Feasibility Study on 10MW-Class Ultra-High Power Cyclotron (UHPC-10MW)

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China Institute of Atomic Energy(CIAE)

2022.12.9

Plan of Talk

- Background
- Advantages and difficulties of cyclotron based high power accelerator
- Preliminary physical design of 150MeV/amu injector
- Preliminary physical design of 1GeV/amu ring cyclotron
- Summary and thanks

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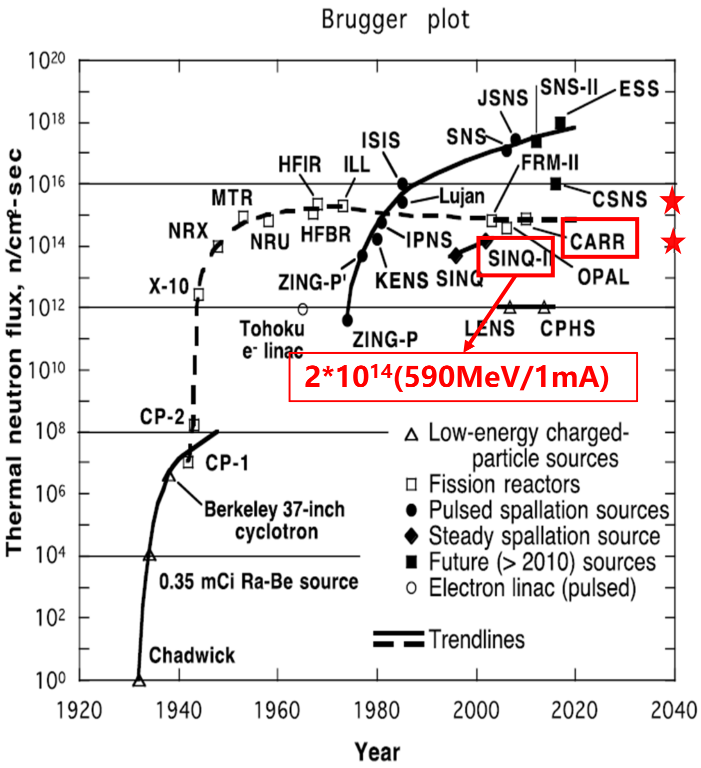
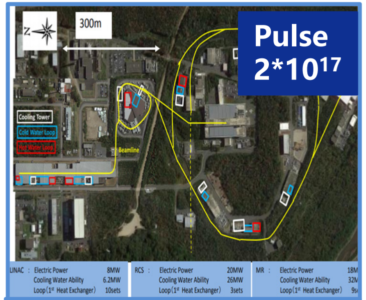


John M. Carpenter，Accelerator-based Neutron Sources: Past, Present, and Future, October 2018

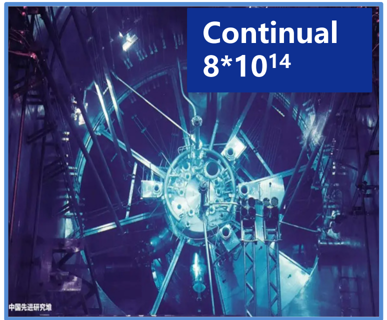


JPARC(3GeV/1.4MW)

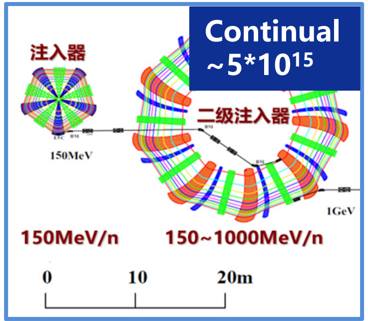
CSNS(1.6GeV/100kW)

SNS(1GeV/1.4MW)

SINQ(590MeV/1.4MW)



CARR(60MW)



CIAE(10MW)

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SC linac: Mainstream

- Linac with several MW is still under development : CiADS, ESS
- Relative higher technical maturity
- High cost, large ground occupation

synchrotron : High energy

- Low average current, limited by cycling frequency
- Low beam/grid efficiency
- large ground occupation

Circular accelerator : CW

- CW beam, high average current, ~3mA.
- bottleneck problems: energy and current are limited.

	Circular accelerator		SC linac	synchrotron
	Cyclotron	FFAG		
Time structure of beam	CW/pulse	CW/pulse	CW/pulse	pulse
Magnetic field	Varying	constant	---	Varying
Frequency of cavity	Constant	Varying/constant	Varying	constant
Trajectory	Varying	Varying	Constant	Constant
Maximum energy	<1GeV	>1GeV	>1GeV	>1GeV
average current	high	high	high	low
Size	compact	medium	large	large
manufacturing cost	low	medium	high	high
beam/grid efficiency	high	high	low	low

Summary

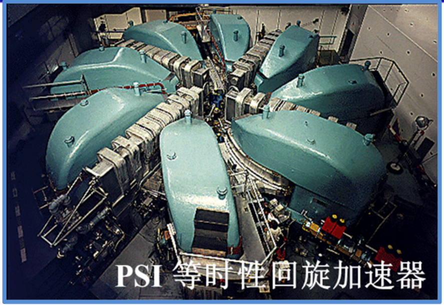
Beam power efficiency

- Beam power efficiency is an issue for high intensity accelerator.

$$BPE = \frac{\text{beam power } (E \times I_{beam})}{\text{total operatonal power}}$$

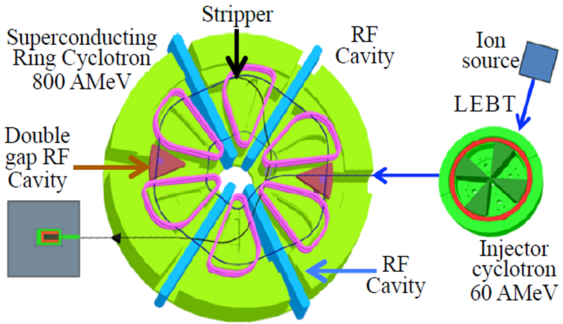
- BPE>30% for P_b>10MW, otherwise
  - Environment problem: CO_2
  - ADSR becomes nonsense ; Creating nuclear wastes more than treating!
- Superconducting magnet
  - High temperature SC is very attractive.

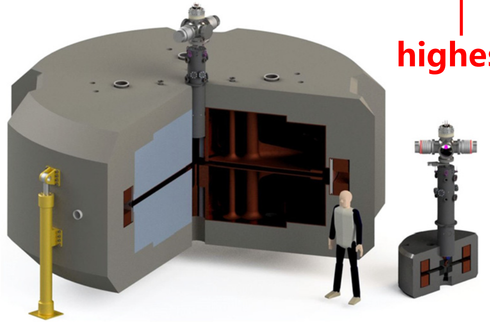
W. Weng, Developments of High Power Proton Accelerators, BNL, 2018



Institute	Accelerator	Energy (MeV)	Current (mA)	Frequency (Hz)	Power(MW)	Efficiency
ORNL	SNS	1000	1.3	60	1.3	8.6%
KEK	J-PARC	3000	0.33	25	1.0	3%
PSI	SINQ	590	2.4	CW	1.4	18%

highest

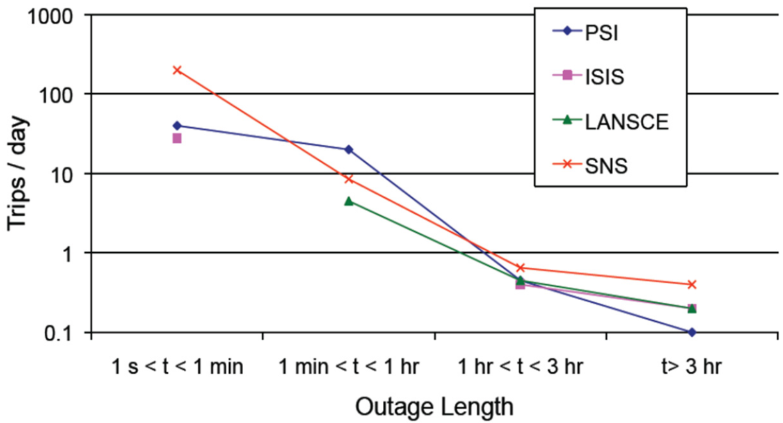


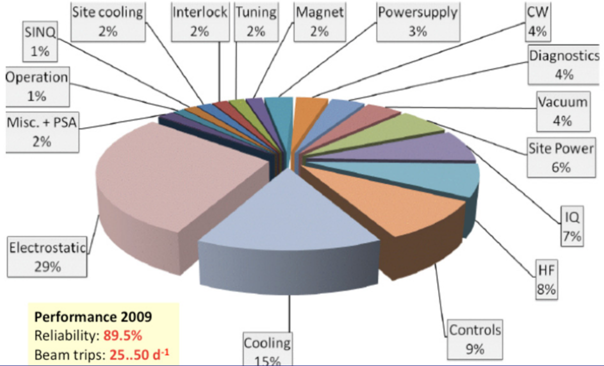


Efficiency of DAEδALUS cyclotron Superconducting Ring Cyclotron(SRC) is expected to be 60% and 65%.

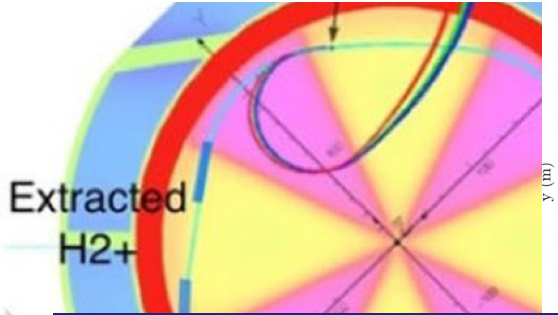
LUCIANO CALABRETTA, CYCLOTRONS AND FFAG ACCELERATORS AS DRIVERS FOR ADS, BNL-111770-2016-JA

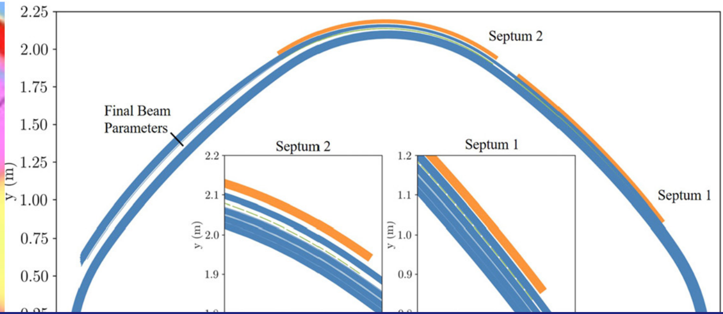
	Transmutation test	Industrial grade transmutation	Industrial grade Energy storage	Industrial grade grid connected
Beam power	1~2 MW	10~75 MW	10~75 MW	10~75 MW
Beam Energy	0.5~3 GeV	1~2 GeV	1~2 GeV	1~2 GeV
Time structure	pulse/cw	cw	cw	cw
Beam trip (t<1s)	N/A	<2.5e4/y	<2.5e4/y	<2.5e4/y
Beam trip (1-10s)	<2500/年	<2500/y	<2500/y	<2500/y
Beam Trip (10s-5m)	<2500/年	<2500/y	<2500/y	<250/年
Beam trip (t>5m)	<50/年	<50/年	<50/年	<3/年
Availability	>50%	>70%	>85%	>90%





LUCIANO CALABRETTA, CYCLOTRONS AND FFAG ACCELERATORS AS DRIVERS FOR ADS, BNL-111770-2016-JA



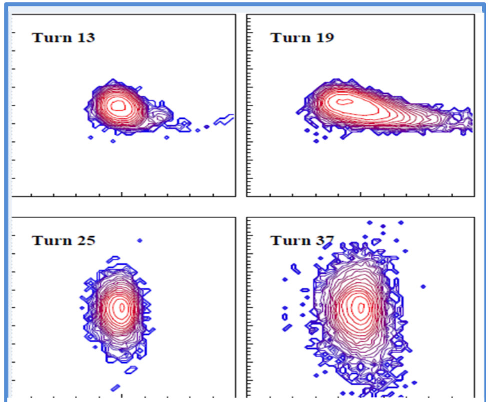


H_2^+ particles that would hit the septum are broken up into protons by means of a narrow stripper foil placed upstream of the septum.

DanielWinklehner1, JanetMConrad, Devin Schoen, Order-of-magnitude beam current improvement in cyclotrons, New J. Phys. 24 (2022) 023038

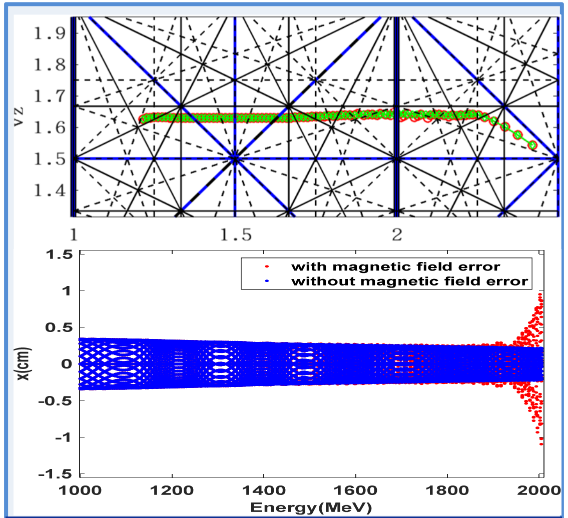
Bottleneck problem of Ultra-High Power Cyclotron (UHPC)

- **In low energy region**: Halo is induced by strong space charge effect and nonadiabatic acceleration.
- **In high energy region**: Beam energy is limited by integer resonance.
- **In extraction region**: For 1GeV/10mA beam, relative losses should less than 2E-5. (Upper limit: 200W)

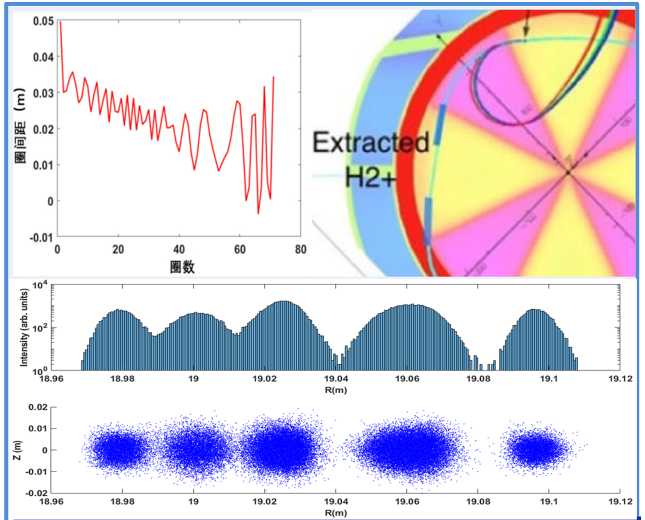


$$K = \frac{qI\cdot(1-\gamma^2 f_e)}{2\pi\epsilon_0 m\gamma^3\beta^3},$$

Accelerating 5 mA of H_2^+ instead of 10 mA of protons.



Accelerate beam to beyond the integer resonance



Extraction with low power deposition is the key problem of the upper limit of current.

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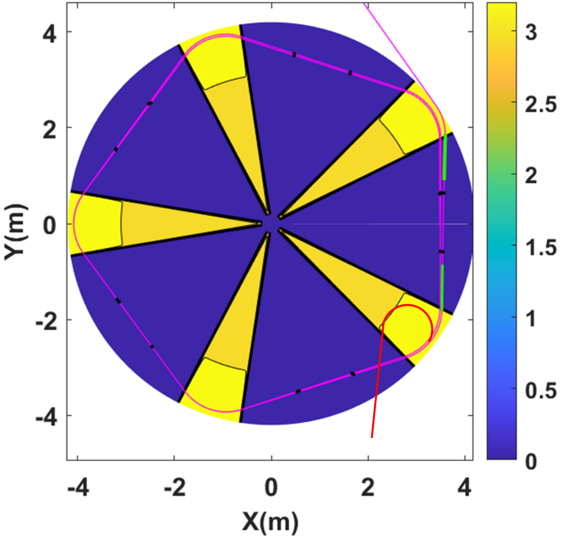
Injector

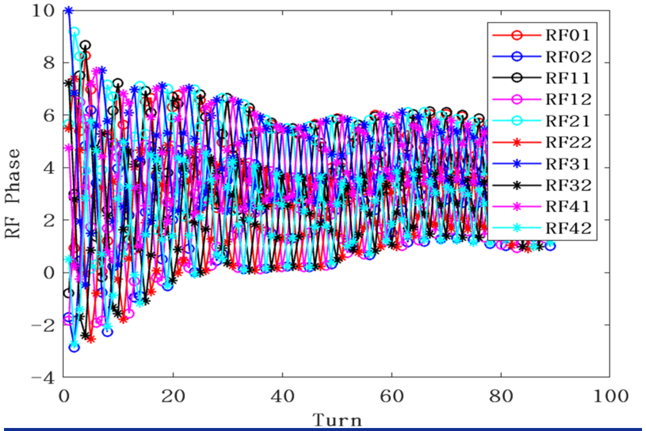
- 5 sectors, superconducting technology.
- Generous space between neighboring sectors can be used to install 5 powerful RF cavities.
- Beam is injected radially by a 1MeV/amu RFQ pre-injector.
- Electrostatic deflector with a stripper foil placed upstream is used to high efficiency extraction.



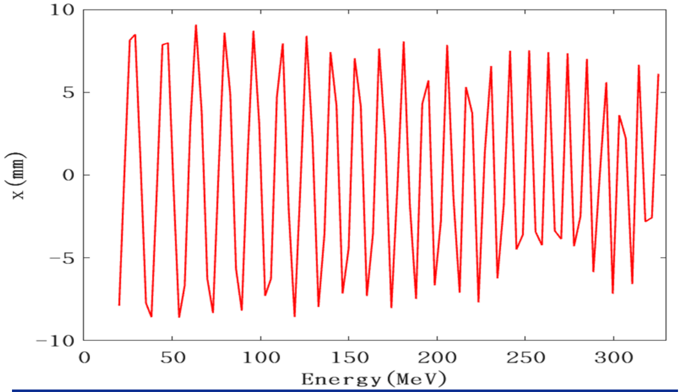
Parameter	value	Parameter	value
Accelerating particles	H2+	Radius of pole	4.2m
Extraction particles	H2+	Cavity number	5
Injection energy	1MeV/amu	Harmonic number	7
Extraction energy	160MeV/amu	Cavity frequency	~57MHz
Extraction type	Electrostatic deflector	Cavity Voltage	~350kV
Turn separation at Extraction	~3cm	Energy gain per turn	~3.4MeV
Magnet sectors	5		
Magnetic field of hill	3~3.7T		

Injector

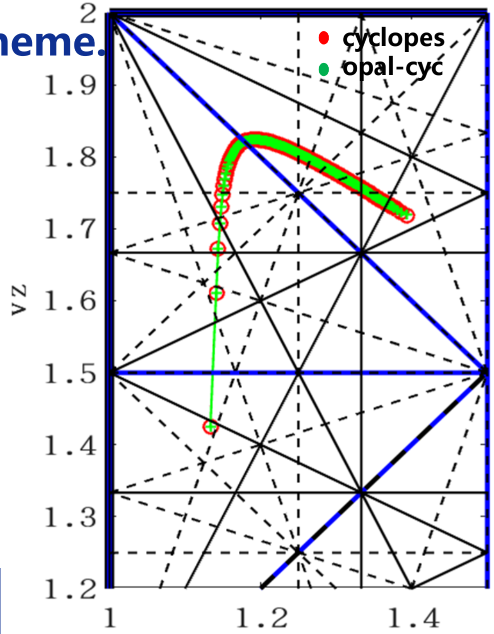
- ~1 cm Off-center injection was adopted to enlarge the turn separation at extraction.
- No intrinsic resonance line was crossed because of 5-sector scheme.
- Due to the high magnetic field flutter, Vz>1.5.



RF phase during acceleration

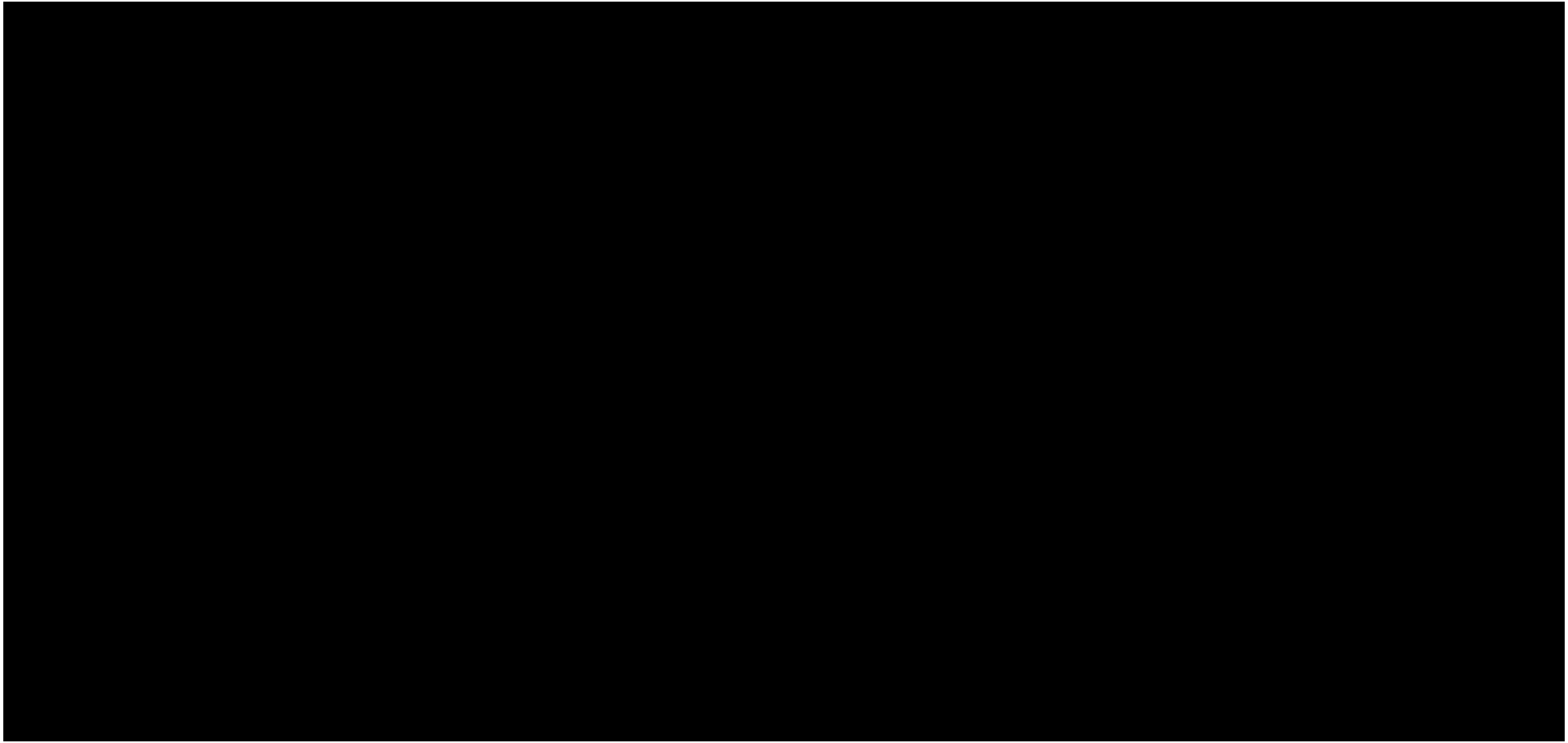


Radial coherent oscillation due to off-center injection



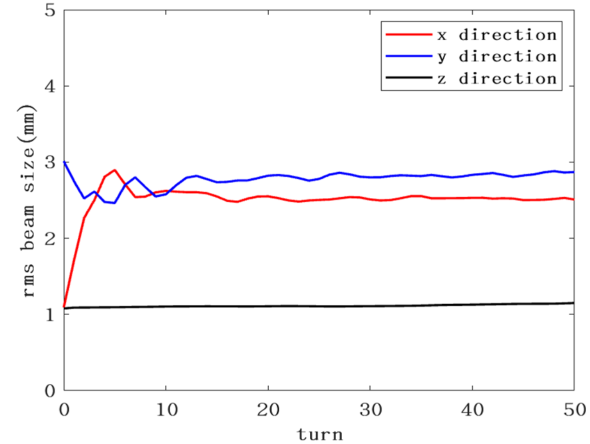
Tune diagram

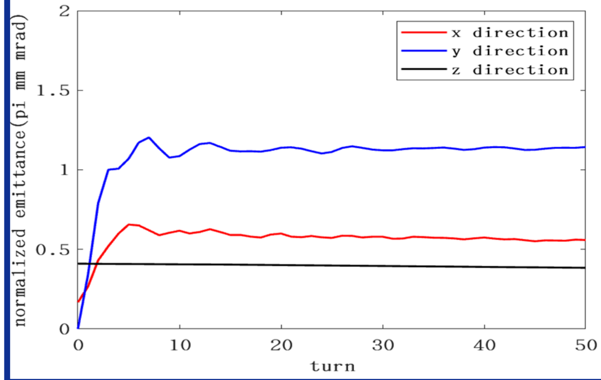
Coasting at 1MeV/amu closed orbit to find the matched distribution(5mA)



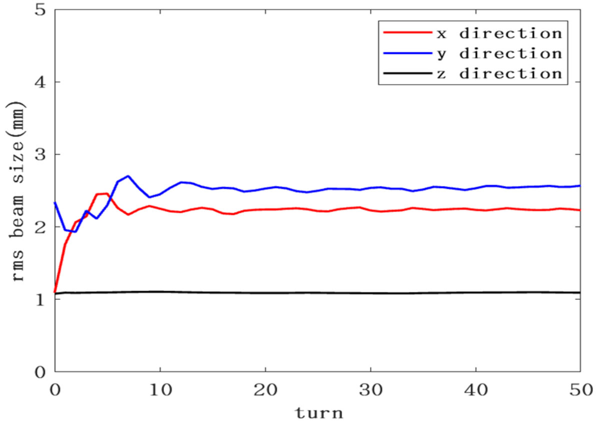
Coasting at 1MeV/amu closed orbit to find the matched distribution (5mA)

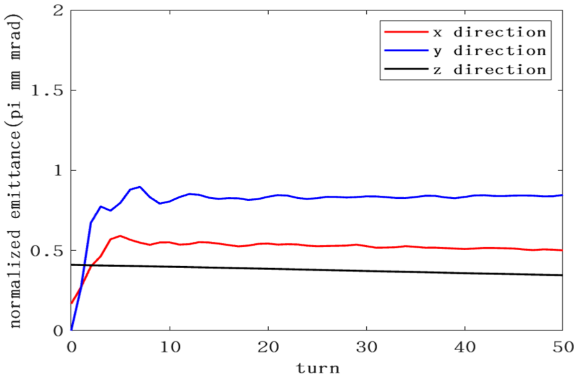
9° phase width



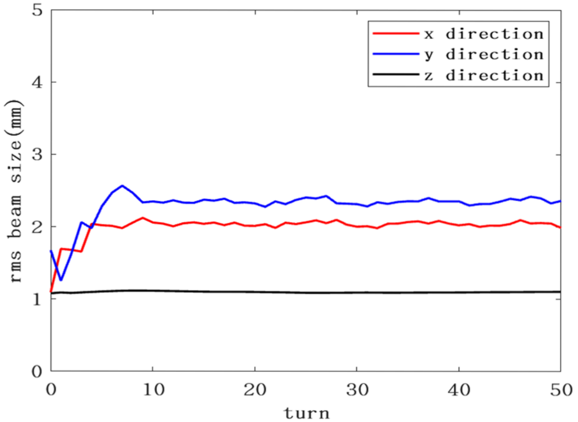


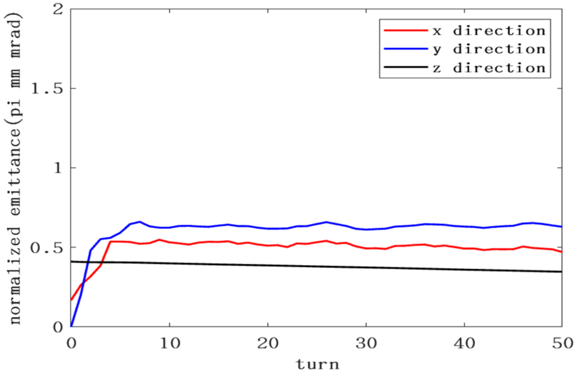
7° phase width





5° phase width

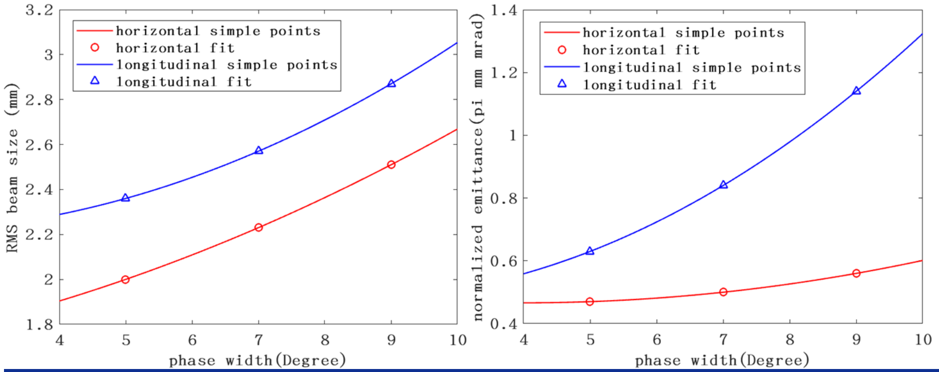




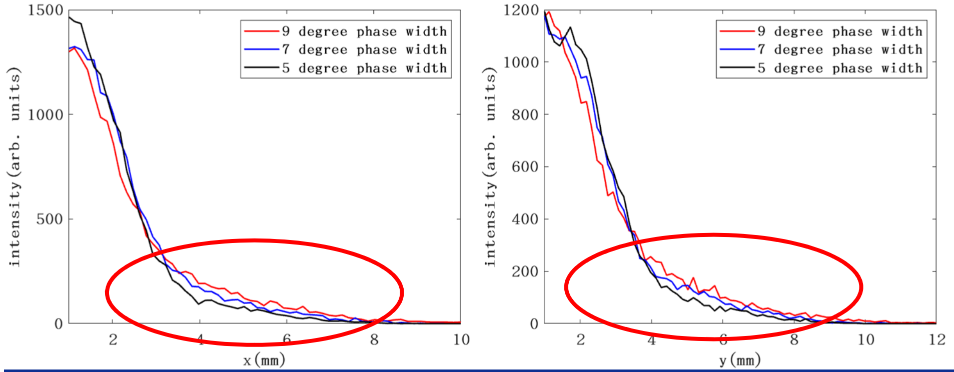
Coasting at 1MeV/amu closed orbit to find the matched distribution (5mA)

Injector

- For this simulation, 10^4 particles and mesh of 32^3 grid points is used.
- Snapshot and statistical information(beam size, emittance) shows that the sizes of the initial unmatched beam converge to constant values within ~20 turns.



Beam sizes and emittances increase with the phase width.

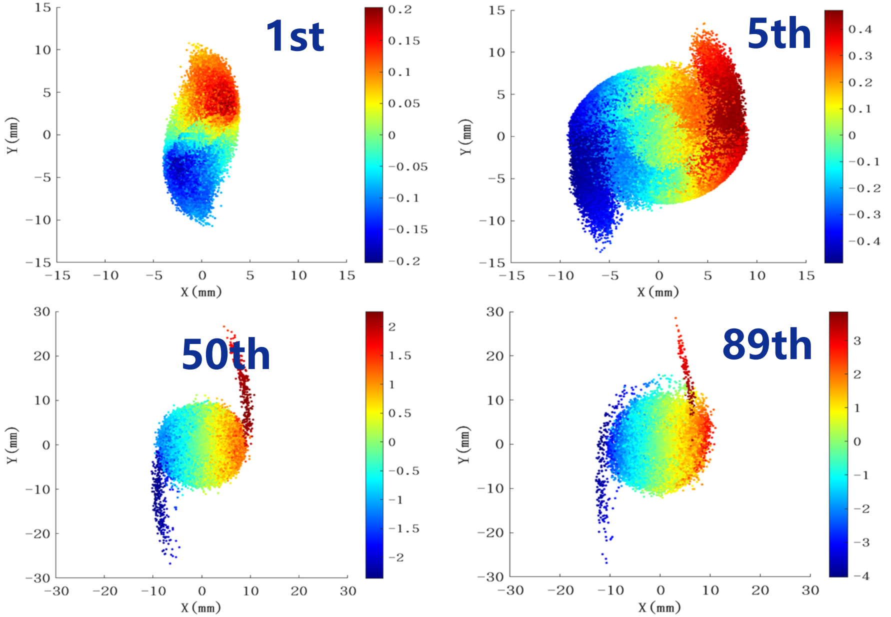


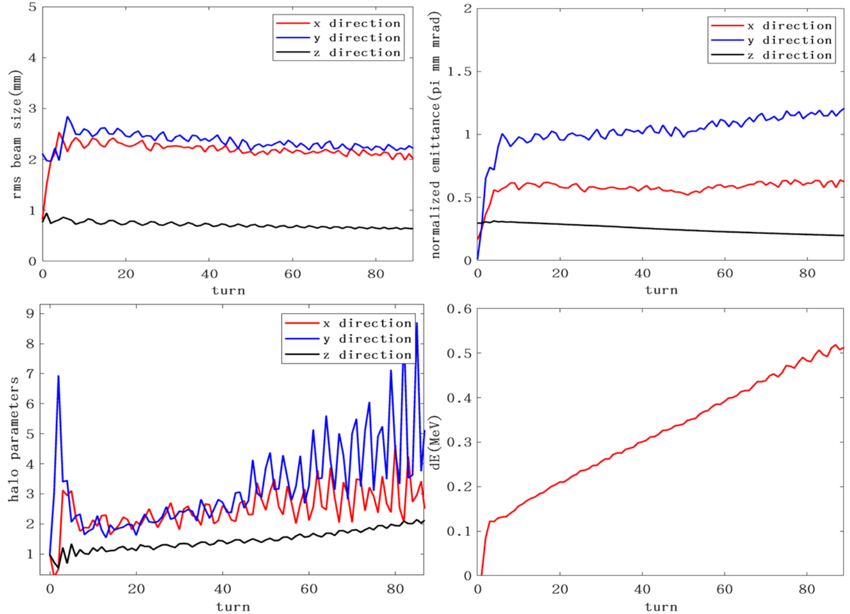
Bunch tail increase with the phase width.

Space charge effects during acceleration

Injector

- For this simulation, 10^6 particles and mesh of 64^3 grid points is used.
- Beam sizes and emittances changes rapidly during the first 20 turns.
- The horizontal(x) and longitudinal (y) dimensions converge to nearly same size.

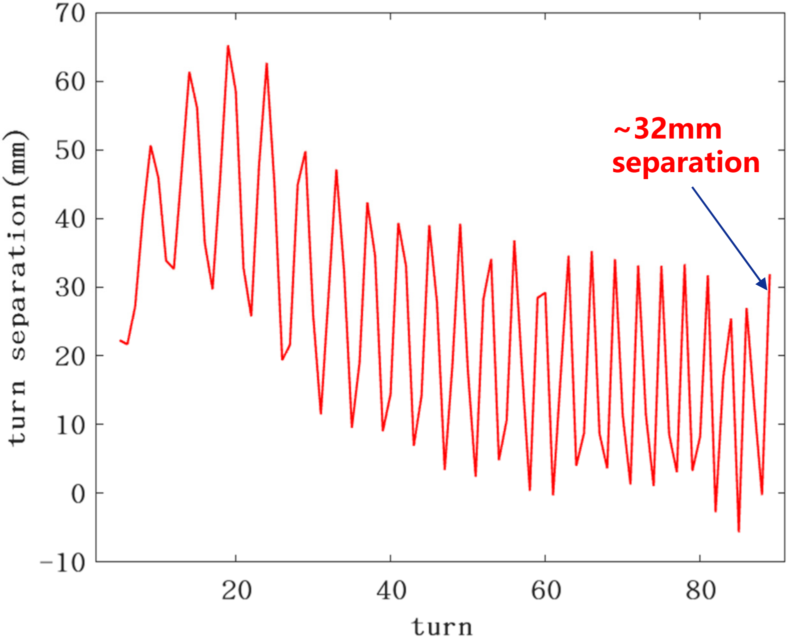


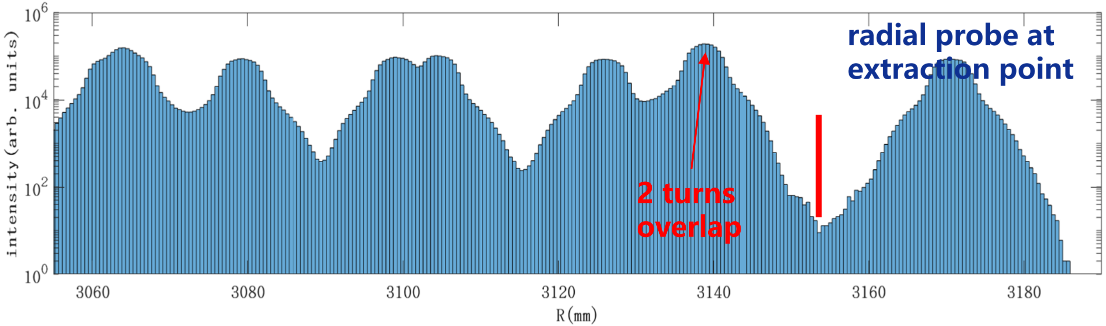


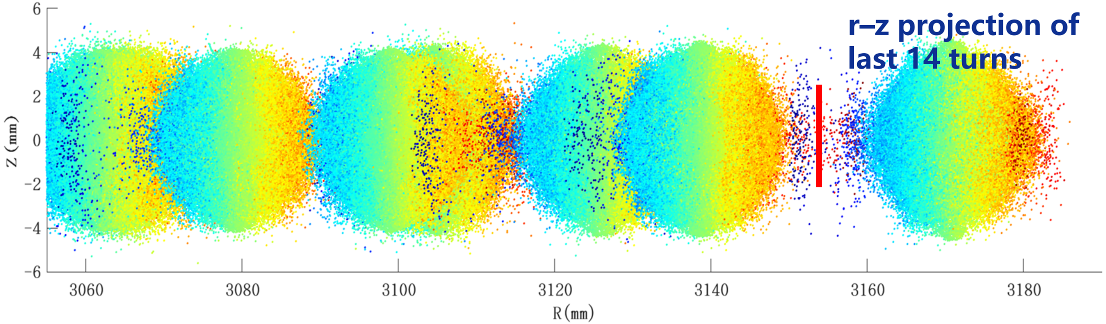
Single turn extraction

Injector

- If 0.5mm is chosen as the septum thickness, the beam power at the deflector is <30W.
- The contribution of acceleration and precession are 12 mm and 20 mm respectively.



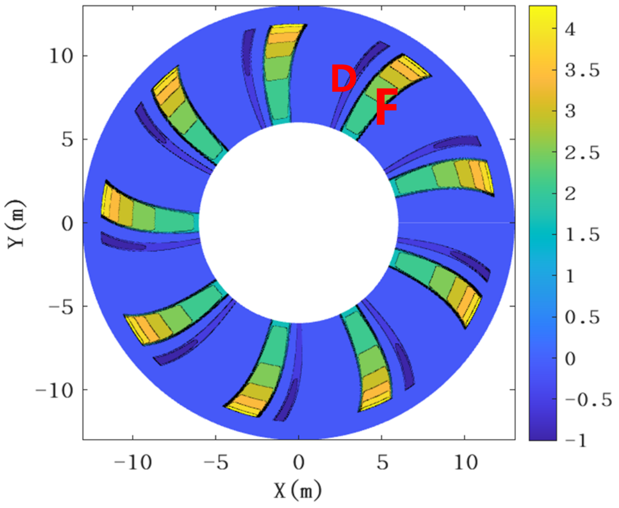




Plan of Talk

1GeV/amu ring cyclotron

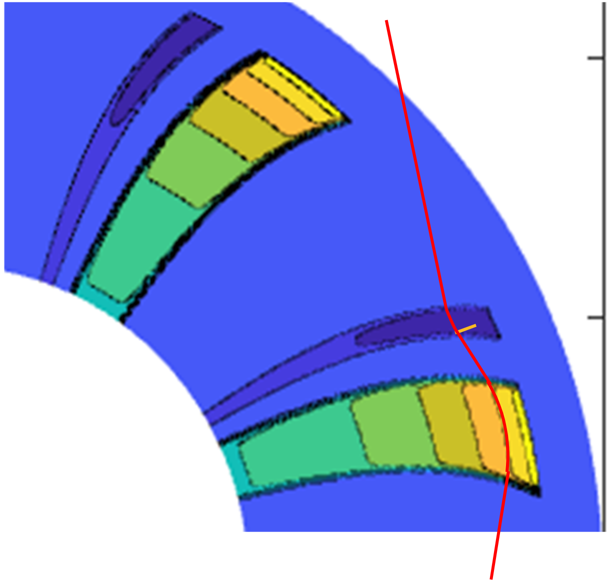
- 9 cells, superconducting technology.
- Generous space between neighboring sectors can be used to install 9 powerful RF cavities.
- Electrostatic deflector with a stripper foil placed upstream is used to obtain high efficiency extraction.



Parameter	value	Parameter	value
Accelerating particles	H2+	Radius of pole	3.3~11.2m
Extraction particles	H2+	Cavity number	9
Injection energy	160MeV/n	Harmonic number	14
Extraction energy	1GeV/n	Cavity frequency	~57MHz
Extraction type	Electrostatic deflector	Cavity Voltage	~1.3MV
Turn separation at Extraction	>2.5cm	Energy gain per turn	~12MeV
Cell number	9	3rd harmonic Cavity number	3
Magnetic field of hill	2.7~4 T		

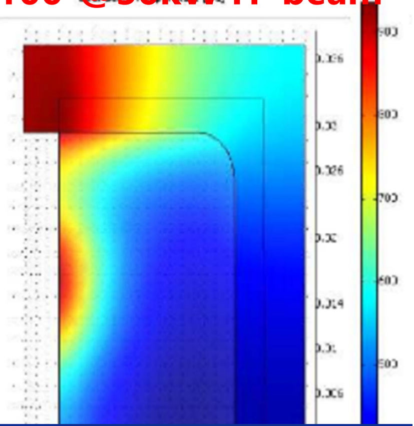
1GeV/amu ring cyclotron

- Extraction by strip foil is also considered.
- Thermal power deposited on the stripper foil will be 500 times larger than TRIUMF 500MeV cyclotron.
- New frame geometry and foil material are under research.



Particle	Energy	Current	Thermal power on foil
H^-	500MeV	0.1mA	55W
H_2^+	1GeV/amu	5mA	2720W

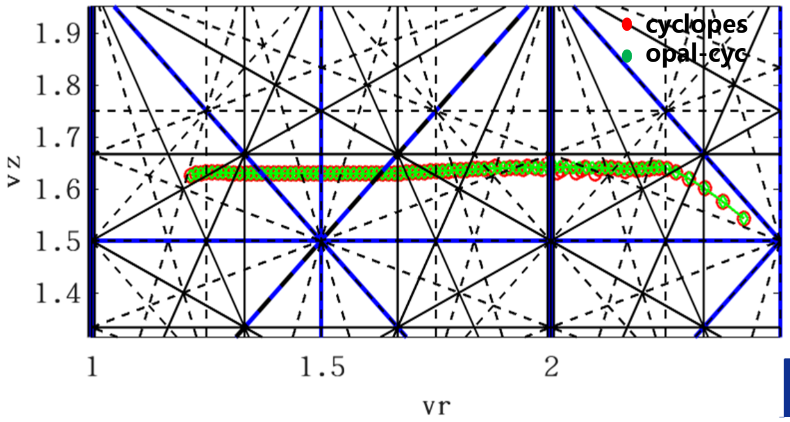
1100°@50kW H^- beam

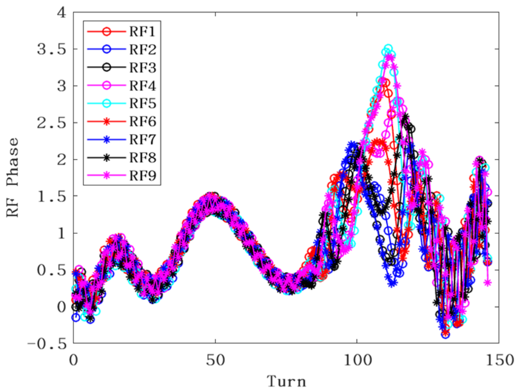


I. Bylinskii, R. A. Baartman, P. E. Dirksen, RECENT DEVELOPMENTS FOR CYCLOTRON EXTRACTION FOILS AT TRIUMF, IPAC2018, Vancouver, BC, Canada

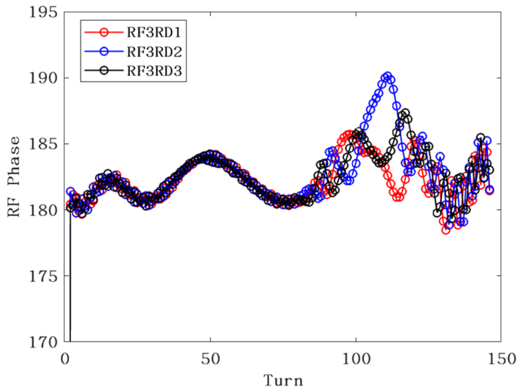
1GeV/amu ring cyclotron

- vr extend to nearly 2.5 to enlarge the turn separation at extraction.
- Integer resonance vr=2 and intrinsic 4vr=9 is crossed.
- The integer resonance crossing problem becomes the major bottleneck of GeV-class isochronous accelerator.





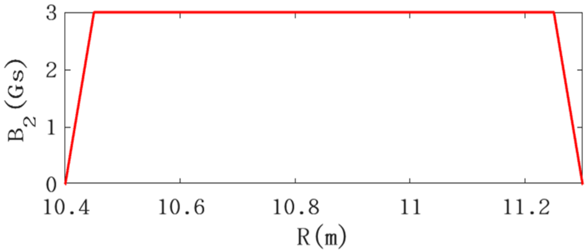
RF phase

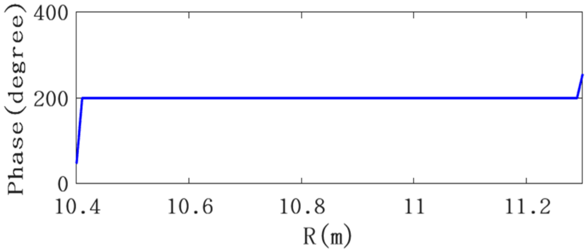


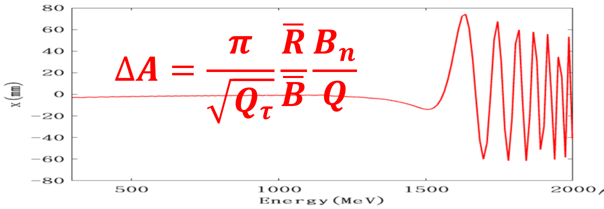
3rd harmonic RF phase

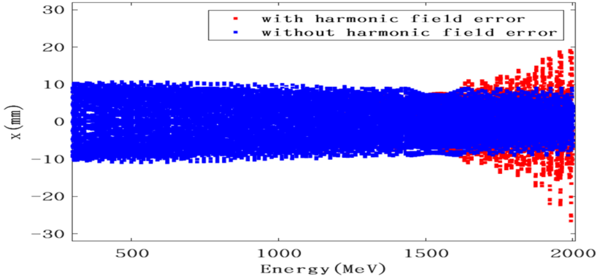
1GeV/amu ring cyclotron

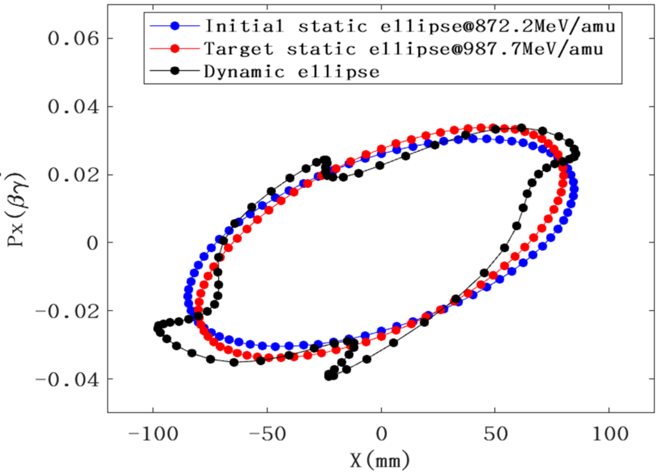
- Beam integrates the harmonic field when passing through the integer resonance region, which drives large coherent oscillation. B_2 of only 3Gs will drive coherent oscillation of ~70mm.
- The large coherent oscillation driven by B_2 is incompatible with the following resonance $4\nu r = 9$.
- When radial beam size of 20mm($10\pi\ mm\ mrad$) is injected, beam size will increase to 40mm.





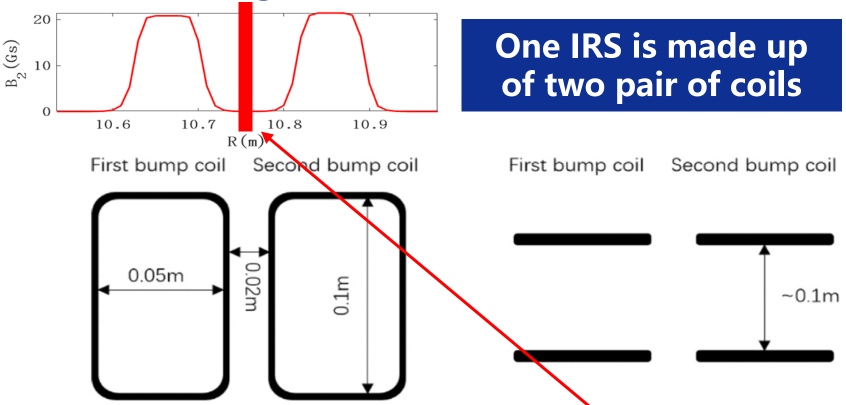






1GeV/amu ring cyclotron

- In order to correct the large coherent motion before reaching the $4\nu_r = 9$, we propose an idea of integer resonance suppressor (IRS),which intentionally introduces the harmonic magnetic field.
- The basic idea of IRS is introducing the harmonic magnetic field intentionally to reduce the integration of driving harmonic field rather than shimming it.

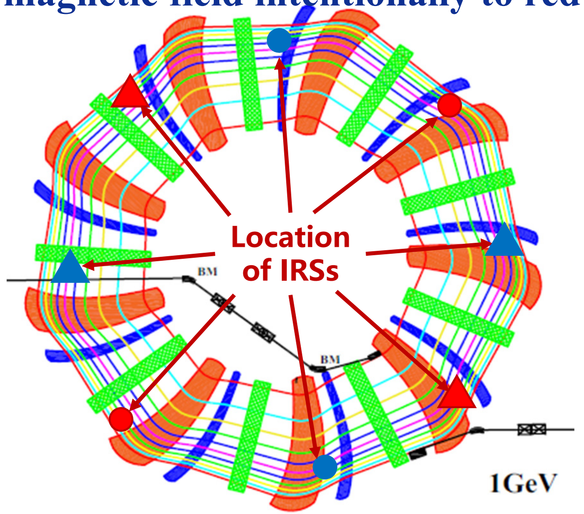


One IRS is made up of two pair of coils

Top view

side view

integer resonance region

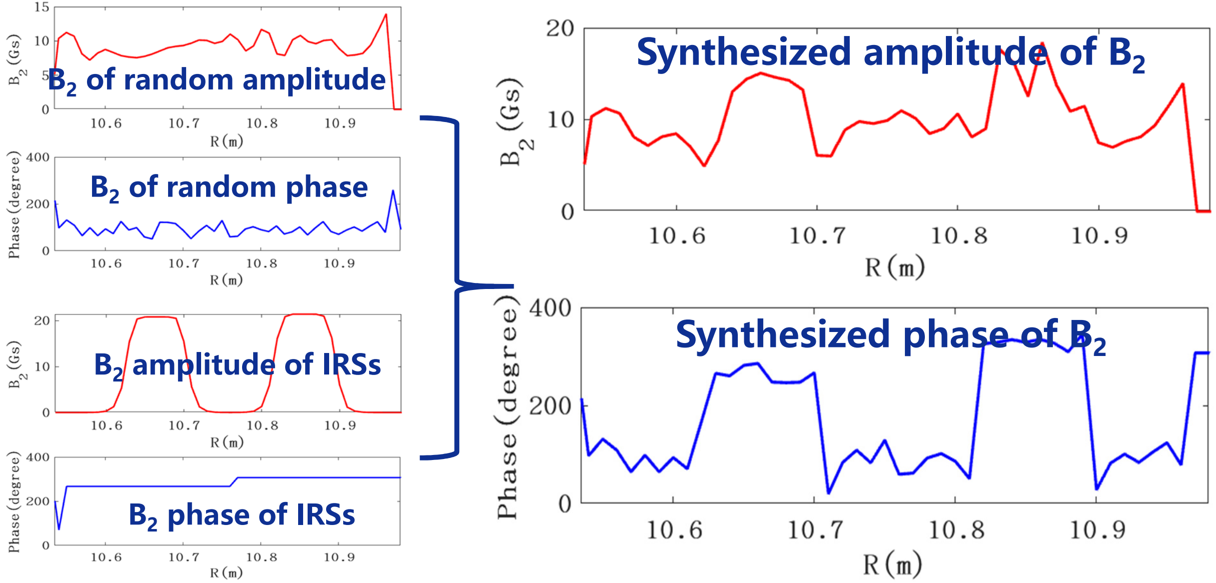


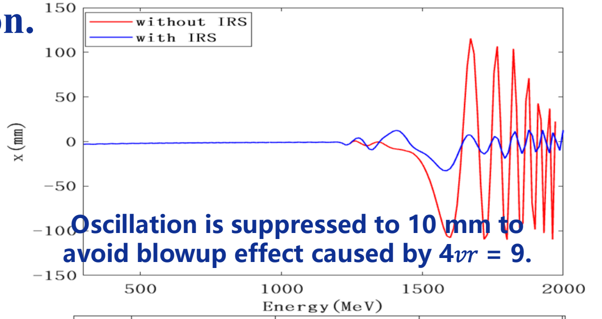
Bian, T. , et al. "Possible solution for the integer resonance crossing problem of GeV-class isochronous Fixed-Field Alternating Gradient accelerators." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1031(2022):166594-.

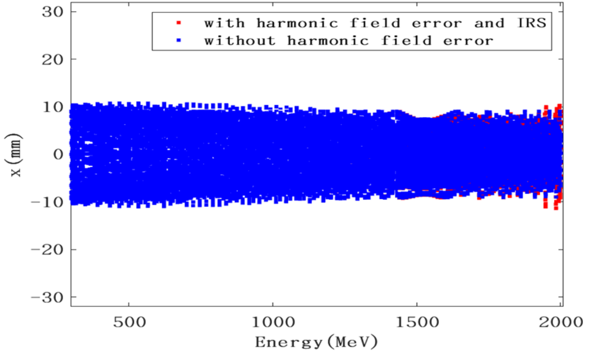
- coil current of triangle and circle are oppositely directed.
- IRSs with same color have same current value.

1GeV/amu ring cyclotron

- In order to correct the large coherent motion before reaching the $4\nu r = 9$, we propose an idea of integer resonance suppressor (IRS),which intentionally introduces the harmonic magnetic field.
- Assuming B_2 of ~10Gs is caused by positional and magnetic imperfection.

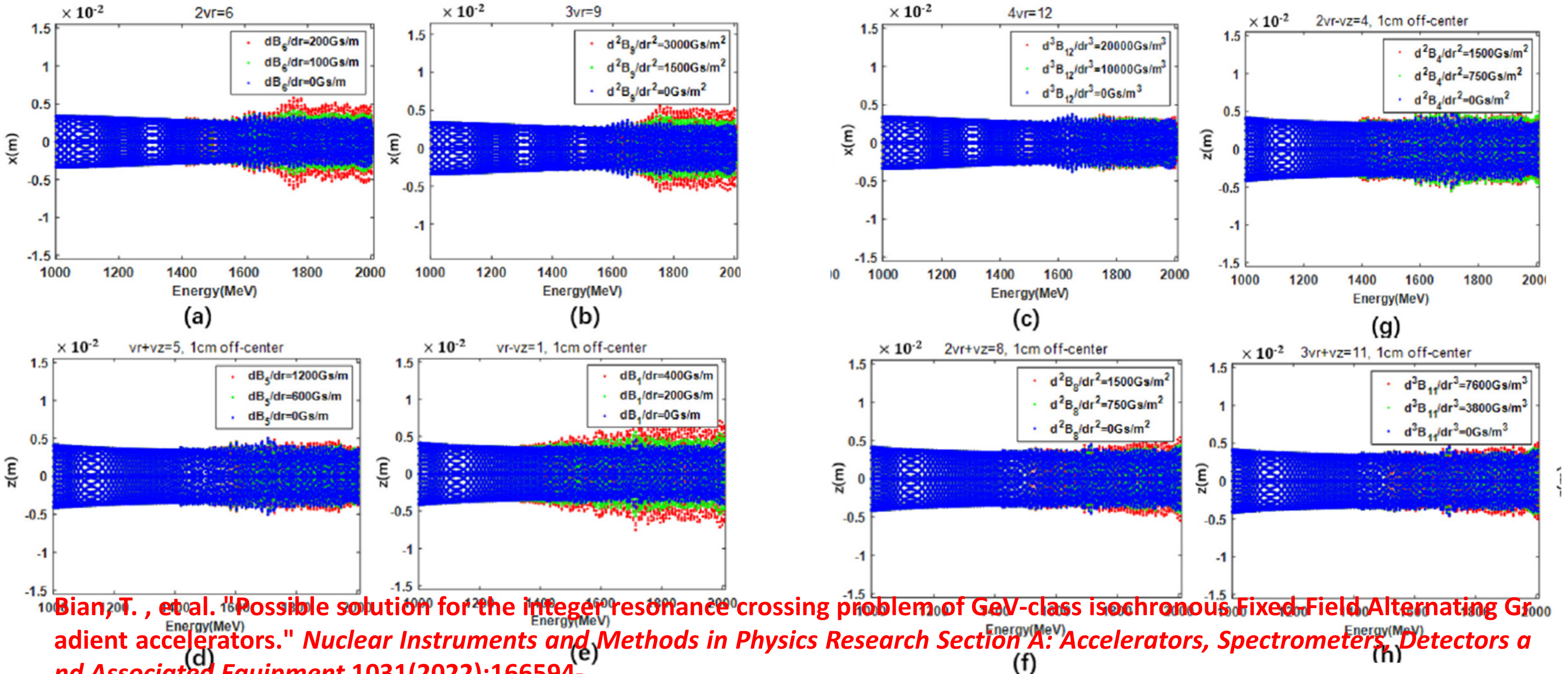






1GeV/amu ring cyclotron

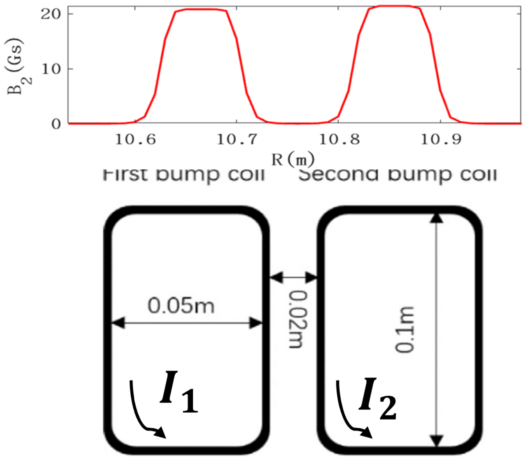
- It is important to note that some other resonances are also crossed, such as vr-2vz=-1, vr+2vz=6, etc...
- Beam profile plots show that the margin of safety is quite large for those resonances.

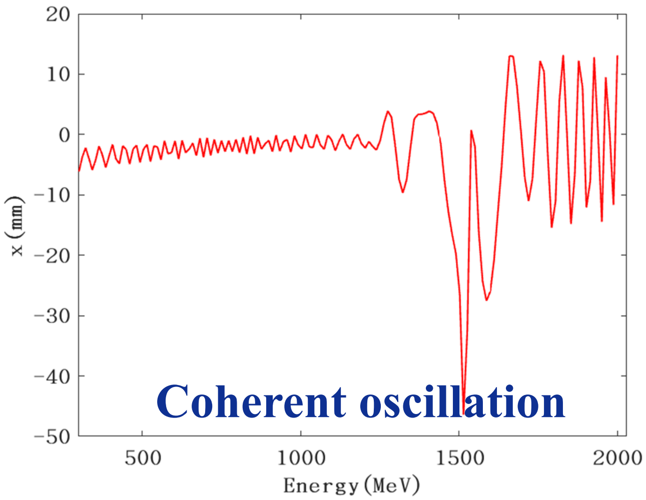


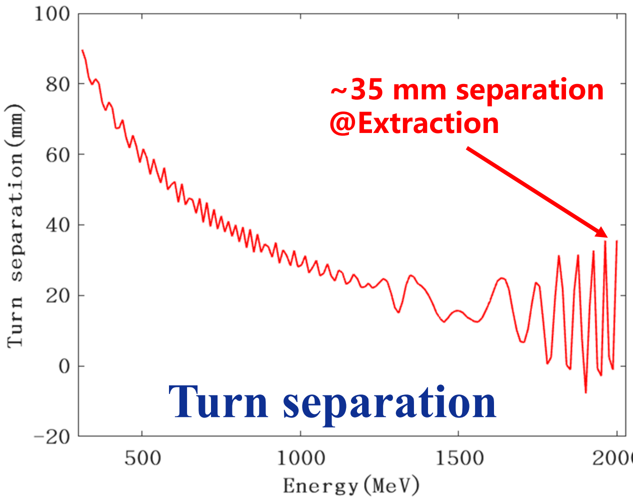
Bian, T. , et al. "Possible solution for the integer resonance crossing problem of GeV-class isochronous Fixed-Field Alternating Gradient accelerators." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1031(2022):166594-.

1GeV/amu ring cyclotron

- **In principle, one B_2 bump can already correct the coherent oscillations.**
- **We prefer the two-bump scheme because we want use it as knobs to optimize the turn separation at extraction.**





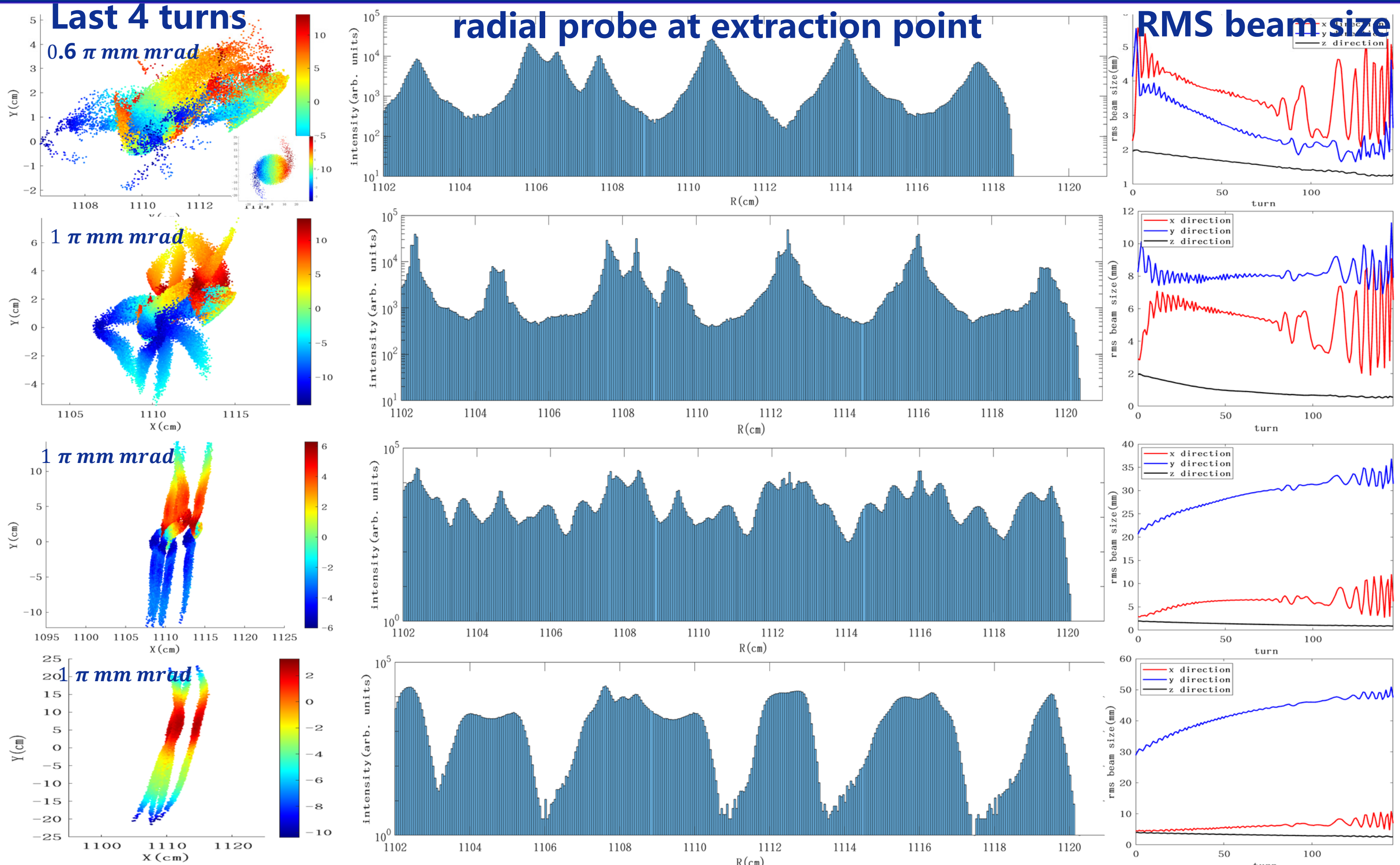


1° rms phase width

2° rms phase width

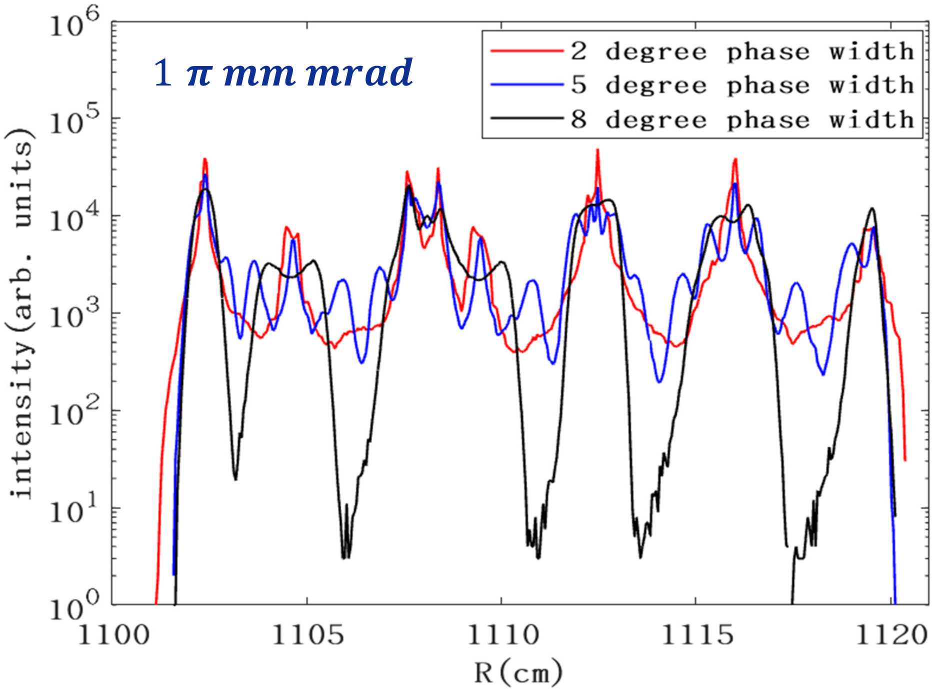
5° rms phase width

8° rms phase width



1GeV/amu ring cyclotron

- **This ring cyclotron works at the emittance-dominated mode, in which vortex motion should be prohibited.**



With the decrease in the charge intensity, it operates from the space charge-dominated to the emittance-dominated regime.

- **1° rms phase width: vortex motion break up.**
- **2° rms phase width: Incomplete vortex motion occurs.**
- **5° rms phase width: vortex motion occurs at center locally.**
- **8° rms phase width: emittance-dominated, no vortex motion.**
- **Wider phase width: energy spread due to different energy gain.**

1GeV/amu ring cyclotron

- If 0.5mm is chosen as the septum thickness, the beam power at the deflector is ~100W.
- For this simulation,25E4 particles and mesh of 32^3 grid points is used.

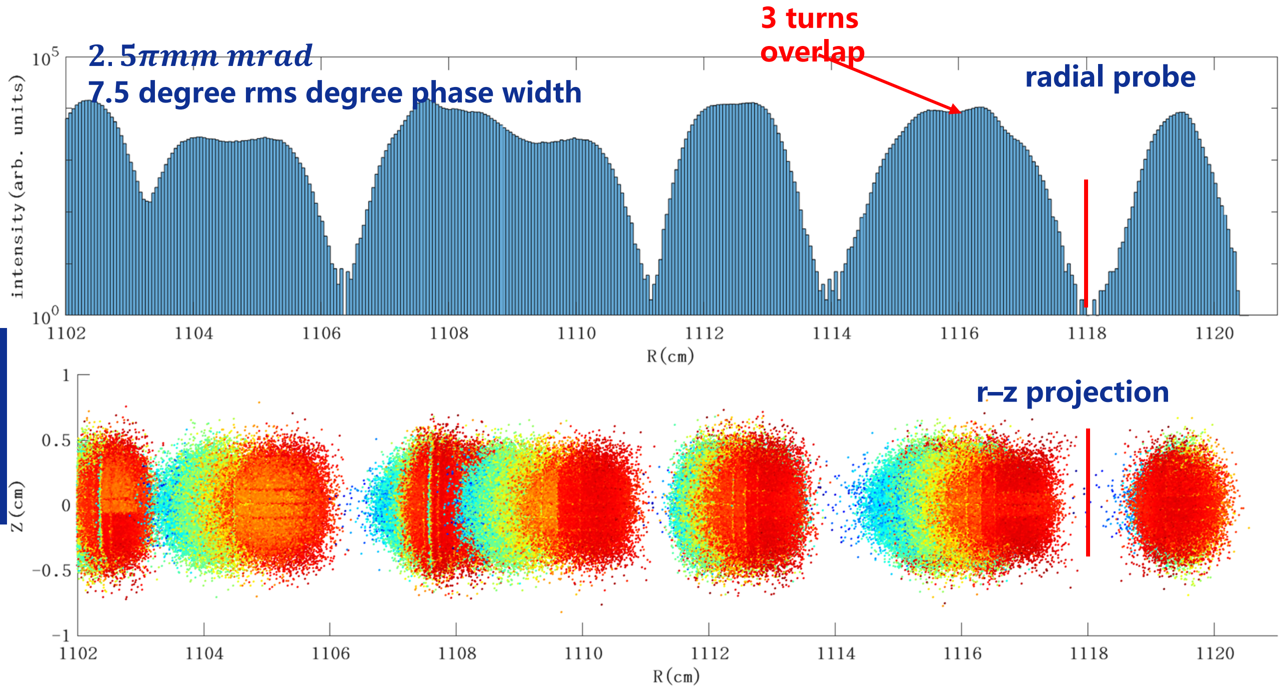
$$k_x = h^2(1+n) = h^2\left(1 + r\frac{d\varepsilon}{dr} + \gamma^2 - 1\right)$$

$$= h^2\left(\gamma^2 + r\frac{d\varepsilon}{dr}\right) = h^2\gamma^2 + h\frac{d\varepsilon}{dr}$$

$$b = K_z\left(K_x - h\frac{d\varepsilon}{dr}\right).$$

Longitudinal focusing requires a strong enough horizontally defocusing space charge force.

Baumgarten, C. Transverse-Longitudinal Coupling by Space Charge in Cyclotrons:, 10.1103/PhysRevSTAB.14.114201. 2011.



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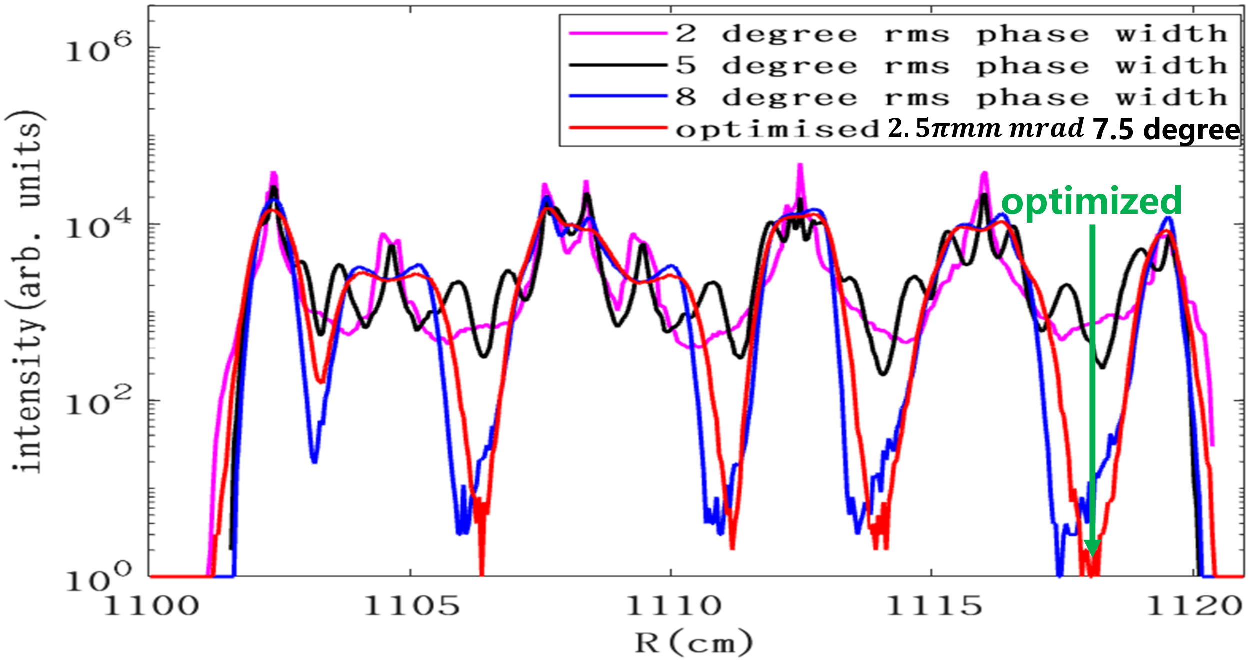


Plan of Talk

- Background
- Advantages and difficulties of cyclotron based high power accelerator
- Preliminary physical design of 150MeV/amu injector
- Preliminary physical design of 1GeV/amu ring cyclotron
- **Summary and thanks**

Summary

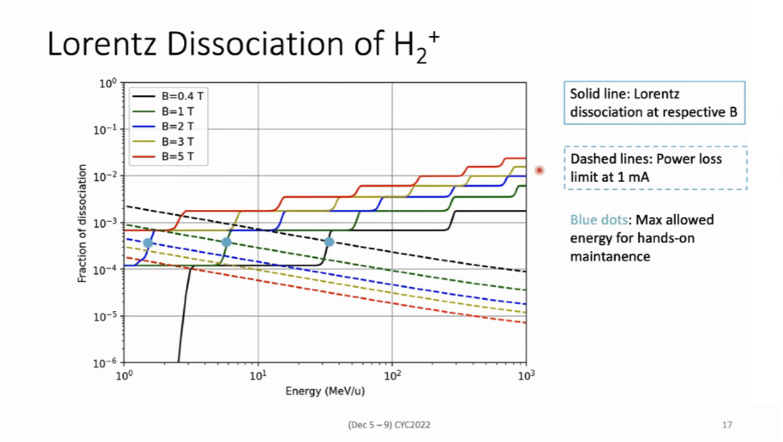
- Feasibility of 10MW-Class Ultra-High Power Cyclotron has been investigated, and preliminary physical design is shown.
- From our limited knowledge, we do not see any fundamental theoretical nor technical limits that prevent the construction of a 10MW-Class Ultra-High Power Cyclotron.
- The size of injector and 1GeV/amu ring cyclotron are defined by turn separation for low power deposition on deflector and the results show that the margin is sufficient.
- The IRS method can also used in inhibition and utilization of vr=3.
- The central region, collimator system, SC magnet, ion source and RFQ injector are also very important parts, design work will be launched in the future.

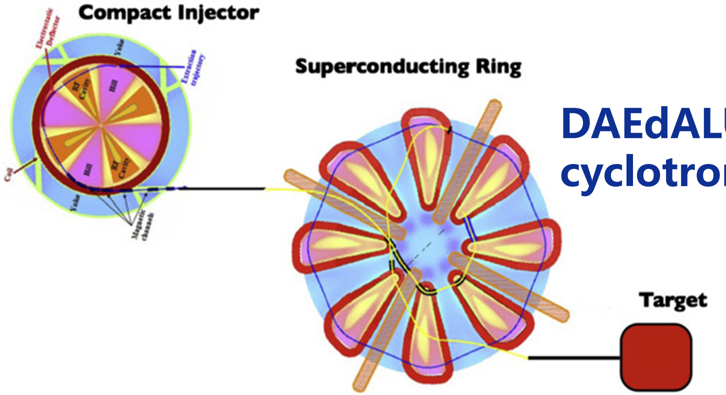
Thanks

- We would like to thank our colleagues of CIAE cyclotron team.
- Thank OPAL team to provide beam dynamics simulation software.
- This work was supported by the National Natural Science Foundation of China (Grant No. 12105370) and the Scientific Research Program for Young Talent Elite Project of China National Nuclear Corporation (Grant No. FY212406000404).

My question

Hui Wen Koay, Stripping Extraction and Lorentz Dissociation, TRIUMF





DAEdALUS cyclotron

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