

Central Region Design of the HUST SCC250 Superconducting Cyclotron

Zhijie, ZENG



Content

- 1、 Introduction
- 2、 Central region design
- 3、 Beam dynamics
- 4、 Conclusions

1 Introduction

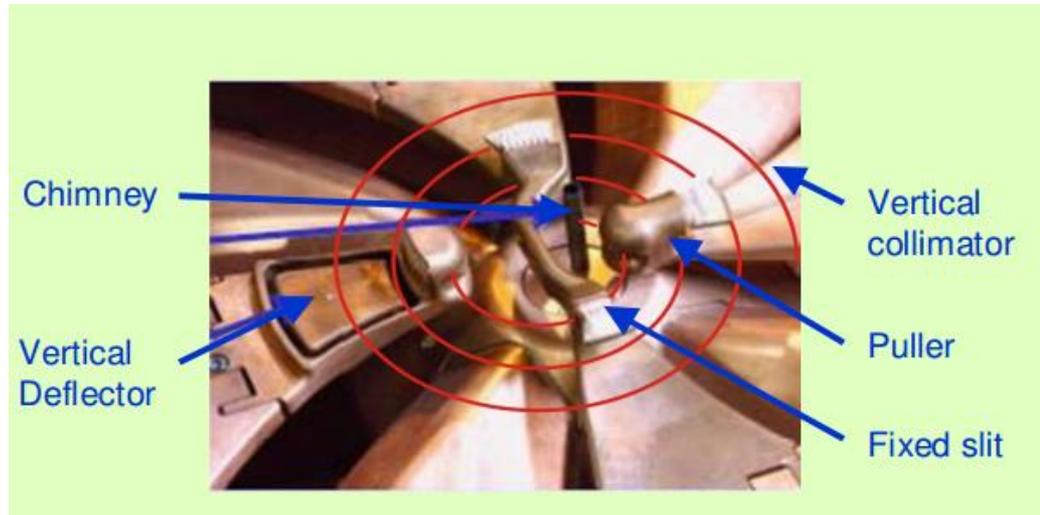
- **Proton therapy** has shown advantages in treating several kinds of cancer and has become a **favorable treatment option** for patients.
- At 2016, we decided to develop a **superconducting cyclotron based proton therapy facility** in the National Key Research and Development Program.
- The superconducting cyclotron HUST-SCC250,
Advantage: minimizing the size,
Difficulty: compact **central region**.



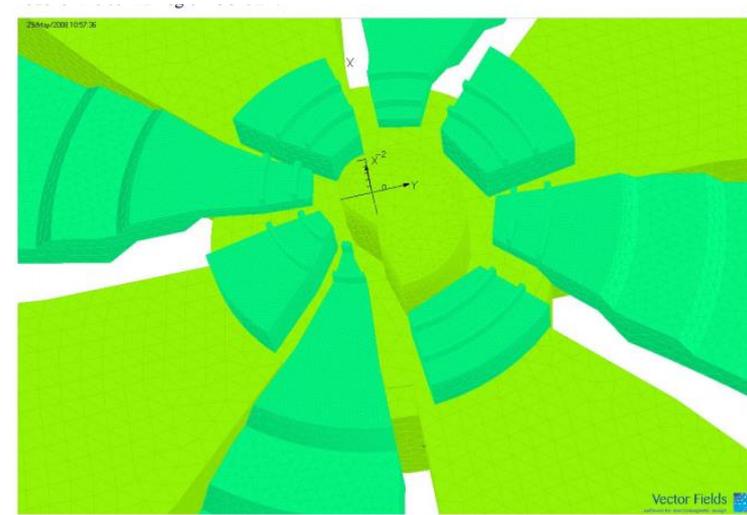


2 Central region design

2 Central region design



PSI



SCENT300

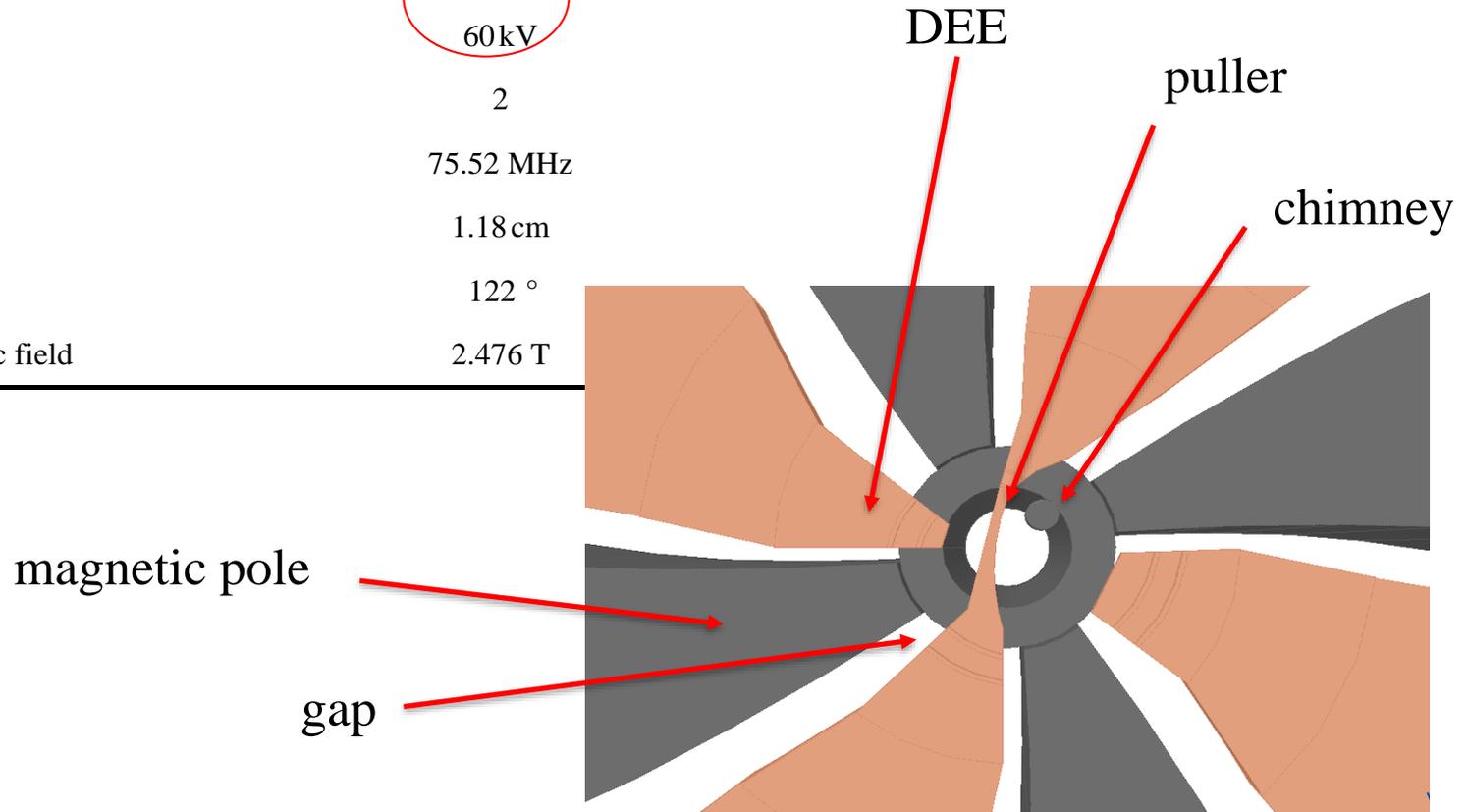
- One of the challenging design tasks of a superconducting cyclotrons is the **central region**.
- The **initial proton orbits** are crucial in determining the properties of the final beam.

2 Central region design

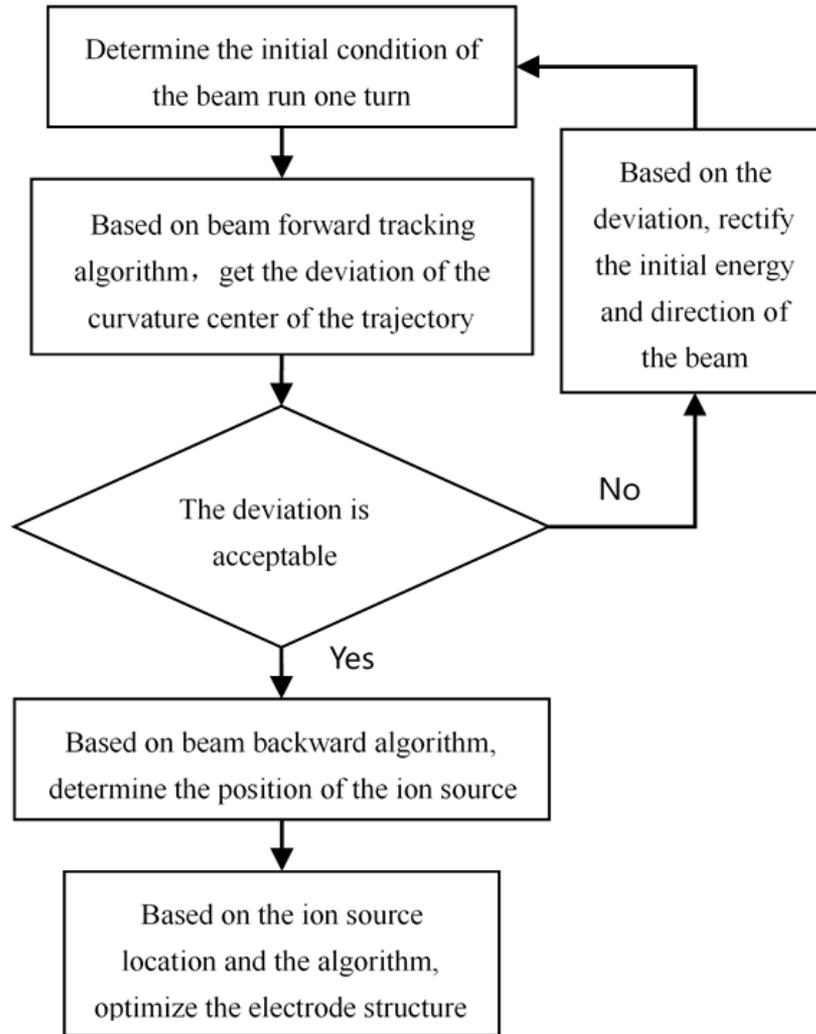
- Two main problems : the **axial motion** and **radial motion**.

Basic parameters

Parameters	Value
DEE width	50 °
DEE voltage	60kV
Harmonic mode	2
RF frequency	75.52 MHz
Injection radius	1.18 cm
Injection angle	122 °
Central magnetic field	2.476 T



2.1 Design process

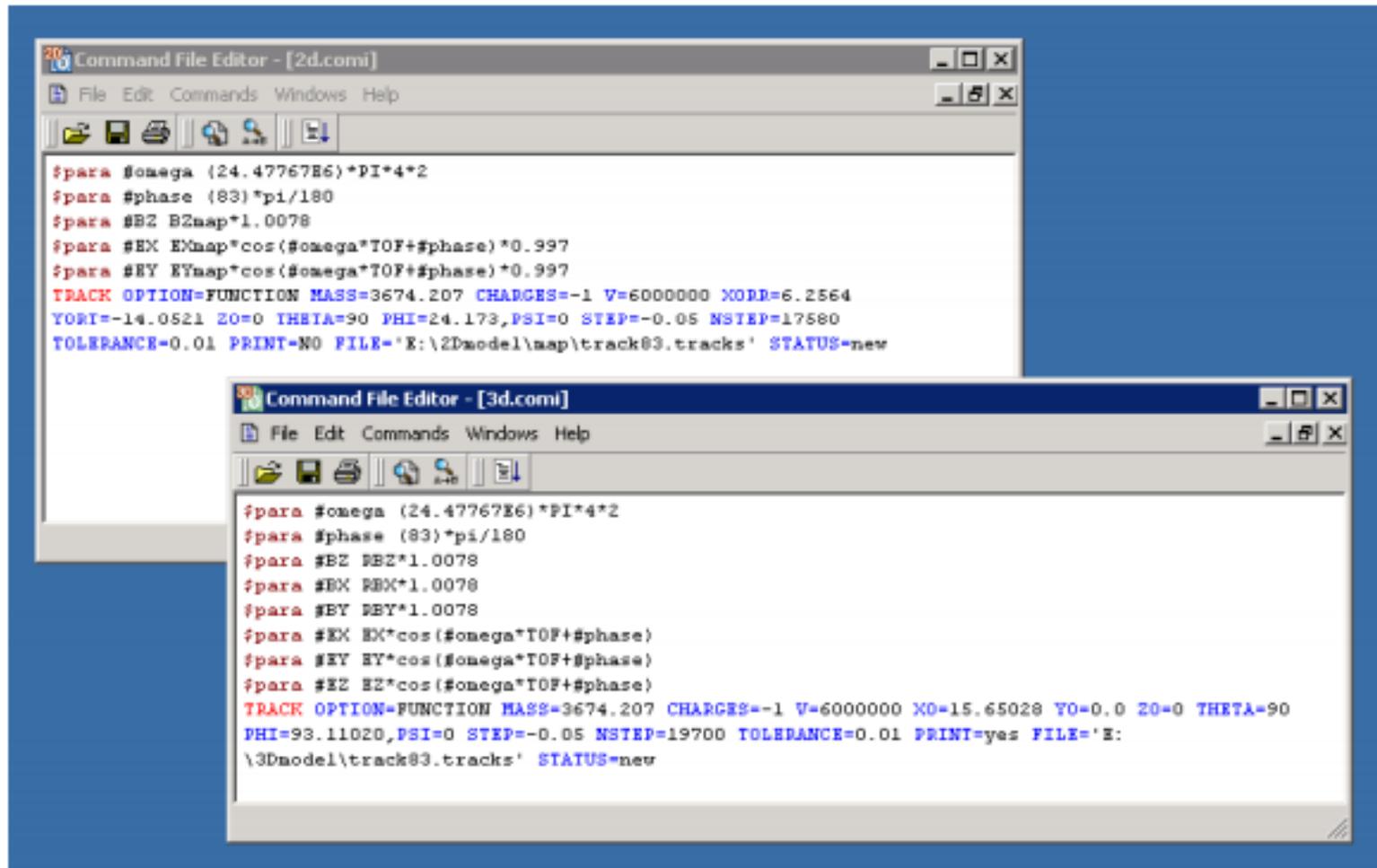


1. Choose a particle state on the **AEO**.
2. **Back tracking** to determine the position of the ion source.
3. **Forward tracking** to optimize the electrode structure.

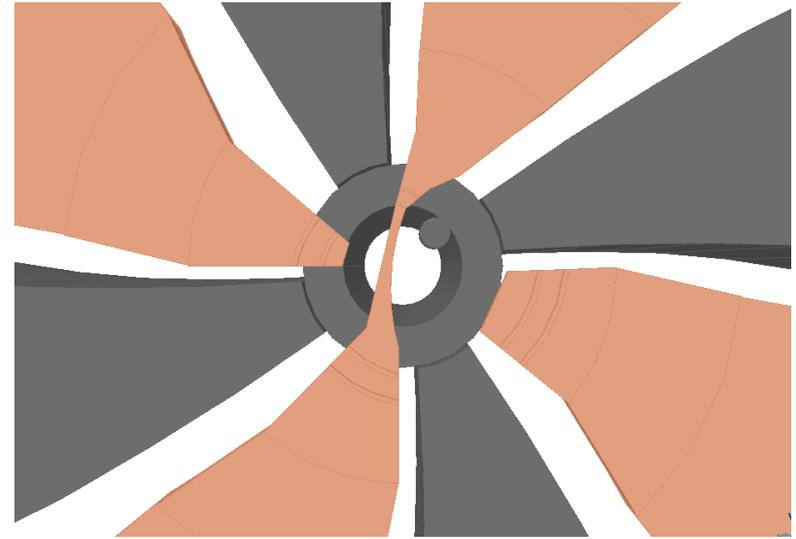
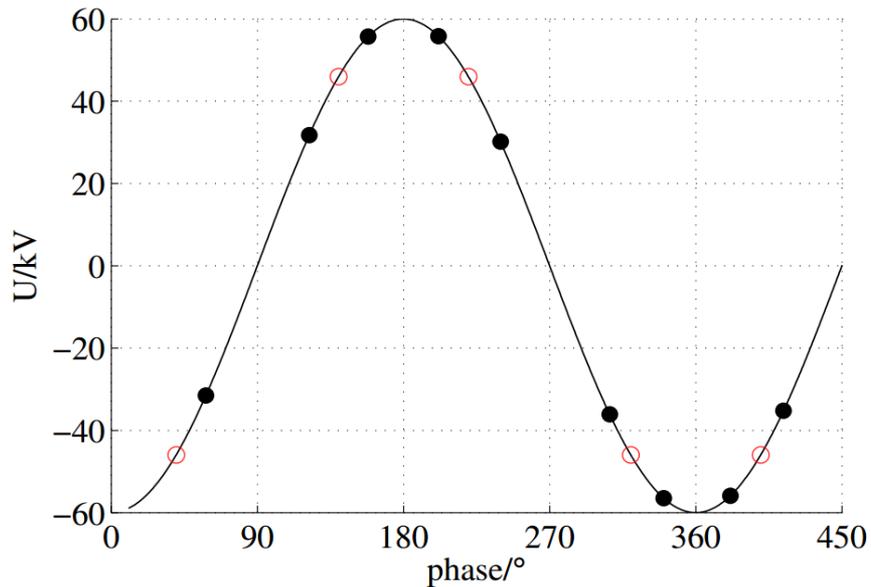
The beam tracking codes **Z3CYCLONE** and the **track command in OPERA** are both used in the design process.

2.1 Design process

Track command in OPERA

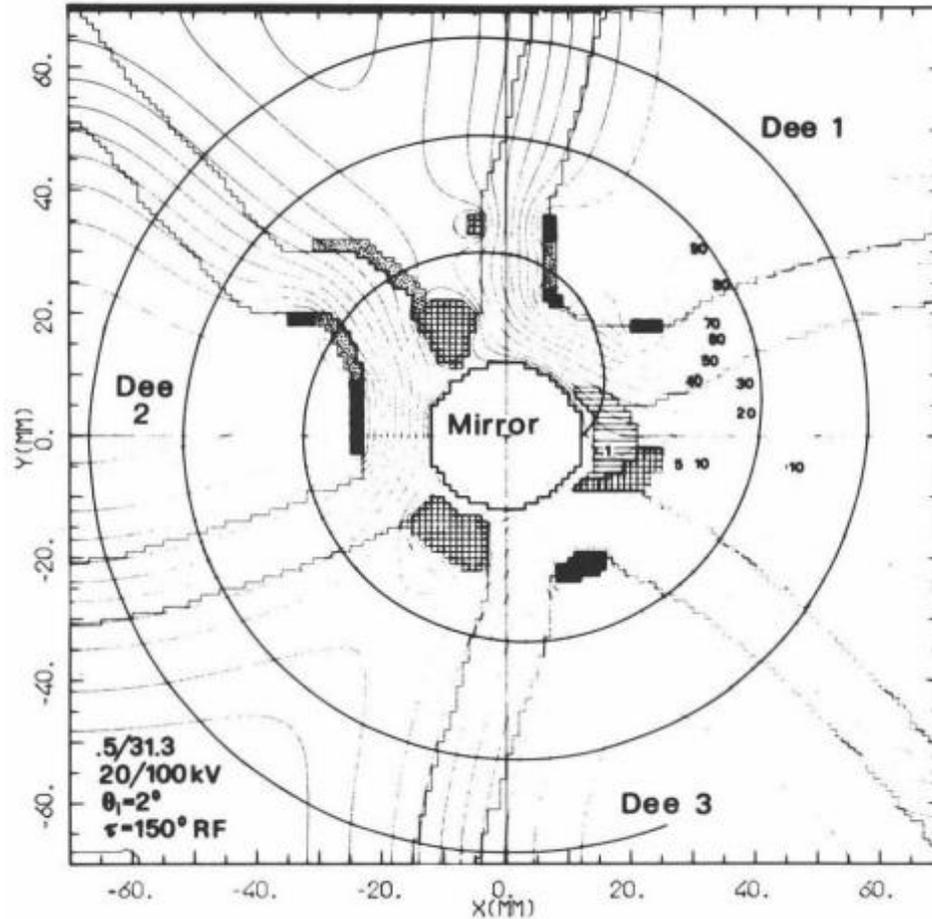


2.1 Design process



- the hollow circles marks the maximum energy gain.
- the solid circles marks the proton crosses the DEE boundaries.
- The electrode structure is revised precisely to adjust the RF phase the proton crosses the DEE boundaries.

2.2 Design tips

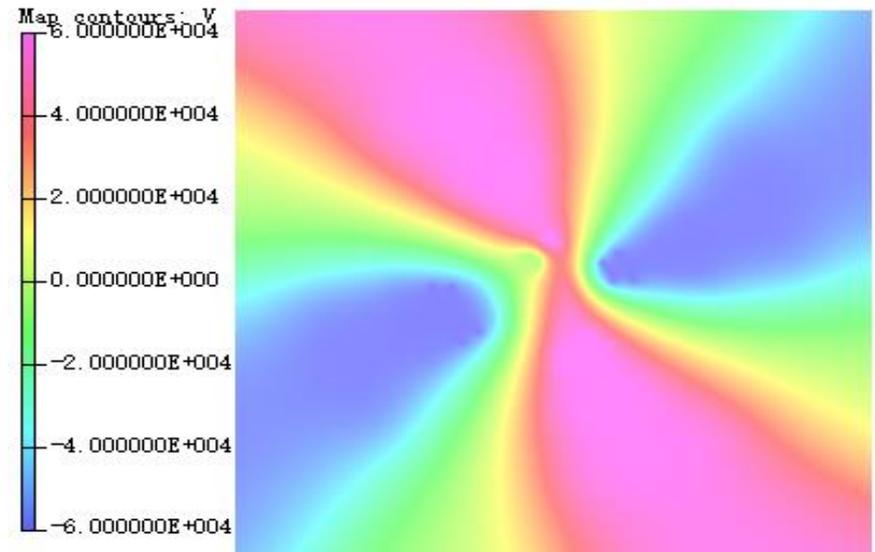
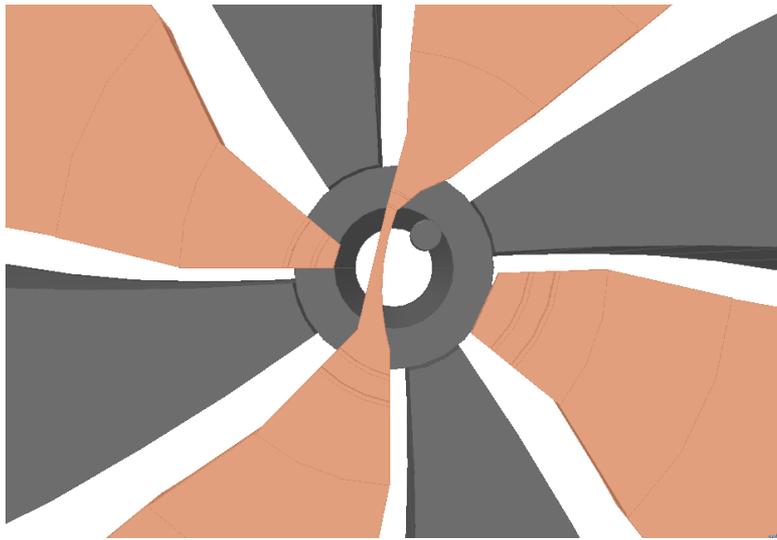


Milan

Increase axial Electric focusing

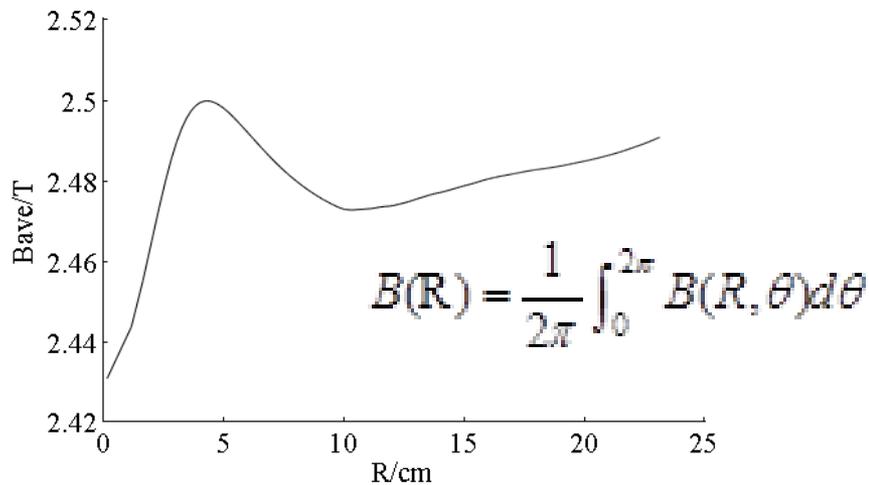
- Decrease the gap height
- Decrease the gap height only on the **entrance side**
- Place two symmetric pillars on the **exit side** of the gap

2.3 Electromagnetic distribution

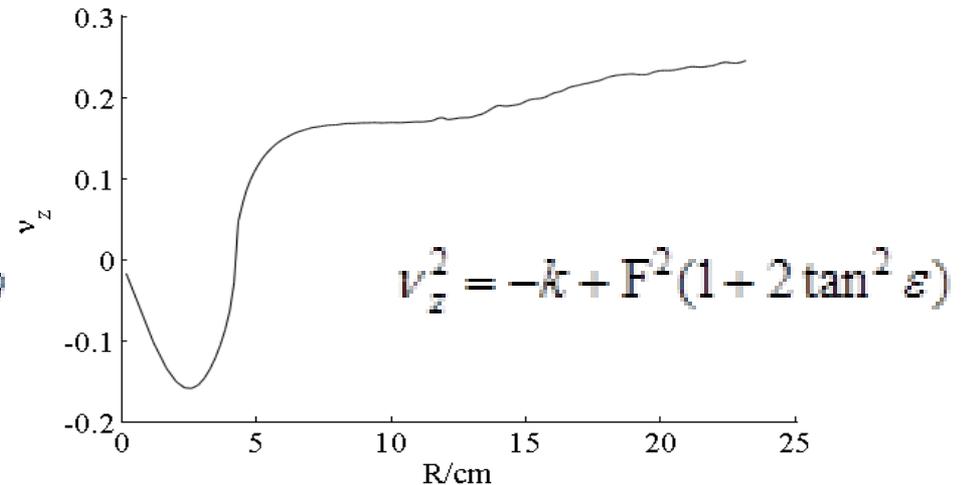


The electrode structure in the central region

Potential map of the central region



The average magnetic field distribution



The radial distribution of the vertical focusing tunes



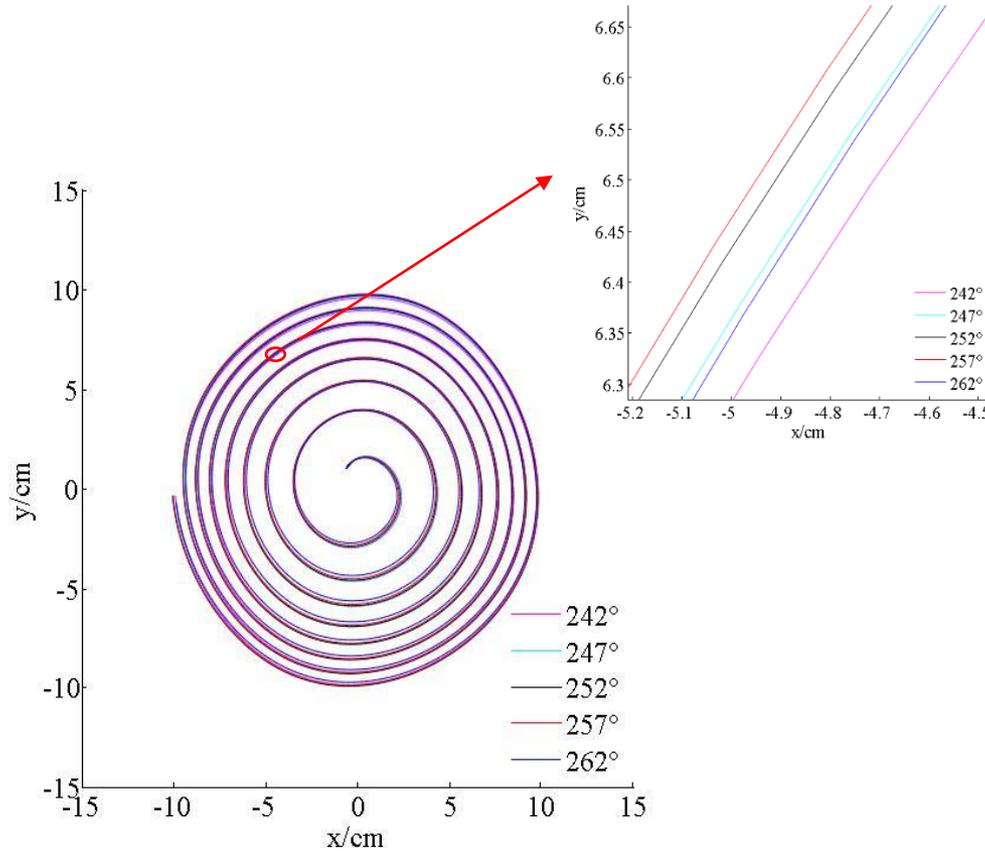
3 Beam dynamics

3.1 Single particle tracking

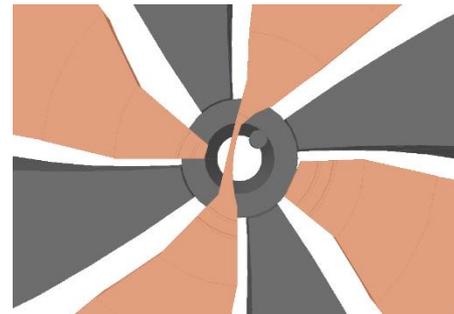
3.1.1 radial motion

Initial state

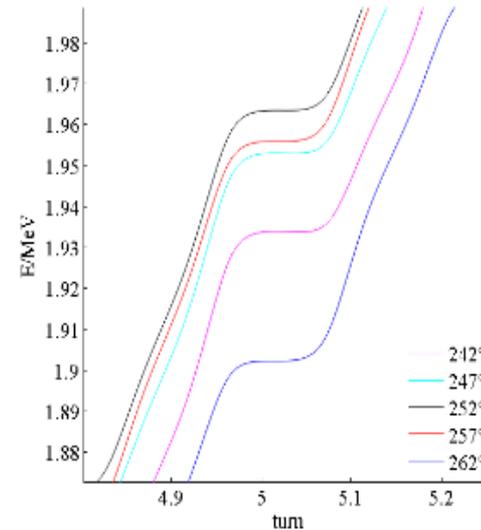
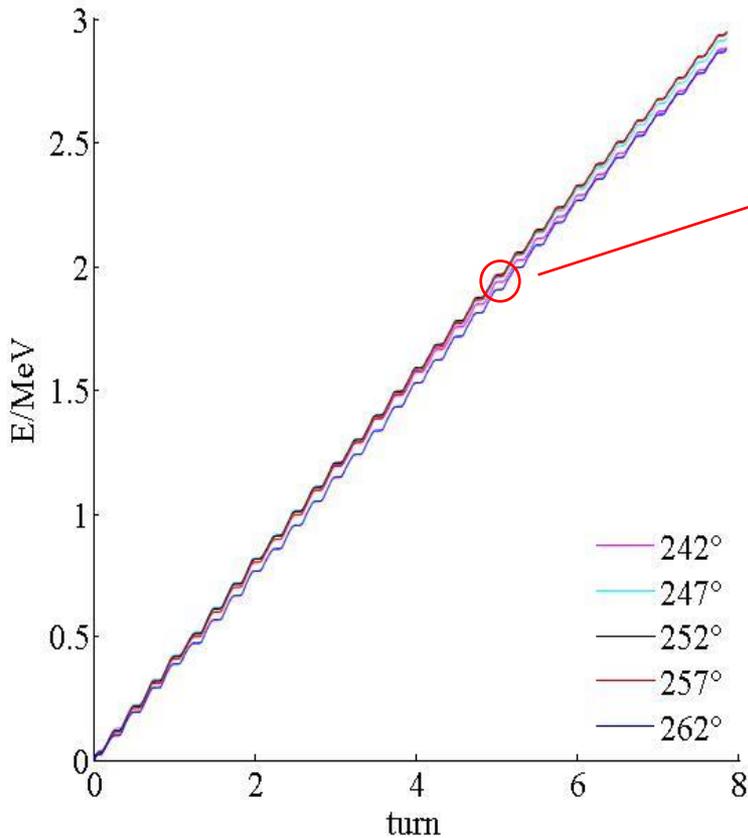
Parameters	Value
DEE width	50 °
DEE voltage	60kV
Harmonic mode	2
RF frequency	75.52 MHz
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The radial RF phase acceptance is about 20° , from 242° to 262° .



3.1.1 radial motion

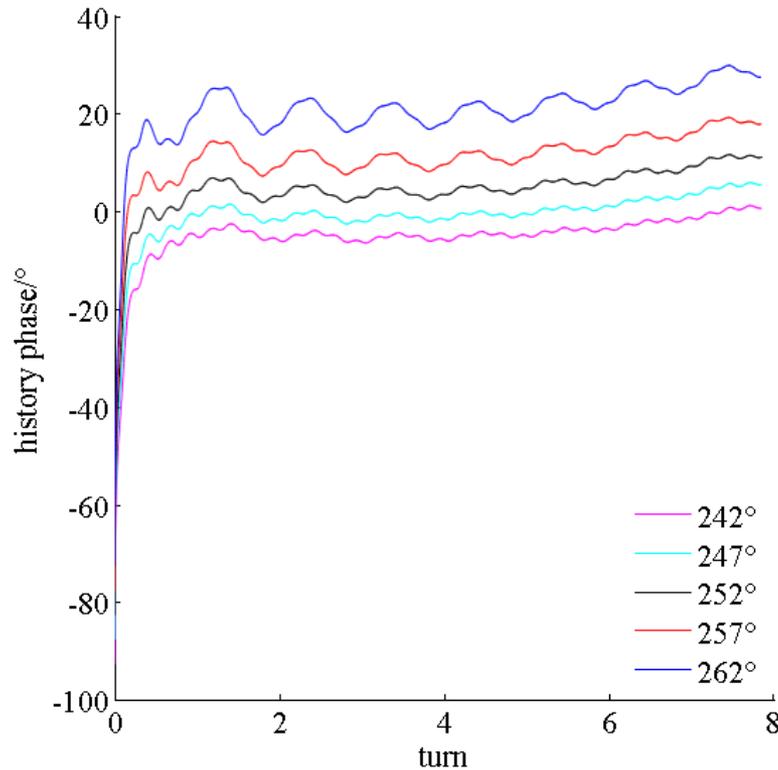


Theoretical energy gain per turn :

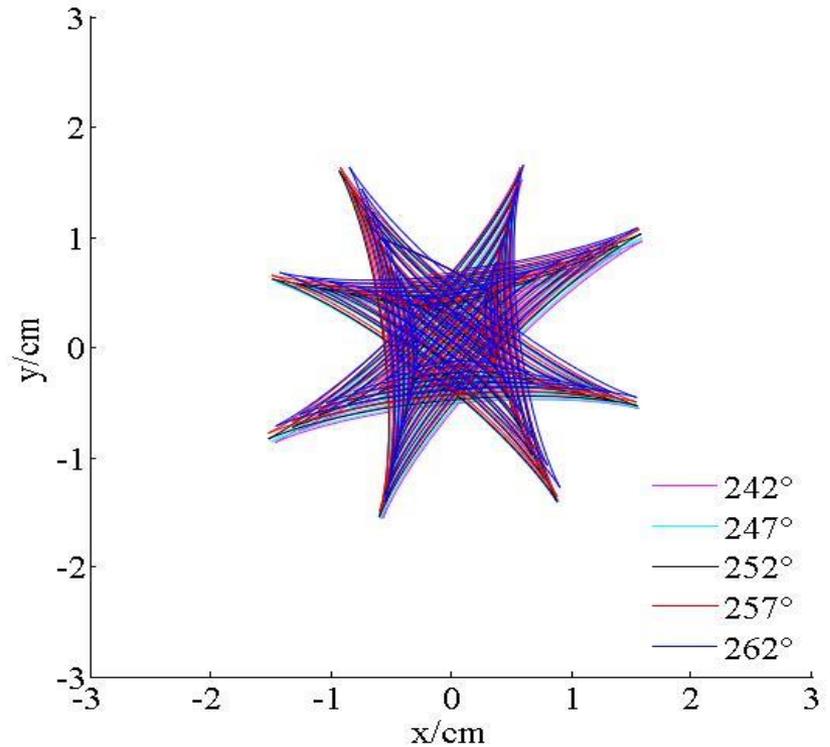
$$E_{\text{gain}} = n \cdot U_m \cdot \sin\left(\frac{\theta_D \cdot h}{2}\right) = 8 \times 0.06 \times \sin\left(\frac{50 \times 2}{2}\right) = 0.3677 \text{ MeV}$$

- maximum energy gain per turn : 0.35 MeV , 17.7 keV smaller.

3.1.1 radial motion



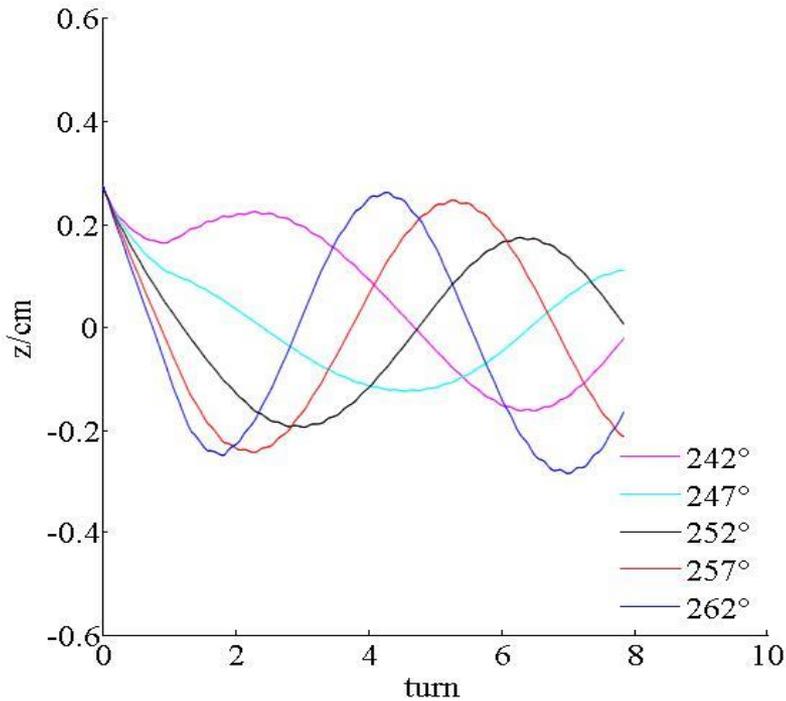
History phase



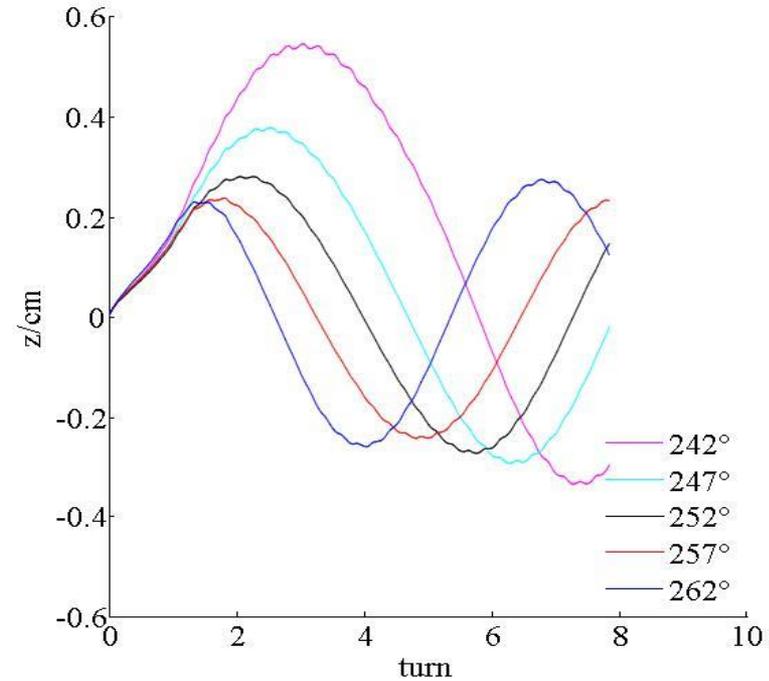
The instantaneous beam curvature center

- ✓ The **phase shift range** within 30° .
- ✓ The **deviation** less than 1.8cm.

3.1.2 Axial motion



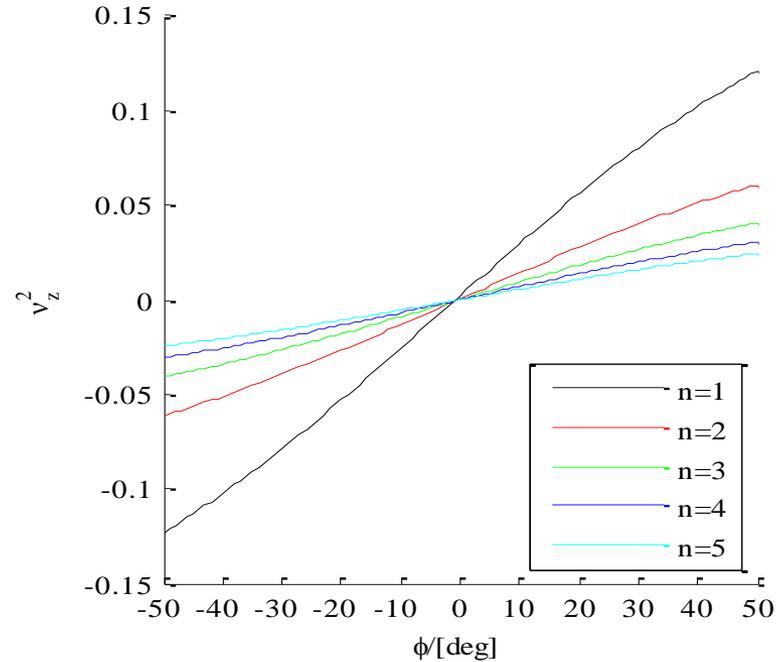
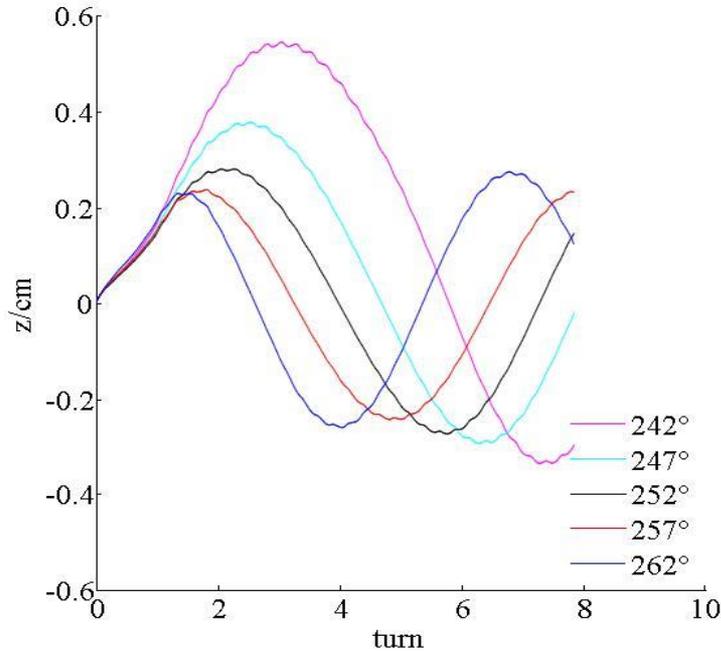
$z=0.275\text{cm}, p_z=0$



$z=0, p_z=0.0203\text{cm}$

- Ion source slit half height 0.275cm.
- Channel half height 0.45cm ($r \leq 5\text{cm}$), beam not lost.

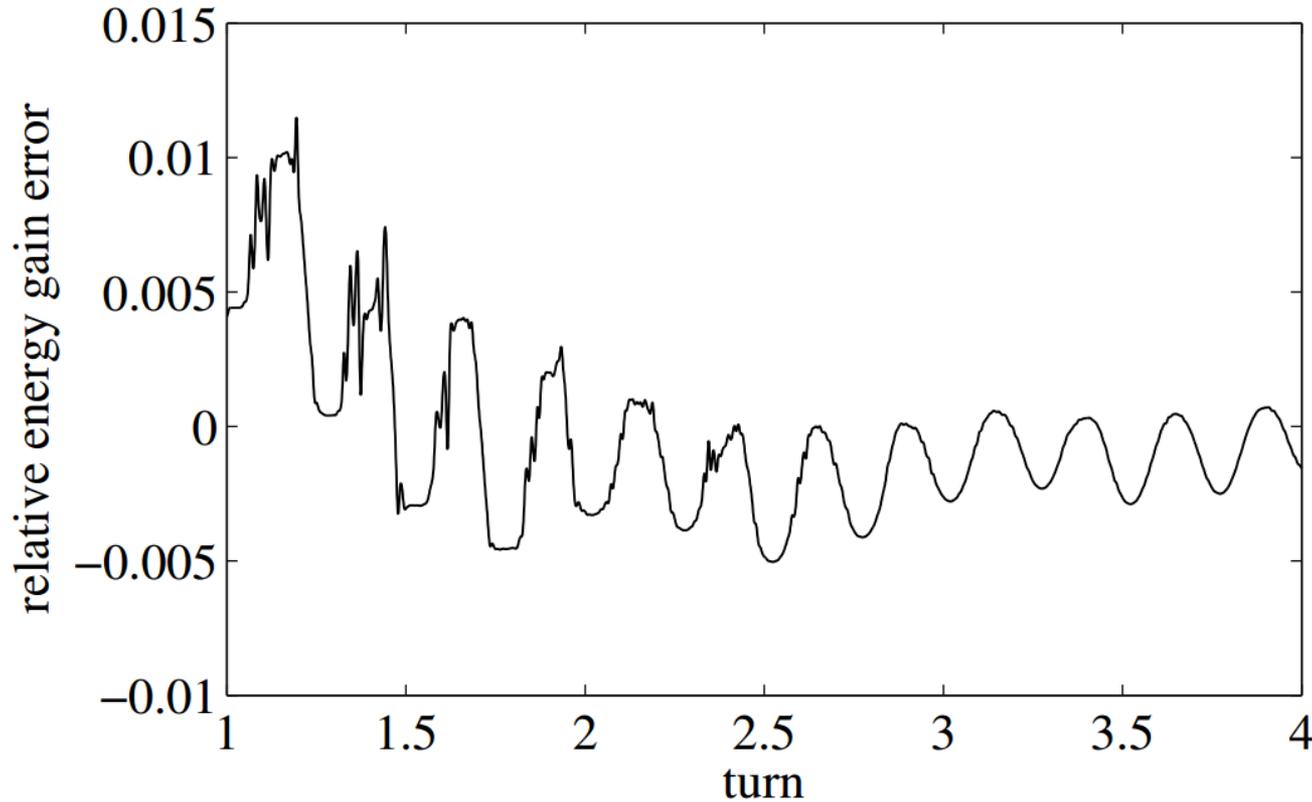
3.1.2 Axial motion



$$(v_z^2)_e = \left(\frac{h}{4\pi n}\right) \sin \varphi + \left(\frac{h}{8\pi n}\right)^2 \cdot \left(\cot^2\left(\frac{h\theta_D}{2}\right) \cos^2 \varphi - \sin^2 \varphi\right) \left(\frac{2\pi}{N_d} - \theta_D\right) \theta_D$$

The electric **axial focusing force** greater for **positive phases** beam.

3.1.3 Z3CYCLONE vs OPERA



Energy gain with Z3CYCLONE cross checked with track command in OPERA.

- ✓ Relative energy gain error **less than 1%**.

3.2 Multi-particle tracking

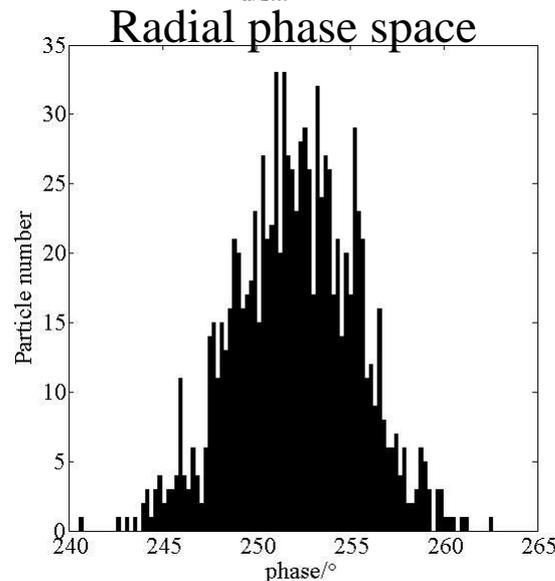
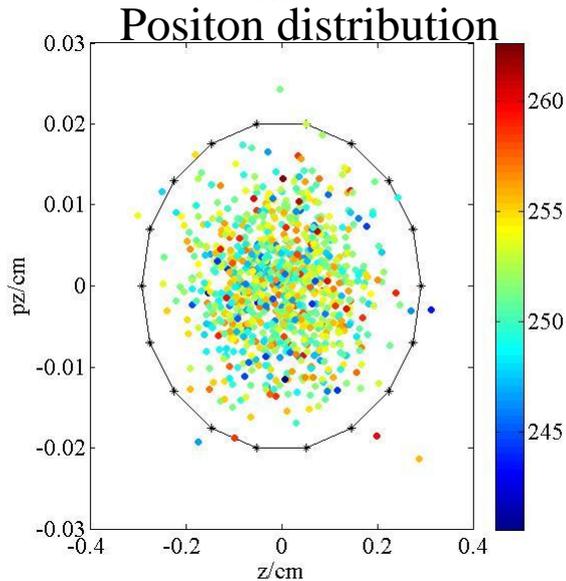
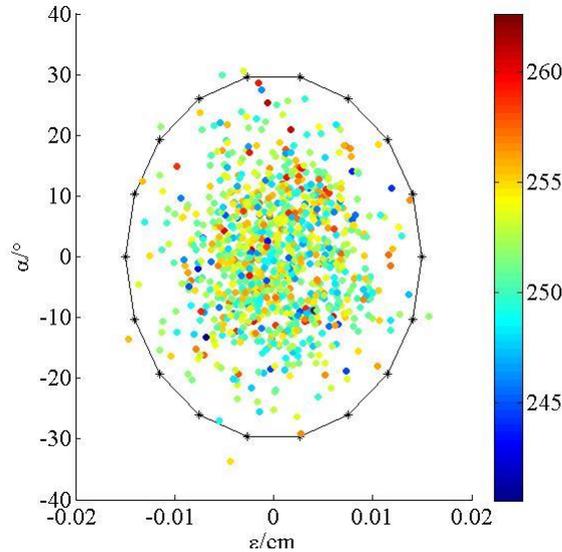
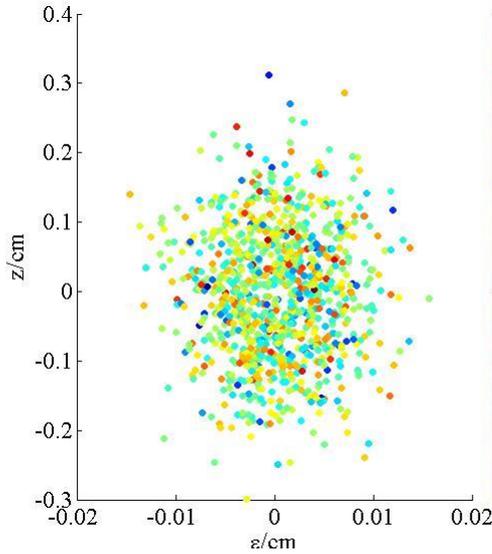
Initial particle parameters in **Gaussian distribution**.

Parameters	μ	σ
ε	0	0.015/3 cm
α	0	30/3°
z	0	0.274/3 cm
pz	0	0.02/3 cm
φ	252°	10/3°

- perpendicular to the ion source establish the **local coordinate system**.
- The ε and α are the x offset and the deflection angle in the local coordinate system respectively.

3.2 Multi-particle tracking

The initial particle state.



Parameters

**Gaussian
distribution**

parameters

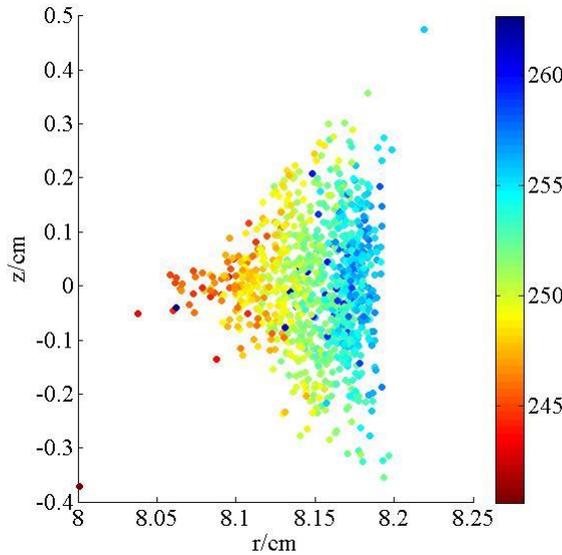
Parameters	μ	σ
ε	0	0.015/3 cm
α	0	30/3°
z	0	0.274/3 cm
p_z	0	0.02/3 cm
φ	252°	10/3°

Axial phase space

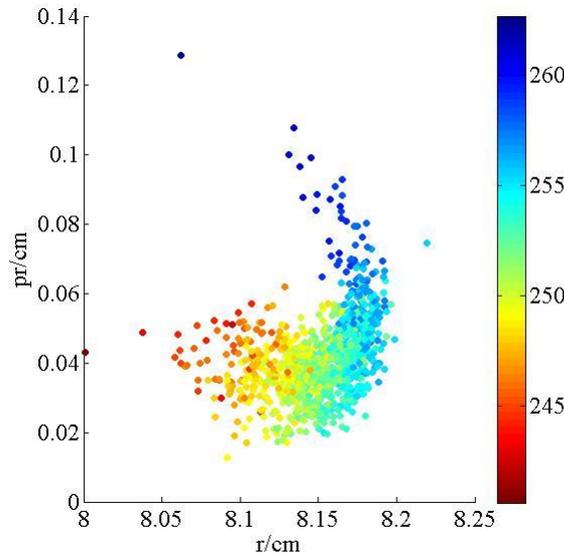
Phase distribution

3.2 Multi-particle tracking

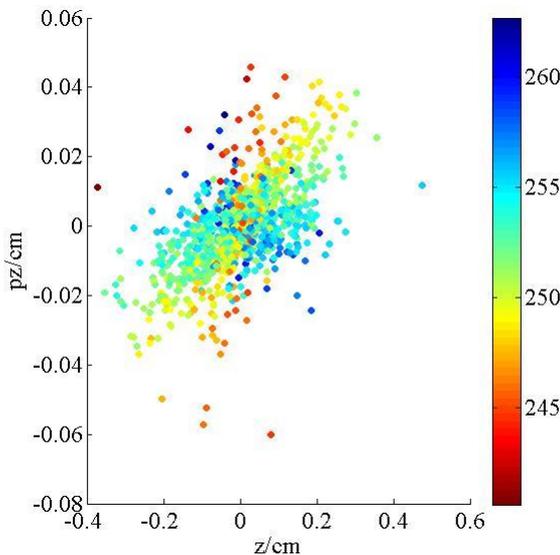
The beam state after 5 turns.



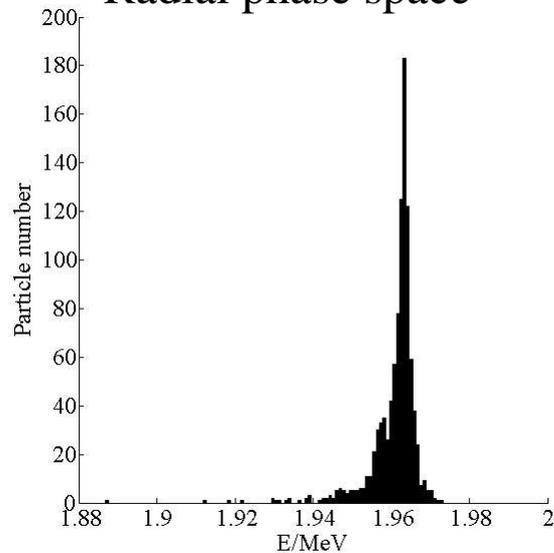
Position distribution



Radial phase space



Axial phase space



Energy distribution

- Most particles energies 1.96MeV.
- The **radial** motion of the **positive phase** particles is more unstable.
- The **axial** motion of the **negative phase** particles is more unstable.

4 Conclusions

- The compactness of the superconducting cyclotron HUST-SCC250 makes the design difficult.
- The central region is optimized iteratively by using several softwares, **SOLIDWORKS**, **OPERA** and **Z3CYCLONE**.
- The optimal parameters are as follows, the **phase acceptance** is about 20° , the maximum **deviation** between the instantaneous beam curvature center and the center of the cyclotron is controlled within 1.8cm.



Thanks for your attention!