Beam commissioning and operation status of LEAF

Yao Yang

On behalf of LEAF team

Institute of Modern Physics (IMP),
Chinese Academy of Sciences, Lanzhou, China

LINAC2022, Liverpool, England, 28 August-2 September, 2022

Outline

- Brief Introduction
- LEAF beam commissioning
- Beam energy adjustment system
- LEAF-AMS
- Summary

Brief introduction of HIAF

HIAF

High Intensity heavy ion Accelerator Facility

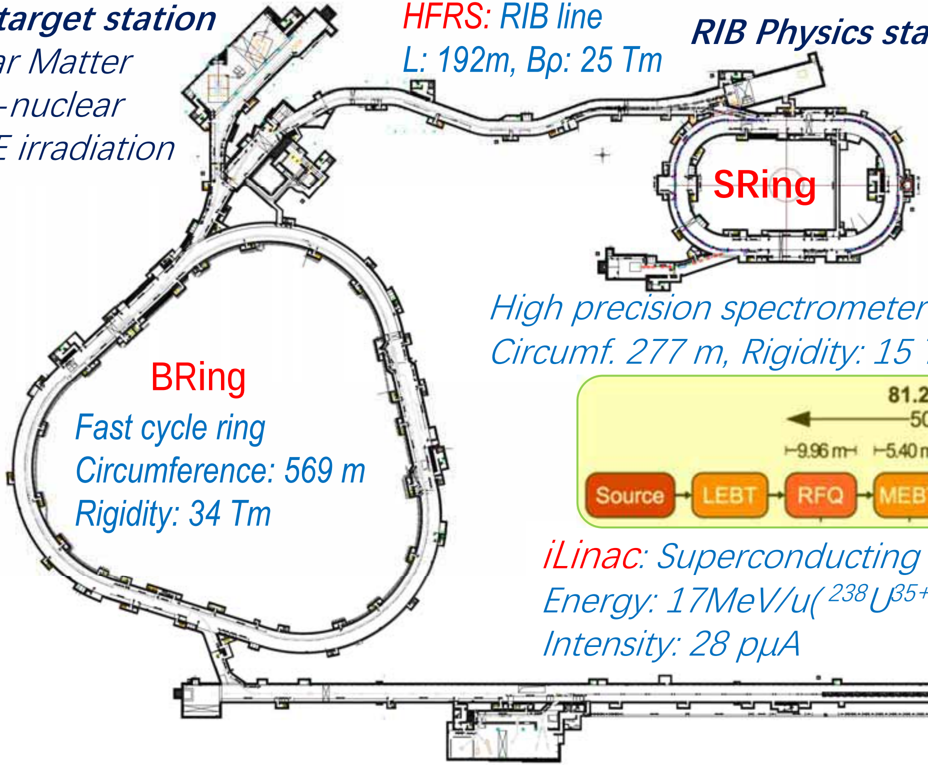
- **Nuclear physics research**
  - ✓ to explore the limit to the existence of nuclei in terms of proton and mass numbers
  - ✓ to find exotic nuclear structure and study the physics behind
  - ✓ to understand the origin of the heavy elements in the cosmos
  - ✓ to depict the QCD phase diagram of nuclear matter, etc
- Total budget: 2.8 B CNY ¥ (424 M USD $)
- Schedule: 2018-2025
- Construction started officially Dec. 2018
- Located in Huizhou City of Guangdong Province in south China

Brief introduction of HIAF

External target station
- *Nuclear Matter*
- *Hyper-nuclear*
- *High-E irradiation*

HFRS: RIB line
L: 192m, Bρ: 25 Tm

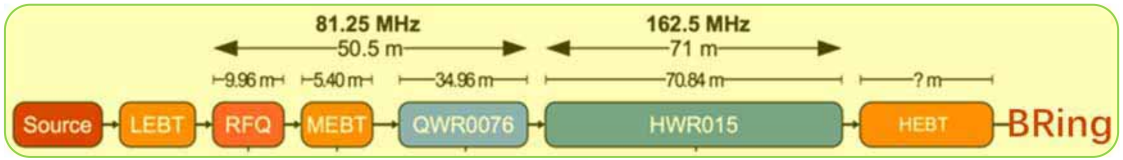
RIB Physics station



Fast cycle ring
Circumference: 569 m
Rigidity: 34 Tm

	FE	iLinac	BRing	HFRS	SRing
Energy (MeV/u)	0.8 (U^{35+})	17 (U^{35+})	835 (U^{35+})	800 (U^{92+})	800 (U^{92+})
Intensity	28 ***pμA*** (U^{35+})	28 ***pμA*** (U^{35+})	$2*10^{11}$ ppp (U^{35+})	--	10^{10} PPP (U^{92+})
Operation mode	CW or pulse	CW or pulse	Fast ramping 12T/s 3Hz	Momentum resolution 1100	DC, deceleration

High precision spectrometer ring
Circumf. 277 m, Rigidity: 15 Tm



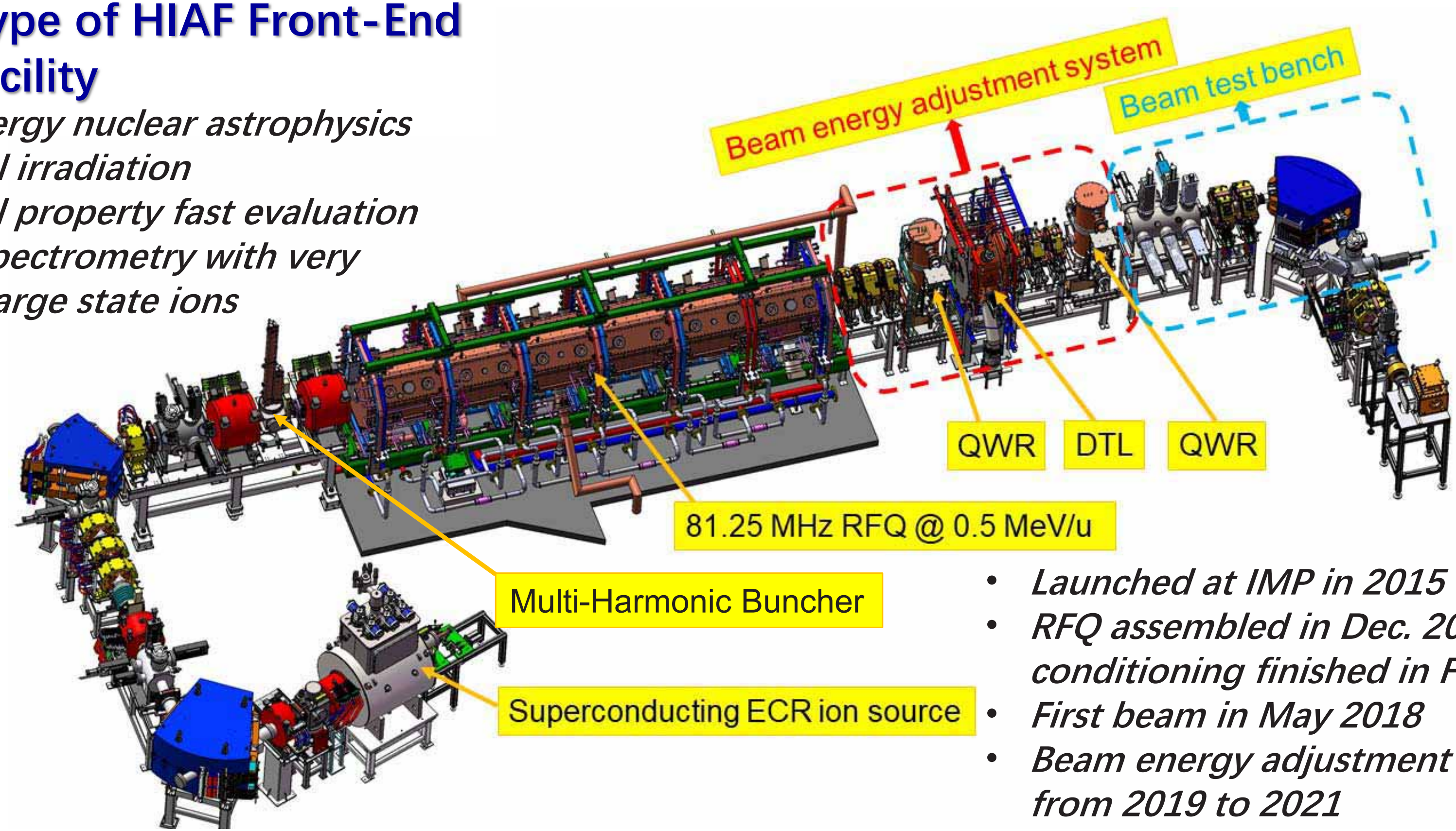
iLinac: Superconducting linac
Energy: 17MeV/u($^{238}U^{35+}$)
Intensity: 28 pμA

RT Front End
Energy: 0.8MeV/u
Intensity: ***28 pμA*** *($^{238}U^{35+}$)*

Low energy nuclear structure and irradiation terminal

LEAF—Low Energy Accelerator Facility

- ✓ **Prototype of HIAF Front-End**
- ✓ **User facility**
  - *Low energy nuclear astrophysics*
  - *Material irradiation*
  - *material property fast evaluation*
  - *X-ray spectrometry with very high charge state ions*

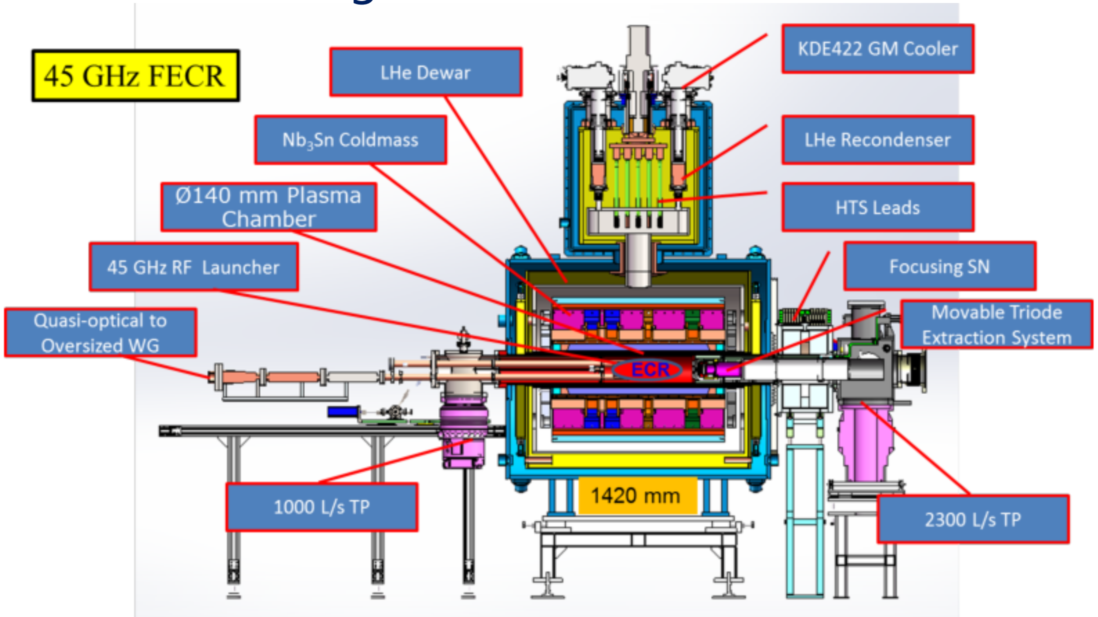


- *Launched at IMP in 2015*
- *RFQ assembled in Dec. 2017 and RF conditioning finished in Feb. 2018*
- *First beam in May 2018*
- *Beam energy adjustment system: from 2019 to 2021*

The world first 4th generation ECR ion source FECR

- ✓ FECR will be installed on LEAF by the end of this year
- ✓ A 28 GHz super-conducting ECR source SECRAL is used for commissioning

Zhao's talk in IPAC'22 and this conference

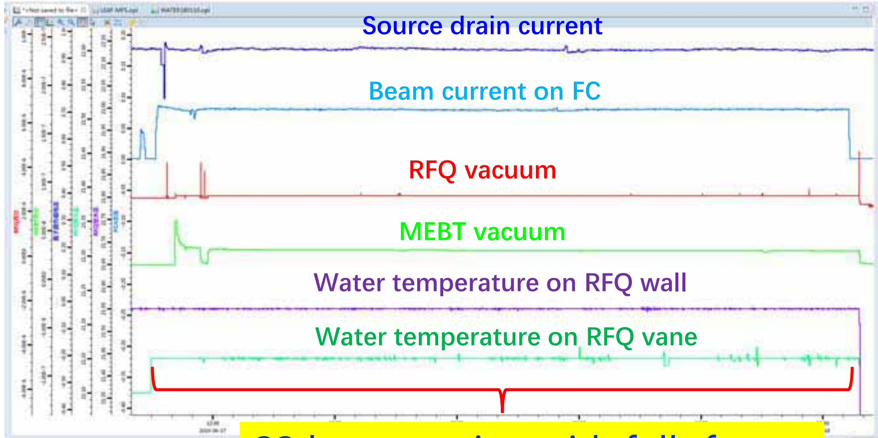


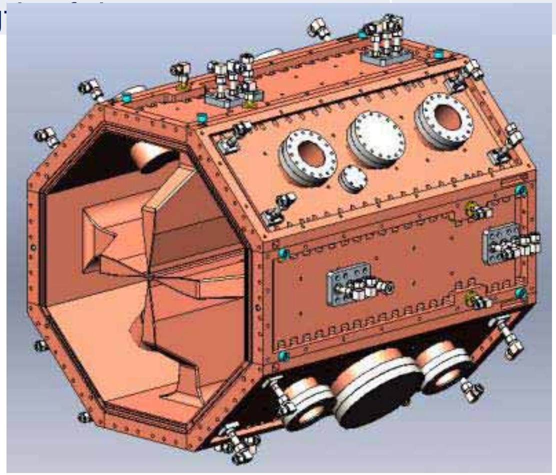
FECR key parameters

Microwave	45 GHz/20 kW
Magnet conductor	Nb_3Sn
Axial field [T]	6.5/1.0/3.5
Sextupole field [T]	3.8@r=75 mm
Maximum field [T]	11.8 T
Maximum stress [Mpa]	150
Magnet bore [mm]	>Φ160
Stored energy [MJ]	1.6
Extraction voltage [kV]	50
Typical beam	1.0 emA U^{35+}

4-vane RFQ

Duty cycle	100%
Operating frequency (MHz)	81.25
Resonant cavity	4-vane
Input particle energy (keV/u)	14
Output particle energy (keV/u)	500
	70 (M/q=7)
Max. Vane voltage (kV)	60 (M/q=7)
CW RF power (kW)	1.57 Kilpatrick units
Peak field at electrode surface	~596.4
Leng	

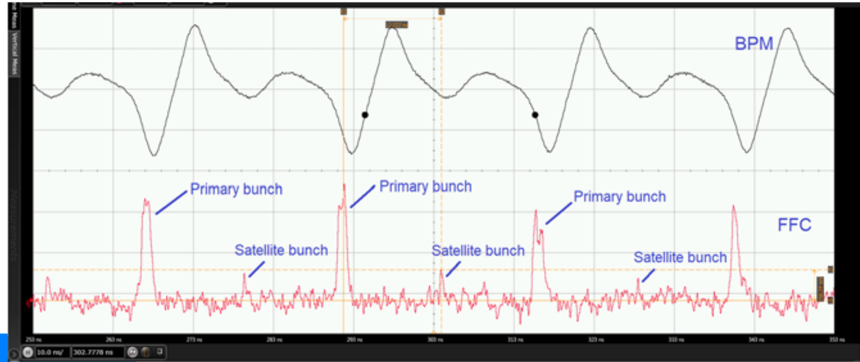


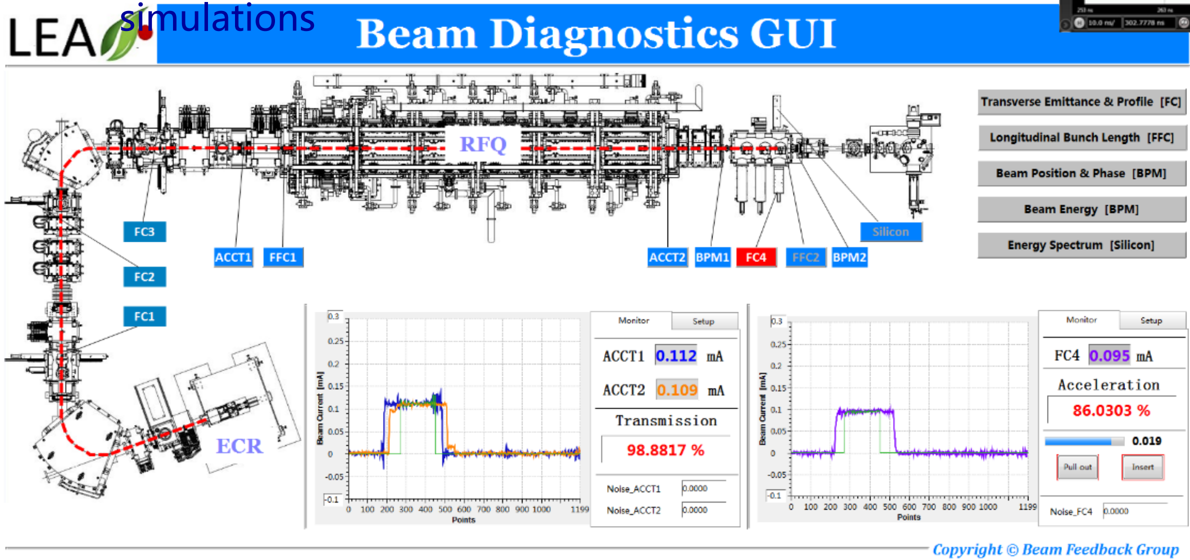


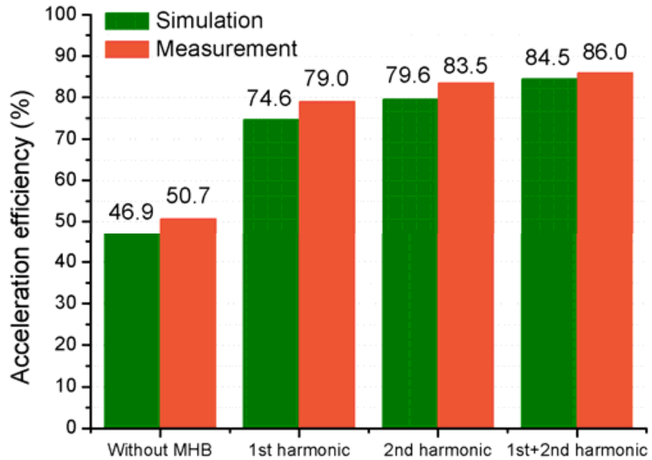
Beam commissioning and measurements

- ✓ Ion M/q=2~7
- ✓ Beam current~100 eμA
  - Transmission efficiency > 97%
  - Acceleration efficiency>85% (with Pre-buncher, operation with two frequencies, RFQ fundamental and sub-harmonic)
  - Good agreement between the measurements and simulations

- Y. Yang, *et al. Phys. Rev. Accel. Beams* 22, 110101 (2019)

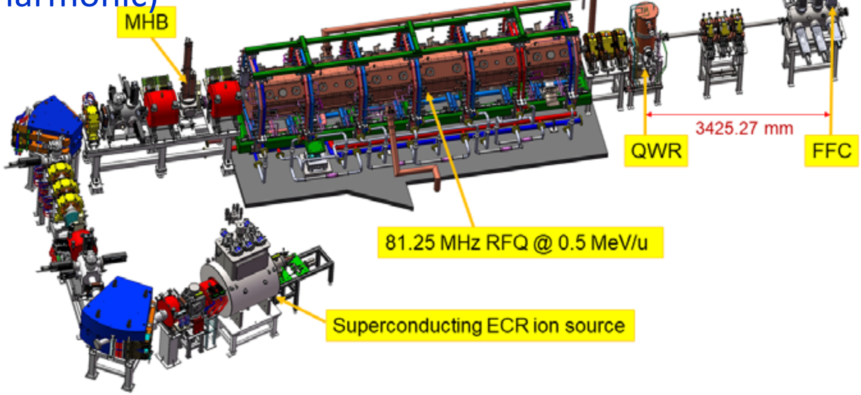




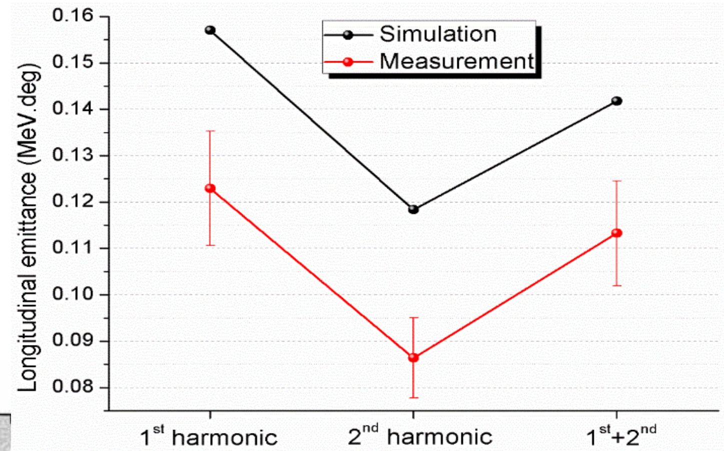


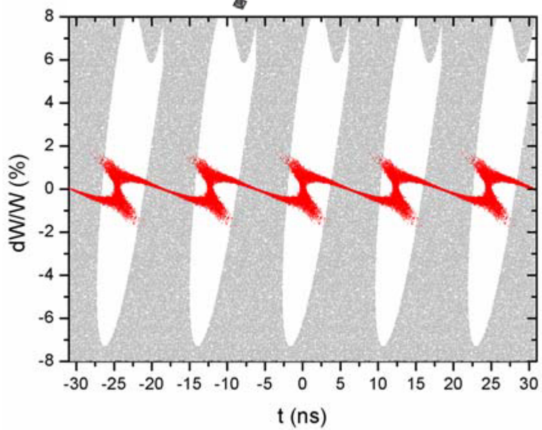
Longitudinal emittance measurement

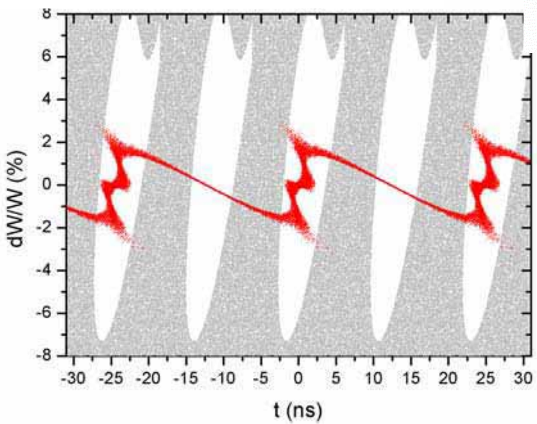
✓ MHB operates with two frequencies (RFQ fundamental and sub-harmonic)



- Yao Yang, *et al*, *Nuclear Inst. and Methods in Physics Research, A* 1029 (**2022**) 166457



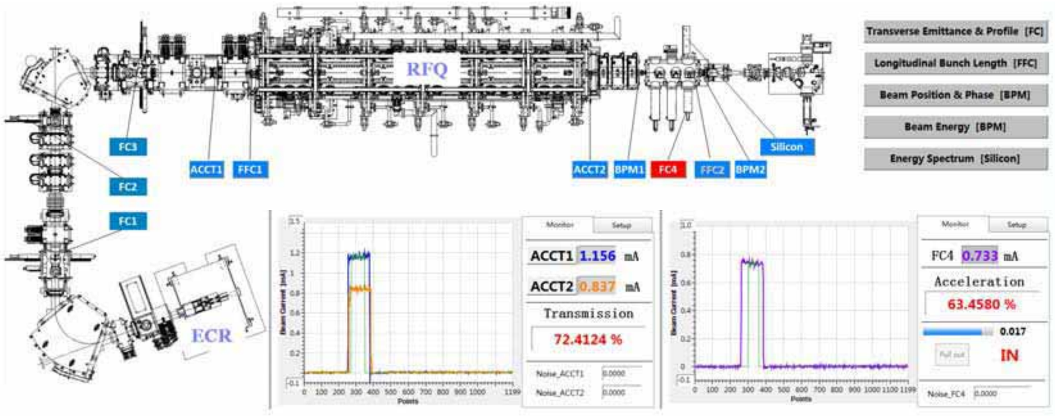




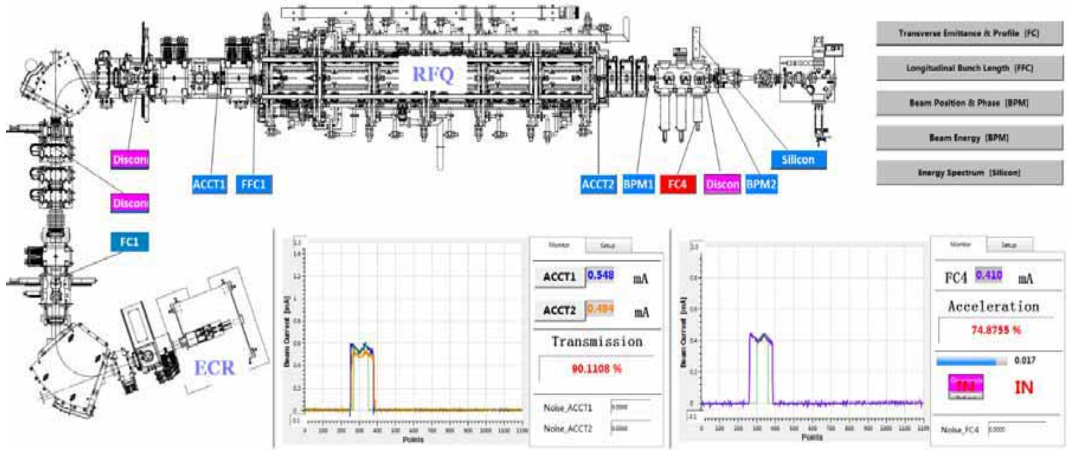
- Three-gradient technique
- The measured emittances are systematically 1.2~1.4 times lower than those expected from simulations due to the methodic error
- Lower emittance with the MHB operating with the RFQ fundamental frequency by lowering the bunch charge

Challenges in intense heavy ion beam acceleration

- **Ar^{9+} 1.2 mA from source**
- Without LEBT collimator
- Accelerated current: 733 eμA
- RFQ transmission ~ 72.4%

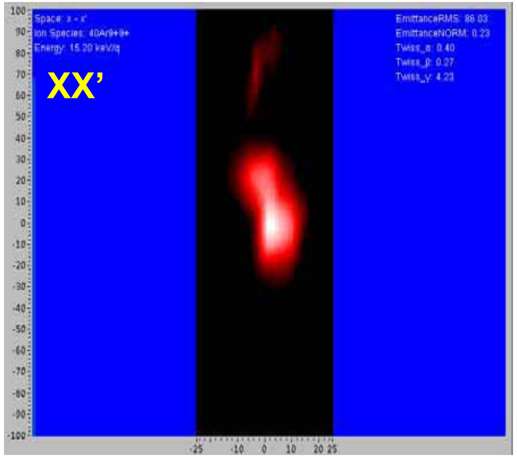


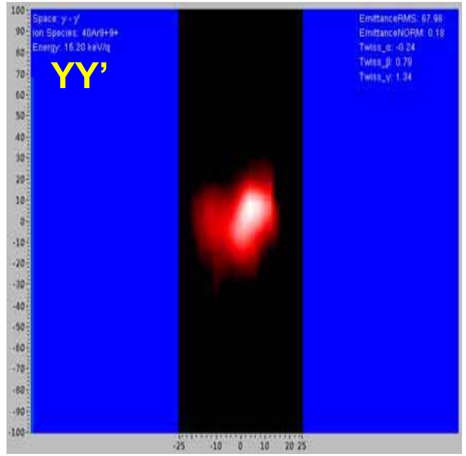
- ✓ With LEBT collimators
- ✓ Half of the current removed
- ✓ RFQ transmission >90%
- ✓ Accelerated current: 410 eμA



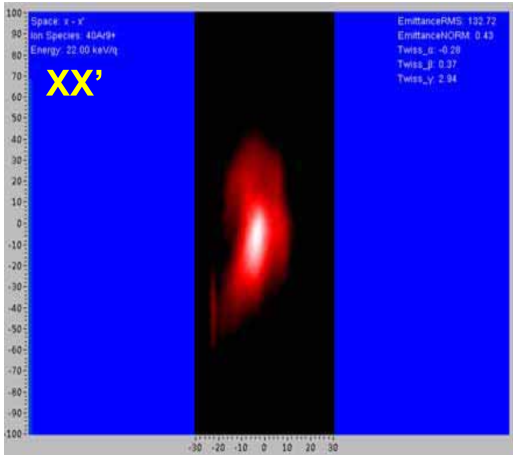
Challenge: Beam quality degrades with current

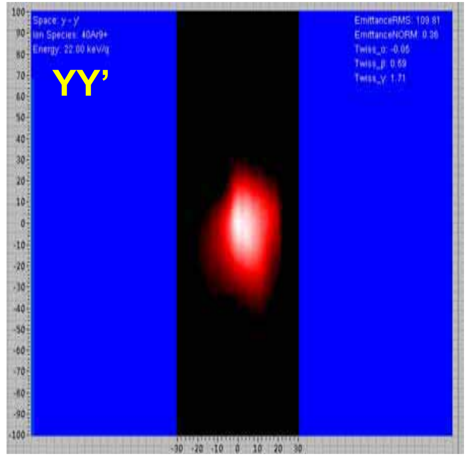
- Ion source current： **690 eμA**
- Drain current： 10.3 emA
- $\varepsilon_{xx'}$: 0.23 π.mm.mrad
- $\varepsilon_{yy'}$: 0.18 π.mm.mrad



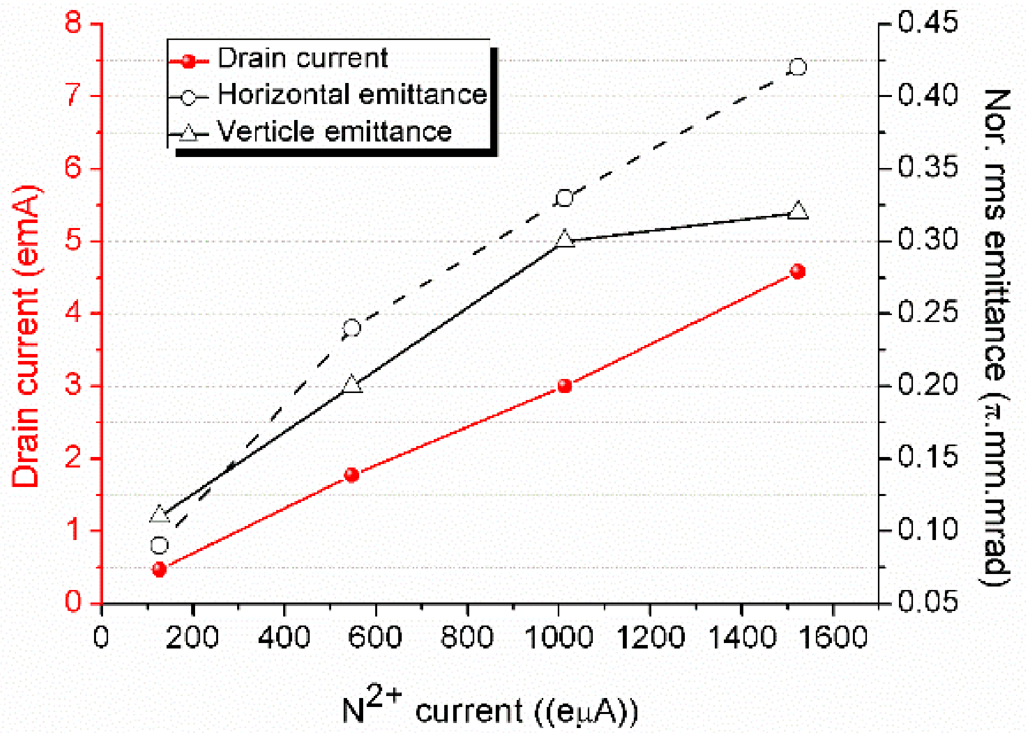


- Ion source current： **1370 eμA**
- Drain current： 19.9 emA
- $\varepsilon_{xx'}$: 0.43 π.mm.mrad
- $\varepsilon_{yy'}$: 0.36 π.mm.mrad





Challenge: Beam quality degrades with current

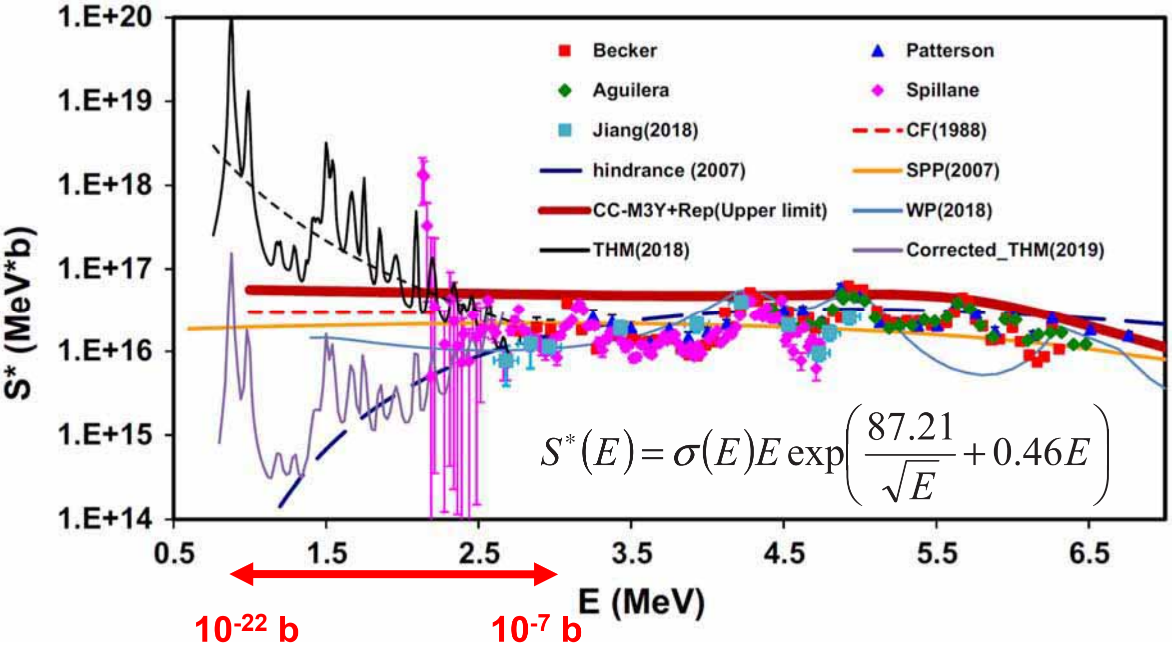


How to maintain beam quality while increasing the current is an important task!

Beam energy adjustment system-Motivation

Uncertain Cross section at stellar energies：

- Beck, Mukhamedzhanov and Tang, Eur. Phys. J. A (2020) 56:87
- Mukhamedzhanov, Kadyrov and Pang, Eur. Phys. J. A (2020) 56:233

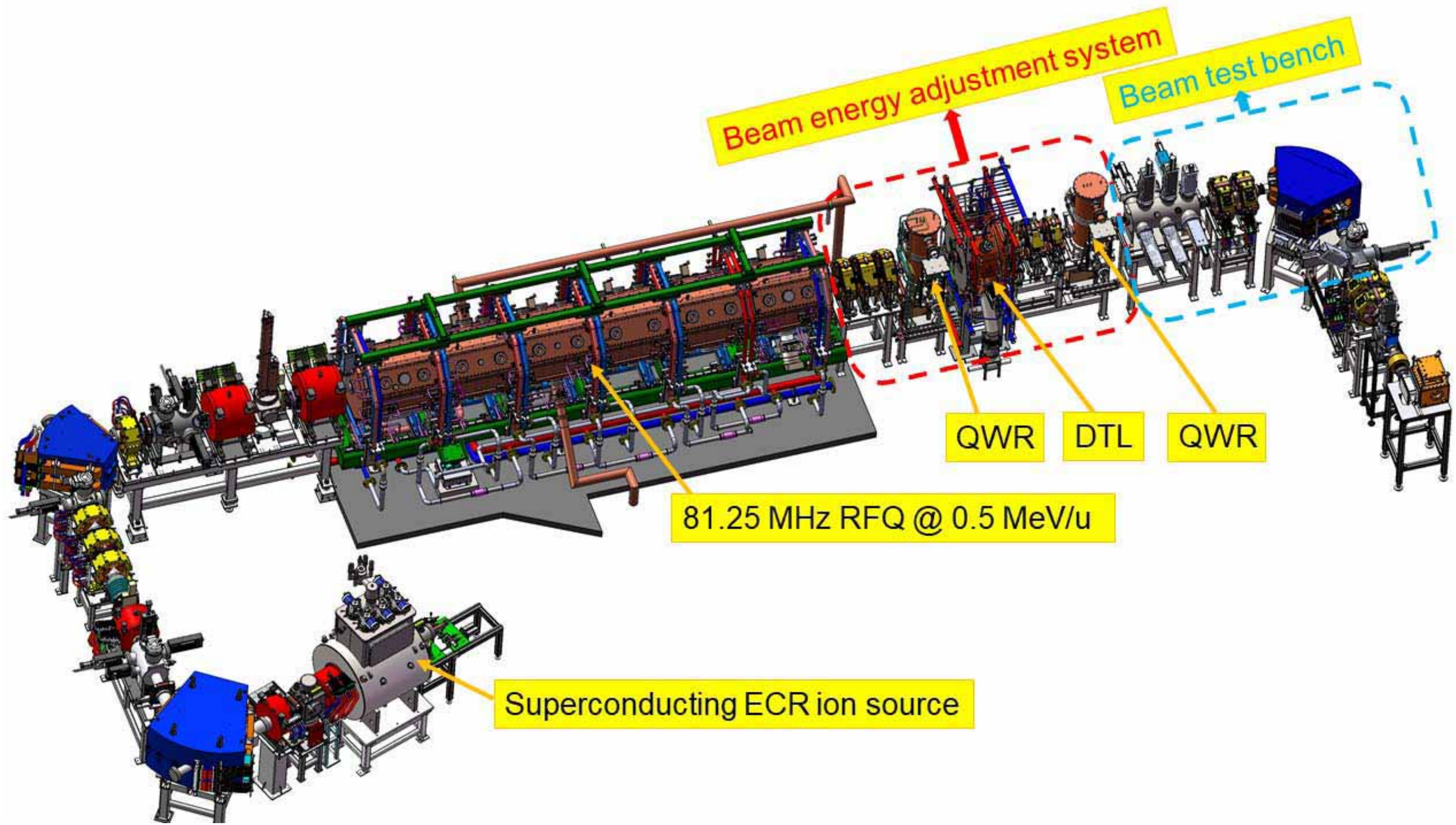


- Large difference between THM and Hindrance→Highly uncertain rate
- INDIRECT: Corrected THM exhibits a trend similar to Hindrance by replacing PWIA with DWIA
- Unknow resonances

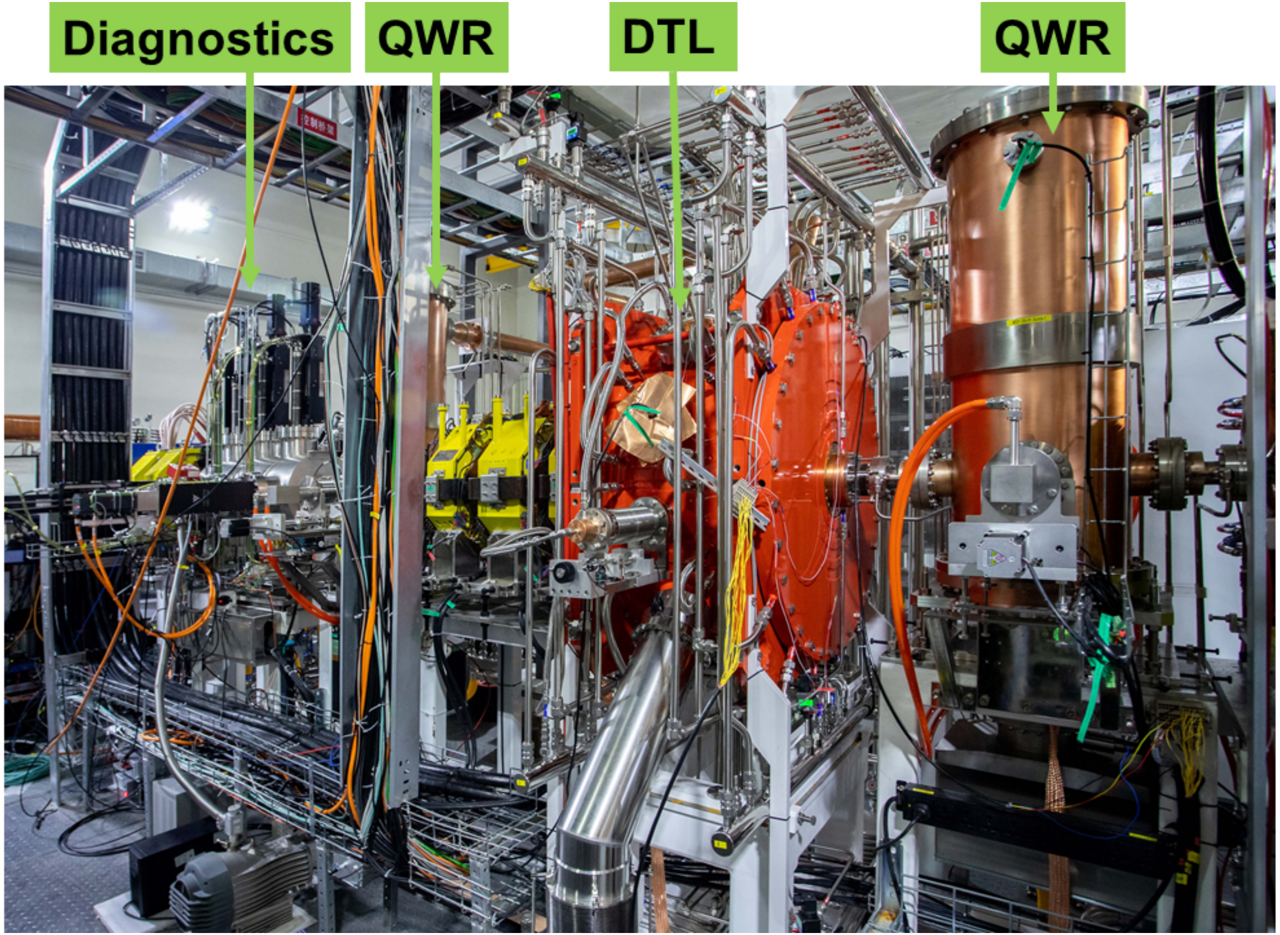
$^{12}C(^{12}C,p)^{23}Na$ (Q=2.24 MeV)
$^{12}C(^{12}C,\alpha)^{20}Ne$ (Q=4.62 MeV)
$^{12}C(^{12}C,n)^{23}Mg$ (Q=-2.62MeV)

LEAF, which can provide a high intensity of ^{12}C beam up to 100 pμA, will be an ideal platform to measure cross sections of $^{12}C+^{12}C$ reaction at astrophysical energies if it could provide a broad beam energy variation of 0.3~0.7 MeV/u with carbon ions while maintaining energy spread

Beam energy adjustment system



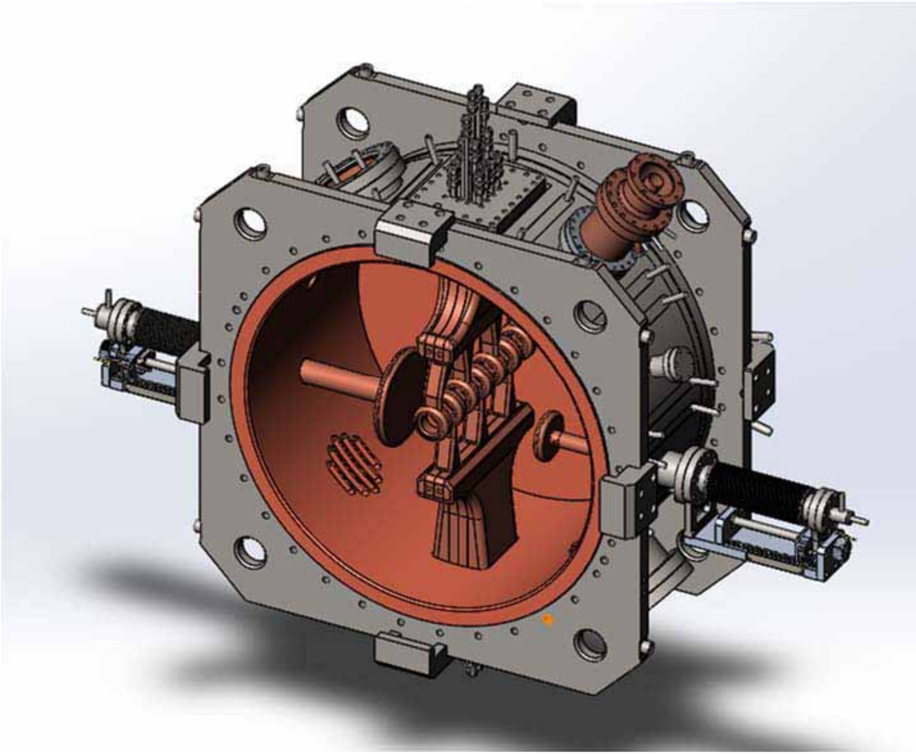
Beam energy adjustment system



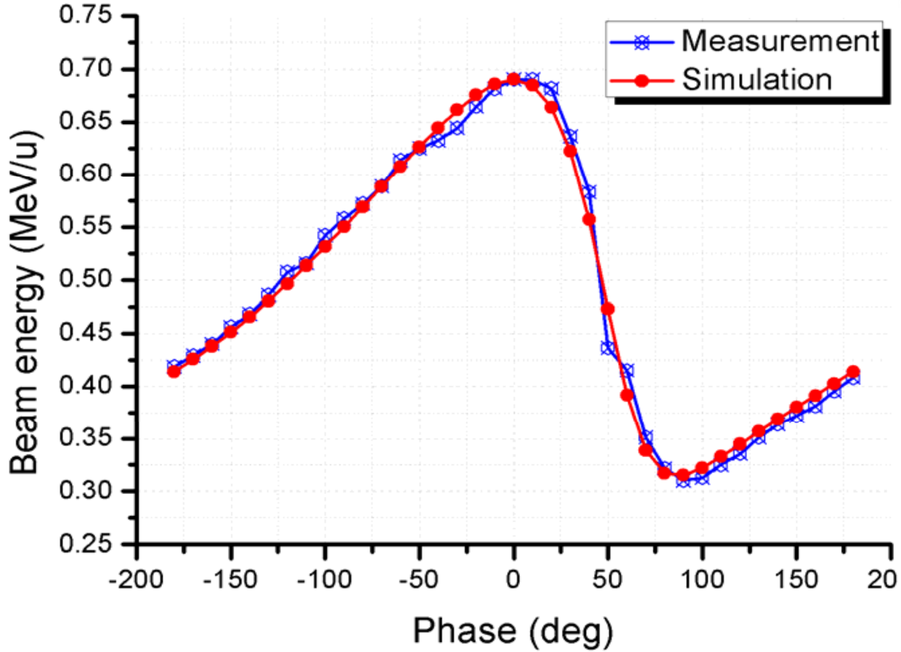
IH-DTL

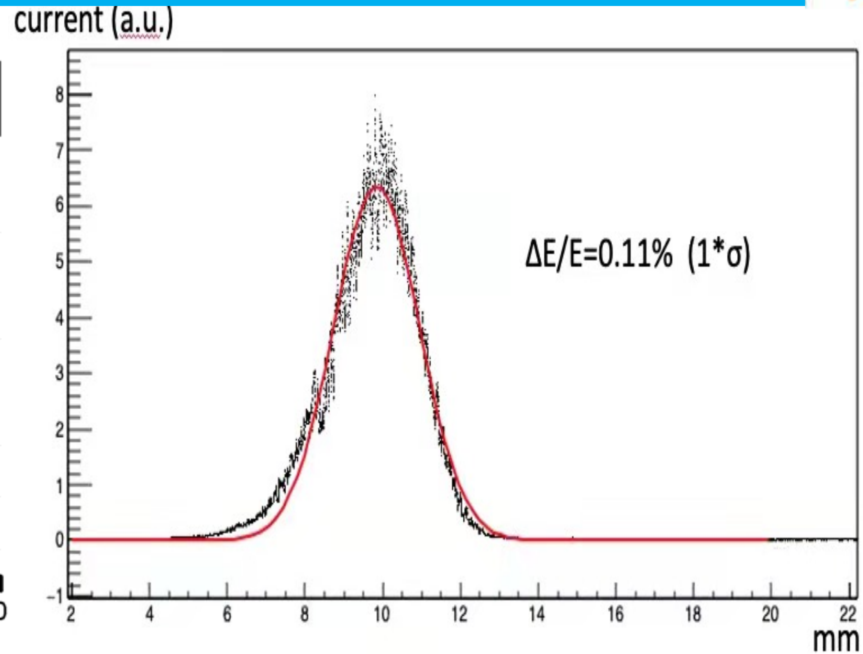
Basic design specifications of the DTL

Duty cycle	100%
Operating frequency (MHz)	81.25
Number of gaps	8
Design ion M/Q	4
Input particle energy (MeV/u)	0.5
Output particle energy (MeV/u)	0.3~0.7
Max. gap voltage (kV)	195
Q factor	11928
Peak field (Kilpatrick units)	1.43
Max. RF power (kW)	~18.6
Tube length (mm)	32
Gap (mm)	25.96
Drift tube inner diameter (mm)	40
Cavity length (mm)	~563.7
Cavity diameter (mm)	~910.6



Beam test



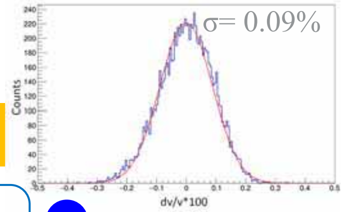


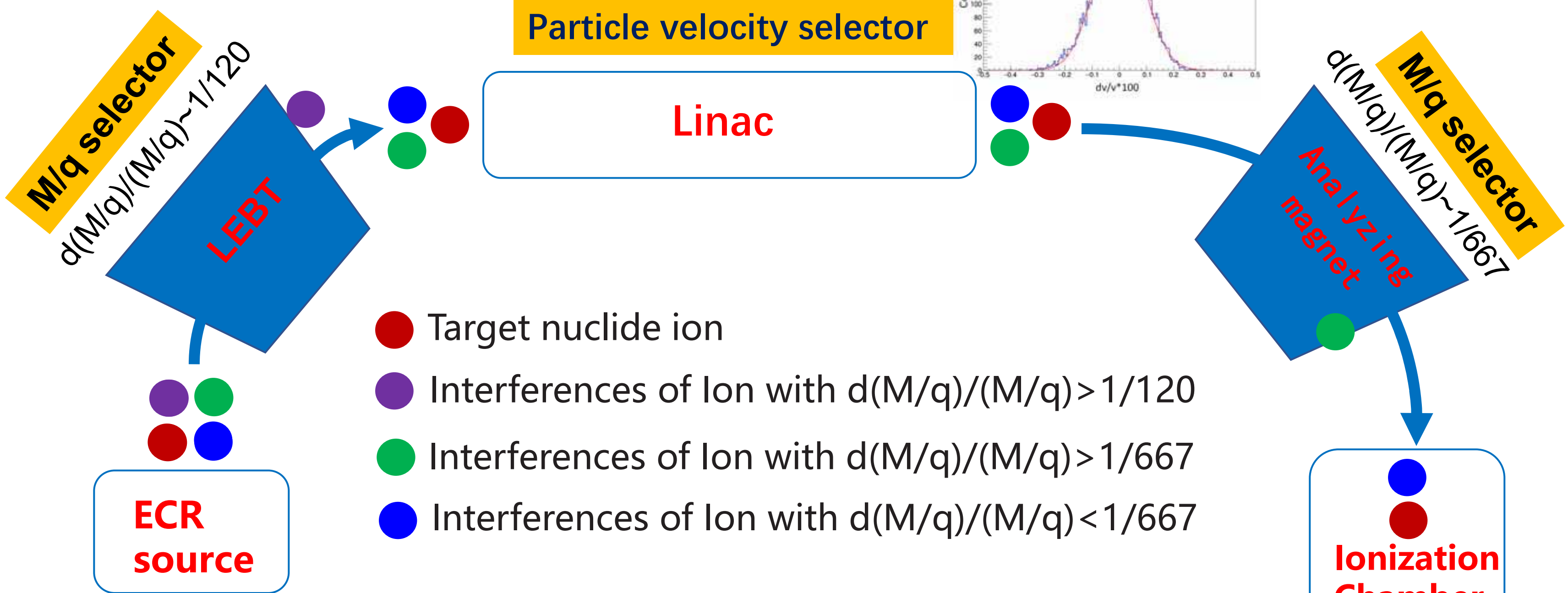
- Measurements agree well with simulations, demonstrating continuously adjustable energy in the range of 0.3-0.7 MeV/u
- Measured energy spread ~0.11% (1*σ)

- **Y. Yang**, *et al*, *Nuclear Inst. and Methods in Physics Research, A* 1039 (**2022**) 167095

LEAF-AMS (Accelerator Mass Spectrometry)

Trace actinide detection





Energy/range measurement

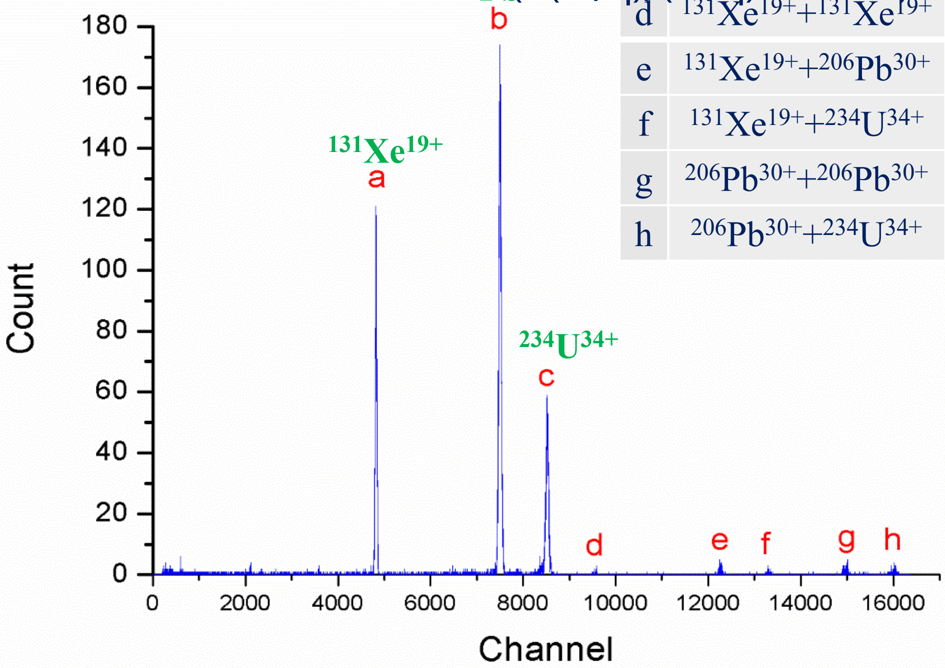
- Effcient production of high-charge state ions ensures the elimination of molecular ions at the source stage

Preliminary results-detection of Uranium

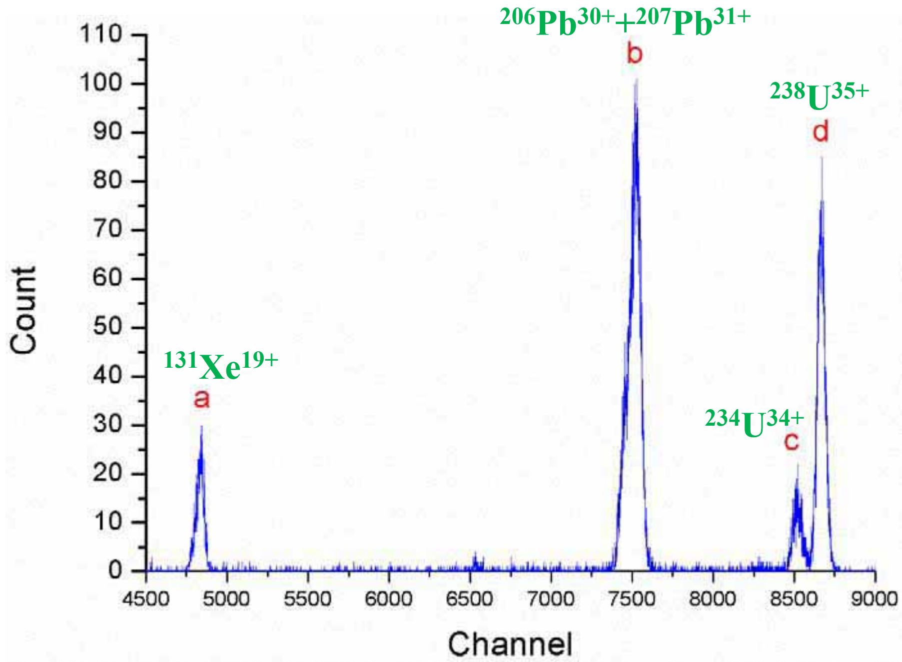
- Detection of ^{234}U
- $^{234}U^{34+}$ ions were selected from the source
- Pilot beam: $^{131}Xe^{19+}$ (Δ(M/q)/(M/q)~0.0009)

✓ Successful to detect and identify Uranium isotopes and interferences

× Measurement of isotopic abundance $^{234}U/U$ is still being explored



d	$^{131}Xe^{19+}+^{131}Xe^{19+}$
e	$^{131}Xe^{19+}+^{206}Pb^{30+}$
f	$^{131}Xe^{19+}+^{234}U^{34+}$
g	$^{206}Pb^{30+}+^{206}Pb^{30+}$
h	$^{206}Pb^{30+}+^{234}U^{34+}$



Summary

- As the prototype of HIAF Front-End, LEAF has been constructed and successfully commissioned. Key performance parameters demonstrated.

- High transmission efficiencies (typically higher than 97%) were relatively easy to achieve for beam currents of ~100 eμA level. However, while beam current goes to several hundred eμA or emA level, the transmission efficiency of the RFQ is gradually reduced because of degraded beam quality.

- A setup of ion beam energy adjustment system has been developed, precise beam energy tuning with 0.3~0.7 MeV/u has been achieved, and more than 50 pμA carbon beam with an energy spread of ~0.11% (1*σ) has been delivered to the experimental terminal.

- Accelerator Mass Spectrometry has been developed based on LEAF, preliminary detection of Uranium was implemented, feasibility demonstrated.

Thanks for your attention

and for your patience in listening to the remote speaker!

yangyao@impcas.ac.cn