HB2016

Two-plane painting injection in BRing of HIAF project

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Outline

- Introduction of HIAF & BRing
- Why we use the two-plane painting injection
- Introduction of the two-plane injection scheme
- Injection orbit design
- Injection simulation
- Optimization of injection parameters
- Key devices consideration
- Summary and future work

Introduction of HIAF

BRing: Booster ring

Circumference: 531.2 m

Rigidity: 34 Tm

Beam accumulation

Beam cooling

Beam acceleration

Spectrometer Ring （SRing）

SRing: Spectrometer ring

Circumference:240m

Rigidity: 13Tm

Electron/Stochastic cooling

Two TOF detectors

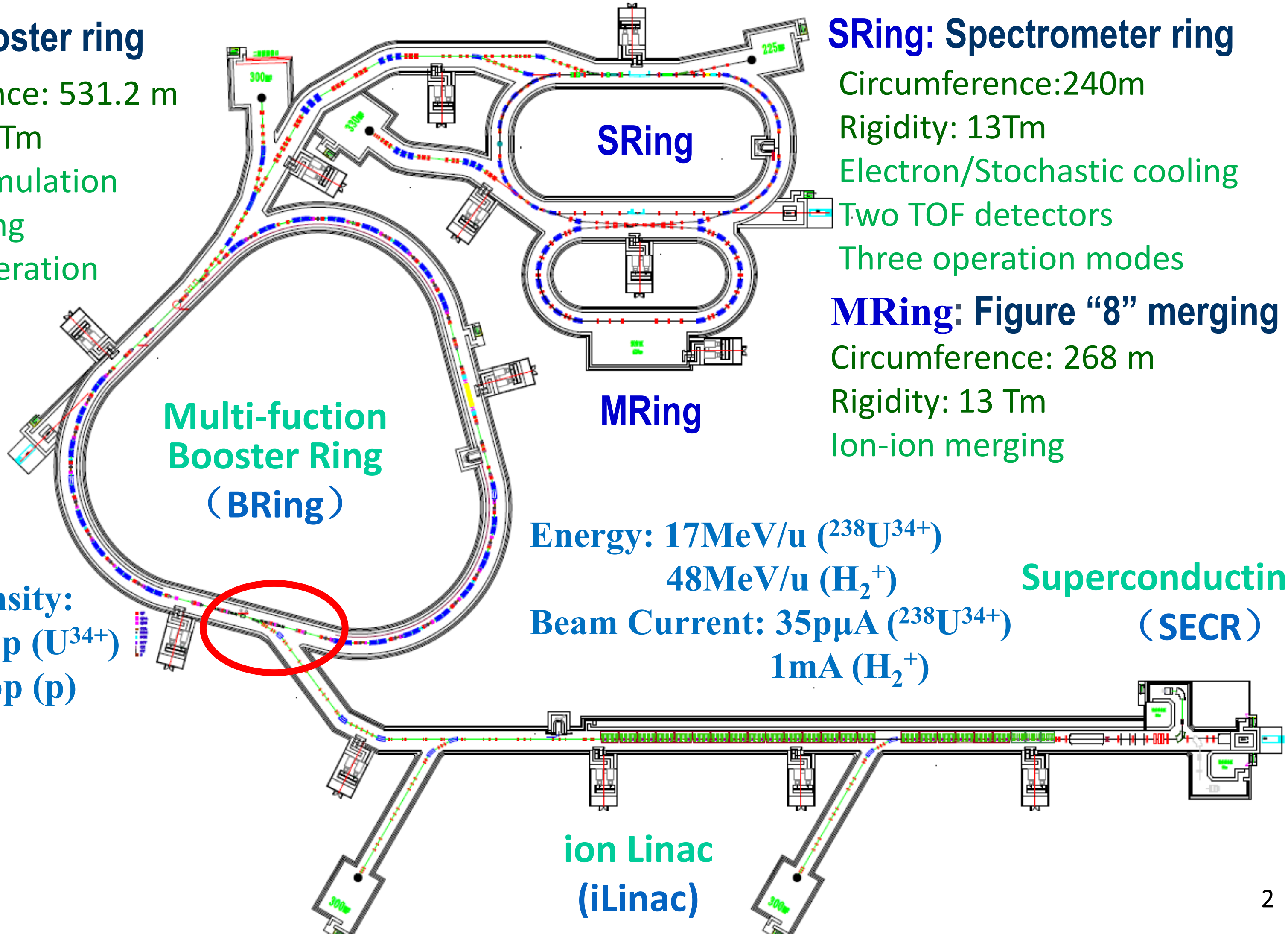
Three operation modes

MRing: Figure “8” merging ring

Circumference: 268 m

Rigidity: 13 Tm

Ion-ion merging

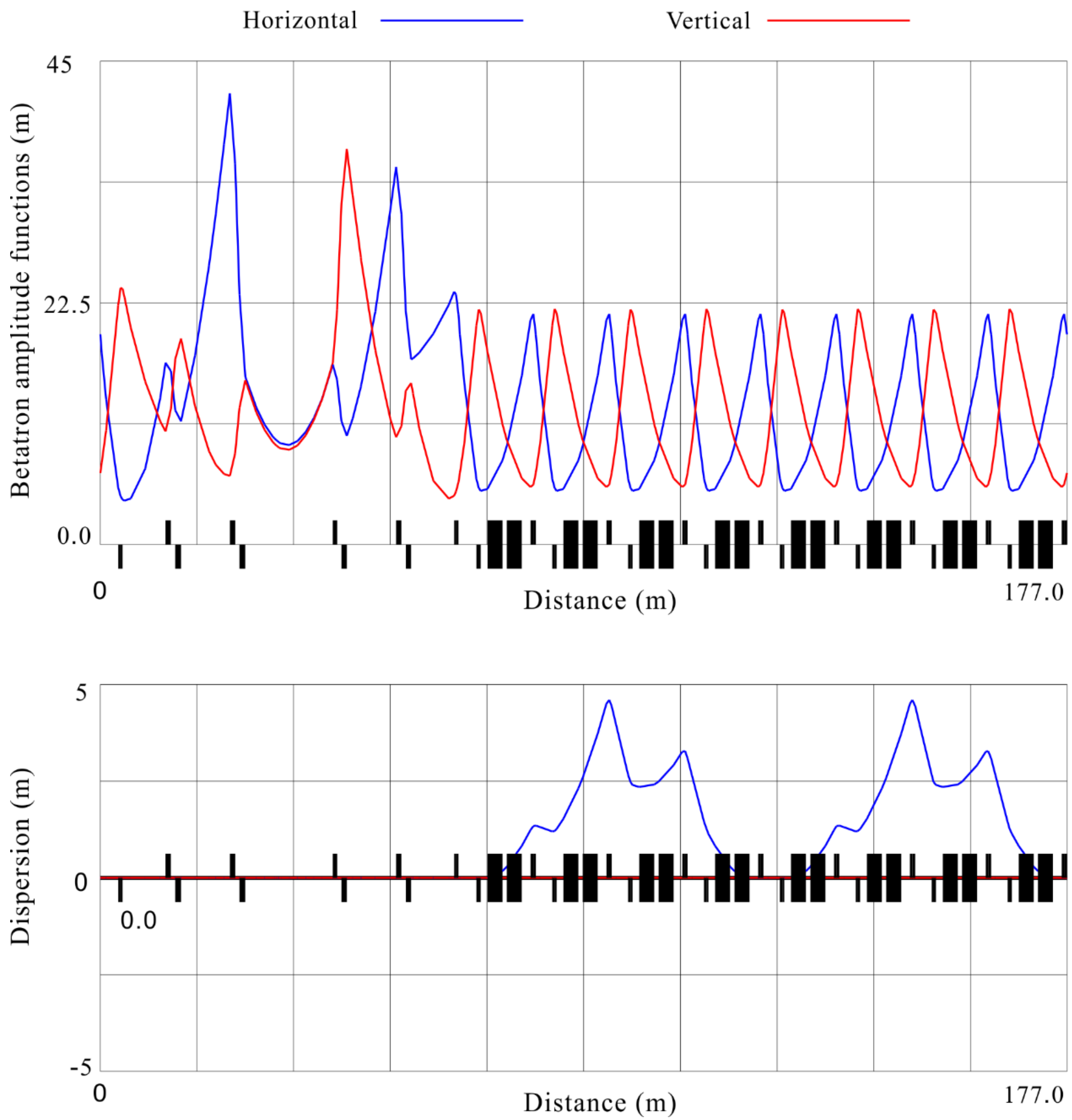


Energy: 17MeV/u ($^{238}U^{34+}$)
48MeV/u (H_2^+)
Beam Current: 35pμA ($^{238}U^{34+}$)
1mA (H_2^+)

Superconducting ECR
（SECR）

Design Intensity:
1.5×10^{11} ppp (U^{34+})
2.0×10^{12} ppp (p)

Lattice of BRing



Max β_x (straight section)	42m
Max β_y (straight section)	37m
Max β_x (Arc)	21.5m
Max β_y (Arc)	22m
Max dispersion	4.6m
Q_x	8.18
Q_y	8.30

Main parameters of BRing

Circumference	531.2 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^{34+}) 48 MeV (p)
Injection beam intensity	35 pμA(U^{34+}) 2 mA (proton)
Injection beam emittance	5 π·mm·mrad (for both x and y plane)
Injection beam momentum spread	±0.5%
Particle number	1.5×10^{11}(U^{34+}) 2.0×10^{12}(proton)
Revolution period at injection energy	9.40μs (U^{34+}) 5.75μs (p)

Injection & accumulation scheme

iLinac	BRing	Gain	Scheme
35pμA (U^{34+}) → 2.27×10^{9}	1.5×10^{11}	66	Multi-turn injection + ? Electron Cooling
2mA (p) → 6.37×10^{10}	2.0×10^{12}	32	

- Multi-turn Injection
- Multiple Multi-turn Injection

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

Conventional Multi-turn Injection

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: $$N_{inj} \approx \frac{A}{1.5\varepsilon_i}$$

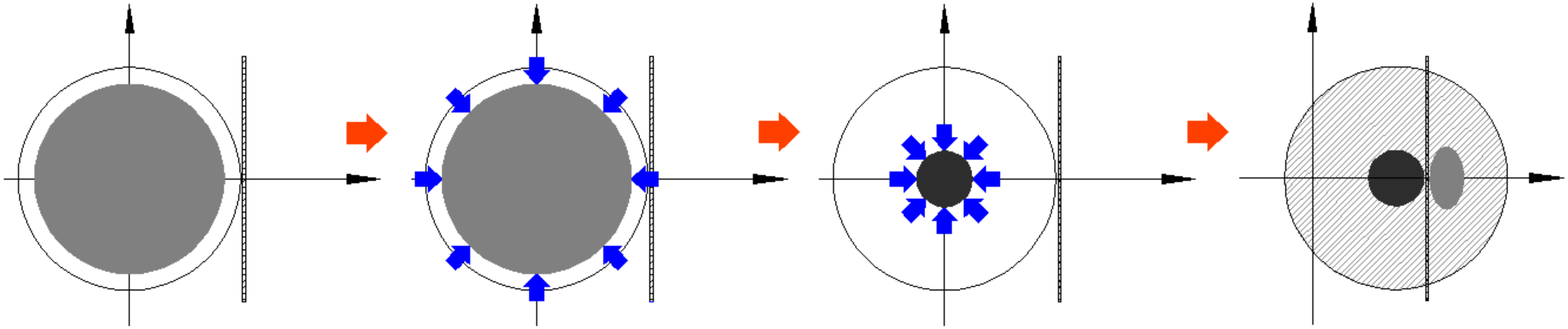
Our case: $$N_{inj} \approx \frac{200\ \pi\ \text{mm mrad}}{1.5\times 5\ \pi\ \text{mm mrad}} \approx 26$$ **<<66**

Far from enough!

Some contents come from **C.R. Prior**'s presentation

Multiple Multiturn Injection

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 **several 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!

Two-plane painting injection

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 turns for **two-plane** injection?

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

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

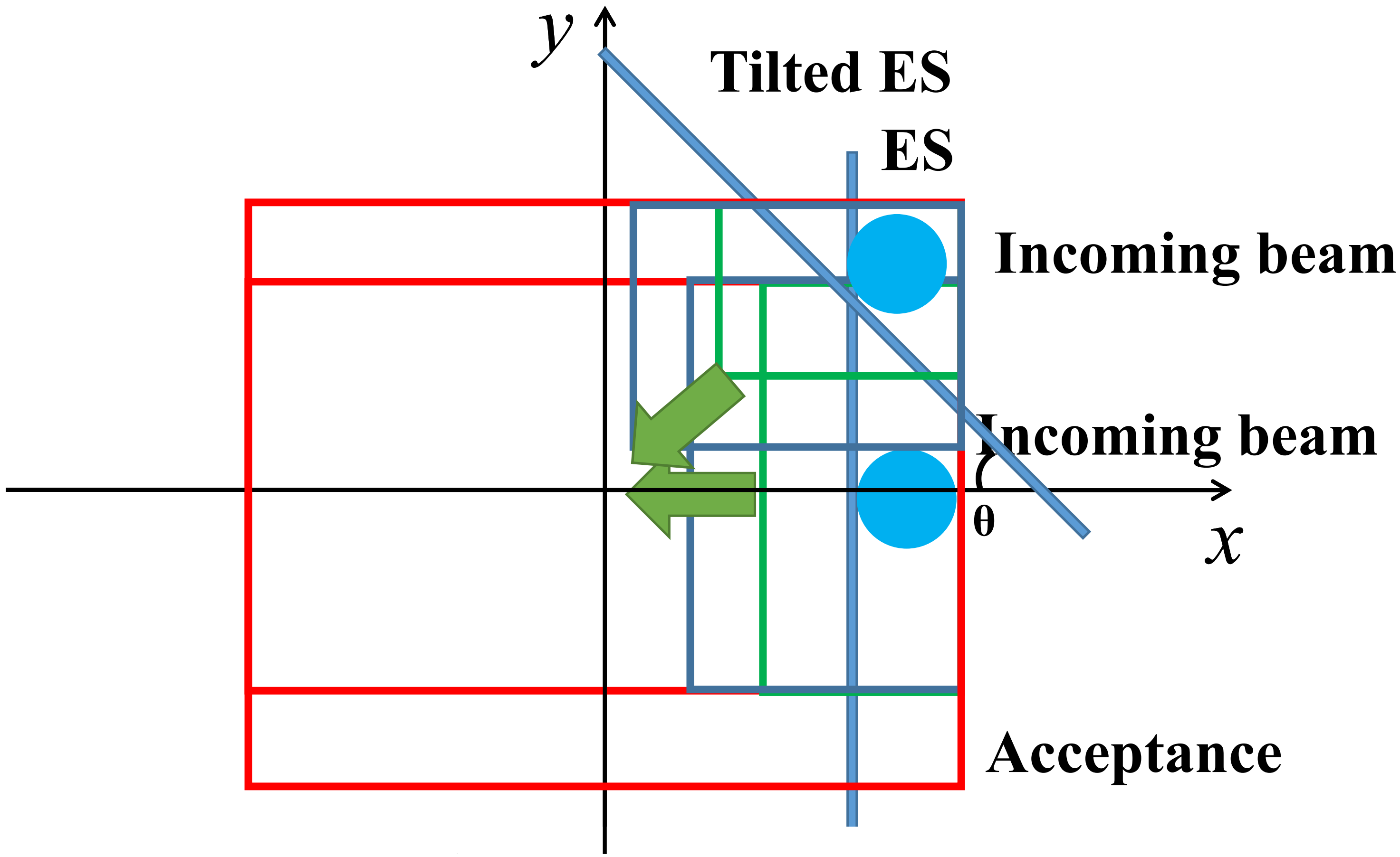
$$\frac{200}{5} \times \frac{100}{5} \times (0.1 \sim 0.125) = 80 \sim 100$$

$f \approx 0.1 \sim 0.125$

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

Time scale: ~ms (9.4μs*100)

Two-plane phase space painting injection

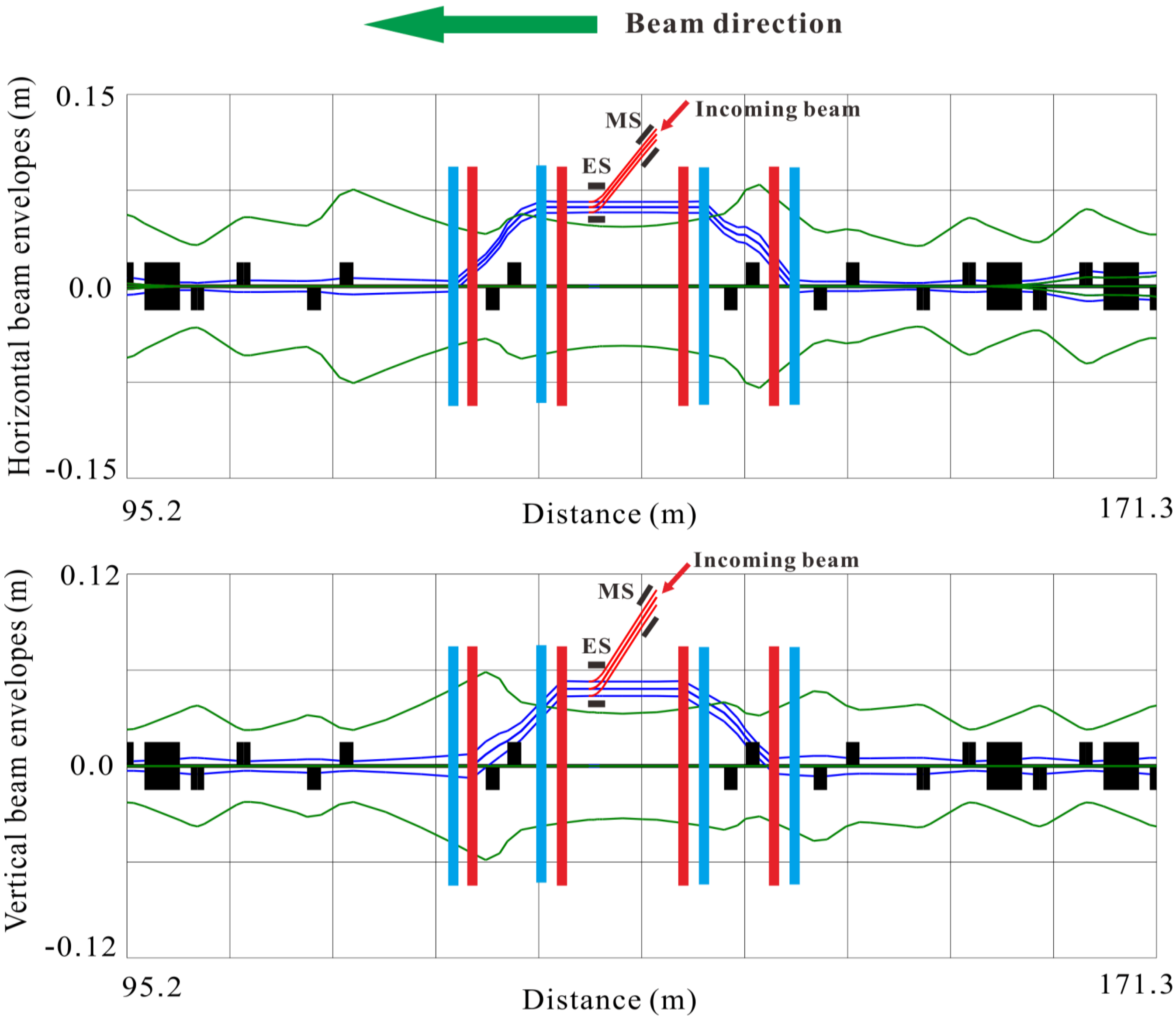


Two-plane painting multiturn injection

Conventional multi-turn injection

Special hardware: An tilted electrostatic septum

Injection orbit design



Initial design injection-parameters

Parameter	Horizontal	Vertical
ES tilt angle	45°	
ES Position (mm)	57.7	43.7
Incoming beam position (mm)	61.8	48.3
Incoming beam size (mm)	8.2	9.2
Initial closed orbit (mm)	55.62	43.47
Tune	8.18	8.30
β function of the ring (m)	11.364	11.364
α function of the ring	0.2318	0.2318
β function of the injection line (m)	3.4	4.2
α function of the injection line	0.0694	0.0857

Two-plane painting injection simulation

ORBIT

ORBIT program modification:

Tilted e-septum node implemented

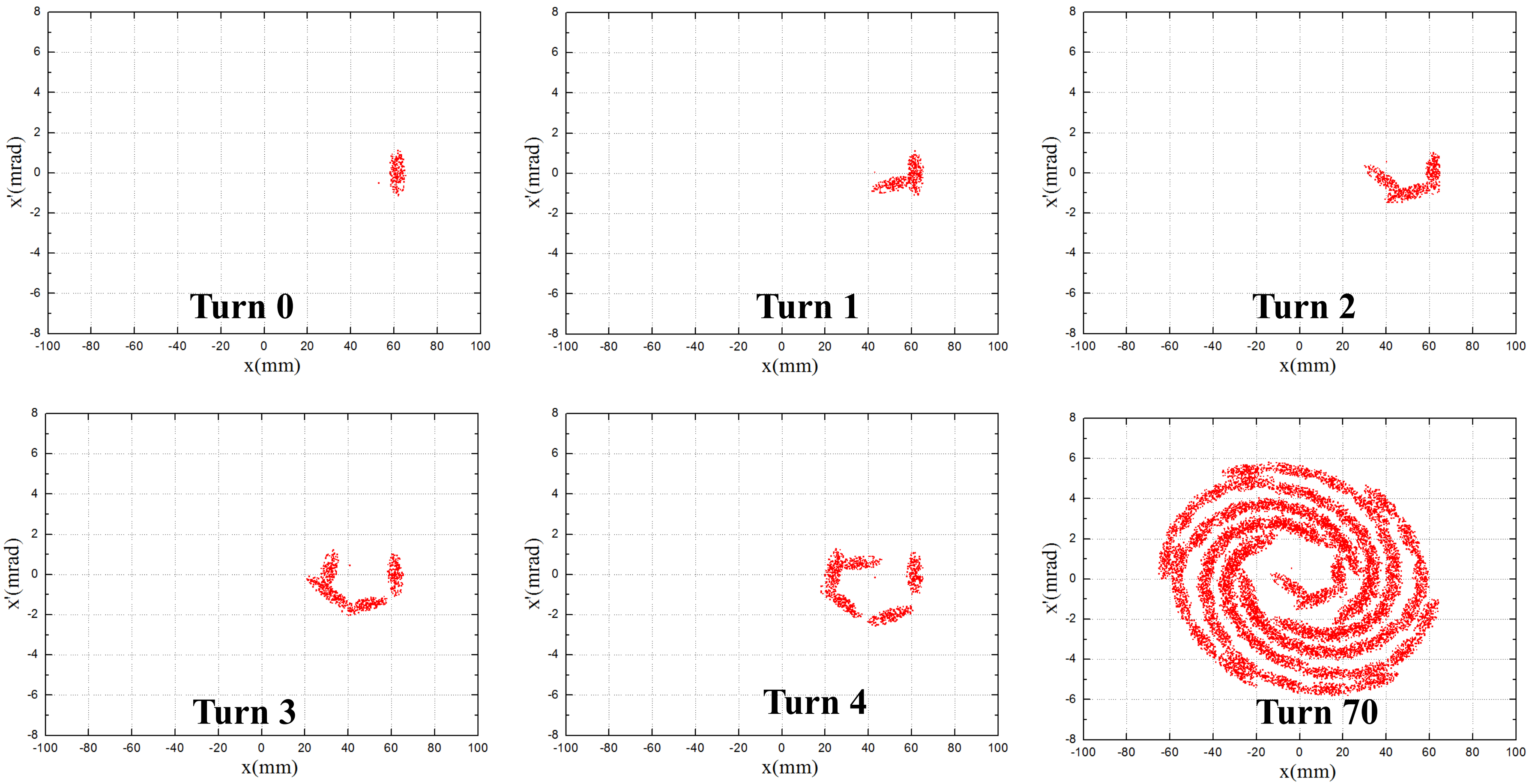
- Beam injection
- Beam loss

Why choose ORBIT program?

- Widely used for synchrotron injection
- Open Source, easy to modify
- Well support for space charge effect for further study

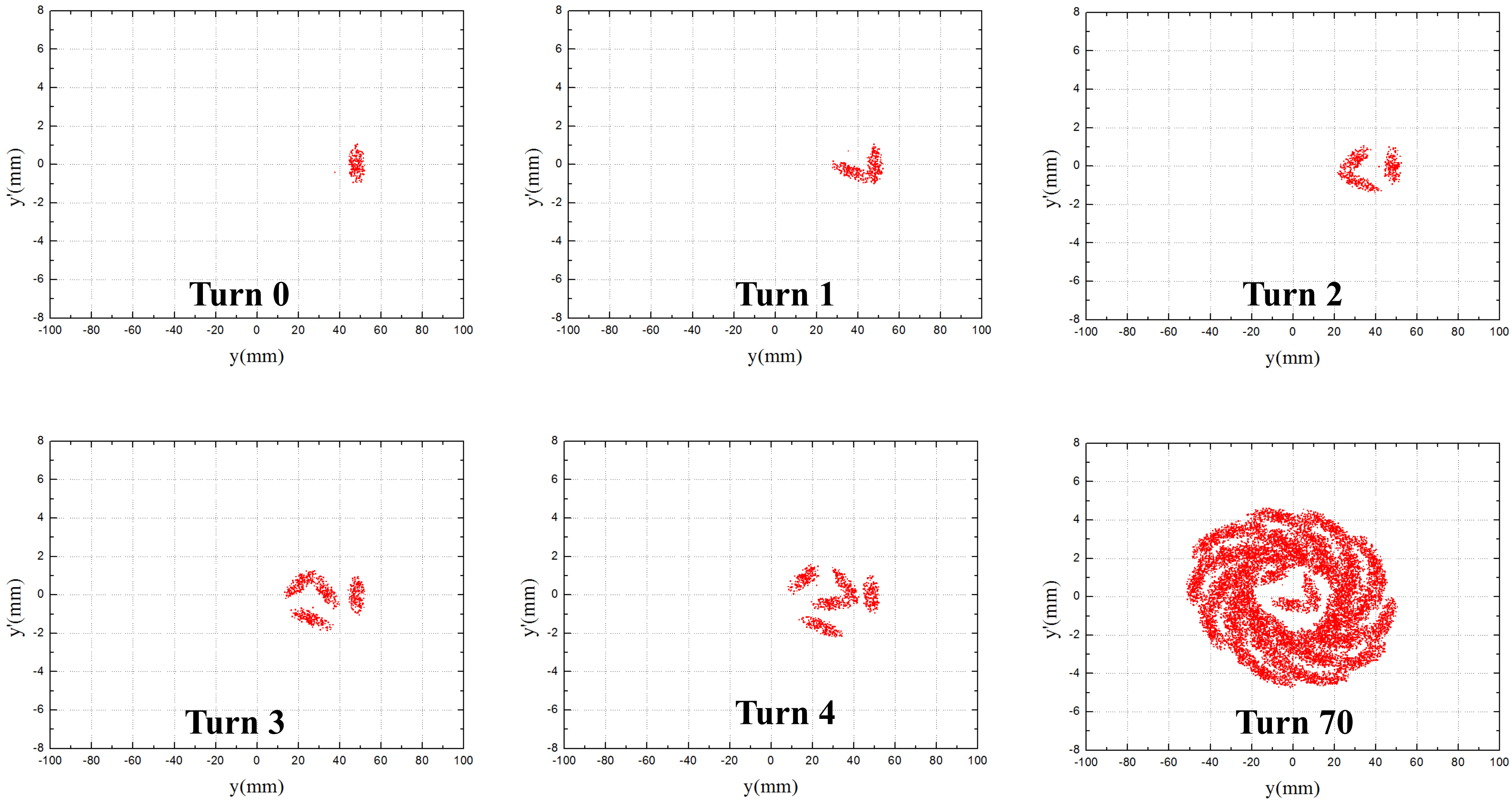
Particles injected per turn: 200
Total injection turn: 70

Simulation by modified ORBIT: X-X’



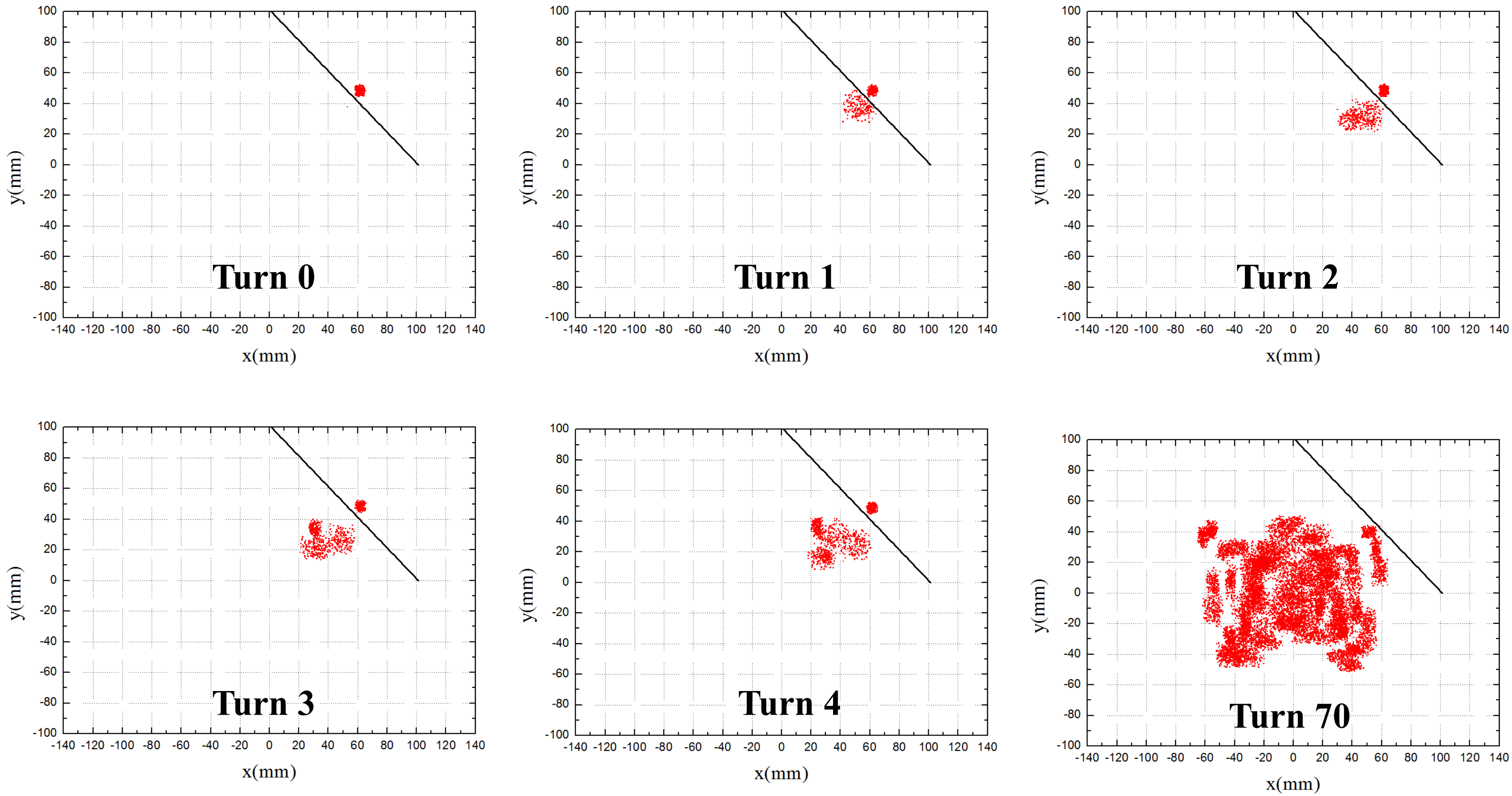
x-x’ phase space

Simulation by modified ORBIT: Y-Y’



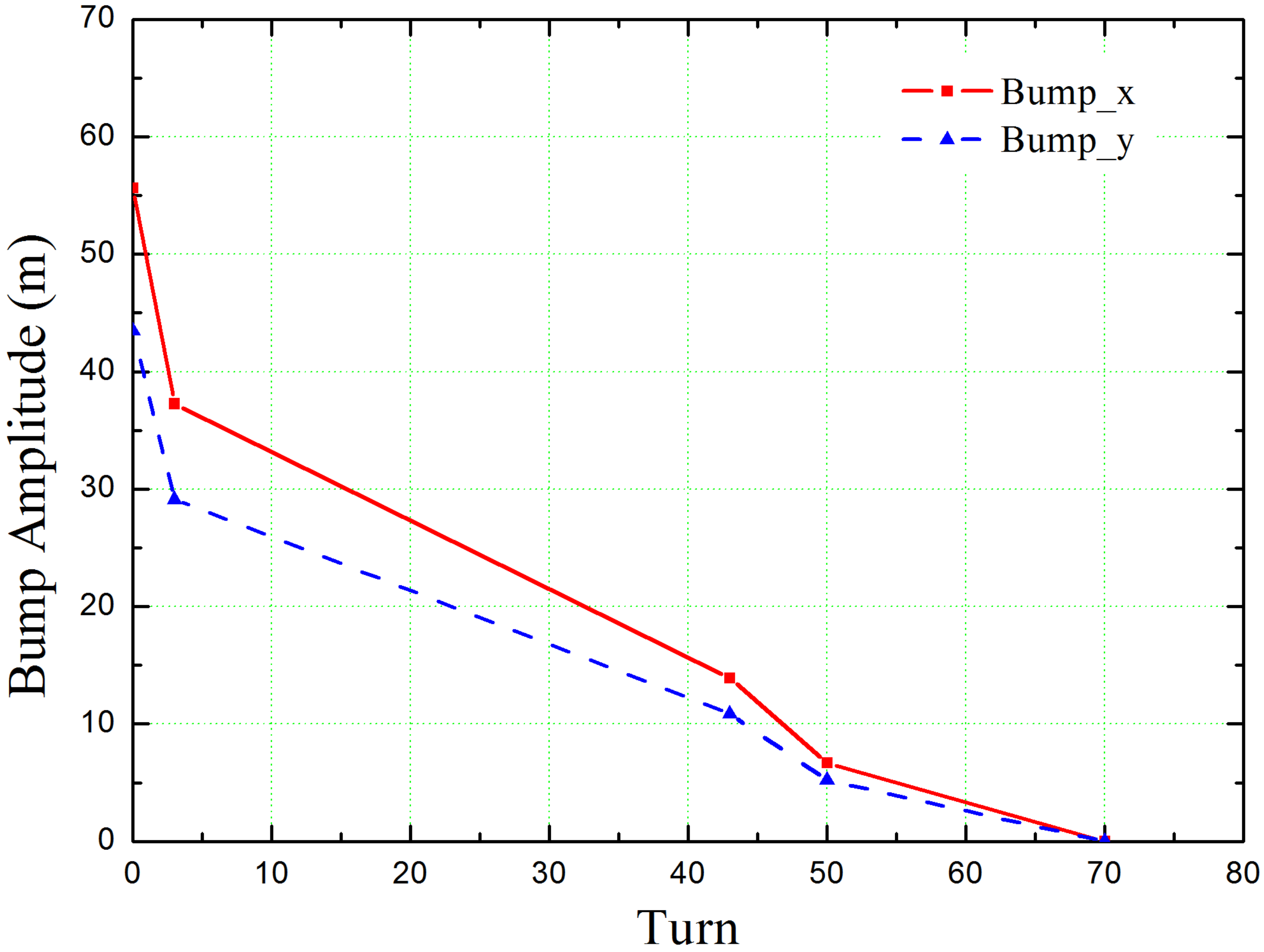
y-y’ phase space

Simulation by modified ORBIT: X-Y

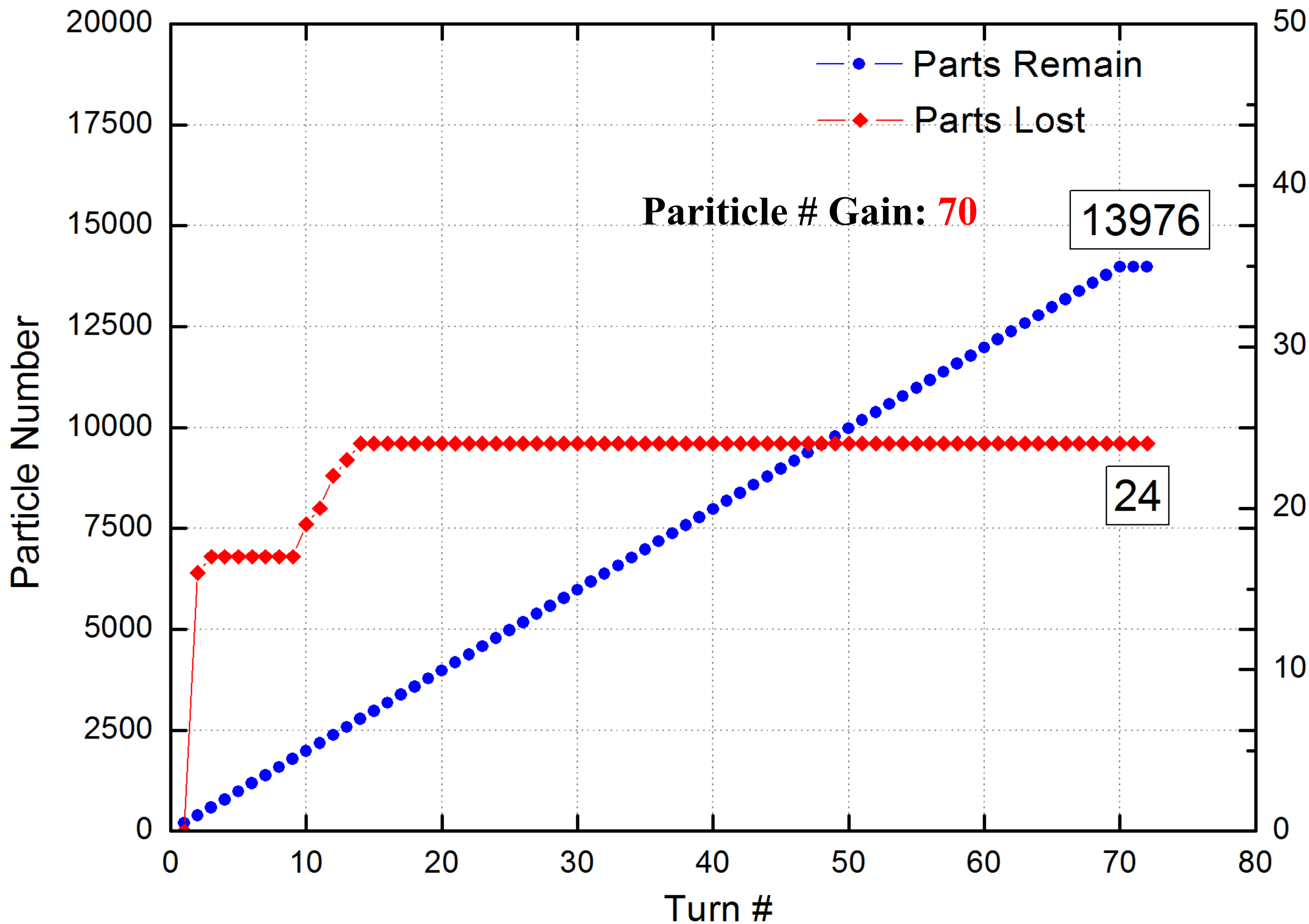


x-y real space

Simulation by modified ORBIT: Bump Function



Simulation by modified ORBIT: Particle Number



Parameters Optimization

Design objective of the injection system:

- **Maximize** the accumulation gain factor, i.e., maximum gain from the linac beam to the storage ring
- **Minimize** beam loss (on septum and acceptance)
- **Minimize** emittance dilution (saving the acceptance & cost)

Particle number and injection efficiency dependences:

F_part# = $F(\theta, Q_x, Q_y, \beta_{xm}, \beta_{ym}, \alpha_{xm}, \alpha_{ym}, x_{0inj}, y_{0inj}, x'_{0inj}, y'_{0inj}, \beta_{xi}, \beta_{yi}, \alpha_{xi}, \alpha_{yi}, CO_x(t), CO_y(t))$

F_efficiency = $F(\theta, Q_x, Q_y, \beta_{xm}, \beta_{ym}, \alpha_{xm}, \alpha_{ym}, x_{0inj}, y_{0inj}, x'_{0inj}, y'_{0inj}, \beta_{xi}, \beta_{yi}, \alpha_{xi}, \alpha_{yi}, CO_x(t), CO_y(t))$

Parameters: $\theta, Q_x, Q_y, \beta_{xm}, \beta_{ym}, \alpha_{xm}, \alpha_{ym}, x_{0inj}, y_{0inj}, x'_{0inj}, y'_{0inj}, \beta_{xi}, \beta_{yi}, \alpha_{xi}, \alpha_{yi}$

Functions: $CO_x(t)$, $CO_y(t)$

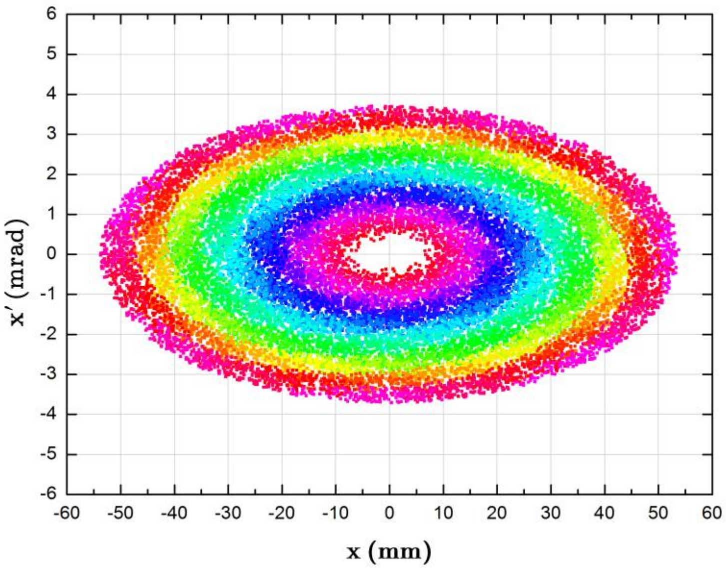
Optional functions: $Q_x(t)$, $Q_y(t)$, $\beta_{xm}(t)$, $\beta_{ym}(t)$, $x_{0inj}(t)$, $y_{0inj}(t)$

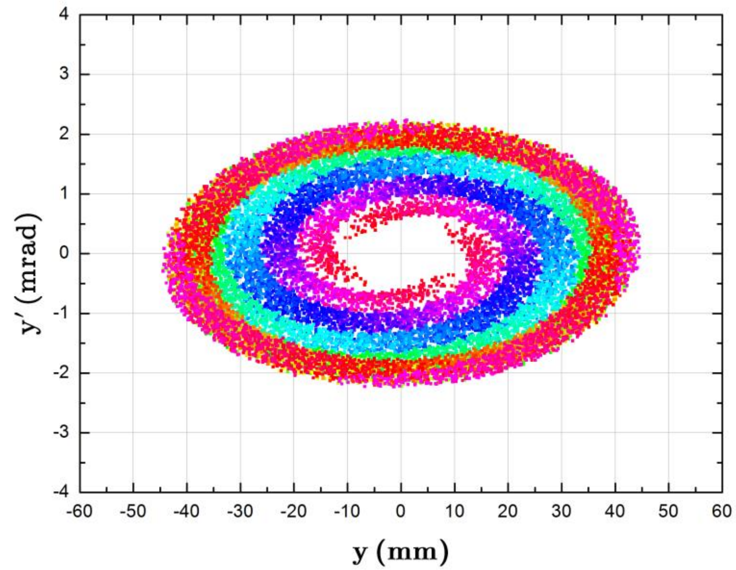
Particle swarm optimization algorism

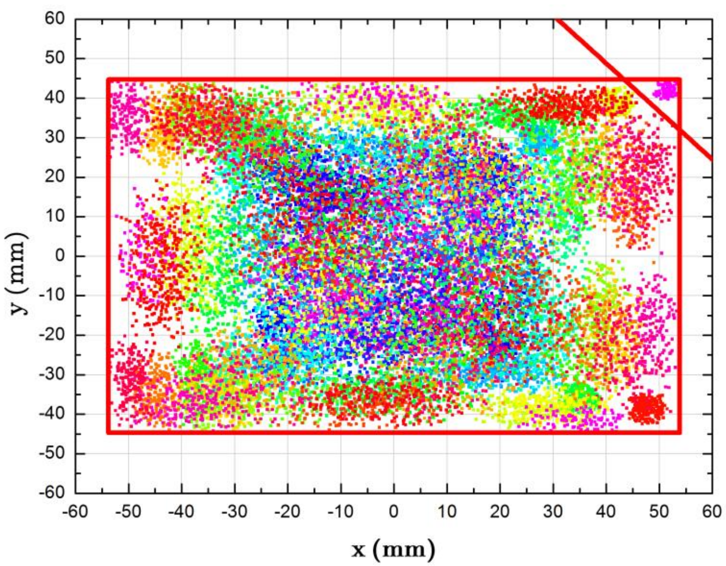
The basic concept:

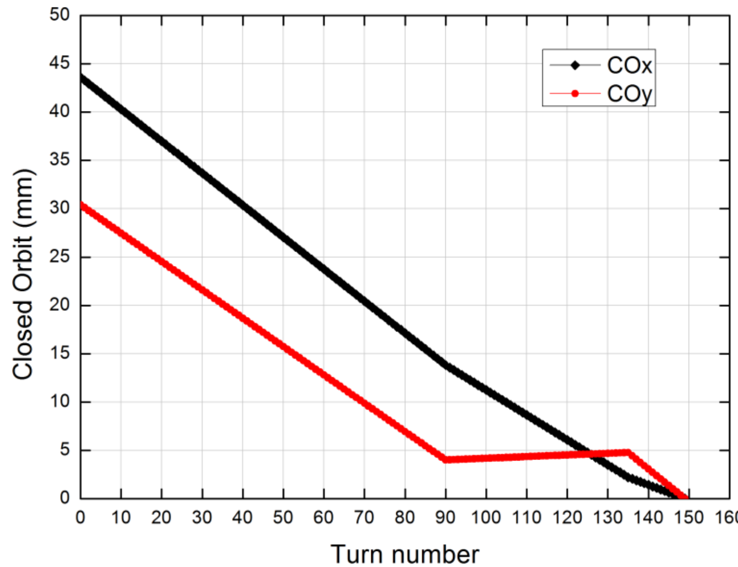
- Every solution finder are treated as a bird or fish, called **Particle**
- Every particle has its own **Memory**
- Every particle assess the goodness of its position according to the **Fitness Function**
- Every particle moves a certain distance towards a specific direction by **Velocity Function**

150 turn injection with PSO

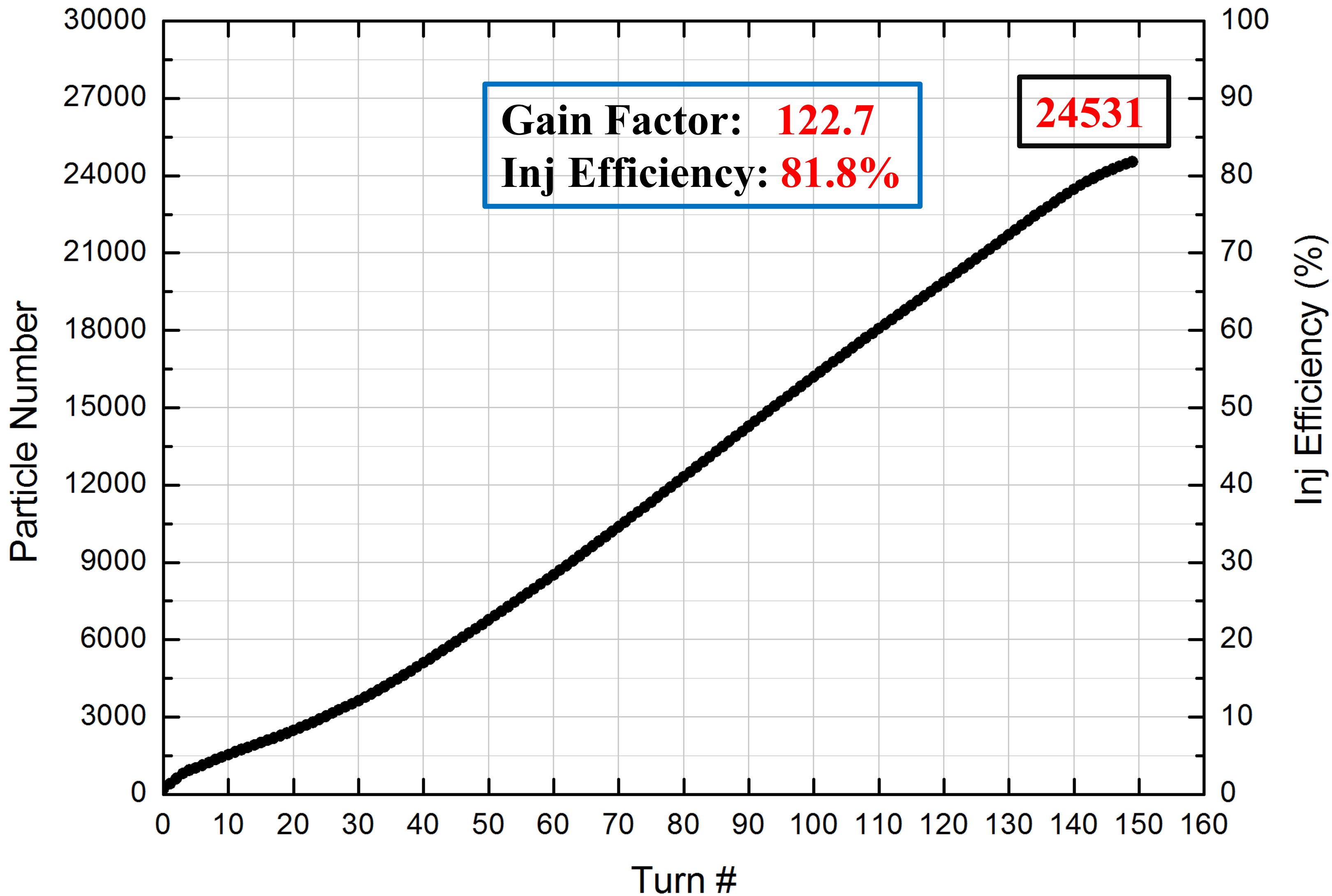








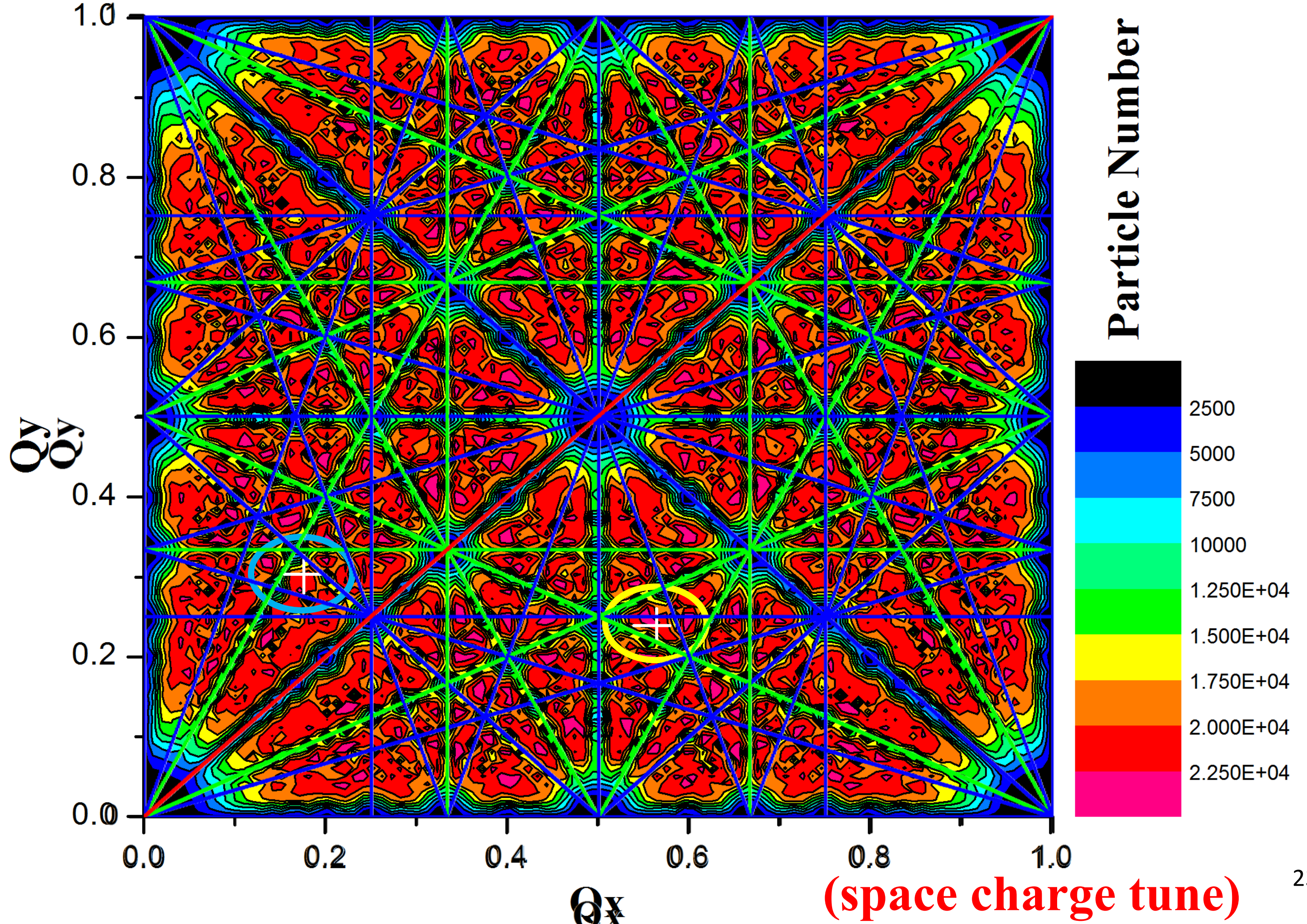
150 turn injection with PSO



Parameters of 150 turns' injection

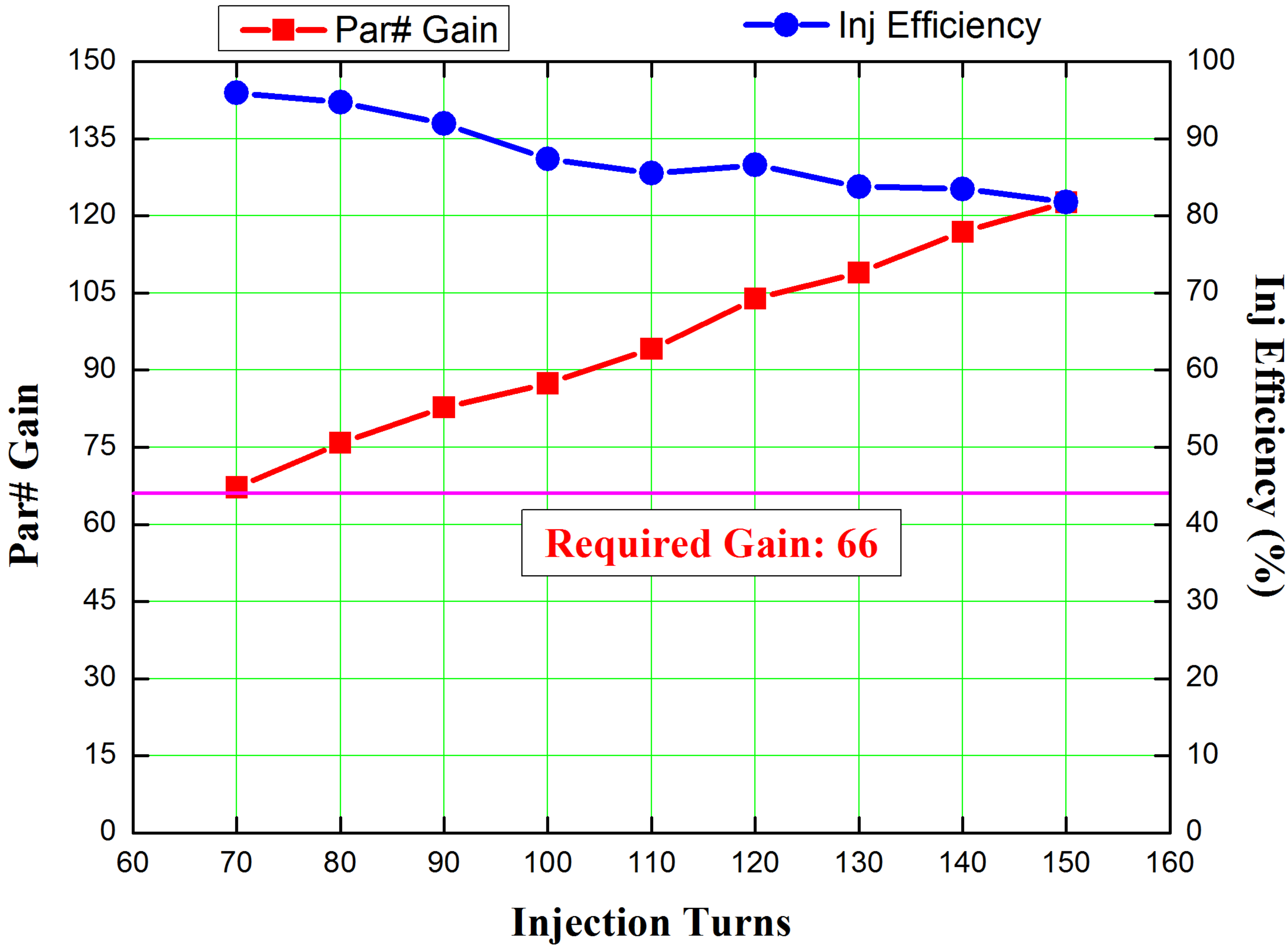
Parameter	Horizontal	Vertical
ES tilt angle	51.6°	
ES Position (mm)	48.3	38.7
Incoming beam position (mm)	52.4	43.3
Incoming beam size (mm)	8.2	9.2
Initial closed orbit (mm)	43.6	30.4
Tune	8.56	8.24
β function of the ring (m)	14.47	20
α function of the ring	-0.0085	-0.0477
β function of the injection line (m)	3.4	4.2
α function of the injection line	0.0694	0.0857

Tune choosing @ 150 turns' injection

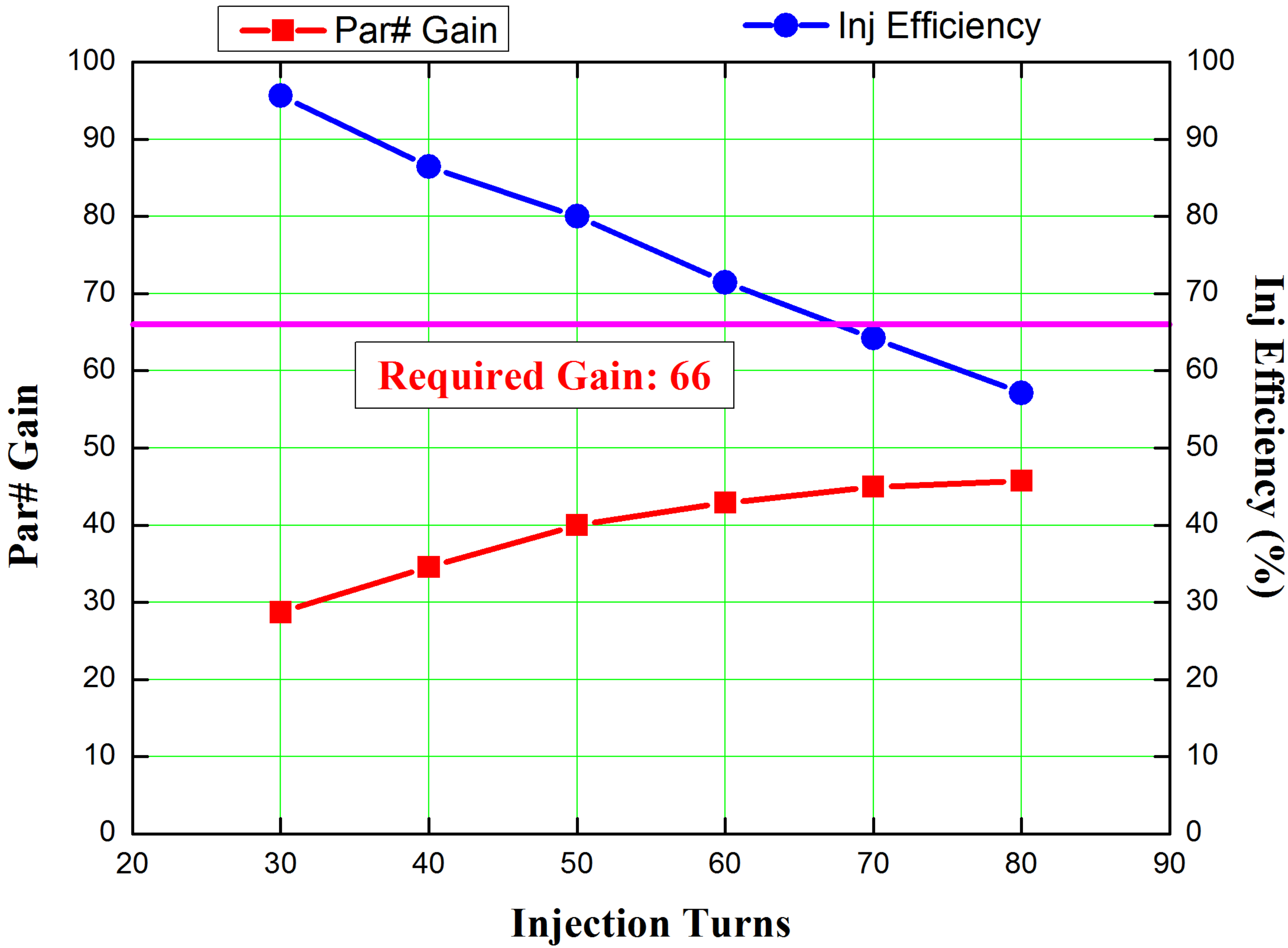


(space charge tune)

Gain and efficiency for different injection turns



Single-plane injection

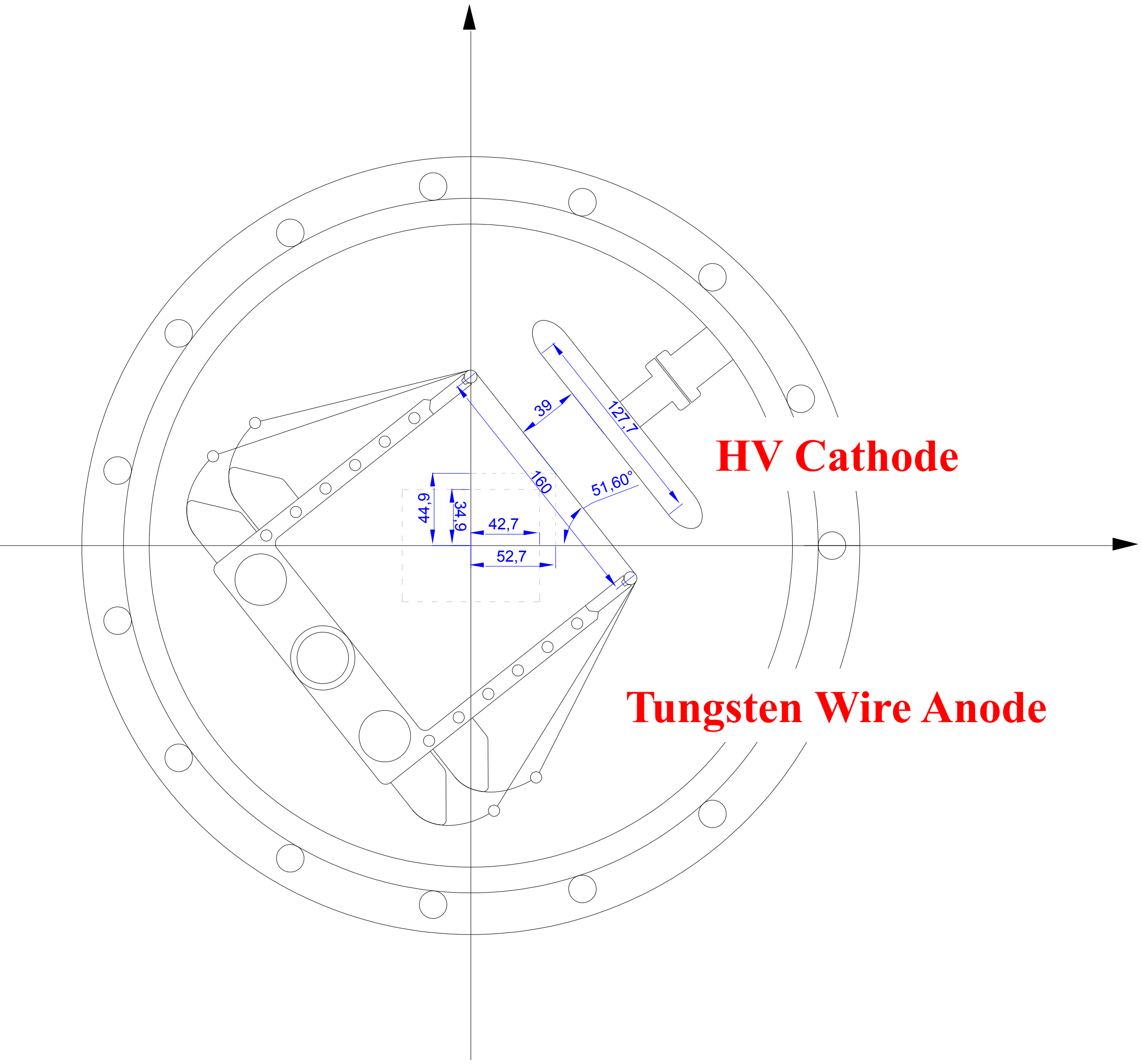


Key devices consideration

Special devices required by the two-plane painting injection scheme

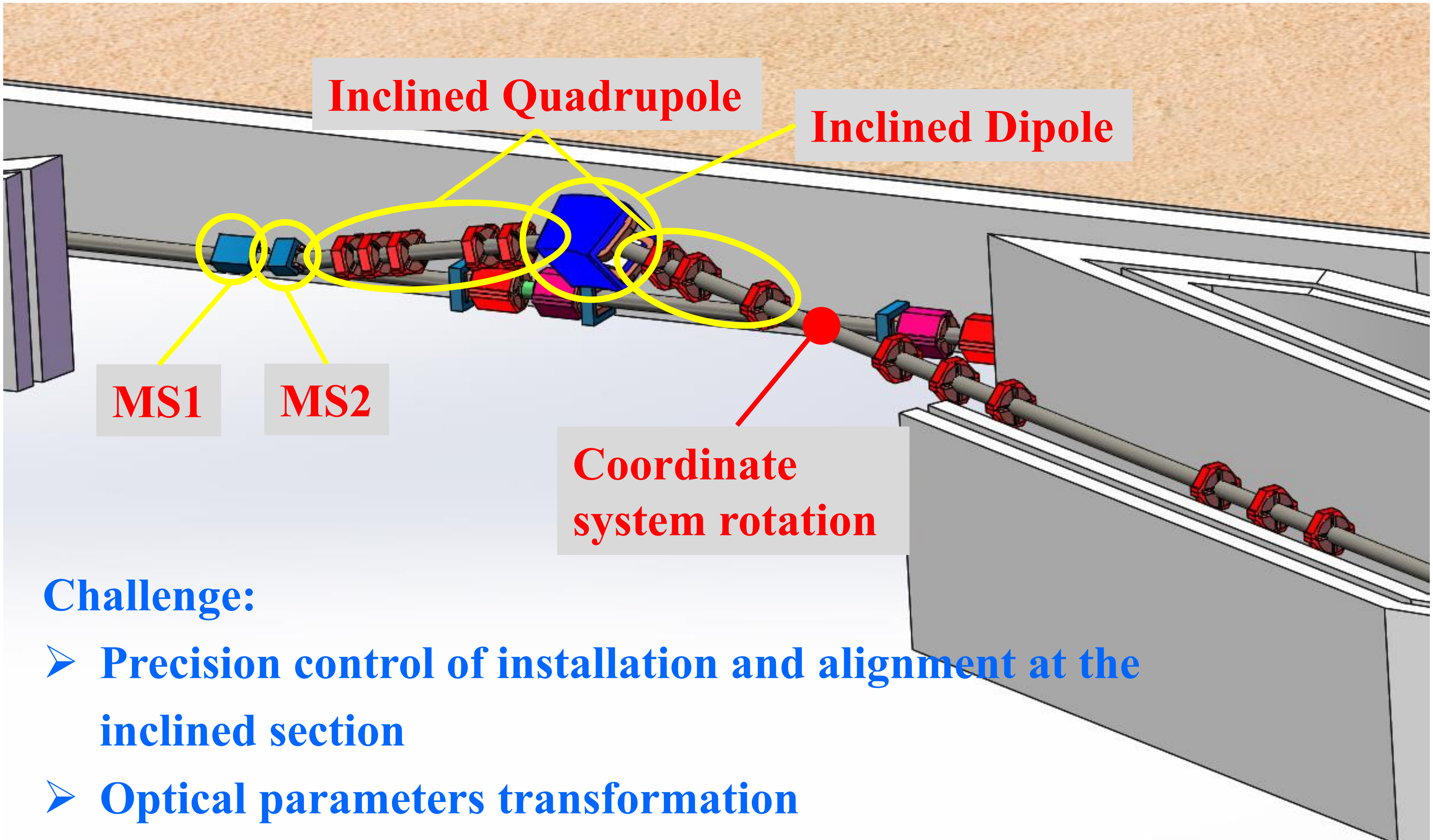
- Tilted electrostatic septum
- Inclined injection beam transfer line
  - Inclined quadrupole
  - Inclined dipole
- High precision bump magnets power supply

Prototype of key device – Tilted e-septum



Effective length	1.5m
Tilt angle	51.6°
Tilt angle adjustable range	±10°
Tilt angle measurement / adjustment precision	0.1° / 0.5°
Cathode / Anode position adjustable range	±15mm
Gap between electrodes	39mm
Electrical field strength	20kV/cm
Voltage	90kV

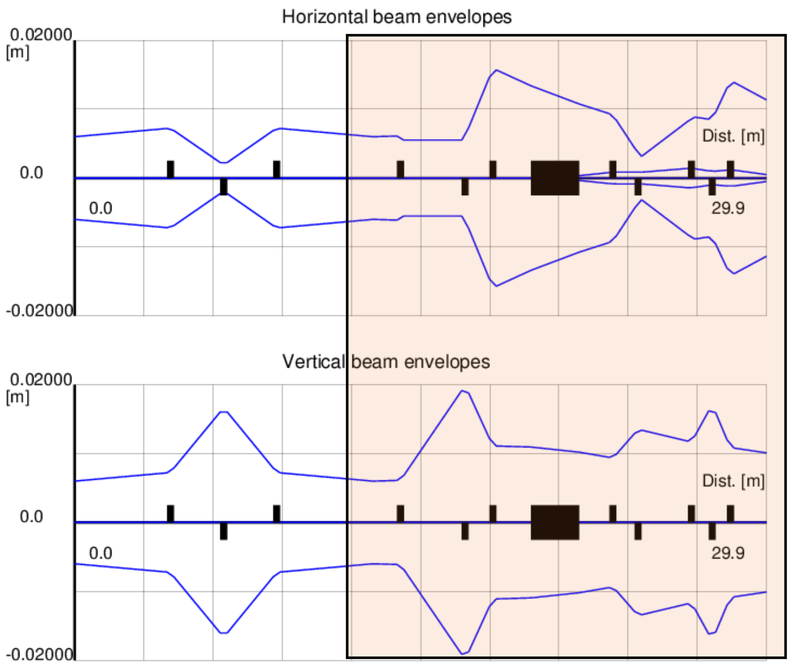
Injection beam transfer line



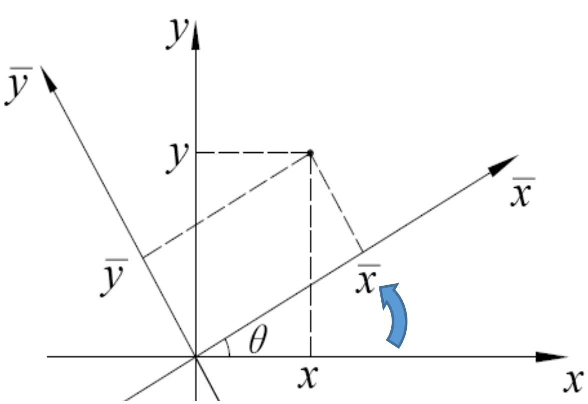
Challenge:

- **Precision control of installation and alignment at the inclined section**
- **Optical parameters transformation**
- **Dispersion control**

BRing injection transport line

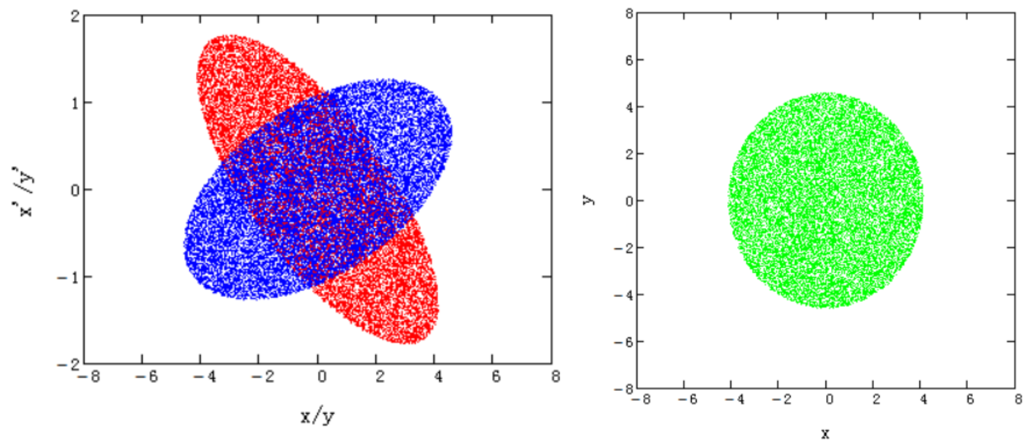


Note: Linear optics

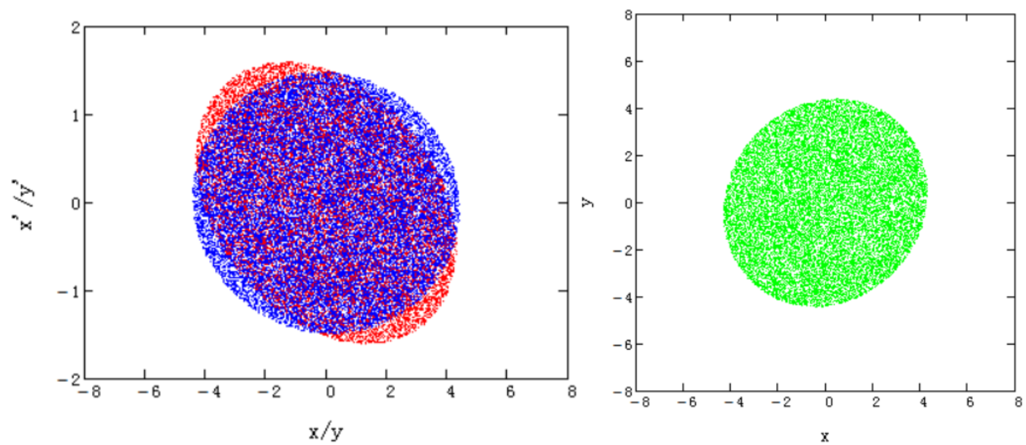


Coordination system rotation

Before rotation



After rotation



Summary

- 1. Discussed the necessity of 2-D painting injection
- 2. Designed the injection orbit
- 3. Done the simulation modified ORBIT
- 4. Optimized the injection parameters with PSO algorism
- 5. According to the optimization results, an acceptance of 200×100 π mm $mrad^2$ can meet the particle number gain requirement

Future work

- 1. Find a better method to deal with the Bump function
- 2. Do the simulation and parameters optimization with space charge effect
- 5. High precision fast quadrupole: dynamically adjust the tune
- 6. High precision bump magnets power supply

Thank you for your attention

Any comments and suggestions are welcome