大阪大学　核物理研究センター

CONCEPTUAL DESIGN OF CENTRAL REGION FOR HIGH-TEMPERATURE SUPERCONDUCTING SKELETON CYCLOTRON (HTS-SC)

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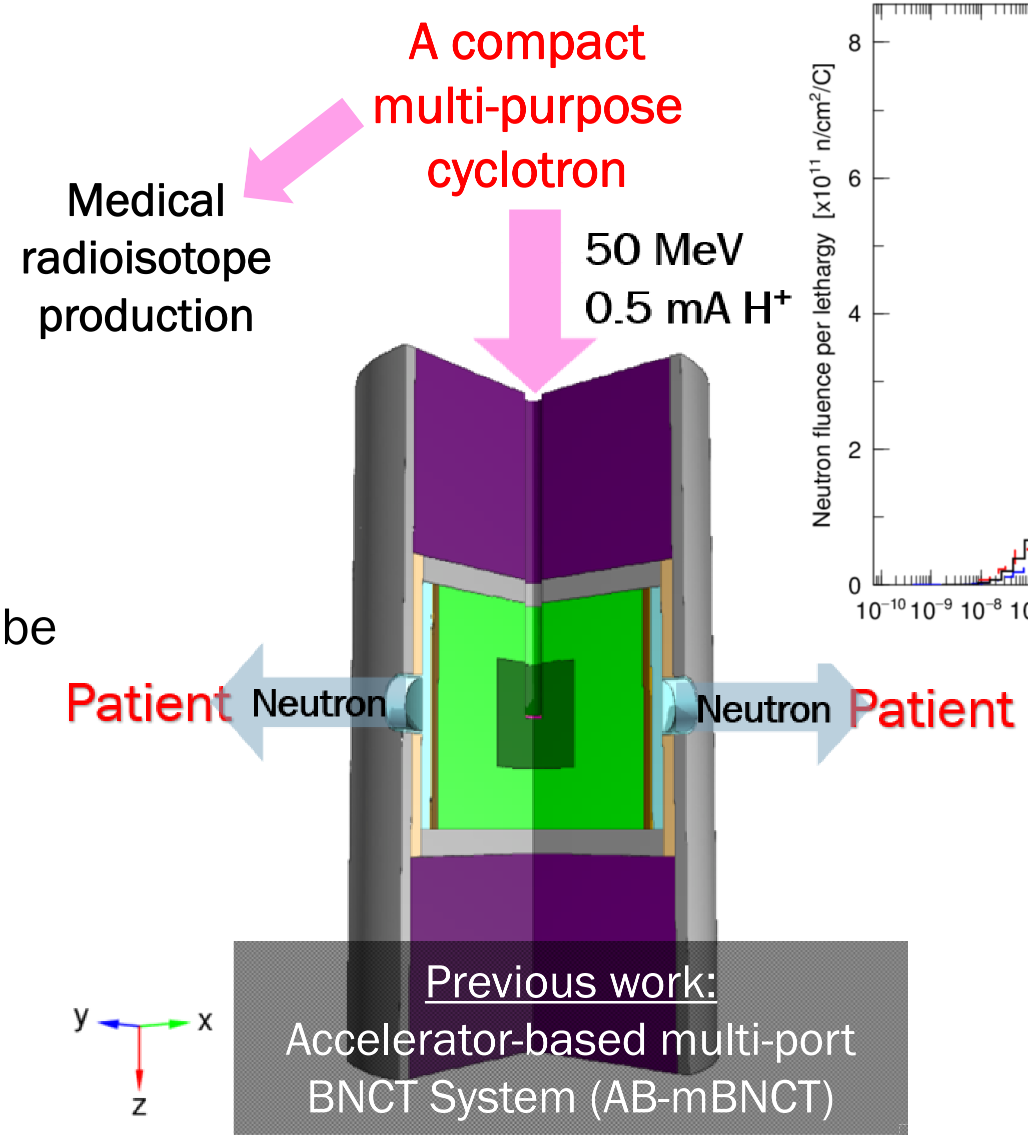
Contents

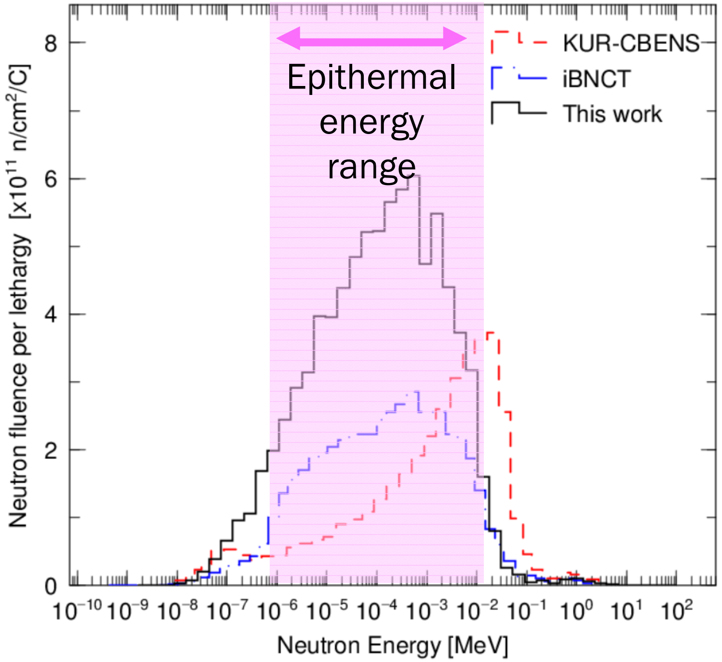
1. Introduction and Aim
2. Design Specifications and Magnetic Field Distribution of HTS-SC
3. Conceptual Design of Central Region
4. Single Particle Tracking in Central Region
5. Beam Dynamics in Central Region
   - Beam acceptance
   - Current dependence
   - Phase width dependence
   - Transverse beam size
6. Conclusion
7. Future Work

1.0 Introduction and Aim

1. In need of an in-hospital multi-purpose cyclotron for:
   a) BNCT
   b) production of medical radioisotopes for
      - ✓ diagnostic
      - ✓ therapeutic purposes

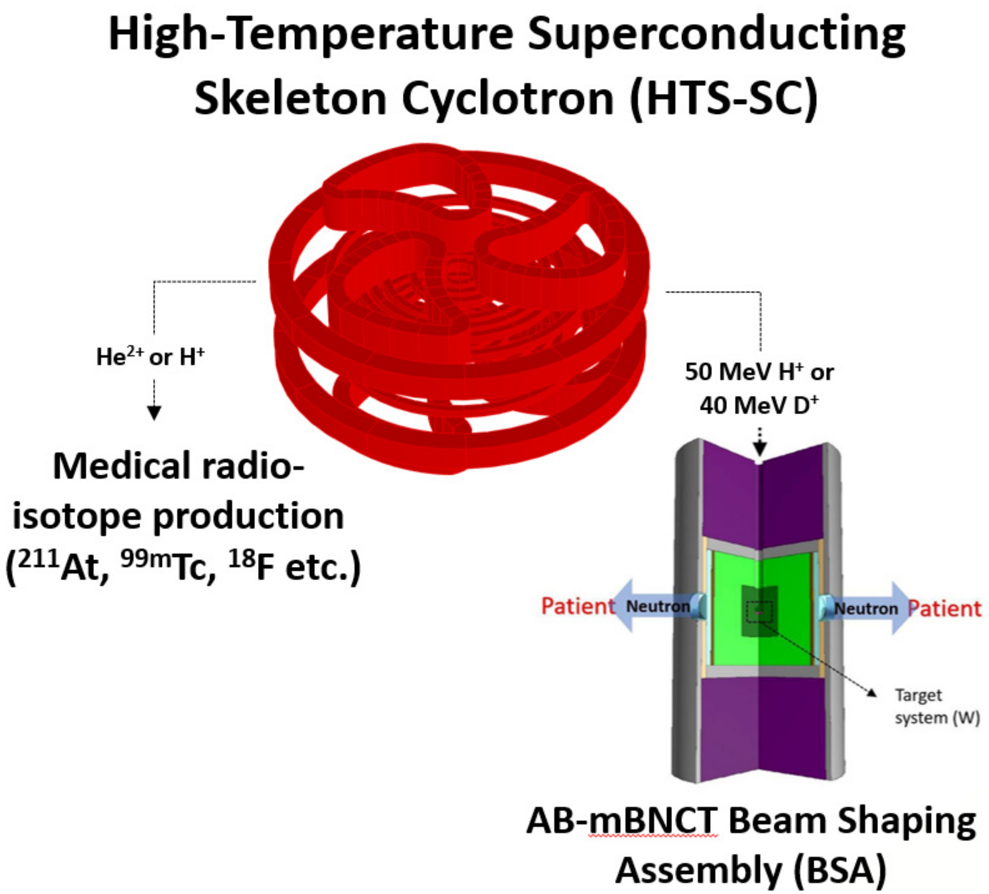
2. For a hospital environment, the multi-purpose cyclotron should be
   - compact
   - high intensity
   - cost efficient
   - easy handling
   - low radiation



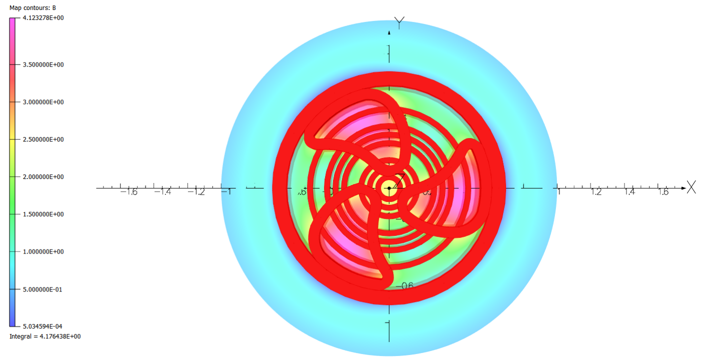


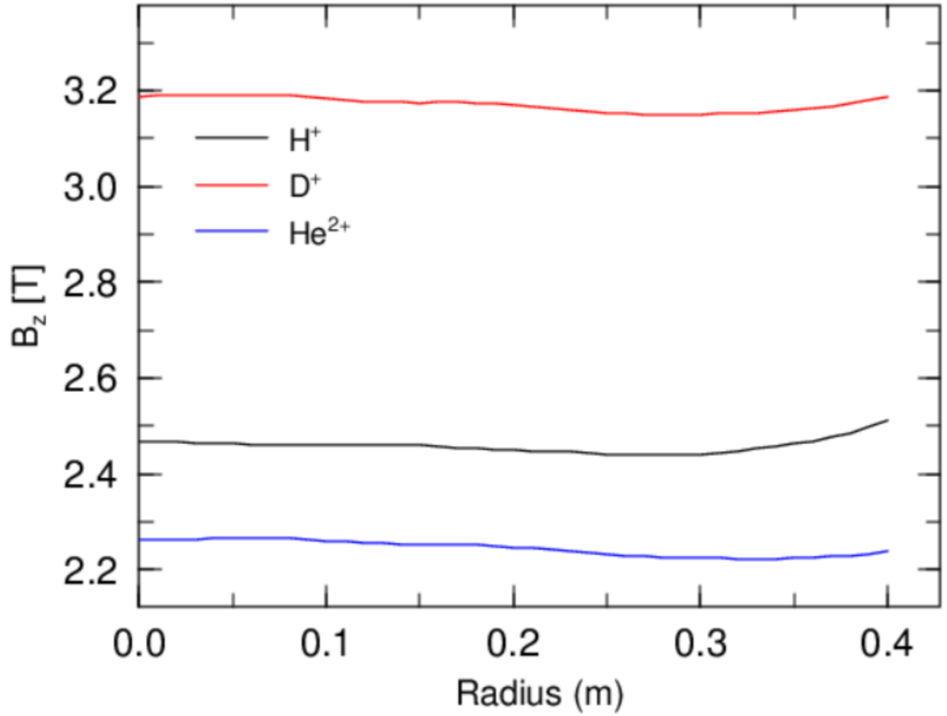
1.0 Introduction and Aim

1. A multi-purpose high-temperature superconducting skeleton cyclotron (HTS-SC) is proposed.
2. High-temperature superconducting coil is used due to its compact size and high $\vec{B}$ field especially at hill region
3. It is named "skeleton" because it is an ironless cyclotron to avoid hysteresis effect and to improve the stability as well as the reproducibility of $\vec{B}$ field.



2.0 Design Specifications and Magnetic Field Distribution of HTS-SC





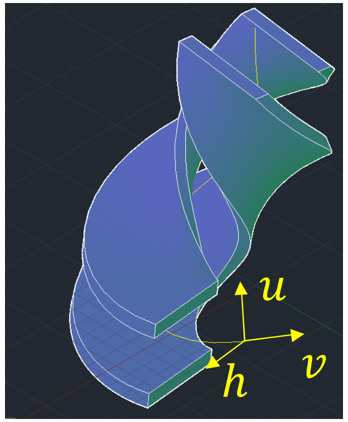
Particle type	H^+	D^+	He^{2+}
Max energy (MeV)	50	40	40
Ave. magnetic field (T)	2.48	3.18	2.26
Revolution frequency (MHz)	37.42	24.40	17.33
RF frequency (MHz)	74.84	48.80	34.66
Harmonic mode	2 (push-push)		
Dee number/angle	2 / 90º		
Dee Voltage (kV)	80		
Sector number	3		
Max spiral angle	40º		
Extraction radius (cm)	~ 40		

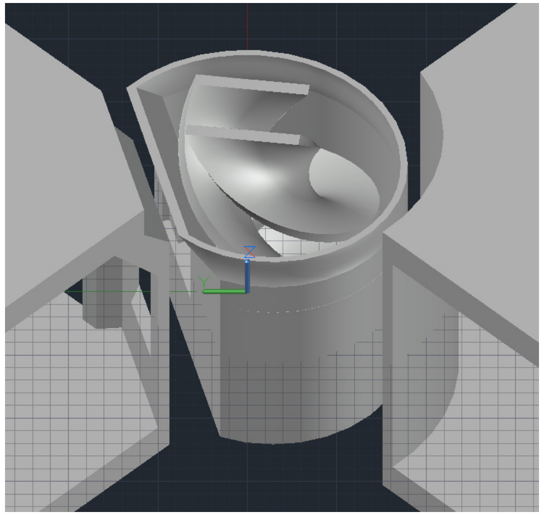
Contents

3.0 Design of Central Region

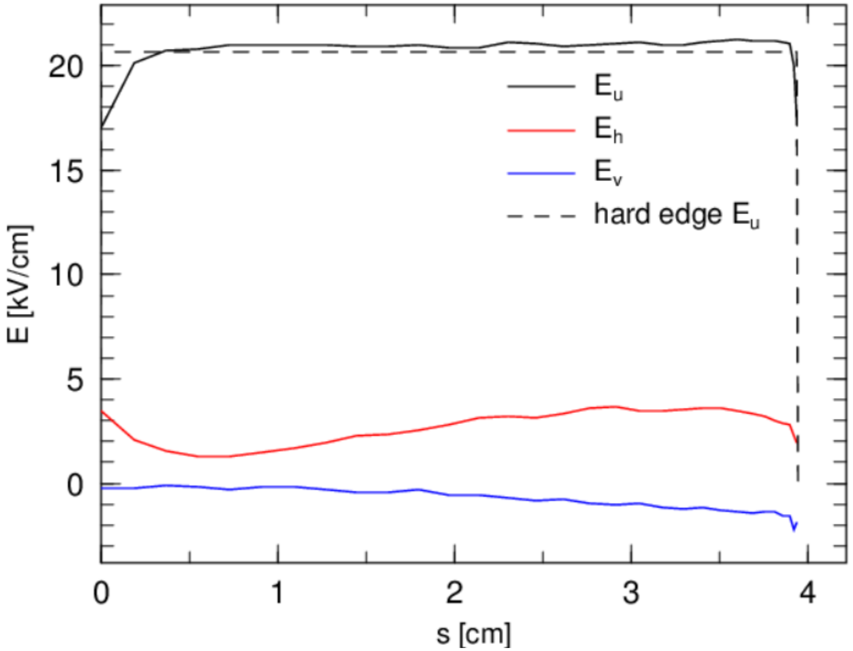
Optimized Inflector Parameters:

Beam Energy	40 keV
Inflector Height (A)	3.6 cm
Magnetic radius (cm)	1.24 cm
K (A/2ρ+k')	1.62
Tilt (k')	0.17
Electric Field (E_u)	20.93 kV/cm
Electrode width/ gap (entrance)	1.6 cm/ 0.8 cm





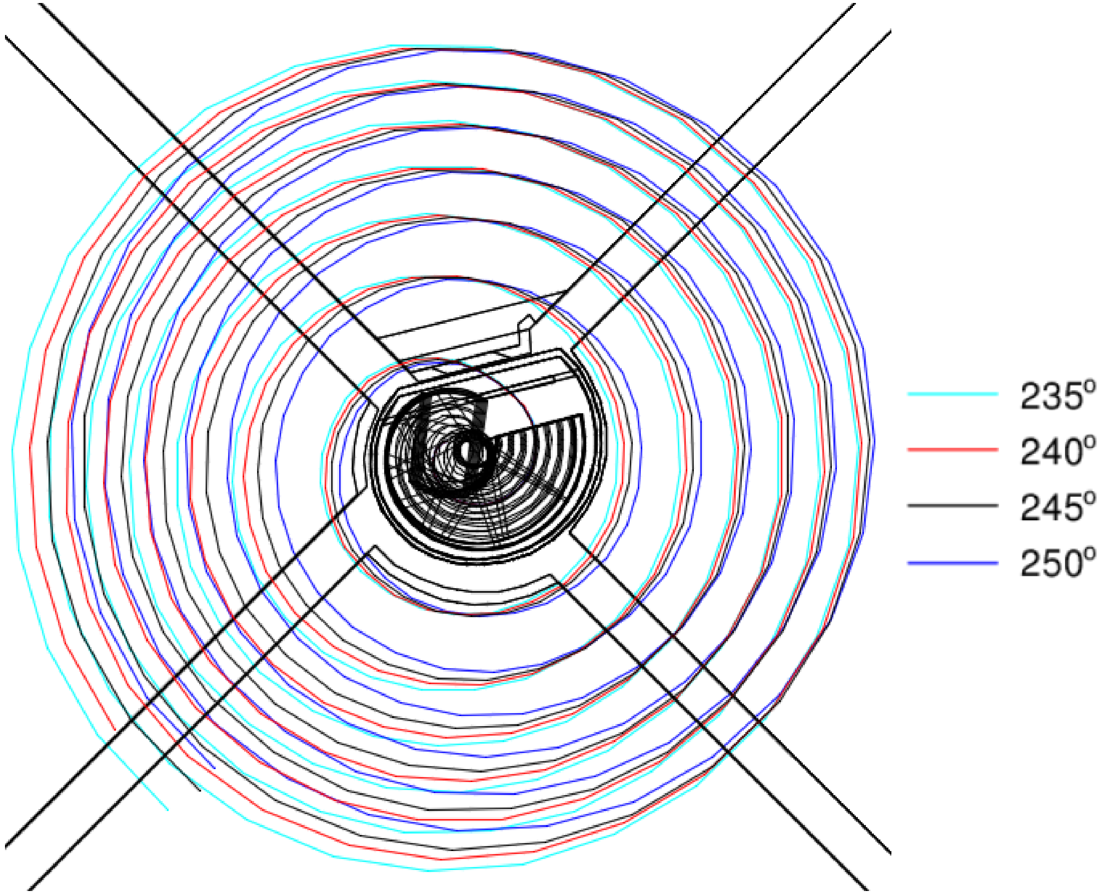
3D CAD drawing of the spiral inflector and the central region of HTS-SC.



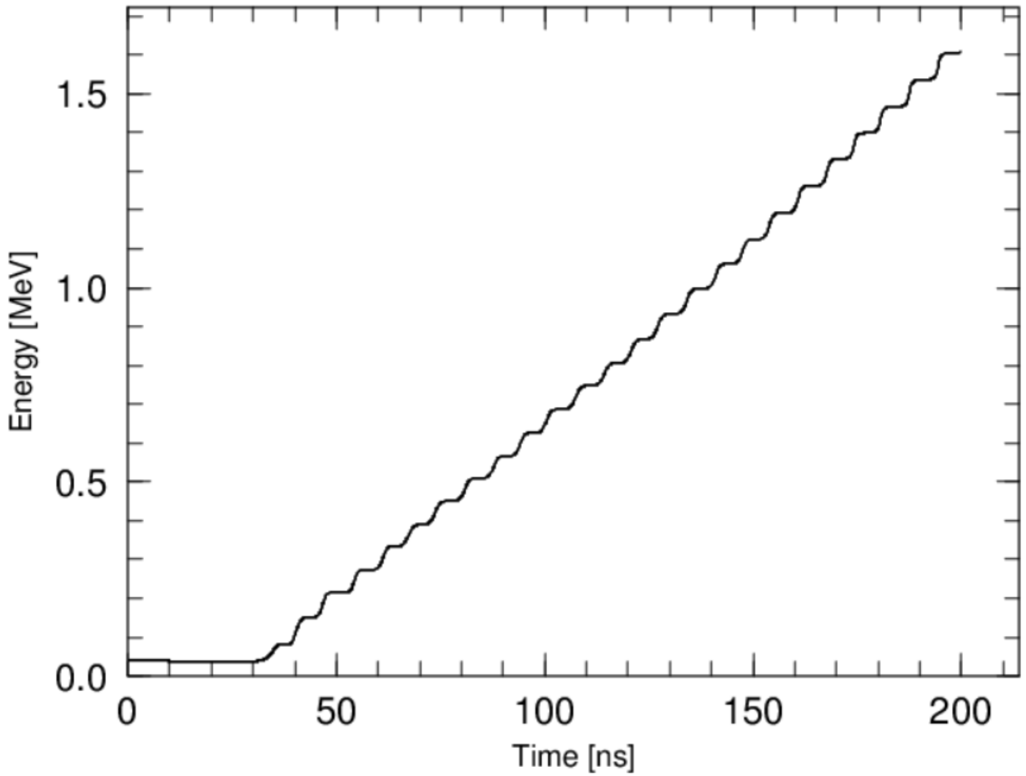
The electric field $\vec{E}$ directed in $\hat{u}$ (black solid), $\hat{h}$ (red), $\hat{v}$ (blue) along the beam trajectory simulated by TOSCA. The black dashed line represents the analytical hard edge E_u.

4.0 Single particle tracking in central region

Trajectory of H^+ from z = 40 mm



Energy of particle with initial phase = 245º

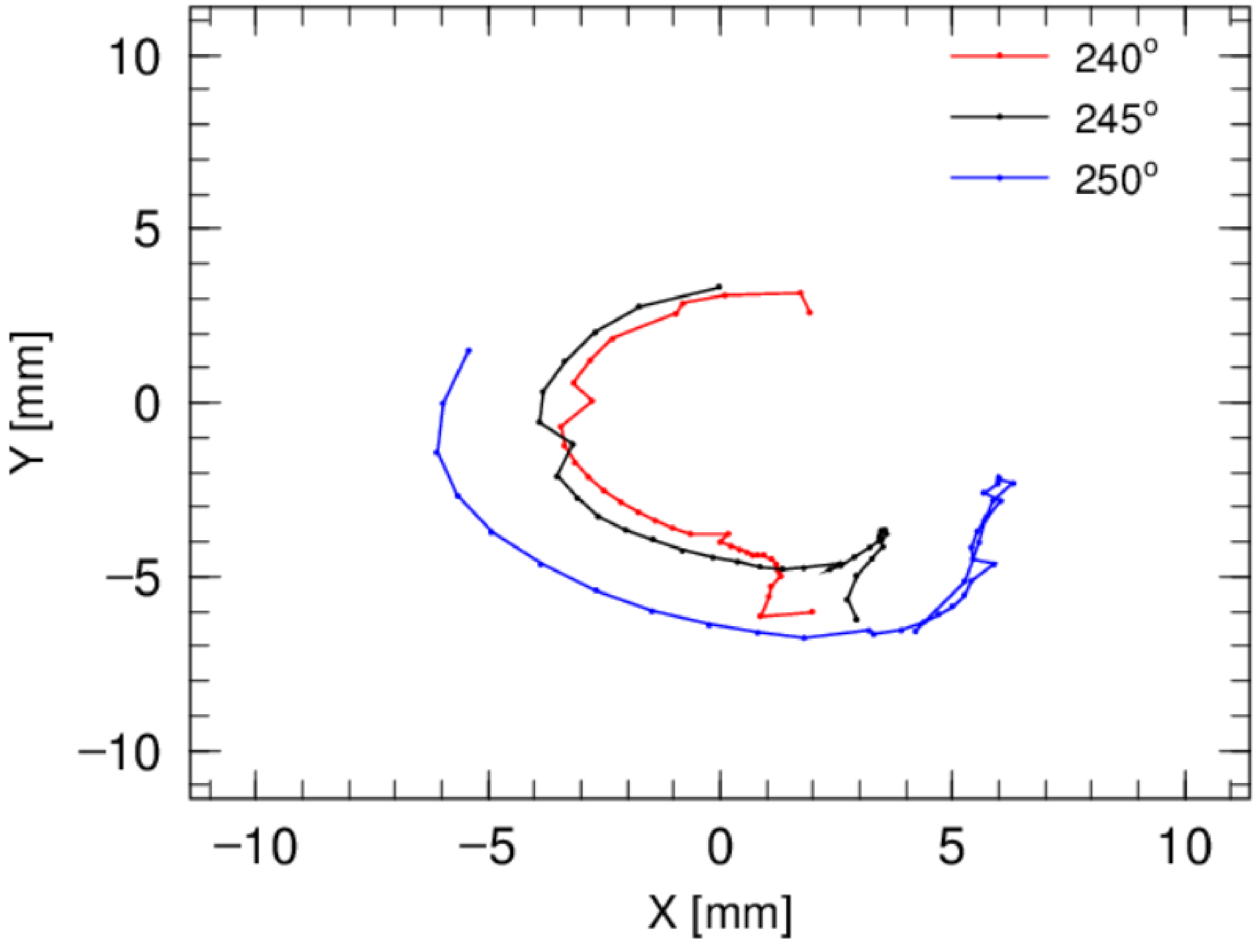


*Calculations are performed by using SNOP

V. L. Smirnov et. al., "SNOP—beam dynamics analysis code for compact cyclotrons" 2012

4.0 Single particle tracking in central region

Orbit Centre Motion from exit of inflector to the 36th turn



- The motion of orbit centre is confined within ±10 mm
- Correction using harmonic coil is possible (next study)

**Calculations are performed by using SNOP*

V. L. Smirnov et. al., "SNOP—beam dynamics analysis code for compact cyclotrons" 2012

5.1 Beam Acceptance

Initial injection parameters:

$\boldsymbol{\sigma_x = 1.5\,mm}$; $\boldsymbol{\sigma_y = 3.0\,mm}$
$\boldsymbol{\sigma_{x'} = 30\,mrad}$; $\boldsymbol{\sigma_{y'} = 70\,mrad}$
$\boldsymbol{\sigma_{rf} = 0^o}$; $\boldsymbol{\sigma_E = 0\%}$
Z_o = 40 mm;
Number of macro particle = 3000

Surviving particles defines acceptance (Up to the 6th turn)

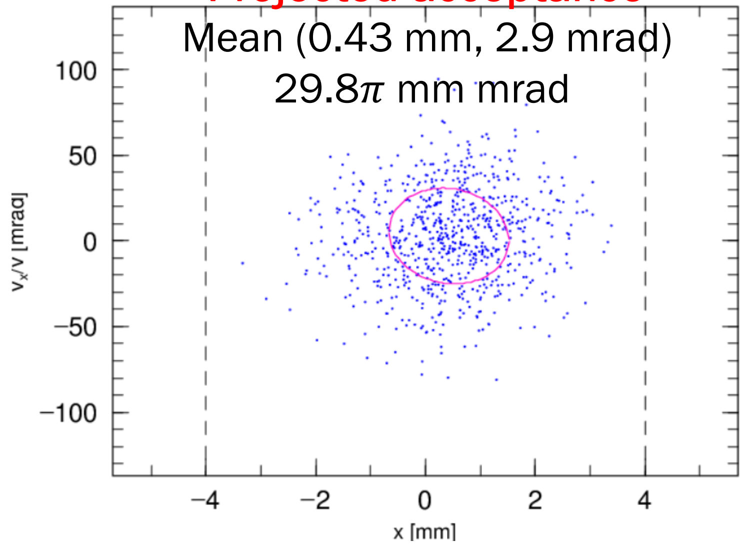
6D Beam Matrix

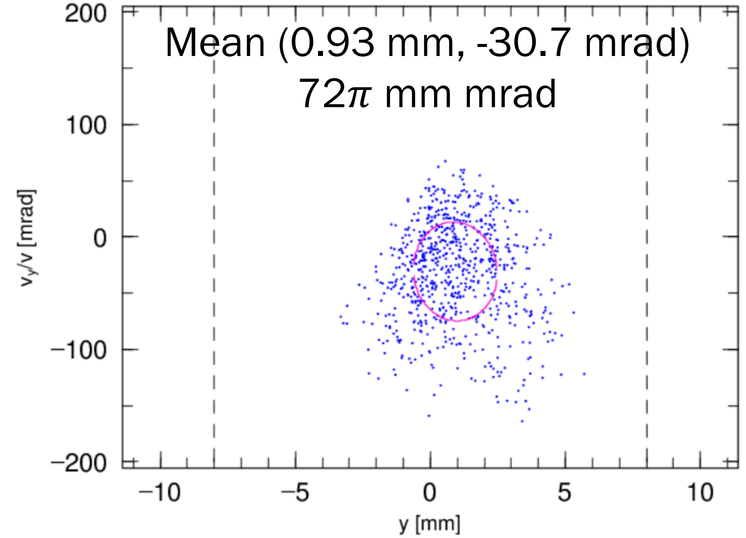
Coupling of xy — Coupling of xz — Coupling of yz

$$\begin{bmatrix} \sigma_x^2 & \sigma_x\sigma_{x'} & \sigma_x\sigma_y & \sigma_x\sigma_{y'} & \sigma_x\sigma_z & \sigma_x\sigma_{z'} \\ \sigma_{x'}\sigma_x & \sigma_{x'}^2 & \sigma_{x'}\sigma_y & \sigma_{x'}\sigma_{y'} & \sigma_{x'}\sigma_z & \sigma_{x'}\sigma_{z'} \\ \sigma_y\sigma_x & \sigma_y\sigma_{x'} & \sigma_y^2 & \sigma_y\sigma_{y'} & \sigma_y\sigma_z & \sigma_y\sigma_{z'} \\ \sigma_{y'}\sigma_x & \sigma_{y'}\sigma_x & \sigma_{y'}\sigma_y & \sigma_{y'}^2 & \sigma_{y'}\sigma_z & \sigma_{y'}\sigma_{z'} \\ \sigma_z\sigma_x & \sigma_z\sigma_{x'} & \sigma_z\sigma_y & \sigma_z\sigma_{y'} & \sigma_z^2 & \sigma_z\sigma_{z'} \\ \sigma_{z'}\sigma_x & \sigma_{z'}\sigma_{x'} & \sigma_{z'}\sigma_y & \sigma_{z'}\sigma_{y'} & \sigma_{z'}\sigma_z & \sigma_{z'}^2 \end{bmatrix}$$

Projected emittance in x, y and z

Projected acceptance





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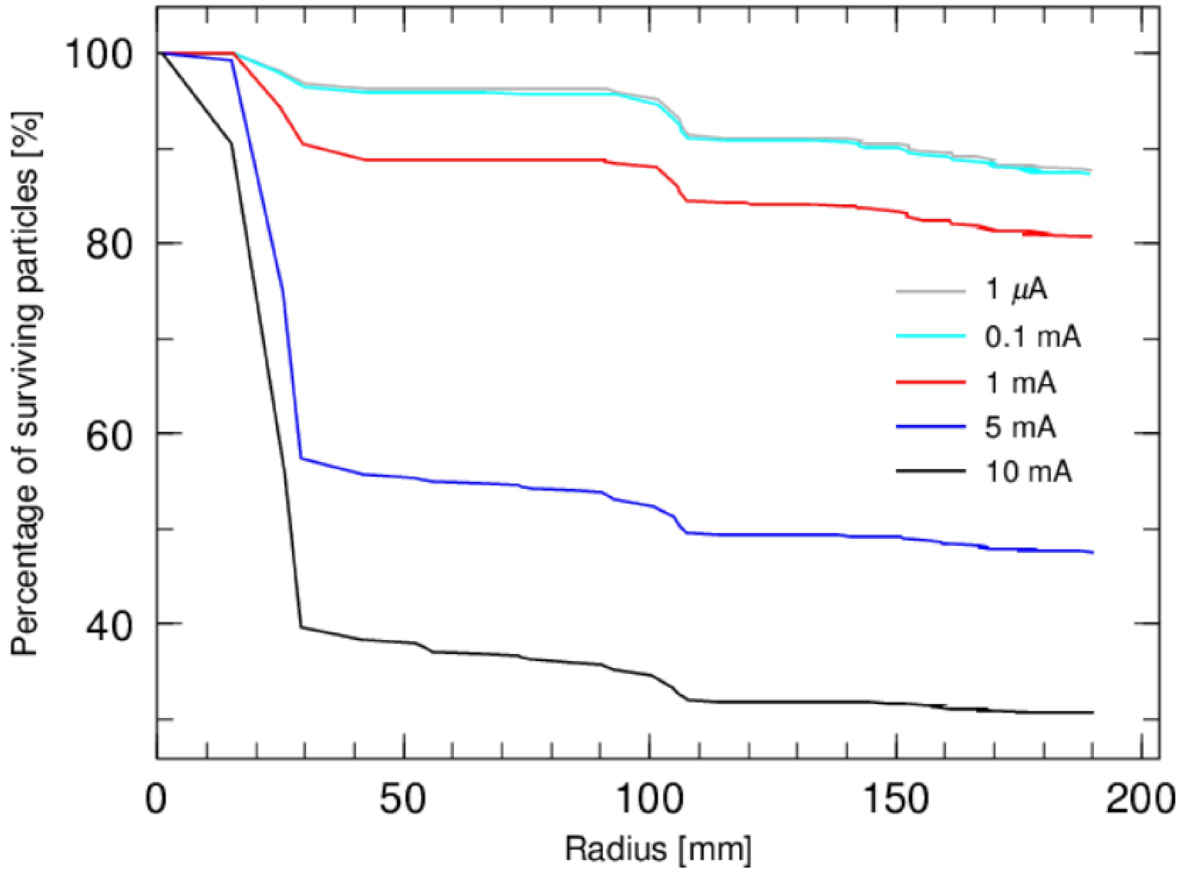
5.2 Current Dependence

Injection bounded by the projected acceptance:

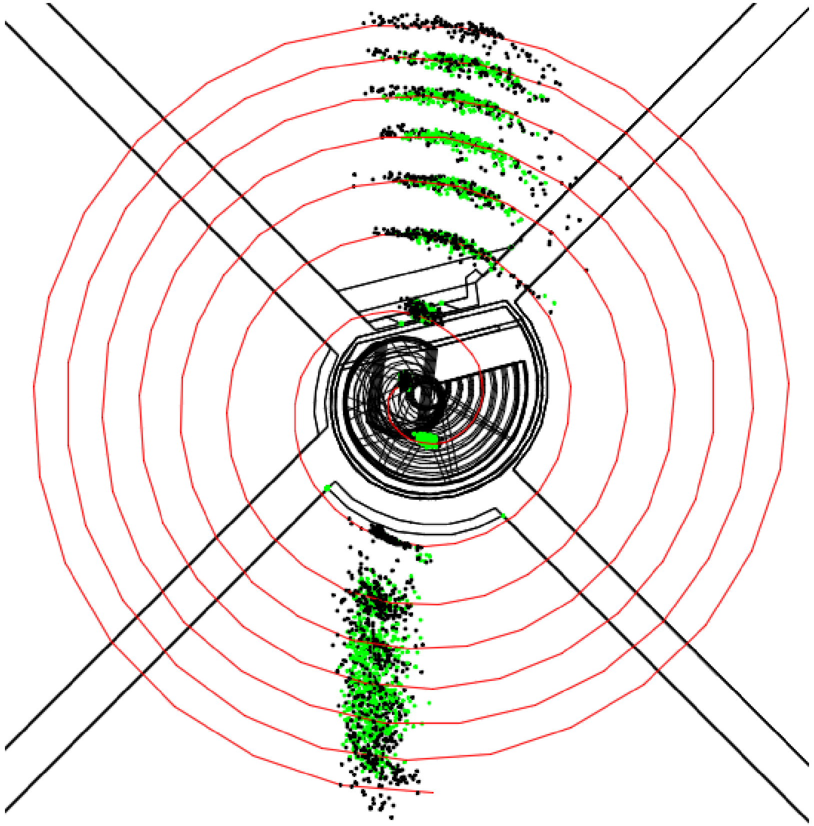
$$\varepsilon_x \approx 29.8\pi \text{ mm mrad} \,;\; \varepsilon_y \approx 72\pi \text{ mm mrad}$$
$$\sigma_x \approx 0.57 \text{ mm} \,;\; \sigma_y \approx 0.82 \text{ mm}$$
$$\sigma_{x'} \approx 14.2 \text{ mrad} \,;\; \sigma_{y'} \approx 21.5 \text{ mrad}$$
$$\text{phase} = 245^o \,;\, E_{in} = 40 \text{ keV}$$
$$\sigma_{rf} = 2.5^o \,;\, \sigma_E = 1\%$$

Z_o = 40 mm;
Number of macro particle = 3000

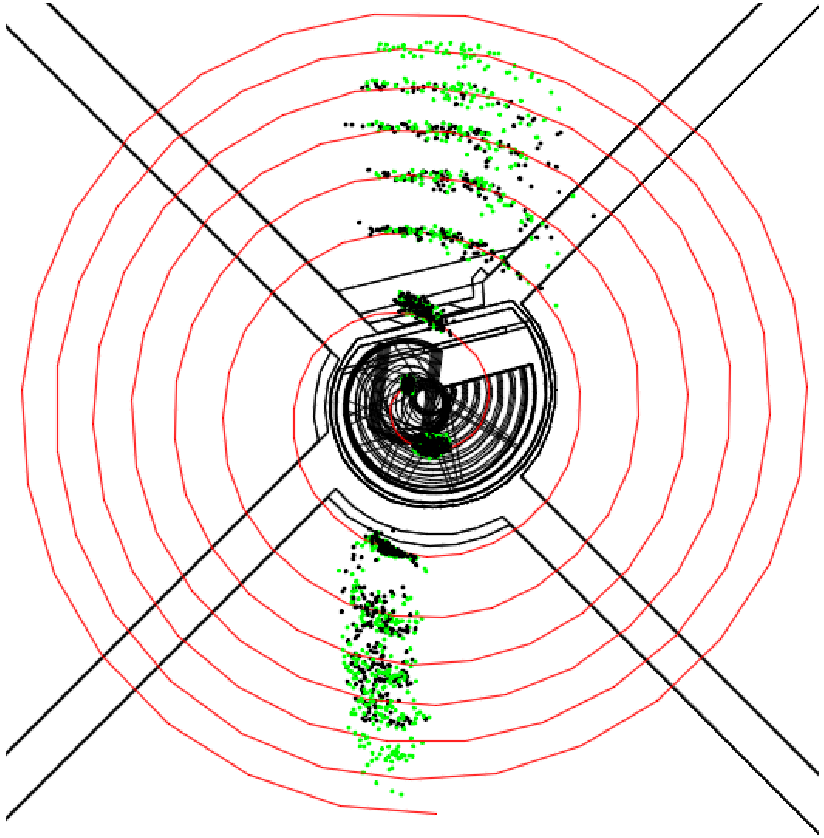


5.3 Phase width dependence

I = 1 μA

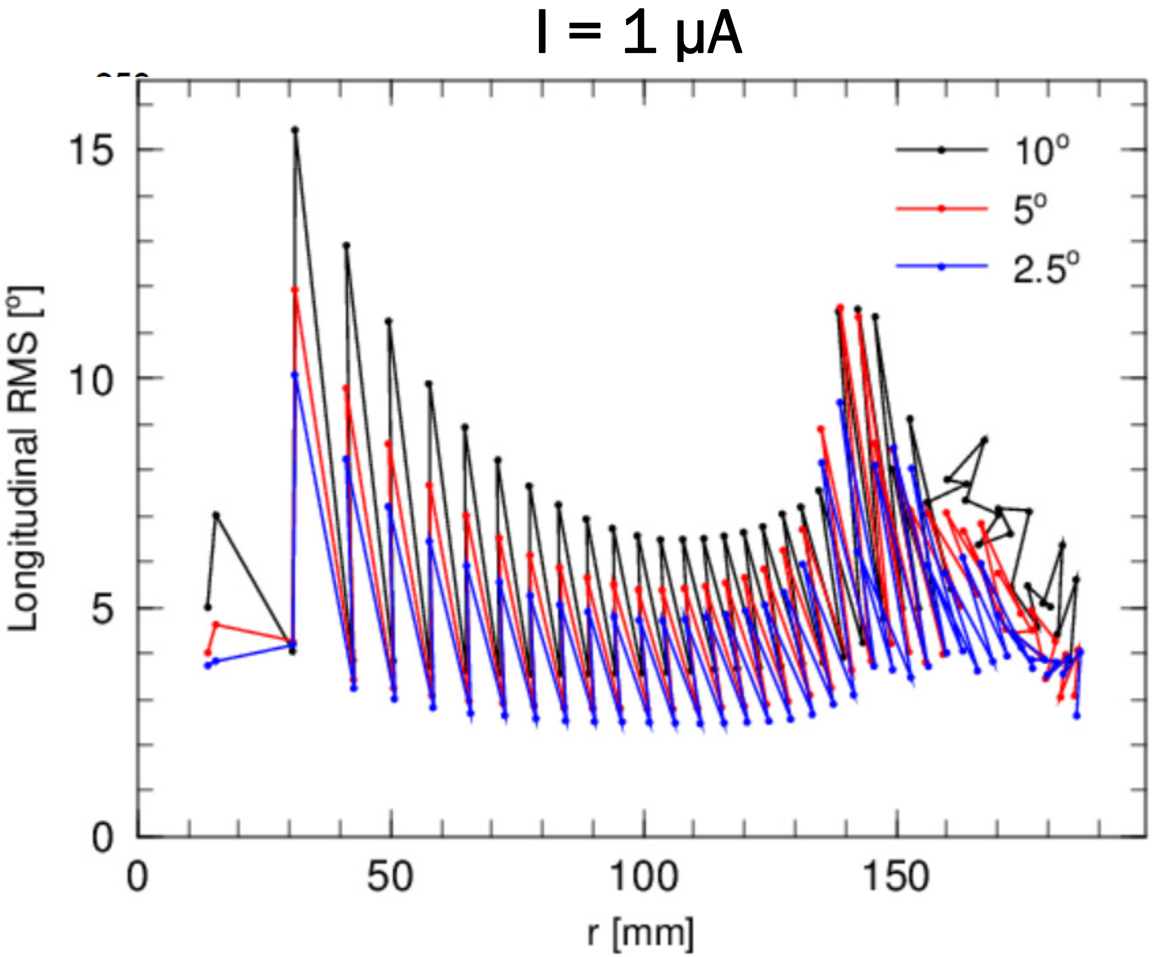


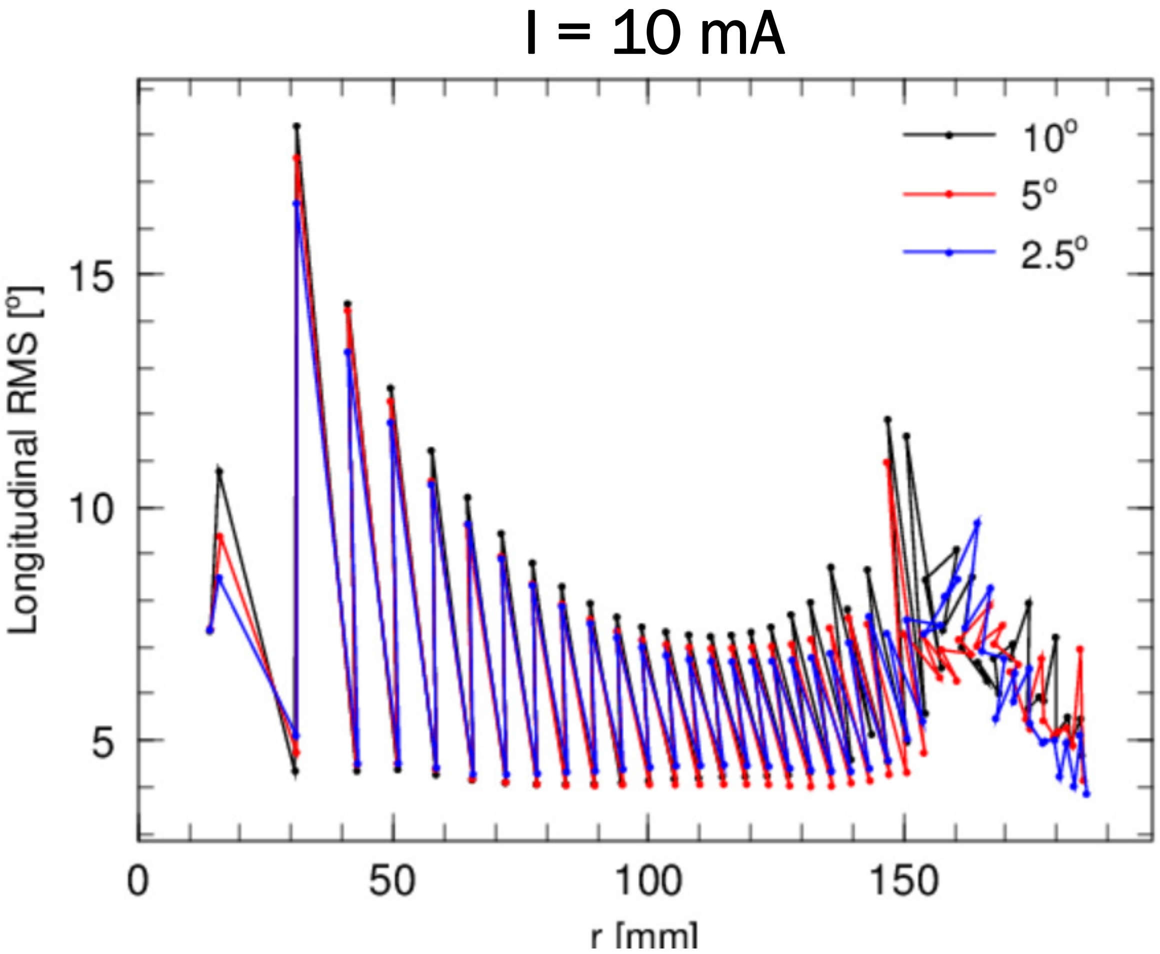
I = 10 mA



- Beam median plane for $\sigma_{rf} = 2.5^o$ (green) and $\sigma_{rf} = 10^o$ (black) beams respectively.

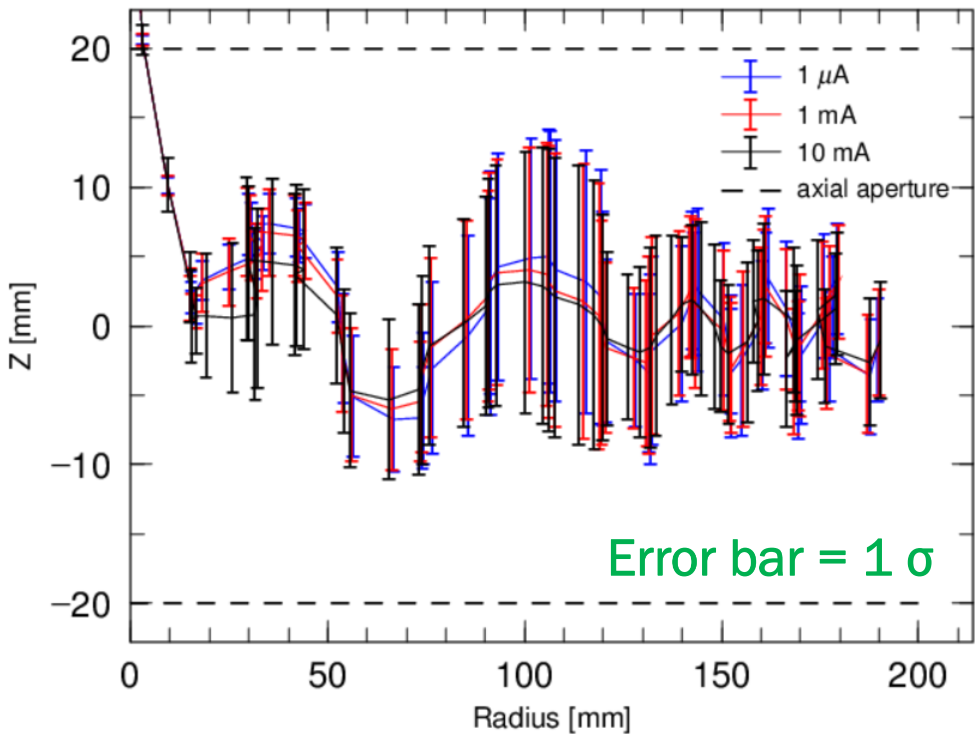
5.3 Longitudinal distribution

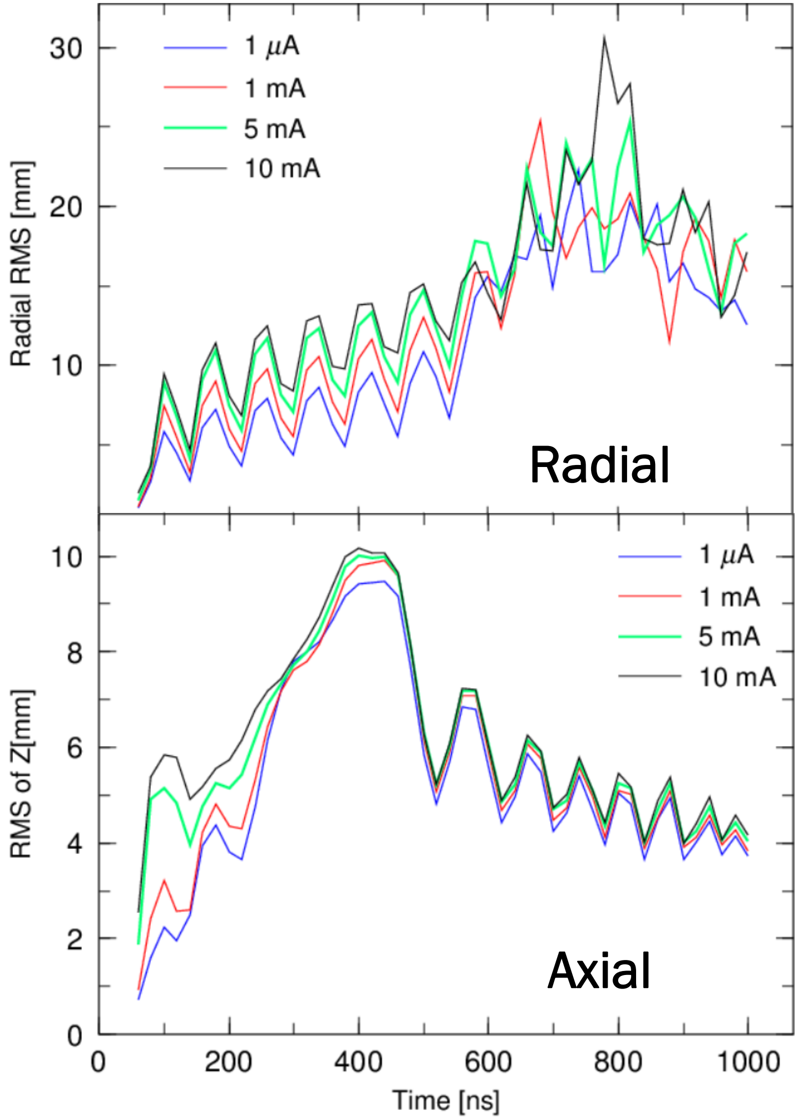




- RMS distribution in longitudinal direction with initial $\sigma_{rf} = 2.5^o$ (blue), $\sigma_{rf} = 5^o$ (red) and $\sigma_{rf} = 10^o$ (black) for 1 μA (left) and 10 mA (right) beams respectively.

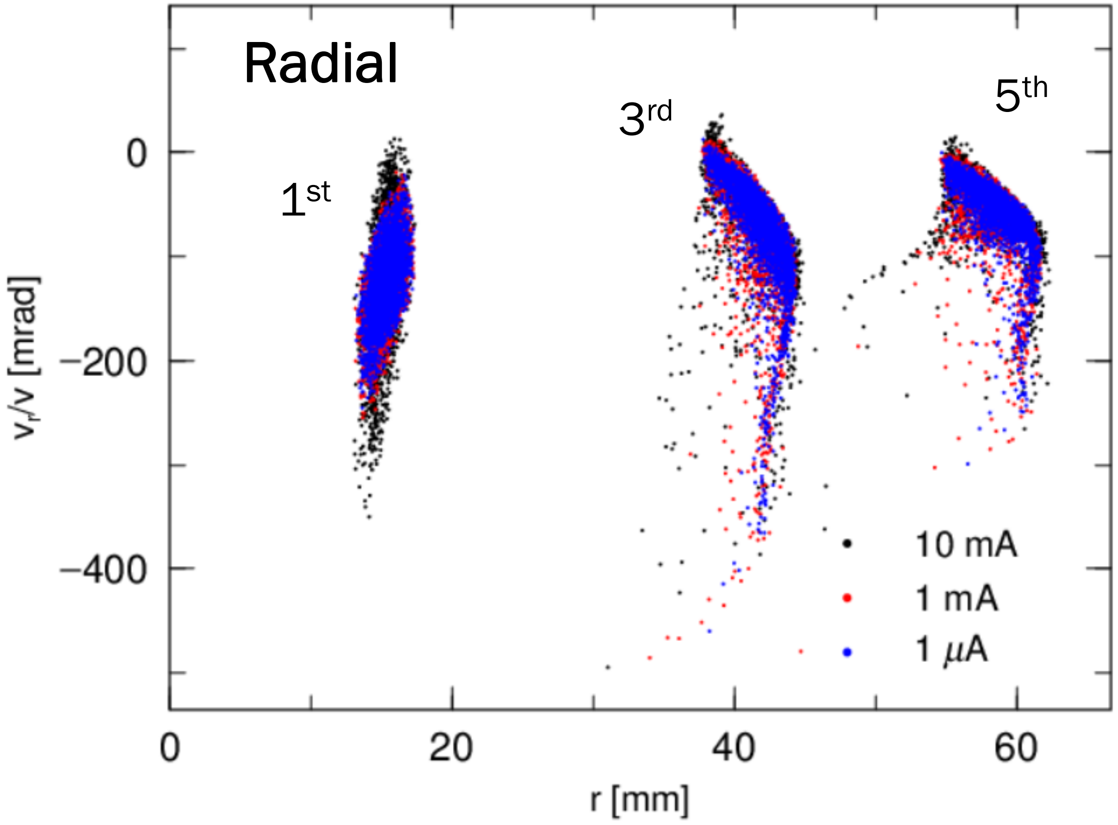
5.4 Transverse Beam Size

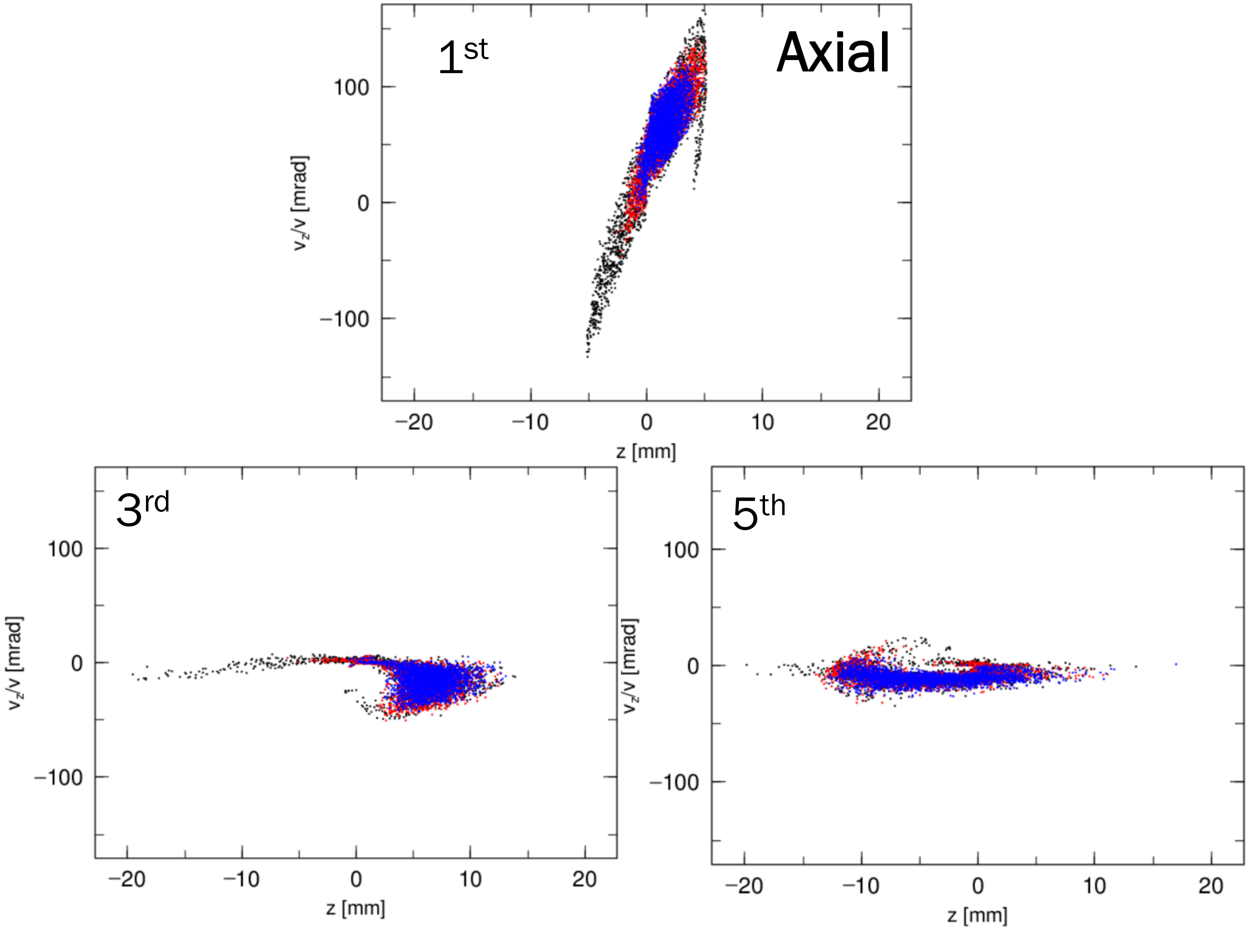




- Generally the bunch is well confined within the axial aperture (dashed line in figure above).
- Space charge effect is the most significant only during the first two turns (low energy).
- If the particles managed to survive in the first two turns, they are very likely to stay in the beam until the final turn.

5.4 Beam Emittance





- Beam emittance in radial (left) and axial (right) direction during the 1st, 3rd and 5th turn at 45º (first gap).
- The beam current are 1 μA (blue), 1 mA (red) and 10 mA (black) respectively.

6.0 Conclusion

1. Most of the particles in a high intensity beam are killed during the first two turns.

2. Despite of the high central magnetic field of > 2.4 T for H^+ beam, more than 80% of survival rate for a 1 mA beam is achieved.

3. Longitudinal spread due to rf width at injection is more significant in low-current beam.

4. The axial and radial beam spread is not much affected by space charge effect especially at larger radius.

5. This satisfactory performance confirms the feasibility of the central region design in this work.

7.0 Future works

1. Harmonic coil is needed to correct the offset of orbit motion.

2. Additional element such as an external buncher and a quadrupole magnet are needed along the injection line in order to improve the survival rate of beams for high-current injection.

3. Multi-bunch beam dynamics should also be studied to check the neighbouring space-charge effect which directly affects the turn separation.

4. Suitable extraction system which possesses the maximum extraction efficiency.

Thank you for your attention!