Design and study of the injection and extraction schemes for the FFAG at CSNS

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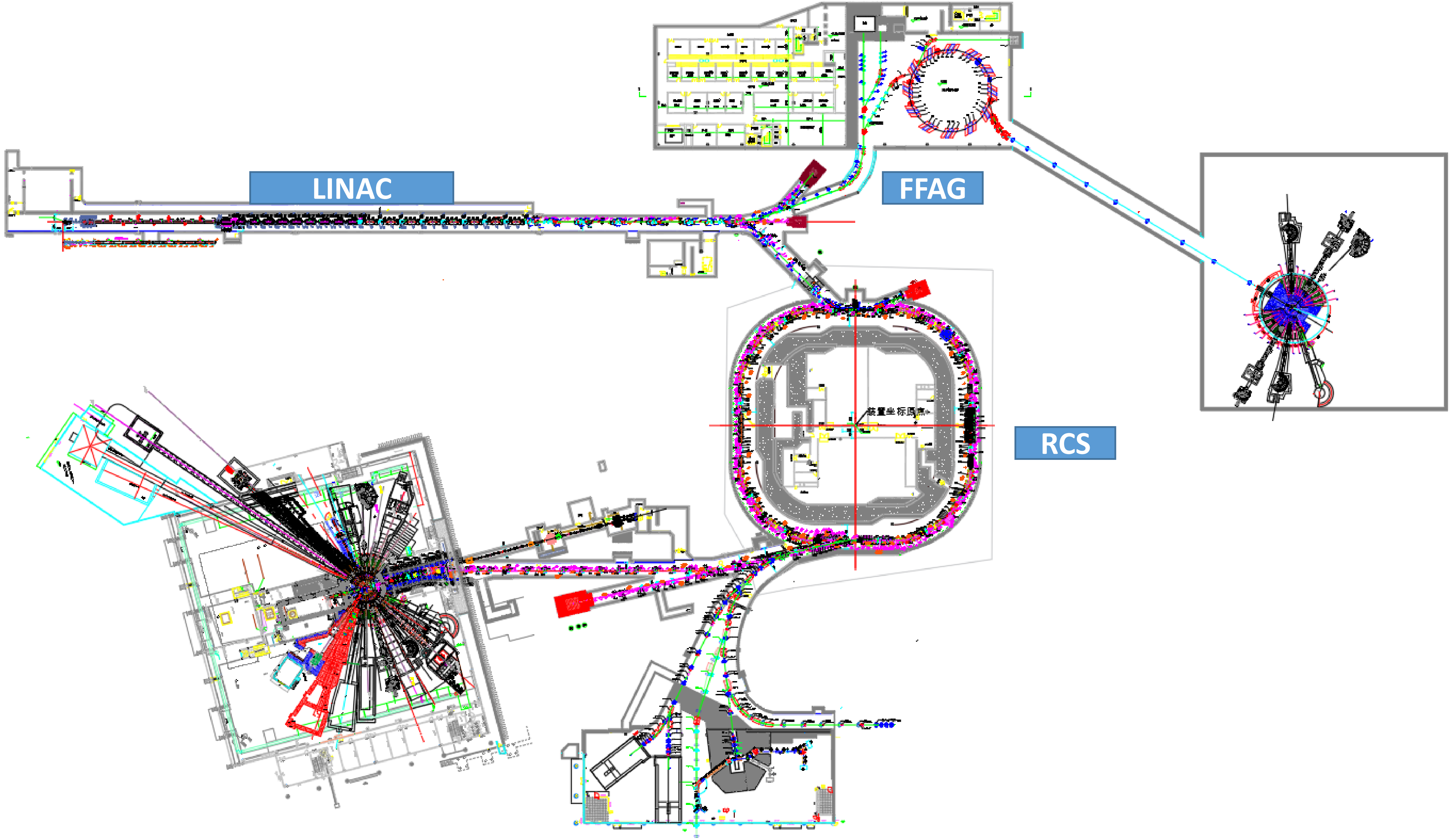
01 Introduction

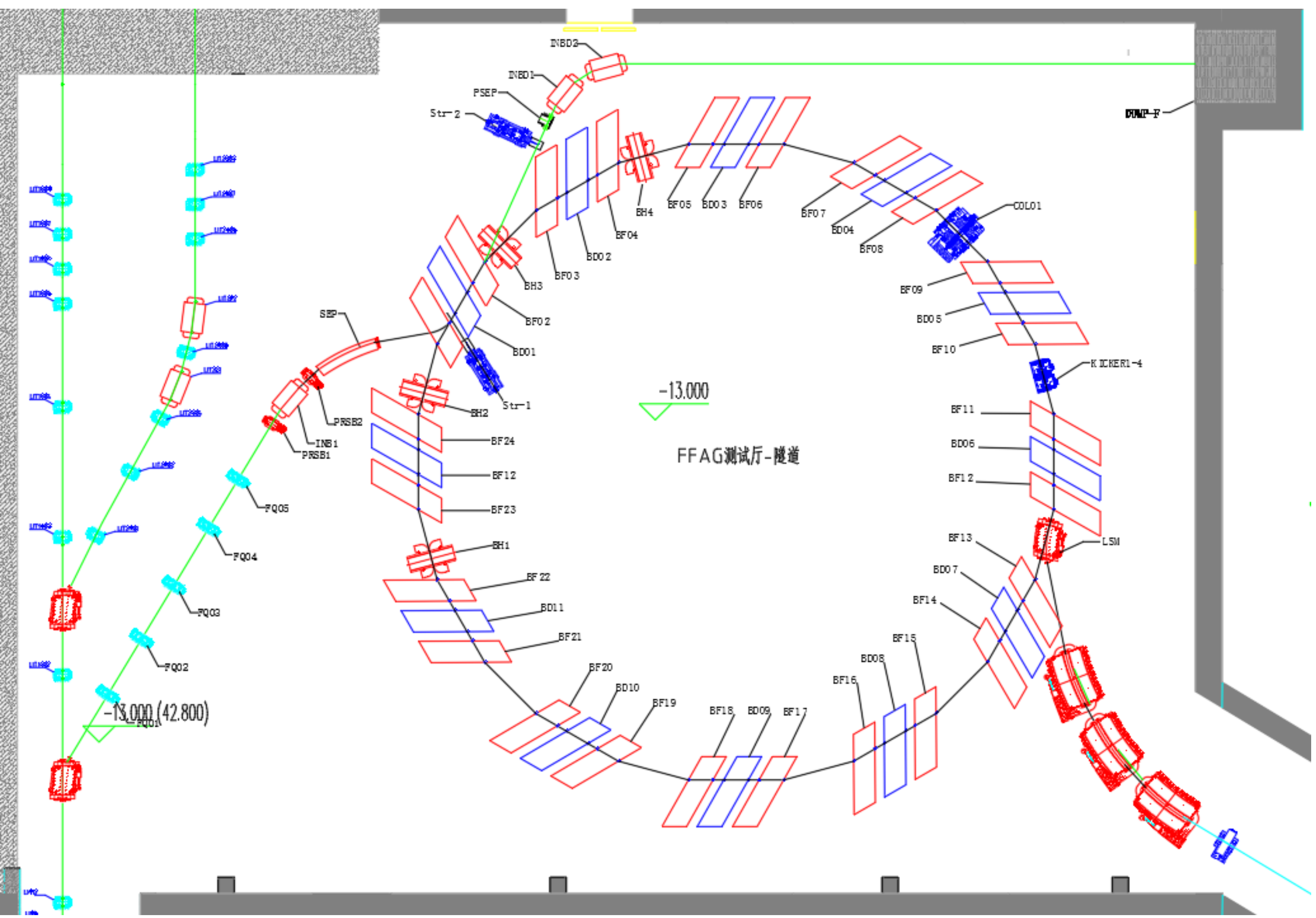
The general layout of CSNS and FFAG



FFAG project at CSNS

- **300 MeV CSNS linac as a injector**
  - ✓ **The repetition rate of linac will upgrade to 50 Hz**
  - ✓ **25 Hz for RCS and 25 Hz for other applications**
- **H^- stripping and painting injection**
- **Repetition rate of FFAG 25 Hz**
  - ✓ **Limited by the repetition rate of linac**
  - ✓ **Capable of operating at 200 Hz or higher**
- **FFAG extraction energy 600 MeV**
- **Average beam power 50 kW / Average beam current 83.4 uA**
- **Scaling type**

Design parameters for the FFAG accelerator



Parameters	Design value
Circumference (m)	75.34
Number of periods	12
Lattice	FDF
Drift length (m)	2.2
Injection energy (MeV)	300
Injection beam power （kW)	25.0
Average beam current (μA)	83.4
Particles per pulse	2.08×10^{13}
Injection beam width （μs)	300
Repetition rate (Hz)	25
Extraction energy (MeV)	600
Extraction beam power (kW)	50.0
Extraction beam width （1σ）(ns)	10

Space charge tune shift

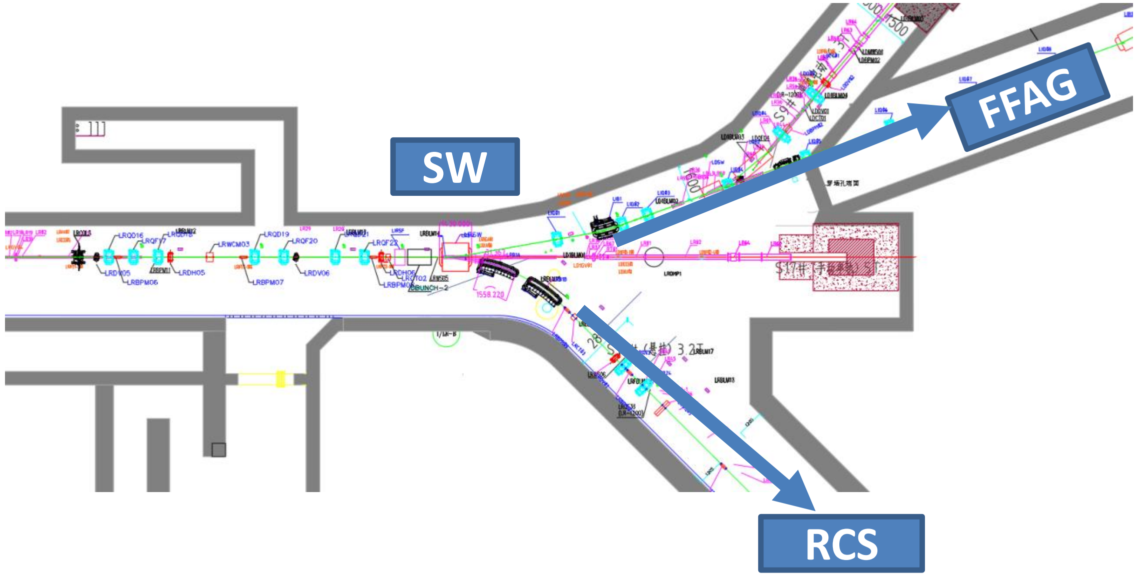
Machine	Particles per pulse ($\times 10^{13}$)	Emittance (π mm mrad)	Bunch factor	Space charge tune shift
CSNS RCS	1.56	300	0.24	0.28
CSNS-II RCS	7.8	250	0.41	0.19
FFAG	2.08	200	0.1	0.26
FFAG	2.08	250	0.1	0.21
FFAG	2.08	300	0.1	0.18
FFAG	2.08	400	0.1	0.13
FFAG	2.08	500	0.1	0.10
FFAG	2.08	600	0.1	0.09

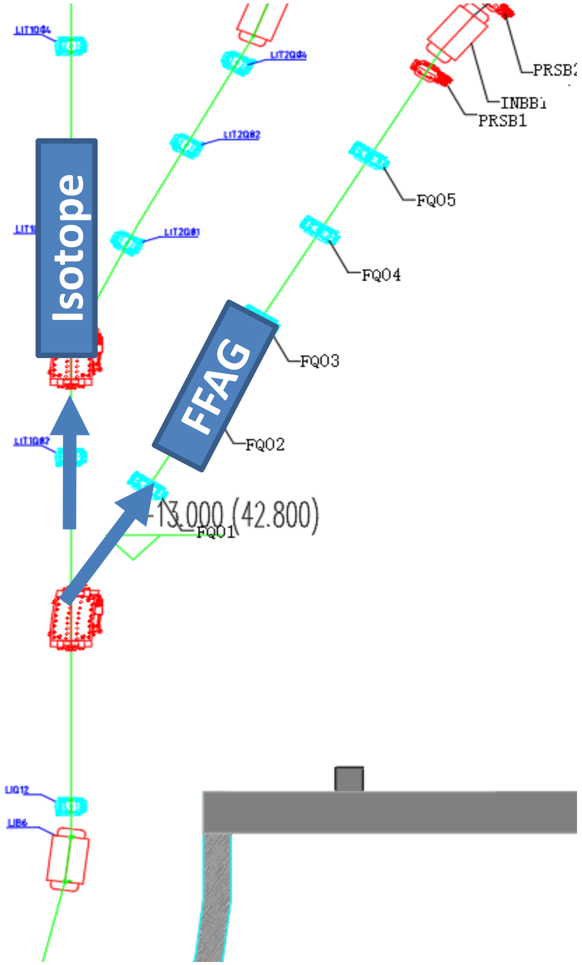
$$\Delta\upsilon = -\frac{N r_0}{2\pi\varepsilon\beta^2\gamma^3 B_f}$$

02 Injection scheme

The line from Linac to FFAG

- The Linac works on 50 Hz
  - ✓ 25 Hz beam goes to RCS and another 25 Hz goes to Isotope Station and FFAG

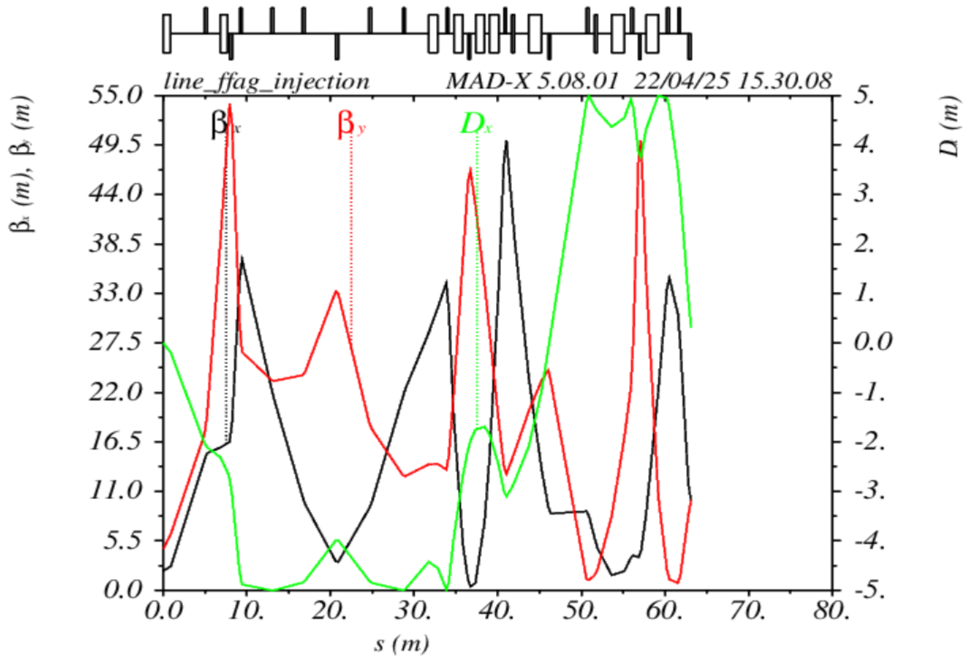


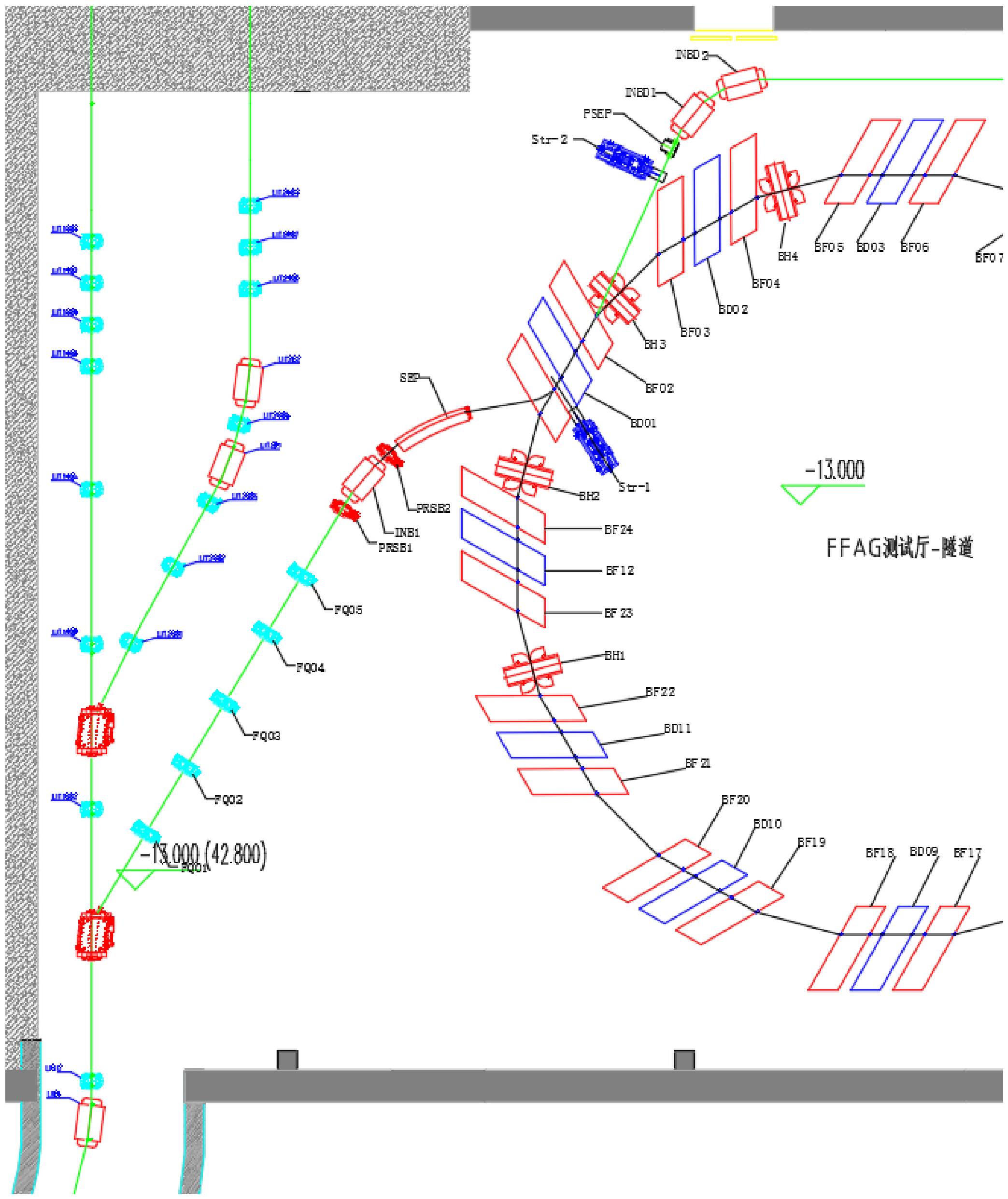


- The line to FFAG is split from Isotope line by kicker + septum

The match to the injection point

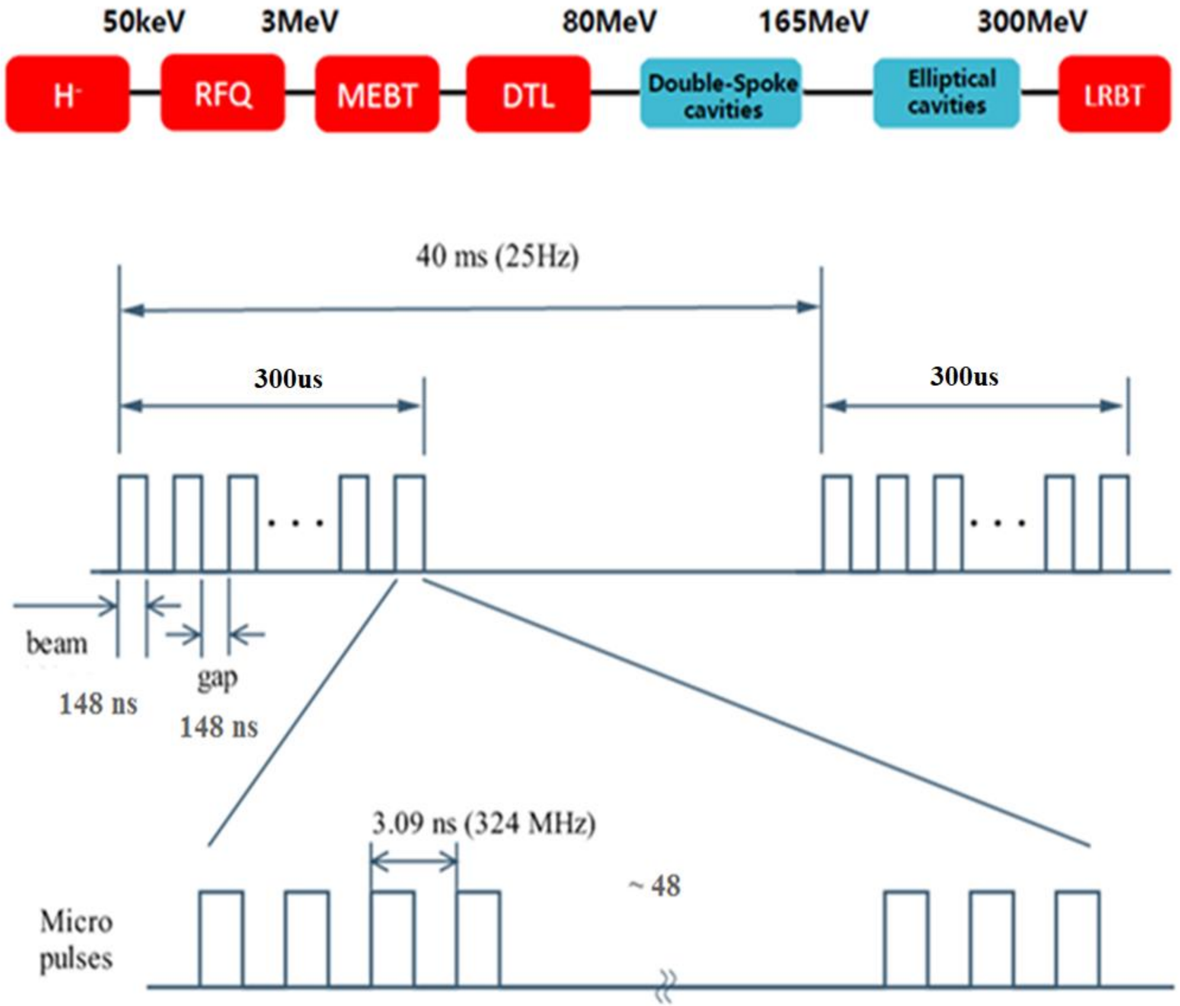
- There is about 15 m from last bend to injection point
  - ✓ This leaves some room for line adjustment
- Need to be updating according to injection scheme
- The maximum beta function is 75 m
- The aperture of magnet is selected as 100 mm





Injection system parameters

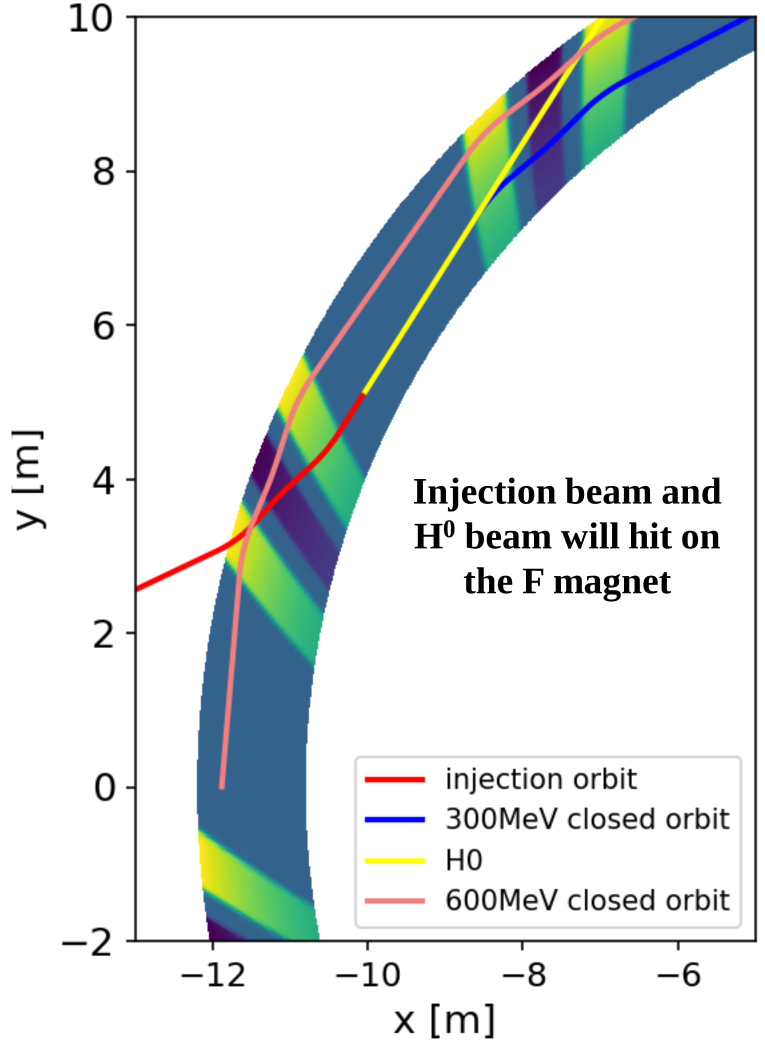
➢ Timing structure:



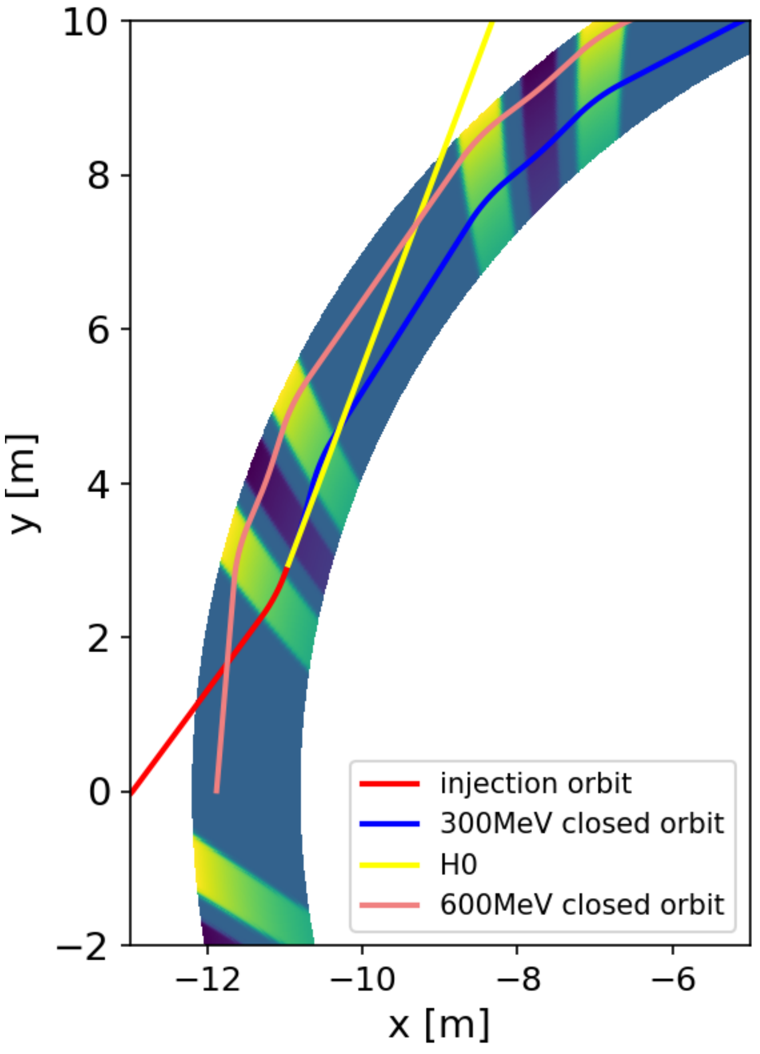
Parameters	Design value
Injection energy (MeV)	300
Injection beam width (μs)	300
Injection cycle (μs)	0.296
Harmonic number	1
Injection turn	~1013
Chopping rate	75% ~ 80%
Momentum spread	0.1%

- ✓ Injection process should remain in a non-accelerating state (Fixed injection radius).
- ✓ RF phase should not exceed 30°.

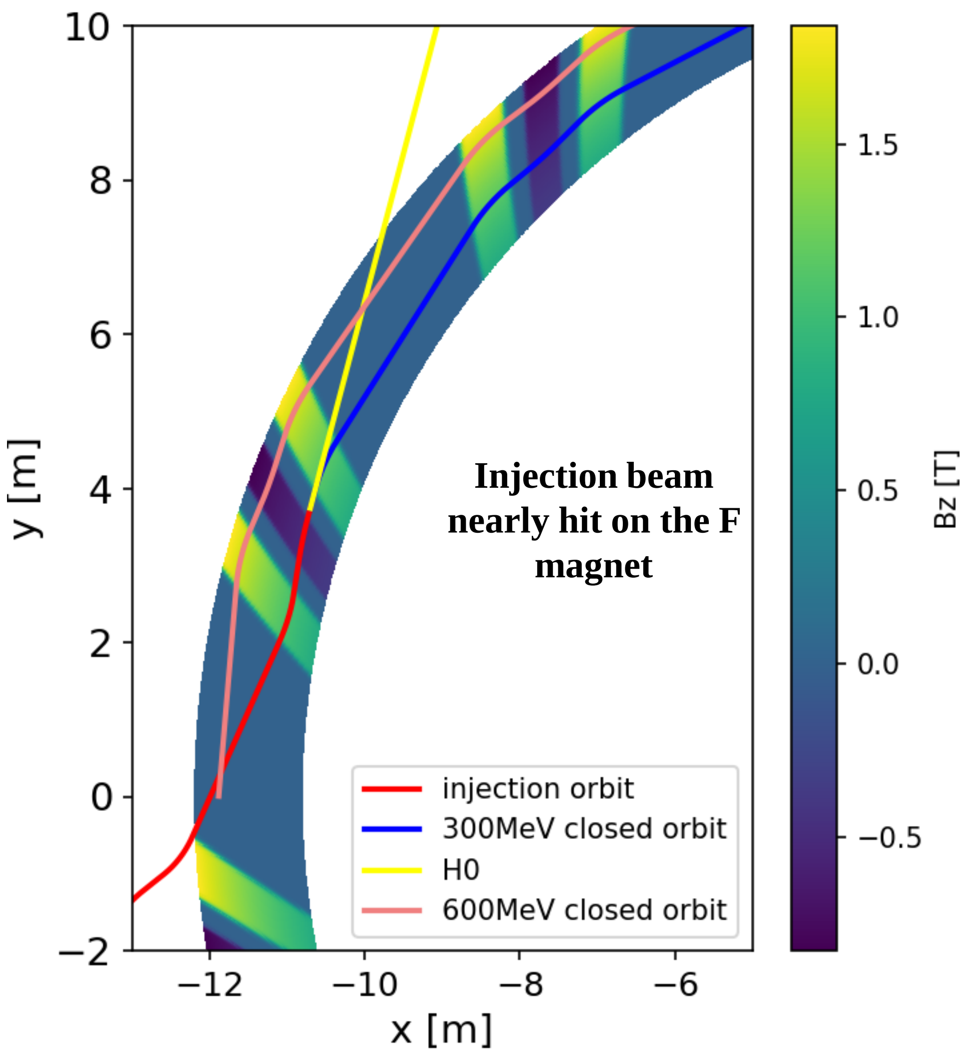
Injection beam orbit



The main stripping foil is placed at the drift section
(Not feasible)



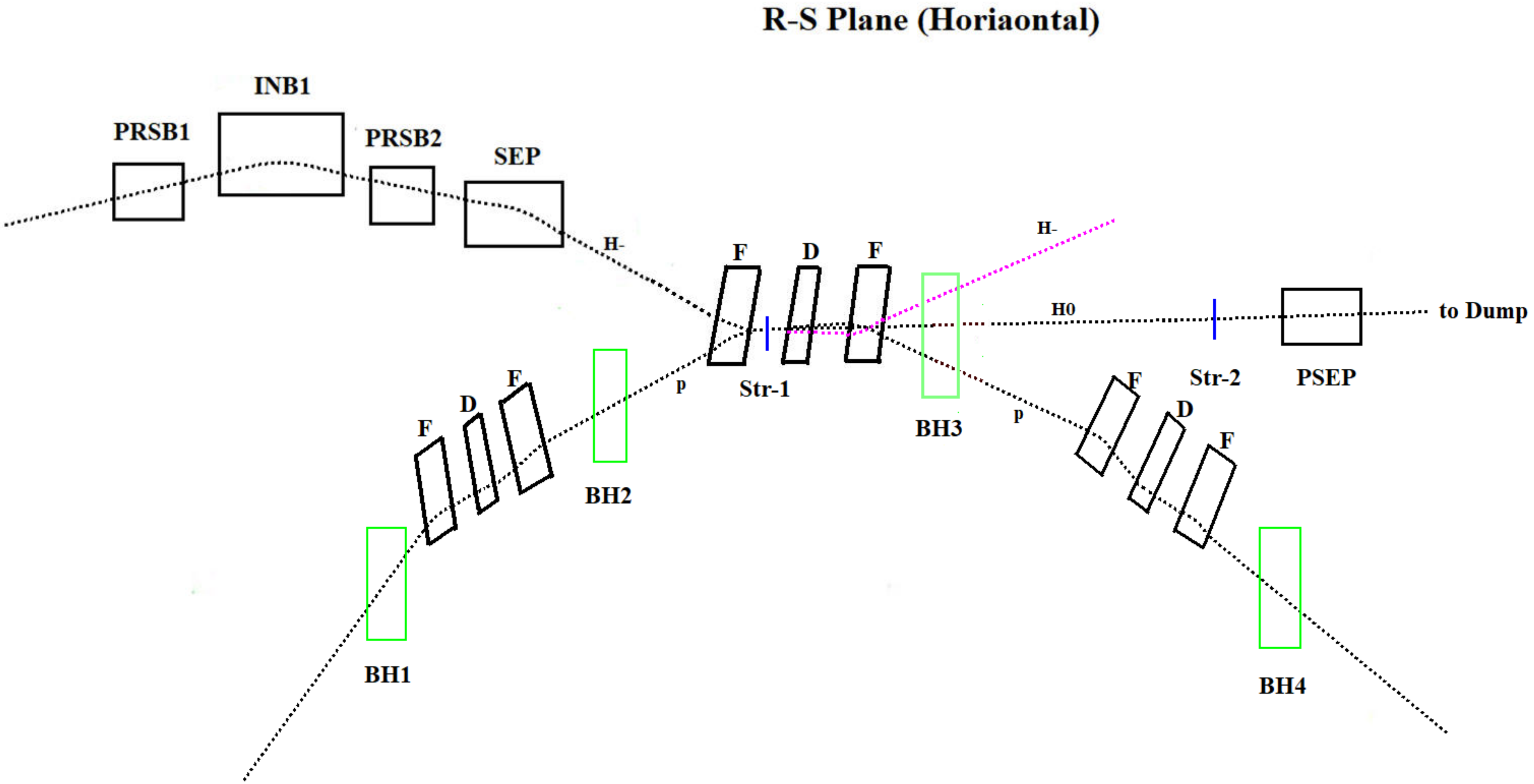
The main stripping foil is placed in the gap between the first F and D magnets



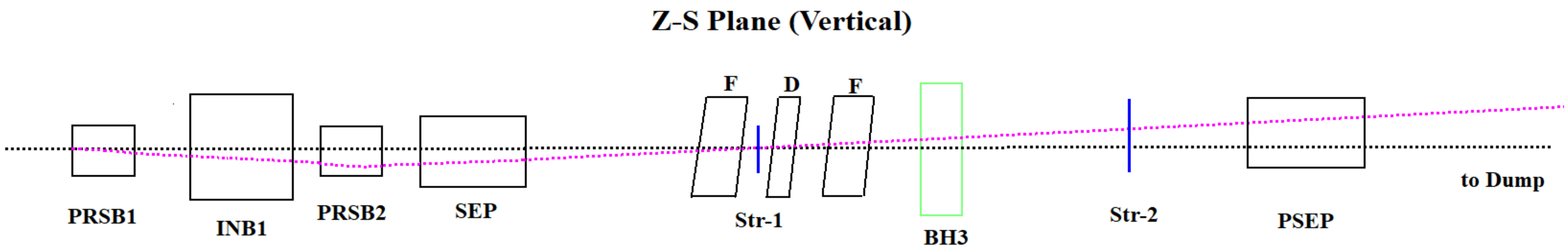
The main stripping foil is placed in the gap between the second F and D magnets
(Not feasible)

Design scheme of the injection system

- The injection system consists of 2 vertical sweeping magnets, 4 horizontal painting magnets, 1 septum magnet, 1 pulsed septum magnet, and two stripping foils.



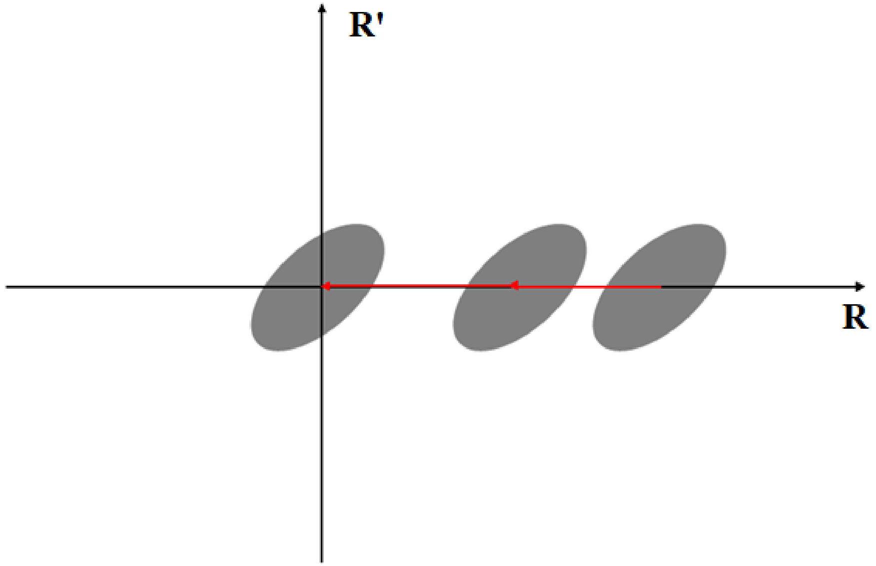
Design scheme of the injection system

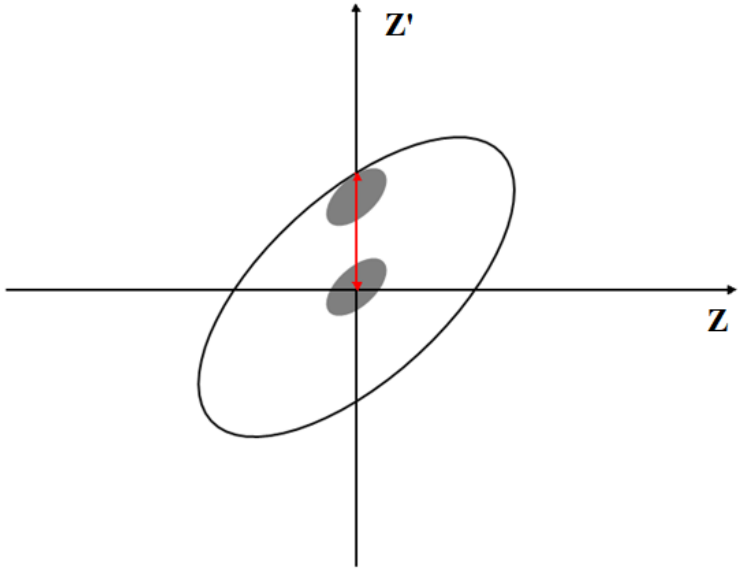


- In order to accumulate more beam particles and reduce the intense beam effects, the injection system employs H^- stripping and phase space painting.

Parameters	Values
Non-normalized RMS emittance (π mm mrad)	0.31/0.35
Injection beam sizes (mm)	2.5/2.5
Painting area (π mm mrad)	200/200
β_R/β_Z (m)	3.806/4.917
α_R/α_Z	0.139/-0.367
Horizontal sweeping angle（mrad）	8.0
Vertical painting range（mm）	30

Painting injection scheme





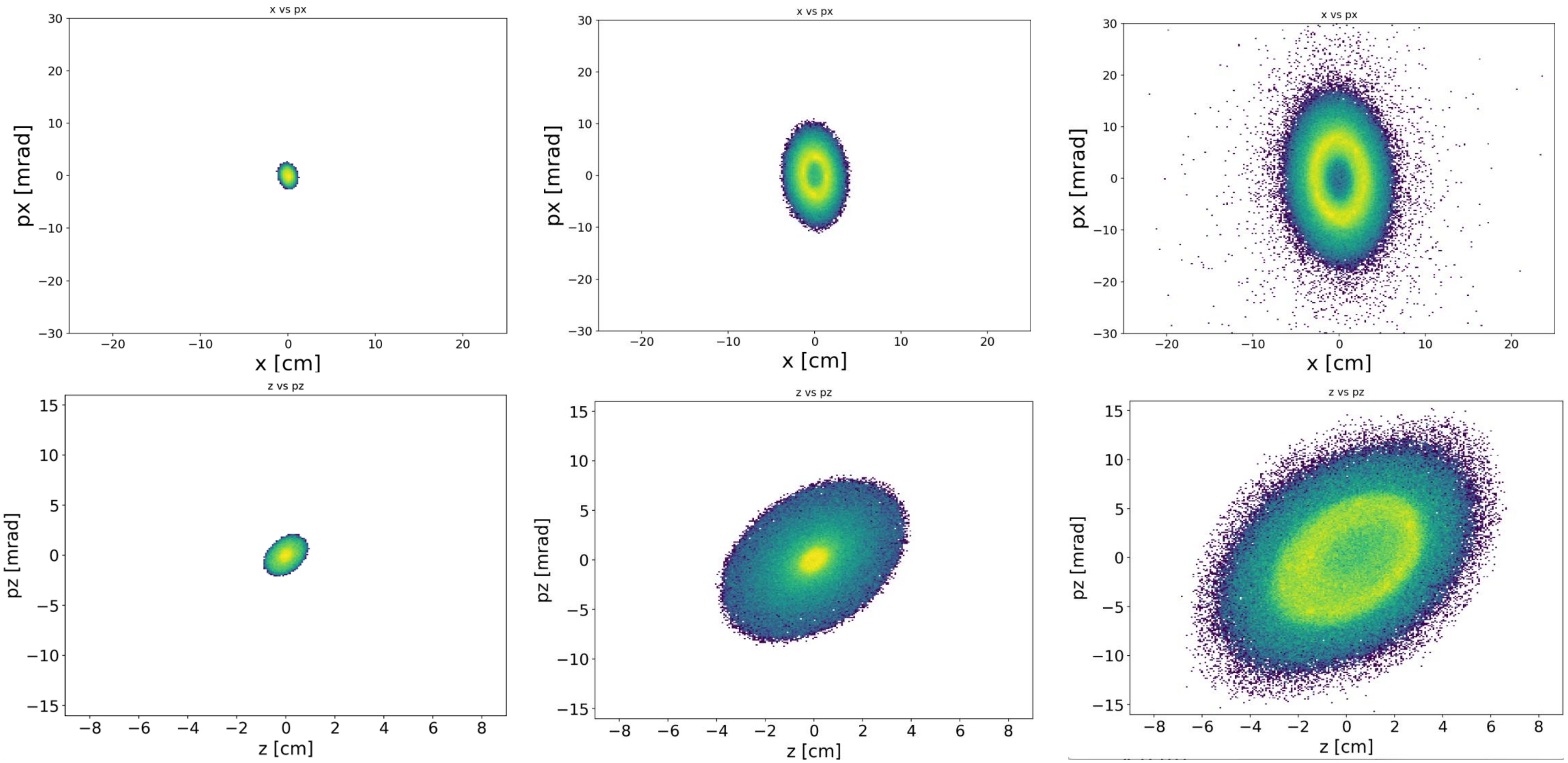
- During the injection process, the beam is not accelerated to maintain a fixed orbit.
- In the horizontal plane, to reduce average traversal times of the circulating beam, the injection beam is painted from 60 mm to 30 mm. After the injection, the vertical orbit is reduced from 30 mm to 0.
- In the vertical plane, the injection beam angle scans from 0 to 8.0 mrad (correlated) or from 8.0 mrad to 0 (anti-correlated). The painting scheme allows free switching between the correlated and anti-correlated painting.
- The optimization of vertical angular scanning can increase the beam size on the stripping foil, thereby reducing the peak temperature of the main stripping foil.

Simulation of the correlated painting injection

100 turn | 500 turn | 1000 turn

Horizontal

Vertical

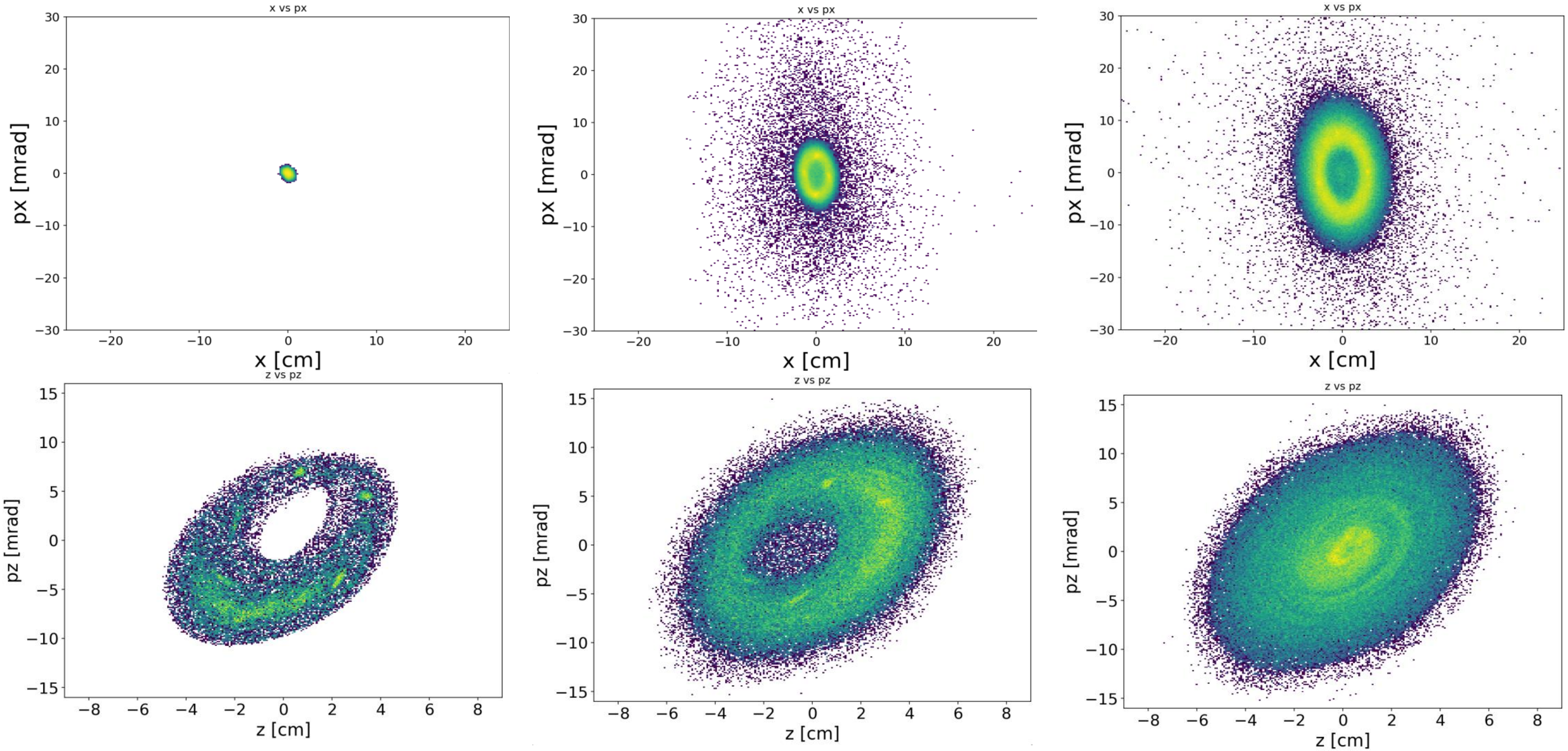


Simulation of the anti-correlated painting injection

100 turn | 500 turn | 1000 turn

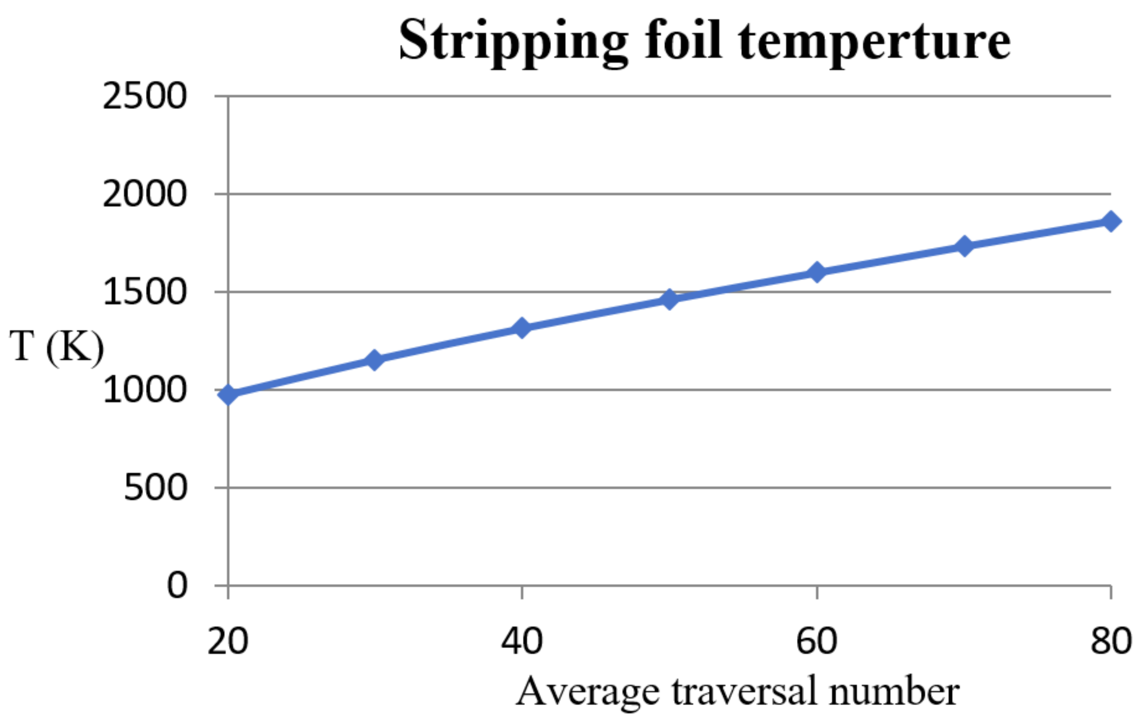
Horizontal

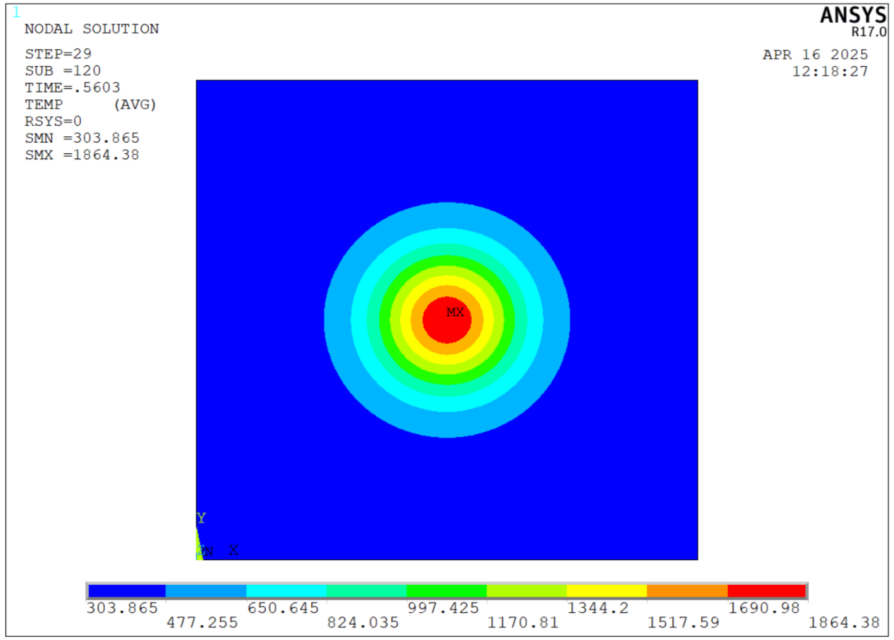
Vertical

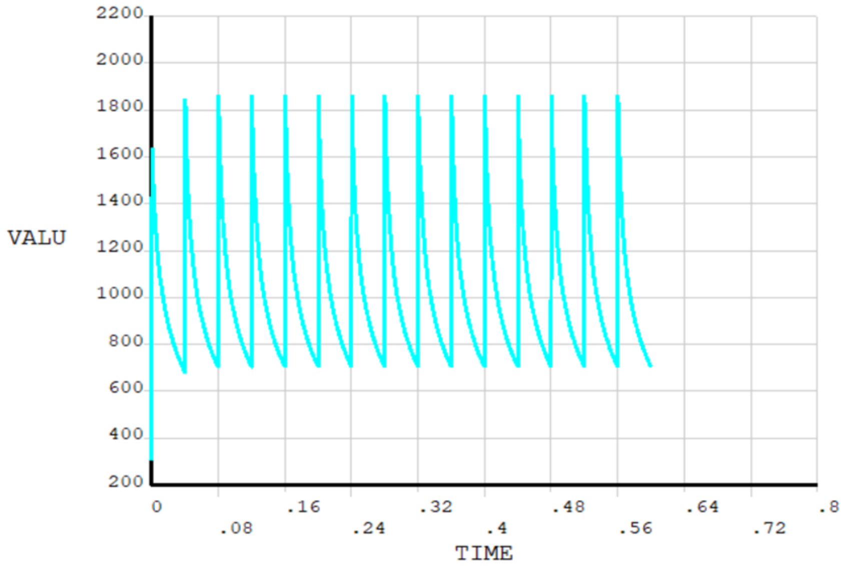


Refer to Dr. Kai Zhou' report

Simulation of the stripping foil temperature (25Hz)

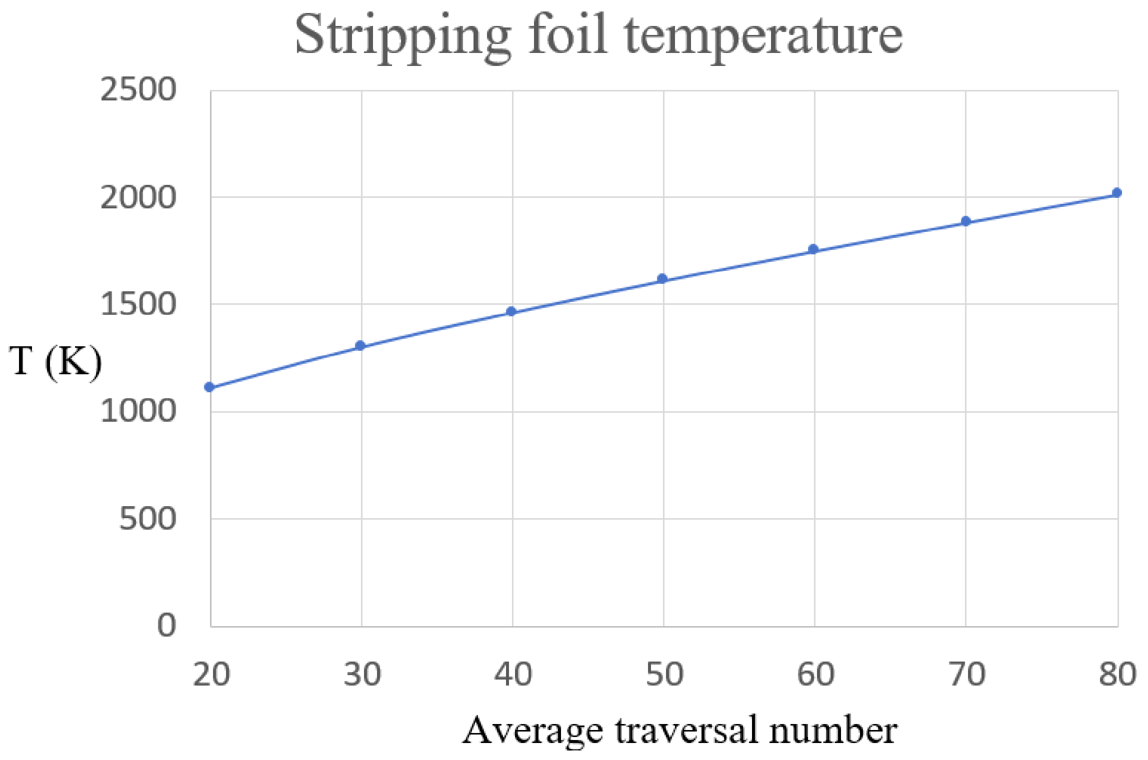


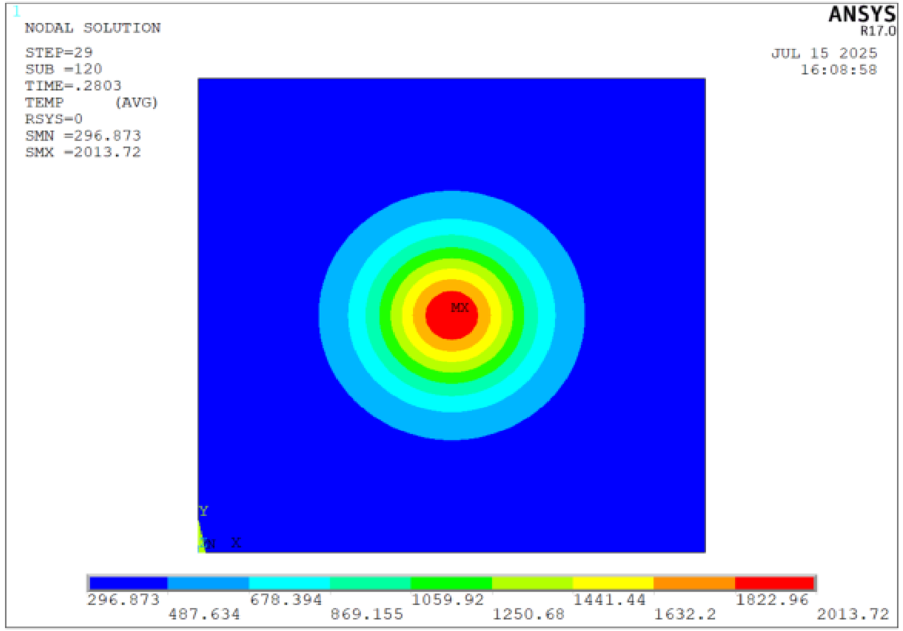


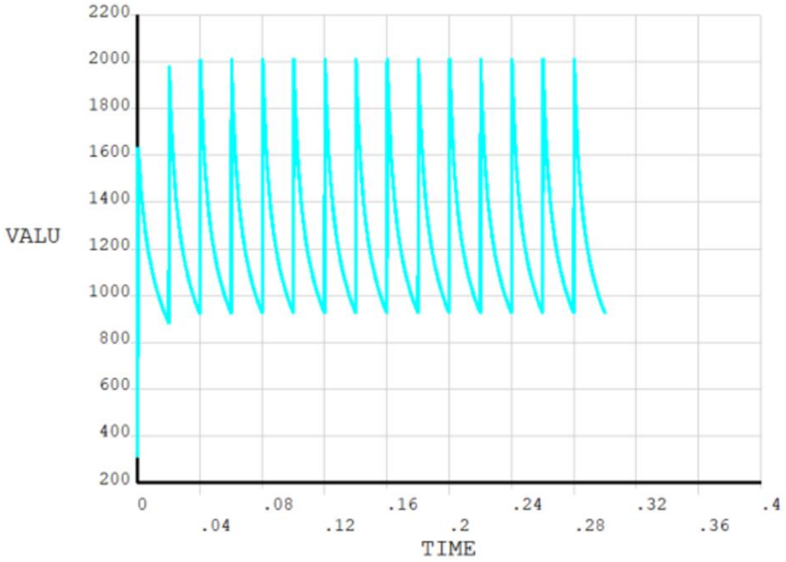


- For the design beam power on the target of 50 kW (25 kW injection power), if the horizontal and vertical RMS injection beam sizes are controlled about 2.5 mm, the peak temperature of the stripping foil will not exceed 1900 K, meeting operational requirements.

Simulation of the stripping foil temperature (50Hz)







- When the repetition rate reaches 50Hz, the peak temperature of the stripping foil will increase 150K， which is about 2000K, meeting operational requirements.

Preliminary parameters of key hardware in the injection system

Parameters	PRSB1	PRSB2
Sweeping angle (mrad)	25	35
Integral field (T m)	0.0674	0.0943
Effective length (m)	0.5	0.5
Magnetic field strength (T)	0.1348	0.1886
Horizontal gap (mm)	100	100
Horizontal good field range (mm)	±45	±45
Vertical gap (mm)	120	200
Vertical good field range (mm)	±55	±95
Good field uniformity	1%	1%

Parameters	BH1-4
Bump height (mm)	60
Center distance between BV1-2 or BV3-4 (m)	4
Integral field (T m)	0.0404
Effective length (m)	0.75
Magnetic field strength (T)	0.0539
Vertical gap (mm)	110
Vertical good field range (mm)	±55
Horizontal gap (mm)	1016
Horizontal good field range (mm)	[-505, -340]
Good field uniformity	1%

Preliminary parameters of key hardware in the injection system

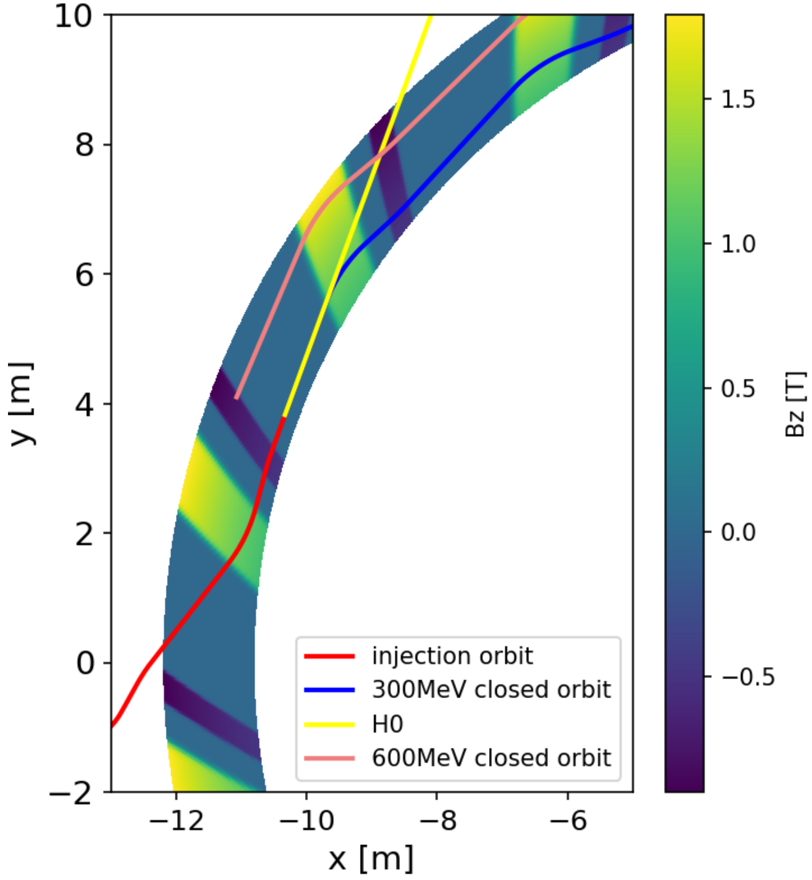
Parameters	PSEP
Sweeping angle（mrad)	±5
Integral field（T m)	0.01348
Effective length（m)	0.2
Magnetic field strength（T)	0.0674
Horizontal gap（mm)	70
Horizontal good field range（mm)	±33
Vertical gap（mm)	90
Vertical good field range（mm)	±43
Good field uniformity	1%

Drift	Value
Number	4
Length（m）	>2m

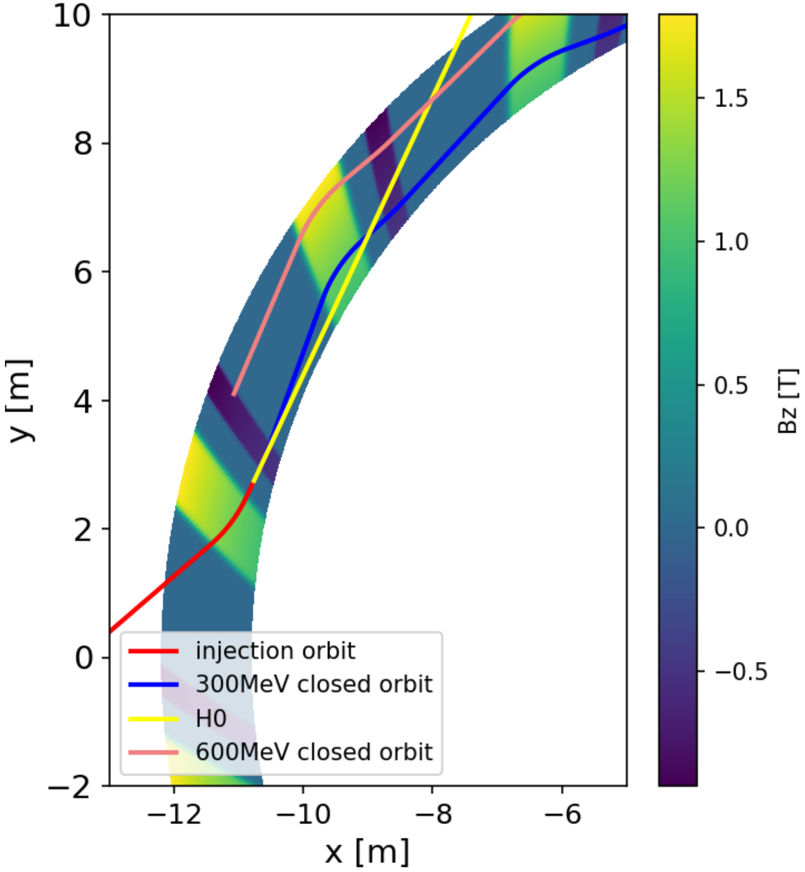
Parameters	Str-1	Str-2
Materials	HBC/Graphene	HBC/Graphene
Thickness（$\mu g/cm^2$）	260	450
Stripping efficiency	99.7%	100%
Structure	Double-layer	Double-layer

Injection beam orbit (16-period, FD)

- **The problem with choosing the FDF Lattice is that the main stripping foil needs to be placed in the gap between the first F and D magnets.**
- When the FD Lattice structure with 16-period is selected, the injection beam orbit is shown as follows.



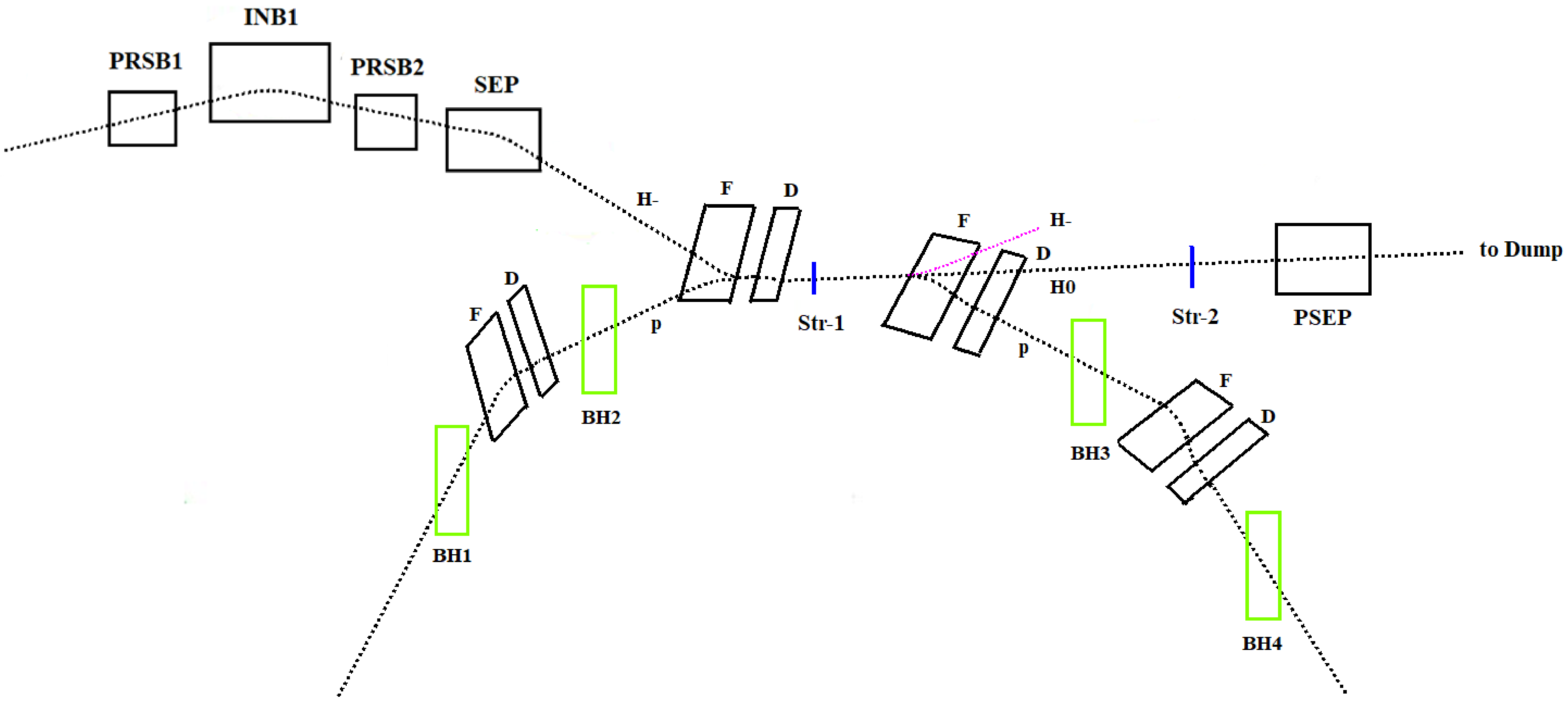
The main stripping foil is placed at the drift section



The main stripping foil is placed in the gap between the F and D magnets

Design scheme of the injection system (16-period, FD)

R-S Plane (Horiaontal)



03 Extraction scheme

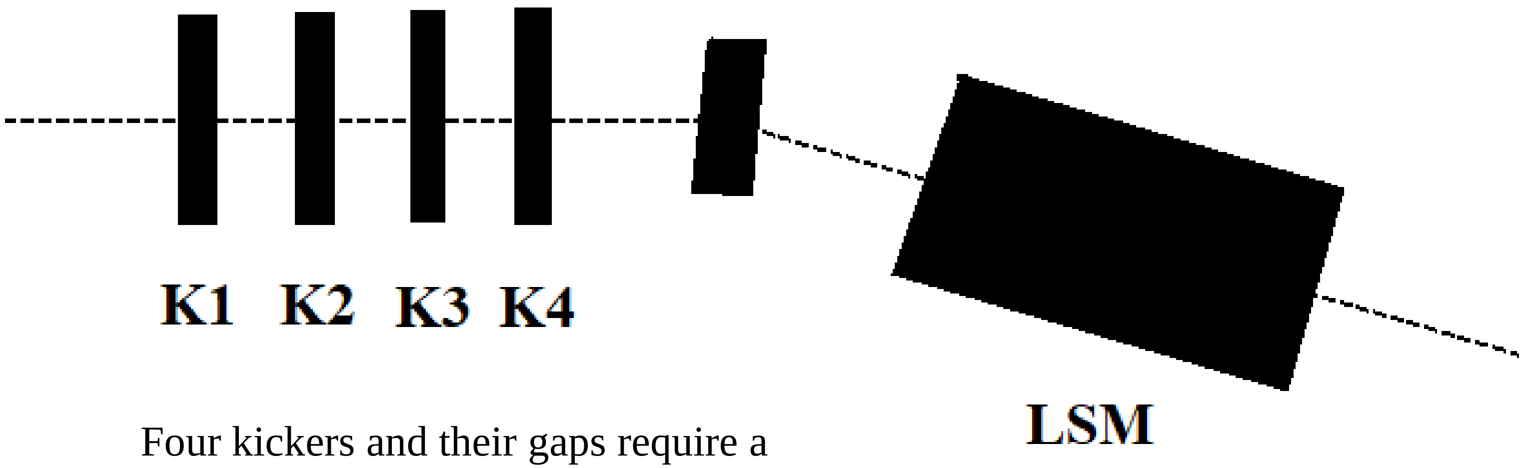
Extraction scheme

- A single-turn fast extraction scheme is used for the FFAG.
- The longitudinal dynamics must be optimized to minimize the bunch length, with the ultimate goal of compressing it to 10 ns (1σ).

Parameters	**Values**
Extraction energy (MeV)	600
Extraction beam width （1σ） (ns)	10
Extraction period (ns)	236
Number of bunches	1
Particles per pulse	2.08×10^{13}
Average beam current (μA)	83.4
Extraction beam power （kW）	50.0

Physical design of the extraction system

- The extraction system consists of four Kicker magnets and one Lambertson magnet.
- The kickers cause a horizontal beam deviation (75mm horizontal position at LSM entrance, total horizontal angle of 21.4mrad). The Lambertson magnet induces a horizontal beam angular separation (246mrad).
- Two drift sections are required: one for Kicker 1-4 and the other for Lambertson magnet.



Four kickers and their gaps require a space of more than 1.8m

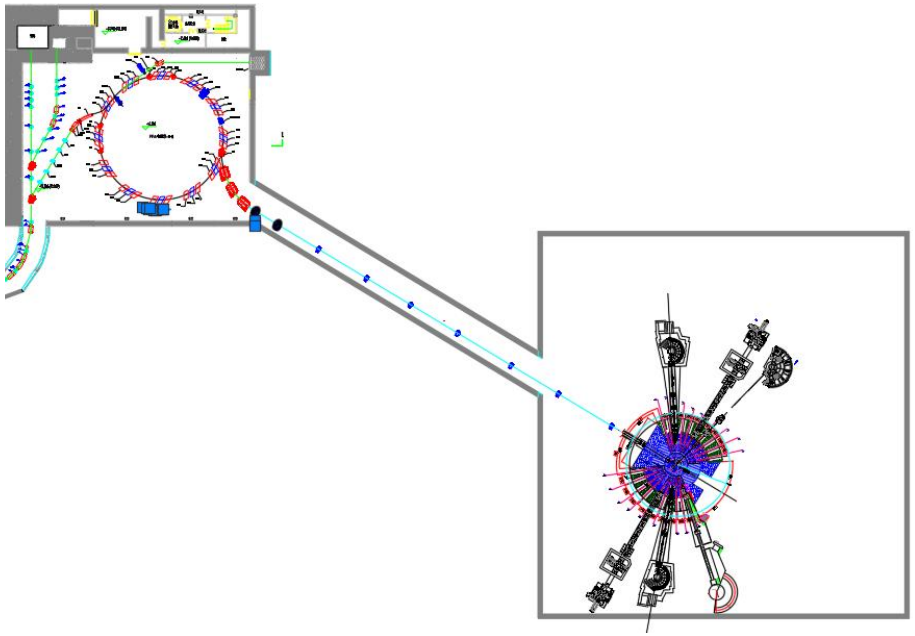
Magnetic parameters of the extraction system

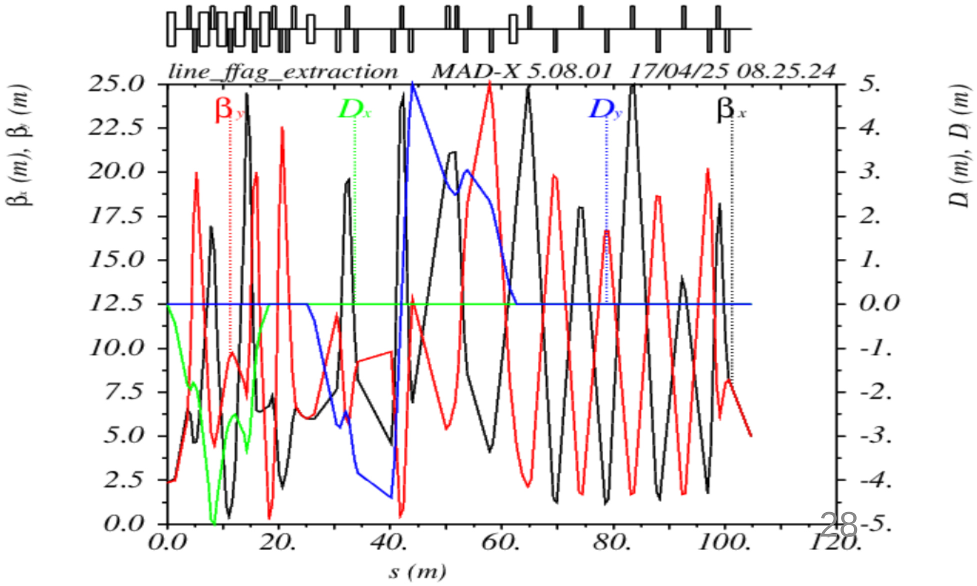
Lambertson	Values
Deflection angle（mrad）	246
Integral field（T m）	1.0
Effective length（m）	1.0
Vertical gap（mm）	110
Vertical good field range（mm）	±55
Horizontal gap（mm）	1016
Horizontal good field range（mm）	[340, 505]
Good field uniformity	0.1%

Kicker（1-4）	Values
Deflection angle（mrad）	5.5
Integral field（T m）	0.022
Effective length（m）	0.25
Vertical gap（mm）	110
Vertical good field range（mm）	±55
Horizontal gap（mm）	1016
Horizontal good field range（mm）	[340, 505]
Good field uniformity	0.1%
Flat-top time of pulsed power supply（ns）	>100
Rise time of pulsed power supply（ns）	<140

The Extraction Line

- The line is designed as achromatic in both planes
- A FODO-like lattice is arranged at the end
- A RF cavity can be used to control the energy and energy spread
- Octupoles can be used to perform beam uniformation





04

Response to the questions of last online meeting

Response to the questions of last online meeting

- **Question1**:1.8 m space for injection and extraction seems very tight, but it seems a reasonable design has been made.

  Answer: Yes.

- **Question2**: Bunching factor is very low, maybe because of the fast acceleration.

  Answer: Yes, that's one reason. Another reason is that the requirement of the extraction bunch length is very short.

- **Question3**: It is interesting why a bump orbit in vertical and orbit gradient in horizontal. Usually, it is opposite because a bump in vertical costs the magnet aperture. (Later I thought that they already have enough vertical aperture at the injection energy because the gap shape magnet.)

  Answer: There were two reasons for the previous design. Firstly, the horizontal aperture of the main magnets is already very large. And a new horizontal bump make the required inner diameter even larger. Secondly, since the extraction system adopts vertical separation scheme and the vertical must be large. To maintain a suitable field index (Ki), the lattice design requires an even larger vertical gap during the injection. This larger vertical gap during the injection is satisfied the height of a vertical bump.

  After the online meeting and in-depth study, a horizontal separation extraction scheme has been proposed and the extraction vertical gap is significantly reduced. Meanwhile, in order to reduce the injection vertical gap, the painting scheme that position scanning in the horizontal plane and angular scanning in the vertical plane has been adopted.

Reply to the questions of last online meeting

- **Question4:** Temperature rise seems to be calculated for 50 Hz operation. It will be higher when the repetition rate increases.

  Answer: Yes. If the repetition rate increases from 25Hz to 50Hz, , the peak temperature of the main stripping foil will increase 150K，which is about 2000K.

- **Question5:** It is not clear to me that if the extraction hardware equipment is feasible, e.g. strength of septum, kicker, etc.

  Answer: After preliminary study, there is no problem for the feasible of the extraction hardware equipment.

- **Question6:** In the future, laser stripping will be another option instead of foil. Is there enough space for this?

  Answer: For the laser stripping injection, the space should be insufficient. We need to re-optimize the layout of the injection system in the future.

05

Summary

Summary

- For the FFAG, the feasible injection and extraction schemes have been proposed.
- Simulation results after optimization indicate that the peak temperature of the stripping foil is acceptable.
- More optimization and simulation are required for the beam injection and extraction.

Thank you very much for your attention!

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