Central Region for A High-Intensity Compact Superconducting Cyclotron SK1000

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Outline

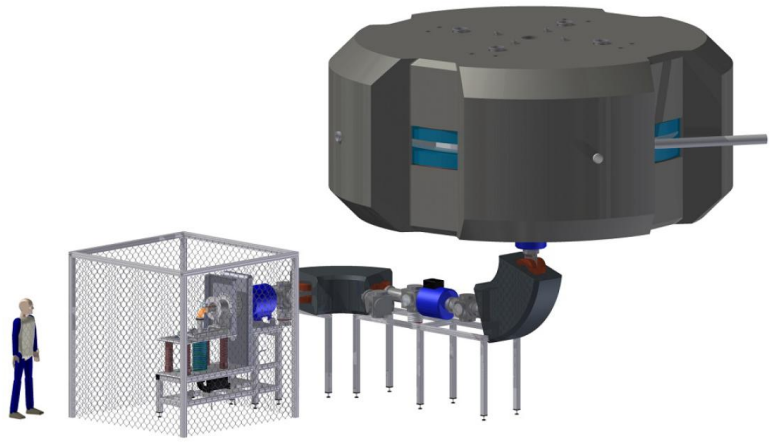
- **Motivation and application**
- **Main parameters and challenges of SK1000 Cyclotron**
- **LEBT and Central Region Design**
  - LEBT
  - Buncher
  - Spiral Inflector
  - Central region
- **Central region transmission efficiency calculation**
- **Conclusions**

High intensity cyclotron applications

Country	Cyclotron name	Beam current	Application
Japan	HM-30 Cyclotron (SHI)	1 mA	BNCT
USA	IsoDAR Cyclotron (MIT)	10 mA	Neutrino experiment
Belgium	Cyclone® 70 P (IBA)	700 μA	Radioisotope Production



HM-30



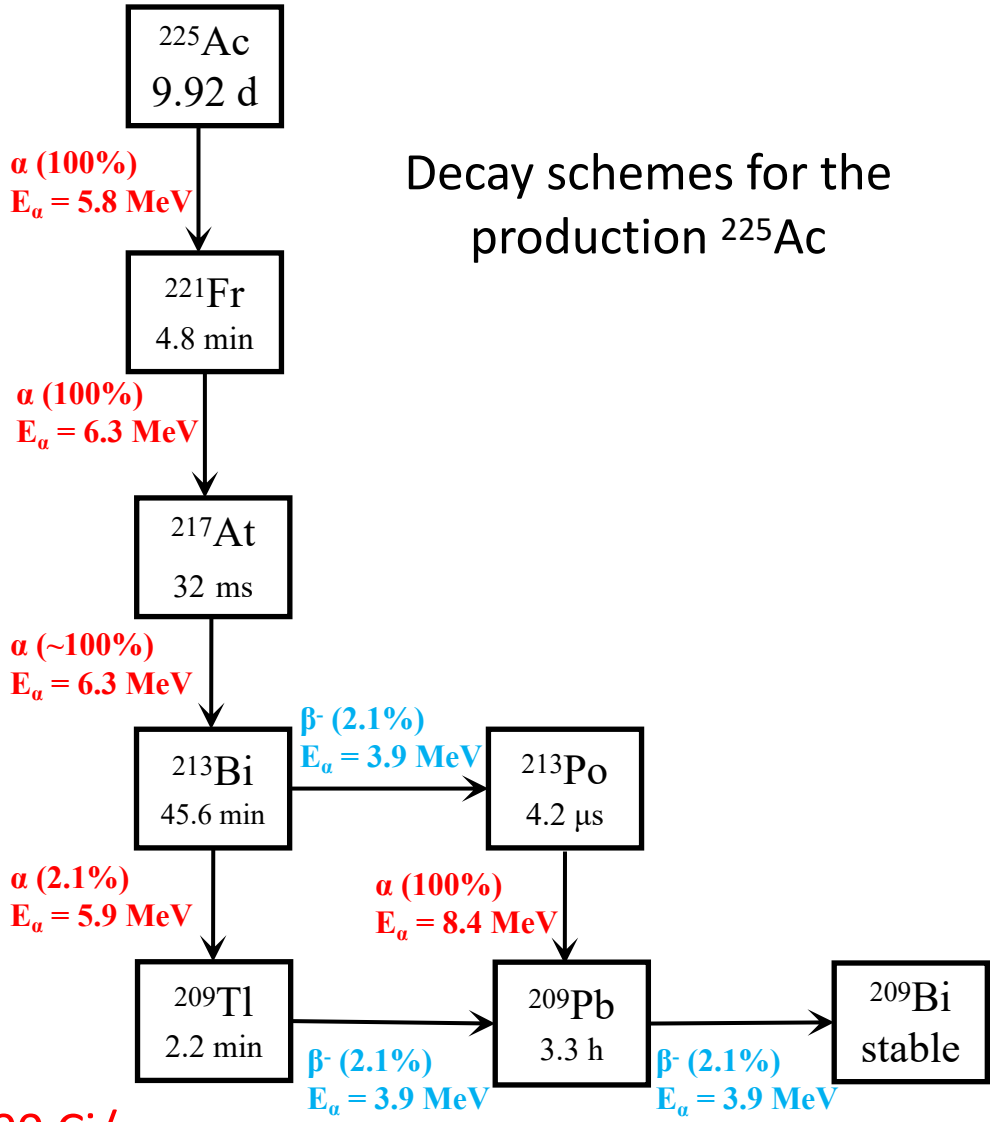
IsoDAR Cyclotron



Cyclone® 70 P

Targeted Alpha Therapy

α-emitters	Half-Life	Emission Type	Decay chain alpha energy range (MeV)
^{225}Ac	**9.9 d**	**$5\alpha, 3\beta^-$**	**5.8–8.4**
^{211}At	7.2 h	$1\alpha, 1EC$	5.9–7.5
^{212}Bi	60.6min	$1\alpha, 1\beta^-$	6.1–8.8
^{213}Bi	45.6min	$1\alpha, 2\beta^-$	5.9–8.4
^{212}Pb	10.6h	$1\alpha, 2\beta^-$	6.1–8.8
^{223}Ra	11.4d	$4\alpha, 2\beta^-$	5.6–7.4
^{149}Tb	4.1h	α/ EC/ β^+	3.9
^{227}Th	18.7d	$5\alpha, 2\beta^-$	5.7-7.4

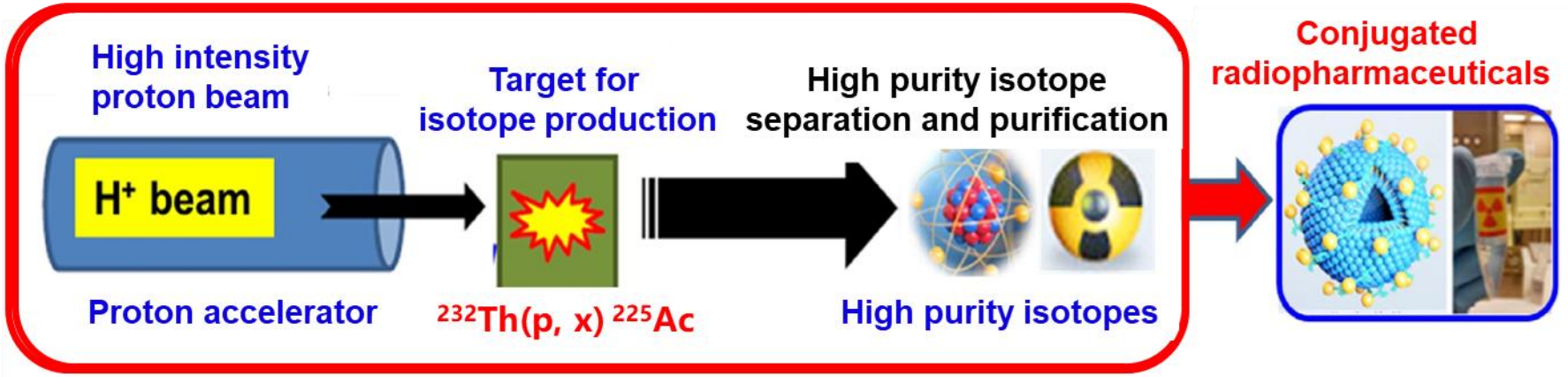


Decay schemes for the production ^{225}Ac

■ Key considerations of ^{225}Ac:

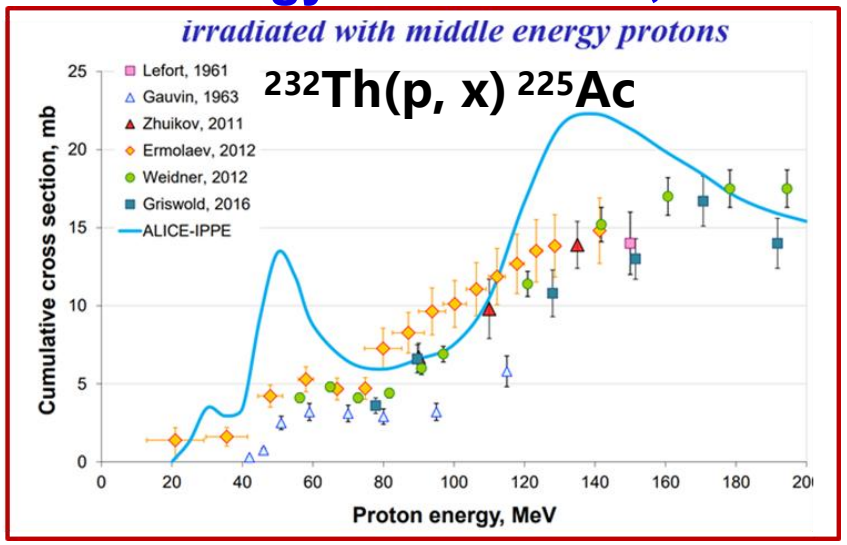
- Suitable half-life (9.9 days);
- high linear energy transfer (LET);
- Current publicly available supply: ~2.5 Ci/year, future need: 500–800 Ci/year.

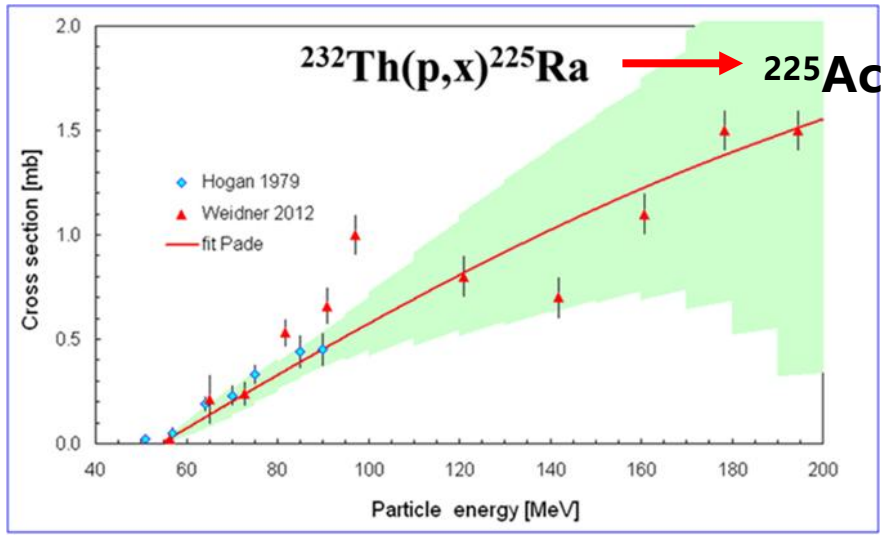
^{225}Ac isotope production



- INR-RAS, linac
- DOE Tri-Labs, linac
- IMP, cyclotron, linac
- TRIUMF, cyclotron (H^-)
- iThemba Labs, cyclotron (H^-)
- CIAE, cyclotron (H^-)
- ….

Proton beam energy: 70-500 MeV, 100-300 μA, future > 500 μA ; ^{225}Ac, ^{223}Ra, ^{213}Bi, ^{212}Pb …





➢ **^{225}Ac isotope production for targeted α-therapy needs high intensity H^+ beam**

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Background

■ Design a high-intensity compact Superconducting Cyclotron of the isotope Ac-225

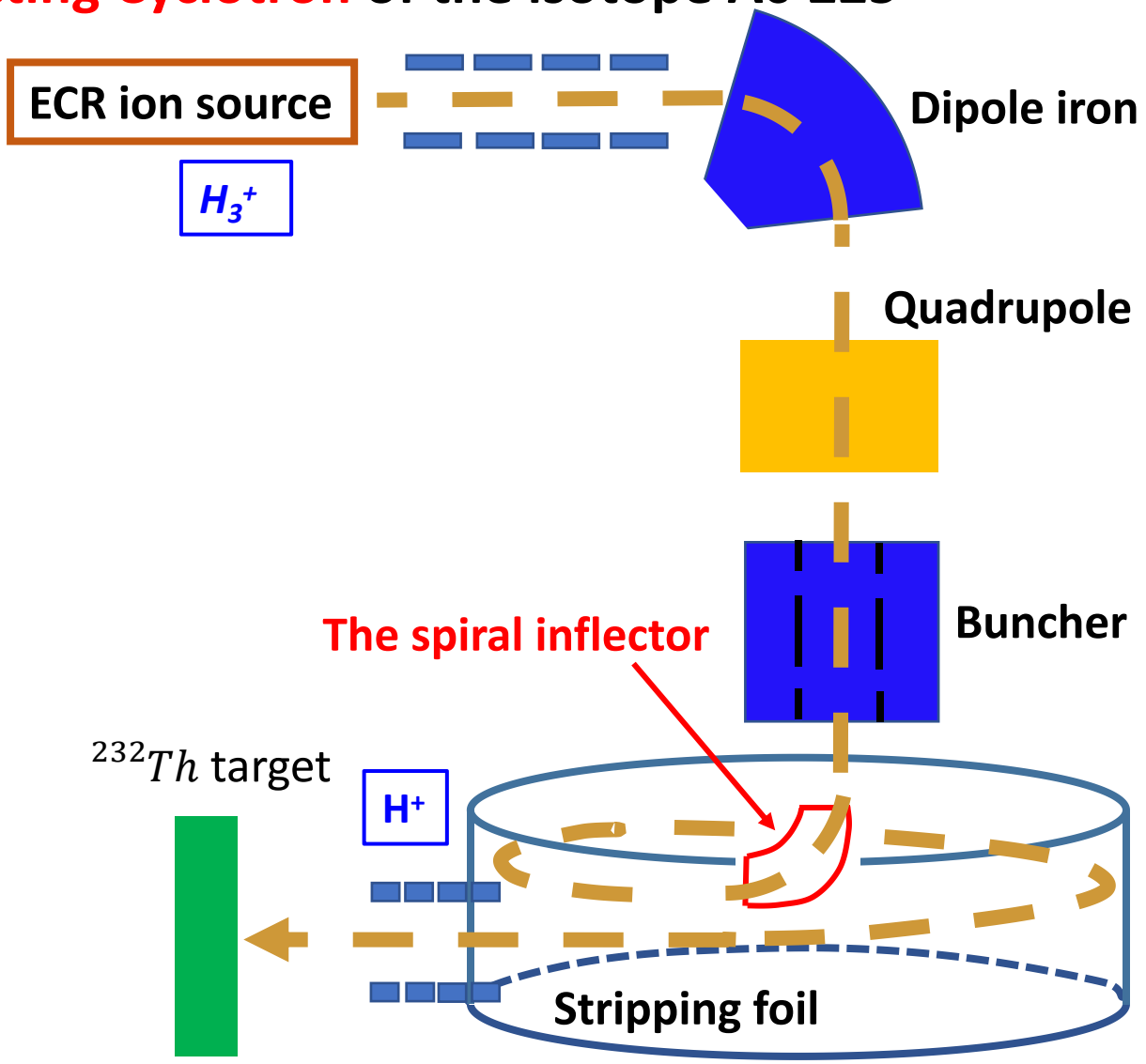
◆ **SK1000**: $^{232}Th(p\,,\,x)^{225}Ac$, requiring extraction of a 1 mA, 120 MeV proton beam.

■ Accelerator requirements

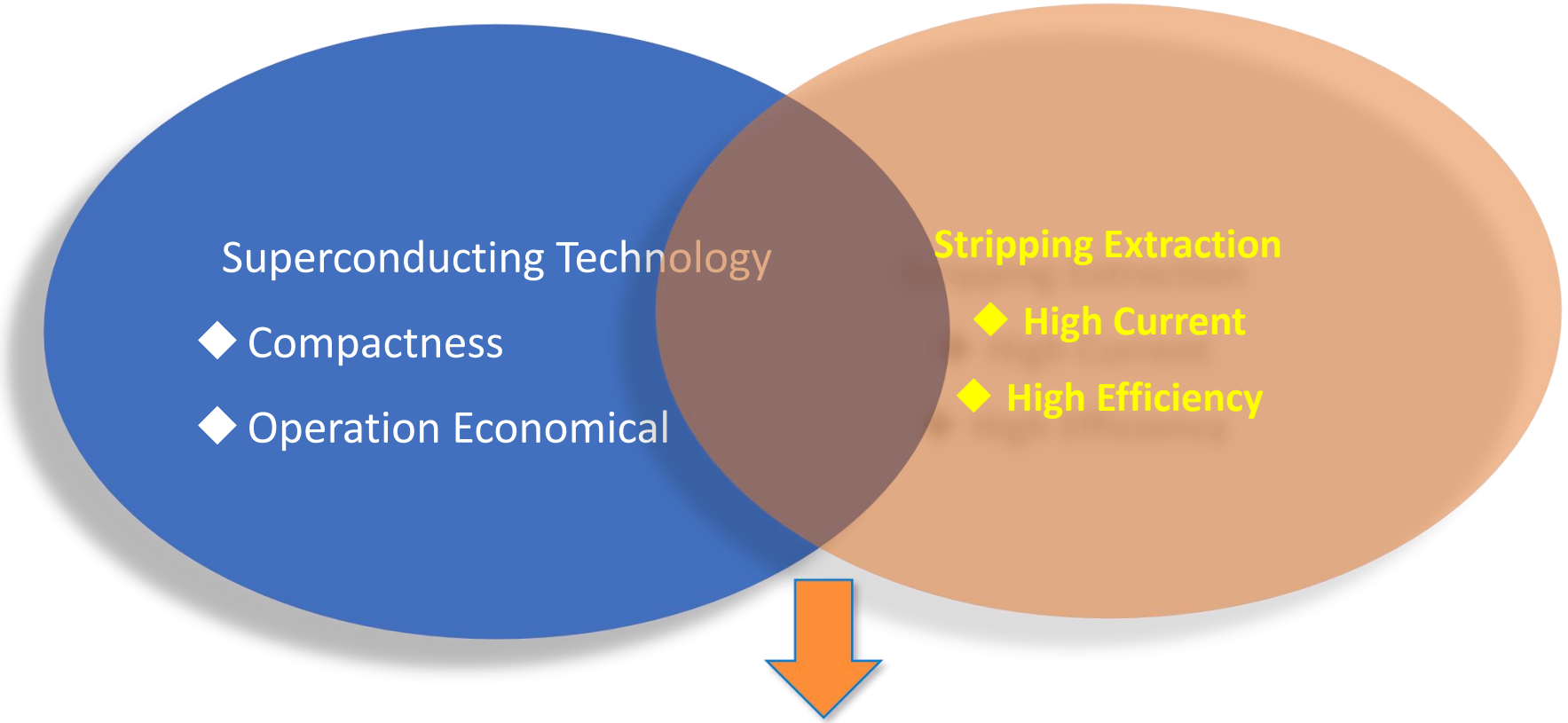
- 120MeV proton
- 0.5-1.0mA proton beam for long-time operation
- As compact as possible, cost-effective

■ Main Features : H_3^+ , Superconducting, Spiral

- Accelerate H_3^+ before extraction to get high intensity
- Superconducting coils to get higher Bz
- Spiral angle for high focusing to reduce envelope



Why H_3^+



Superconducting Cyclotron with stripping extraction

(H^-, H_2^+, H_3^+)

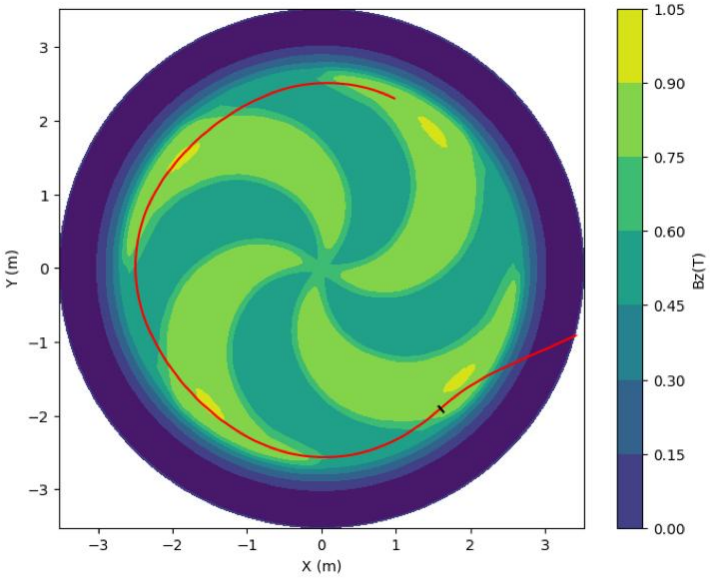
For an economical high-power machine

Why H_3^+

H^- machine:
(E_{bind} = 0.75 eV)

Commercial cyclotrons
for isotopes production;
TRIUMF 520 MeV cyclotron

(p traj. bends outward,
but low magnetic field)

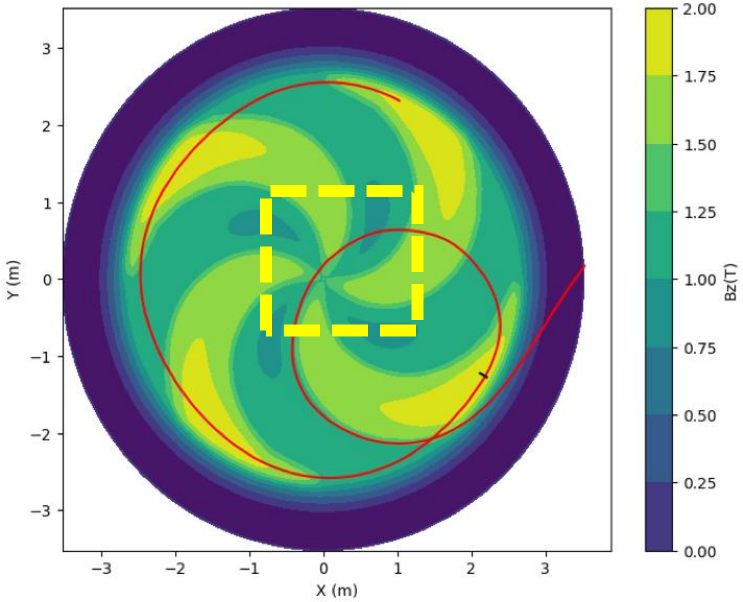


(a) H^- at $B_0 \sim 0.7$ T

H_2^+ machine:
(E_{bind} = 2.75 eV)

Preceding design study:
SCENT project;
IsoDAR

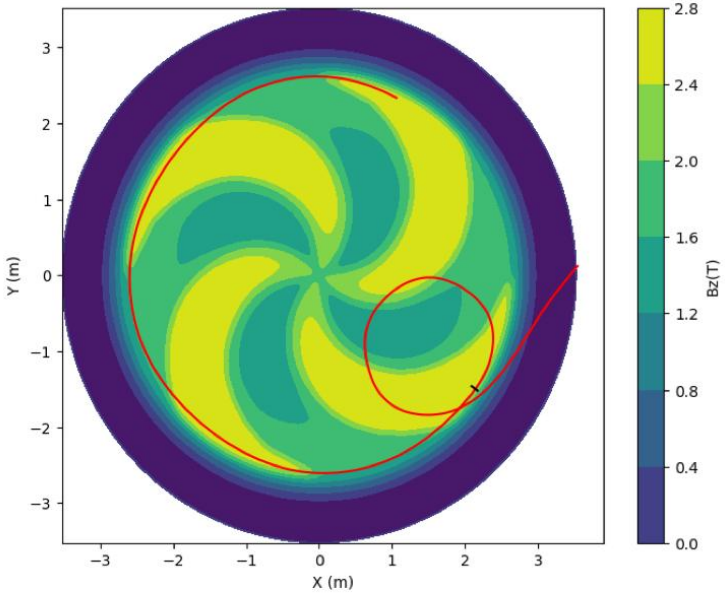
(p orbit loops to centre region)



(b) H_2^+ at $B_0 \sim 1.3$ T

H_3^+ machine:
(E_{bind} = 4.37 eV)

TR100+(TRIUMF)
SK1000(IMP)
(p orbit radius =1/3 of H_3^+,
far from centre region)



(c) H_3^+ at $B_0 \sim 1.9$ T

Koay, H. W. Stripping Extraction and Lorentz Dissociation

Why H_3^+

	H^-	H_2^+	H_3^+
Energy (MeV/u)		100	
Momentum, $\beta\gamma$		0.47	
Extraction radius, ρ (m)		1.5	
Ave. B field, B_0 (T)	1	2	3
Peak B field (T)	1.5	3	4.5
Max. Lorentz dissociation (%)	0.4	0.4	< 0.01
Energy (MeV/u)		500	
Momentum, $\beta\gamma$		1.2	
Extraction radius, ρ (m)		3.64	
Ave. B field, B_0 (T)	1	2	3
Peak B field (T)	1.5	3	4.5
Max. Lorentz dissociation (%)	100	1	0.01
Energy (MeV/u)		1000	
Momentum, $\beta\gamma$		1.8	
Extraction radius, ρ (m)		5.65	
Ave. B field, B_0 (T)	1	2	3
Peak B field (T)	1.5	3	4.5
Max. Lorentz dissociation (%)	100	1.5	0.1

Koay, H. W. Stripping Extraction and Lorentz Dissociation

High current + High Energy →

H_3^+ SC Cyclotron may apply

100 kW, loss~10 W beam power dissipation

Even 1‰ beam loss during acceleration might not be acceptable

Why H_3^+

Space-Charge tune shift in un-bunched beam

$$\Delta\nu = -\frac{r_p N}{2\pi\beta^2\gamma^3\epsilon_{geom}}\frac{Q^2}{A}G$$

For the same energy of protons: with H_3^+, only 1/3 number of ions needed for the same final proton intensity → 3× smaller Δν.

Intensity limit in cyclotron*

$$\Delta(\nu_z^2) = -\frac{2}{\pi}\frac{r_p N R}{\beta^2}\left[\frac{1}{b(a+b)} + \frac{\epsilon_l}{g^2}\right]$$

$$\hat{I}_{max} = \beta\left(\frac{\nu_{z0} b_{max}}{R_\infty}\right)^2 \frac{A}{Q^2}(7.8\times 10^6 \textbf{\textit{Amp}})$$

H_3^+ applicable !

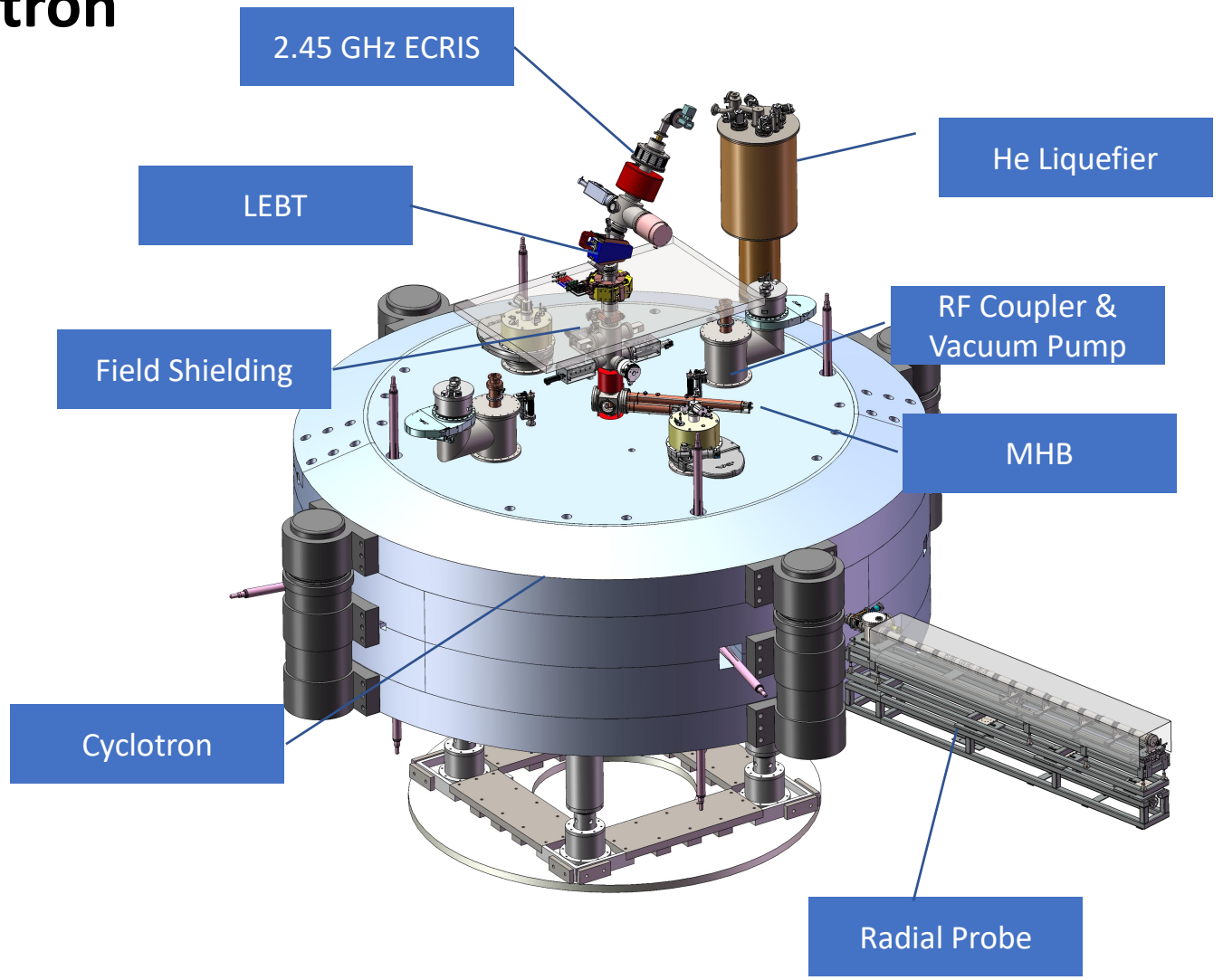
*R. Baartman. Intensity Limitations in Compact H− Cyclotrons

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- Summary

■Main parameters of SK1000 Cyclotron

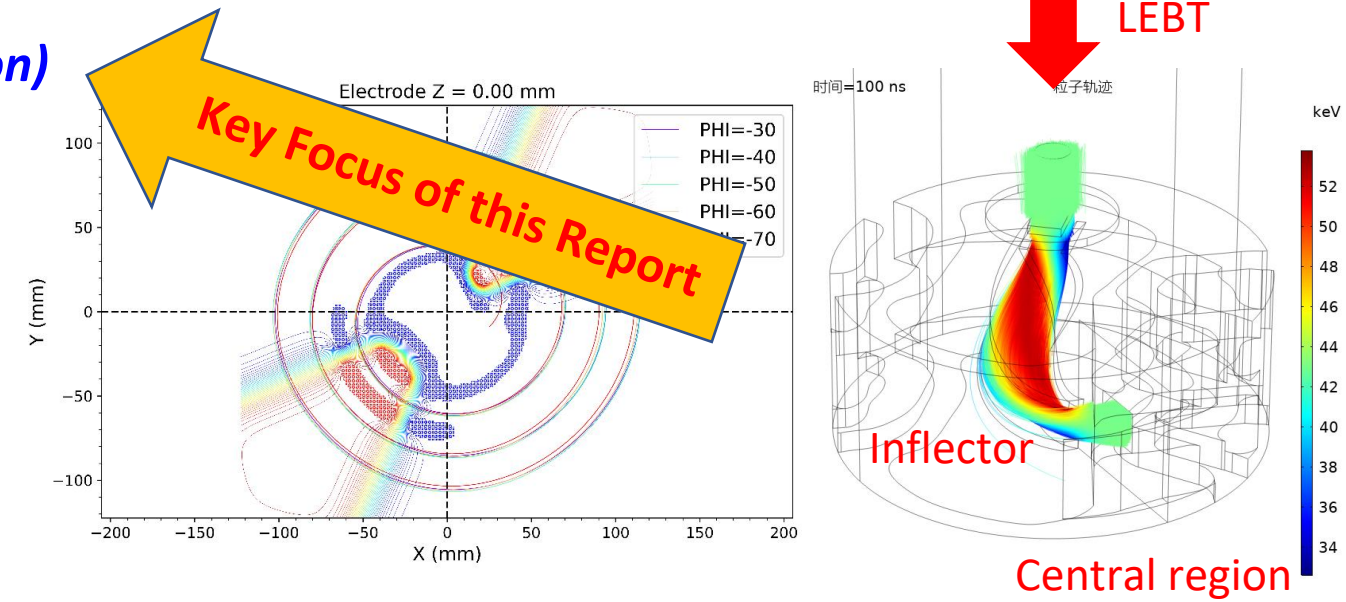
Parameters	Value
Acceleration Ion	H_3^+
Harmonic number	4
Injection	43 keV
Extraction energy	120 MeV/u
Extraction intensity	0.5~1 mA (proton)
Injection/Extraction radius	24 mm/2000 mm
Central Magnetic Field	2.175 T
Maximum Magnetic Field	3.129 T
RF Cavities	2*λ/2 resonant cavities
RF frequency	44.2 MHz
RF Voltage	85 kV (CR)
Sector shape	Spiral
Pole Gap (half)	~ 45 mm



Key issues and challenges

Challenges:

- ***High-intensity injection (LEBT and central region)***
  - Good match between LEBT and inflector;
  - High phase acceptance exceeding ±20°;
  - space charge effects;
  - Proper axial acceptance in central region;
  - Good beam orbit centering;
- ***Good Acceleration and excellent extraction***
  - Avoiding dangerous resonances;
  - The isochronism error should be less than 5 Gauss, making magnetic field measurement and shimming challenging;
  - Control the extraction envelope to achieve almost no beam loss;
- ***Stable RF system***
  - Large Dee/liner radii (~2m): difficult to guarantee manufacturing accuracy, precise installation, and reliable RF contact.
  - High dissipated power (56.03 kW): challenging water-cooling design.
- ……



- ***Superconducting Magnet***
  - Machining of large 5 m cryostat
  - Fine tuning of magnets
  - Quench protection(52 MJ Stored Energy)
  - Ensuring magnetic field quality after thermal cycling (warm-up and cool-down)

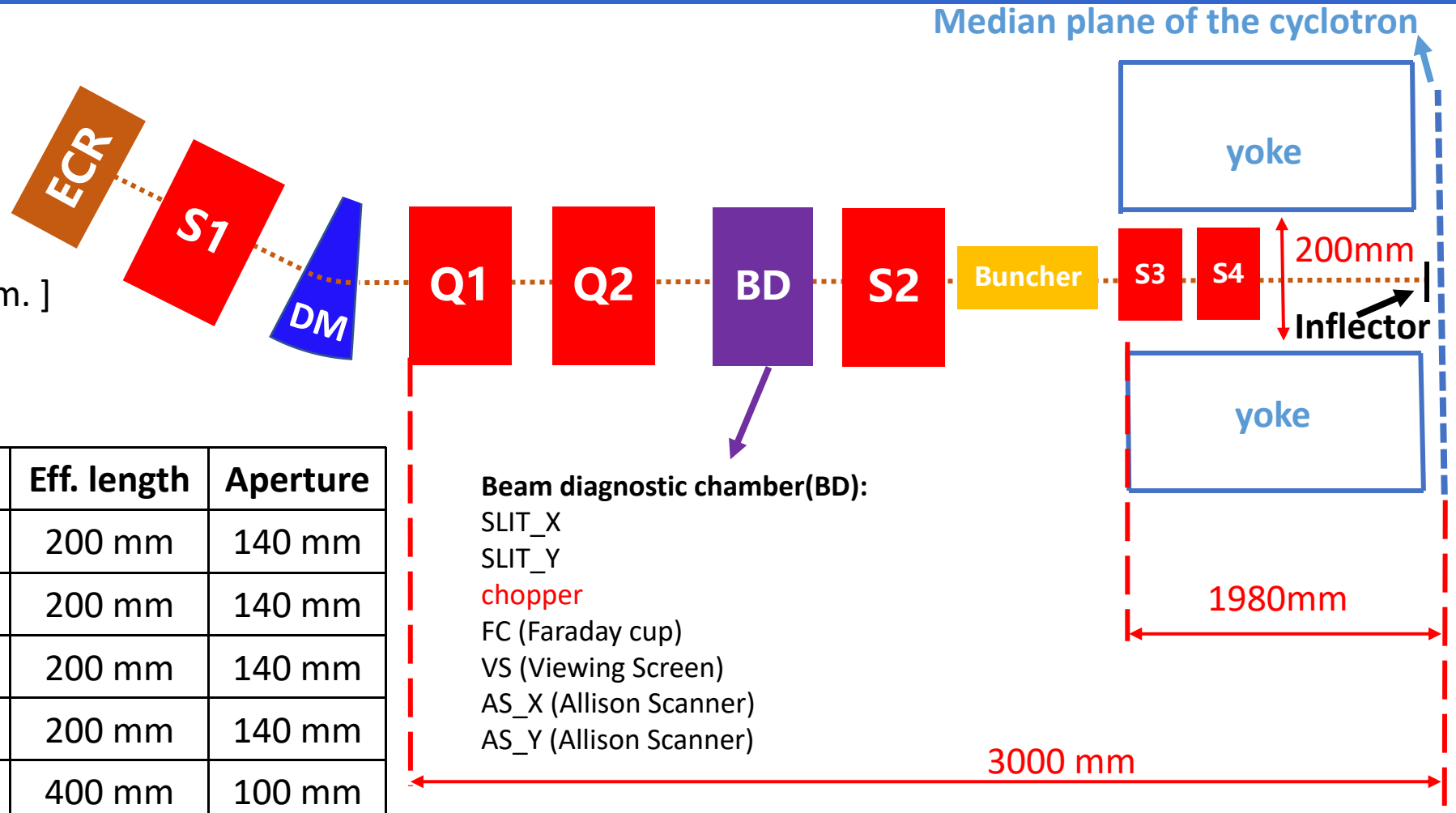
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Schematic of the SK1000 injection beam line

- Initial conditions
- Injection current: 0-5 mA
- Kinetic energy: 43 keV
- Bunch frequency: 44.2 MHz
- Twiss:
  - ε_{rms} = 0.2 π.mm.mrad [Norm.]
  - β = 0.44 mm/π.mrad
  - α = 0.0

Element	Field	Max. Field	Eff. length	Aperture
Q1	0.308 T/m	2.0 T/m	200 mm	140 mm
Q2	-0.31 T/m	2.0 T/m	200 mm	140 mm
S1	0.35 T	< 0.67 T	200 mm	140 mm
S2	-0.33 T	< 0.67 T	200 mm	140 mm
S3	0.30 T	< 0.32 T	400 mm	100 mm
S4	-0.31 T	< 0.32 T	400 mm	100 mm
Buncher	1.14	< 2.5 kV		60 mm

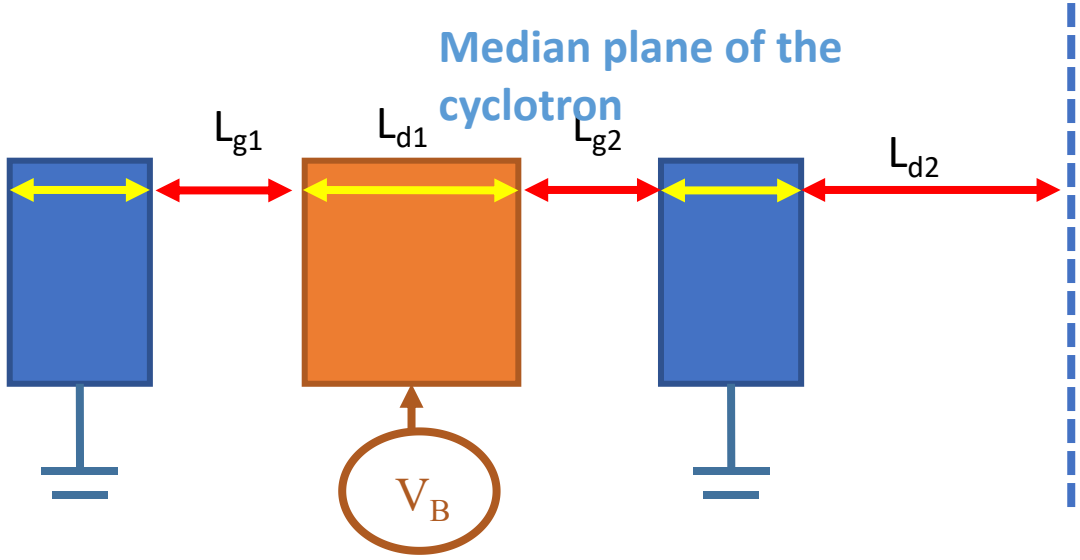


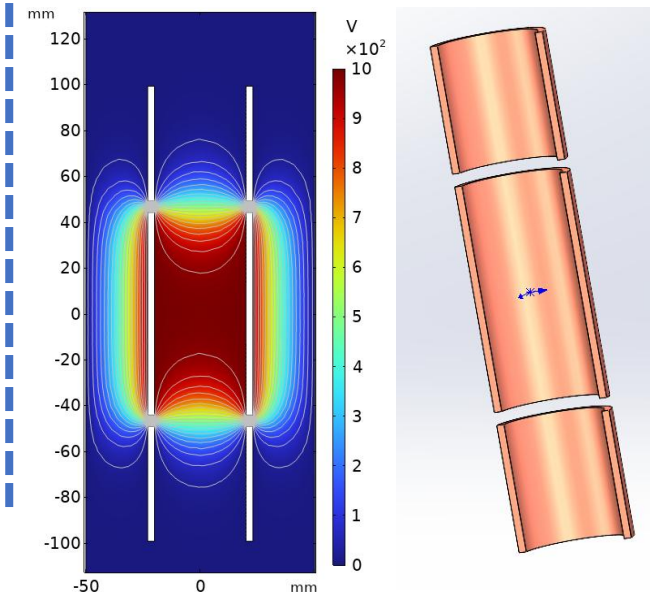
Design of the 5/2 βλ buncher

- **Basic Parameters**
- Rest mass m_o = 2815.209 MeV/c²
- Kinetic energy E_k = 0.043 MeV
- Charge state q = 1
- Frequency f = 44.205 MHz

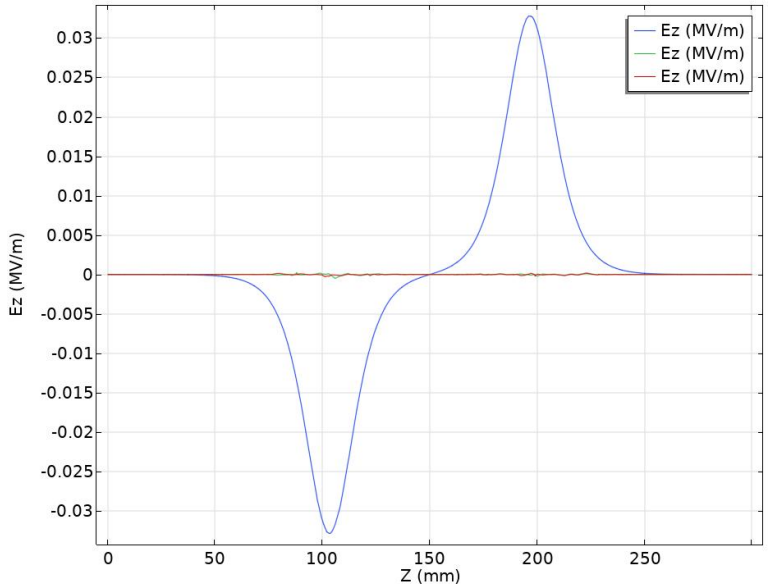
- **βλ is the actual path length traveled by the particle during one period of the RF electric field variation:**
- βλ = 37.48 mm
- 3/2βλ = 56.225560 mm
- 5/2βλ = 93.71 mm

This length is chosen so that $L_{d1}+L_{g1}$ is an odd integer multiple of the (N+1/2) βλ/2 in our case with N=2 and βλ= 37.48 mm.

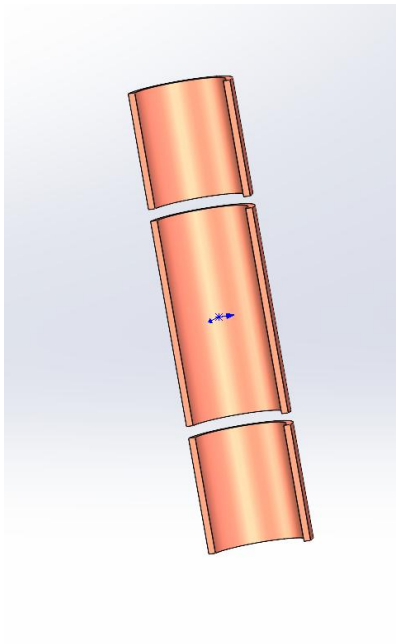


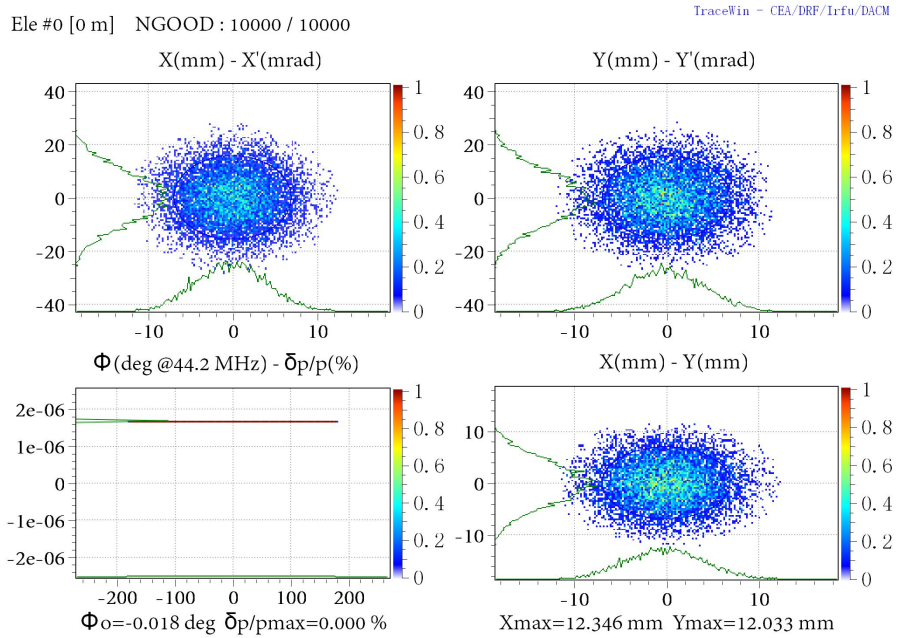


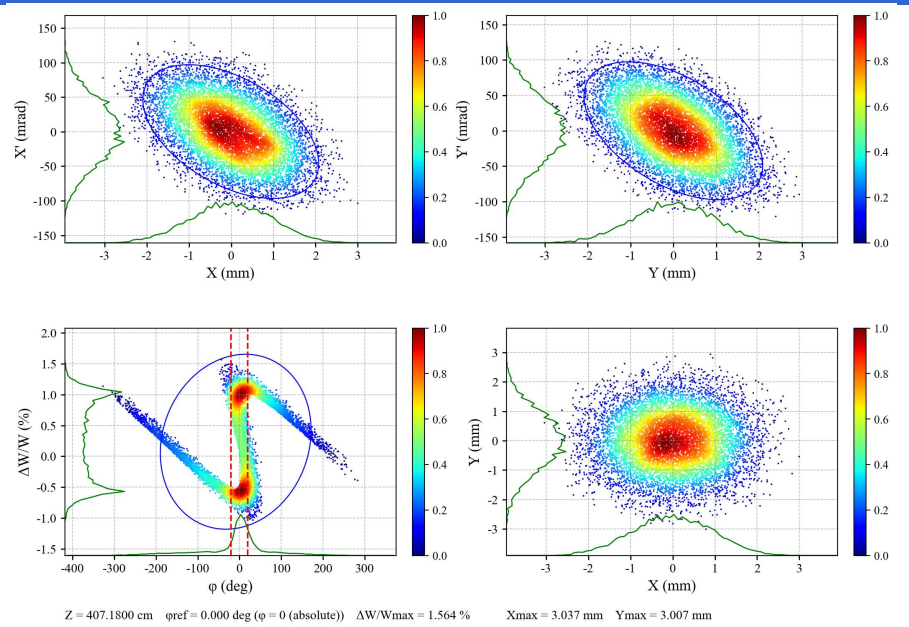
Element	Length(mm)	Diameter(mm)
GND1	40	40
L_{g1} (Gap1)	5	40
L_{d1} (Drift tube)	88.47	40
L_{g2} (Gap2)	5	40
GND2	40	40
L_{d2}	1950	

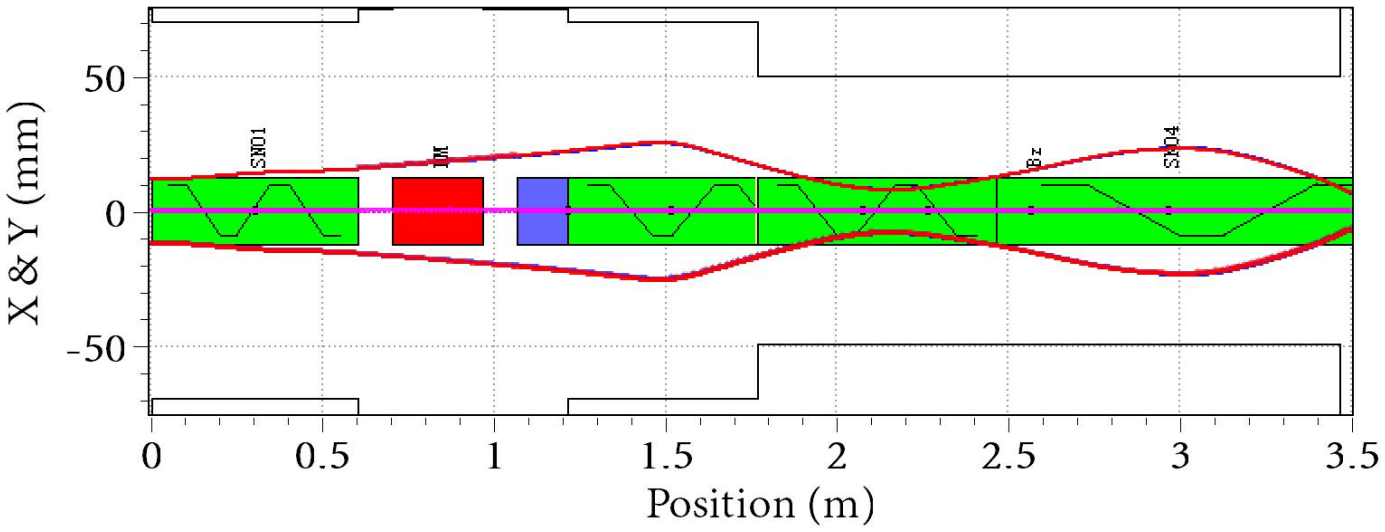


Buncher efficiency







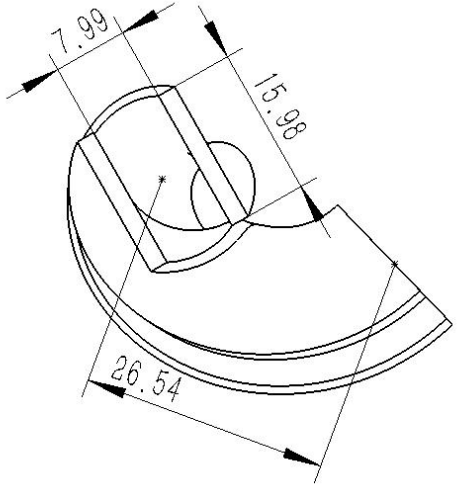


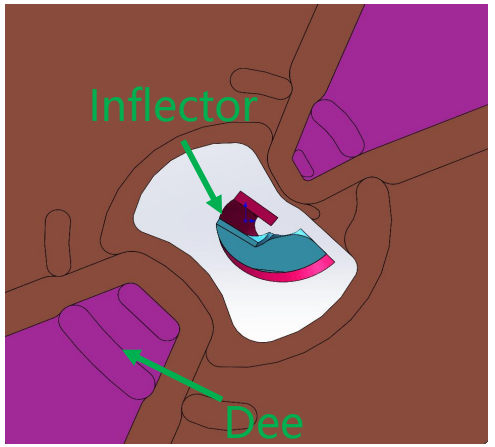
Current/mA	U1/kV	Bunching Efficiency |ϕ|≤20°
0	1.14	47.47%
0.5	1.14	44.23%
1	1.12	40.69%
1.5	1.13	36.56%
2	1.075	32.44%
3	1.06	26.44%

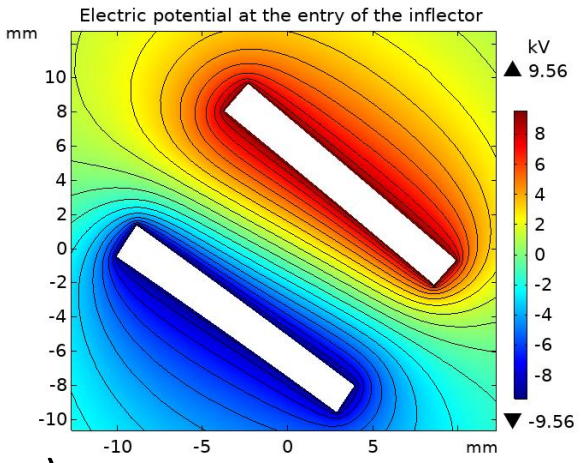
Spiral inflector design parameters

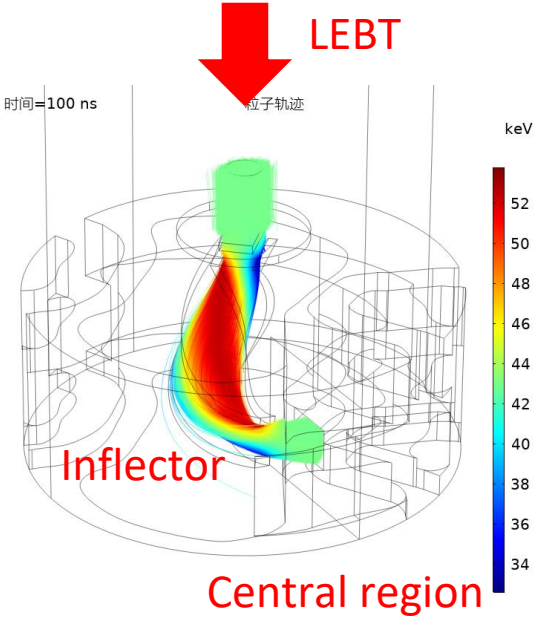
SK1000 inflector design parameters(H_3^+)

Parameter	Symbol	Value
Injection energy	E_0	43(KeV)
Magnetic field	B_0	2.175(T)
Magnetic radius	ρ	23.86(mm)
Voltage on the electrodes	V_d	±9.56(kV)
Maximum Central E-field	E_{max}	26.8(kV/cm)
Electric radius	A	36(mm)
Tilt parameter	k'	-0.52
Electrode gap at the entry	d_{en}	8(mm)
Electrode gap at the exit	d_{ex}	7.13(mm)
Width of the electrodes	l	16(mm)
Position at exit	r, θ	26.54(mm), 340(deg)

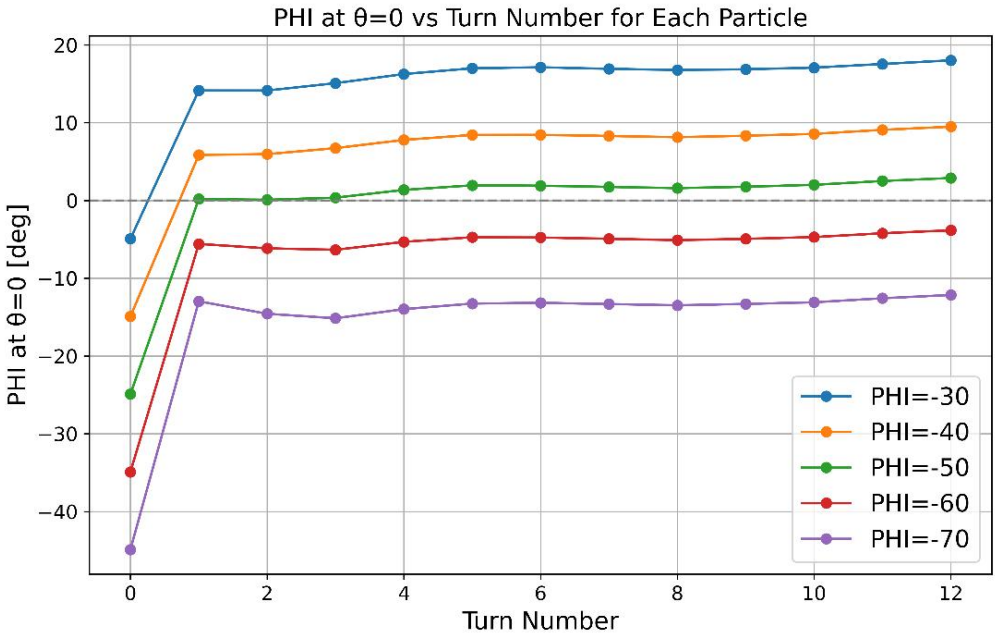


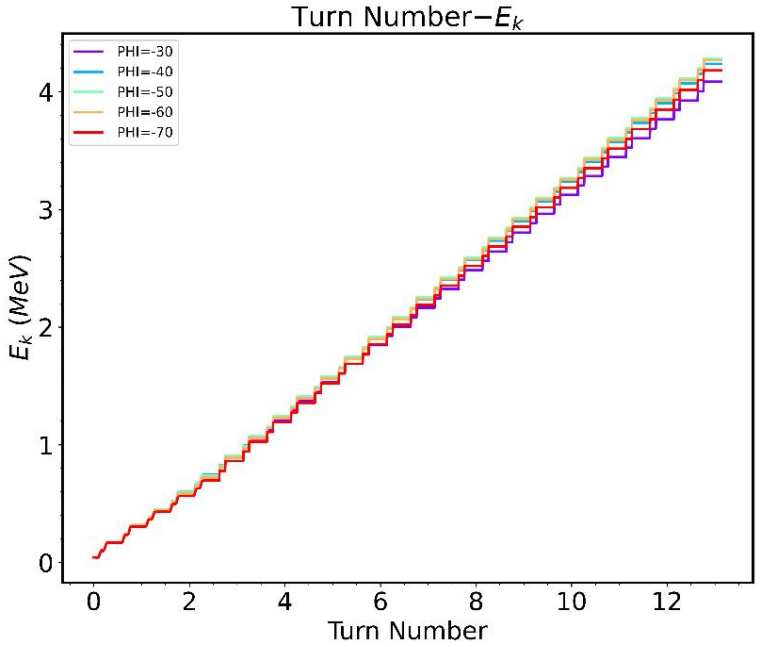


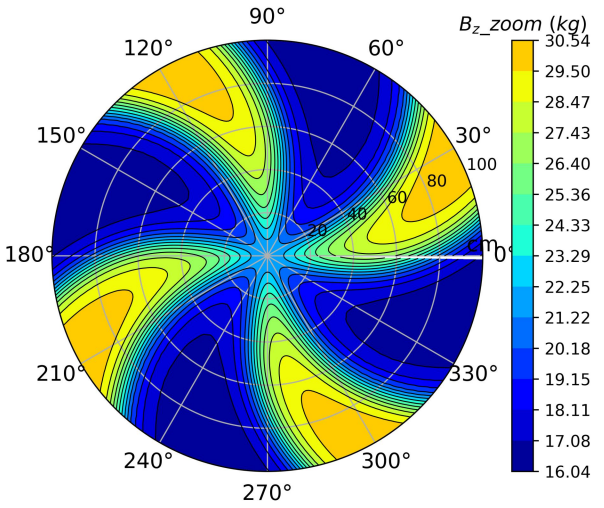


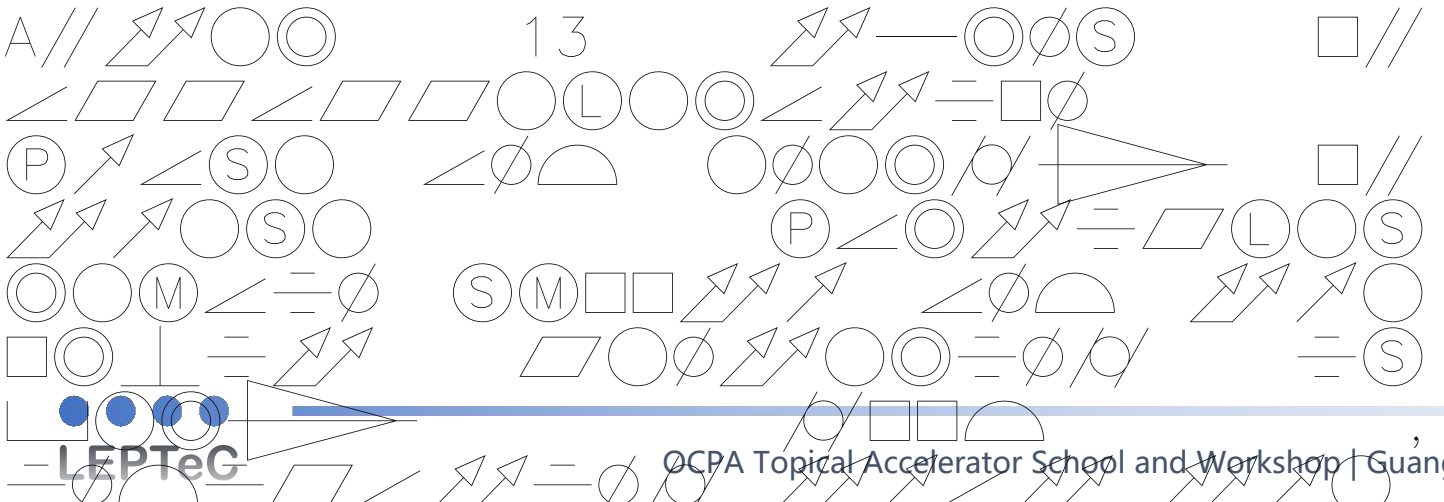


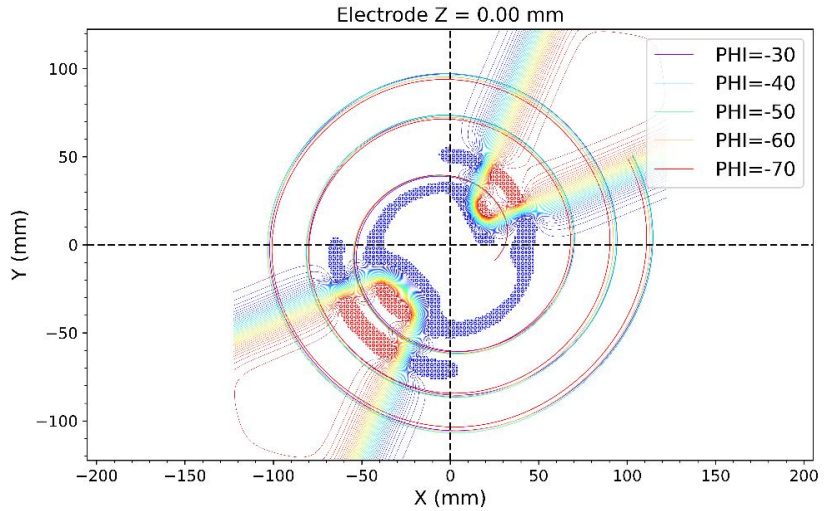
Single Particle Tracking of the Central Region



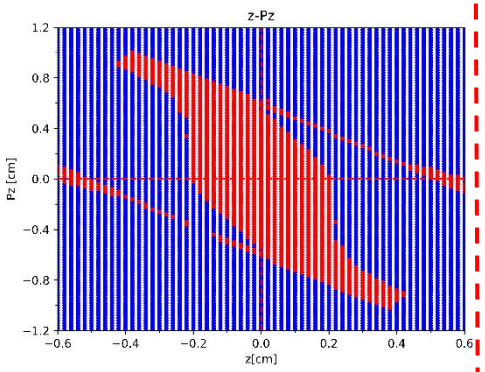
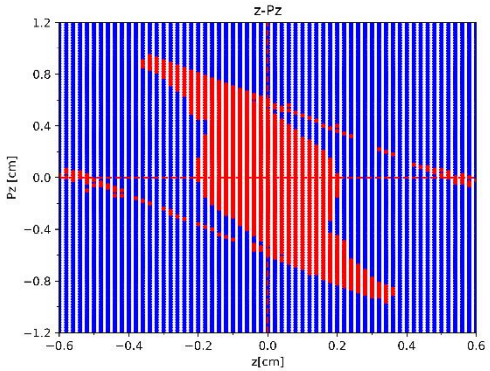
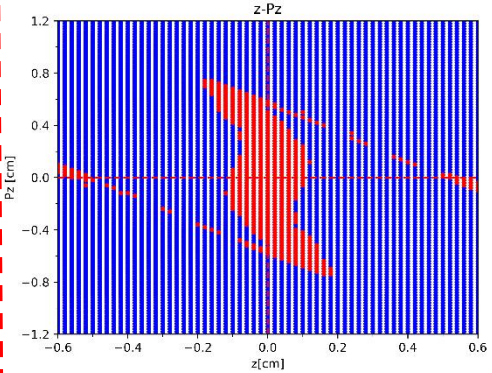
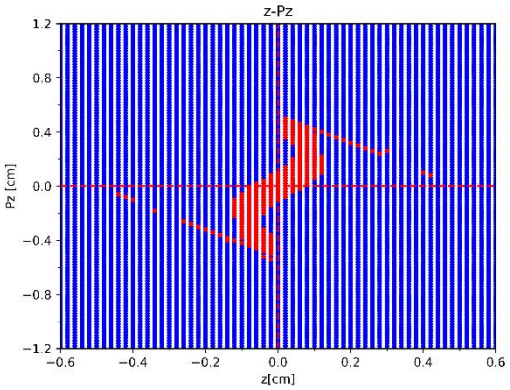
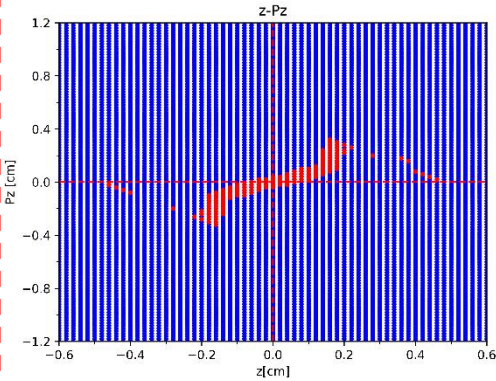








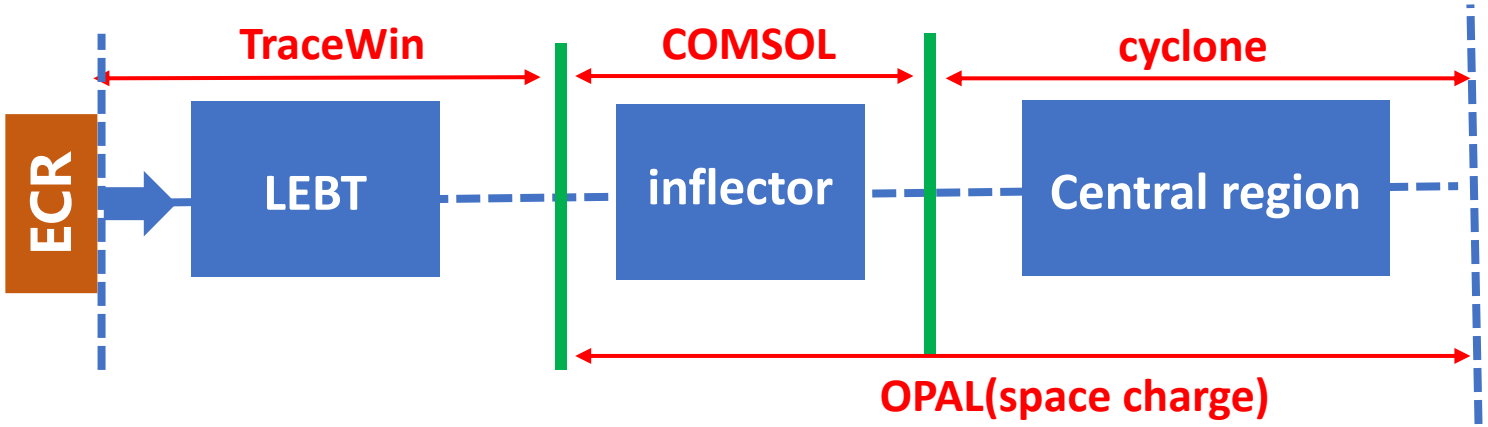
Axial Acceptance of the Central Region

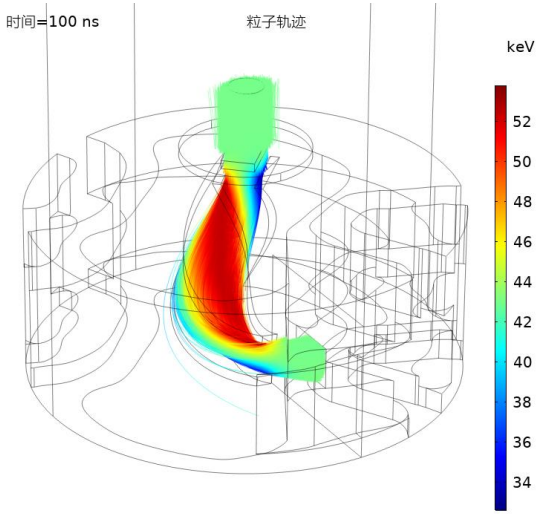
PHI = -30°	PHI = -40°	PHI = -50°	PHI = -60°	PHI = -70°
				
Z_emittance_rms = 321.8864 π·mm·mrad	Z_emittance_rms = 263.0766 π·mm·mrad	Z_emittance_rms = 242.591761 π·mm·mrad	Z_emittance_rms = 89.4883 π·mm·mrad	Z_emittance_rms = 67.081965π·mm·mrad

Outline

- Motivation and application
- Main parameters and challenges of SK1000 Cyclotron
- LEBT and Central Region Design
  - LEBT
  - Buncher
  - Spiral Inflector
  - Central region
- **Central region transmission efficiency calculation**
- Conclusions

Simulation workflow





■ Simulation workflow

1. Central region acceptance calculation:

- The inflector entrance is taken as the matching point between the LEBT and the central region. A large-divergence beam is injected at the inflector entrance, and the corresponding acceptance of the central region at the inflector entrance is calculated.

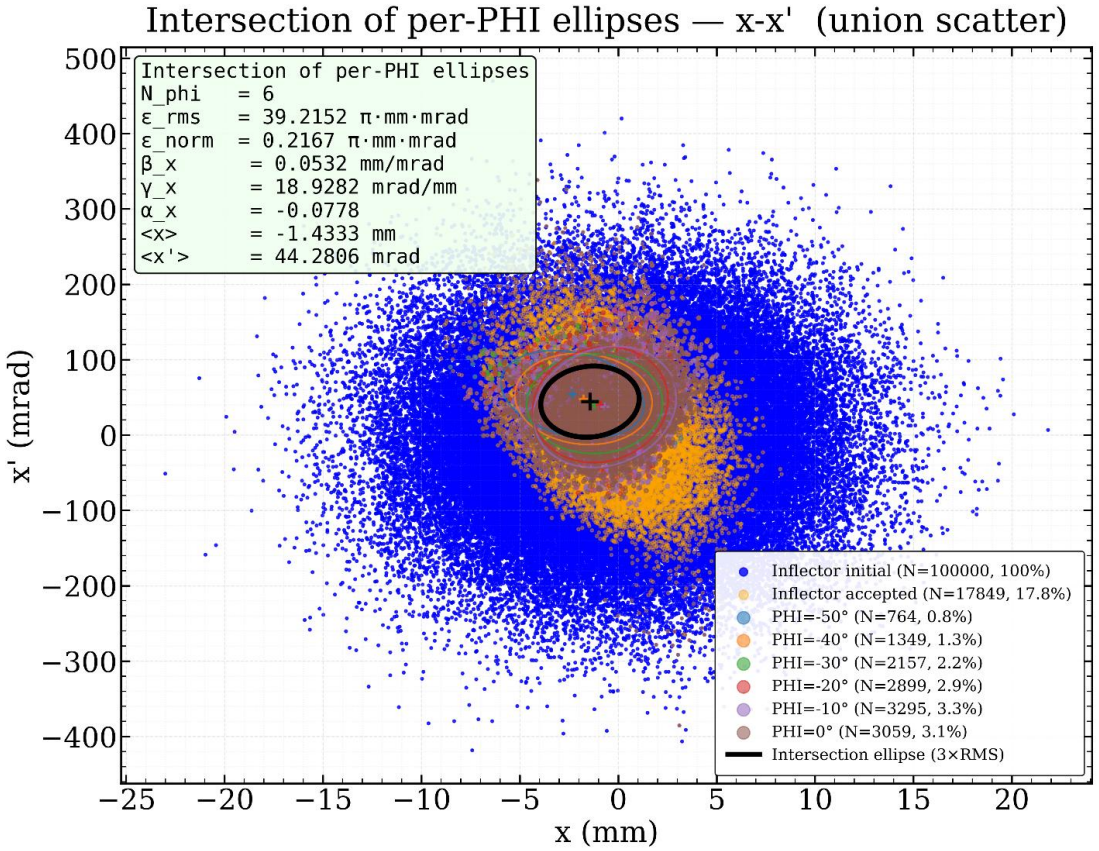
2. TraceWin bunching and phase space matching:

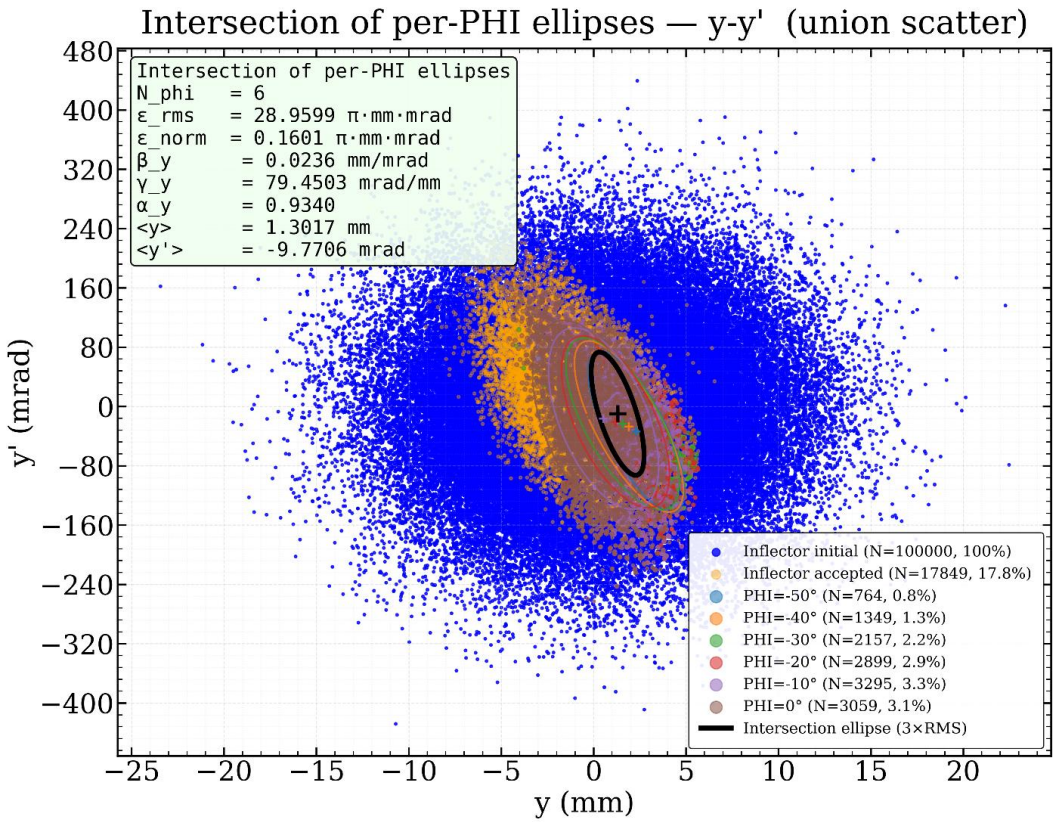
- Based on the acceptance calculated in Step 1, matching is performed in TraceWin. The required Twiss parameters at the matching point are determined, and a buncher is used to bunch the beam.

3. Central region transmission efficiency calculation:

- COMSOL and Cyclone are used to study the central region acceptance with and without the buncher. OPAL is then used for verification and to calculate the central region acceptance when space charge effects are taken into account.

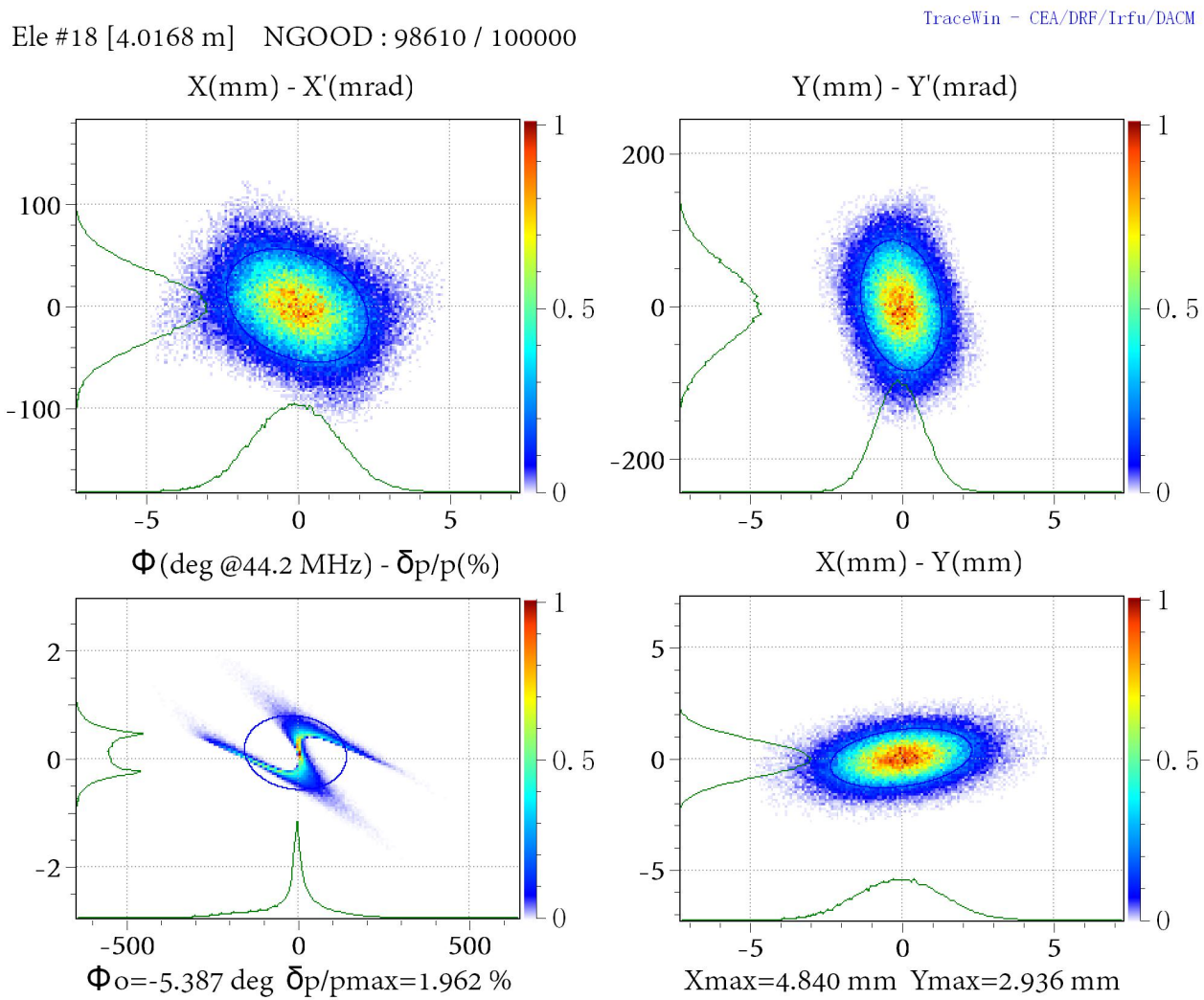
1- Central region acceptance calculation

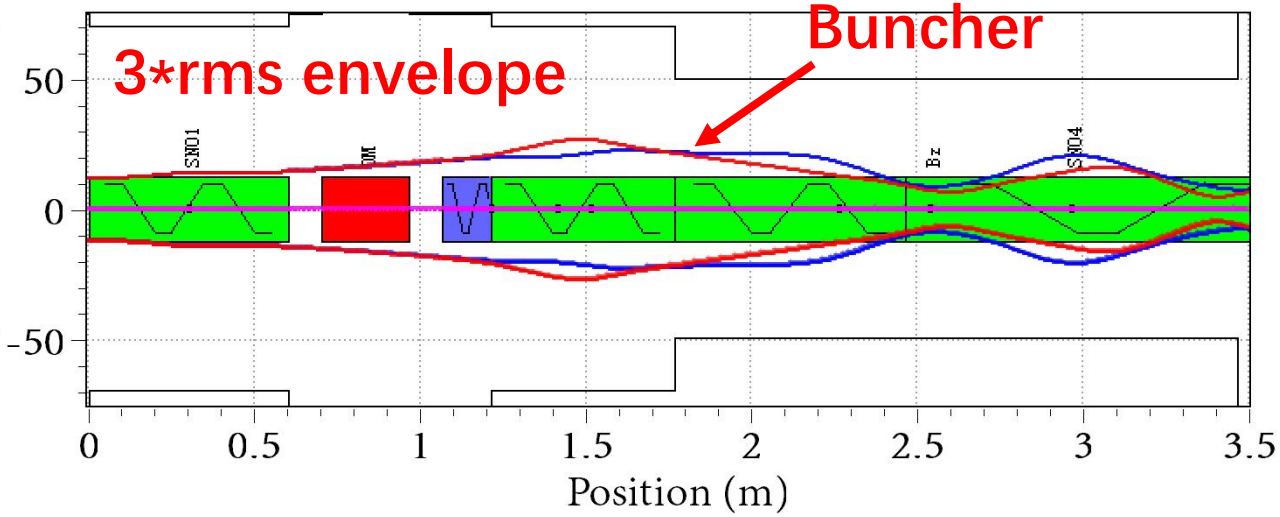




- Using different initial phases, the acceptance phase ellipses of the central region are obtained for each phase. The overlapping region of these ellipses is then defined as the matching point between the inflector entrance and the LEBT. The central region has different acceptance and Twiss parameters in the two transverse directions.

2 - TraceWin bunching and phase space matching





X-X'
Ɛrms = 0.230085 π.mm.mrad [Norm.]
Ɛ [77.39%] = 0.690255 π.mm.mrad [Norm.]
β = 0.043400 mm/π.mrad
α = 0.286158

Y-Y'
Ɛrms = 0.206709 π.mm.mrad [Norm.]
Ɛ [76.87%] = 0.620127 π.mm.mrad [Norm.]
β = 0.015870 mm/π.mrad
α = 0.206747

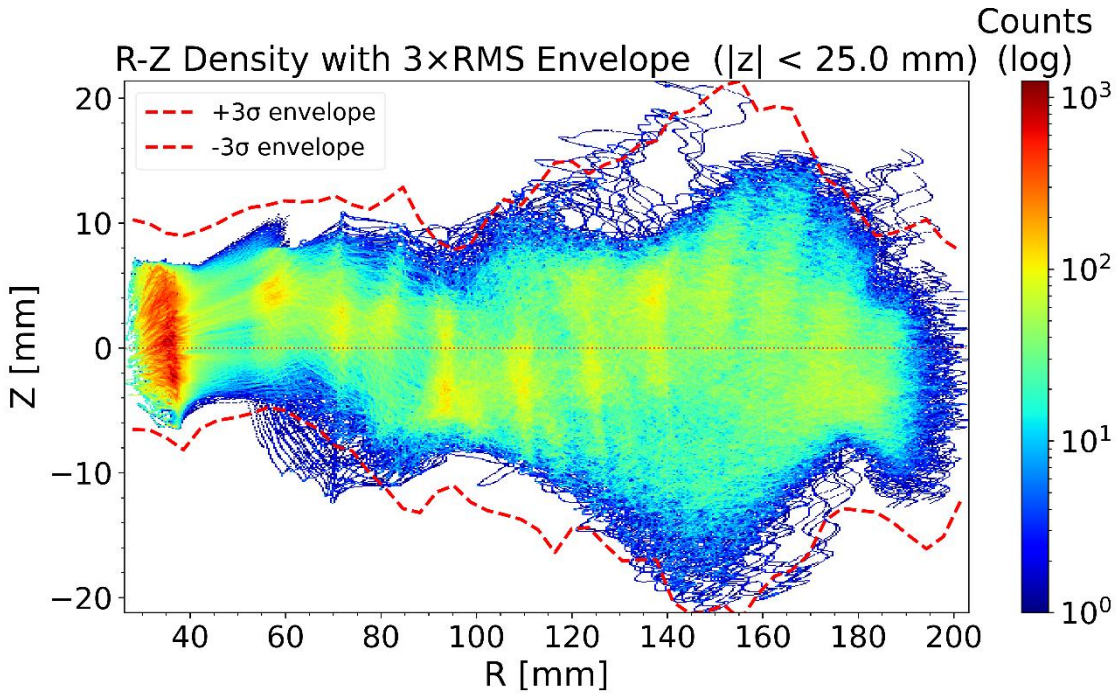
Φ-δp/p
Ɛrms = 0.186925 π.deg.% [Norm.]
Ɛ [81.51%] = 0.560775 π.deg.% [Norm.]
β = 217.640221 deg/π.%
α = 0.105059

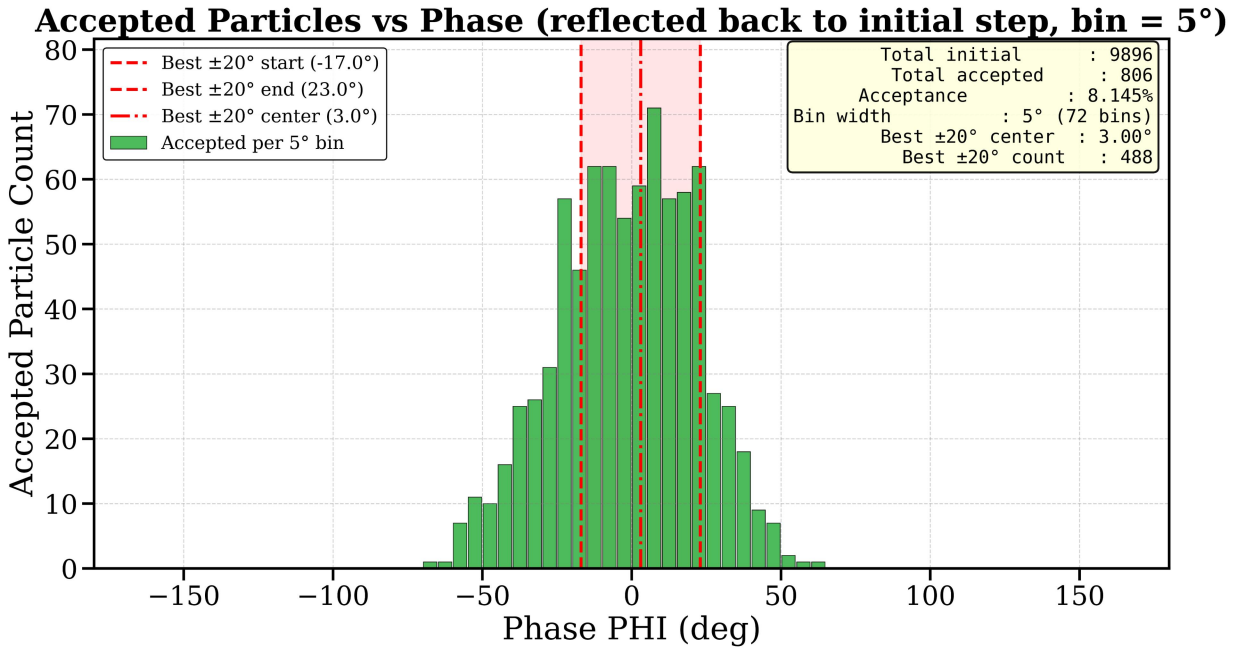
X-Y
Ɛrms = 0.998239 mm² [Norm.]
Ɛ [77.57%] = 2.994718 mm² [Norm.]
β = 1.810087
α = -0.276315

- The overall 3RMS envelope of the LEBT is less than 30 mm, and the envelope is relatively small at the buncher position.
- Use two quadrupoles to adjust the phase ellipses in the x and y directions so that the LEBT phase ellipse matches the inflector entrance.

3-Central region transmission efficiency calculation

☐ Without a buncher, using CYCLONE for calculation.



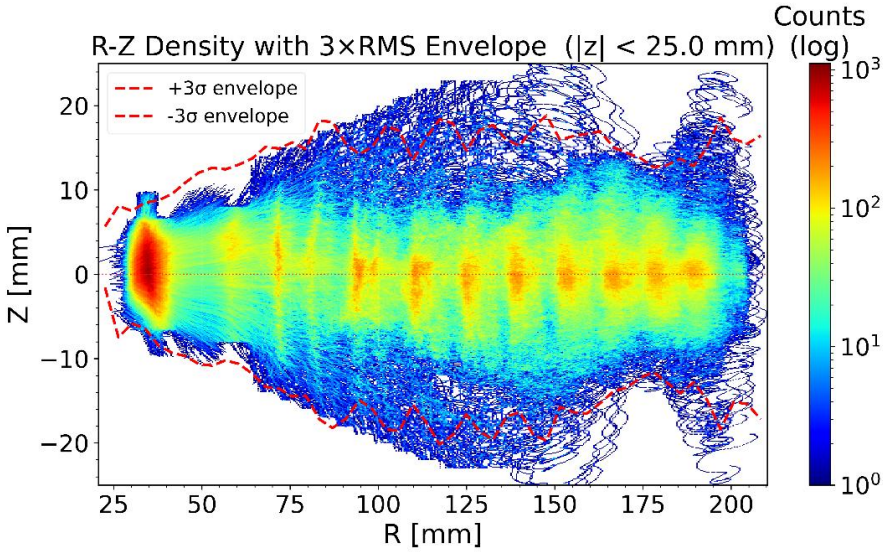


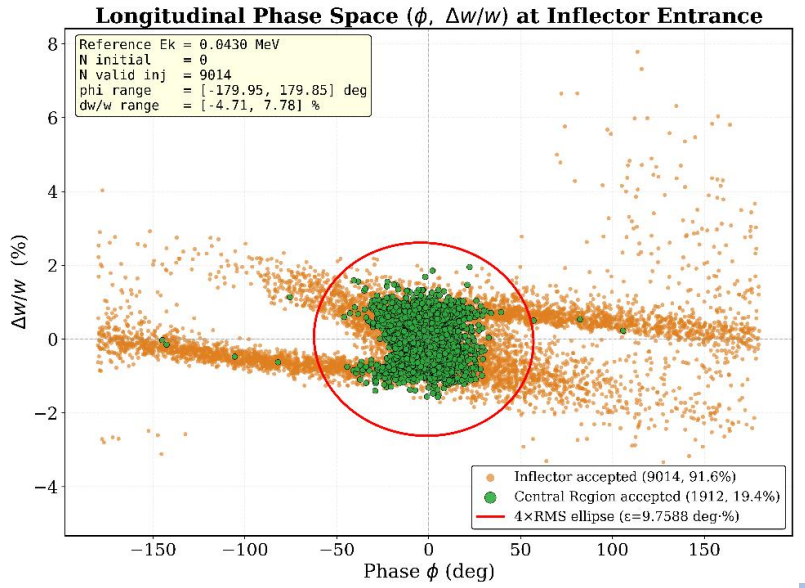
■ Without the buncher results

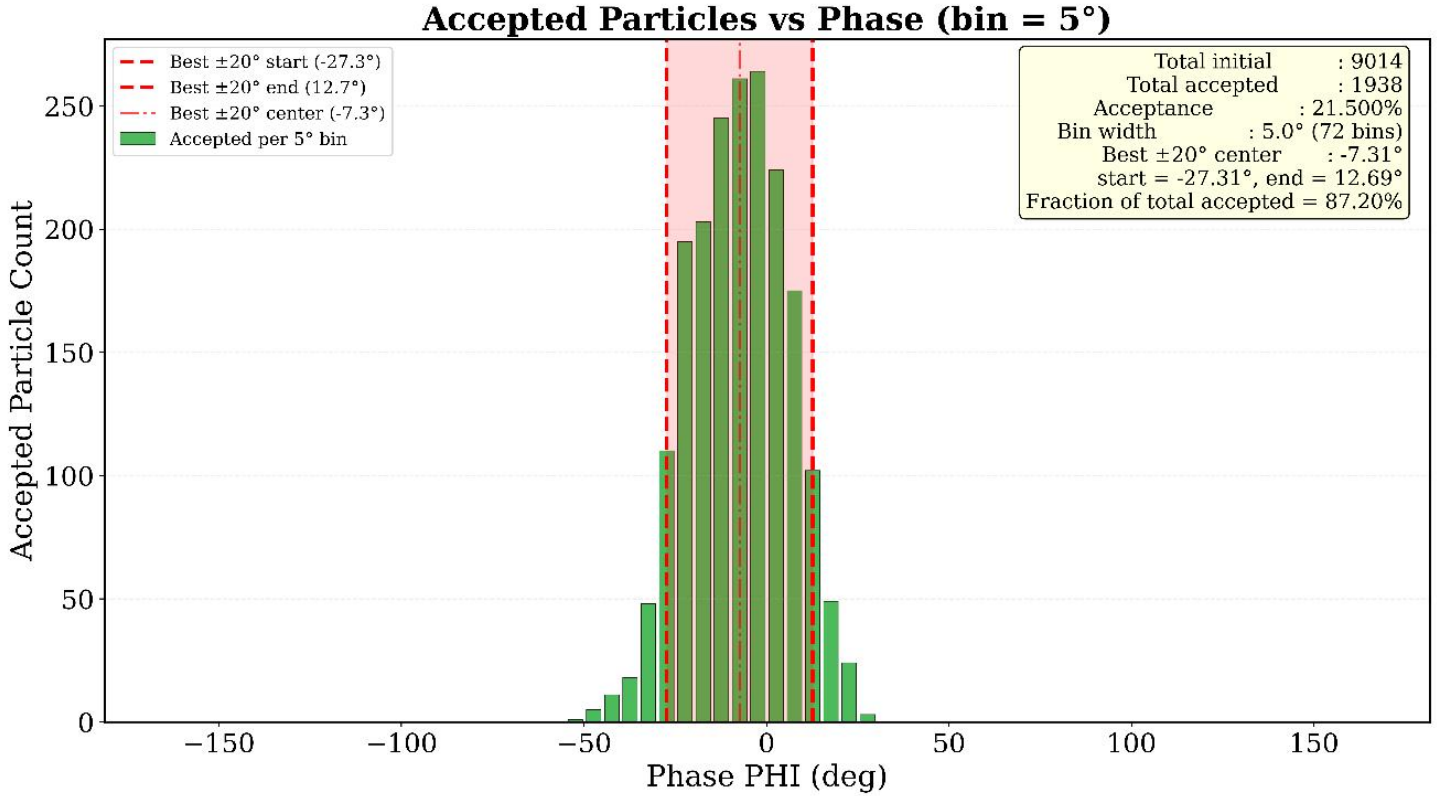
- Without the buncher (DC beam, initial phase width taken as 360°), the central region efficiency is 8.145%, the longitudinal acceptance is greater than ±20°, and the axial 3RMS envelope is within 20 mm, which is smaller than the beam aperture.

3-Central region transmission efficiency calculation

With a buncher, using CYCLONE for calculation.





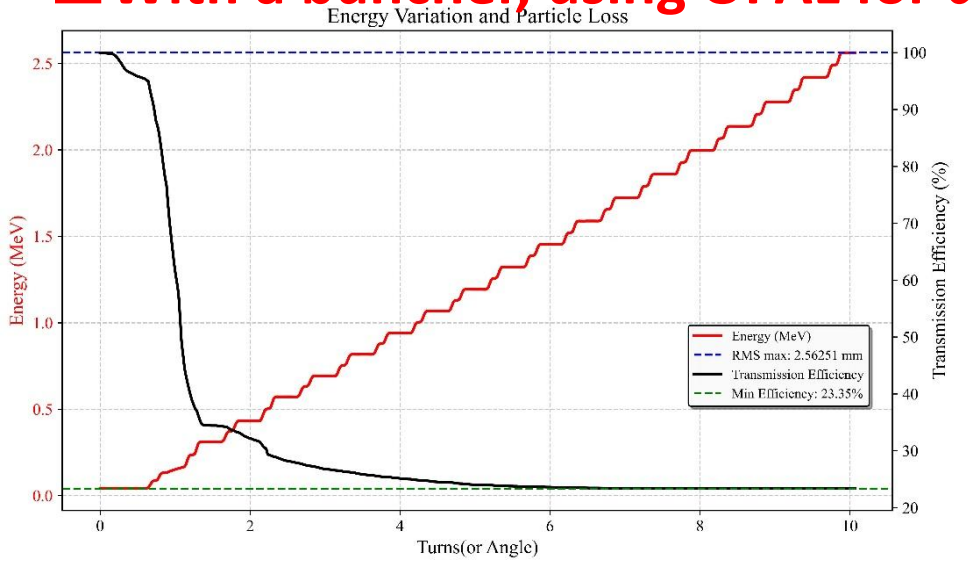


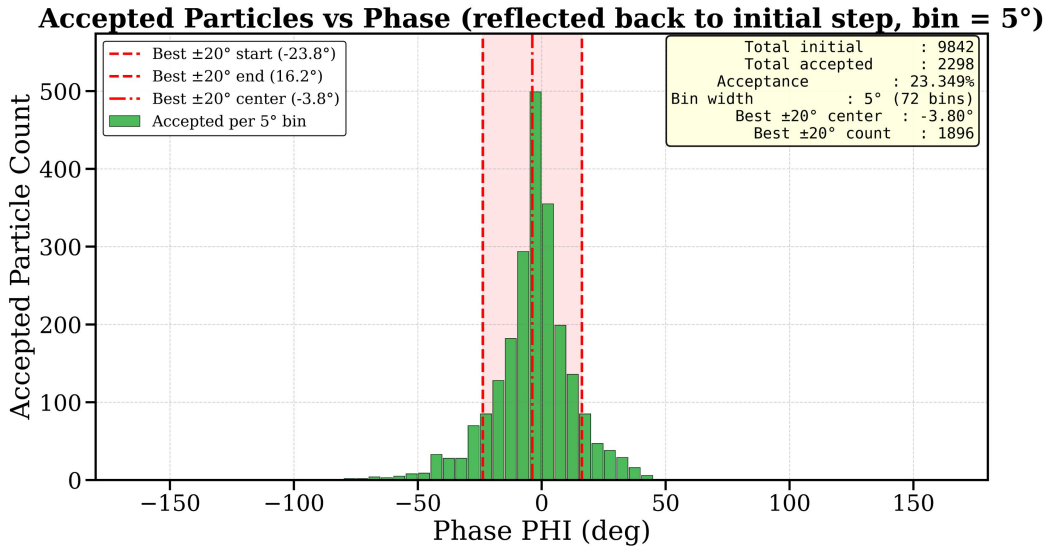
With the buncher results

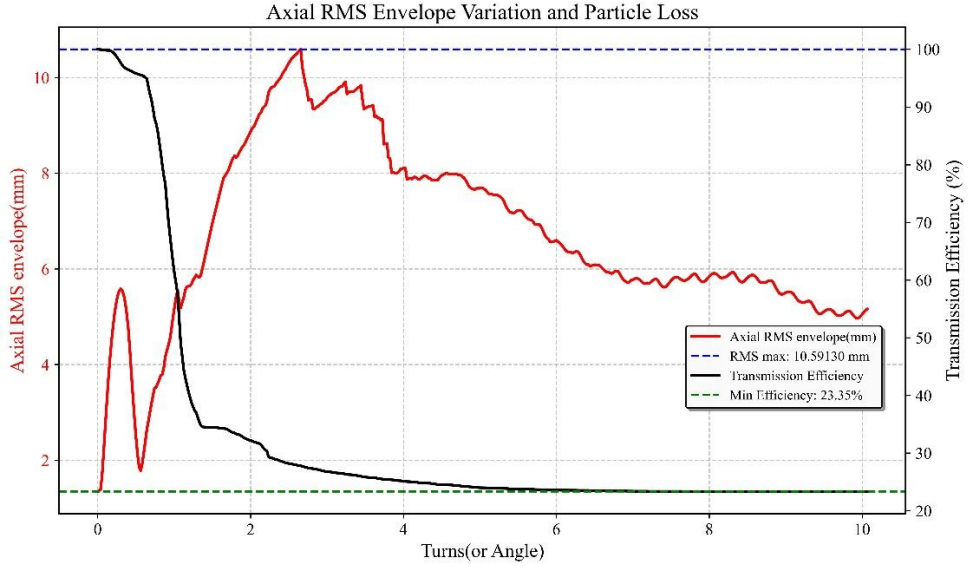
- With the buncher ,the central region efficiency is 19.4%, the longitudinal acceptance is greater than ±20°, and the axial 3RMS envelope is within 20 mm, which is smaller than the beam aperture.

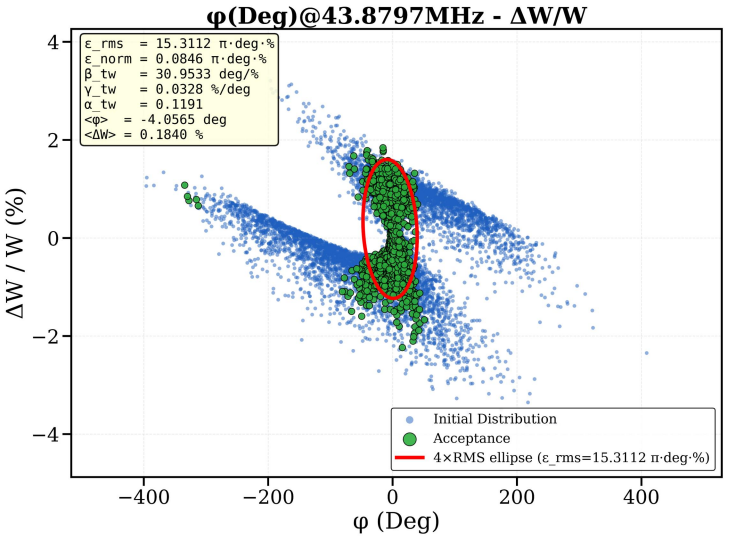
3-Central region transmission efficiency calculation

With a buncher, using OPAL for double check



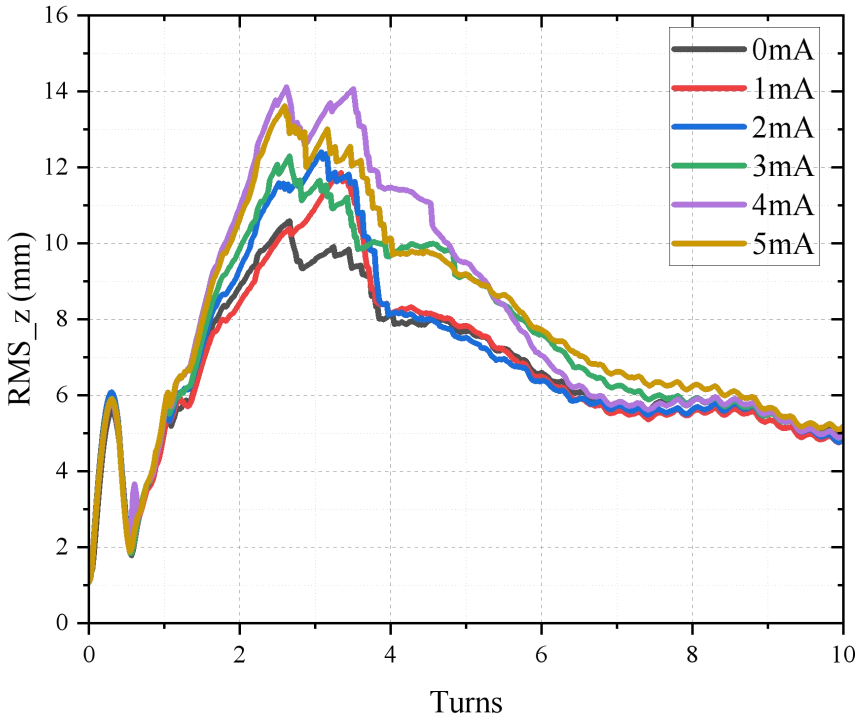


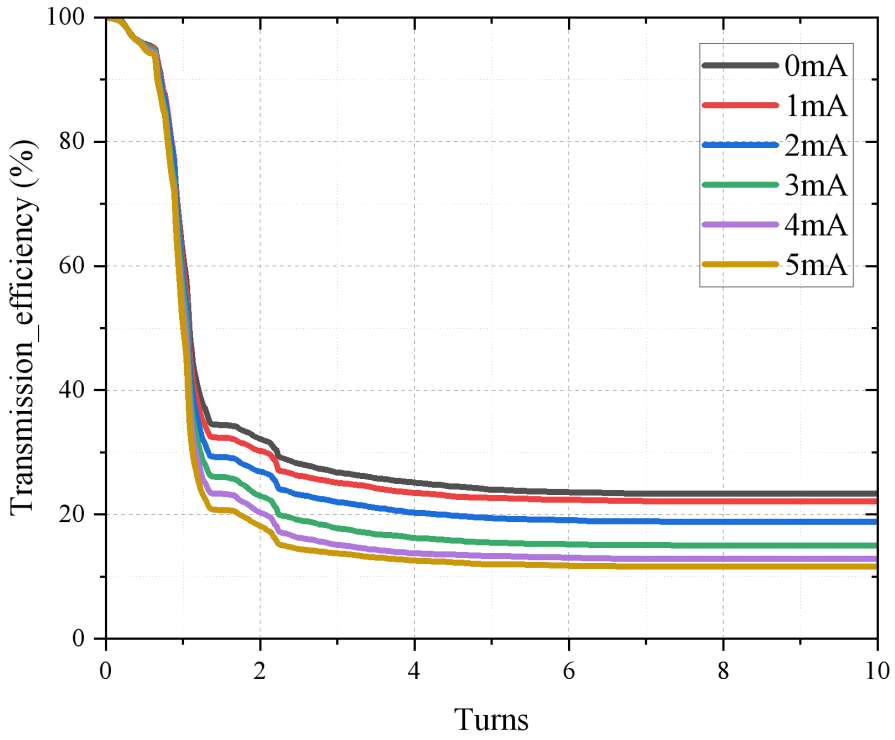




- **With the buncher results**
- Central region efficiency: 23.35% — comparable to Cyclone
- Longitudinal acceptance: > ±20°
- Axial 3RMS envelope: < 20 mm — within beam aperture

Multi-Particle Tracking(OPAL)





Injection Current	Transmission Efficiency	Accepted current
0 mA	23.35%	--
1 mA	22.11%	221.1 μA
2 mA	18.81%	376.2 μA
3 mA	15.00%	450.0 μA
4 mA	12.84%	513.6 μA
5 mA	11.59%	579.5 μA

- The simulation is done for the beam currents at 0, 1, 2, 3, 4, 5 mA respectively. For the space charge calculation, 10^4 macro-particles and a 16^3 rectangular grid are used in the simulations.
- For the 2 mA beam current, both the axial envelope and the transmission efficiency still meet our design requirements.
- Preliminary estimate: maximum H_3^+ current ~500 μA

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- **Conclusions**

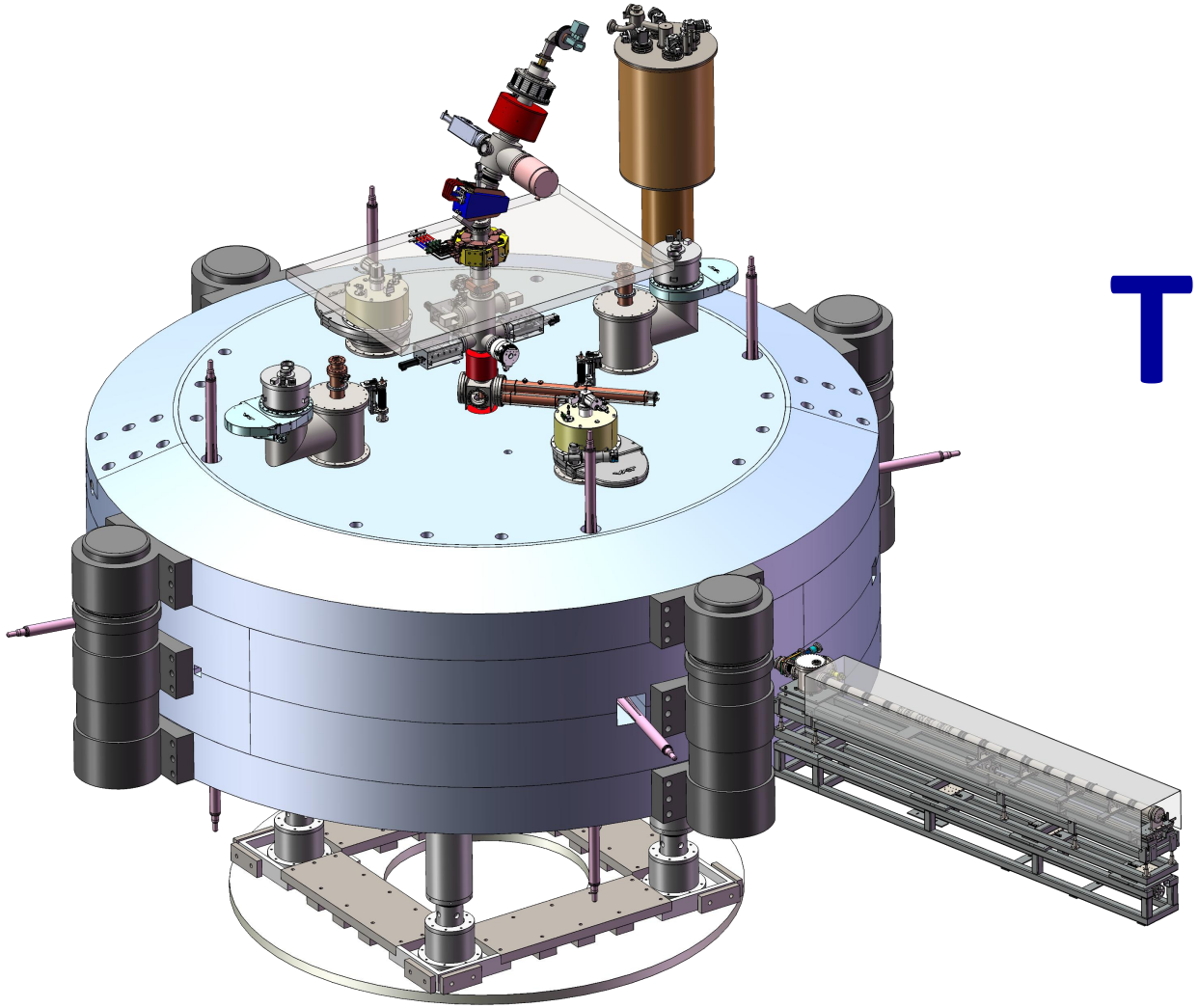
Conclusions

■ Conclusion

- H_3^+ offers a promising route to overcome Lorentz stripping limits for high intensity compact cyclotron.
- The design study of a high-acceptance central region (>±20°) for a ~500 μA, 120 MeV/u H_3^+ superconducting cyclotron has been completed.
- Many challenges still remain, and more efforts are needed.

■ Future plan

- Apply special treatment at high particle-loss locations in the central region (e.g., water cooling or high-Z materials).
- Advance engineering design of the injection line and central region.



Thanks for your attention!

Q&A