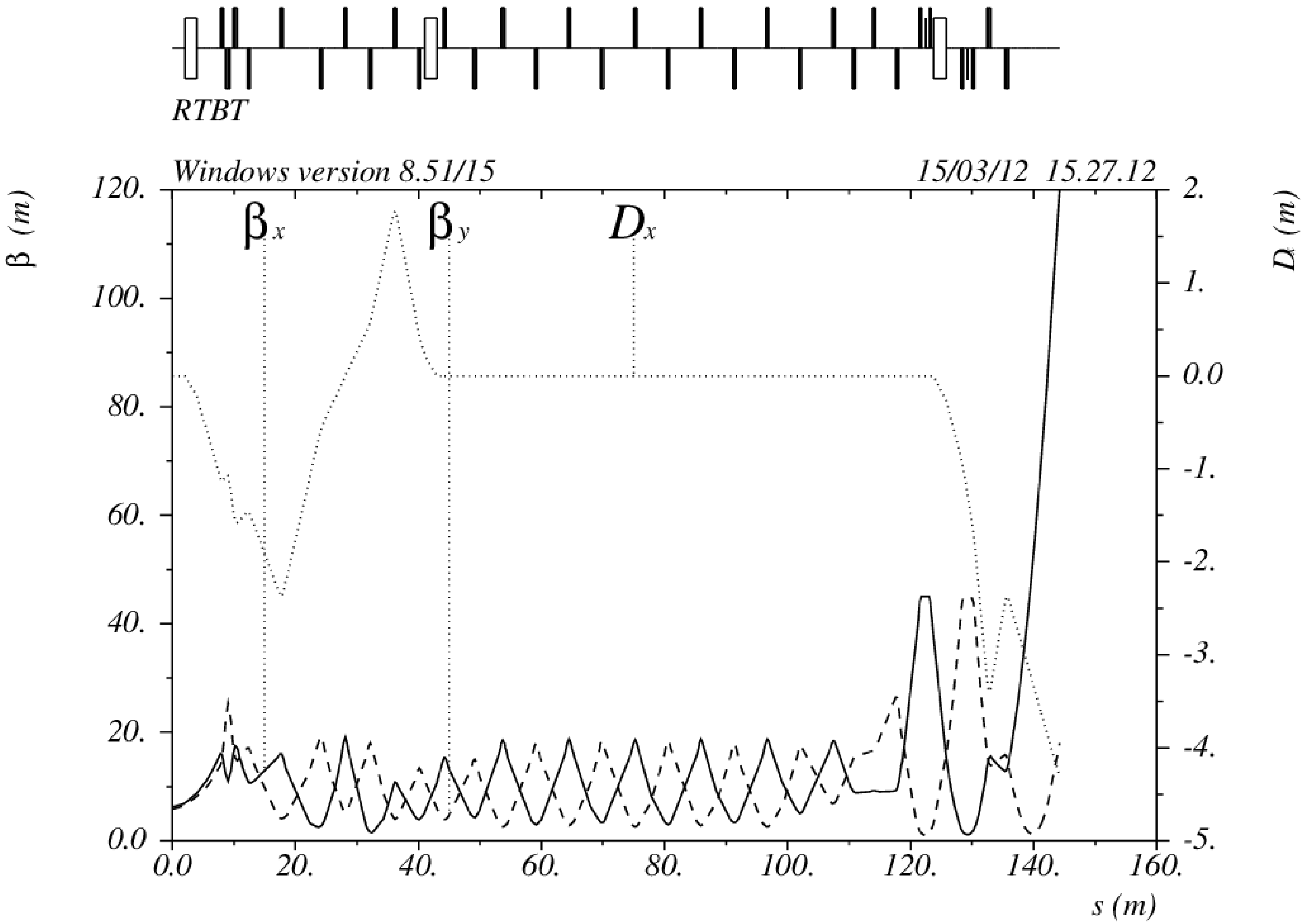
Two 1.6 GeV proton bunches are extracted by one-turn extraction from RCS in each RCS cycle. 8 vertical kickers and 1 horizontal Lambertson type septum are used for the extraction. The beam has a 20 mrad vertical angle after the Lambertson magnet produced by the kickers. Two vertical bending magnets are placed next to the lambertson magnet to cancel the vertical angle.



The dispersion produced by the lambertson is cancelled after RTB01 which bending angle is 228 mrad. The transport line between RTB01 and RTB02 adopts FODO focusing structure. Some quadrupoles in this region are also used for the twiss parameters matching which are demanded by the beam expanding system of RTBT when commissioning parameters are different from the theoretical parameters.

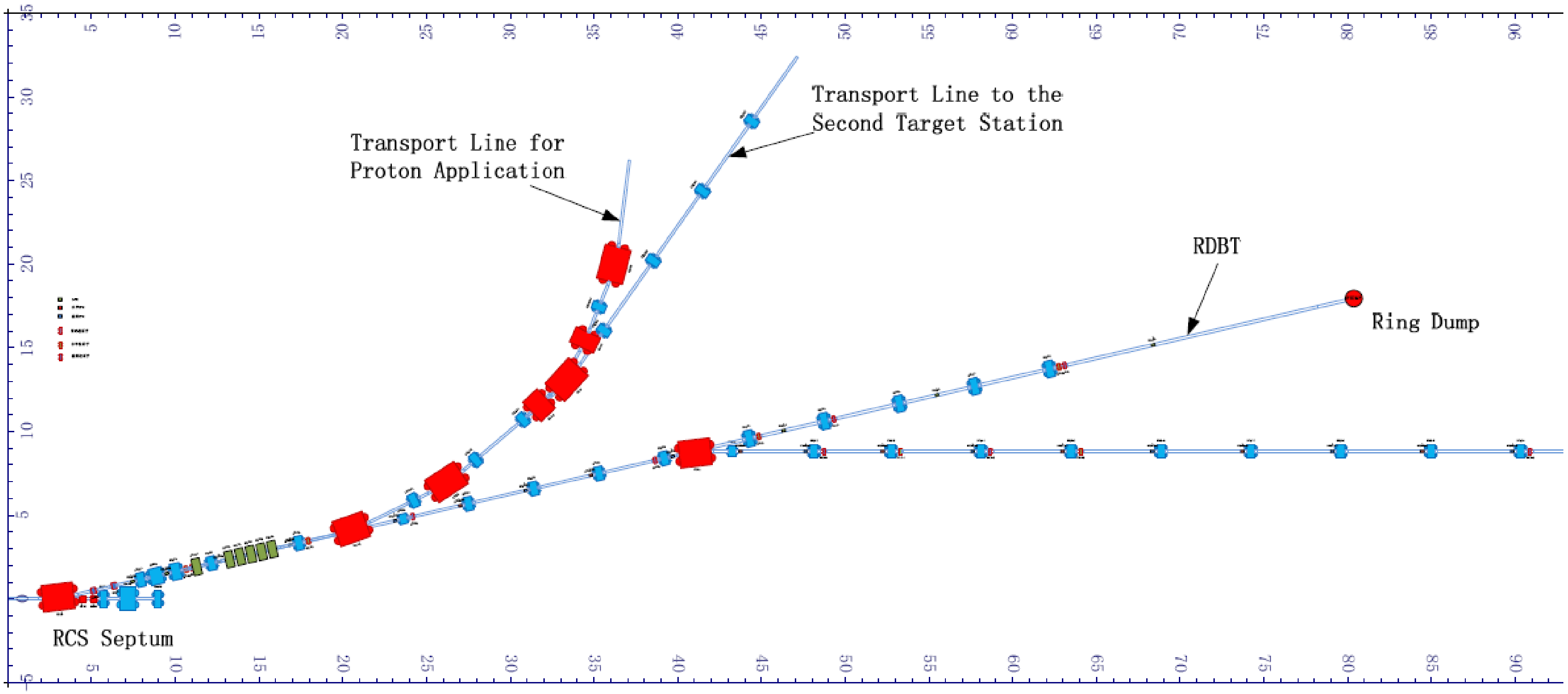
4 beam profile monitors (Harp) are placed before RTB01, and another 4 Harps are placed between RTB01 and RTB02. These Harps are used to measure the beam emittance and twiss parameters.





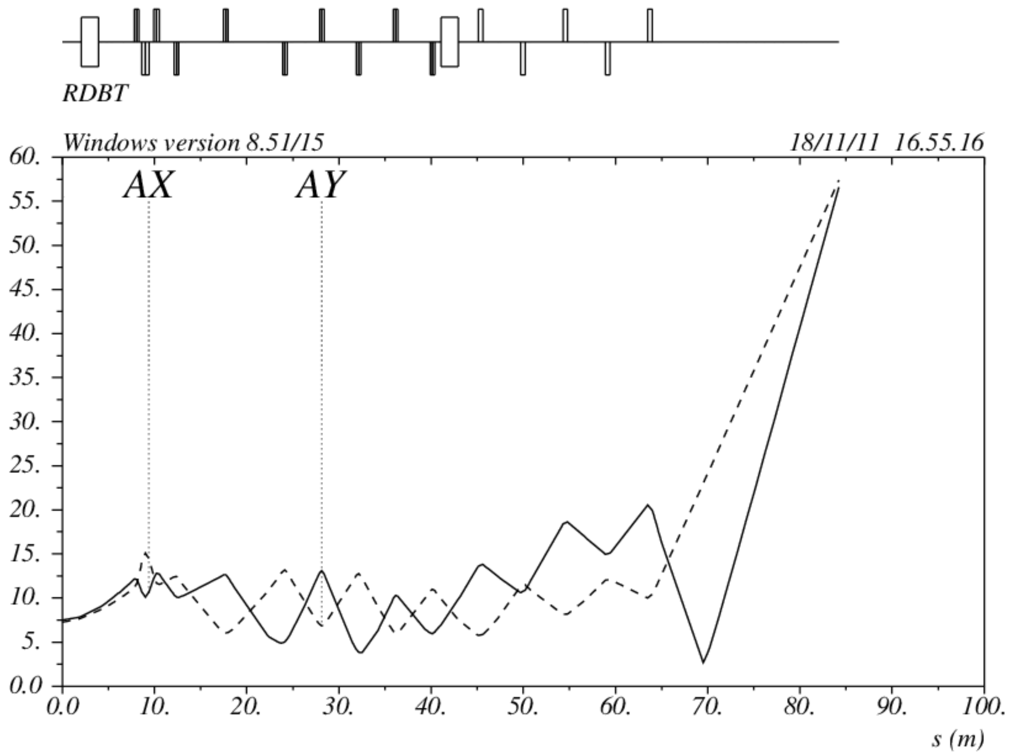
Linear lattice of RTBT for 100 kW beam power

With the consideration of future arrangements of the second target station and a proton application station, two auxiliary branches will be attached to RTBT before RTB01.



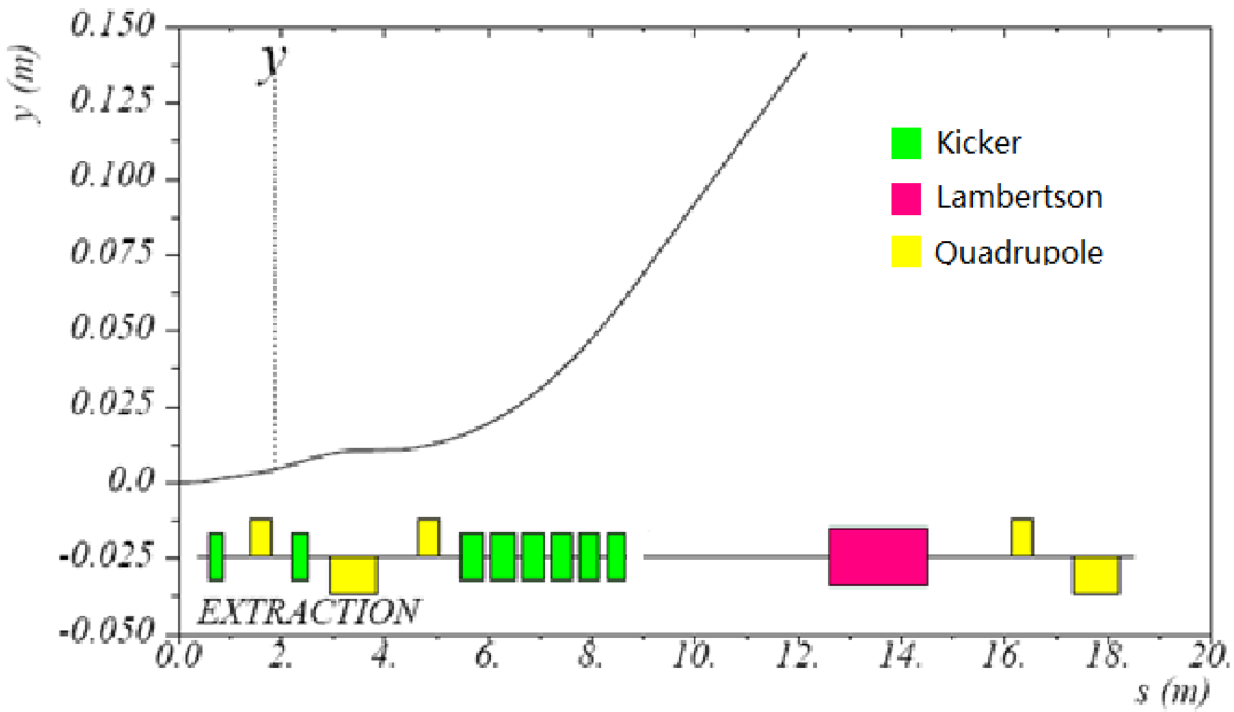
RDBT

RDBT is designed for beam commissioning. A beam dump is placed at the end of this transport line. The maximum power of the beam dump is 7.5 kW. Then the beam repetition rate or the beam intensity will be restricted for beam commissioning. Such as decreasing the RCS repetition rate from 25 Hz to 1 Hz, which means the beam power will be lowered from 100 kW to 4 kW.



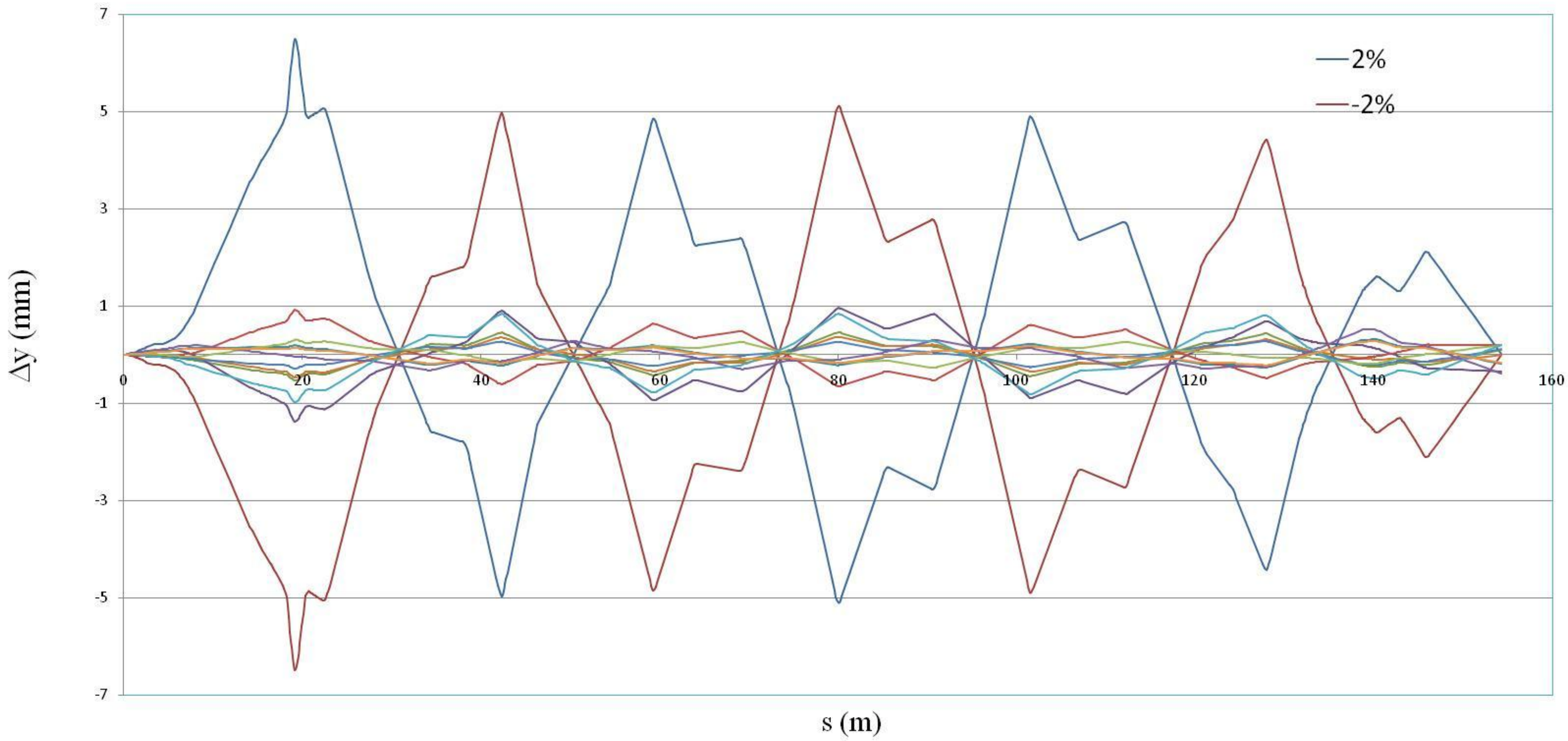
Beam envelope (3σ) along RDBT

Kicker Effects Study

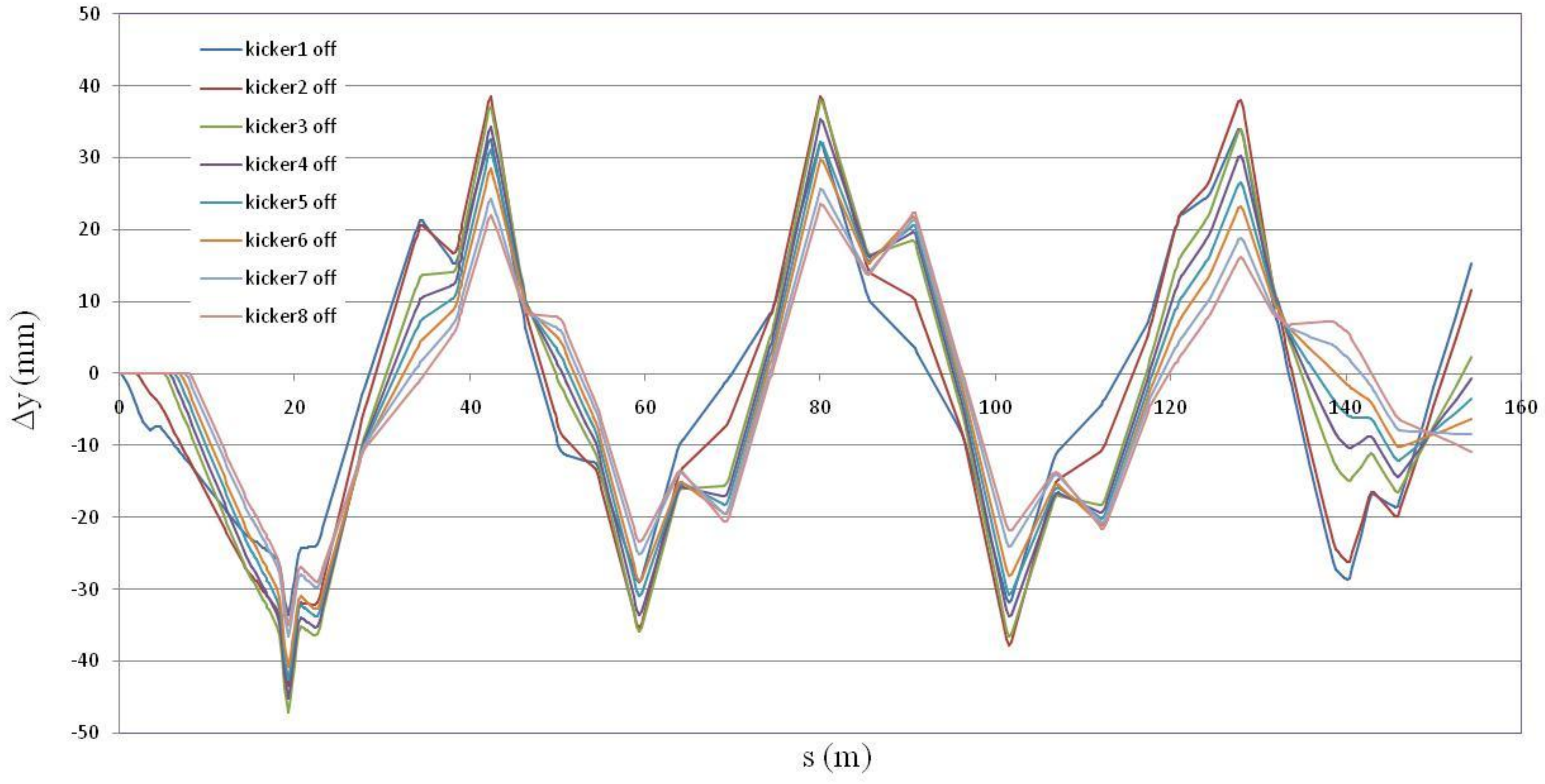


8 kickers are used for beam extraction from the RCS. The wobble of kickers will arouse the orbit jitter. To restrain the beam orbit variation at the target, vertical phase advance from the kickers to the target is optimized.

The orbit along RTBT caused by the random kicker wobble is simulated. In the simulation, the wobble amplitude of each kicker is set to 2% (3σ). The simulation results show that the maximum orbit variation at the target is less than 1 mm normally.



Each kicker has the probability of misfire. The beam orbits are also calculated with different kicker off. Most of the particles (>90%) can pass through the whole transport line and get to the target.

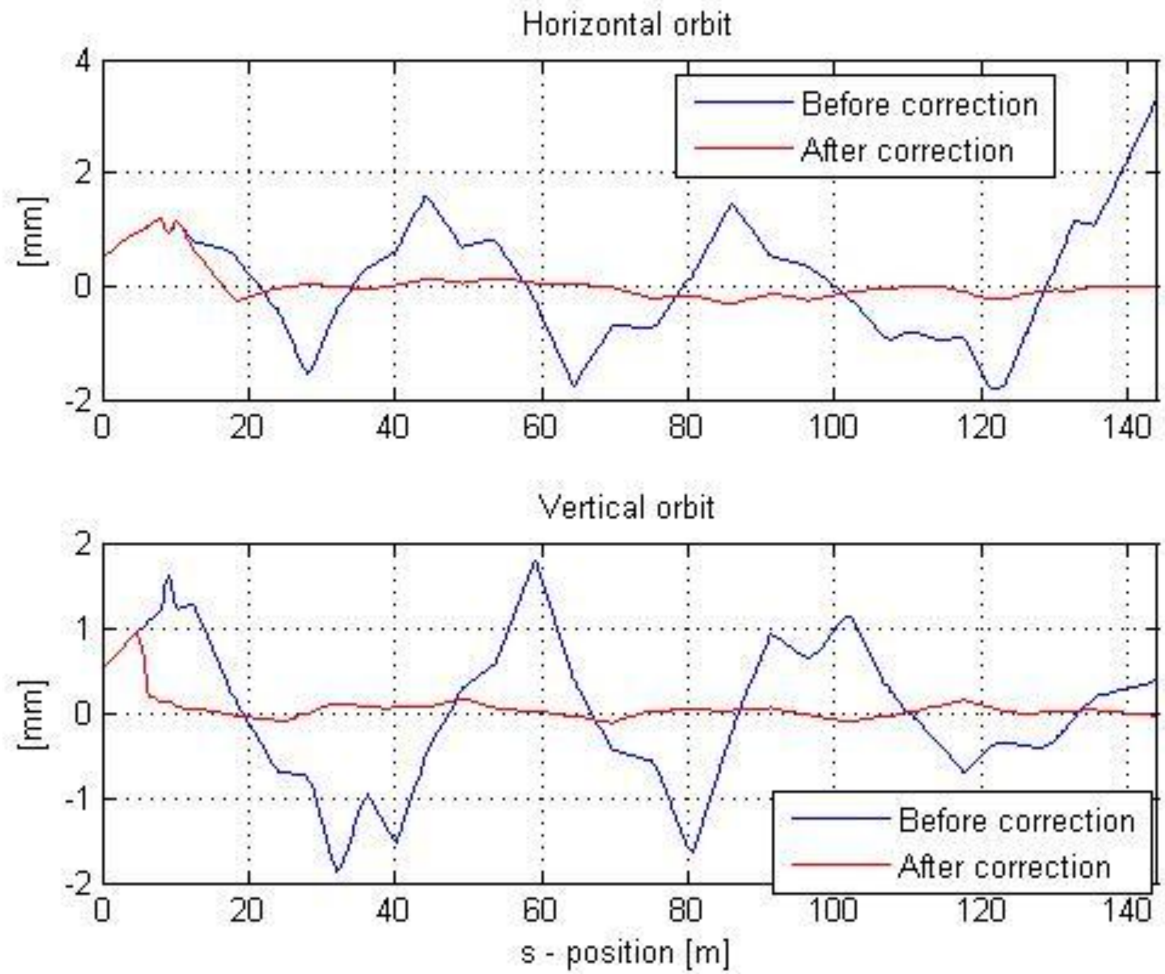


Orbit Correction

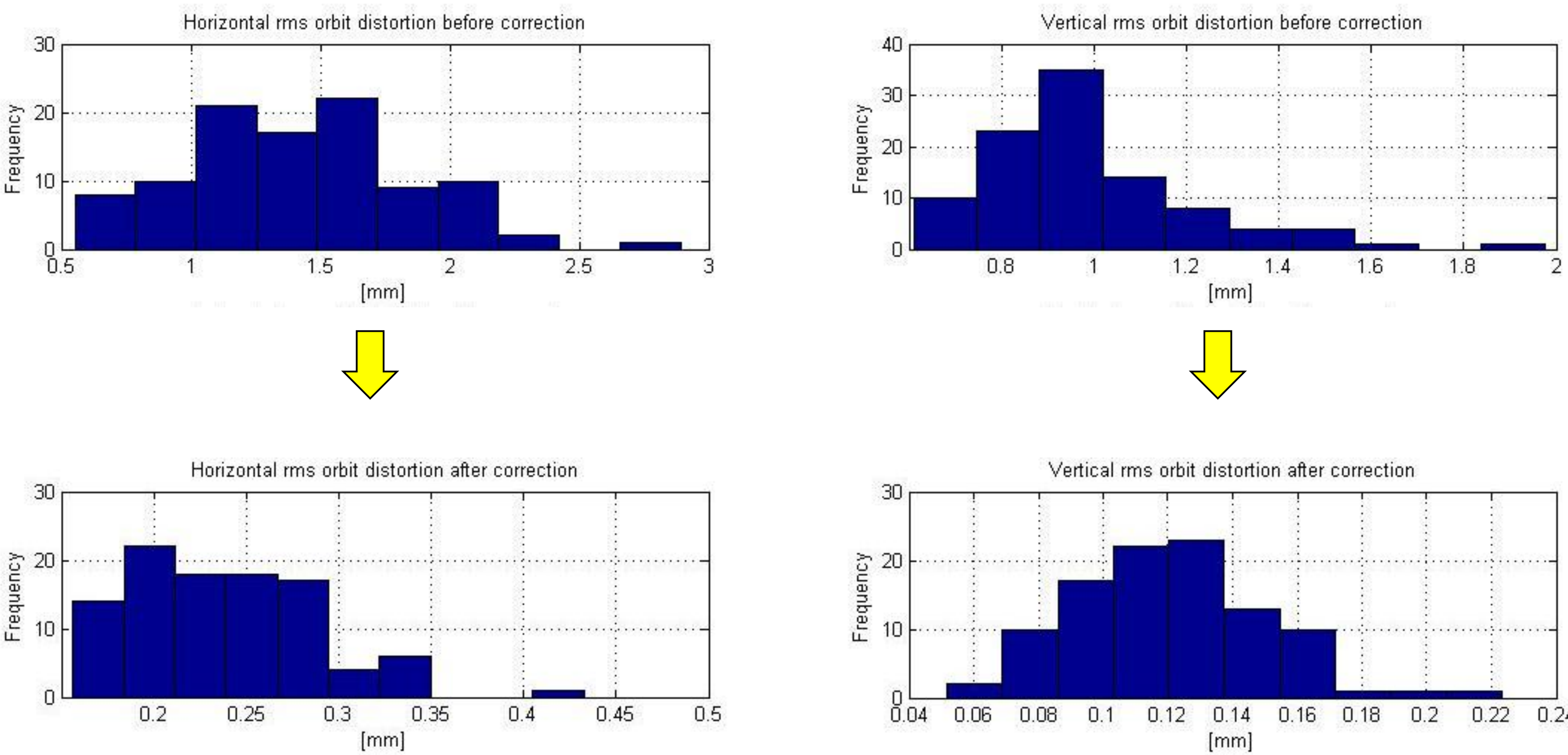
8 horizontal and 9 vertical correctors are used for orbit correction. With some assumption of alignment and magnet strength errors, we did some orbit correction simulation by using AT program. 100 group simulation results show that the orbit aberration can be corrected significantly.

Element	Δx (mm)	Δy (mm)	Δz (mm)	$\Delta\theta_z$ (mrad)
Bending magnet and Lambertson	0.2	0.2	0.2	0.1
Quadrupole	0.15	0.15	0.5	0.2
corrector				0.5

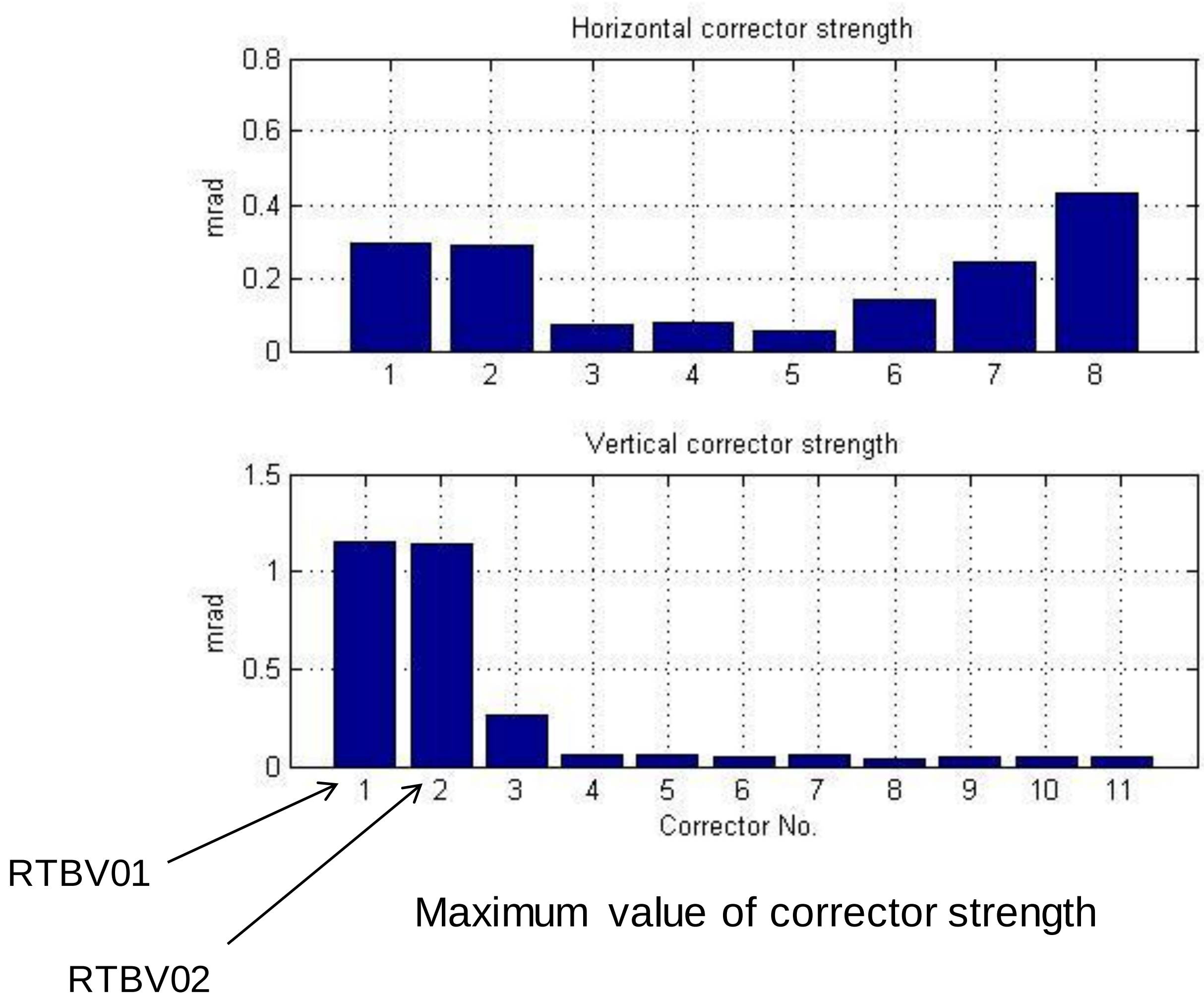
The alignment errors used in the correction simulation.



Orbit comparision before and after correction



The root mean square of orbit before and after orbit correction (100 groups)



Maximum value of corrector strength

RTBT Beam Expanding System

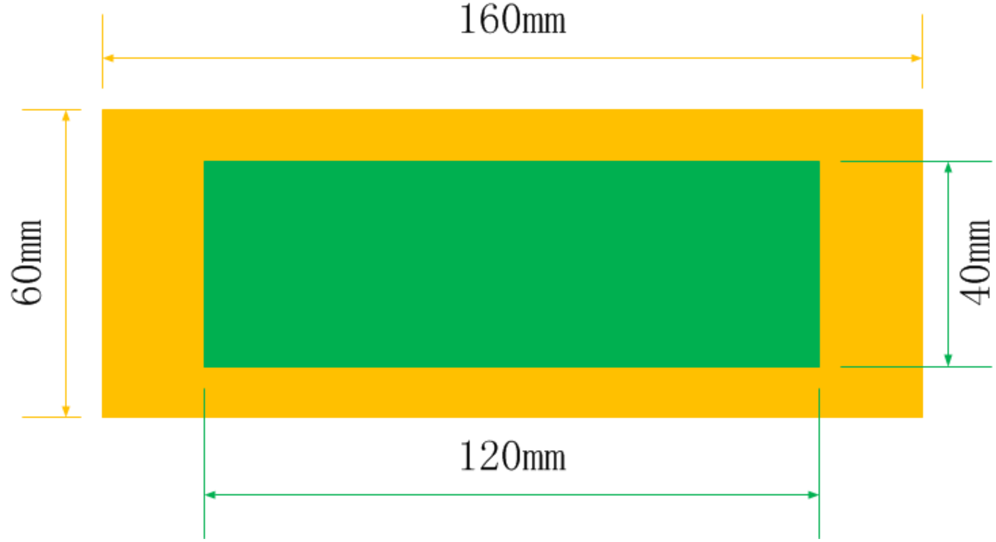
Target

The size of tungsten beam target which is used to produce neutrons is 160 mm (H) × 60 mm (V).

Green region: Most beam (95%) is concentrated in this region for CSNS-I (100 kW).

Orange region: This region will be used for CSNS-II (500 kW).

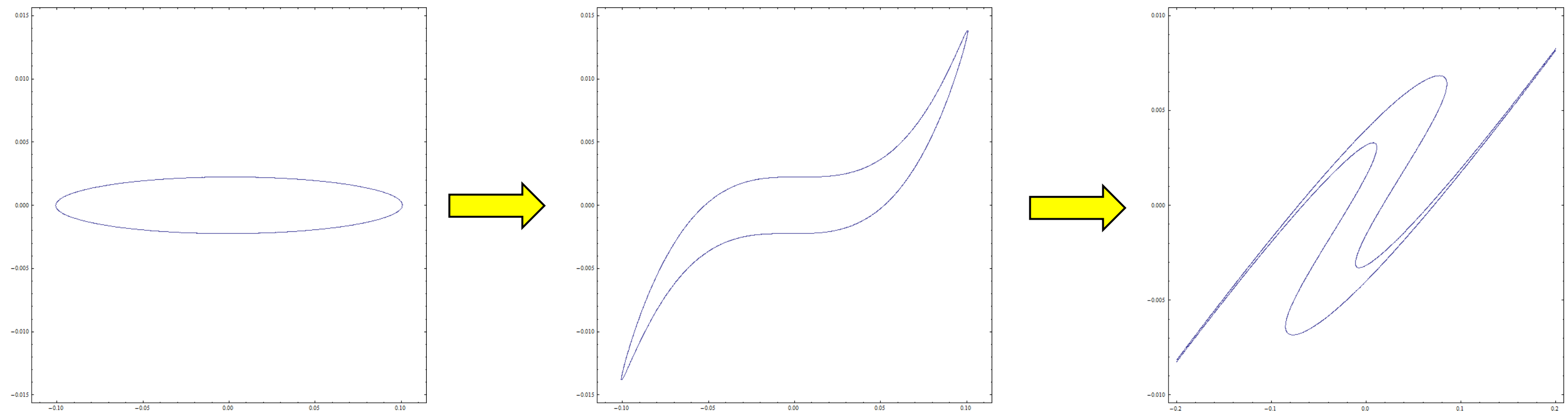
Because the power of the beam bombard on the target is very high, the damage to the target and the target lifetime must be considered. The beam density at the target surface is expected to be uniform as much as possible. A beam expanding system is needed to satisfy the demand.



Octupole Effect

When beam pass through an octupole, the phase ellipse will be twisted because of nonlinear effect. This property can be used to uniform beam distributions, but also brings phase space filamentation which means possible beam loss.

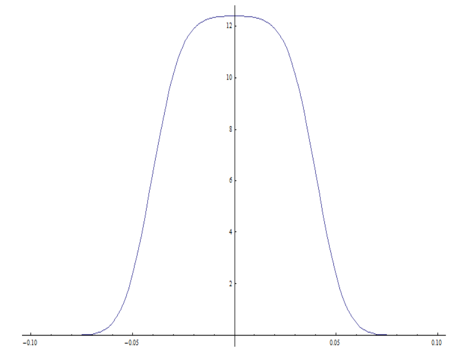
Octupole also brings coupling between horizontal and vertical phase space. The coupling will bring beam loss and affect uniform result. To minimize the coupling effect, flat beam profile is needed at the position of octupole normally.



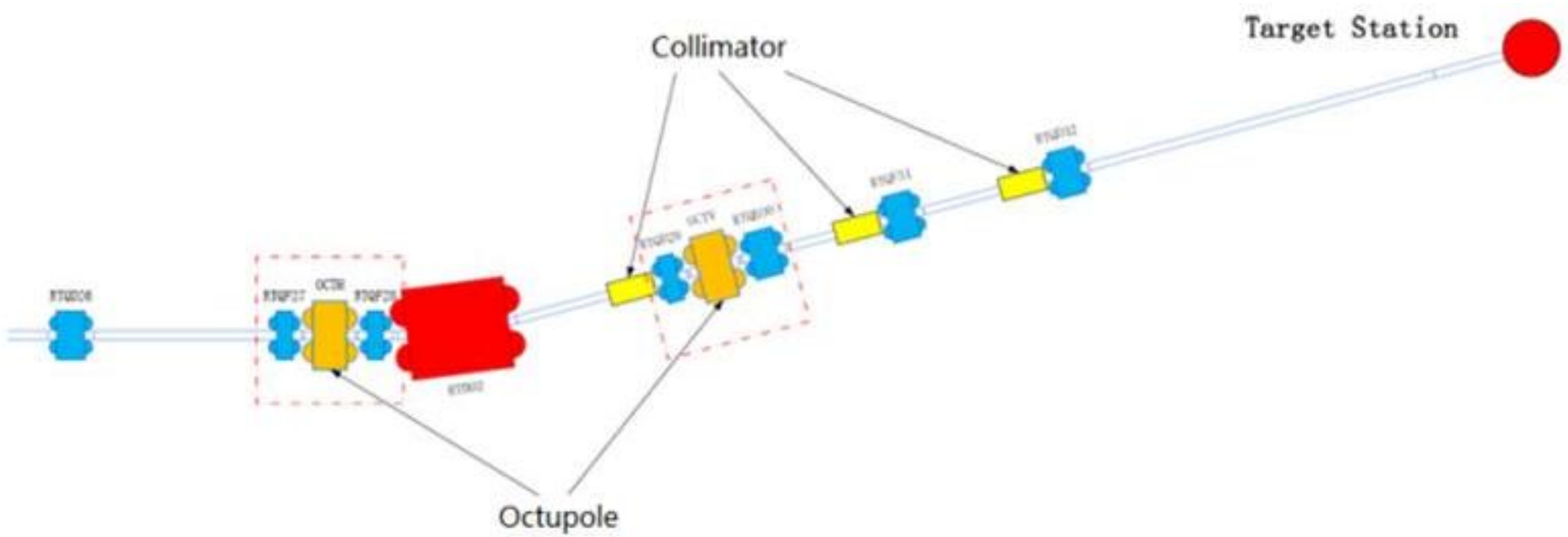
$$\Delta x' = 3KL \cdot x_0 y_0^{\,2} - KL \cdot x_0^{\,3}$$

$$\Delta y' = 3KL \cdot x_0^{\,2} y_0 - KL \cdot y_0^{\,3}$$

Where KL is integral strength of octupole.

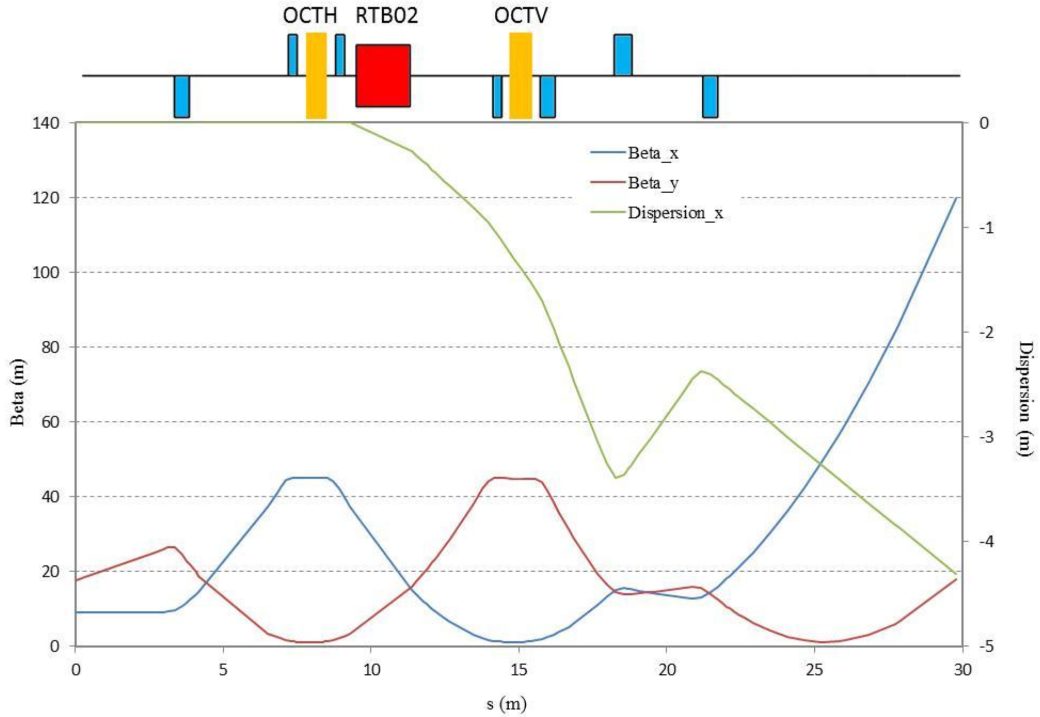


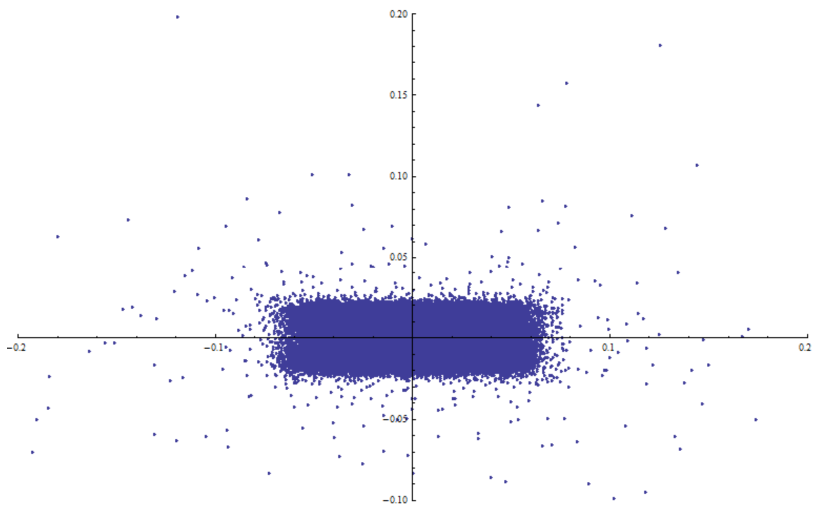
Beam Expanding System



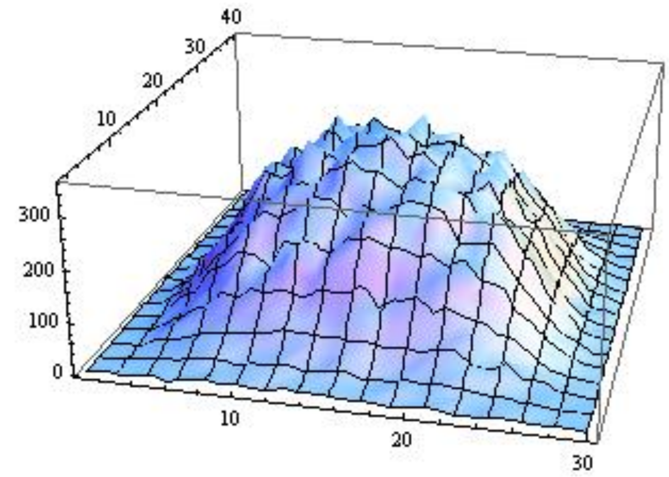
To optimize the beam intensity uniformity at the target surface, a density redistribution scheme with two octupoles is designed. At about 20 m upstream the target, a horizontal bending magnet RTB02 is placed for backscattering neutron stop. With the consideration of the dispersion after RTB02, two octupoles are placed at different side of RTB02. Three collimators are used to shield protons loss because of nonlinear effect brought by the octupoles. The beam loss at every collimator is less than 100 W for 100 kW beam power.

The value of β_x/β_y or β_y/β_x at the positions where the octupoles are placed are designed as large as possible in order to minimize the coupling effect between x-x' and y-y' phase space. The beta function ratio is about 45 m / 1 m for 350 π mm mrad acceptance. The RCS particle tracking simulation results show that the extraction beam emittance for all particles is less than 200 π mm mrad and the core emittance is about 60~80 π mm mrad (3σ). If the real emittance is smaller during commissioning, the lattice will be adjusted to increase the ratio of β function. And the beam expander effect maybe better.





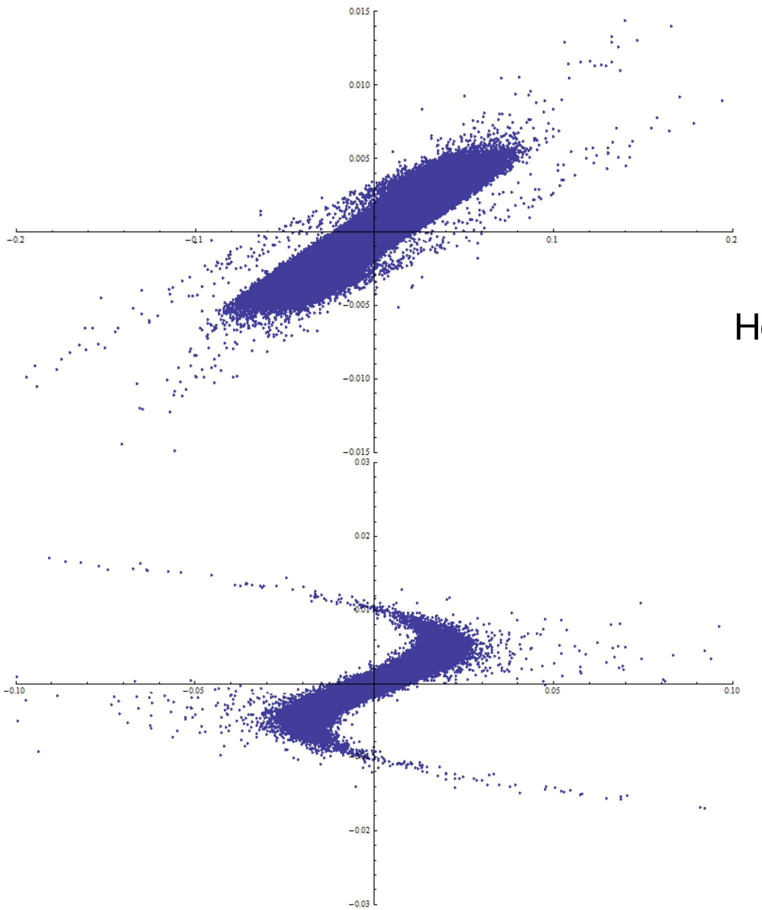
x-y



Some particle tracking simulations were done to check the beam expanding effect. In the simulation, double Gaussian particle distribution is used to stand for the beam core (97% particles, ~80 π mm mrad (3σ)) and the beam halo (3% particles, 250 π mm mrad (3σ)). The momentum spread is set to 0.1% (1 σ). 10^5 macro particles were used for simulations. And over 99.5% particles reach the target. About 97% particles locate in the small region.

The peak beam density is about 2.5 μA/cm^2 which is less than half of Gaussian distribution.

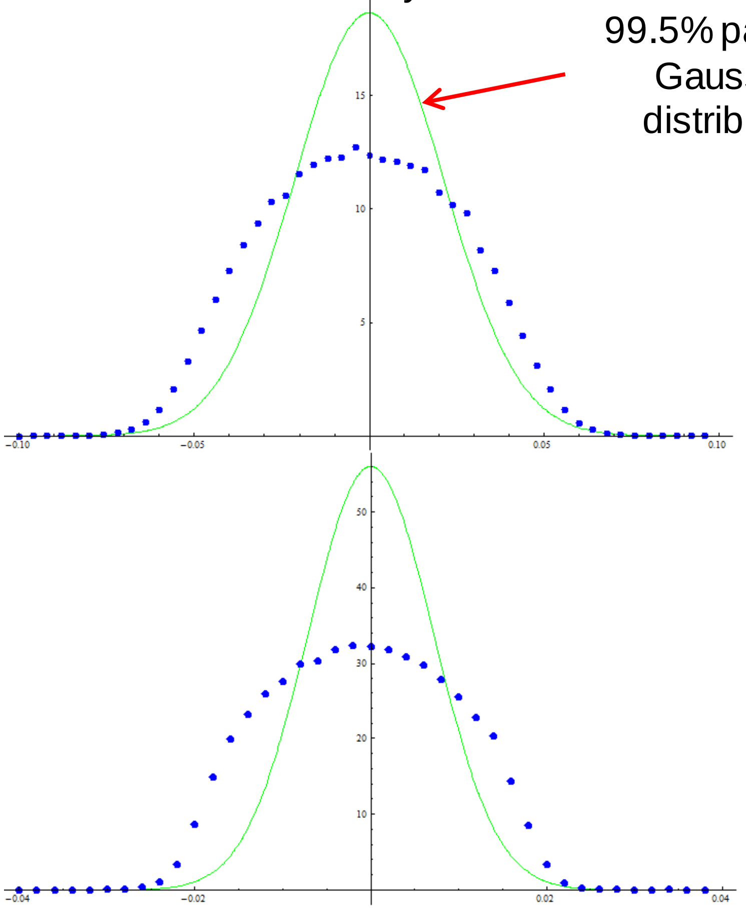
Particle distribution in phase spaces at the target



Horizontal

Vertical

Beam intensity distribution



Numerical Calculation of Beam Density Distribution at Target

In order to check the tracking results, some studies on numerical calculation of beam density distribution have been done.

Assuming the octupoles are thin lenses. When particle passing an octupole, we can get the particle coordinates after the octupole as following:

$$\begin{cases} x = x_0 \\ x' = x_0' + 3KL \cdot x_0 y_0{}^2 - KL \cdot x_0{}^3 \\ y = y_0 \\ y' = y_0' + 3KL \cdot x_0{}^2 y_0 - KL \cdot y_0{}^3 \end{cases}$$

We also can do the reverse calculation to get the initial coordinates by changing the sign of the octupole strength.

$$\begin{cases} x_0 = x \\ x_0' = x' + 3(-KL) \cdot xy^2 - (-KL) \cdot x^3 \\ y_0 = y \\ y_0' = y' + 3(-KL) \cdot x^2 y - (-KL) \cdot y^3 \end{cases}$$

The reverse calculation of other magnets (quadrupoles, bending magnets) can also be gotten. Then we can get the initial particle coordinates before all the octupoles as functions of particles coordinates at the target.

$$x_0(x_t, x_t', y_t, y_t') \quad x_0'(x_t, x_t', y_t, y_t') \quad y_0(x_t, x_t', y_t, y_t') \quad y_0'(x_t, x_t', y_t, y_t')$$

If the initial beam density distribution is Gaussian distribution and has a form as following,

$$f(x_0, x_0', y_0, y_0') = \frac{1}{2\pi\varepsilon_x} e^{-\frac{1}{\varepsilon_x}(\gamma_{x0}x_0^2 + 2\alpha_{x0}x_0x_0' + \beta_{x0}x_0'^2)} \cdot \frac{1}{2\pi\varepsilon_y} e^{-\frac{1}{\varepsilon_y}(\gamma_{y0}y_0^2 + 2\alpha_{y0}y_0y_0' + \beta_{y0}y_0'^2)}$$

We can get the beam density distribution function in phase space at the target by substitution x_0, x_0', y_0, y_0'.

$$f(x_t, x_t', y_t, y_t')$$

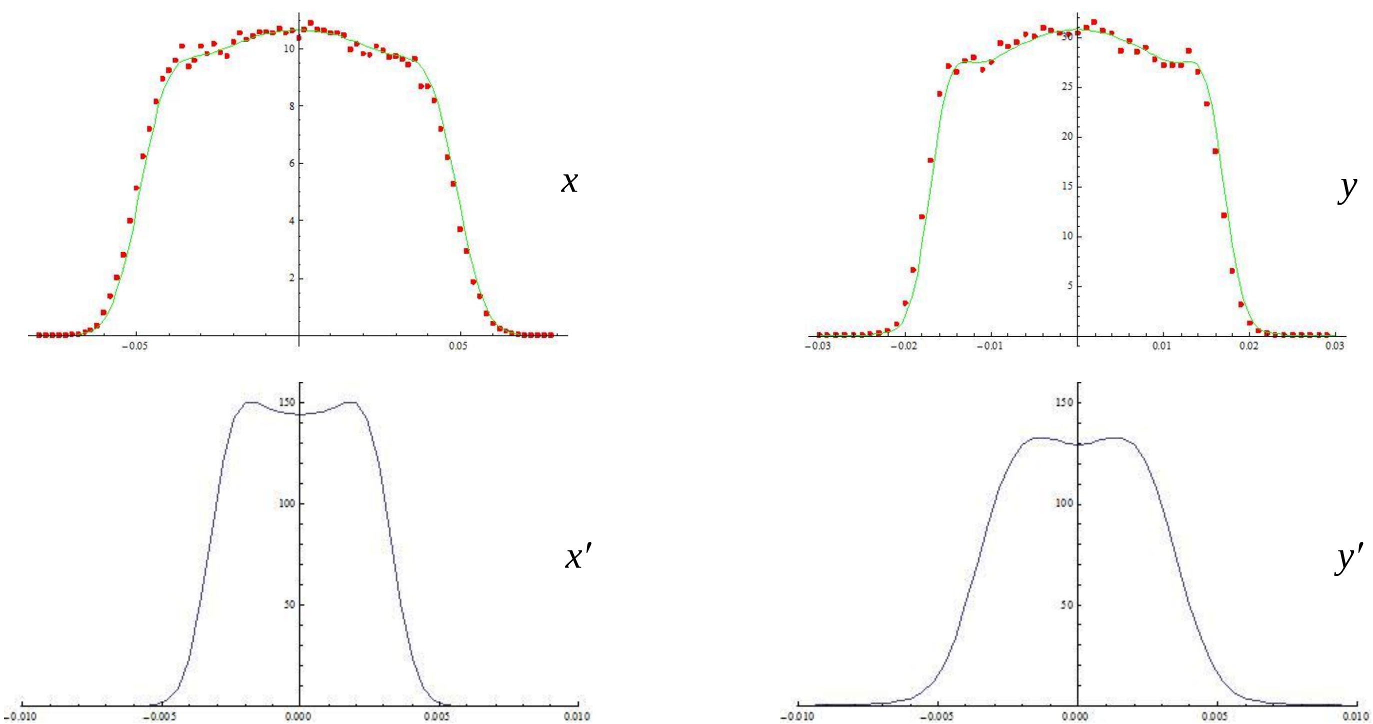
$$= f(x_0(x_t, x_t', y_t, y_t'), x_0'(x_t, x_t', y_t, y_t'), y_0(x_t, x_t', y_t, y_t'), y_0'(x_t, x_t', y_t, y_t')) \cdot \left| \frac{\partial(x_0, x_0', y_0, y_0')}{\partial(x_t, x_t', y_t, y_t')} \right|$$

Jacobian determinant

The beam density distribution expression is very complex. By numerical integral we can get the beam density distribution plots in real space.

$$f(x_t)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(x_t, x_t', y_t, y_t')dx_t' dy_t dy_t'$$

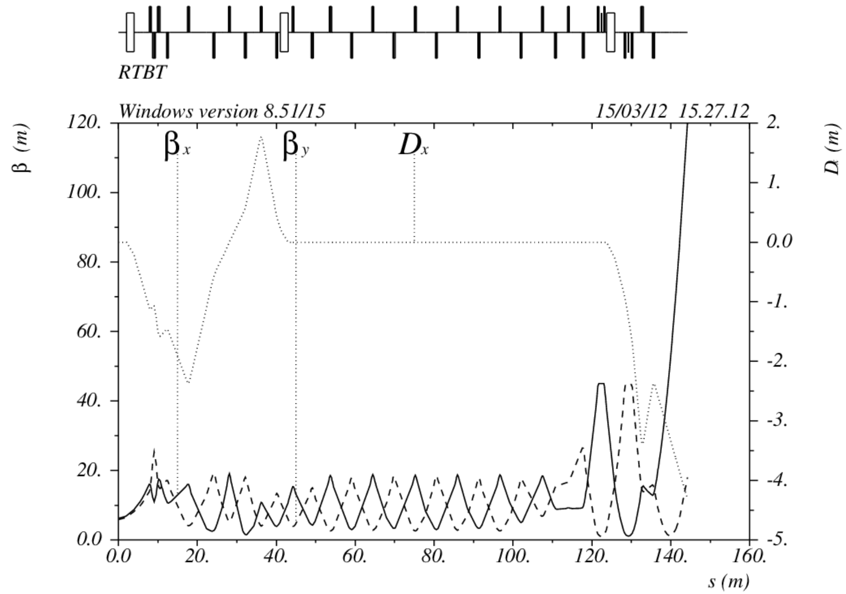
$$f(y_t)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(x_t, x_t', y_t, y_t')dx_t dx_t' dy_t'$$



Comparision Between 100 kW and 500 kW Beam Power

Beam power (kW)	100 kW	500 kW
Average Current	62.5 μA	62.5 $\times$ 5 μA
Core Emittance (3σ)	80 π mm mrad	120 π mm mrad
Target Size	120 mm $\times$ 40 mm	160 mm $\times$ 60 mm
Particles on the Target	99.5%	99.5%
Peak Density	~ 2.5 μA/cm^2	~ 7.7 μA/cm^2
Beam Loss at Every Collimator	< 100 W	< 500 W

The same linear lattice can be used for both 100 kW and 500 kW. Only the octupole strengths need to be adjusted.



Double π Phase Advance Beam Expanding Scheme

During the study of octupole, coupling effects always confuse us. Normally two octupoles are often used for beam expanding. Coupling between horizontal and vertical phase space can not be avoided. But if we adjust the phase advance between two octupoles to π for both horizontal and vertical directions, and set the octupole strengths ratio to a special value according to the twiss parameters, then coupling will be cancelled after the second octupole. In order to minimize the influence of x' and y' on the beam expanding, the phase advance from the second octupole to target should be set to a little larger or smaller than π. With suitable octupole strengths a better expanding result can be gotten.

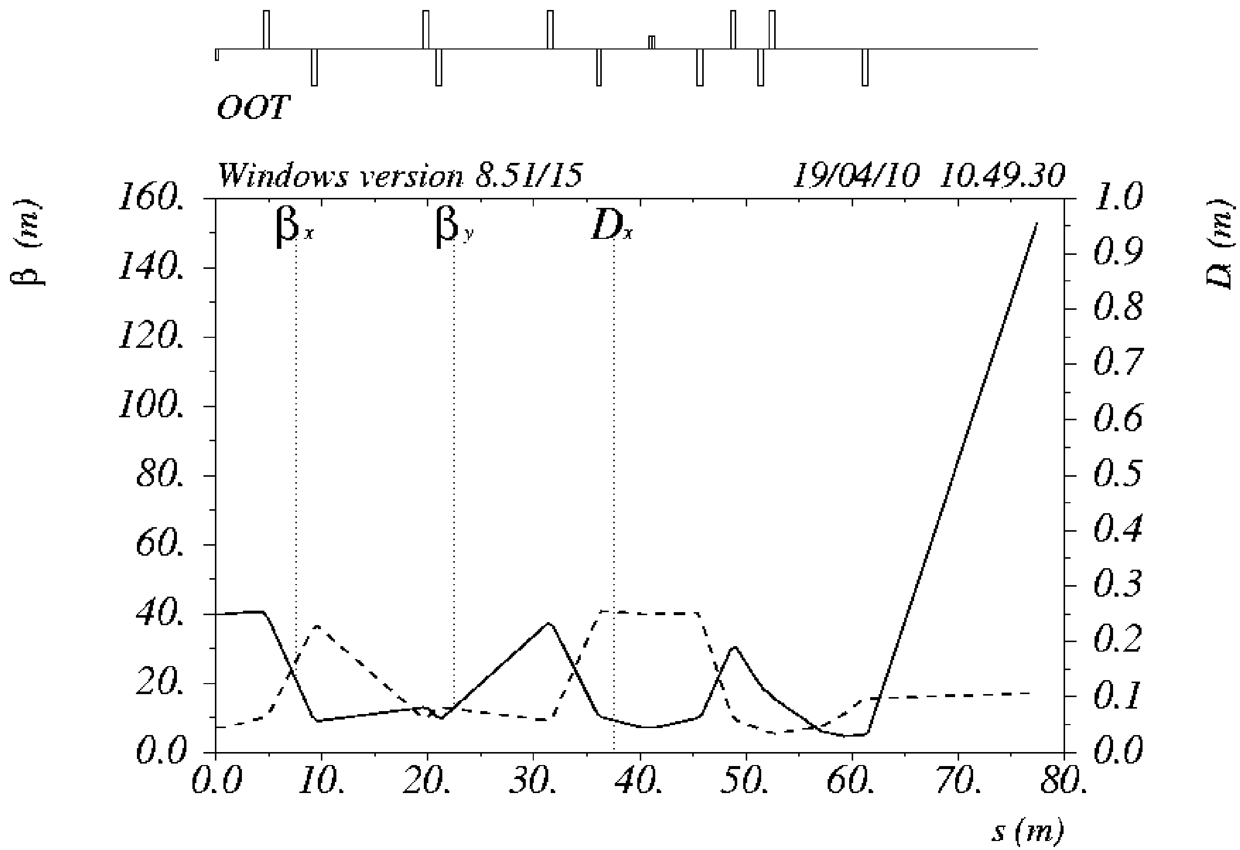
For example, x coordinate at the target can be get as following:

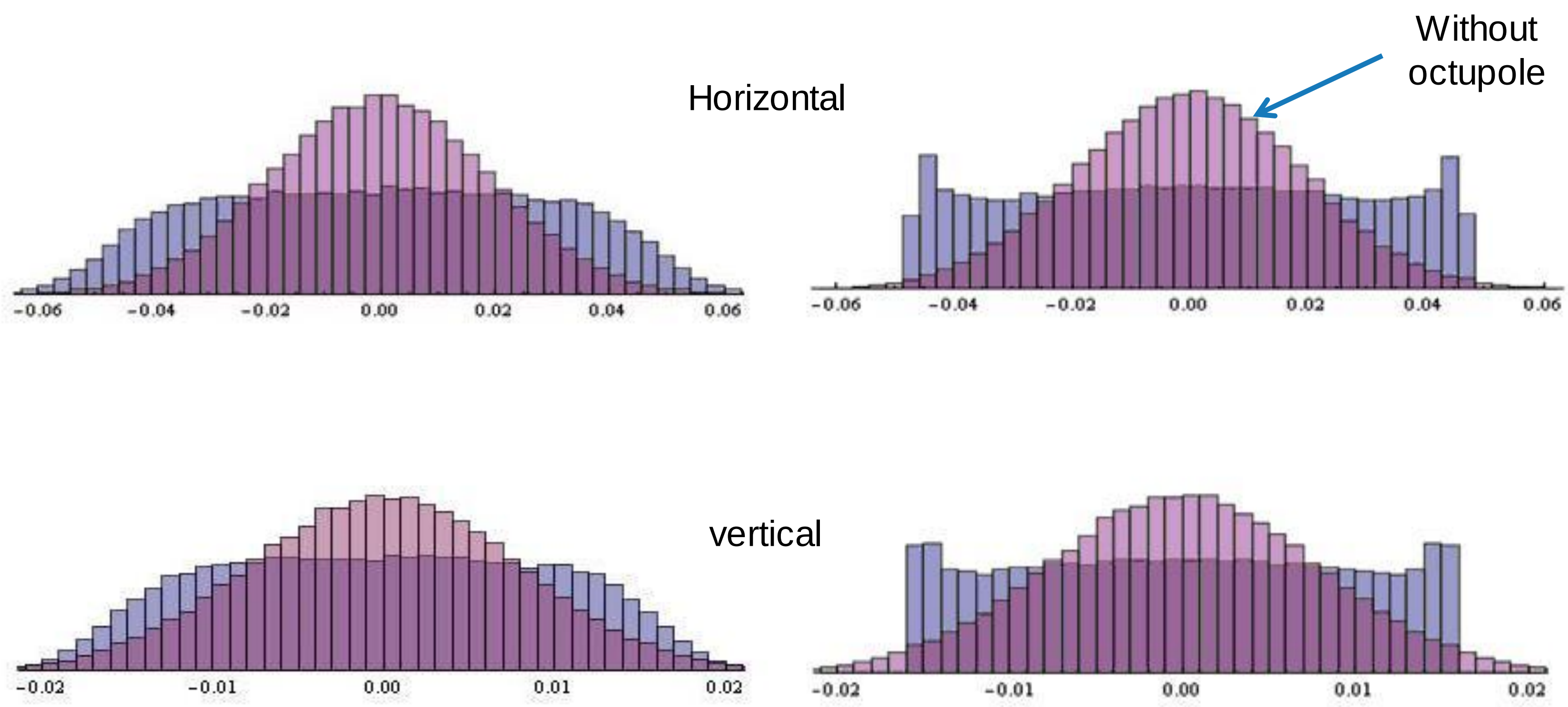
$$x_t = \frac{1}{\beta_{y2}}\sqrt{\frac{\beta_{xt}}{\beta_{x1}}}\left(-\beta_{y2}x_0\cos(\varphi_{xt}-\varphi_{x2}) - \left(\alpha_{x1}\beta_{y2}x_0 + \beta_{x2}\beta_{y1}KL_1x_0^{\ 3} + \beta_{x1}\beta_{y2}(-KL_1x_0^{\ 3} + x_0')\right)\sin(\varphi_{xt}-\varphi_{x2})\right)$$

Where subscript 1 and 2 stand for the positions of the octupoles, subscript t stands for the position of target.

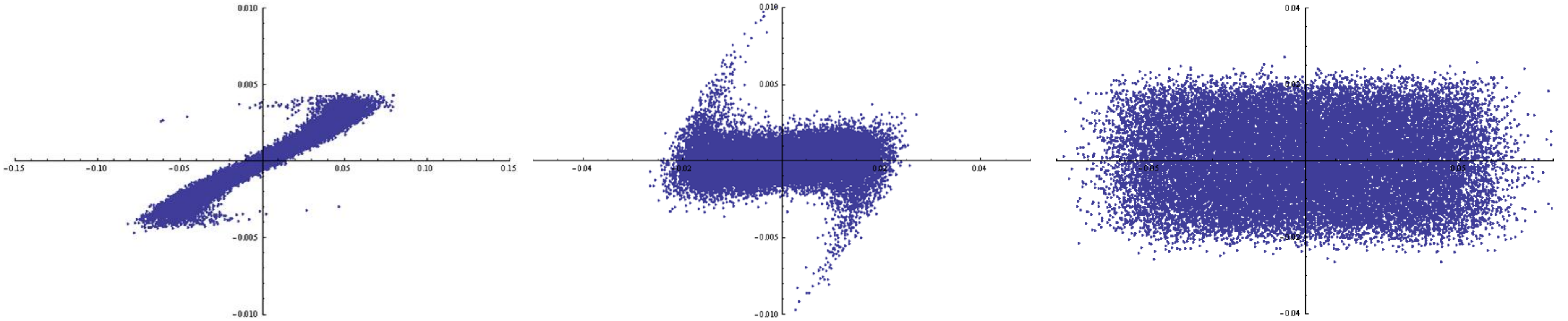
The relation of two octupole strengthes is: $KL_2 = -\frac{\beta_{x1}\beta_{y1}}{\beta_{x2}\beta_{y2}}KL_1$

A preliminary lattice using the double π phase advance beam expander scheme is designed. The tracking results are consistent with the theoretical analysis.

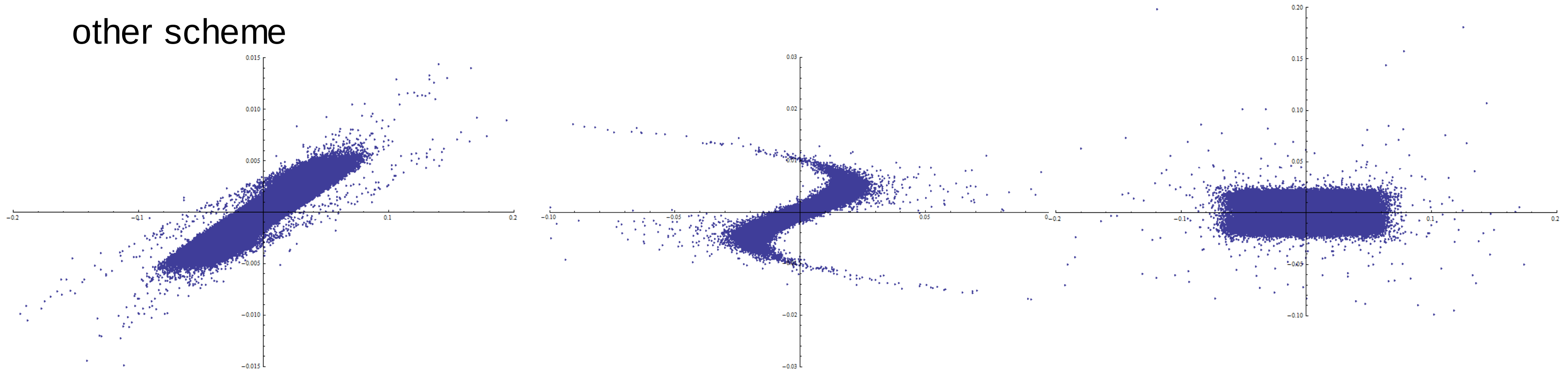




Beam density distribution on the target with different octupole strengths with double π phase advance scheme



other scheme



x-x’ y-y’ x-y

Comparision of particles distribution with double π phase advance scheme and other scheme

Summary

1. The beam transport line from RCS to the target station has been designed. Special requirments for future development are also considered.
2. A beam expanding system with octupoles has been designed for CSNS to satisfy the requirements of the target. Particles tracking simulations and beam loss problems are studied.
3. Some works on effects of kicker error and malfunction, orbit correction have been done.
4. Some preliminary studies on double π phase advance beam expander scheme have been done. Some problems of this scheme need be studied further more.

Thanks for your attention!