Intense highly charged ion beams operation for heavy ion accelerators at IMP

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HB'23, Oct. 9~13, 2023, Geneva, Switzerland

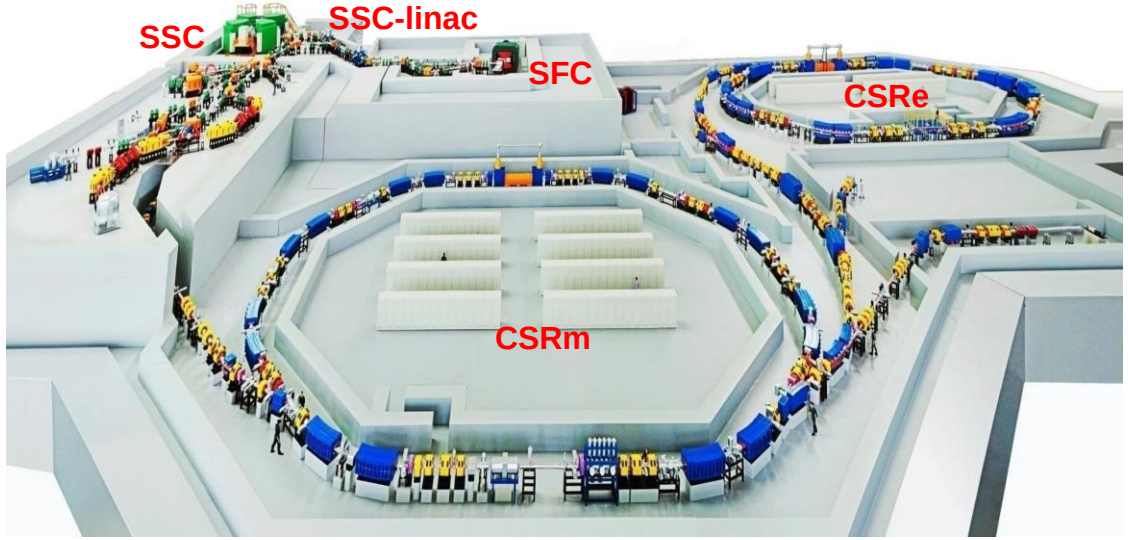
Outline

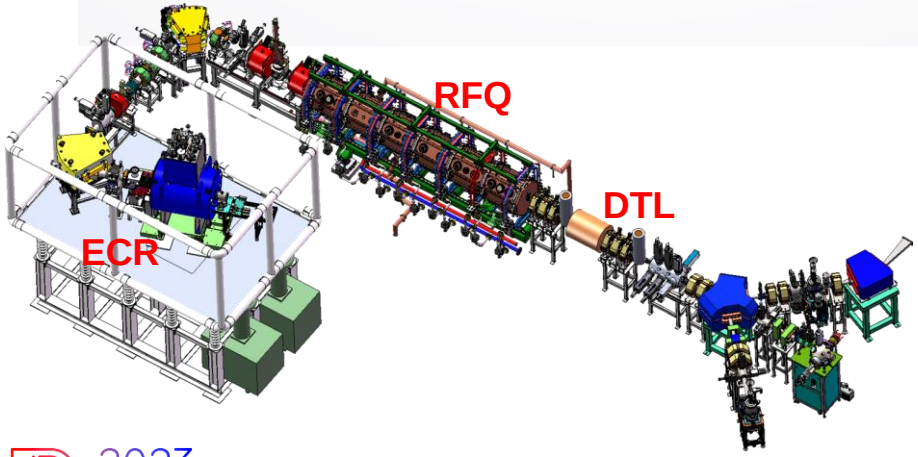
- Heavy ion accelerators at IMP
- Production and acceleration of high-intensity heavy ion beams
- Perspectives in ECRIS development
- Summary

Heavy ion accelerators at IMP (in operation)

HIRFL (Heavy Ion Research Facility in Lanzhou)

- Ion species: H~U
- Beam Energy: several MeV/u ~ 1 GeV/u
- User facility for:
  Nuclear physics, ion beam applications…





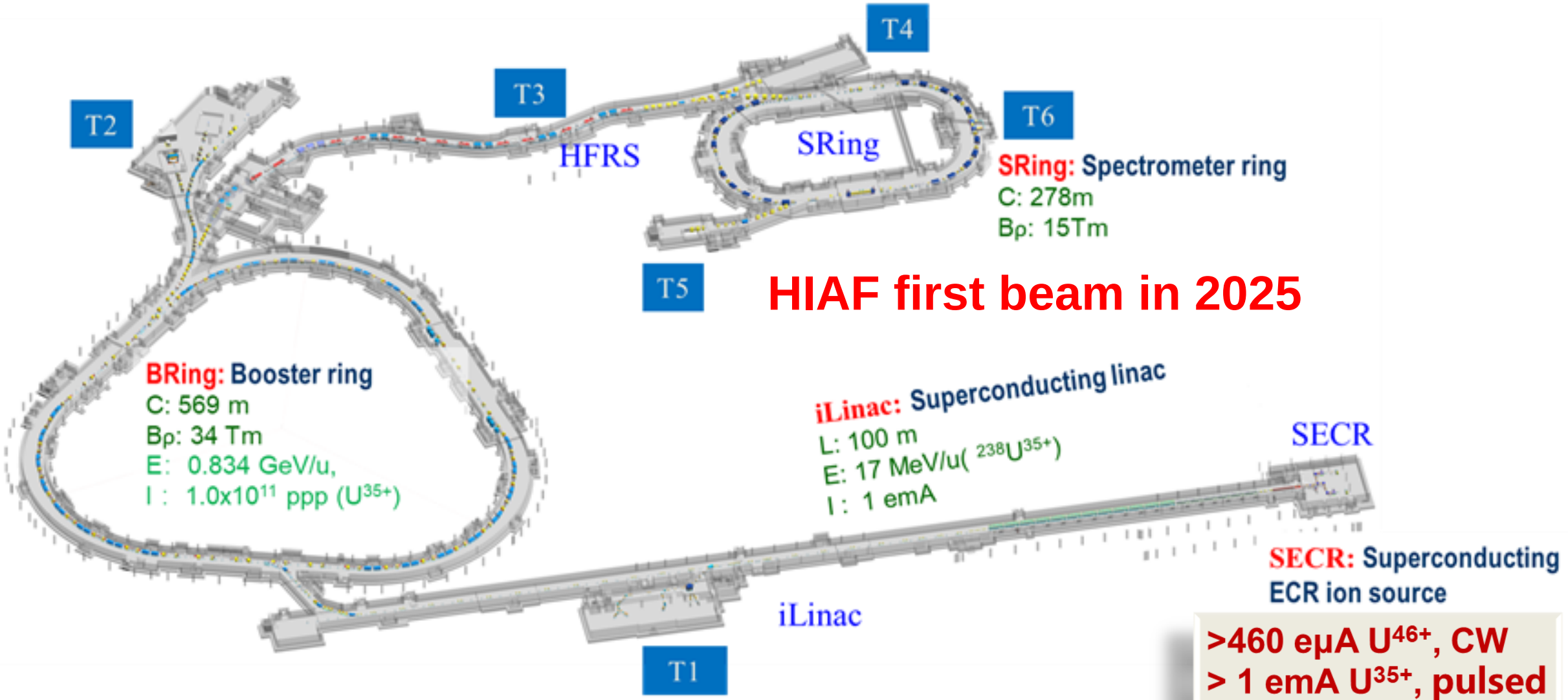
CAFe2 (China Accelerator Facility for new Element)

- Ion species: M/Q≤3
- Beam Energy: 4-8 MeV/u
- User facility for:
  - Super Heavy Element synthesis

LEAF (Low Energy high-intensity heavy ion Accelerator Facility)

- Ion species: H~U
- Beam Energy: 0.3~1.0 MeV/u
- User facility for:
  - Atomic Physics. Astro - Nuclear Physics. Material Science

Heavy ion accelerator HIAF at IMP (under construction)



SECRAL-II delivering high intensity heavy ion beams for HIRFL

Parameters	SECRAL II
28 GHz μW Power (kW)	10.0
18 GHz μW Power (kW)	2.0
Axial Field Peaks (T)	3.7 (Inj.), 2.2 (Ext.)
Mirror Length (mm)	420
No. of Axial SNs	3
B_r at r=63 mm (T)	2.06
SC-material	NbTi
Magnet Cooling	LHe bathing
Chamber ID (mm)	125.0
P_v (liter)	5.1
Max. Power Density (kW/l)	2.3
Dynamic cooling power (W)	6.0 (~8 L/h)

SECRAL-II superconducting ECR ion source in routine operation for HIRFL

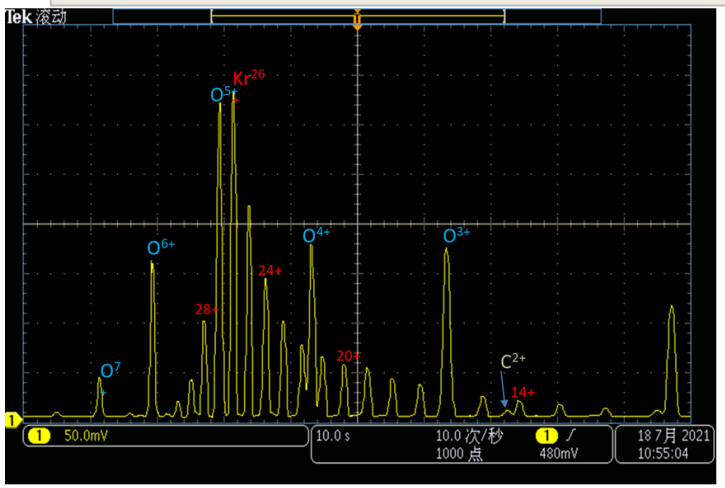
Recent technical advancement of SECRAL-II ion source

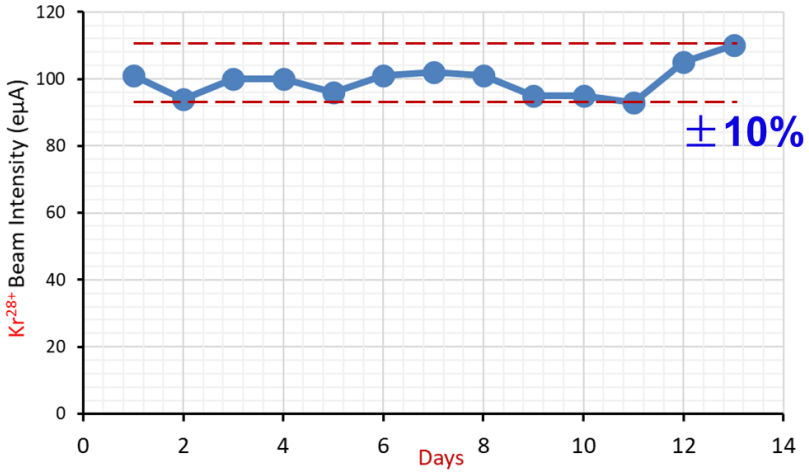
- **More efficient plasma heating**
  Optimized microwave heating scheme with
  - **tapered waveguide**
  - **Vlasov launcher**

- **More efficient plasma-chamber cooling**
  - **Microchannel cooling chamber**

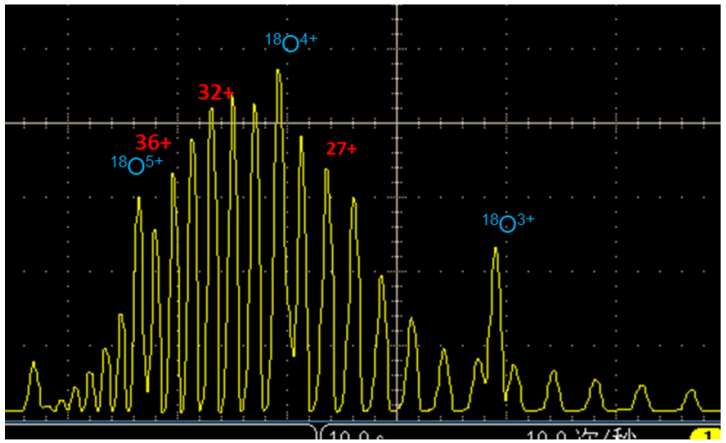
Long-term operation at high-intensities of highly-charged beams

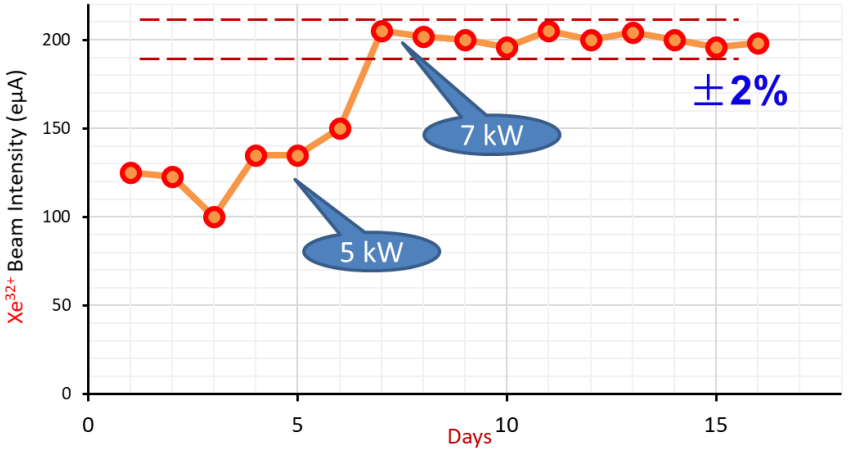
$^{86}Kr^{28+}$= 100 eμA, P_{rf}= 6.0 kW, Power density=1.16 kW/l





$^{129}Xe^{32+}$= 200 eμA, P_{rf}= 7.0 kW, Power density=1.36 kW/l

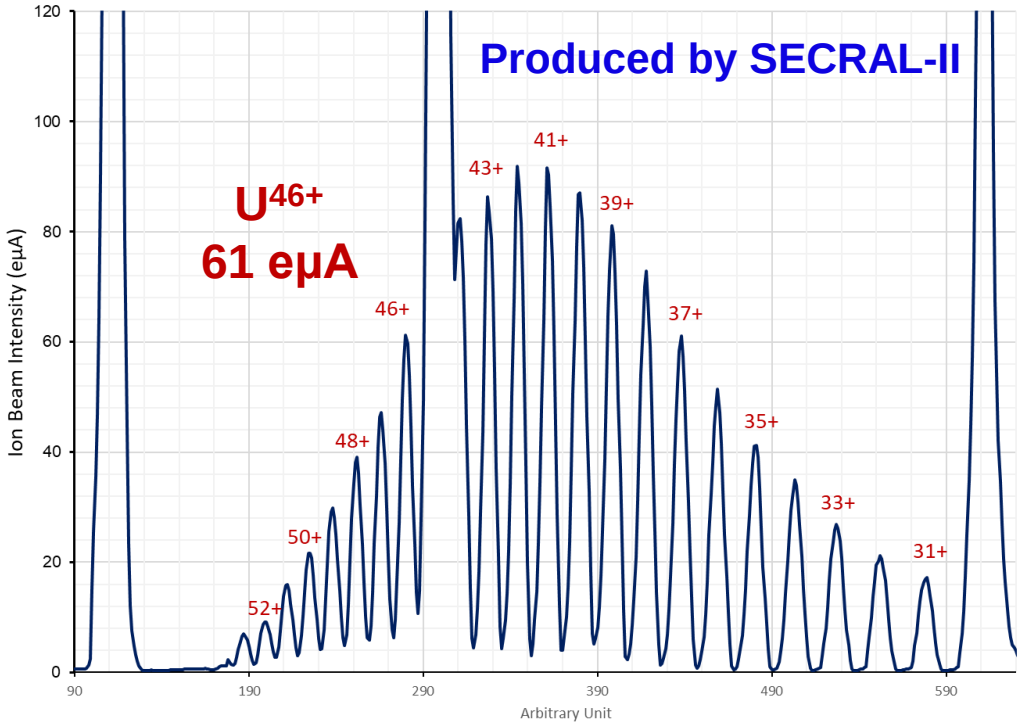


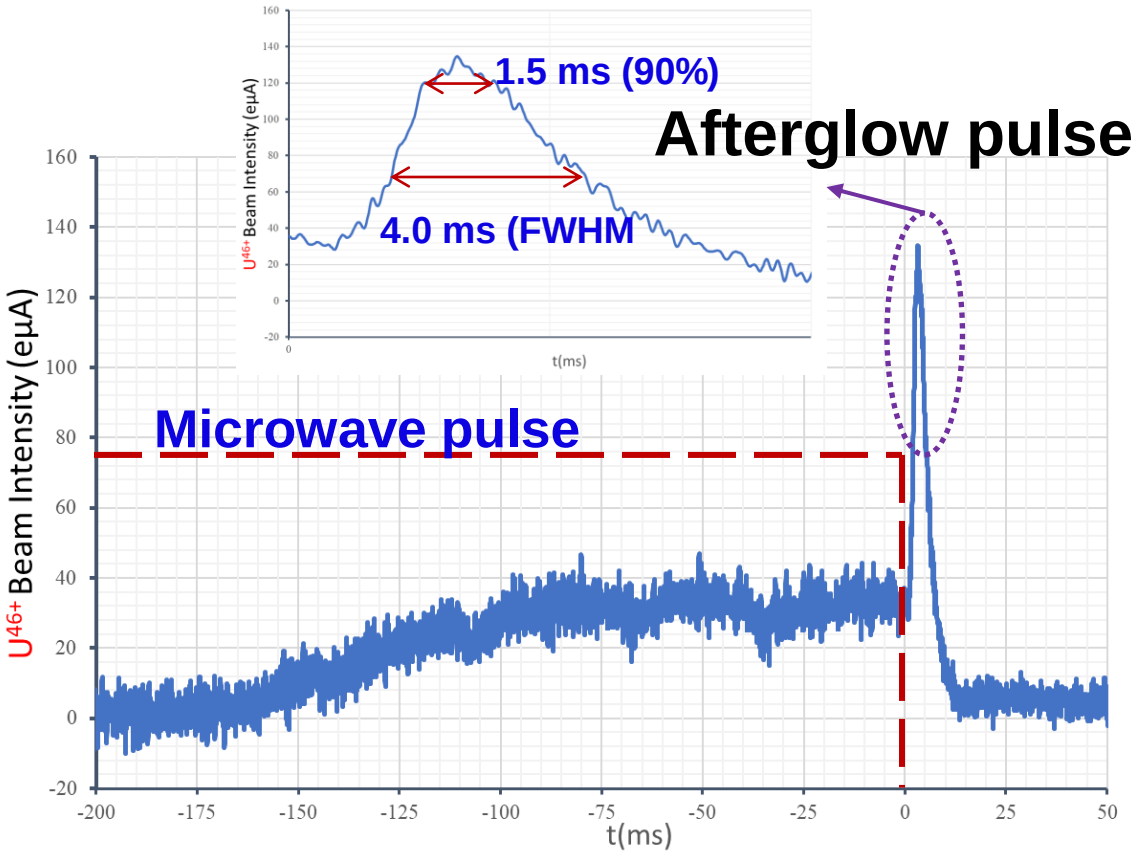


Operation for HIRFL SFC cyclotron

High intensity highly-charged U beams preparing for SSC-linac

World record CW and pulsed beam intensities of $^{238}U^{46+}$ produced by SECRAL-II



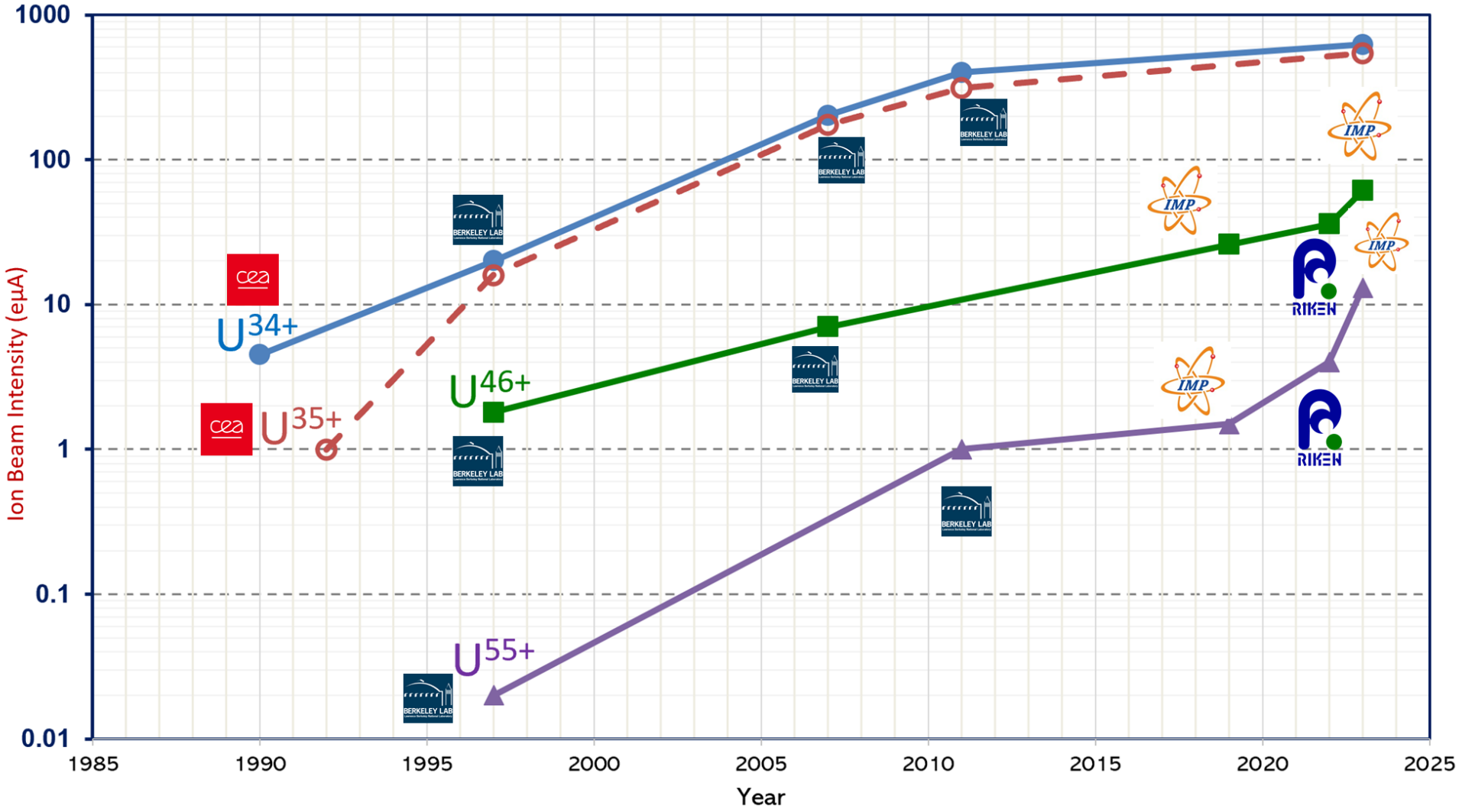


Allows the acceleration of U beam up to 500 MeV/u with CSRm

- **2.2 times gain in beam intensity with 1.5 ms peak pulse**

High intensity highly-charged U beams preparing for HIAF

World record CW intensities of highly-charged U beams produced by SECRAL-II



U^{34+} 620 eμA

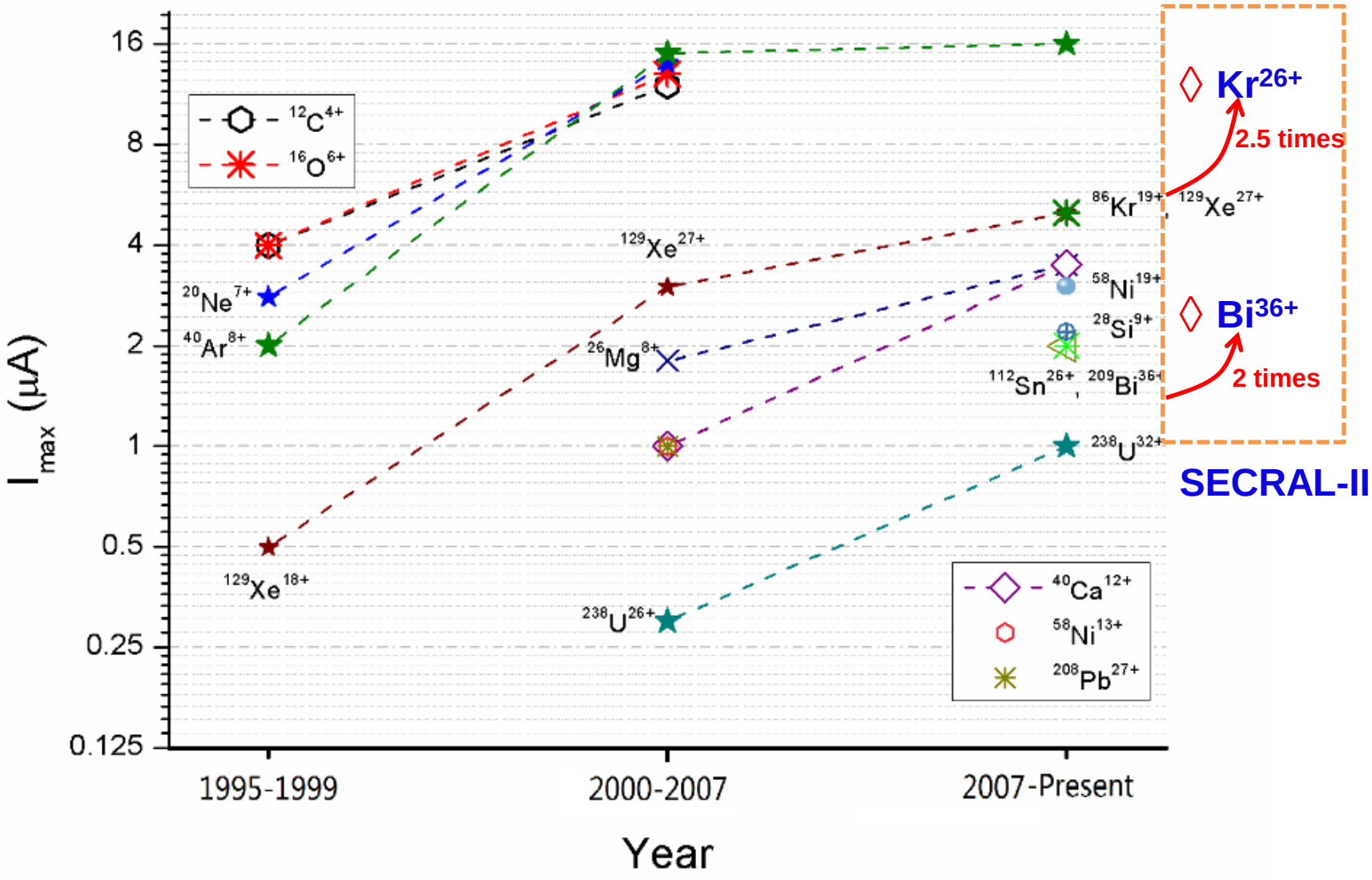
U^{35+} 547 eμA

U^{46+} 61 eμA

U^{55+} 13 eμA

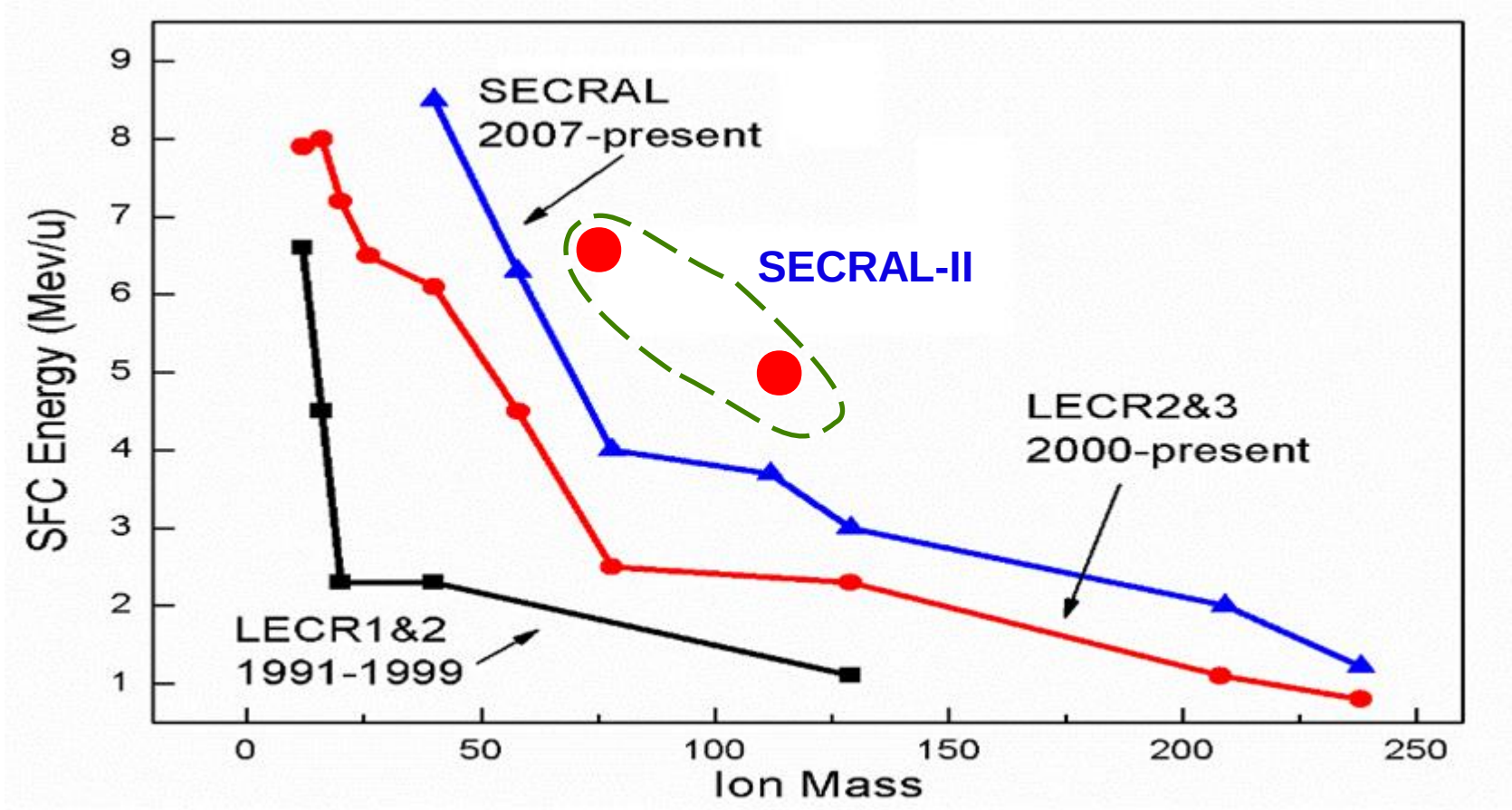
SECRAL-II operation improved performance of HIRFL-SFC cyclotron

Beam intensities from SFC Cyclotron



SECRAL-II operation improved performance of HIRFL-SFC cyclotron

Beam Energies from SFC



SECRAL-II operation improved performance of HIRFL-CSRm

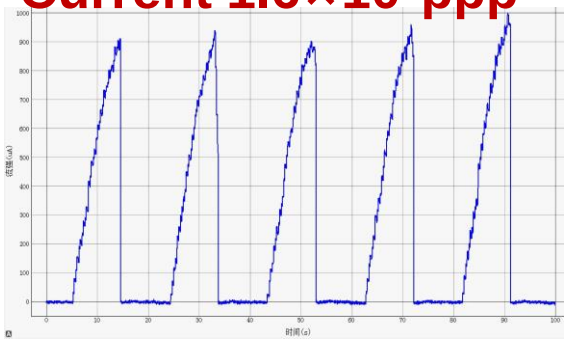
CSRm performance enhancement together with other technical improvements

$^{36}Ar^{15+}$

SECRAL-II: ~350 eμA (~4 times historical operation current)

- High current: SFC--8.5 AMeV/15 eμA
- CSR_m Beam Current Increase by a factor of 5

Current 1.6×10⁹ppp

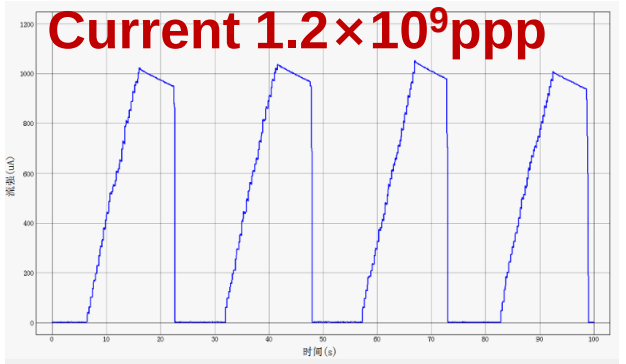


$^{78}Kr^{26+}$

SECRAL-II: ~280 eμA (not available before)

- High current: SFC--6 AMeV/12 eμA
- CSR_m Beam Current Increase by a factor of 10

Current 1.2×10⁹ppp

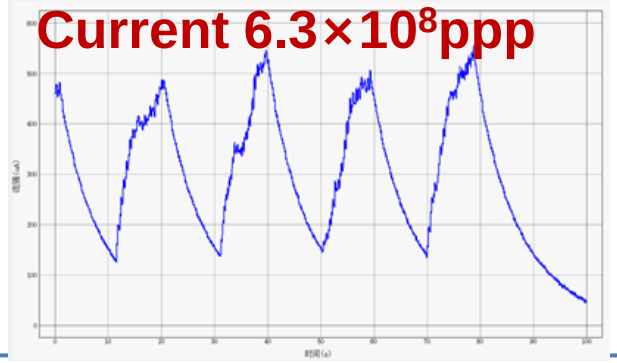


$^{129}Xe^{32+}$

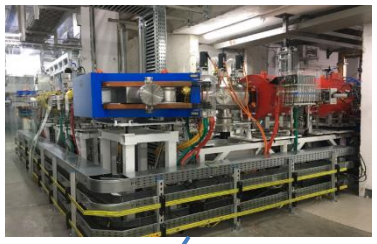
SECRAL-II: ~200 eμA (not available before)

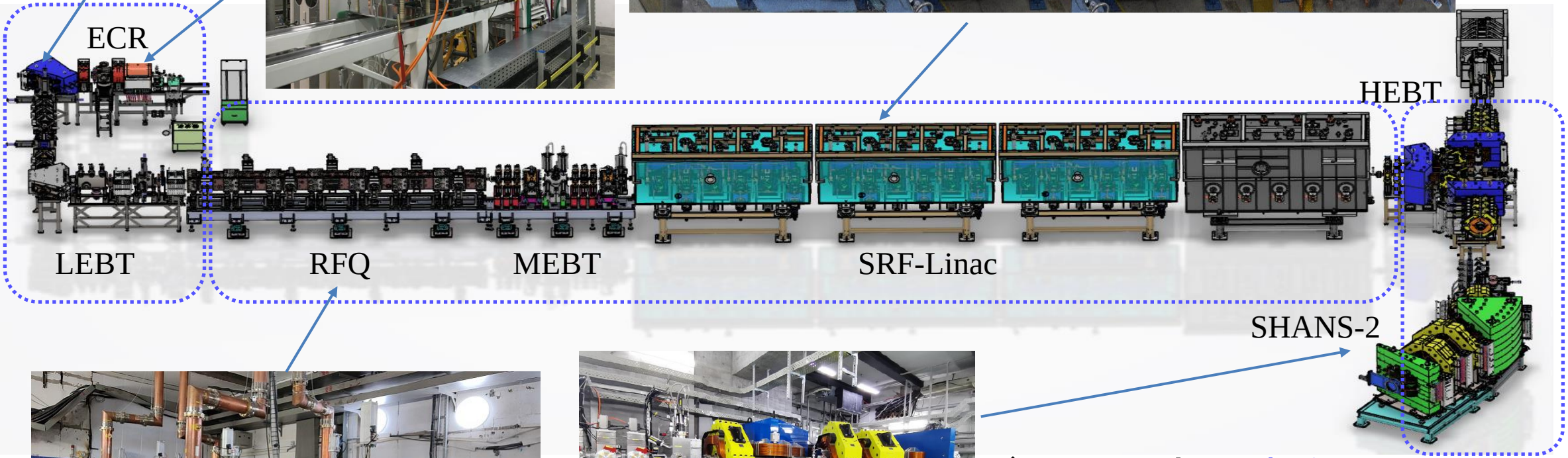
- High current : SFC—3.9 AMeV/8 eμA
- CSR_m Beam Current Increase by a factor of 5

Current 6.3×10⁸ppp



High intensity SC heavy ion linac dedicated to SHE: CAFe2

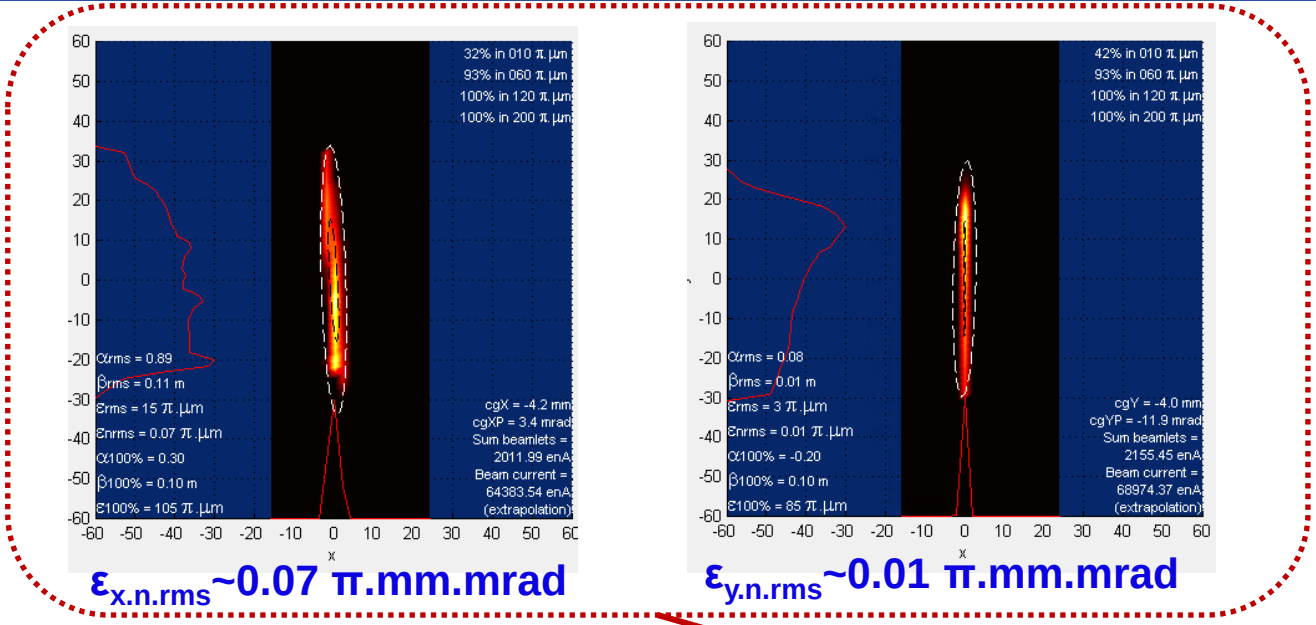




- Ion species: M/Q≤3
- Beam Energy: 4-8 MeV/u
- User facility for:
  - Super Heavy Element synthesis

Acceleration of high intensity heavy ion beams by CAFe2

ECR ion source - LECR5,18GHz



Beam quality control:

- Stable ECR plasma
- Optimum beam line alignment with the ion source
- Proper beam collimation

Ion species	Method	Supporting Gas	IS Ext. Voltage [kV]	FC01 (IS) [eμA]	FC03 (RFQ) [eμA]	RFQ entrance RMS emittance (π.mm.mard)	Transmission efficiency [FC03/FC01]	Delivering time [Hrs]
$^{40}Ca^{13+}$	**^{40}CaO+ Al**	$^{16}O_2$	30.8	**40-60**	**35-50**	εx=0.12, εy=0.05	85~90%	1500
$^{55}Mn^{17+}$	**^{55}Mn**	$^{14}N_2$	32.4	**40-60**	**35-50**	εx=0.08, εy=0.06	85~90%	428
$^{54}Cr^{17+}$	**^{54}Cr**	$^{14}N_2$	31.8	**40-60**	**35-50**	εx=0.08, εy=0.06	85~90%	1183
$^{48}Ca^{14+}$	**^{48}CaO+ Al**	$^{16}O_2$	34.3	**10-40**	**10-35**	εx=0.09, εy=0.08	85~90%	~600

Low Energy high-intensity heavy ion Accelerator Facility: LEAF

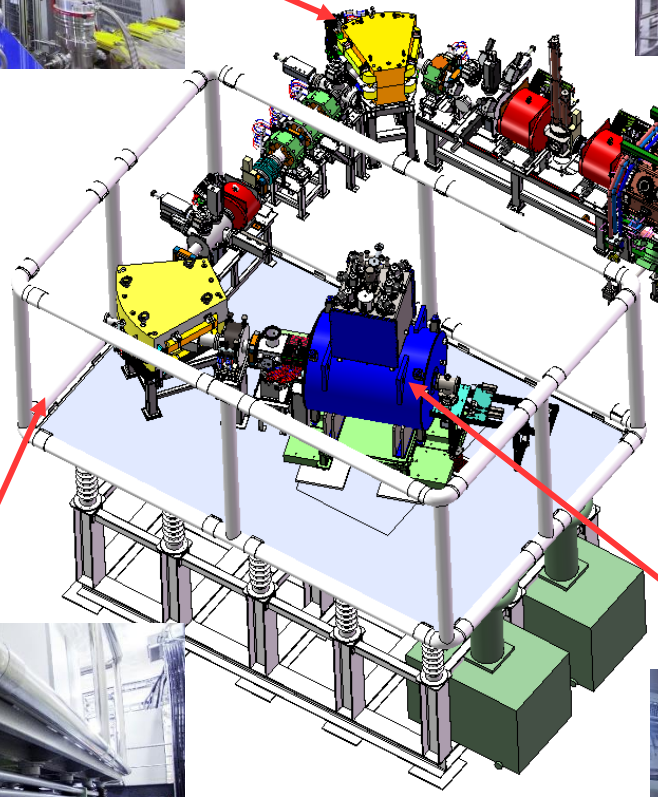
LEBT

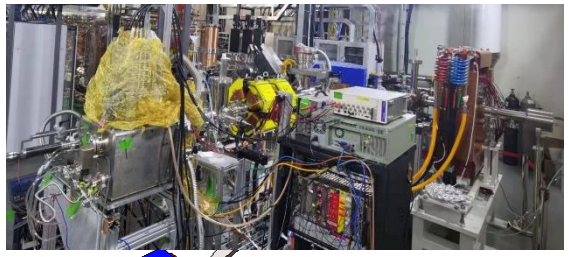
TR1

RFQ

DTL

Enables E: 0.3~0.7 MeV/u





terminals

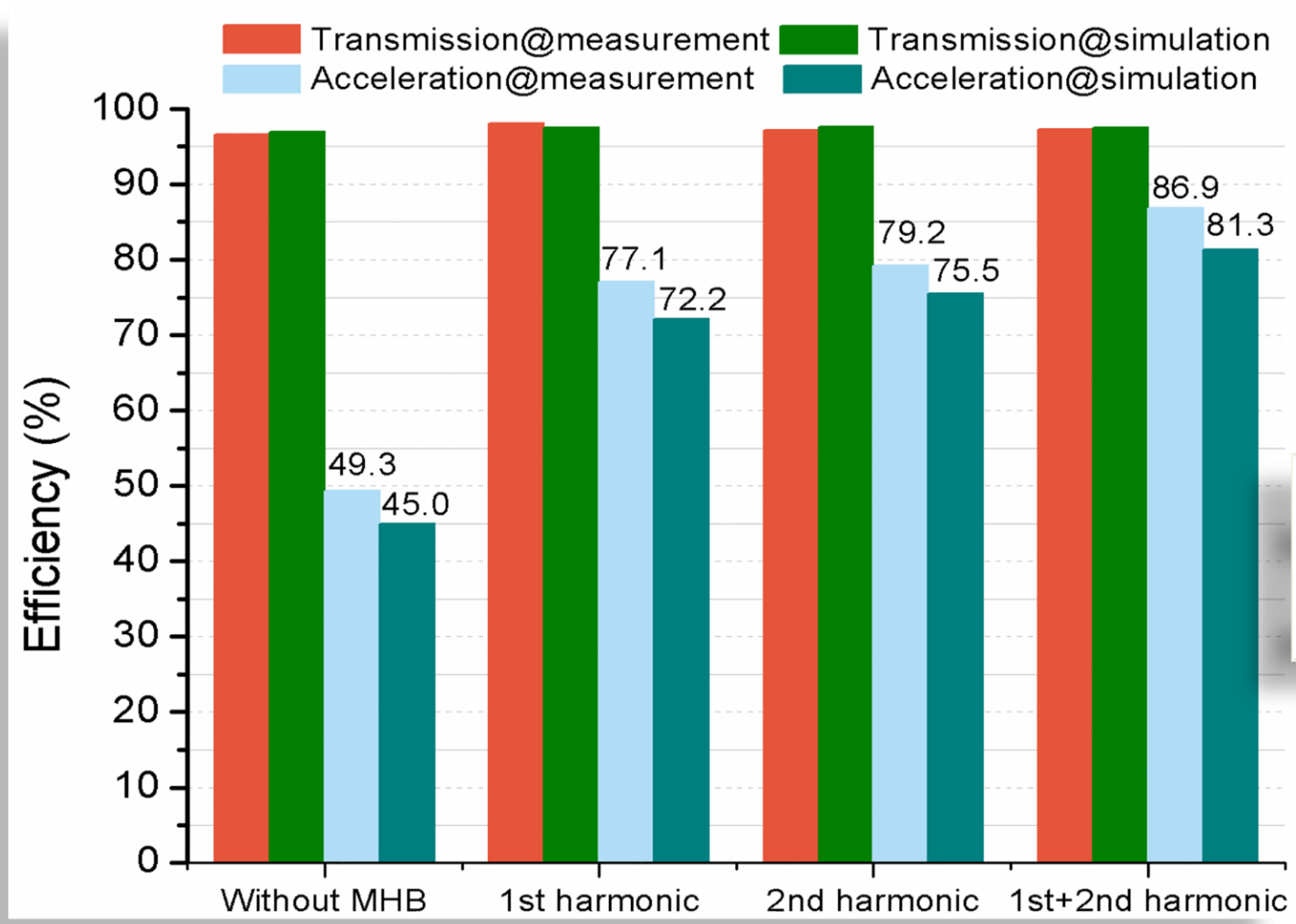
TR3

TR2

High voltage platform

SC ECR ion source

Acceleration of high intensity heavy ion beams by LEAF



RFQ Beam Commissioning

~100 eμA N^{2+}

- **Transmission efficiency: >95%**
- **Acceleration Efficiency >80%**

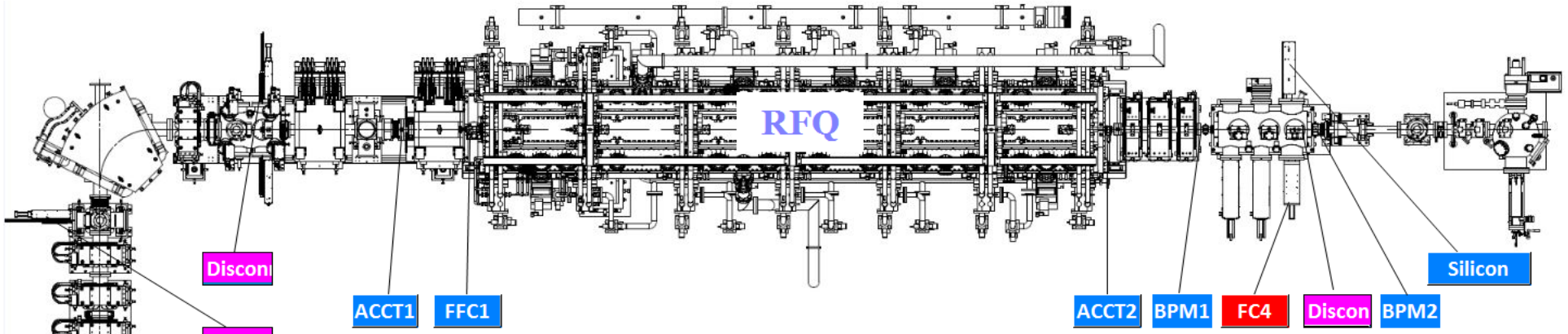
Y. Yang, et al., PRAB **22**, 110101(2019)

Acceleration of high intensity heavy ion beams by LEAF

Heavy ion beam preliminary results

U^{35+} 74 eμA

- Transmission: ~95%
- Acceleration: ~72%

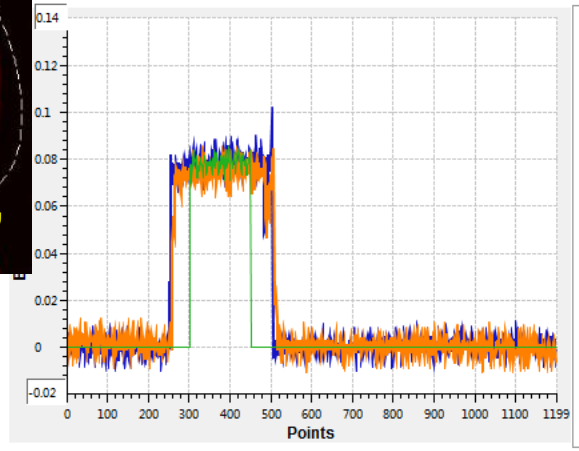


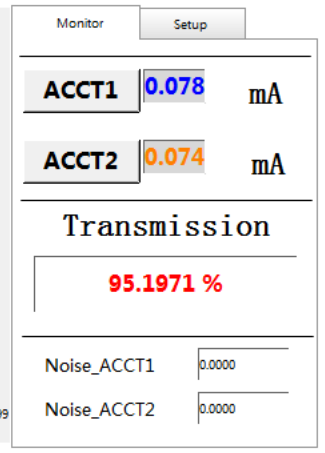
Longitudinal Bunch Length [FFC]

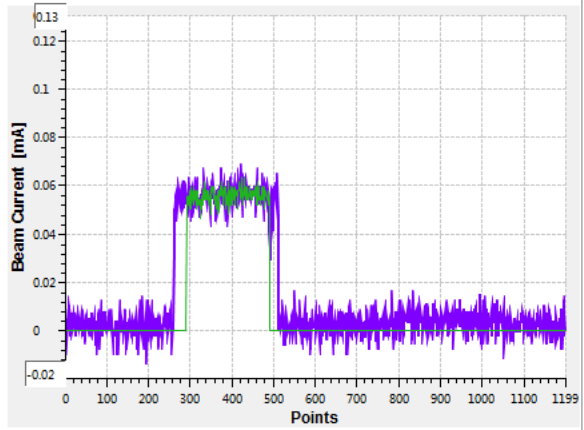
Beam Position & Phase [BPM]

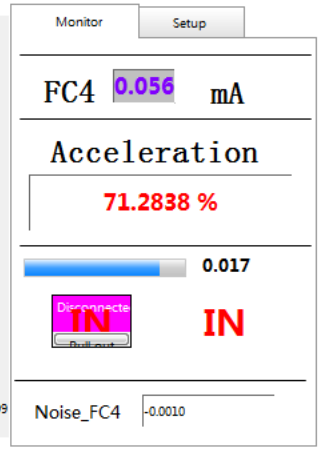
Beam Energy [BPM]

Energy Spectrum [Silicon]









Ion source: 78 eμA

$\varepsilon_{x,y}$ =0.13, 0.15 π.mm.mrad

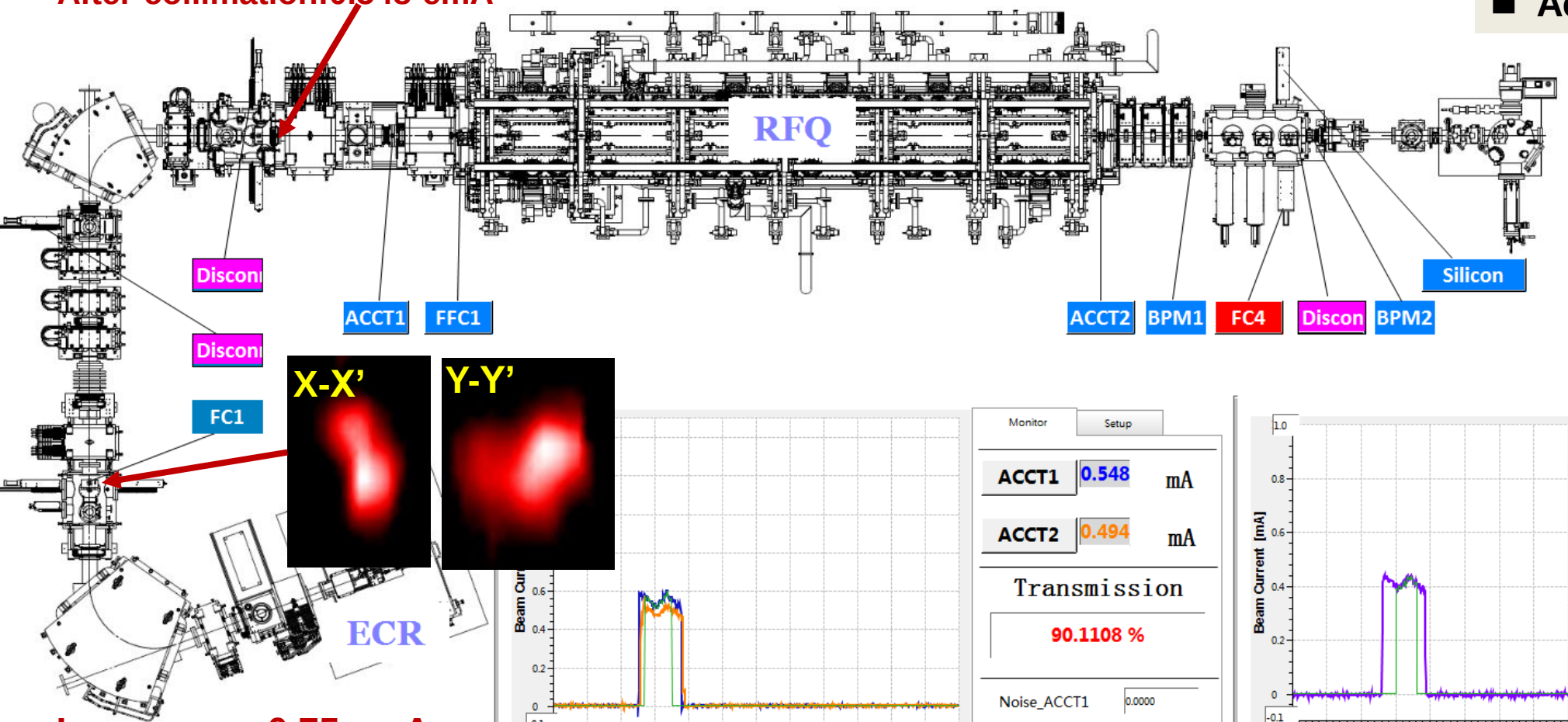
Acceleration of high intensity heavy ion beams by LEAF

Heavy ion beam preliminary results

Ar^{9+} 494 eμA from RFQ

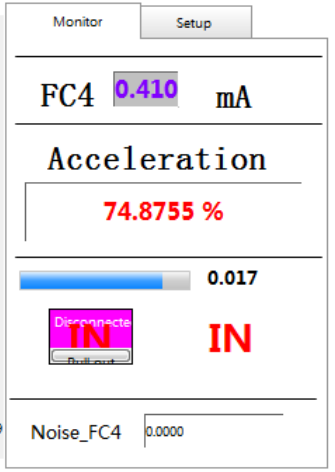
- Transmission: ~90%
- Acceleration: ~75%

After collimation:0.548 emA



Ion source: 0.75 emA

$\varepsilon_{x,y}$ =0.23, 0.18 π.mm.mrad



Transverse Emittance & Profile [FC]

Longitudinal Bunch Length [FFC]

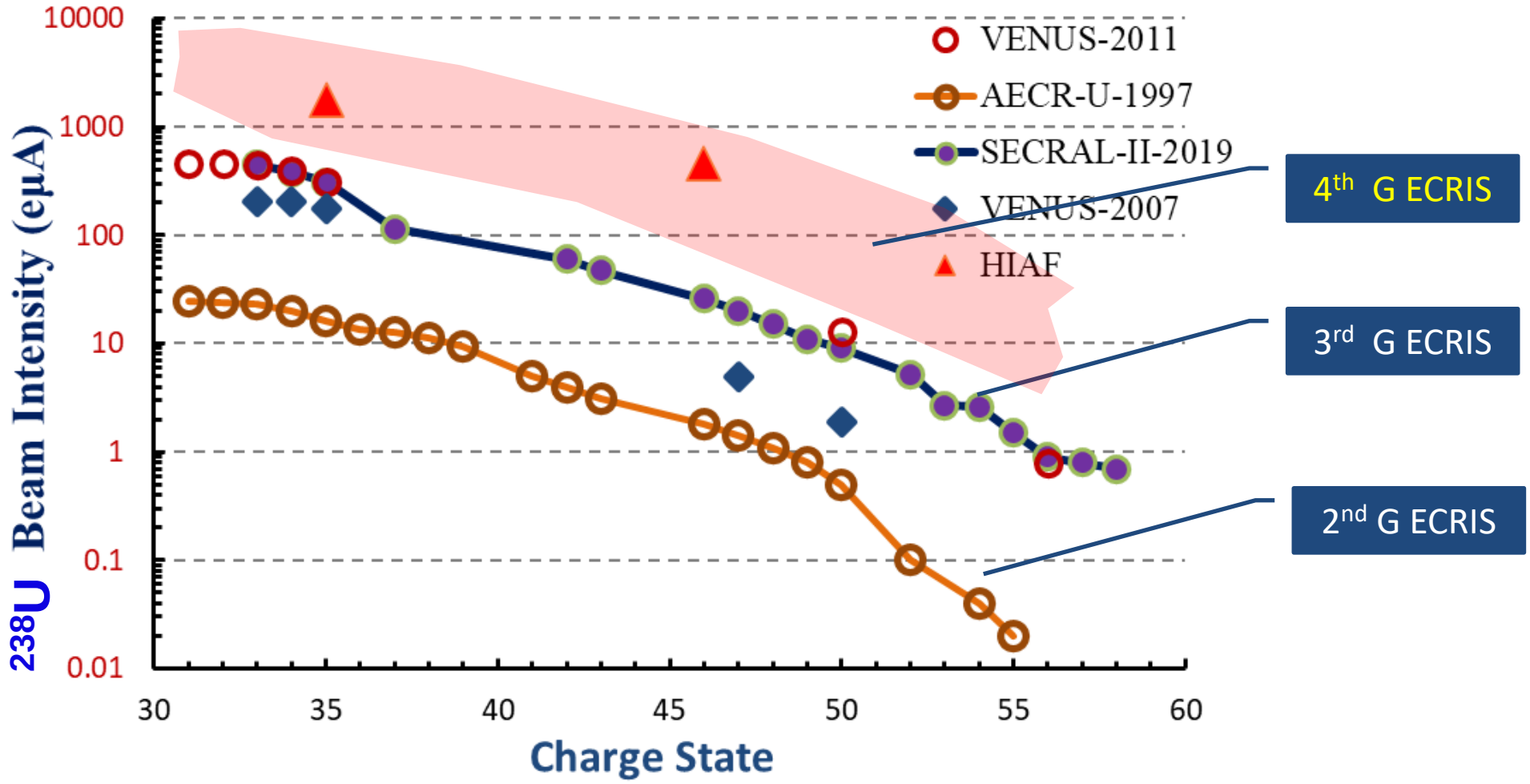
Beam Position & Phase [BPM]

Beam Energy [BPM]

Energy Spectrum [Silicon]

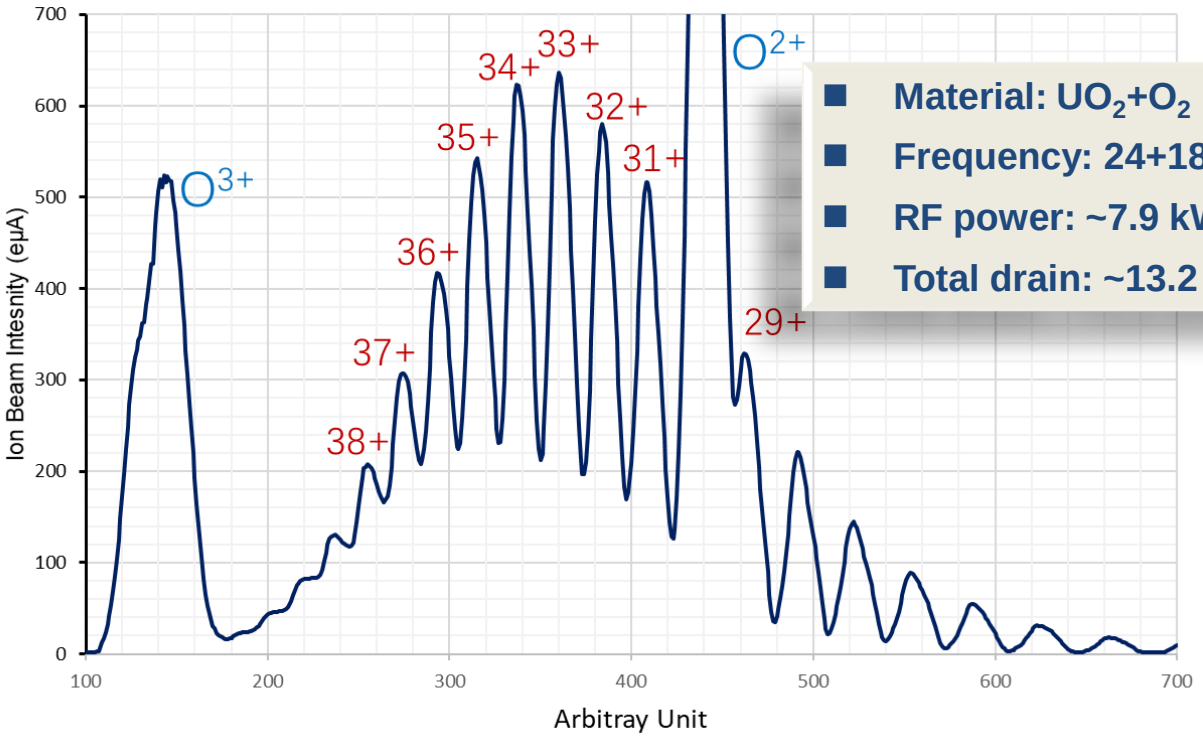
Perspectives in ECRIS development: intensity

The next generation heavy ion accelerators demand high intensity beam

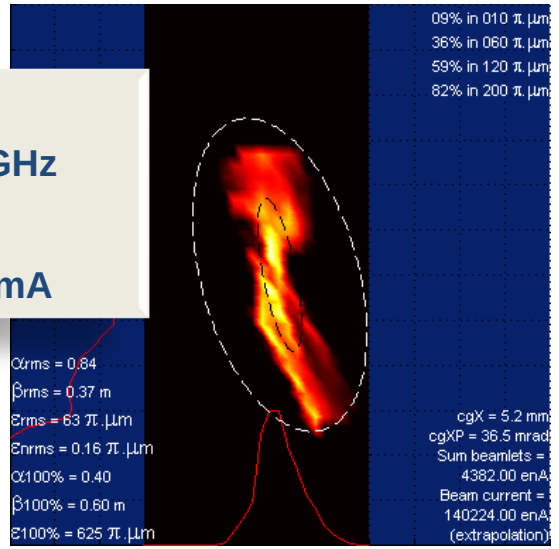


Perspectives in ECRIS development: quality

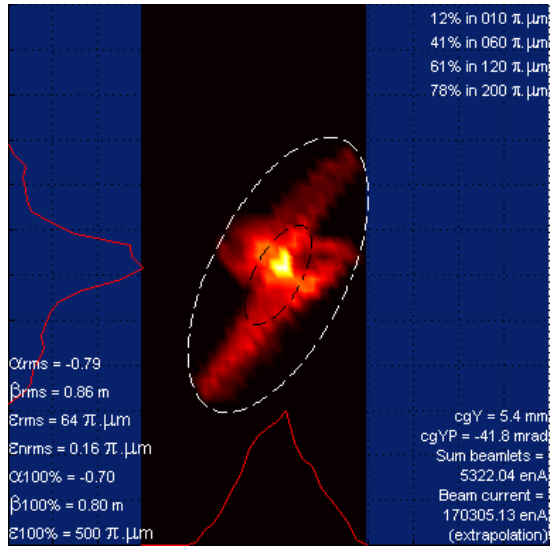
Production of 547 eμA U^{35+} by SECRAL II



- Material: UO_2+O_2
- Frequency: 24+18 GHz
- RF power: ~7.9 kW
- Total drain: ~13.2 emA



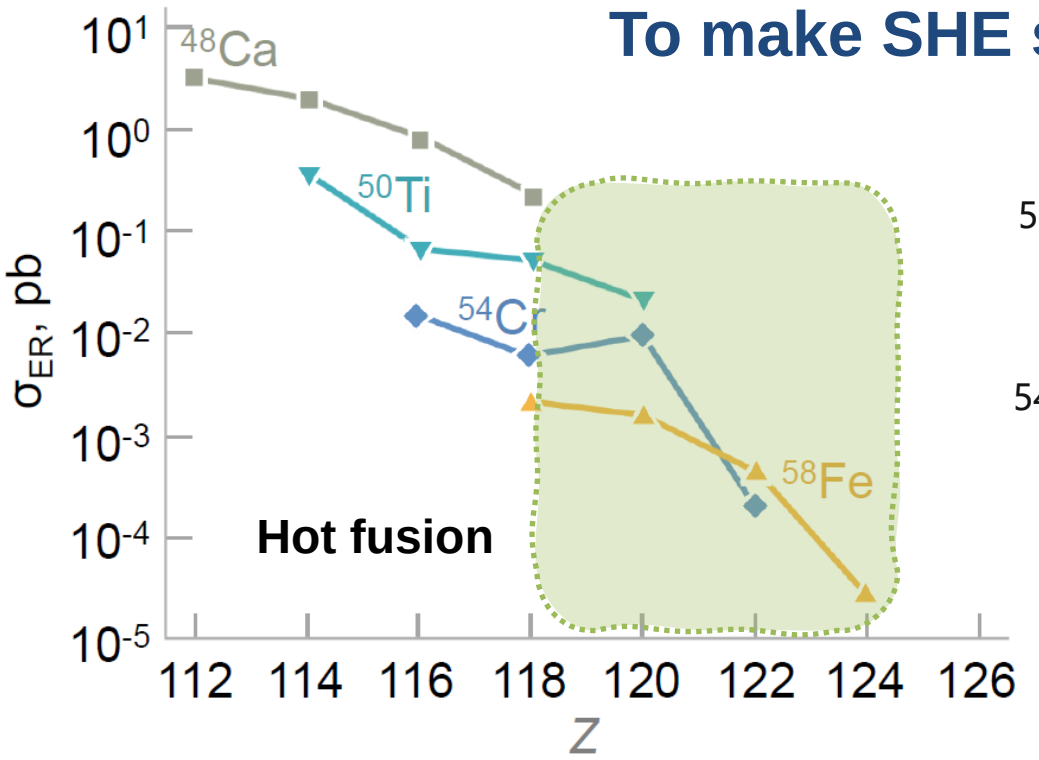
X-$\varepsilon_{n.rms}$: 0.16 π.mm.mrad



Y-$\varepsilon_{n.rms}$: 0.16 π.mm.mrad

- Beam quality not promising!
- How to realize efficient injection to downstream accelerators?

Perspectives in ECRIS development: efficiency



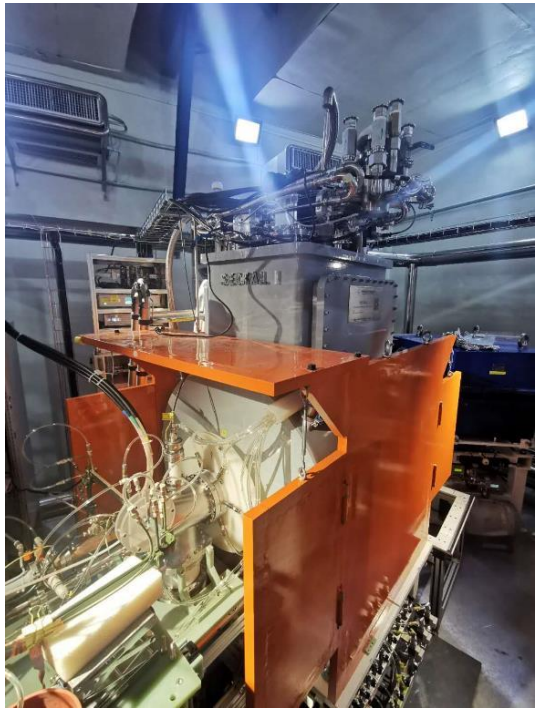
To make SHE synthesis possible:

$^{51}V+^{248}Cm \rightarrow Z= 119$

1 event/year@1 pμA

$^{54}Cr+^{248}Cm \rightarrow Z= 120$

1 event/year@3~5 pμA



New Elements and beyond

Challenges:

- **20~50 pμA highly charged ion beams**
- **Cost efficiency of rare isotopes**
- **Efficient coupling and acceleration**

G. Adamian, N. Antonenko, A. Bezbakh, and R. Jolos, Physics of Particles and Nuclei, Vol. 47, No. 3, pp. 387–455 (2016)

Summary

- **Technical advancement with ECR ion sources have enabled significant improvement in accelerators performance at IMP**
- **Beam intensity and quality both important in high intensity beam acceleration**
  - ✓ Beam intensity determines the final intensity
  - ✓ Beam quality determines the acceleration efficiency
  - ✓ Intensity + quality determines the quality of accelerated beams
- **For next generation heavy ion accelerators, more critical challenges are foreseen**

We appreciate the great support of the accelerator teams at IMP !!