6th ICFA Mini-Workshop on

Space Charge 2024

Study on two-plane painting injection scheme for HIAF BRing

Guodong Shen

On behalf of HIAF Design Group

Institute of Modern Physics (IMP)

Chinese Academy of Sciences (CAS)

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Outline

1. Brief introduction to the BRing injection

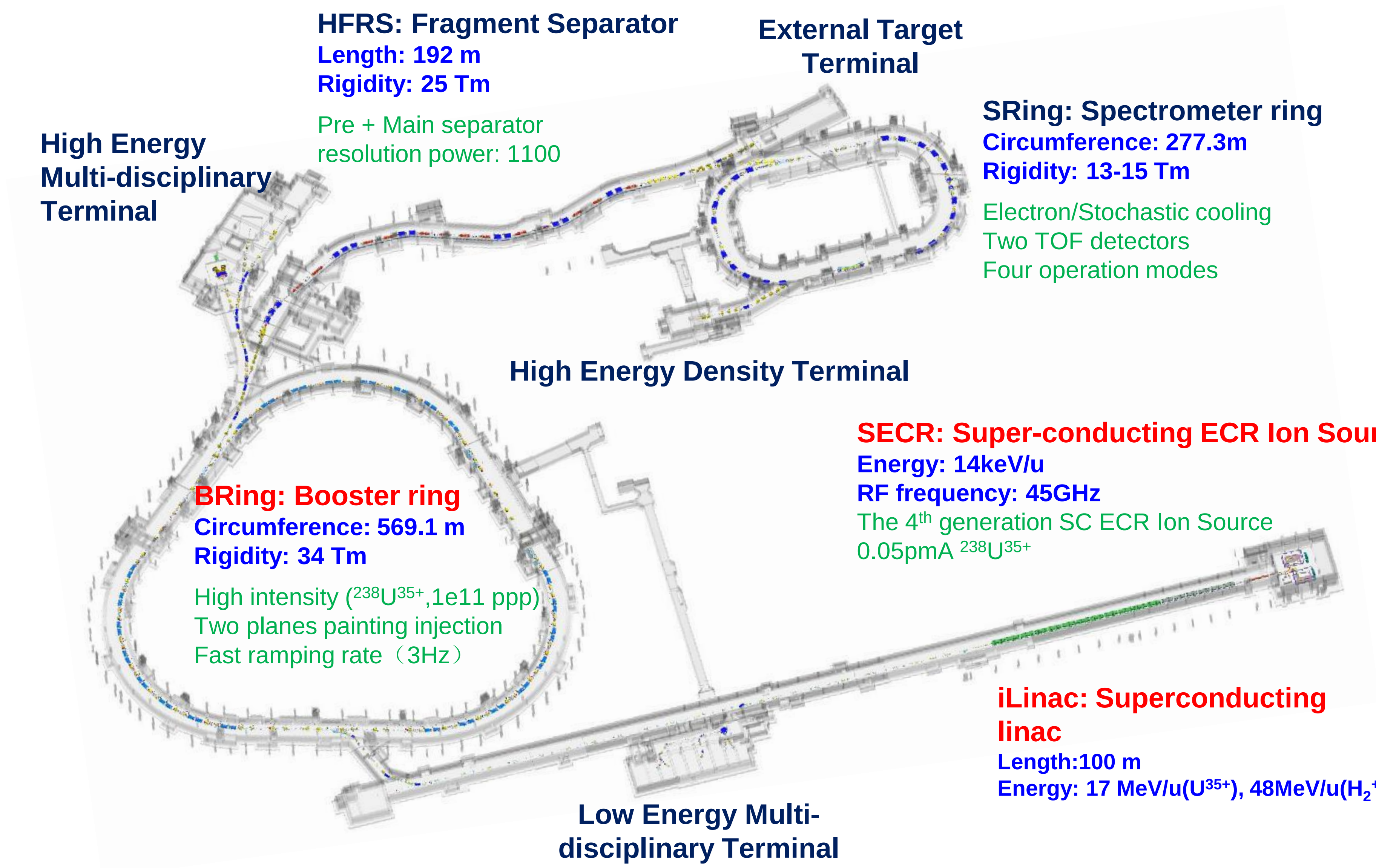
2. Beam loss induced by space charge

3. Dynamic vacuum suppression in ES

4.Summary

Brief introduction to the BRing

High Intensity Heavy-ion Accelerator Facility (HIAF)



Brief introduction to the BRing

Circumference	569.1 m
Magnetic Rigidity	1~34 Tm
Acceptance	200×100 π·mm·mrad (Δp/p ~ ±0.5%)
Ion species	p ~ U
Injection beam energy	17 MeV/u (U^{35+}) 48 MeV (proton)
Injection beam intensity	1 emA(U^{35+}) 1.2 emA (proton)
Injection beam emittance	0.2 π·mm·mrad (x/y, rms, normalized)
Injection beam momentum spread	≤±0.2%
Particle number	1.0×10^{11}(U^{35+}) 2.0×10^{12}(proton)
Revolution period at injection energy	10.07μs (U^{35+}) 6.16μs (proton)

Brief introduction to the BRing

It's challenge for BRing injection design as the demand of

- **High gain:** ECR, high intensity goal
- **Low loss:** Dynamic vacuum

iLinac	BRing	Gain	Loss	Scheme
28pμA (U^{35+}) / 1.79×10^{9}	1.0×10^{11}	56	<10%	Multi-turn injection + ? Electron Cooling
1.2mA (p) / 4.6×10^{10}	2.0×10^{12}	44	<10%	

$$Gain = \frac{Total\ Particle\ number}{Part.num\ injected\ in\ one\ turn}$$

Brief introduction to the BRing

For proton and ion multiturn injection via magnetic or electrostatic septum, Liouville's theorem applies and severely restricts the number of turns

typically ~15 turns for single plane injection with optimized conditions

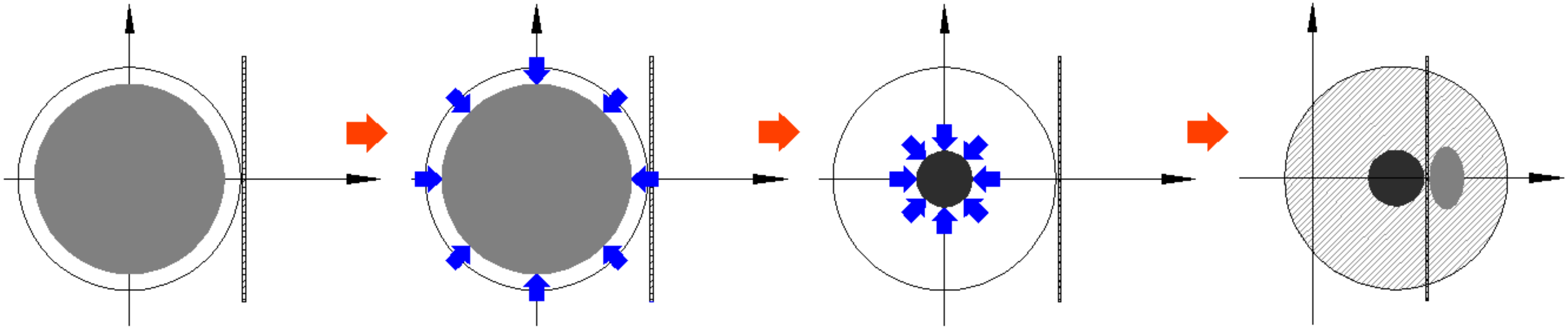
Single Plane: $N_{inj} \approx \dfrac{A}{1.5\varepsilon_i}$

Our case: $\mathrm{N_{inj}} \approx \dfrac{200\ \pi\ \mathrm{mm\ mrad}}{1.5\times5\ \pi\ \mathrm{mm\ mrad}} \approx 26$

Far from enough!

Brief introduction to the BRing

Electron cooling:
The emittance can be shrinked by the e-i interaction. More space can be vacated for later injection.



But the typical cooling process usually takes **more than 10** seconds. In the situation of **high intensity**, the beam may be killed immediately by the **e-i interaction** and **strong space charge effect**.

Beam must be accumulated as fast as possible!

Brief introduction to the BRing

Besides the horizontal phase space, the **vertical phase space** can also be exploited. The injection turns (also the gain factor) can increase dramatically.

How many for **two-plane** injection?

According to G.H. Rees in “Handbook of accelerator physics and engineering” :

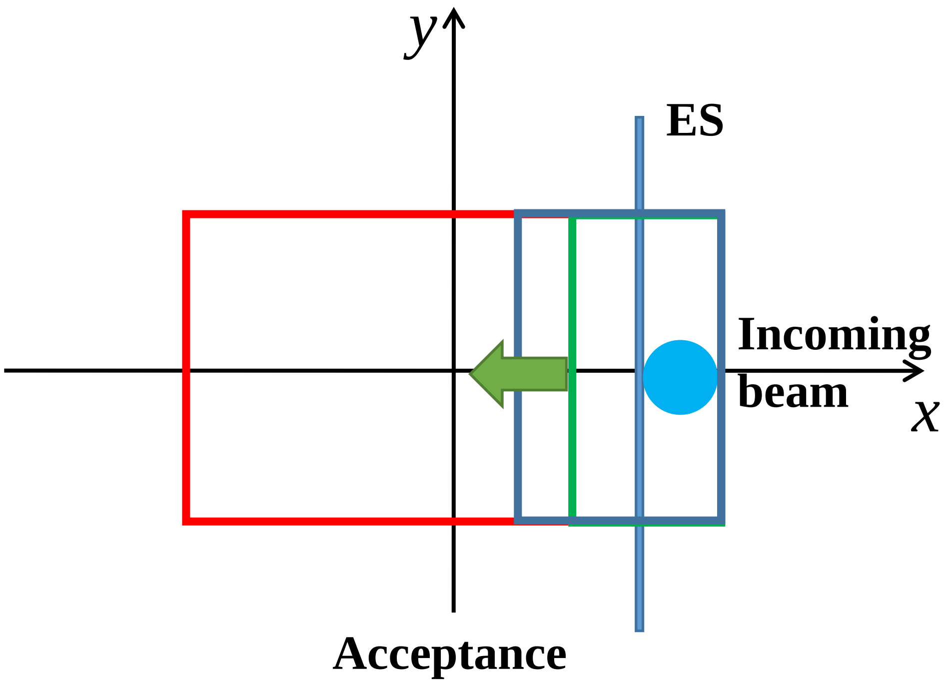
Two-Plane: $$N_{inj} \approx \frac{A_x}{\varepsilon_{ix}} \times \frac{A_y}{\varepsilon_{iy}} \times f$$

$$f \approx 0.1 \sim 0.125$$

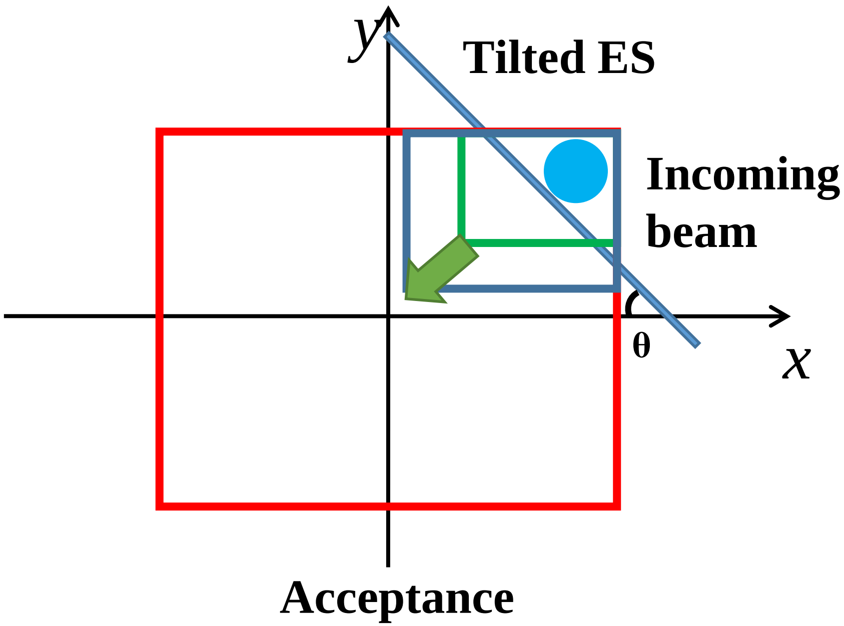
$$\frac{200}{5} \times \frac{100}{5} \times (0.1 \sim 0.125)$$
$$= 80 \sim 100$$

By properly choosing the acceptance ***Ax*** and ***Ay***, the required gain factor can be achieved.

Brief introduction to the BRing



Conventional multi-turn injection



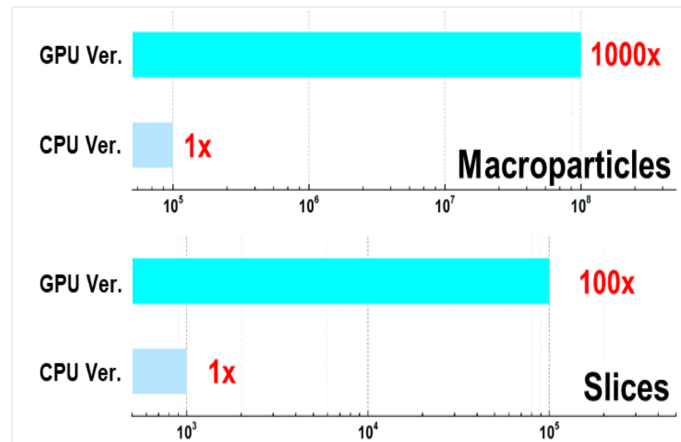
Two-plane painting multi-turn injection

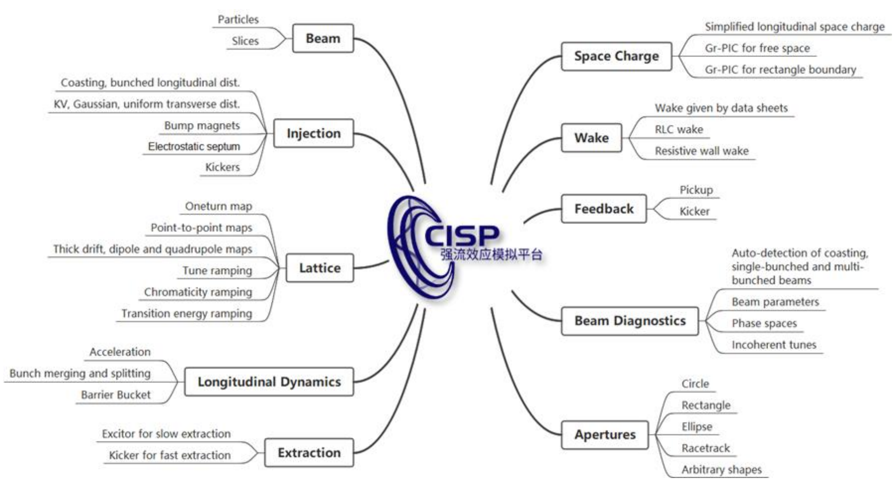
Special hardware: A tilted electrostatic septum

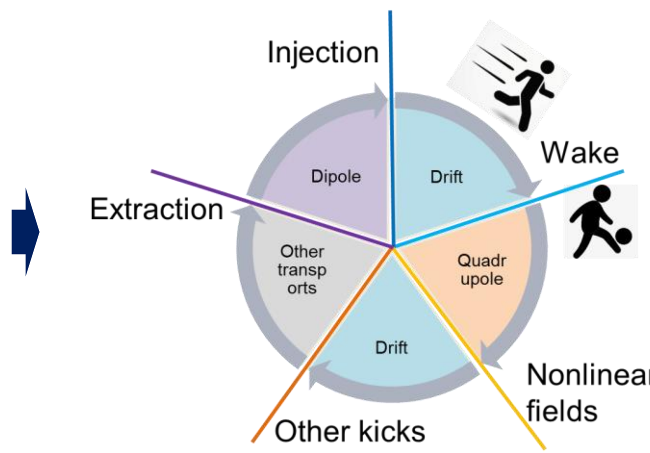
Simulation platform

A simulation code **CISP (Simulation Platform for Collective Instabilities) and its GPU version** are developed to perform **1:1 end-to-end multi-dynamics coupling simulations** in high intensity ion accelerators.

- Employ transport-kick model to **include all these beam dynamics in a single simulation to get closer to the actual accelerators**
- **2.5D space charge**, **nonlinear magnetic errors**, **resonance correction** are available
- GPU-accelerated parallel computing of all beam dynamics: **Higher performance → Much higher accuracy**







2. Beam loss induced by space charge

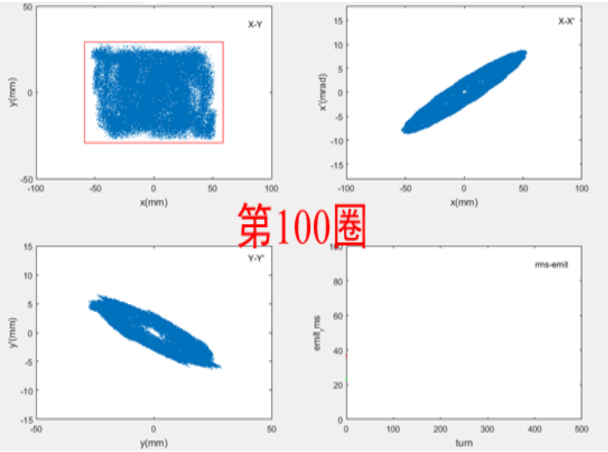
Beam loss induced by space charge

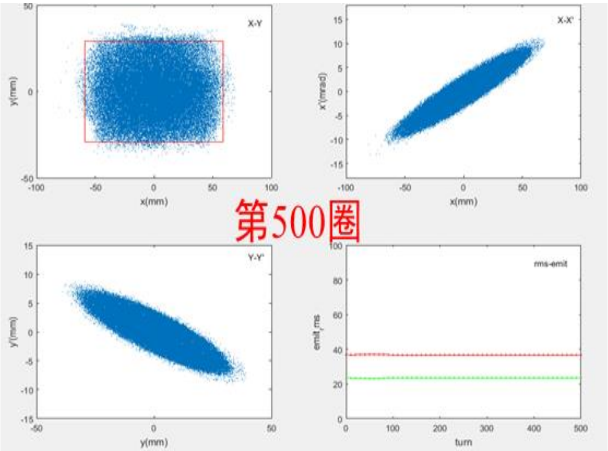
- At very beginning the injection parameters were optimization at the end of injection.
- When tracking is continued a serious beam loss occurred. 20% beam loss in 500turns.
- The process consists a rather fast loss and a slower loss (1% in 500turns).

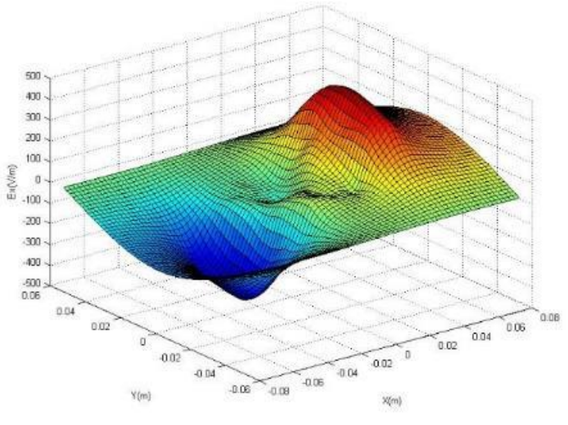
Beam loss induced by space charge

☐ Issue 1: The fast loss is attributed to redistribution of the hollow phase space

- The two-plane painting injection is corelated painting. The injected particles close to the center and the edge of acceptance are easy to lose. The injection parameters optimization results the trend of injection in a ring, which leave **hollow in the center**.
- The hollow phase space generates a distorted space charge field, which imposes serious nonlinear force on particles. The H/V phase space of single particle couples The transverse envelope of beam increase and particles lose. In addition, the rms emittance of H/V remain constant(**Montague resonance?** Tune far from x-y=0 is tried, however redistribution remains).
- The potential of hollow is unstable. The charge density will redistribute to achieve a more stable status. Single particle emittance of partial particles increase.



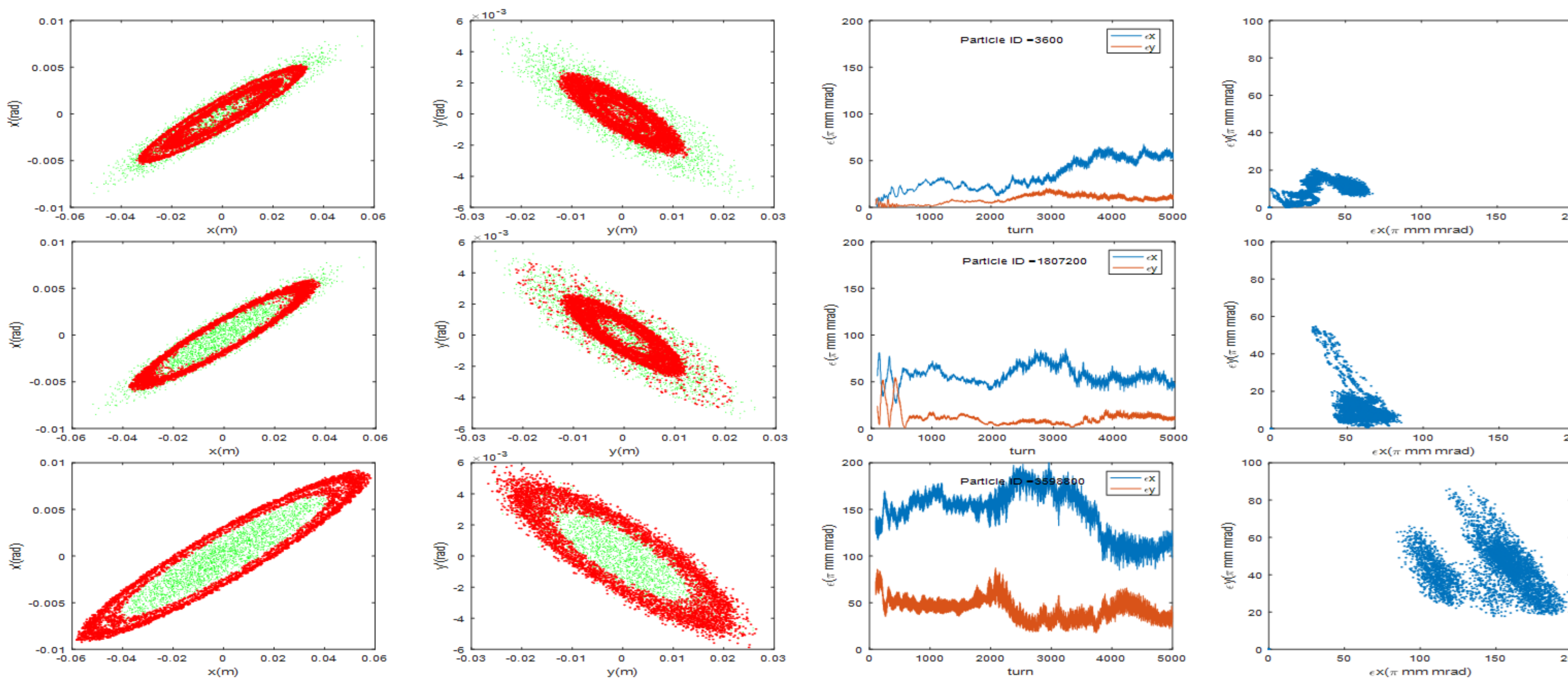




Beam loss induced by space charge

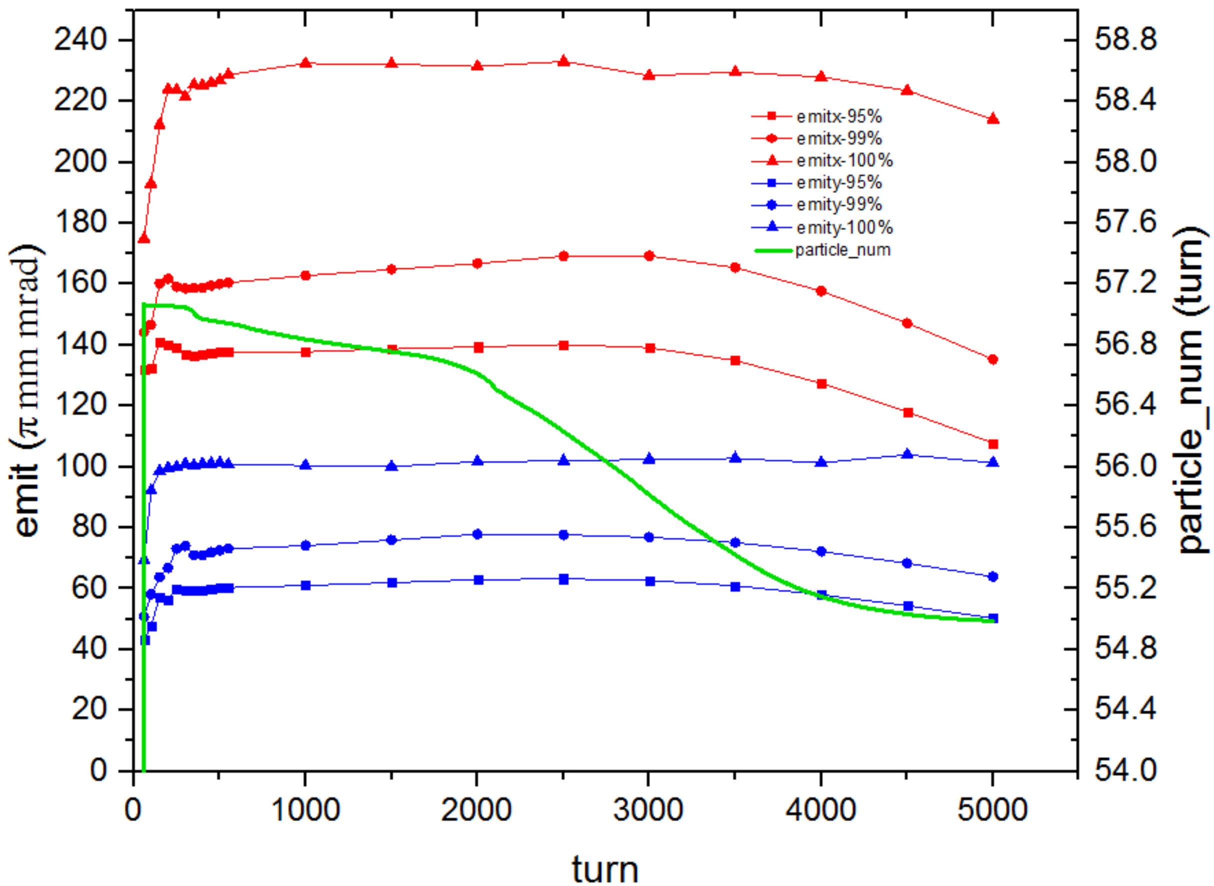
◻ Issue 2: The slow loss is attributed to coupling of H/V single particle phase space

- The evolutions of single particle emittance of three typical particles, which are injected at the beginning, medium and end of the injection process respectively, are illustrated.
- The trajectory of particle in phase space is never an ellipse. It turns into a thick ring.
- It indicate the **exchange of H/V**(also found in RCS of J-PARC, Jx+Jy=const) and **particle with beam simultaneo**usly. Particles lose when hitting the aperture.



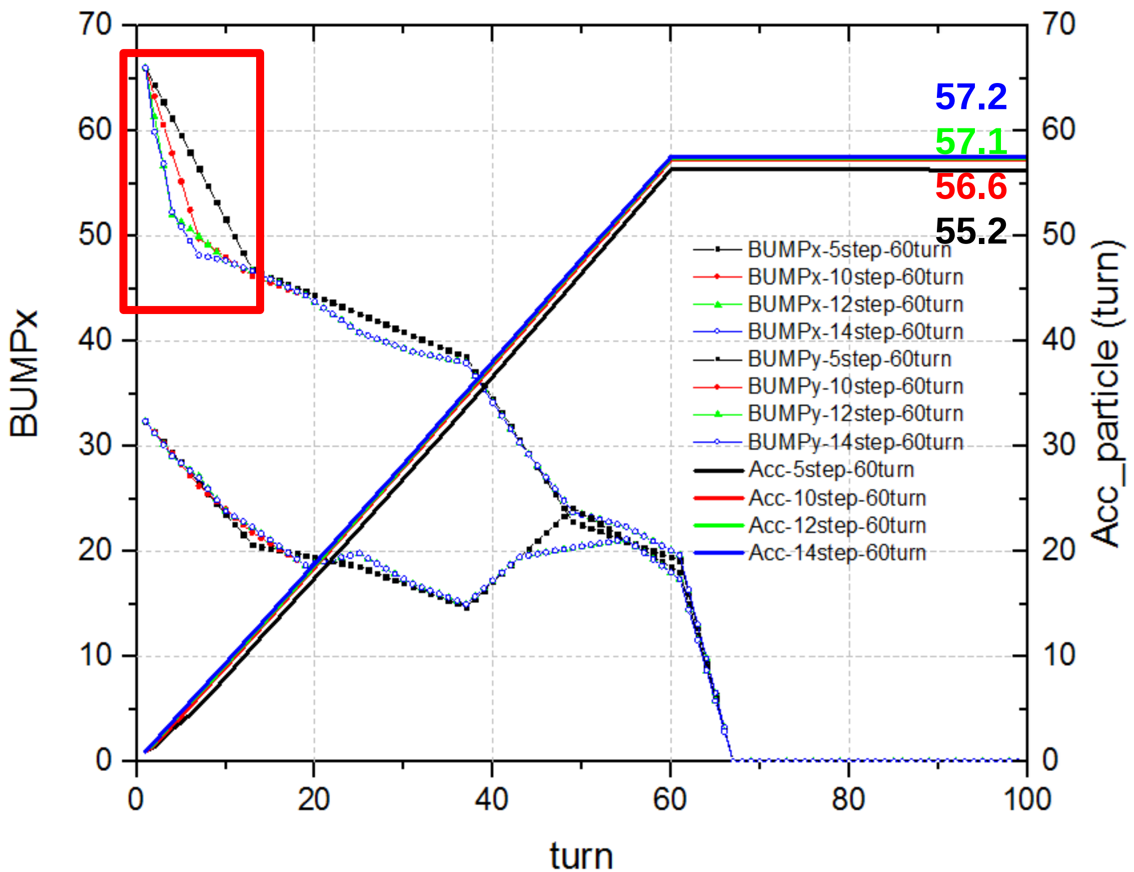
Beam loss induced by space charge

- The 99% emittance is far smaller than acceptance. It's sparse between 99% and 100% emittance.
- Particles skip from beam core to halo continually and vice versa. It is attributed to the significant slow beam loss.



BUMP curve optimization

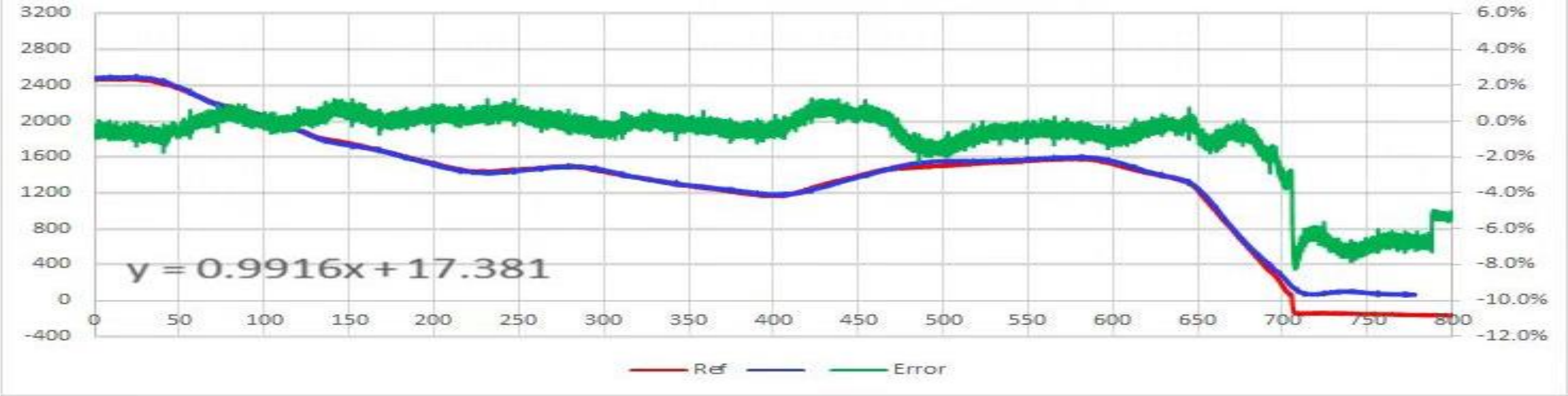
- BUMP curve domains the particle distribution in phase space.
- The BUMP curve is described by polyline and the amplitude of each extreme point is variable. It's optimized by Betaplus and CISP.
- Different segments is selected to investigate the injection gain.

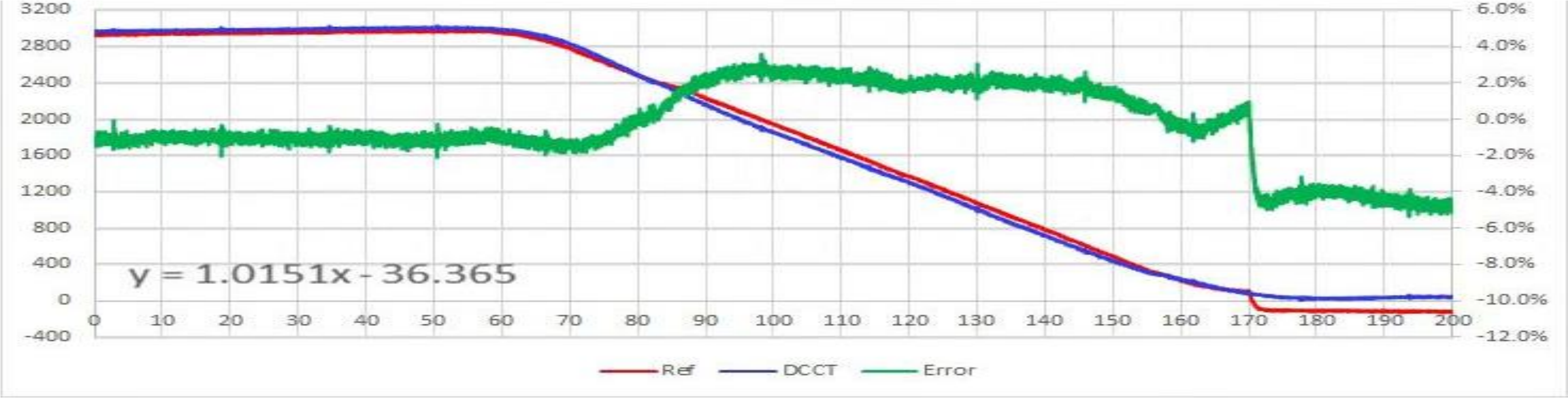


- Different segments hint the phase space center should be fulfill, but sparse.
- 14 segments is almost same as 12 segments and convergent.
- The y BUMPs rise again at the middle.

BUMP curve optimization

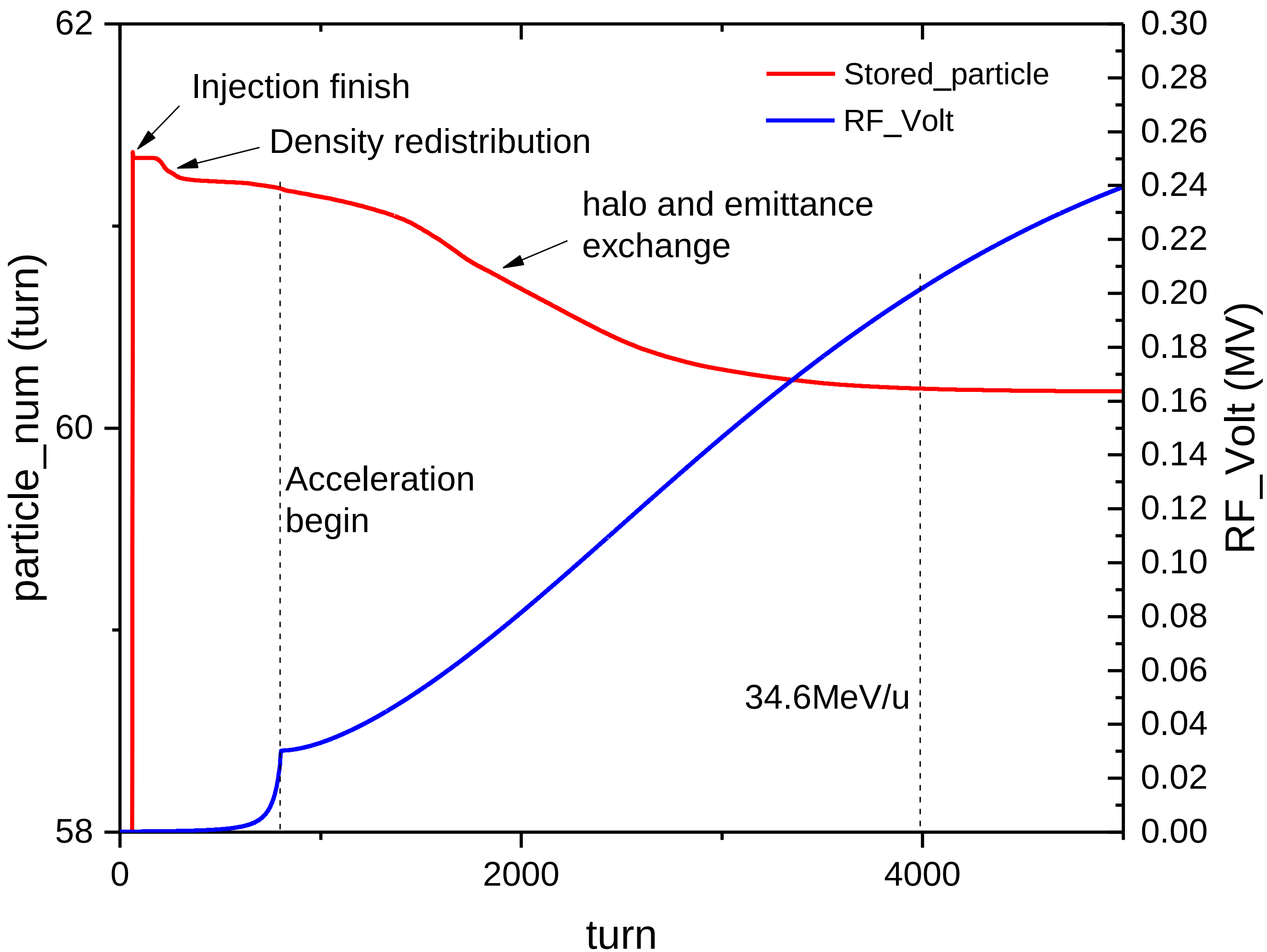
- The first of batch BUMP power supply is developed successfully.
- The tracking error is decreased to ±2% dramatically.
- The adjustment of the batch is still challenge.





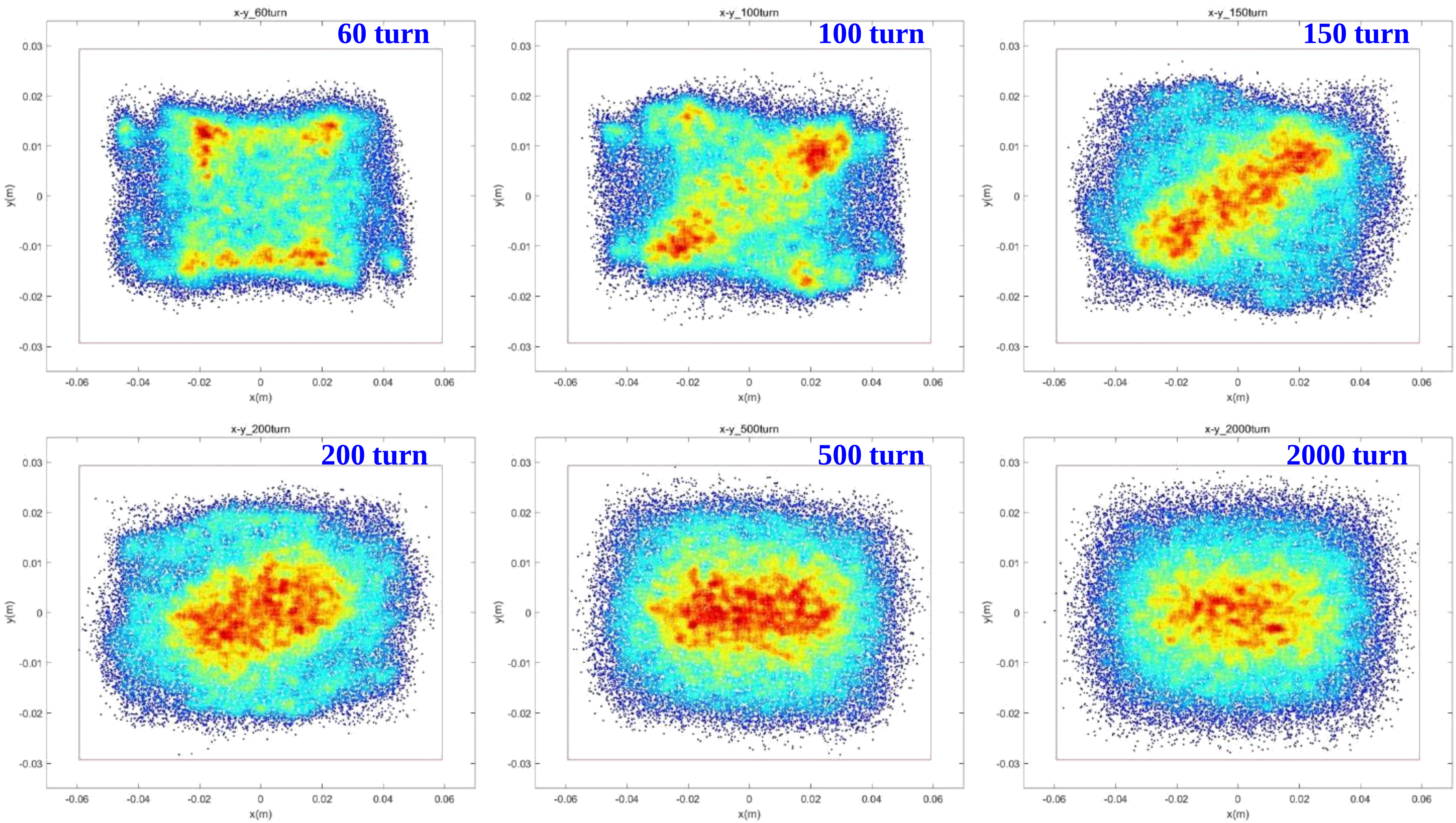
Simulation & optimization

- A python script for injection parameters optimization is developed based on CISP-GPU and Particle Swarm Optimization (PSO) algorism.
- Fast loss is suppressed a lot, while the slow loss is still a problem.



Simulation & optimization

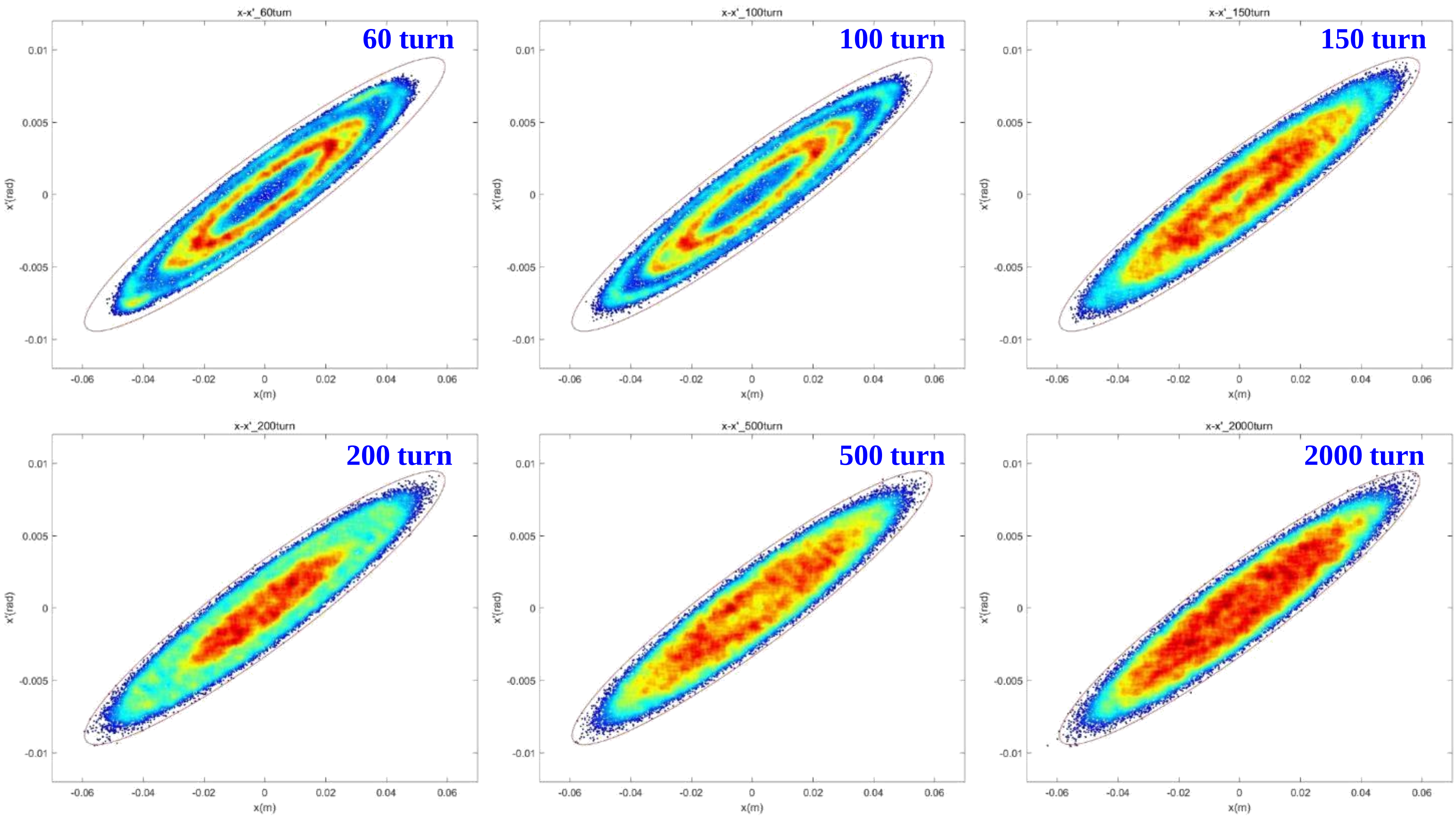
x-y real space evolution



Simulation & optimization

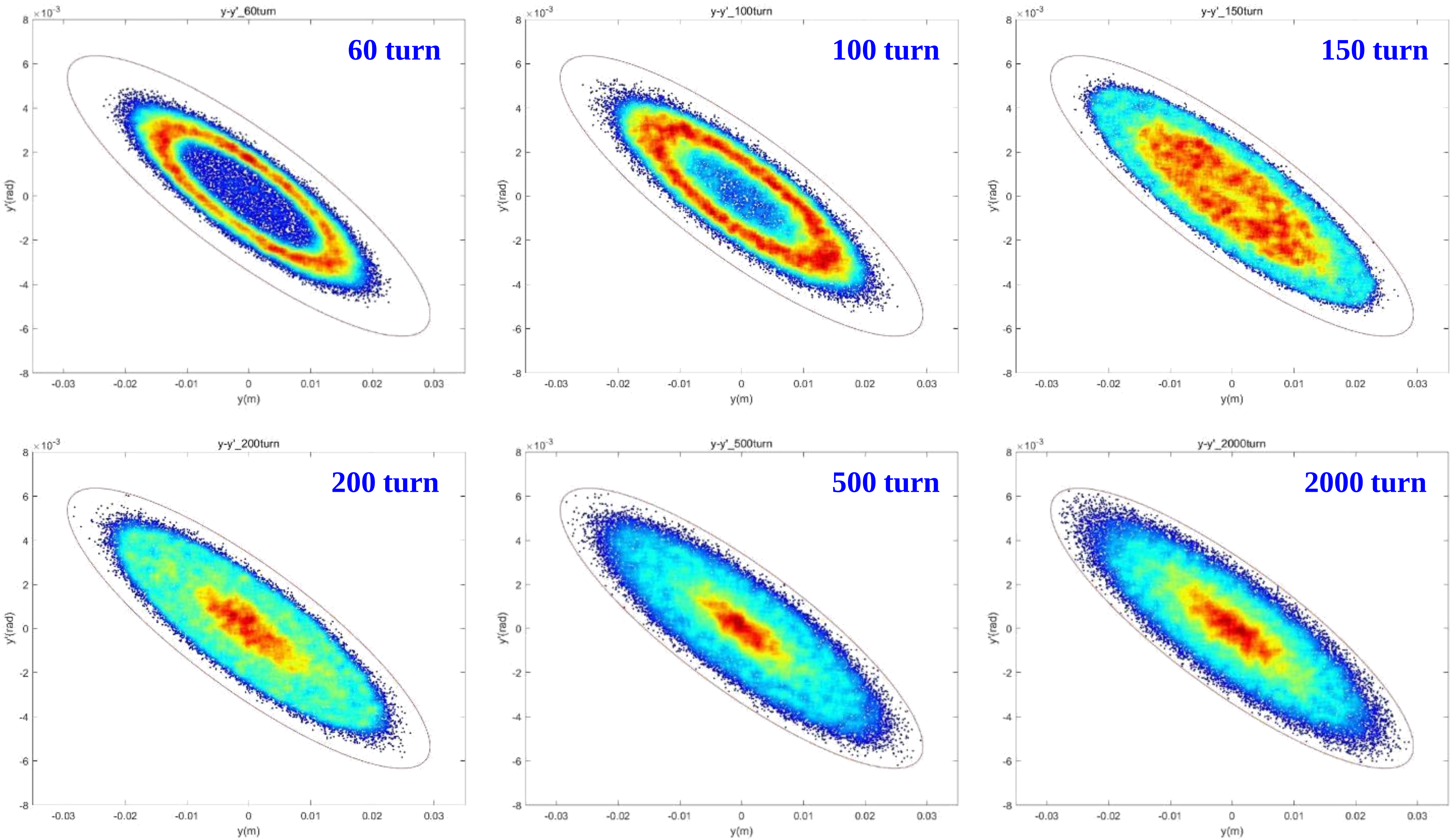
HIAF

x-x’phase space evolution



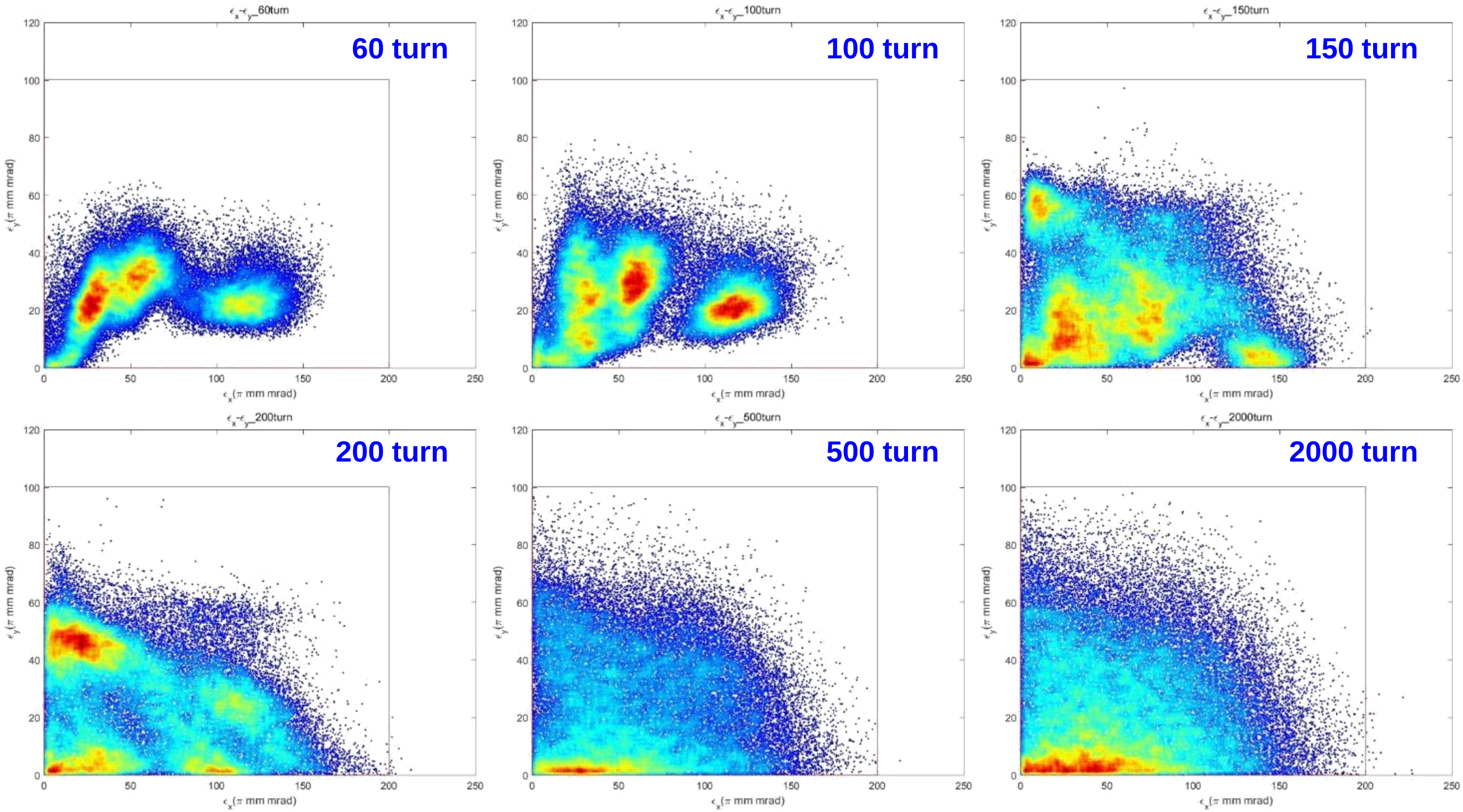
Simulation & optimization

y-y’phase space evolution



Simulation & optimization

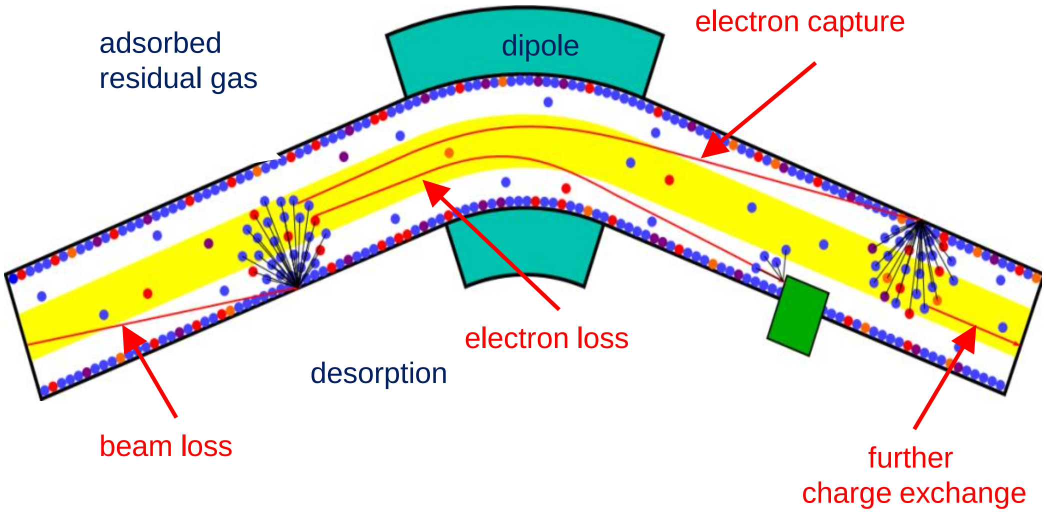
ε_x-ε_y single particle emittance evolution

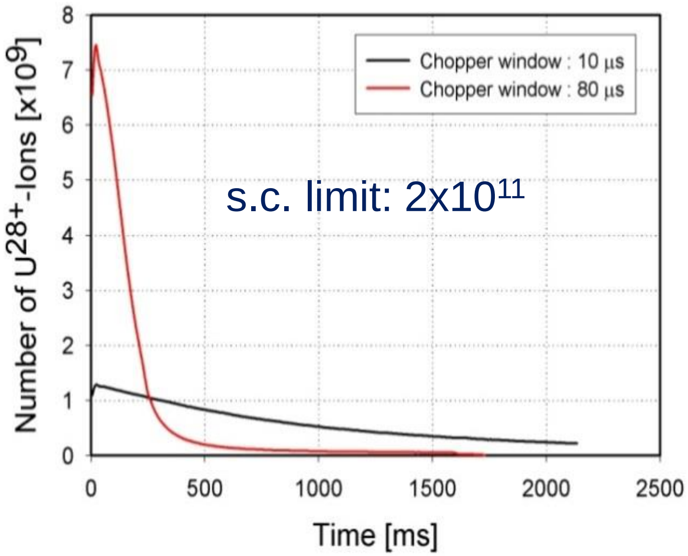


3. Dynamic vacuum suppression in ES

Dynamic vacuum effect

- In high beam intensity heavy ion accelerator, **intermediate charge state** particles are usually chosen to reach designed beam intensity by shifting the space charge limit
- Charge state changing induced beam loss triggers the **avalanche of vacuum pressure and beam lifetime**. It becomes the primary **intensity limitation** in SIS18 and BRing.
- Although the dynamic vacuum effect in the arc section is mitigated intensively by the ion catcher, the injection beam loss depositing on the electrostatic injection septum (ESi) is still a significant **incentive of abundant gas desorption**.

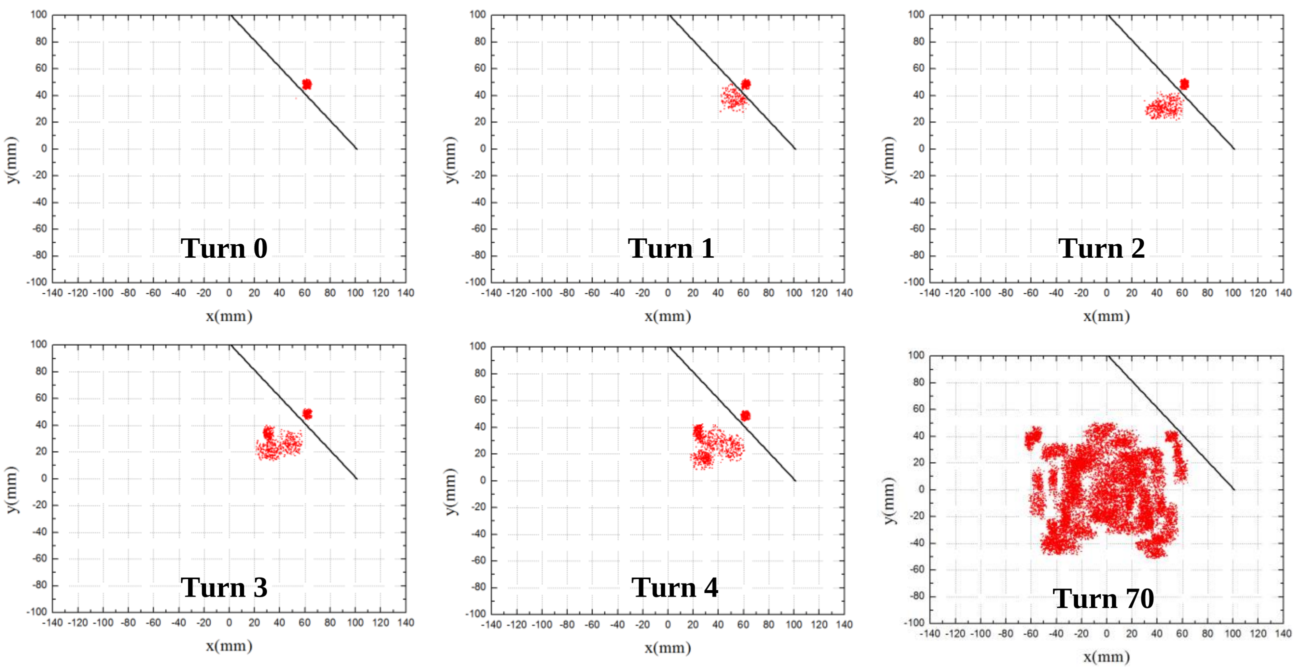




Desorption mechanism in ESi

1. Abundant beam loss

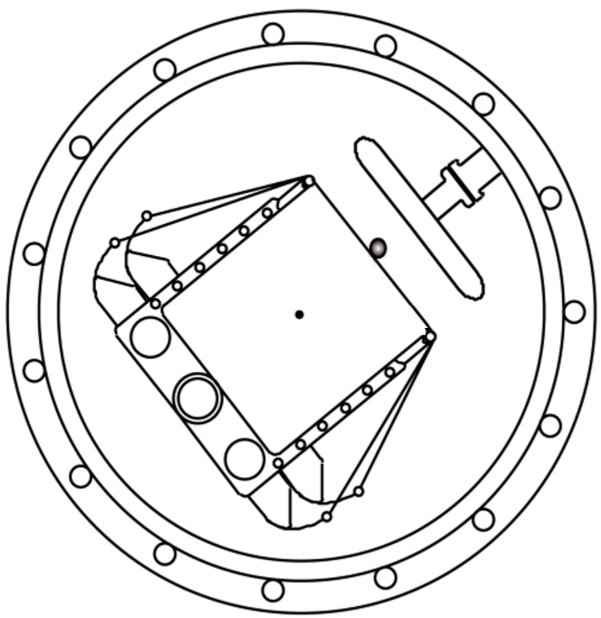
- The ESi is the object **closest to the incident and circulating beams**. Therefore, most of the beam loss during injection locates at the ESi.
- Assume 5% loss of injected particle 1e11 ppp and desorption yield 20000, the desorption gas molecules are 1e14. For the tank of about 0.2 m^3, the vacuum increase by **1.9e-8 mbar** while the static pressure is 1e-11 mbar.

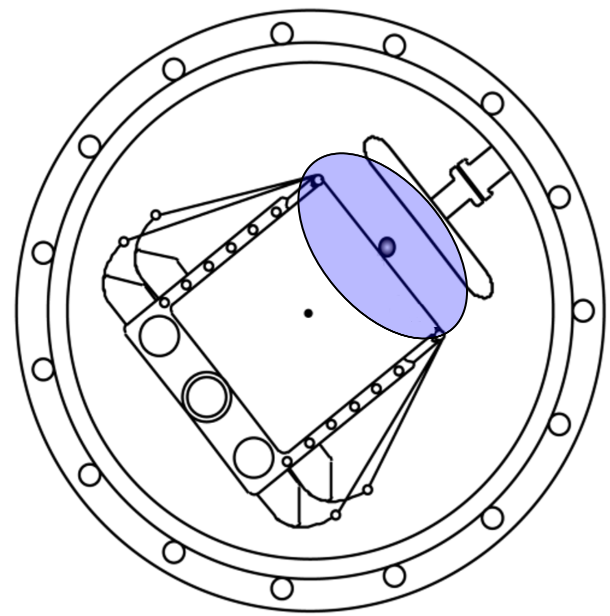


Desorption mechanism in ESi

2. Ultra-short desorption duration

- The injection loss occurs in an ultra-fast process, with multi-turn injection cycle lasting **several tens to hundreds of us**. The average velocity of the gas molecules at room temperature is approximately 600 m/s.
- In this way, gas molecules travel at most **several hundred millimeters** during the injection process, even far from absorbed by pump.
- Therefore, the vacuum in the vicinity of the septum increases suddenly, higher than 1.9e-8mbar, which serves as a **trigger for the dynamic vacuum effect**.

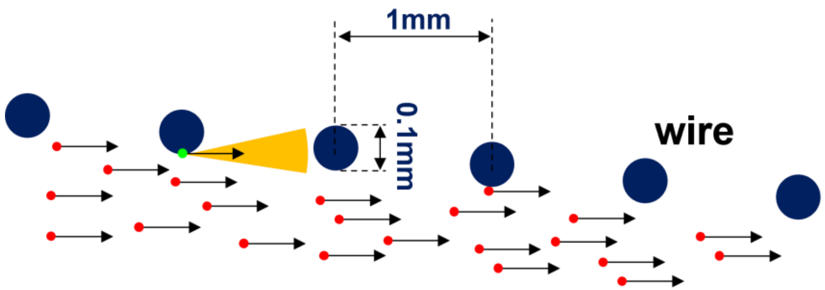


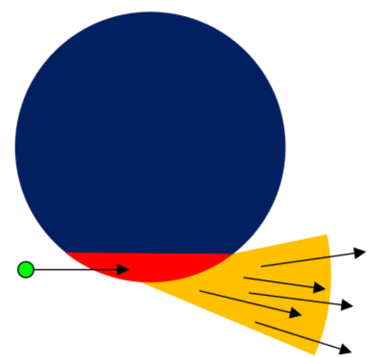


Desorption mechanism in ESi

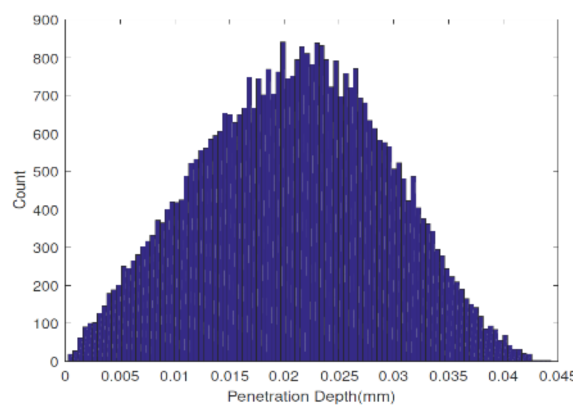
3. Special multi-penetration of septum wires

- The incident and return beams are both nearly parallel with the septum. The beam deposition region occupies small parts of the wires due to the shielding by upstream.
- Ions injected from the edge will penetrate the wires and eject from the opposite side.
- **At least 2 times more gas will be desorbed.**

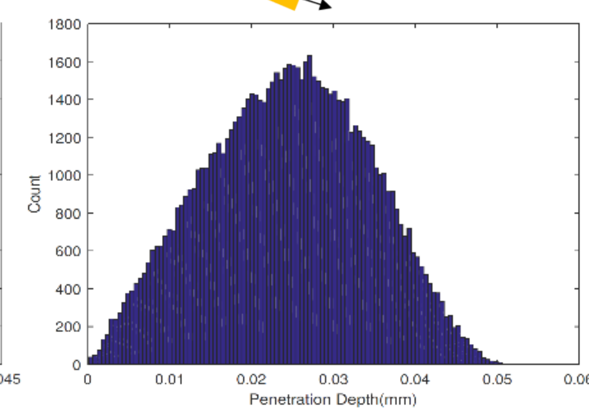




- The penetration depth distribution of the lost particles in the first collision.
- **All of the particles cannot be stopped.**



Incident beam loss

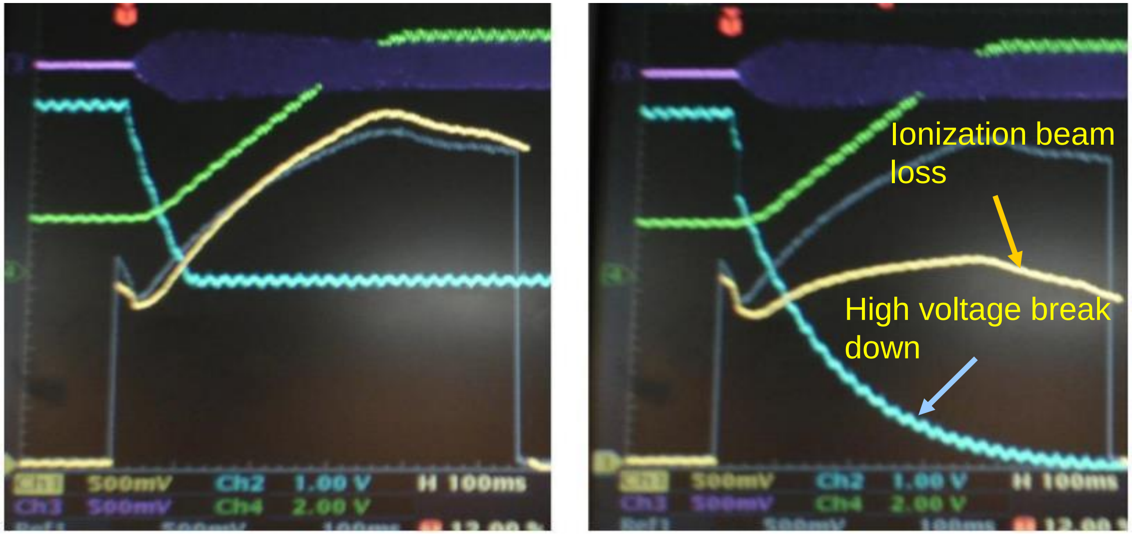


Return beam loss

Desorption mechanism in ESi

4. HV breakdown

- As mentioned above, gas desorbs in ES is characterized **abundant, abruptly, localized**.
- It may results in HV breakdown, which can generates even more desorption and vacuum pressure degradation.
- The particles enter the synchrotron with **an incorrect incident angle**. They will lose on septum or somewhere else in the synchrotron uncontrollably.
- **HV breakdown interrupts the high intensity injection for many seconds**.

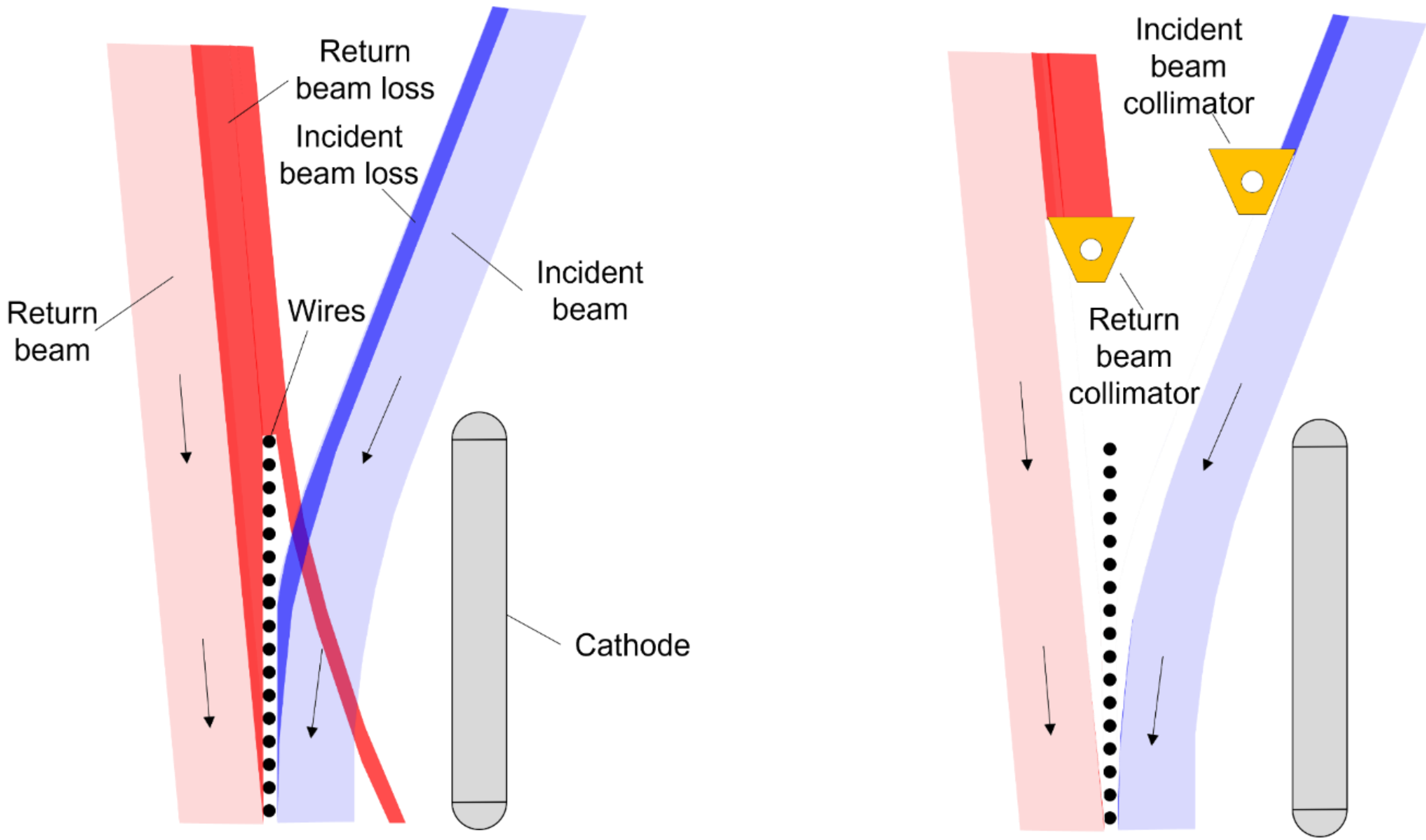


HV breakdown in SIS18 ES

C. Omet, *Dynamic vacuum and beam loss challenges at GSI and FAIR*, Dynamics meets Vacuum (2017).

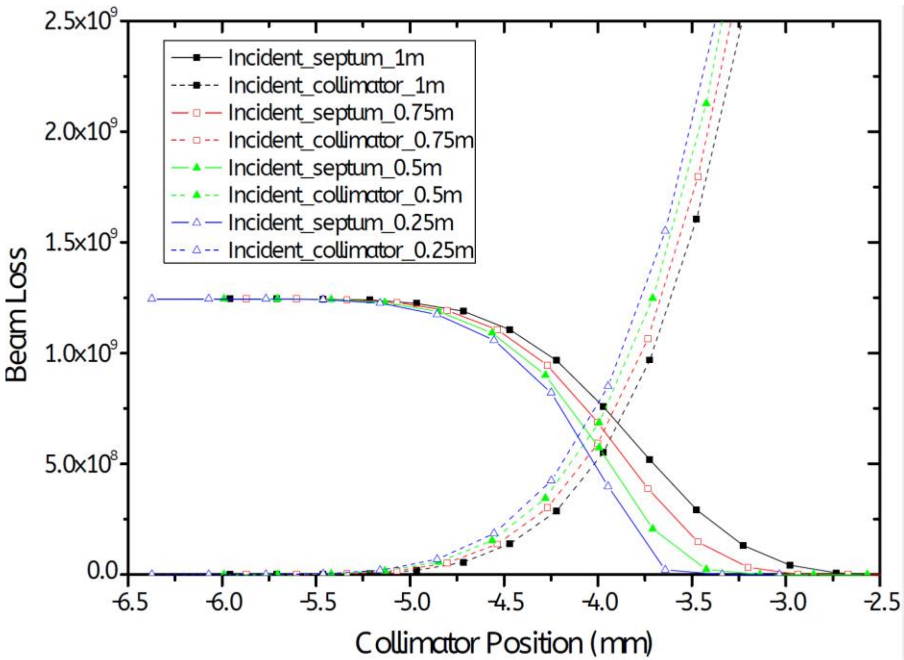
ES collimator

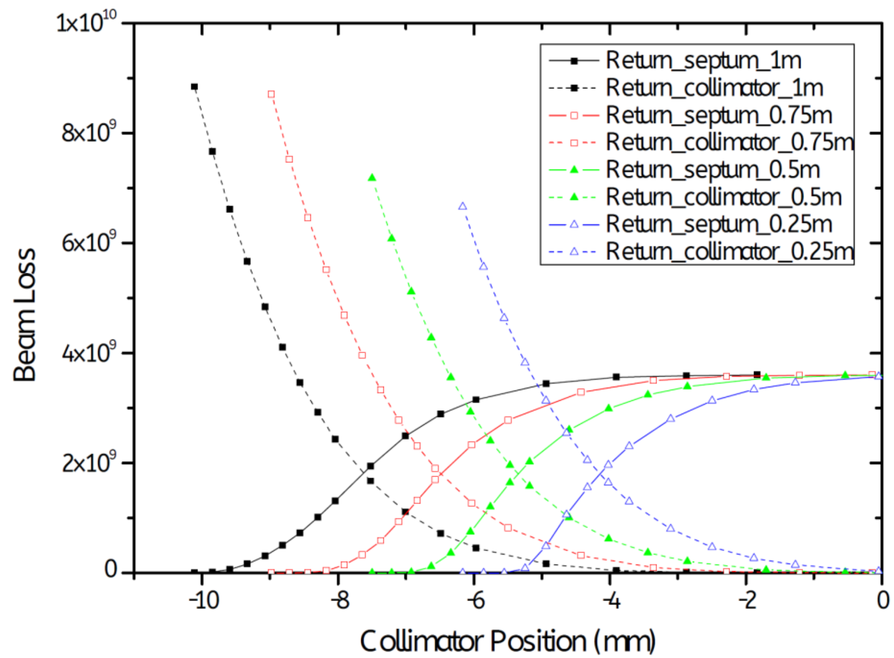
- To suppress the serious dynamic vacuum effect at the ESi, a collimation system dedicated to the absorb the injection beam loss is designed.



ES collimator

- The demarcation upstream becomes broadening and indistinct due to deviated velocity of particles. The larger distance from collimator to ES the lower collimation efficiency. However a smaller d corresponds to a higher electric field in ES.
- The transverse position is compromise collimation efficiency and residual intensity.

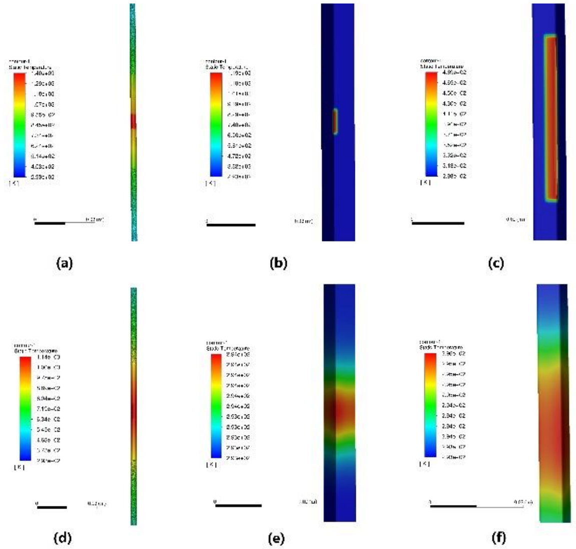


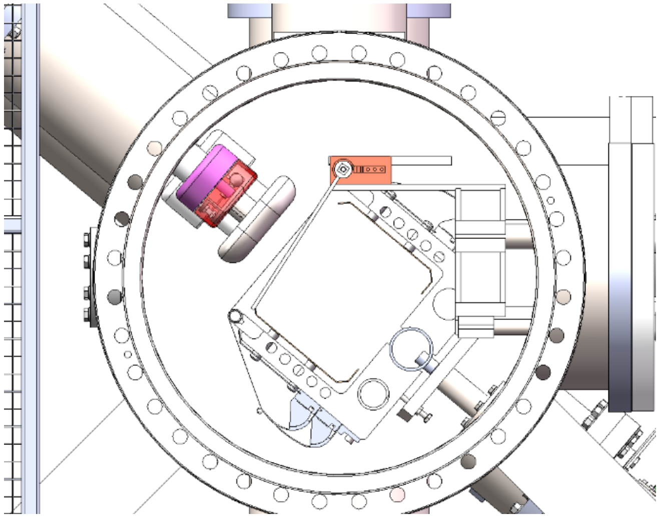


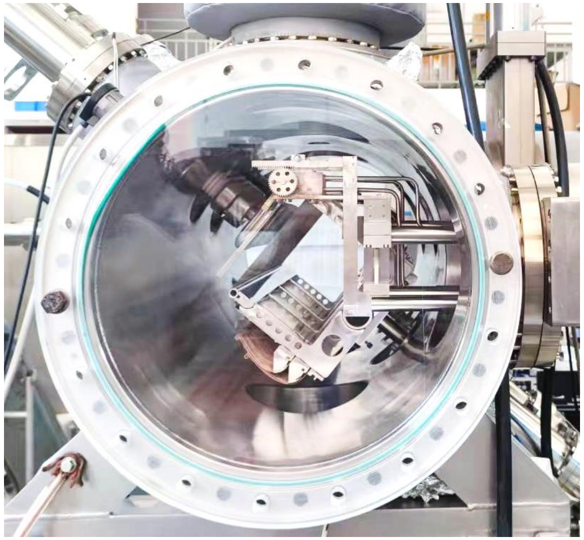
The distance *d* varies from 0.25 m to 1 m. While the abscissa indicates the relative position with respect to injection beam.

ES collimator

- The mechanical design and thermal analysis are performed. It’s temperature performance is much better than wires.
- A full size prototype has been developed successfully. The joint testing with ES is on the way.

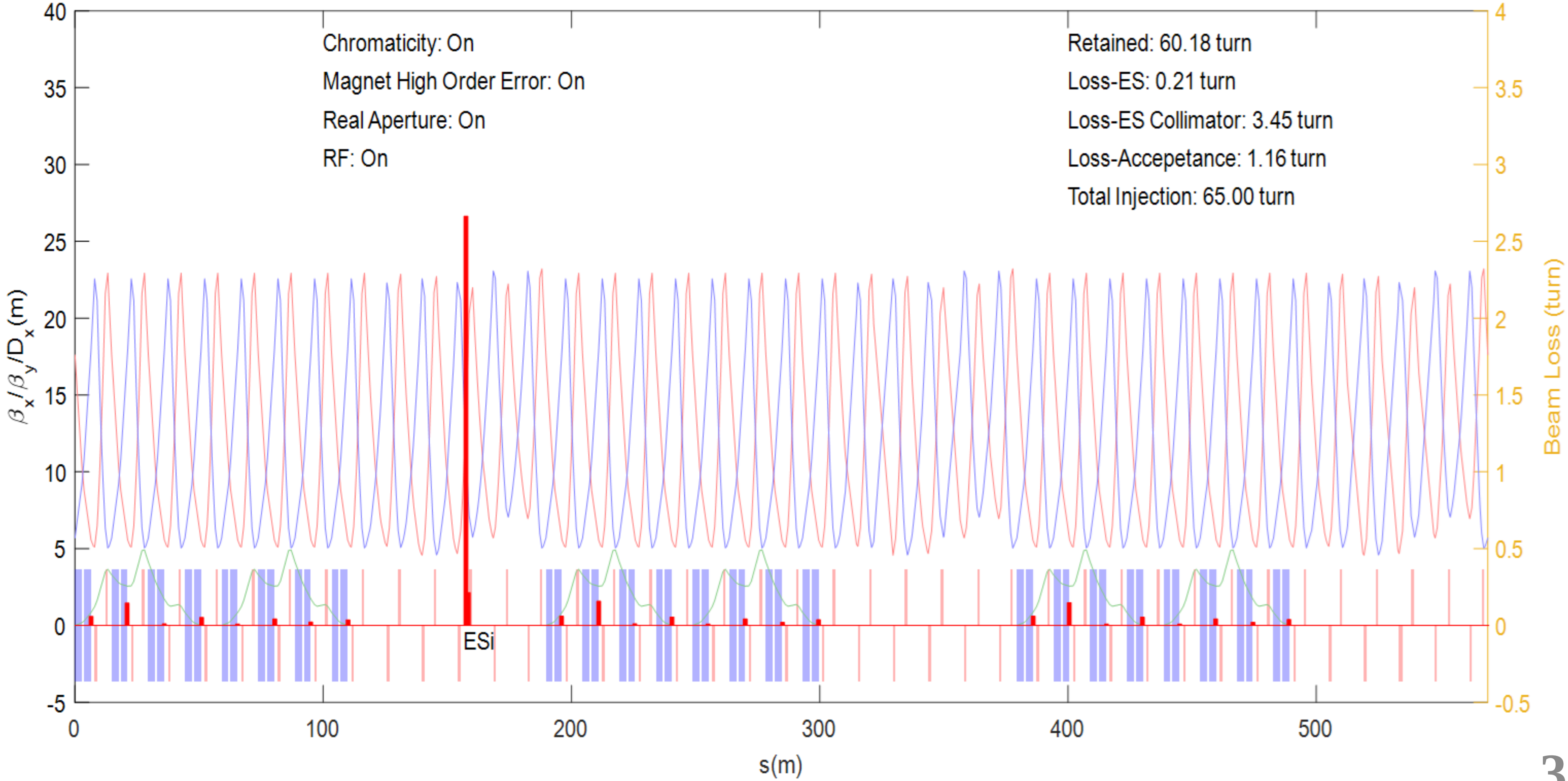






ES collimator

- A series of parameter optimization based on the ES collimators are performed.
- Chromaticity, high order magnet field, vacuum aperture are included.
- The beam loss on ES 4.2% →0.33%, uncontrollable loss 1.8% locates at exit of even num. dipole. The intensity is 1.0×10^{11} ppp.



Summary

- The injection design of BRing is challenge due to the demand of high gain and low beam loss. Two-plane painting is an effective method for high intensity applications.
- The mechanism of beam loss after injection is illustrated as fast loss and slow loss, which are attributed to charge redistribution and coupling under space charge.
- Optimization by tracking and PSO is quiet inefficient. Therefore the complicated relationship between the intensity and injection parameters should be investigated by dynamics research.
- The ES collimator is proposed to eliminate the dynamic vacuum effect. The beam loss on ES is decreased by 13 times. Further suppression is possible at the cost of larger beam loss on ES.
- The first beam injected to BRing is planned in the beginning of 2025. The dynamics simulation result will be demonstrated.

High-Intensity Heavy Ion Accelerator Facility-HIAF