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Performance and upgrade considerations for the CSNS injection

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- New painting injection scheme for the CSNS-II
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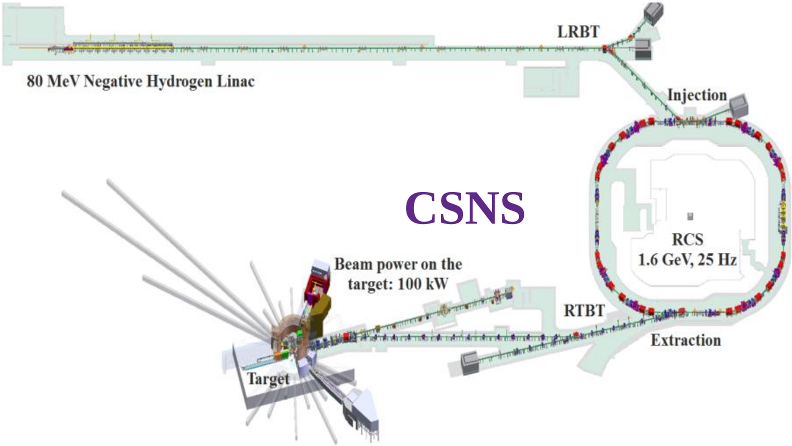
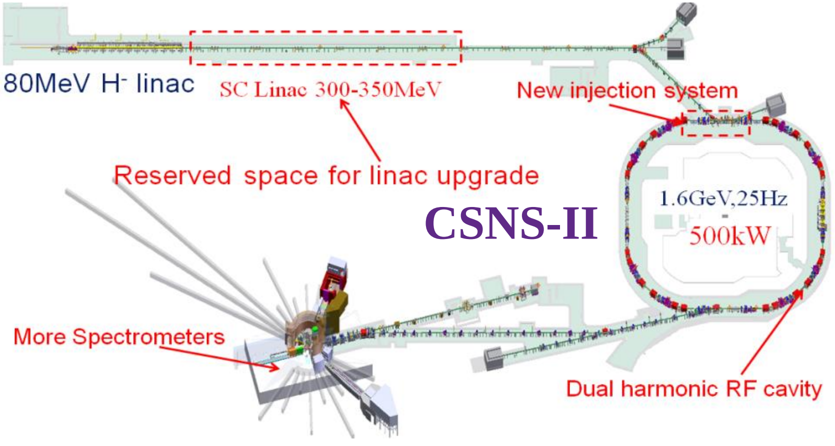
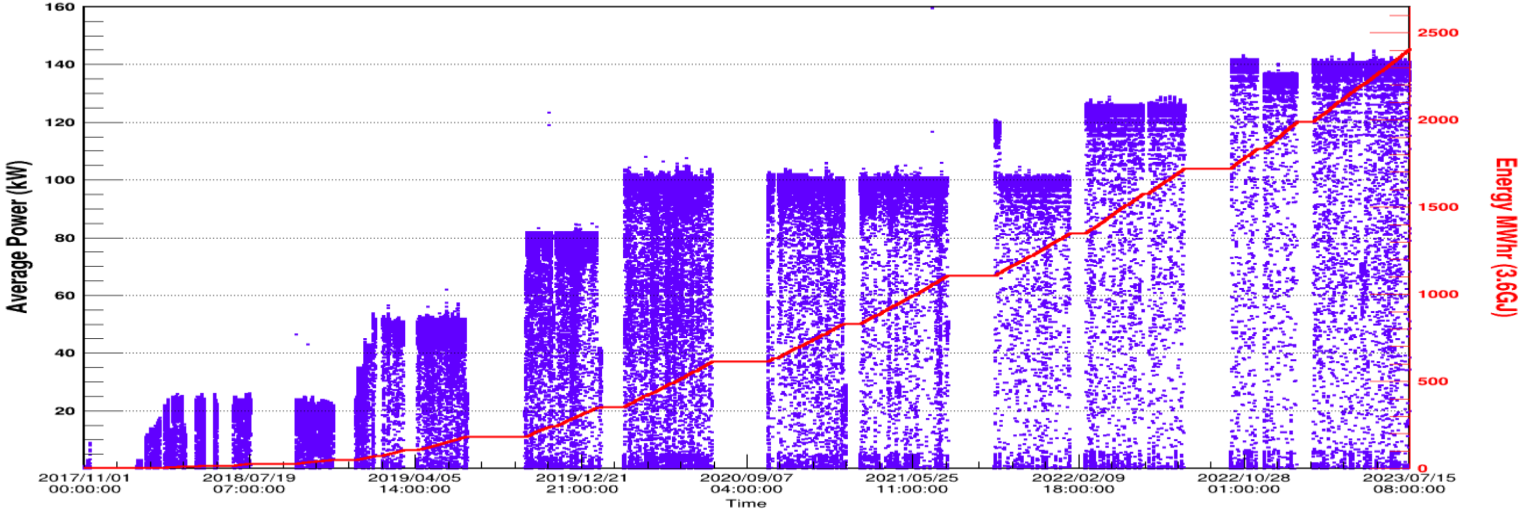
I. Beam injection for the CSNS

- The CSNS facility consists of an 80 MeV H^- Linac, a 1.6 GeV RCS, two beam transport lines, a target station, and several instruments.
- The design goal of beam power on the target for CSNS is 100 kW which has been achieved in Feb. 2020.
- **Main goal of CSNS-II**: increase the beam power on the target to 500 kW.
- **Main contents of CSNS-II accelerator upgrade**: Linac upgrade; injection system upgrade; three dual harmonic cavity would be added to the RCS.





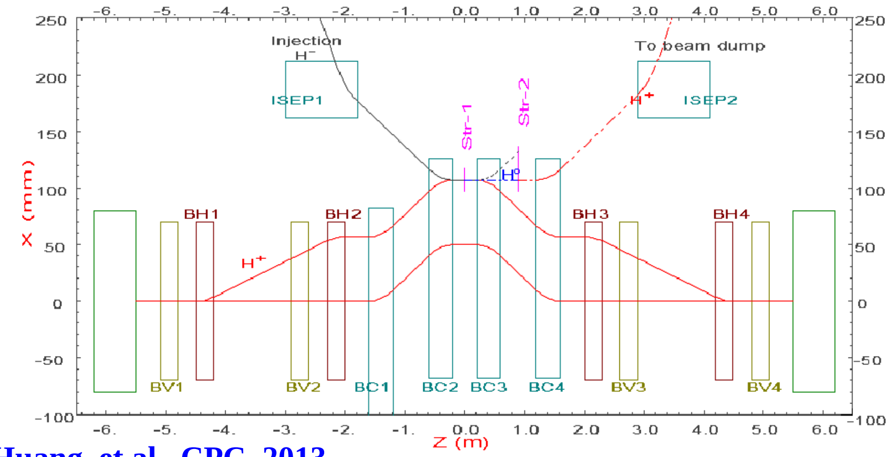
Historical Curve of CSNS Beam Power



- Nov. 2017, First 10 kW beam power on the target for a short while;
- Mar. 2018, beam power over 20 kW in the test operation;
- Jan. 2019, beam power was gradually increased to 50kW+ with well controlled beam loss;
- Sep. 2019, beam power in user operation was increased to 80 kW step by step;
- Feb. 2020, beam power was increased to 100 kW to achieve the design goal;
- Oct. 2021, beam power was increased to 120 kW;
- Oct. 2022, beam power was increased to 140 kW.

Injection system

- For the CSNS, a combination of the H^- stripping and phase space painting method is used to accumulate a high intensity beam in the RCS.
- There are three kinds of orbit-bumps: a horizontal bump (BH1-BH4) for painting in x-x' plane; a vertical bump (BV1-BV4) for painting in y-y' plane; a horizontal chicane bump (BC1-BC4) in the middle for an additional closed-orbit shift.

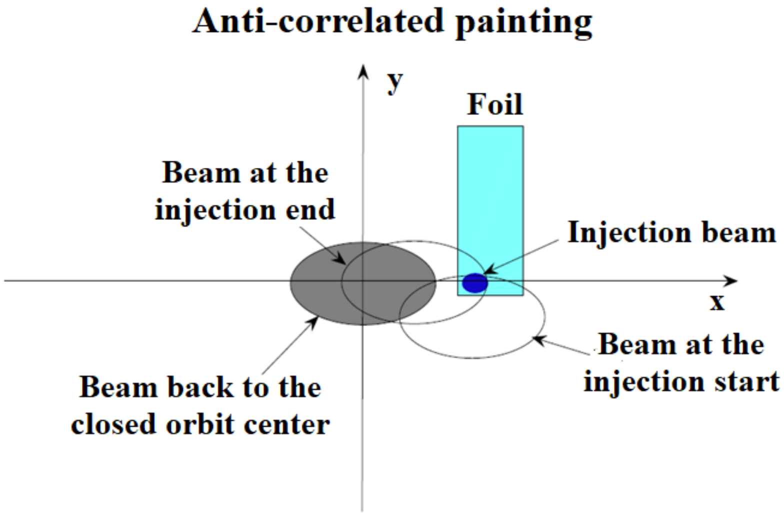


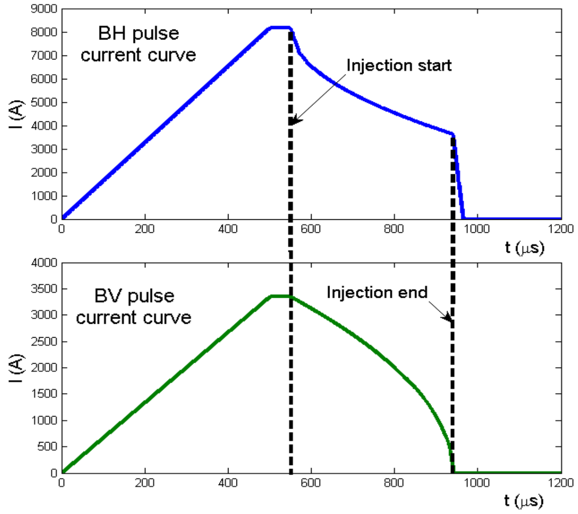
parameters/units	values
circumference/m	227.92
injection energy/GeV	0.08
extraction energy/GeV	1.6
injection beam power/kW	5
extraction beam power/kW	100
nominal betatron tunes	4.86/4.78
RF frequency/MHz	1.0241–2.3723
RF voltage/kV	165
harmonic number	2
repetition rate/Hz	25
number of particles per pulse	1.56×10^{13}
momentum acceptance (%)	1
painting scheme	anti-correlated
chopping rate (%)	50
turn number of injection	200

Huang, et al., CPC, 2013.

Anti-correlated painting

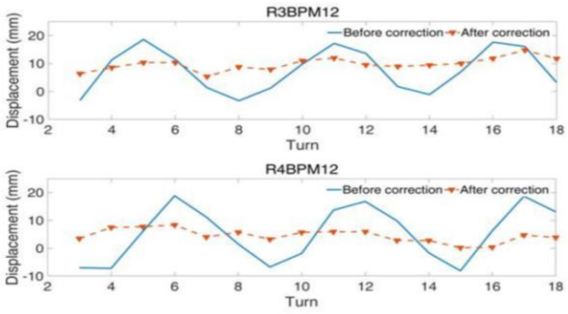
- In order to control the strong space charge effects and reduce the average traversal number of the stripping foil, the phase space painting is used for injecting a small emittance beam from the Linac into the large acceptance of the RCS.
- For the CSNS, the anti-correlated painting is adopted as the design scheme for the injection system.





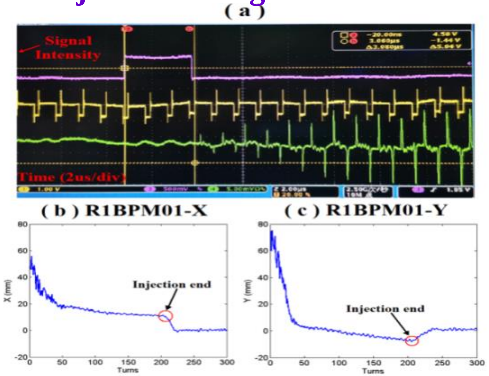
Beam commissioning for the anti-correlated painting (50kW)

Injection beam parameters matching

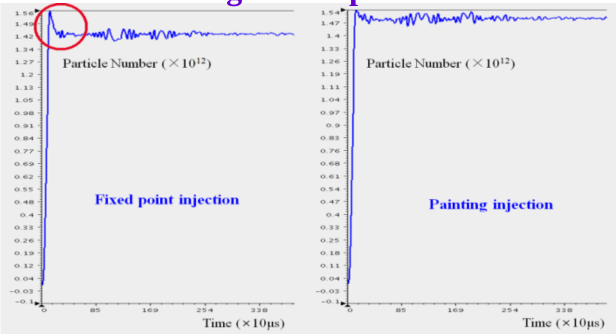


Lu & Huang & Wang, PRAB, 2018.

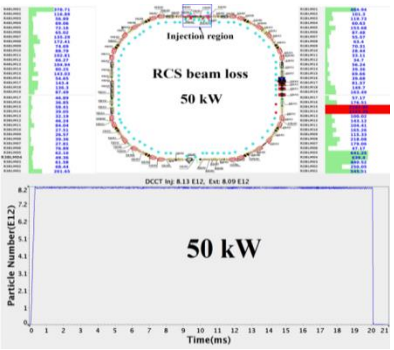
Injection timing calibration

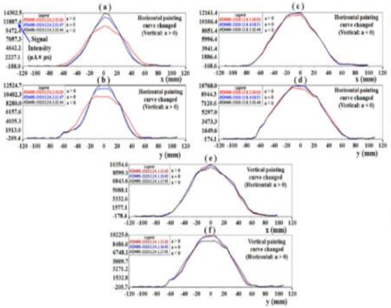


Painting mode optimization

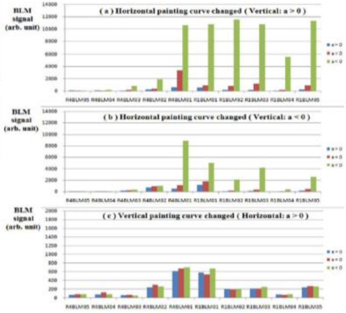


The beam power has successfully reached 50 kW.

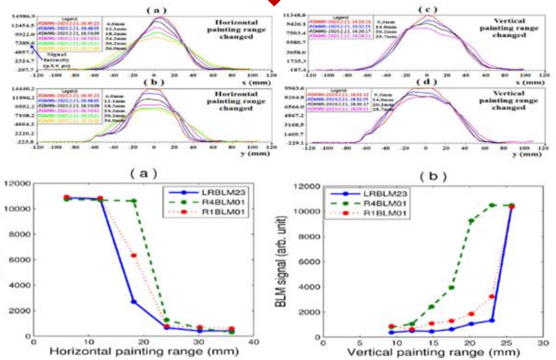




Huang et al., NIM-A, 2021.



Painting curve optimization

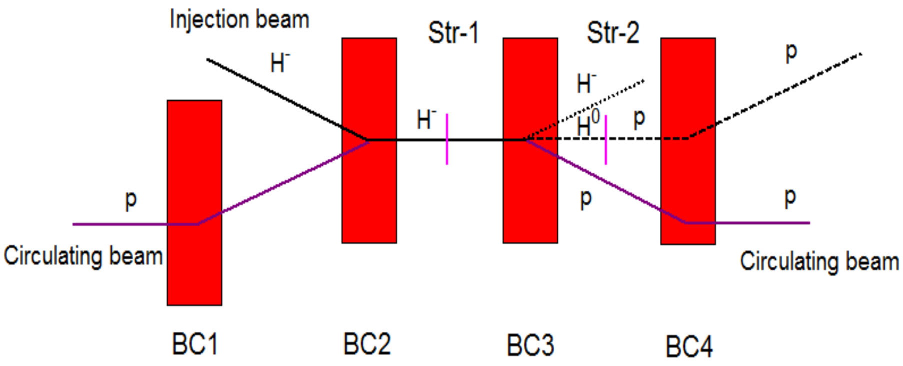


Painting range optimization

H^- stripping scheme

- For the CSNS, the foil stripping is adopted to inject the Linac beam to the RCS with high precision and high efficiency. There are two stripping foils: a main stripping foil and a secondary stripping foil.

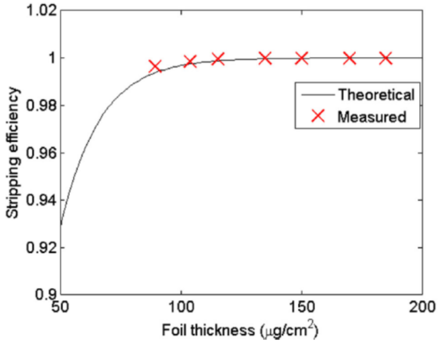
- For the CSNS-II, the foil stripping is also selected as the design scheme. The stripping foil system also consists of two stripping foils.

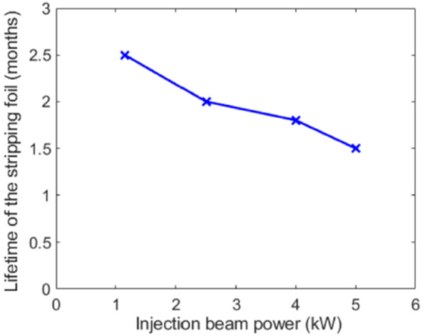


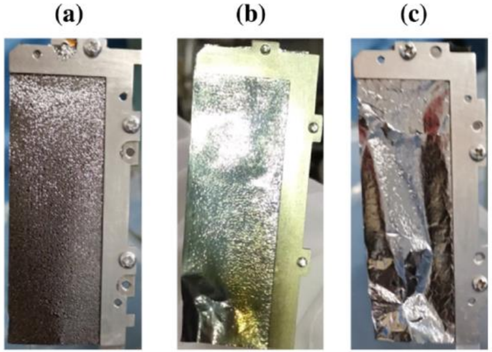
Phase	CSNS		CSNS-II	
Foil	Str-1	Str-2	Str-1	Str-2
Material	HBC	HBC	HBC	HBC
Structure	Double-layer	Double-layer	Double-layer	Double-layer
Thickness (μg/cm^2)	100	200	260	450
Stripping efficiency	99.7%	100%	99.7%	100%

Study on the H^- stripping

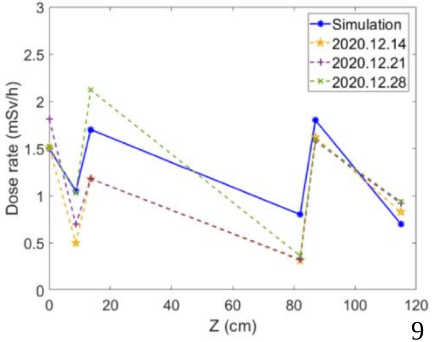
- A method to accurately measure the stripping efficiency has been proposed and the measurement results are consistent with the theoretical results.
- The foil lifetime decreases with the increase in the injection beam power and the foil lifetime under the design power is about 1.5 months.
- It can be confirmed that the foil scattering is the most important source of the residual doses in the injection region.







Huang et al., RDTM, 2022.



Injection beam loss

- Main sources:

(1) Injection parameter mismatch

(2) Unsuitable painting method

(3) Unreasonable injection design scheme

(4) Beam loss associated with foil stripping

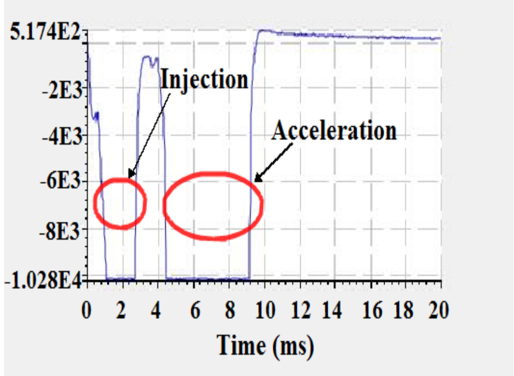
- Main solutions:

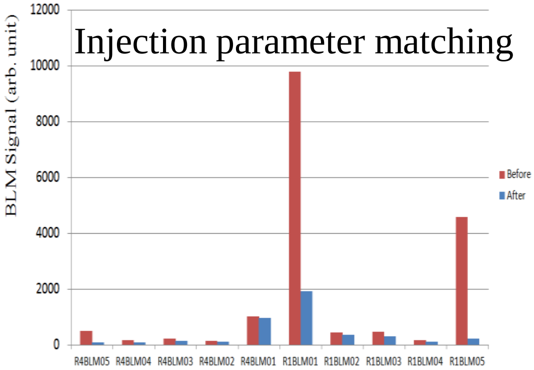
(1) Injection beam parameters matching

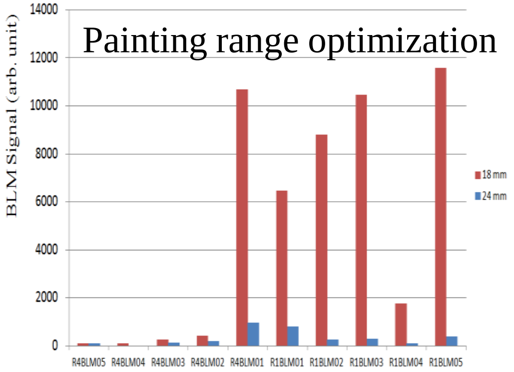
(2) Painting optimization

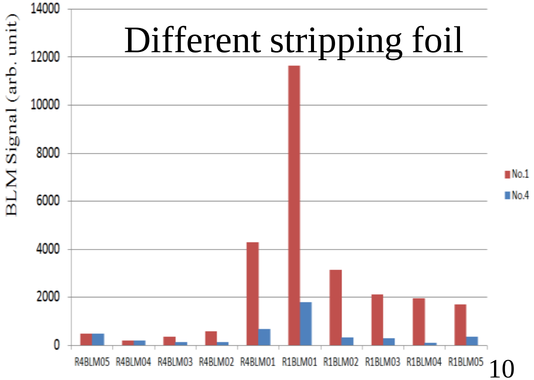
(3) Slight modification of injection system

(4) Optimization of the stripping foil









II. Performance of the correlated painting based on the mechanical structure of the anti-correlated painting scheme

Beam commissioning difficulties (>50kW)

- **Difficulties:** Too large beam size after painting, non-uniform beam distribution, large transverse coupling effect, and so on, resulting in additional beam loss and making it difficult to satisfy the requirements of a stable high-power operation mode.

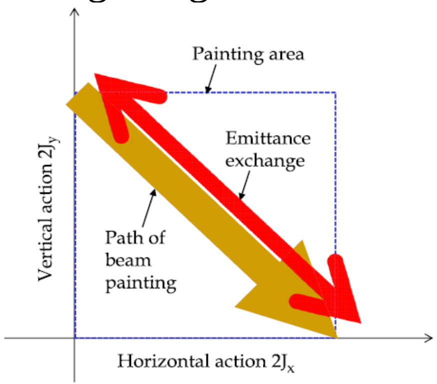
- **Reasons:** (1) In order to reduce the coherent oscillation effects, new betatron tunes (4.81, 4.87) have been used to replace the nominal tunes (4.86, 4.78). However, with the new tunes (4.81, 4.87), the transverse coupling effect on the beam distribution is very strong. (2) Due to changes in operation mode, the actual vertical painting acceptance of the ceramic vacuum chamber at the painting magnet BH3 is much smaller, which is only about 70% of the design value.

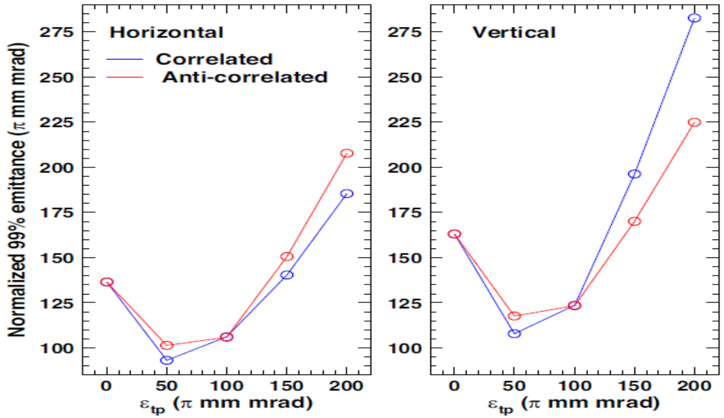
Huang, et al., PRAB, 2022.

Theoretical analysis

- **J-PARC experience:** Because of the effect of the space-charge coupling caused by the Montague resonance, when the betatron tunes are selected close to the coupling, the anti-correlated painting has more advantages for a large painting area and the correlated painting has more advantages for a small painting area.

- **Simulation:** For the betatron tunes (4.81, 4.87) and maximum vertical painting area of about 75 π·mm·mrad in the CSNS RCS, the correlated painting may have more advantages than the anti-correlated painting design scheme.





Hotchi, PRAB, 2020.

- **Goal:** To compare the correlated and anti-correlated painting in the same injection mechanical structure.
- **Method:** The relationship between the emittance of the circulating beam relative to the vacuum chamber center and the machine aperture of the vacuum chamber in different painting processes needs to be figured out.

$$\sigma_x^2 = \beta_x \cdot \varepsilon_x + D_x^2 \cdot \left(\frac{\sigma_E}{E_0}\right)^2$$

$$\sigma_y^2 = \beta_y \cdot \varepsilon_y + D_y^2 \cdot \left(\frac{\sigma_E}{E_0}\right)^2$$

$$D_x \sim 0, \quad D_y \sim 0$$

$$\Rightarrow$$

$$\varepsilon_{ex} = \frac{[|x-x_0|+|\sigma_x|]^2}{\beta_x}$$

$$\varepsilon_{ey} = \frac{[|y-y_0|+|\sigma_y|]^2}{\beta_y}$$

$$\Rightarrow$$

$$\kappa_x = \frac{[|x-x_0|+|\sigma_x|]^2}{R^2-(y-y_0)^2}$$

$$\kappa_y = \frac{[|y-y_0|+|\sigma_y|]^2}{R^2-(x-x_0)^2}$$

$$\kappa_{xy} = \frac{[|x-x_0|+|\sigma_x|]^2+[|y-y_0|+|\sigma_y|]^2}{R^2}$$

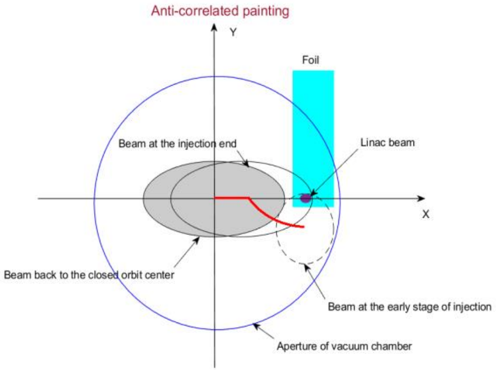
Low beam loss requires that the circulating beam should meet the following conditions for each turn in the injection process：

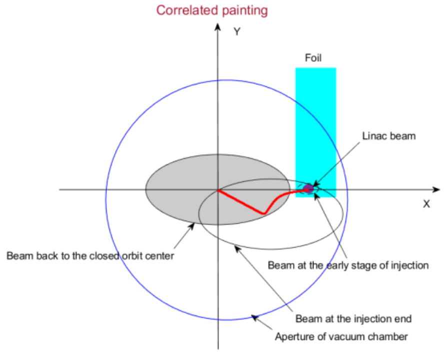
$$\kappa_x < 1, \quad \kappa_y < 1, \quad \kappa_{xy} < 1$$

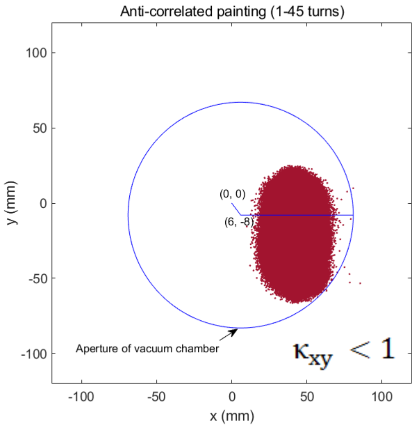
Achieve the correlated painting based on the mechanical structure of the anti-correlated painting scheme

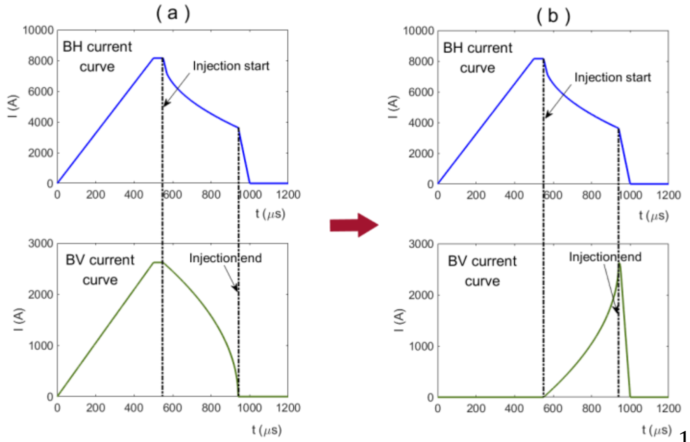
- The location of the vacuum chamber aperture limitation is at the bottom right corner. The condition $\kappa_{xy} < 1$ is the main constraint for the painting beam.

- The rising curve of the BV pulse current is used for the vertical painting to achieve the correlated painting.

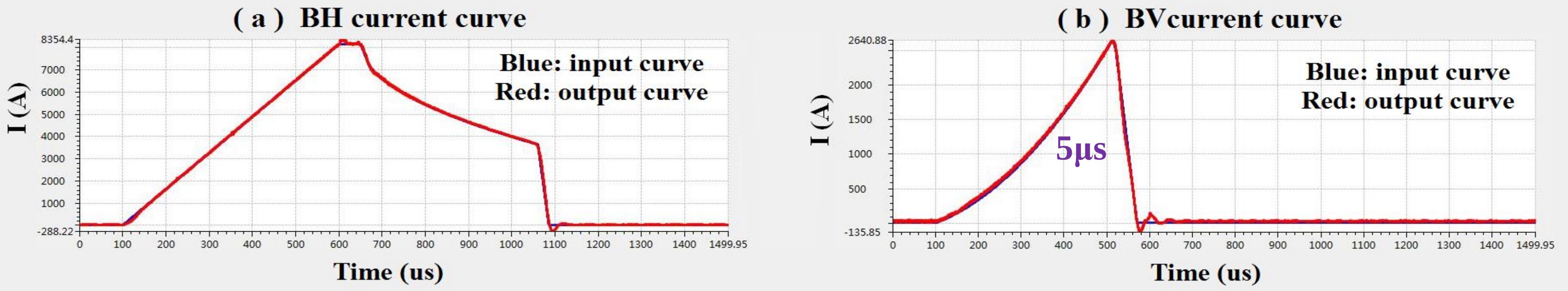








Beam commissioning for the correlated painting



- **Key issues:** Rising speed, falling speed, minimum flattop time, and tracking accuracy.

Beam commissioning

(1) Timing adjustment of the pulse power supply for the correlated painting;

(2) Parameters matching between the injection beam and circulating beam;

(3) Position adjustment of the stripping foil;

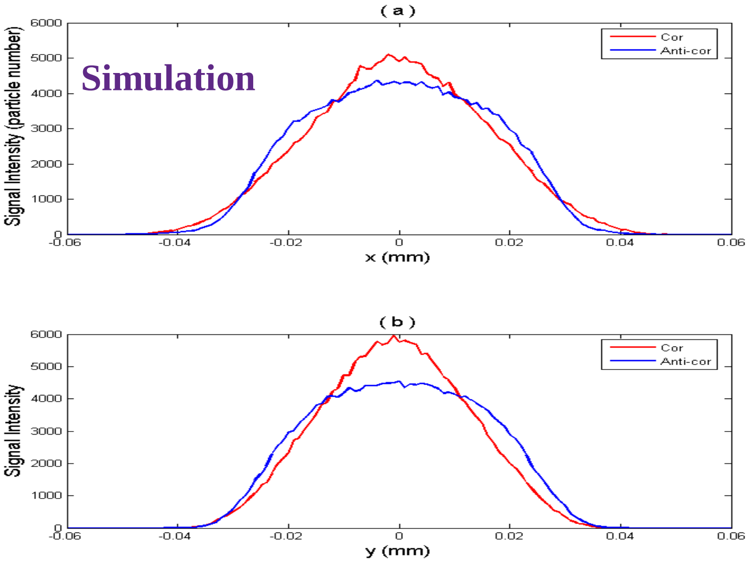
(4) Optimization of the transverse painting ranges and painting curves;

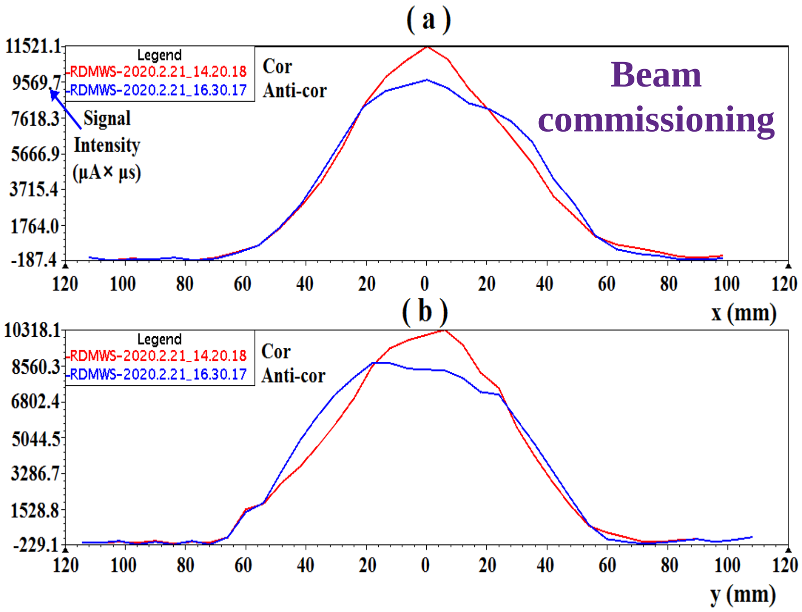
(5) Injection beam loss control.

Transverse beam distributions after painting

- **Simulation:** Compared to the case of anti-correlated painting, the transverse beam size for the correlated painting is smaller and the beam distribution is much better.

- **Beam commissioning:** The beam commissioning results are in good agreement with the simulation results.

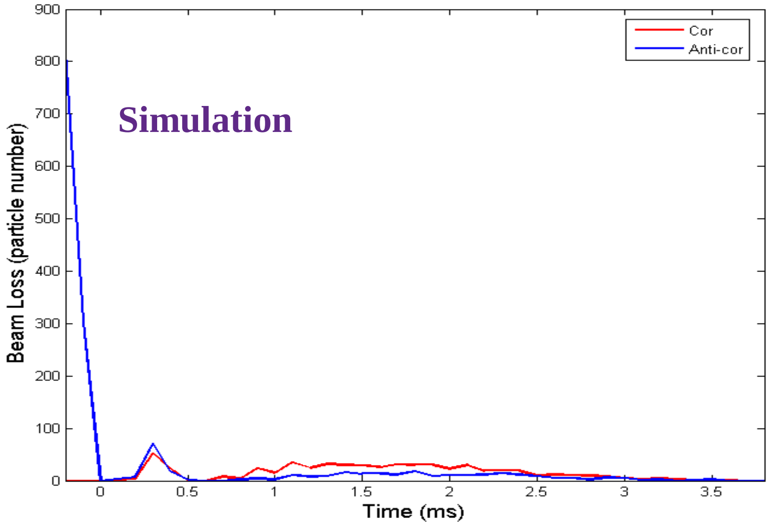


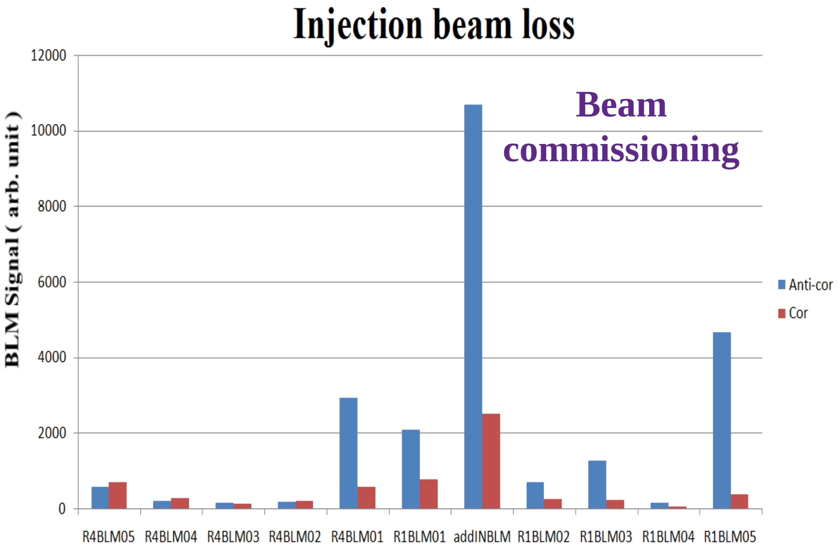


Injection beam loss

- **Simulation:** Compared to the case of anti-correlated painting, the injection beam loss for the correlated painting is reduced.

- **Beam commissioning:** The beam commissioning results are in good agreement with the simulation results.

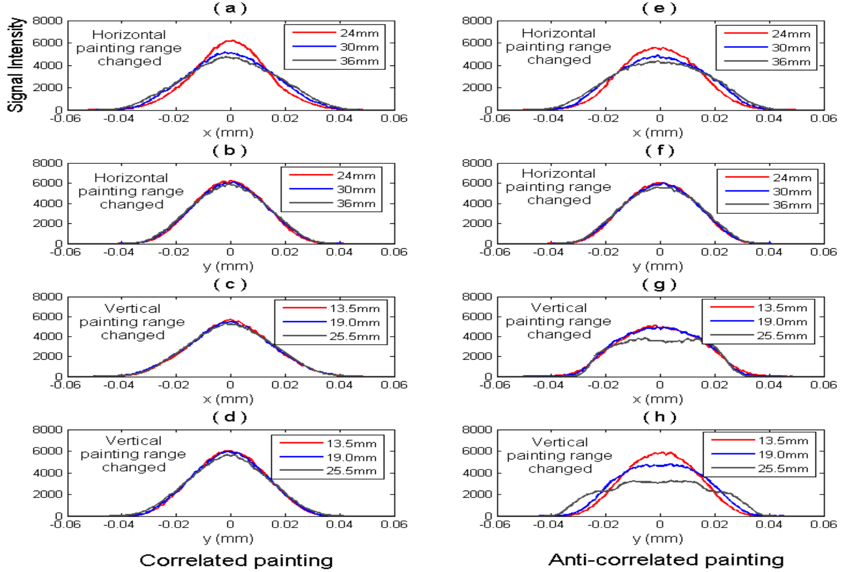




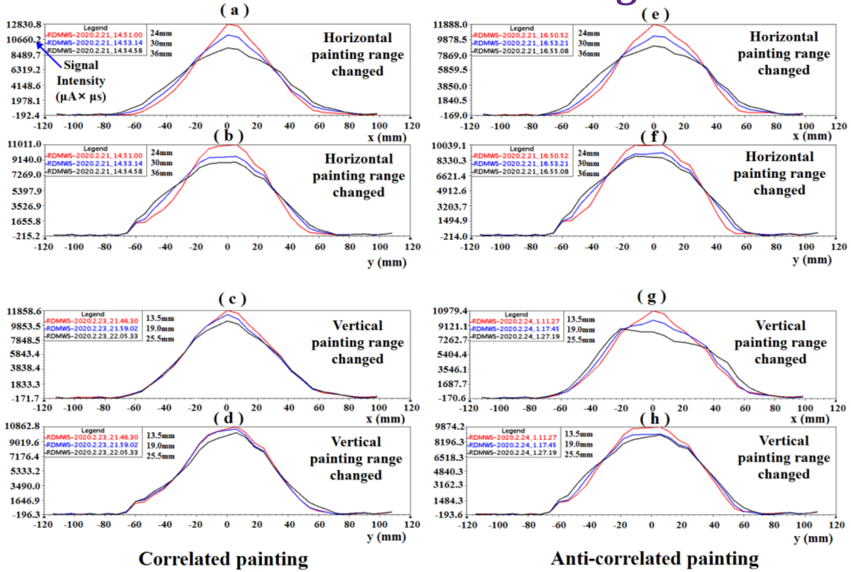
Transverse coupling effects

- **Simulation:** For the anti-correlated painting, the variation of the vertical painting range causes obvious changes in the horizontal painting distribution. These changes can be reduced by using the correlated painting.
- **Beam commissioning:** The beam commissioning results of the transverse coupling effect are somewhat different from the simulation results, but the trend is the same.

Simulation



Beam commissioning



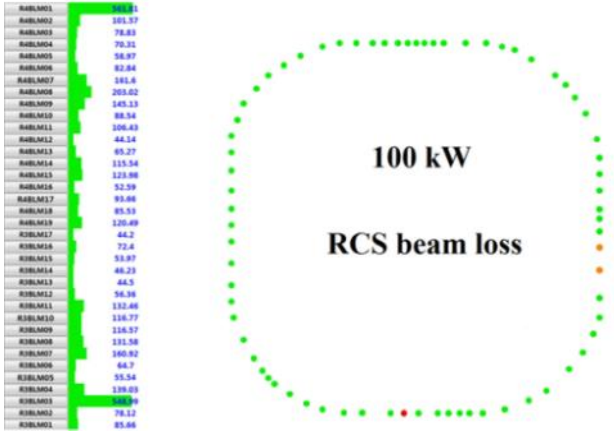
Results

By using the correlated painting:

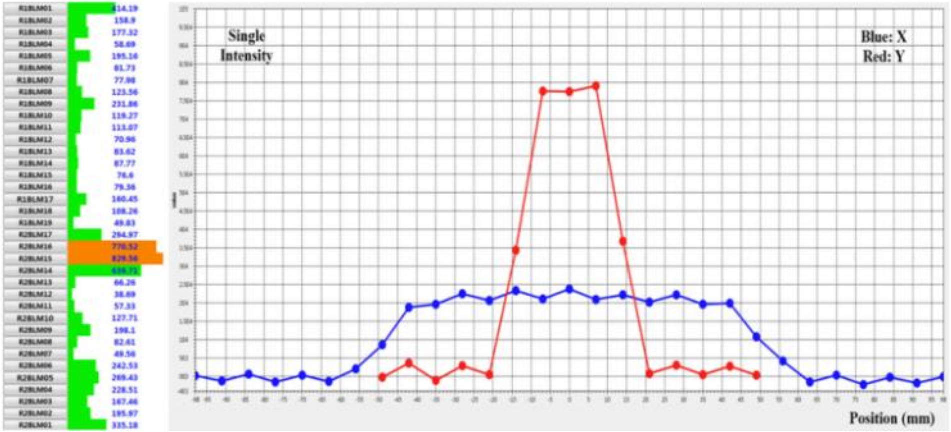
- ✓ Beam loss is well controlled.
- ✓ Transverse beam size is largely reduced.
- ✓ Beam distribution is much better.
- ✓ Transverse coupling effect is improved.

- A new method was proposed to perform the correlated painting.
- **Beam power on the target has successfully risen from 50 kW to the design value of 100 kW.**

(a)



(b)

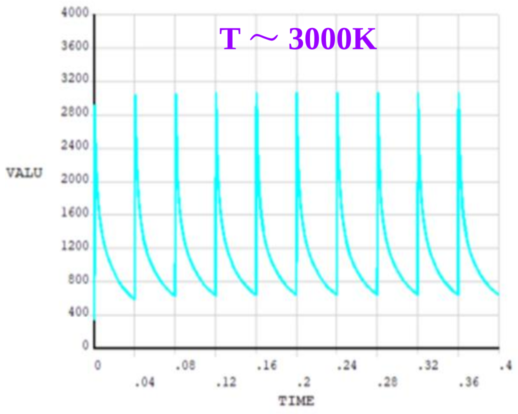


III. New painting injection scheme for the CSNS-II

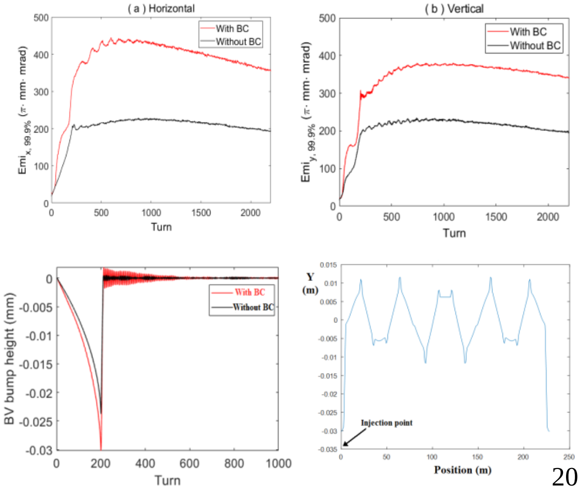
Problems for the CSNS-II accelerator injection

- **Key Problems**: (1) The peak temperature of the stripping foil is too high (close to or beyond the melting point).
  (2) The single fixed painting mode may not be consistent with the future actual beam state.
  (3) The beam dynamics is greatly affected by the edge focusing effect of horizontal chicane bump.

Phase	CSNS	CSNS-II
Injection beam power (kW)	5	94
Linac energy (MeV)	80	300
Extraction beam energy (GeV)	1.6	1.6
Average beam current (μA)	62.5	312.5
Repetition frequency (Hz)	25	25
Proton number per pulse (10^{13})	1.56	7.8
Injection time (μs)	390	500
Injection beam size (mm/1σ)	1.0	1.5



Edge focusing effect



New idea for the CSNS-II painting injection

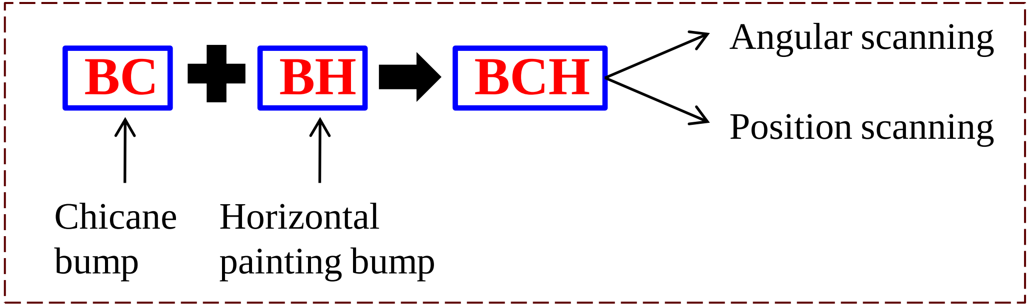
- **Goals**:

  (1) The peak temperature of the stripping foil need to be further reduced.

  (2) Both correlated and anti-correlated painting can be performed.

  (3) The edge focusing effect of the chicane bump should be reduced.

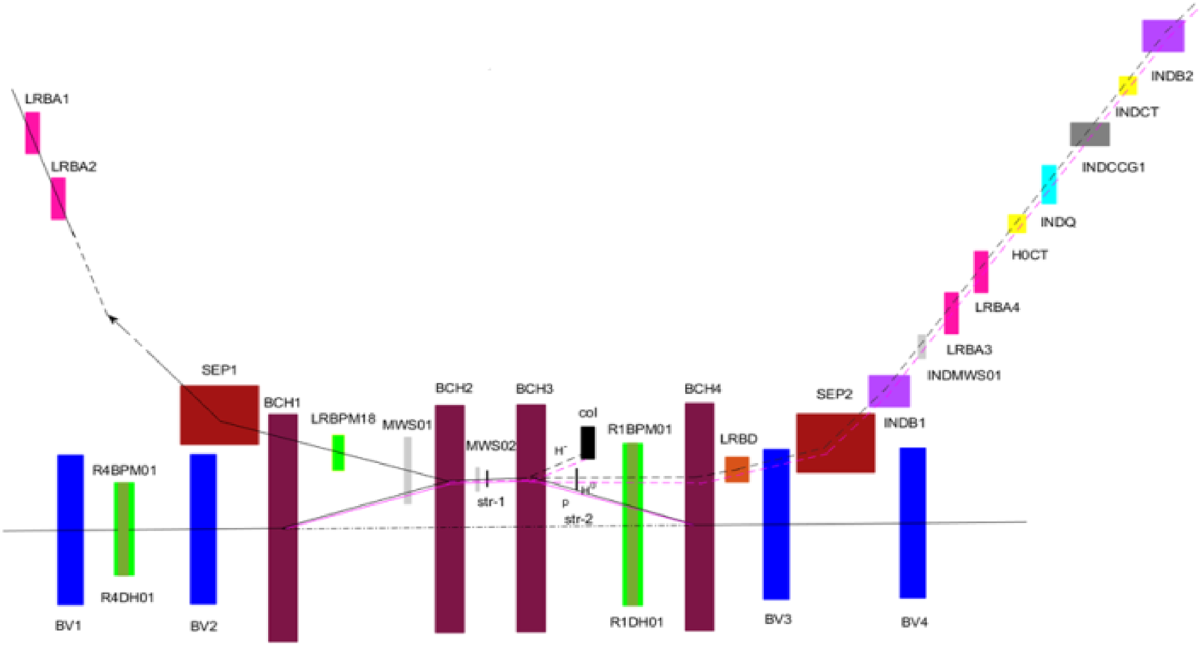
- **New idea**: The chicane bump and horizontal painting bump are combined into one bump which make the chicane bump "move", and the horizontal painting is performed by using the position and angular scanning at the same time.



SNS: B (1-4) + HK (1-4)
J-PARC: SB (1-4) + PBH (1-4)
CSNS: BC (1-4) + BH (1-4)

Huang, et al., 2022.

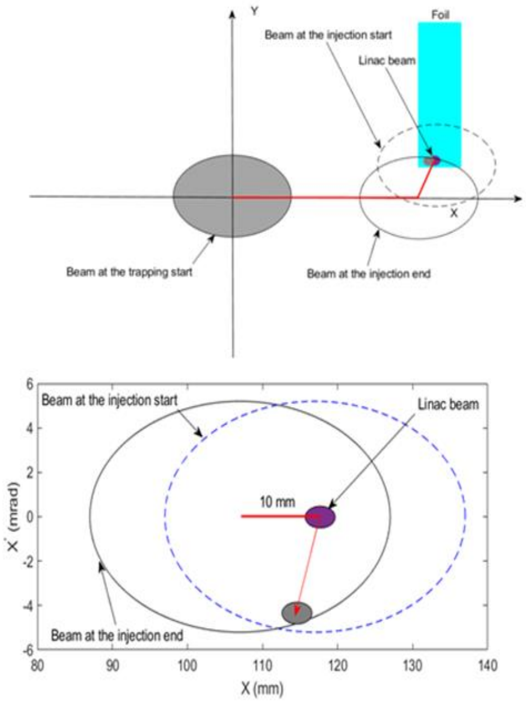
Layout of the new injection system



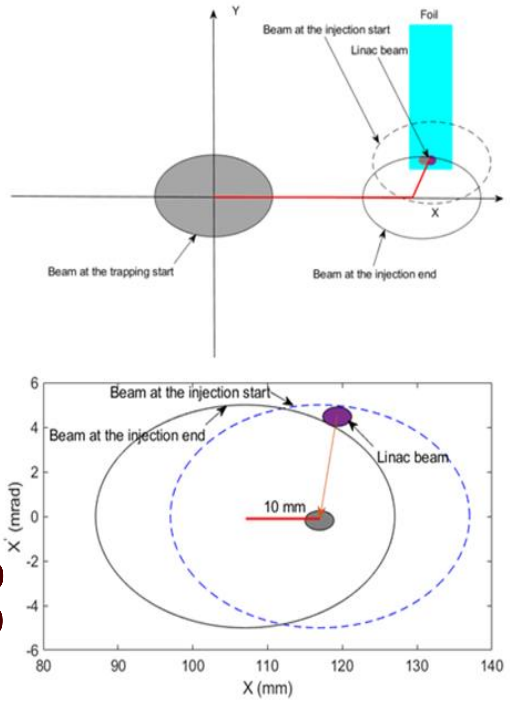
- **Key magnets:** 4 horizontal painting magnets, 4 vertical painting magnets, 2 septum magnets, 1 pulse septum magnet, 2 DC dipole magnets (compensation), 4 vertical DC bump magnets (one of which with auxiliary winding), 1 DC quadrupole magnet.

Description for the new painting scheme

Correlated painting



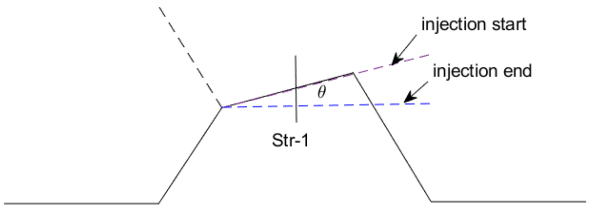
Anti-correlated painting



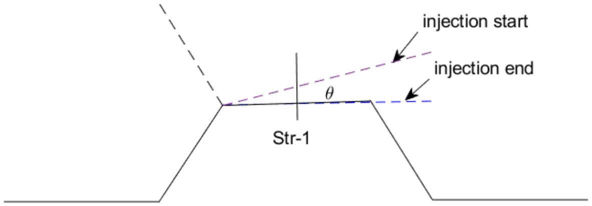
α_x~0
α_y~0

- **Injection beam**: BCH is used for horizontal angular scanning, while the horizontal position is also scanned in a small range.
- **Circulating beam**: horizontal and vertical position scanning can be performed with BCH and BV magnets.
- **Residual H^0 beam**: H^0 beam at the waste beam outlet has an angular distribution with time. A small pulse magnet is installed for angular scanning compensation.
- **Compatibility mode for correlated and anti-correlated painting:** match the angle of SEP and BCH magnets.
- **Spatial optimization**: BCH bump is irregularly shaped to allow the waste beam line to move a short distance along outside the RCS.

BCH bump and key magnets



Scanning angle : 4.5 mrad



Scanning angle : 5.0 mrad

Painting	Time	SEP1 (mrad)	BCH2 (mrad)	BCH3 (mrad)	BCH4 (mrad)	LRBD (mrad)	SEP2 (mrad)	INDB1 (mrad)	INDB2 (mrad)	BCH1 (mrad)
Correlated	Begin	226.713	53.549	64.681	60.181	-4.5	349.82	-13.419	-34.356	58.049
	End	226.713	49.049	60.181	55.681	+4.5	349.82	-13.419	-34.356	53.549
Anti-correlated	Begin	222.32	58. 442	58. 442	58. 442	-5	351.558	-13.066	-34.708	58.442
	End	222.32	53. 442	53. 442	53. 442	+5	351.558	-13.066	-34.708	53.442

Physical process of new painting scheme

Correlated

At the injection point, horizontal and vertical offsets of the time-varying closed orbit relative to the un-bumped closed orbit can be expressed as

$$x = x_{max} - x'_{l,max} \times L_0 \times \sqrt{\frac{t}{T_{inj}}}, \quad x' = 0$$

$$y = y_{max} \times \left[1 - \sqrt{\frac{t}{T_{inj}}}\right], \quad y' = 0$$

In the injection process, the horizontal and vertical time-varying coordinates of the injection beam can be expressed as

$$x_l = x_{max} - x'_{l,max} \times l_0 \times \sqrt{\frac{t}{T_{inj}}}$$

$$x'_l = x'_{l,max} \times \sqrt{\frac{t}{T_{inj}}}$$

Anti-correlated

At the injection point, horizontal and vertical offsets of the time-varying closed orbit relative to the un-bumped closed orbit can be expressed as

$$x = x_{max} - x'_{l,max} \times L_0 \times \sqrt{\frac{t}{T_{inj}}}, \quad x' = 0$$

$$y = y_{max} \times \left[1 - \sqrt{\frac{t}{T_{inj}}}\right], \quad y' = 0$$

In the injection process, the horizontal and vertical time-varying coordinates of the injection beam can be expressed as

$$x_l = x_{max} + x'_{l,max} \times l_0 \times \left(1 - \sqrt{\frac{t}{T_{inj}}}\right)$$

$$x'_l = x'_{l,max} \times \left(1 - \sqrt{\frac{t}{T_{inj}}}\right)$$

Advantages for the new painting scheme

- The advantages of position scanning and angular scanning have been combined. The peak temperature of the stripping foil has been obviously reduced.
- Both correlated and anti-correlated painting can be performed.
- Since the BCHs are pulse magnets, their edge focusing effects are obviously reduced.
- Since the bump magnet BCH2 which is used for angular scanning is very close to the injection point, the difficulty of large aperture of the injection port and transport line required by angular scanning is solved.
- Compared with the traditional painting scheme, it saves a set of bump magnets. The space of the injection area is more loose which is of great significance to the traditional injection area where space is tight.
- As a result of the angular scanning, the residual H^- beam hits an increased area on the vacuum chamber, and the radiation dose caused by it decreases obviously.

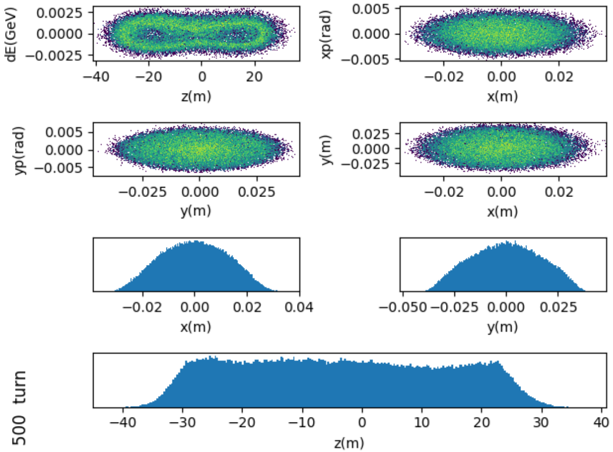
Simulation of the new painting scheme

- **Codes:** The new painting scheme has been simulated by using Py-ORBIT and ANSYS.
- **Typical working points:** (4.86, 4.80) , (4.80, 4.87) , (4.33, 5.30).
- After the optimization of the painting curve, the horizontal and vertical painting ranges differ greatly under different working points.

Painting	Working point	Optimum horizontal sweep angle	Optimum vertical painting range
Correlated	(4.86, 4.80)	θ_x=4.5mrad	y_{max}=25mm
	(4.80, 4.87)	θ_x=3.0mrad	y_{max}=30mm
	(4.33, 5.30)	θ_x=2.5mrad	y_{max}=30mm
Anti-correlated	(4.86, 4.80)	θ_x=5.0mrad	y_{max}=30mm
	(4.80, 4.87)	θ_x=3.75mrad	y_{max}=30mm
	(4.33, 5.30)	θ_x=2.5mrad	y_{max}=30mm

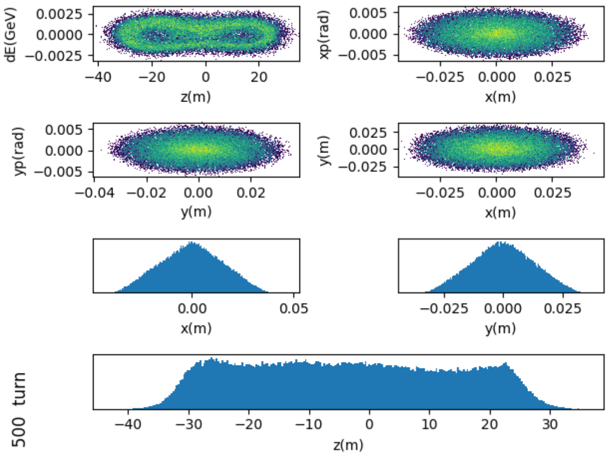
Beam distribution after the correlated painting

(4.86,4.80)



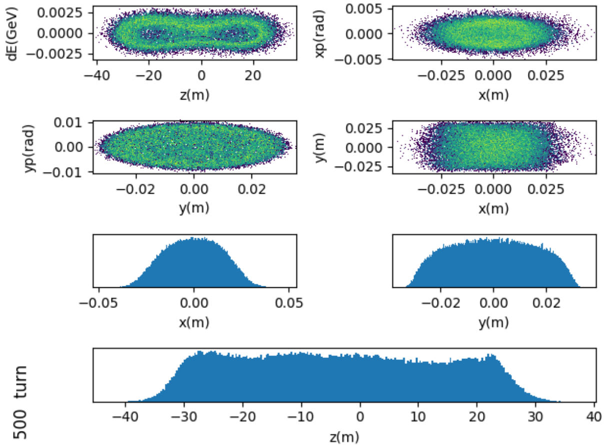
θ_x=4.5mrad
y_{max}=25mm

(4.80,4.87)



θ_x=3.0mrad
y_{max}=30mm

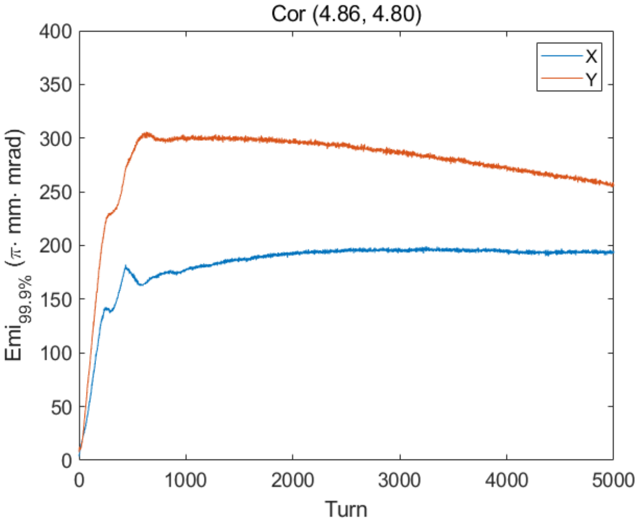
(4.33,5.30)



θ_x=2.5mrad
y_{max}=30mm

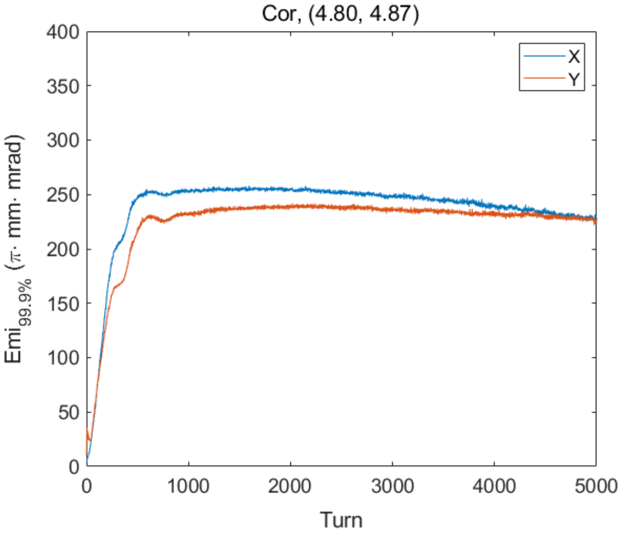
99.9% emittance evolution for the correlated painting

(4.86,4.80)



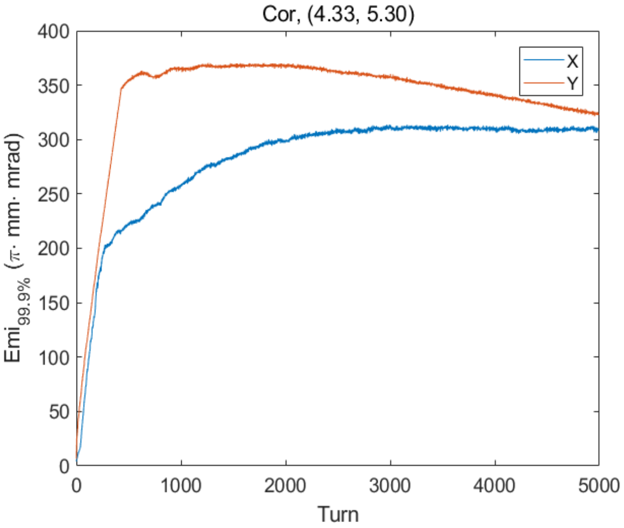
θ_x=4.5mrad
y_{max}=25mm

(4.80,4.87)



θ_x=3.0mrad
y_{max}=30mm

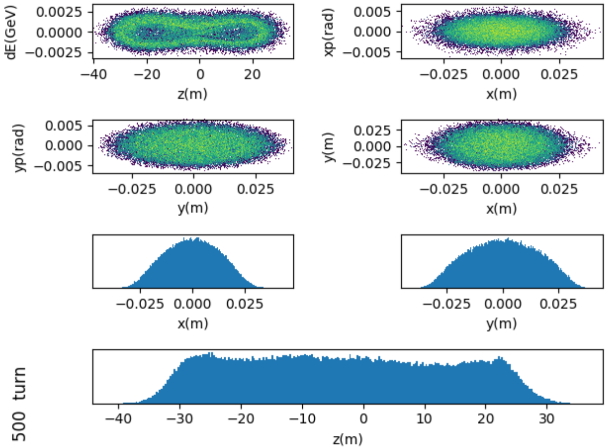
(4.33,5.30)



θ_x=2.5mrad
y_{max}=30mm

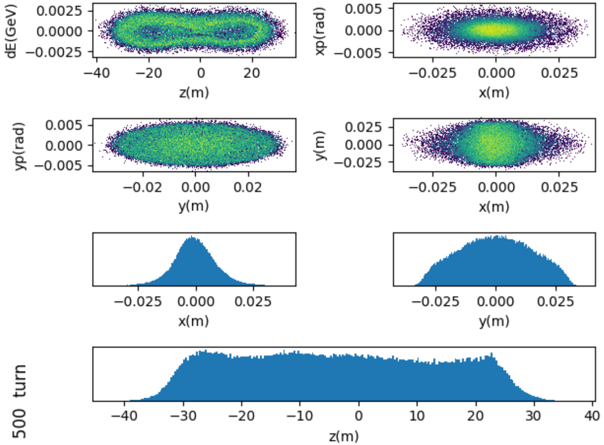
Beam distribution after the anti-correlated painting

(4.86,4.80)



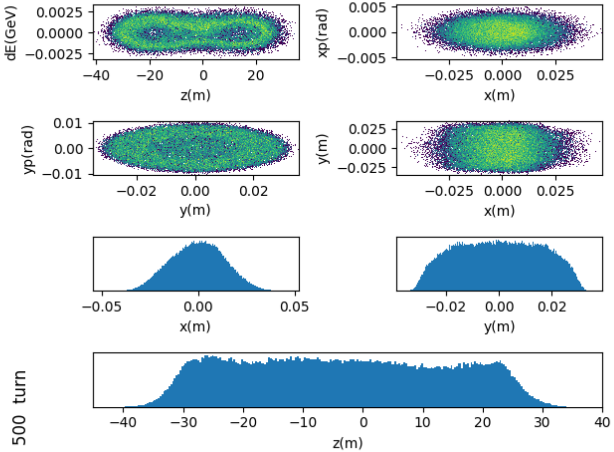
θ_x=5.0mrad
y_{max}=30mm

(4.80,4.87)



θ_x=3.75mrad
y_{max}=30mm

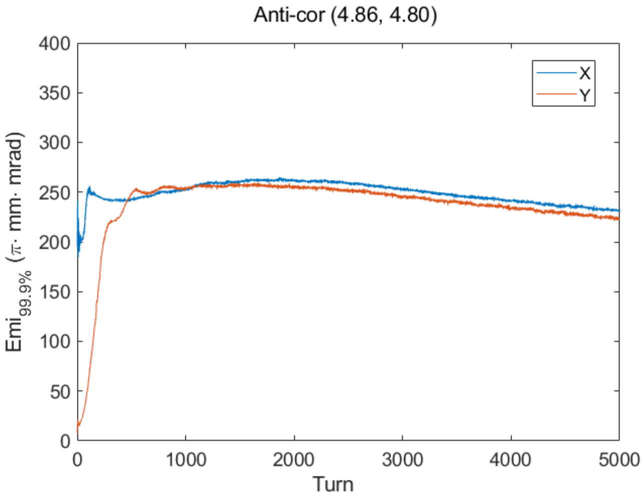
(4.33,5.30)



θ_x=2.5mrad
y_{max}=30mm

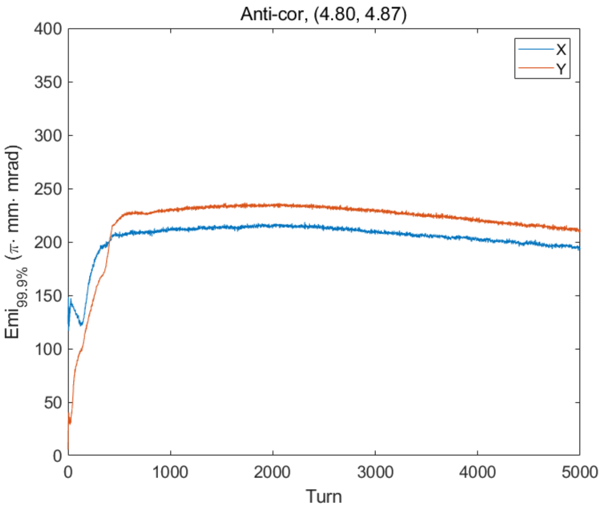
99.9% emittance evolution for the anti-correlated painting

(4.86,4.80)



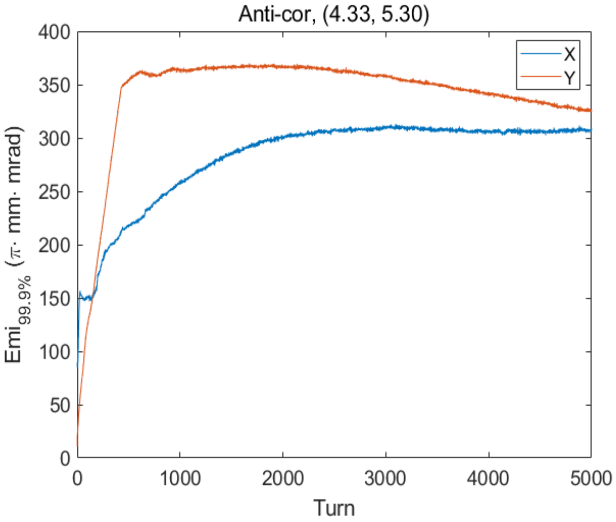
θ_x=5.0mrad
y_{max}=30mm

(4.80,4.87)



θ_x=3.75mrad
y_{max}=30mm

(4.33,5.30)



θ_x=2.5mrad
y_{max}=30mm

Beam loss, average traversal number, peak temperature

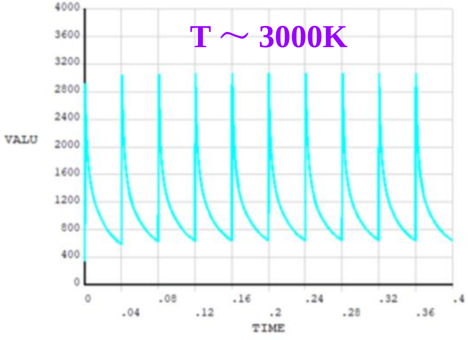
- After the painting optimization, the beam loss, average number of times that each particle passes through the main stripping foil, peak temperature of the main stripping foil can be given below:

Painting	Working point	Optimum horizontal sweep angle	Optimum vertical painting range	Beam loss	Average traversal number of stripping foil	Peak temperature
Correlated	(4.86, 4.80)	θ_x=4.5mrad	y_{max}=25mm	0.0	20	1727K
	(4.80, 4.87)	θ_x=3.0mrad	y_{max}=30mm	0.0	13	1416K
	(4.33, 5.30)	θ_x=2.5mrad	y_{max}=30mm	0.02%	11	1320K
Anti-correlated	(4.86, 4.80)	θ_x=5.0mrad	y_{max}=30mm	0.0005%	10	1269K
	(4.80, 4.87)	θ_x=3.75mrad	y_{max}=30mm	0.0	13	1416K
	(4.33, 5.30)	θ_x=2.5mrad	y_{max}=30mm	0.002%	13	1416K

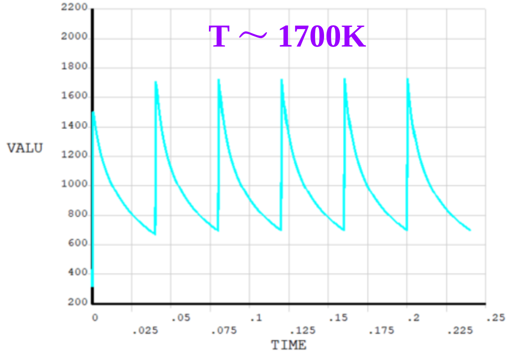
Three key problems have been solved

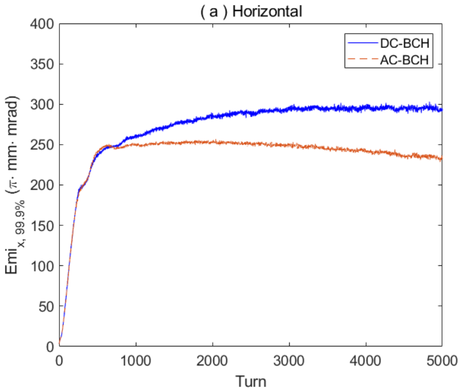
- The difficulty of too high peak temperature for the main stripping foil has been solved.
- Both correlated and anti-correlated painting can be performed.
- The edge focusing effects of the injection bump magnets have been obviously reduced.

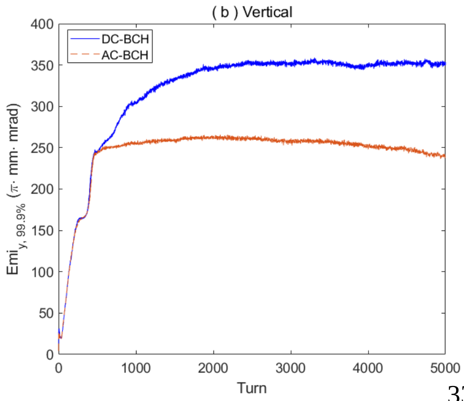
Pre-selected painting scheme



New painting scheme







IV. Summary

- The CSNS injection has been introduced and the beam commissioning of the injection system has been studied.
- In order to solve the difficulties when the beam power exceeds 50 kW, a new method has been proposed to perform the correlated painting based on the mechanical structure of the anti-correlated painting scheme.
- By using the correlated painting, the beam power on the target has successfully risen from 50 kW to the design value of 100 kW.
- A new painting scheme for the CSNS-II has been proposed. It not only realizes the compatibility of correlated and anti-correlated painting, but also greatly reduces the peak temperature of the main stripping foil and the edge focusing effect of the chicane bump.
- In the simulation, the new painting scheme has been verified to be feasible and has obvious advantages compared with the traditional bump painting scheme.

Thank you for your attention!

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Backups

New painting scheme VS Internationally available scheme

Advantages compared with SNS painting scheme

(1) Both correlated and anti-correlated painting can be performed.

(2) It saves a set of bump magnets. It is easier to optimize the layout of the injection system.

(3) The radiation dose caused by the residual H^- beam decreases substantially.

Advantages compared with J-PARC painting scheme

(1) It saves a set of bump magnets. It is easier to optimize the layout of the injection system.

(2) The difficulty of large aperture of the injection port and transport line required by angular scanning is solved.

(3) A third stripping system is saved.