High performance highly-charged ECR ion sources and matching with high-intensity heavy ion accelerator facilities

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Outline

- What type of ECRIS would be built for a heavy ion accelerator in terms of beam intensity, energy and performance-cost-efficiency?

- **Beam quality from ECRIS and efficient acceleration of high intensity heavy ion beams.**

What type of ECRIS should be built for a heavy ion accelerator

- A few tens of ECRISs have been in operation at the cyclotrons and linacs over the world.

- Three types of ECRISs in terms of RF frequency

RT LECR5
14-18 GHz

SC SECRAL-II
24-28 GHz

SC FECR
45-60 GHz

What type of ECRIS should be built to improve performance of a heavy ion accelerator (cyclotron or linac) in terms of beam intensity, energy and cost ?

18 GHz RT ECRIS can meet requirements of typical cyclotron and linac

LECR5
18 GHz

- 50-150 eμA is an appropriate beam intensity for a cyclotron and RT linac.
- Cyclotron beam intensity limit comes from the axial injection system and space charge effect
- Higher beam intensity is quite difficult for a CW RT linac due to thermal loss at high RF power.

Maximum beam intensities produced by LECR5 at 18 GHz

Ion species	Charge state	LECR5 [eμA] 18+ 18 GHz 2-3 kW
^{40}Ar	12+	415
	14+	170
	16+	62
^{78}Kr	18+	220
	23+	73
	26+	32
^{129}Xe	26+	200
	28+	100
	30+	28
^{40}Ca	11+	230
	14+	115
	16+	65
^{50}Ti	11+	50-100*
	16+	30-60*
^{238}U	20+	100*
	33+	50

* estimated

We do need 28 GHz ECRIS to achieve higher energy and current of accelerator

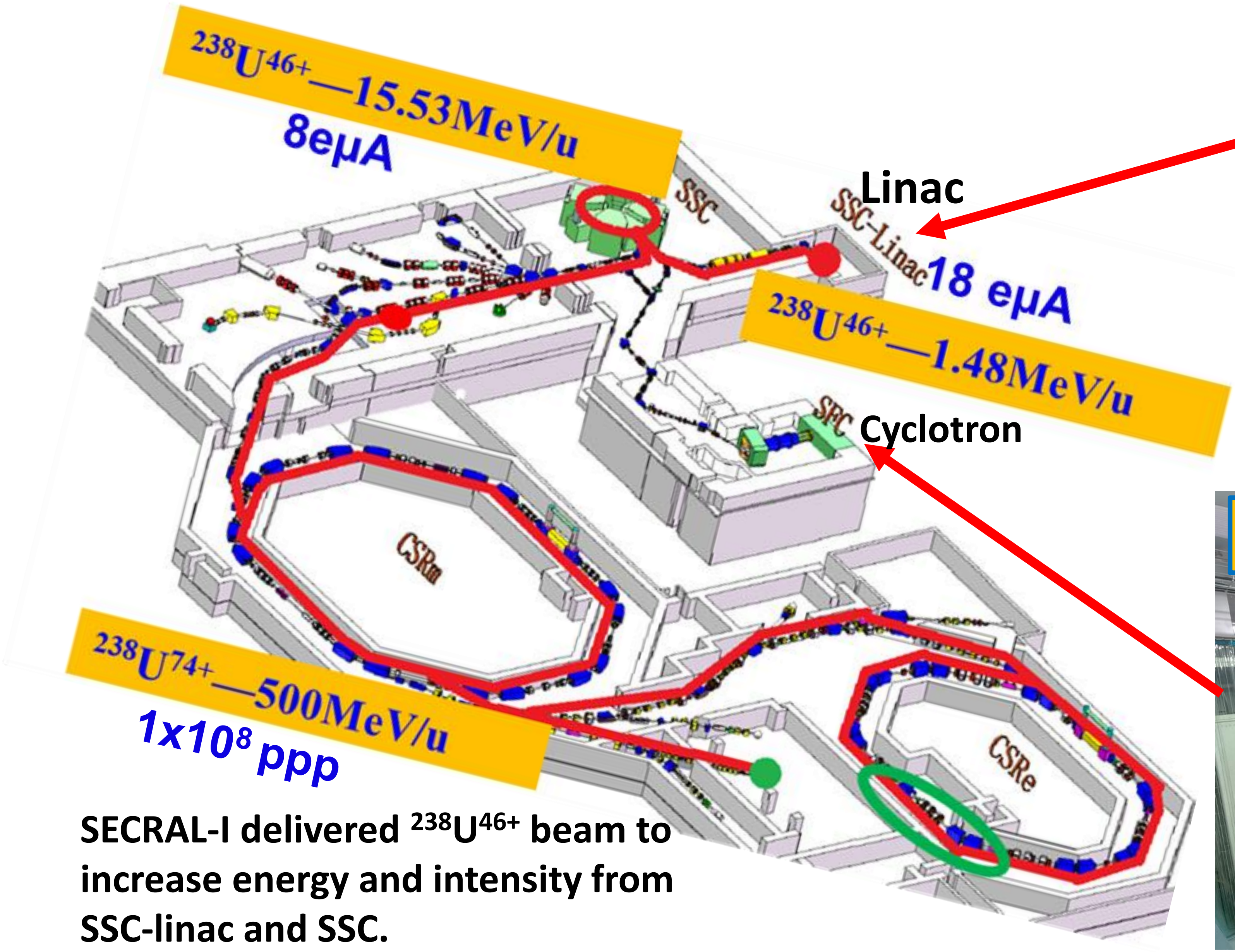
Maximum beam intensities produced by SECRAL&SECRAL-II

SECRAL-II, 24-28GHZ

- Higher charge state beams by 28 GHz ECRIS may upgrade accelerator to higher energy, particularly for existing operational cyclotron.

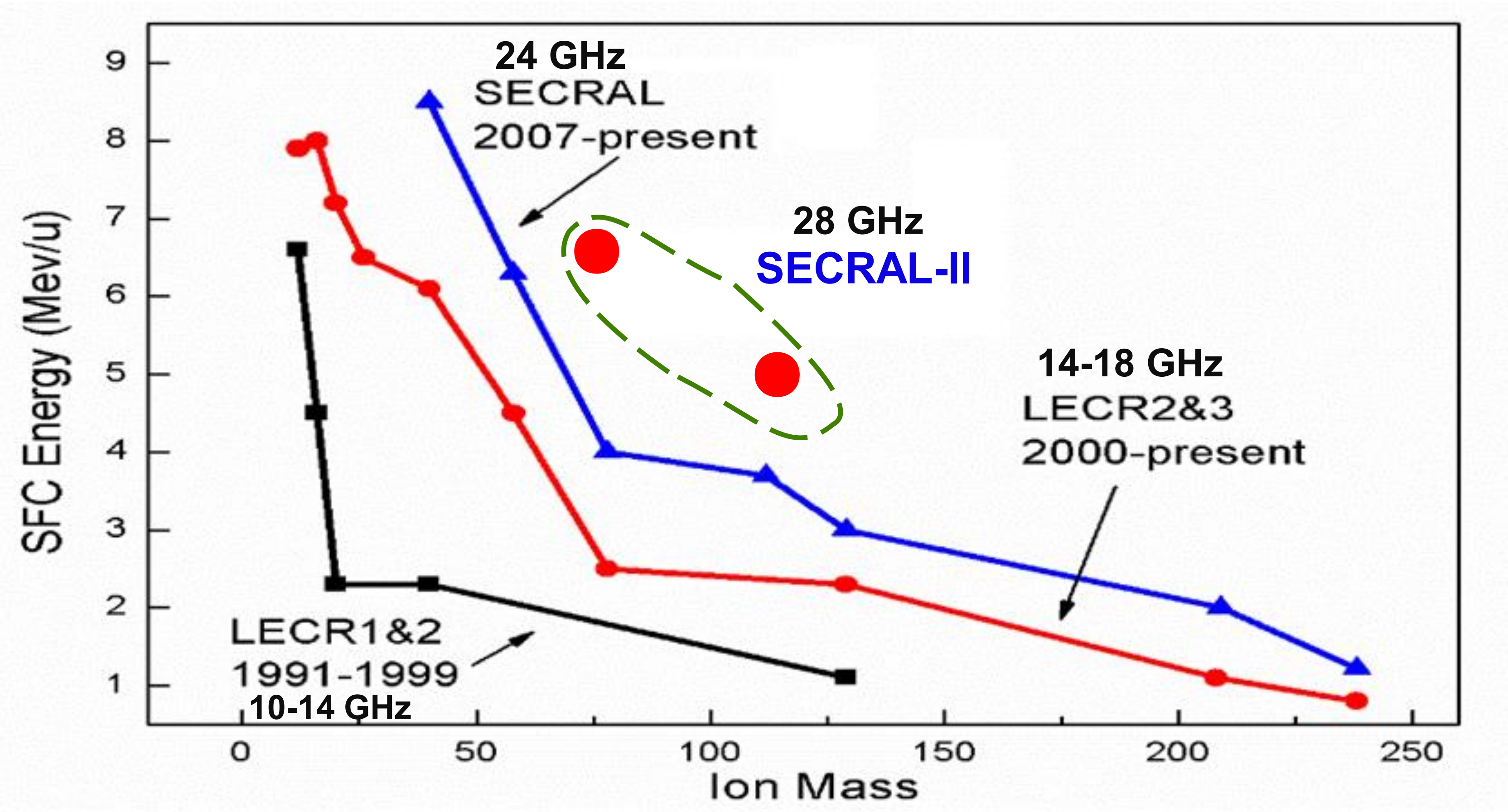
Ion species	Charge state	SECRAL& SECRAL-II 24~28 +18 GHz 6-10 kW [eμA]
^{40}Ar	12+	1420
	16+	620
	18+	15
^{78}Kr	18+	1030
	28+	145
^{129}Xe	26+	1100
	30+	365
	42+	16
^{209}Bi	31+	680
	41+	100
^{238}U	34+	620
	35+	545
	46+	61
	55+	13

24-28 GHz SC-ECRISs at HIRFL



SECRAL-I delivered $^{238}U^{46+}$ beam to increase energy and intensity from SSC-linac and SSC.

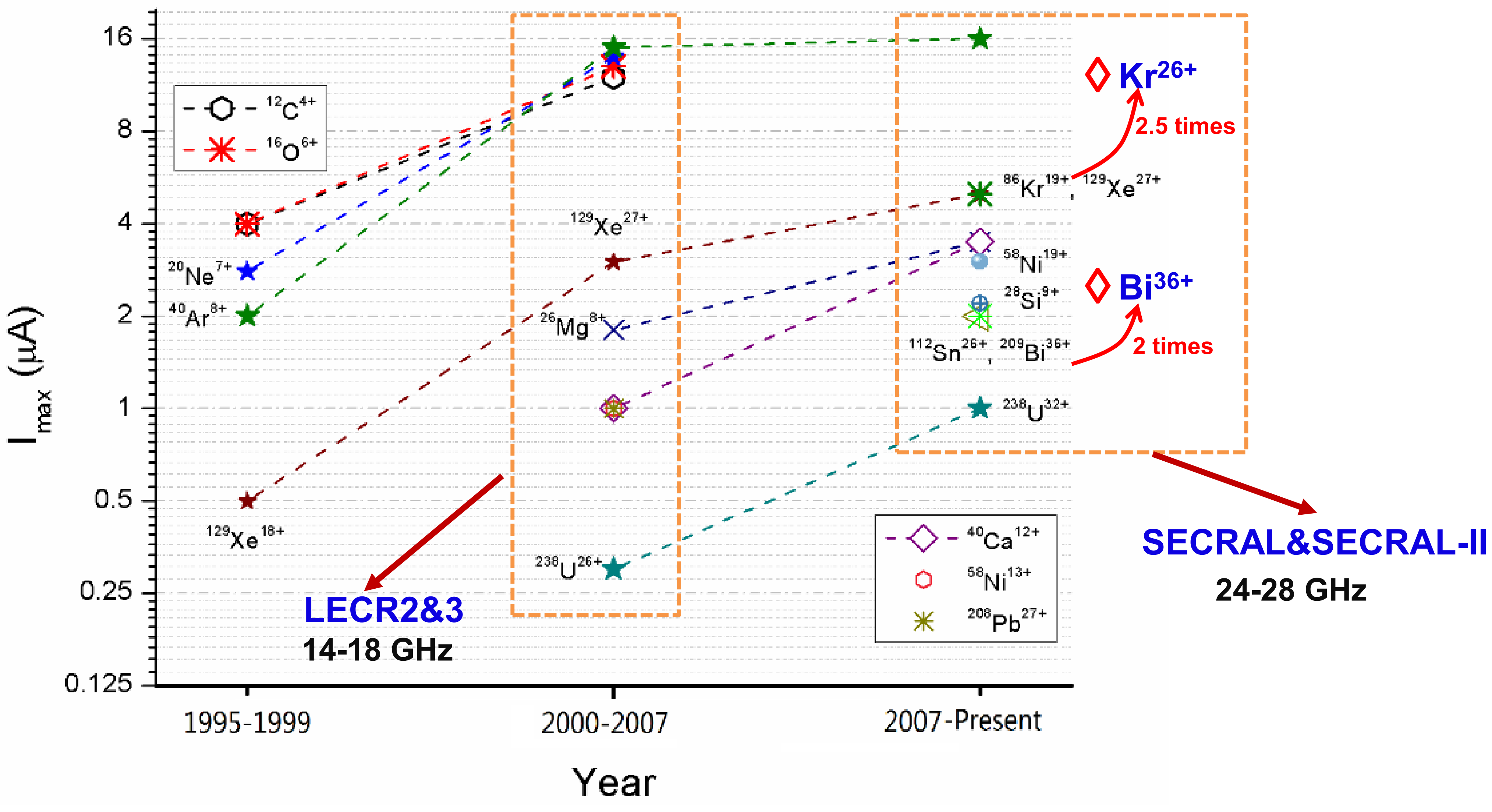
HIRFL-SFC cyclotron (k=69) used as an injector to SSC or CSR



SECRAL operation 2007-2018;SECRAL-II operation 2018-present

SECRAL&II operation improved intensity of HIRFL-SFC cyclotron

Beam operation intensities from SFC Cyclotron



How to improve performance-cost efficiently for a new HI accelerator (1)

Build a new superconducting heavy ion cyclotron, 15 MeV/A Uranium beam.
What ECRIS would be built?

Ion beam	Beam current (eμA)	ECRIS RF (GHz)	Cyclotron RF (MHz)	Extraction Radius R (m)	Cyclotron Magnet R (m)	Magnet cost roughly (M$)	E (MeV/A)
$^{238}U^{46+}$	50-70	28	11.5, h=4,6	1.3	3.6	5.0*	15
$^{238}U^{20+}$	50-70	18	11.5, h=4,6	3.0	6.5	14*	15

* Cost for manpower not included.

- The cyclotron with 28 GHz ECRIS delivering $^{238}U^{46+}$ more compact and performance-cost efficient.
- Only cost difference of the cyclotron superconducting magnet would be 9.0 M$, enough for two 28 GHz ECRIS.

How to improve performance-cost efficiently for a new HI accelerator (2)

Build a new heavy ion RT linac, 15 Me/A Uranium beam.
What ECRIS would be built?

Ion beam	Beam current (eμA)	ECRIS RF (GHz)	Linac length roughly (m)	Linac cost roughly (M$)	E (MeV/A)
$^{238}U^{46+}$	50-70	28	50	65*	15
$^{238}U^{20+}$	50-70	18	105	100*	15

* Cost for manpower not included.

- The RT linac with 28 GHz ECRIS delivering $^{238}U^{46+}$ more compact and performance-cost efficient.
- The cost difference of the RT linac would be 35 M$, enough for eight 28 GHz ECRISs.

Build a new heavy ion cyclotron or SC linac dedicated to SHE, 5-8 Me/A for medium-mass ion beam.

What ECRIS would be built?

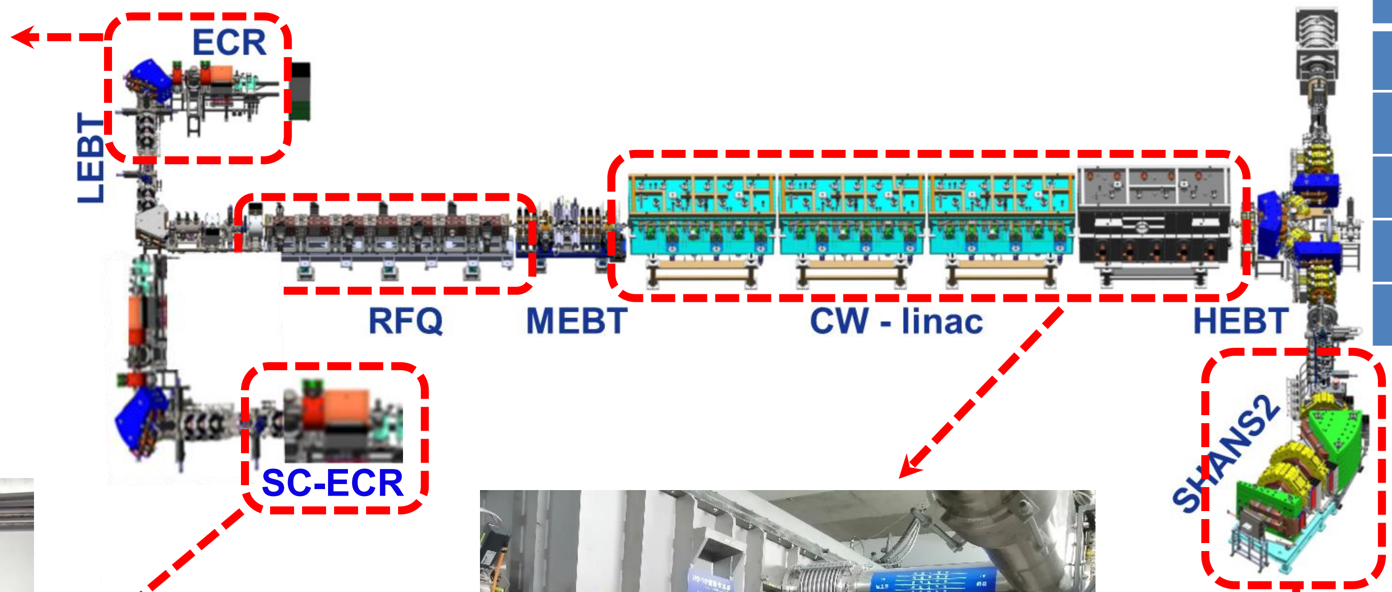
Ion beam	ECRIS RF (GHz)	Typical Beam current (pμA)	Beam current (pμA)	Material consumption (mg)
$^{48}Ca^{15\text{-}16+}$, $^{50}Ti^{16\text{-}17+}$ $^{54}Cr^{16\text{-}17+}$	28	>15	10	<1.0
$^{48}Ca^{9\text{-}10+}$, $^{50}Ti^{10\text{-}11+}$ $^{54}Cr^{11\text{-}12+}$	18	2-10	10	>1.5

- 28 GHz ECRIS can not only increase beam intensity, but also can reduce material consumption with higher charge state.

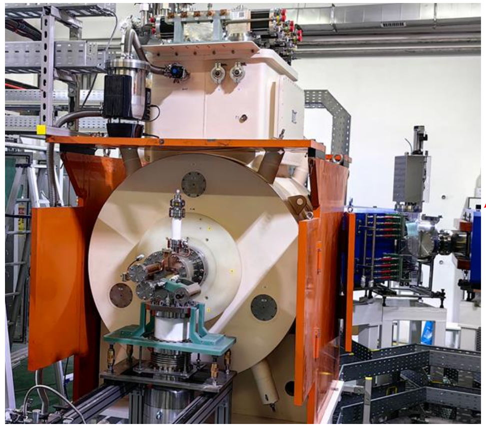
CAFE2 SC-linac Dedicated to SHE Research

China Accelerator Facility for Superheavy Elements (CAFE2)

LECR5,18GHz



Designed parameters	Goal
Ions	Ca～Zn
A/Q	3
Beam energy	4.5-7 MeV/u
Beam intensity	5～10 pμA
Running mode	CW



SECRAL-III, 24-28 GHz
(not ready for beam delivering

Super-conducting linear accelerator
(CW - linac)

Gas-filled recoil separator
(SHANS2)

CAFE2 beam intensities for SHE research at IMP

Operated beam intensities of LECR5 ion source and CAFE2

Ion species	Method	LECR5 Intensity [eμA]	CAFE2 Energy (MeV)	CAFE2 Target [pμA]	Time on target [Hrs]	Consumption Rate [mg/h]
$^{40}Ca^{13+}$	^{40}CaO+ Al	30-40	216-228	1.5-2.5	1500	0.86
$^{55}Mn^{17+}$	^{55}Mn	30-40	238-270	1.3-2.0	504	1.4
$^{54}Cr^{17+}$	^{54}Cr	20-30	217-290	1.0-1.5	1183	0.35
$^{48}Ca^{14+}$	^{48}CaO+ Al	10-20	220-240	0.6-1.2	~600	0.50
$^{40}Ar^{12+}$	^{40}Ar	210	224	11-14	~10	~

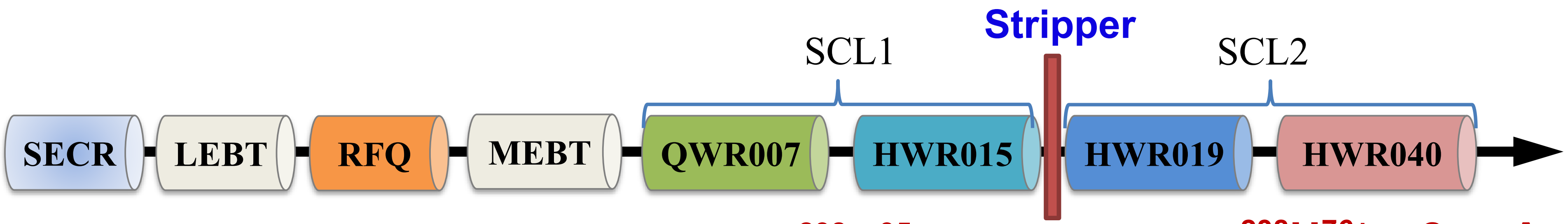
- CAFE2 was operated with 11-14 pμA $^{40}Ar^{12+}$ beam for 10 hours （11 pμA for 9 hrs s and 14pμA for 1 hrs）to validate the high intensity operation and test the target.
- More confident to operate high intensity beam with SECRAL-III
- When SECRAL-III is put into operation, the beam intensities would be increased by a factor 3-5

How to improve performance-cost efficiently for a new HI accelerator (4)

Build a new heavy ion CW superconducting linac, 150 Me/A Uranium beam.

What ECRIS would be built?

(1). 28 GHz ECRIS, stripper low efficiency and lifetime problem



150 MeV/A
>2 pμA U beam

$^{238}U^{35+}$, 12 pμA

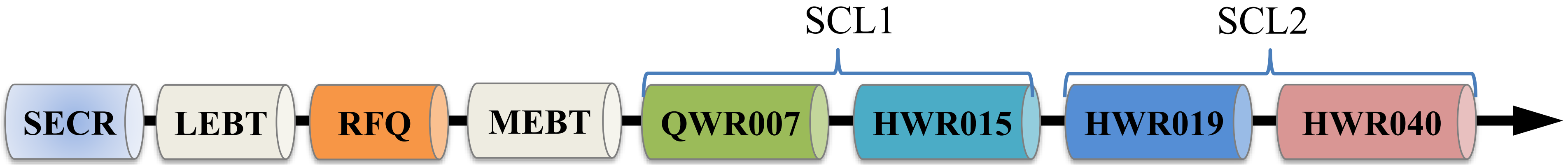
$^{238}U^{35+}$

η~20%
Lifetime?

$^{238}U^{76+}$, >2 pμA

Cavity numbers difference ~5%

(2). Without stripper. 45-60 GHz ECRIS, higher charge state



150 MeV/A
>2 pμA U beam

$^{238}U^{55+}$, 2.5 pμA

$^{238}U^{55+}$

$^{238}U^{55+}$, >2 pμA

Which one is more performance-cost efficient? Open question!

Only need 45-60 GHz SC ECRIS for very high charge state and current

"False" 45 GHz FECR

Estimated beam intensities by 45-60 GHz SC ECRIS

Ion species	Charge state	SC ECRIS 45-60 GHz 10-15 kW [eμA]
^{40}Ar	16+	~1000
	18+	~100
^{129}Xe	30+	~1000
	42+	~100
^{209}Bi	35+	~1000
	55+	~100
^{238}U	35+	~1000
	55+	~100

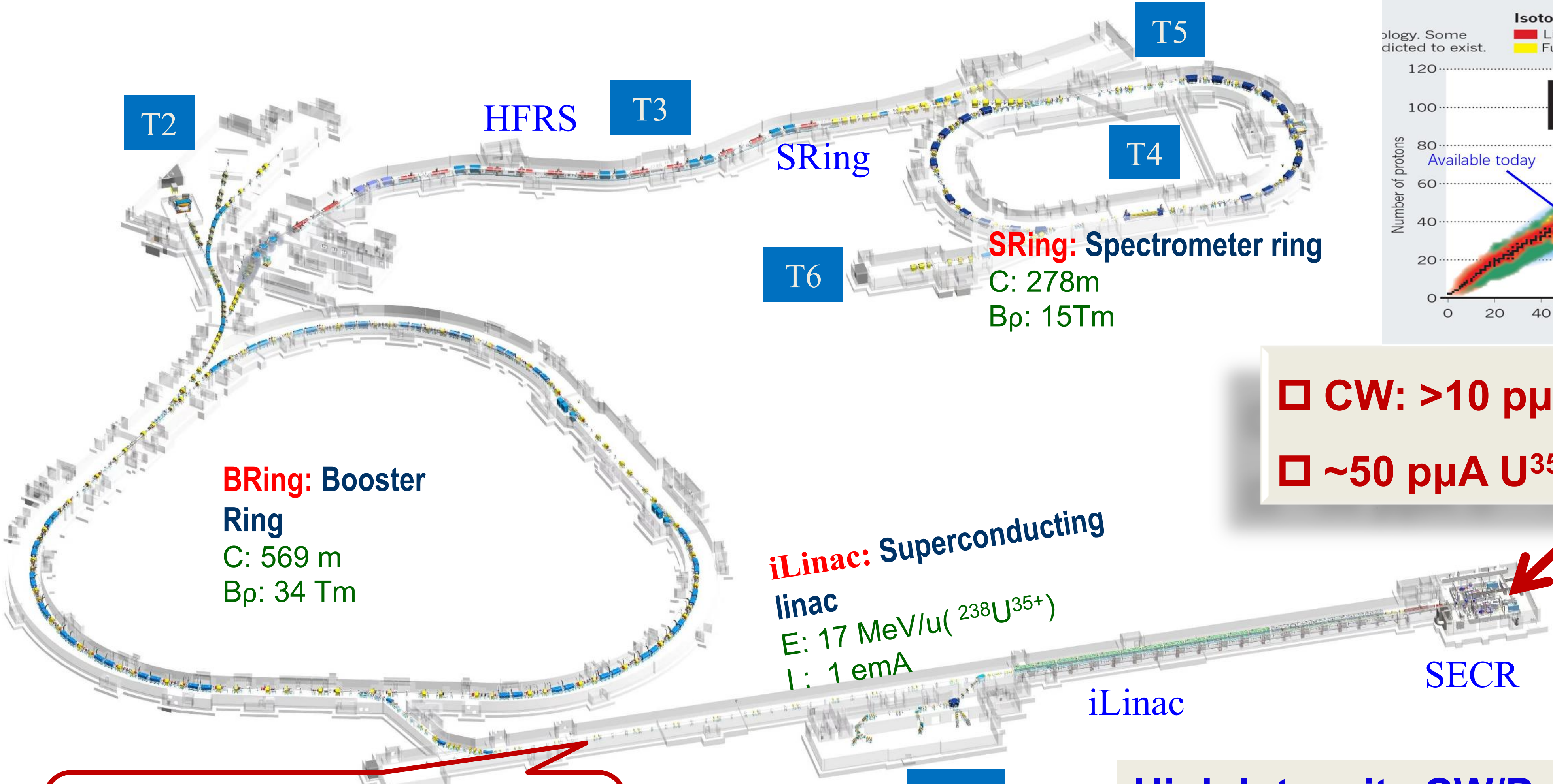
Outline

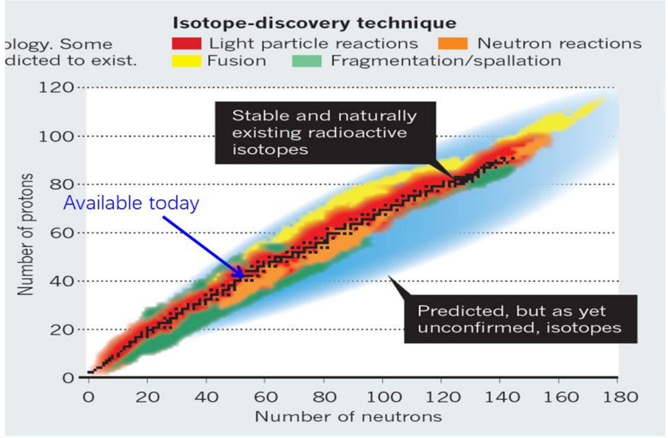
- What type of ECRIS would be built for a heavy ion accelerator in terms of beam intensity, energy and performance-cost-efficiency?

- **Beam quality from ECRIS and efficient acceleration of high intensity heavy ion beams.**

HIAF upgrading plan: iLinac beam enegy 150 MeV/A

High Intensity heavy-ion Accelerator Facility (HIAF)



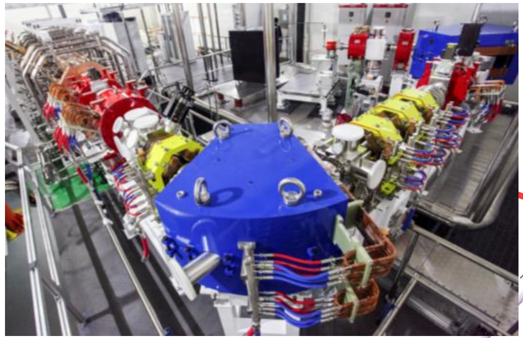


- CW: >10 pμA U^{46+}
- ~50 pμA U^{35+}/ ≤3 Hz@0.5~2 ms

iLinac will be upgraded to 150 MeV/A uranium beam in HIAF Phase II

High Intensity CW/Pulsed Ion Beams

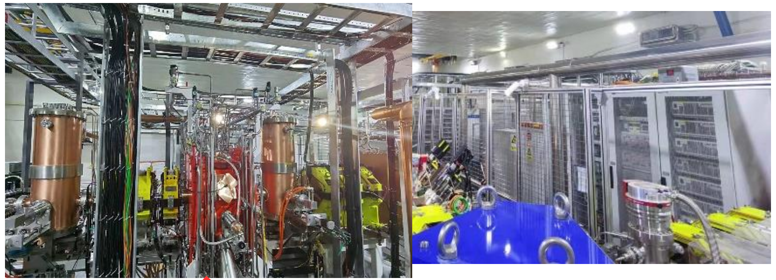
Acceleration of high intensity heavy ion beams: LEAF



LEBT

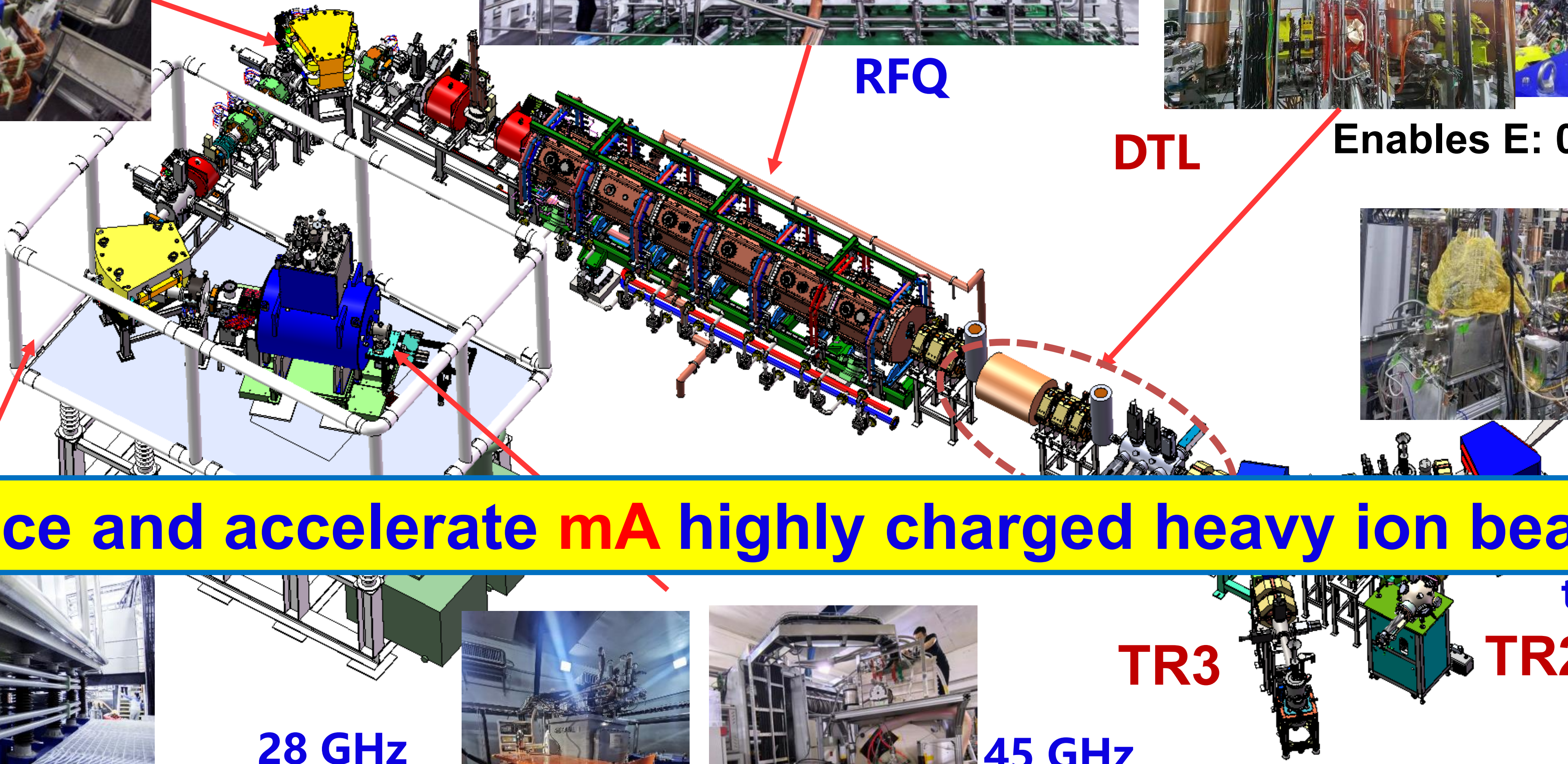
TR1

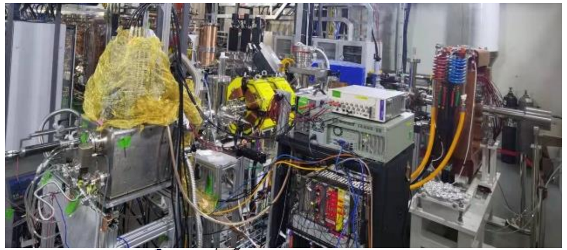
RFQ



DTL

Enables E: 0.3~0.7 MeV/u





Produce and accelerate mA highly charged heavy ion beams

ental
terminals

TR3

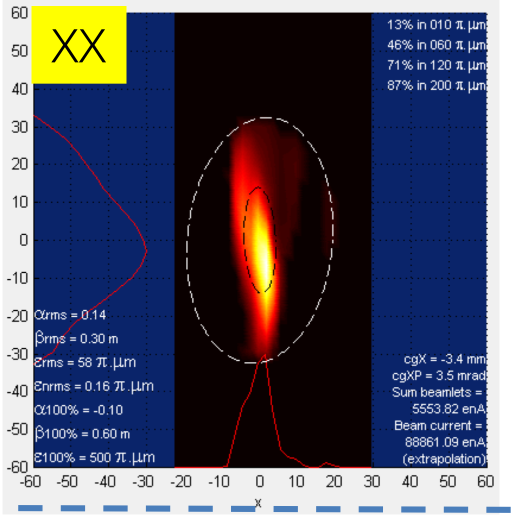
TR2

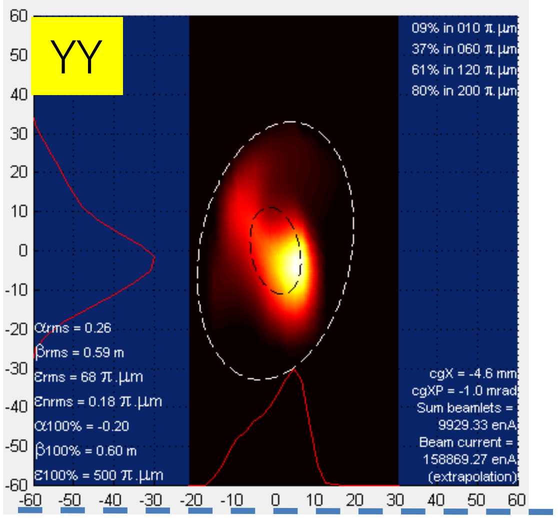
High voltage platform

28 GHz
SECRAL-I

45 GHz
FECR

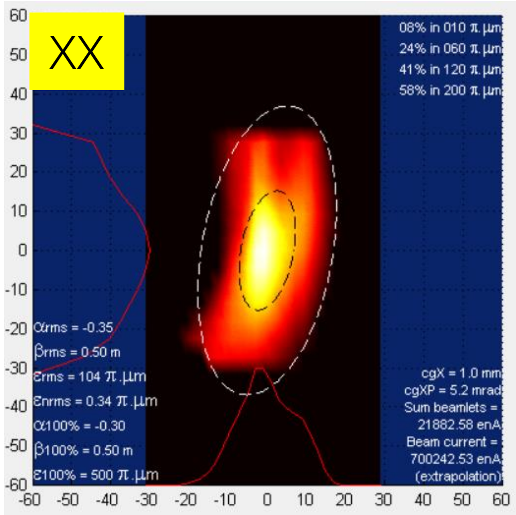
High-intensity beams produced by ECRIS and accelerated by LEAF-RFQ

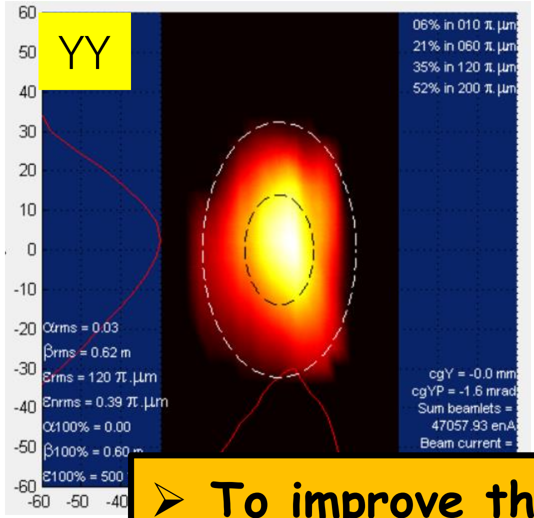




- Current from ECR~**200** eμA by SECRAL-I
- ε_x=0.16 π mm mrad, ε_y=0.18 π mm mrad
- RFQ transmission efficiency >**95%**
- RFQ acceleration efficiency >**83%**
- Accelerated current~**160 eμA**

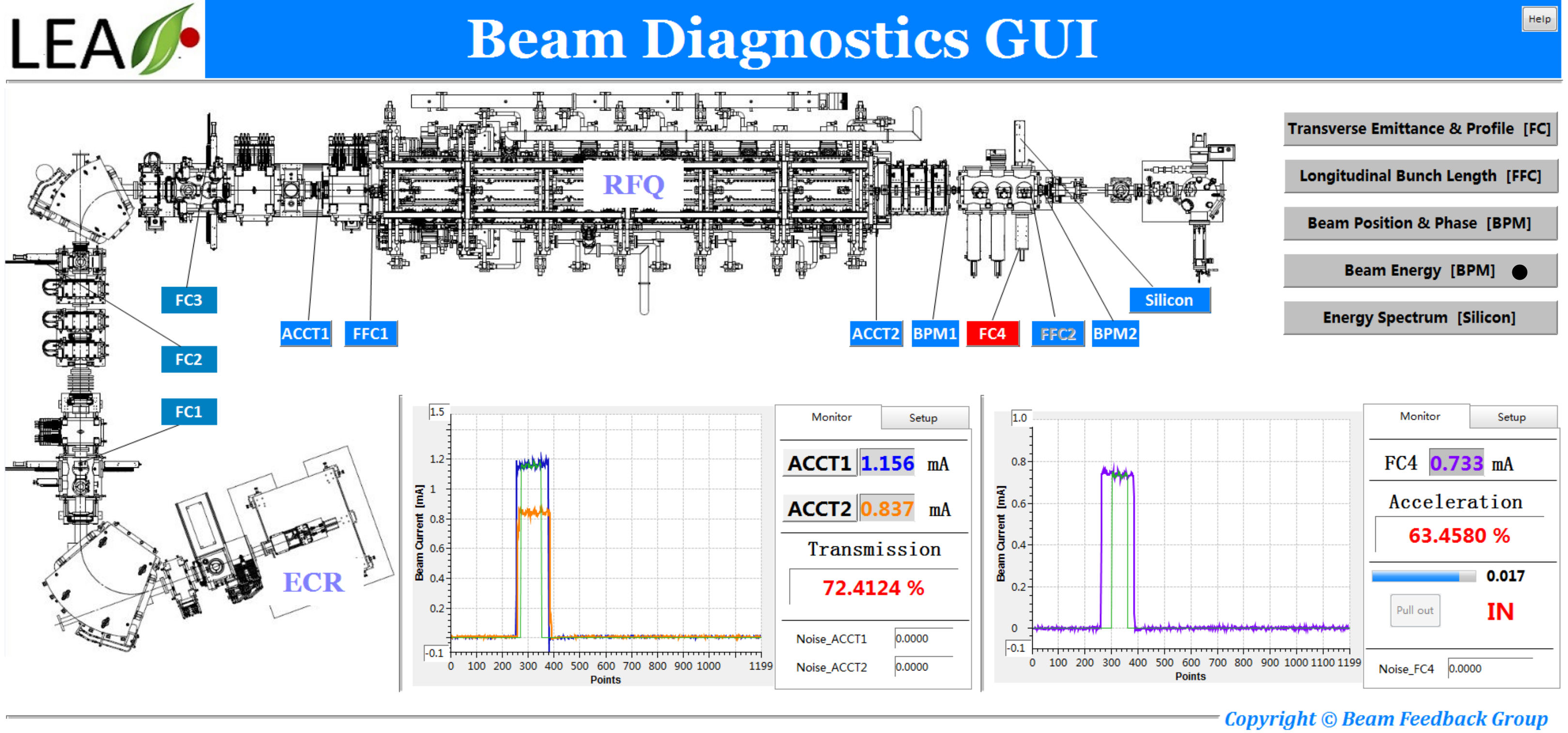
$^{40}Ar^{9+}$





- Current from ECR~**1200** eμA by SECRAL-I
- ε_x=0.34 π mm mrad, ε_y=0.39 π mm mrad
- RFQ transmission efficiency ~**72%**
- RFQ acceleration efficiency ~**63%**
- Accelerated current~**730 eμA**

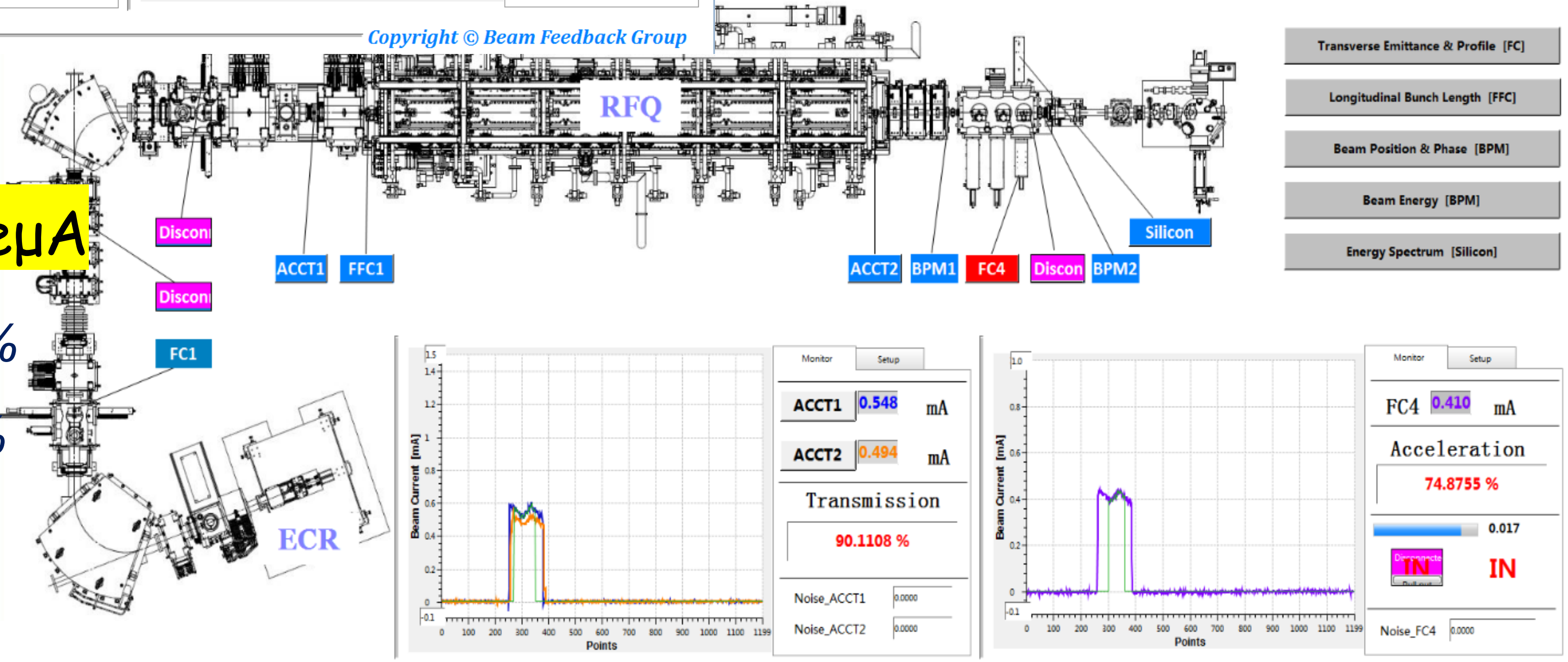
- To improve the RFQ's transmission efficiency ~ higher than 90%
- Nearly half of the current is removed by the LEBT collimator
- Finally, accelerated current~410 eμA



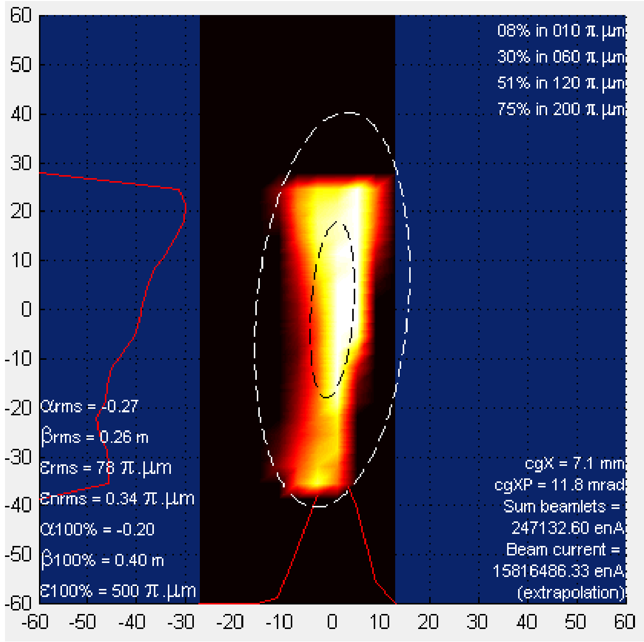
Accelerated current~730 eμA

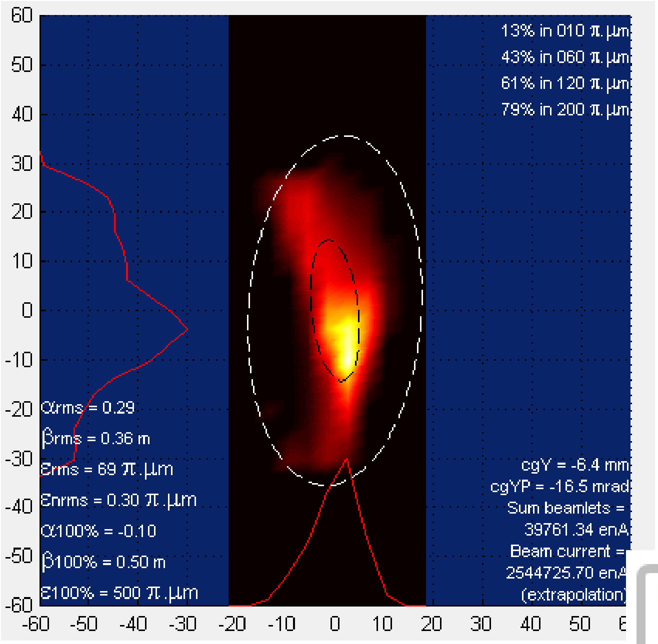
- *RFQ transmission efficiency ~72%*
- *RFQ acceleration efficiency ~63%*

- Accelerated current~410 eμA
- *RFQ transmission efficiency ~90%*
- *RFQ acceleration efficiency ~75%*



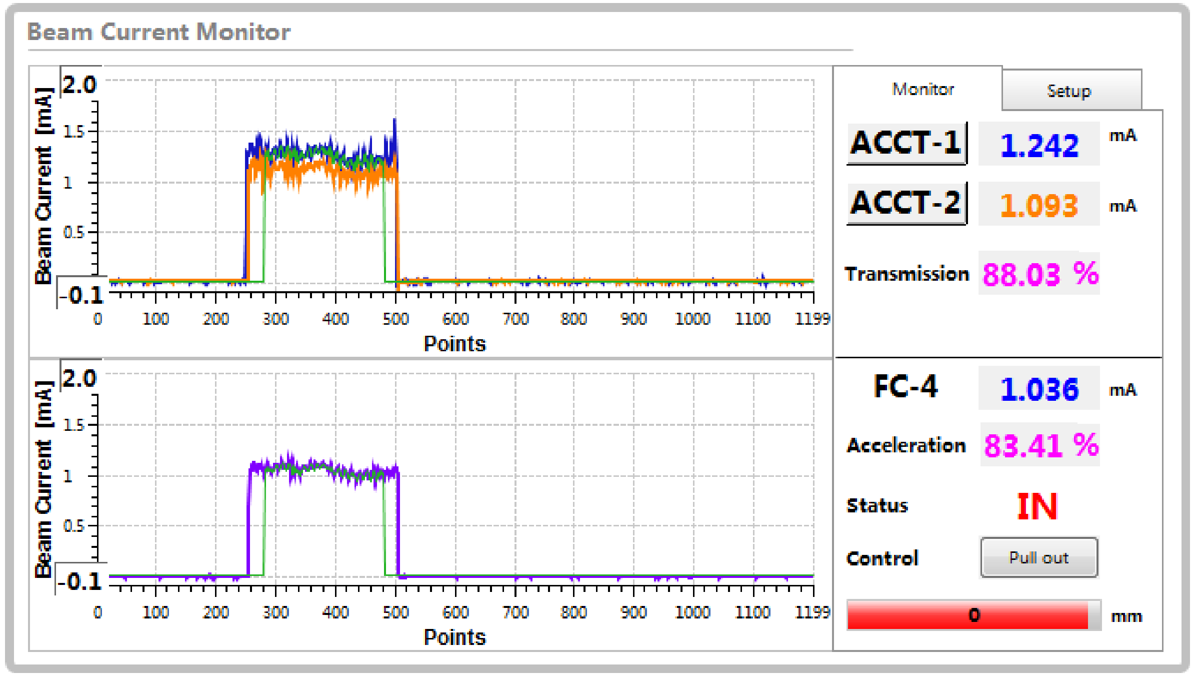
High-intensity beams produced by ECRIS and accelerated by LEAF-RFQ





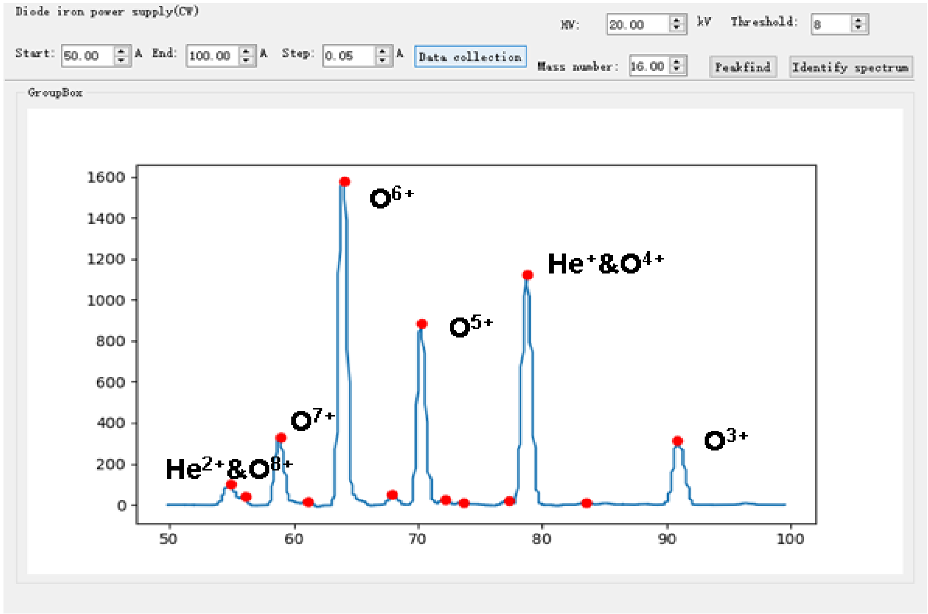
- Current from ECR~**1500** eμA by FECR
- ε_x=0.34 π mm mrad & ε_y=0.3 π mm mrad
- RFQ input~**1242 eμA**
- RFQ transmission efficiency ~**88%**
- RFQ acceleration efficiency ~**83%**
- *Accelerated current~1036 eμA*

$^{16}O^{6+}$

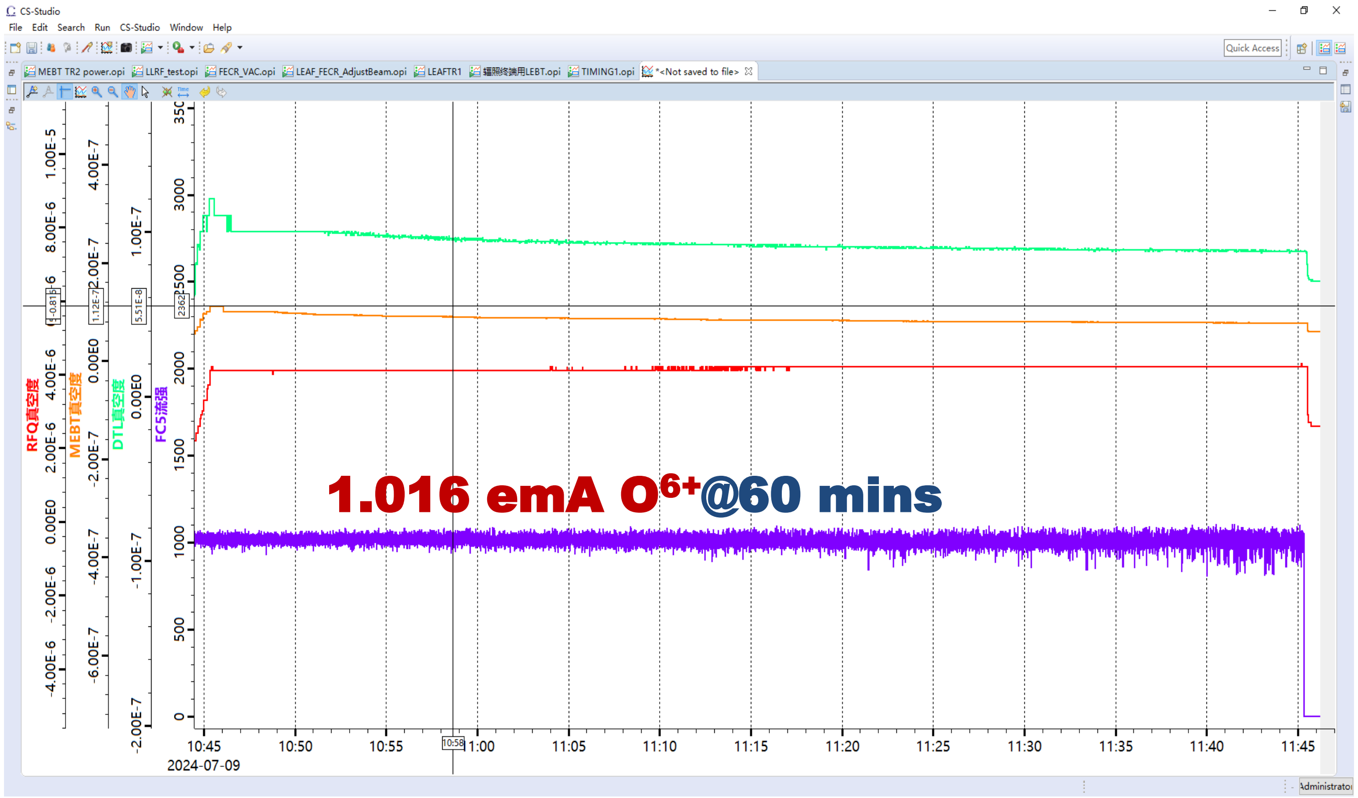


- Low-current cases: ECR beam currents ≤ 200 eμA
- Emittances typically **below 0.2 π mm mrad**
- RFQ transmission > **95%**

1 emA $^{16}O^{6+}$ CW beam acceleration by LEAF-RFQ



FECR: 1.6 emA O^{6+}

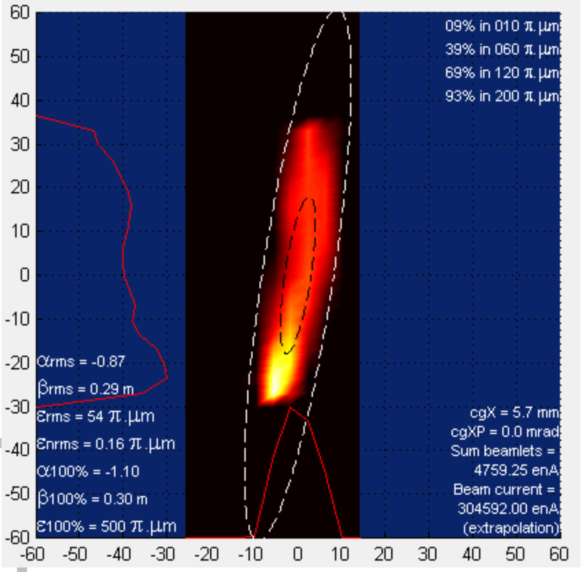


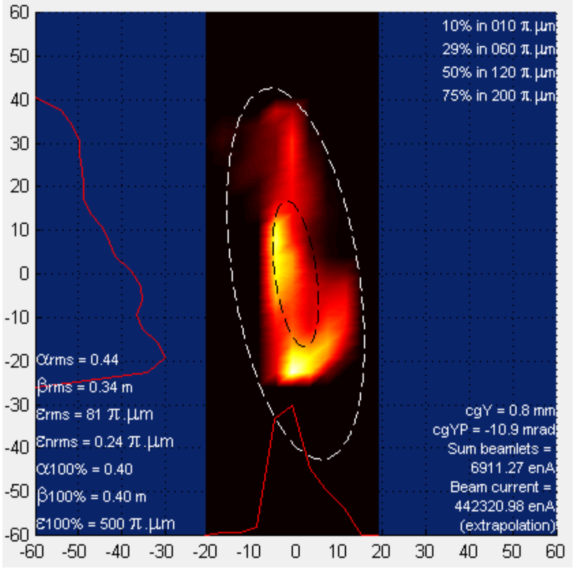
CW beam acceleration of 1.0 emA $^{16}O^{6+}$

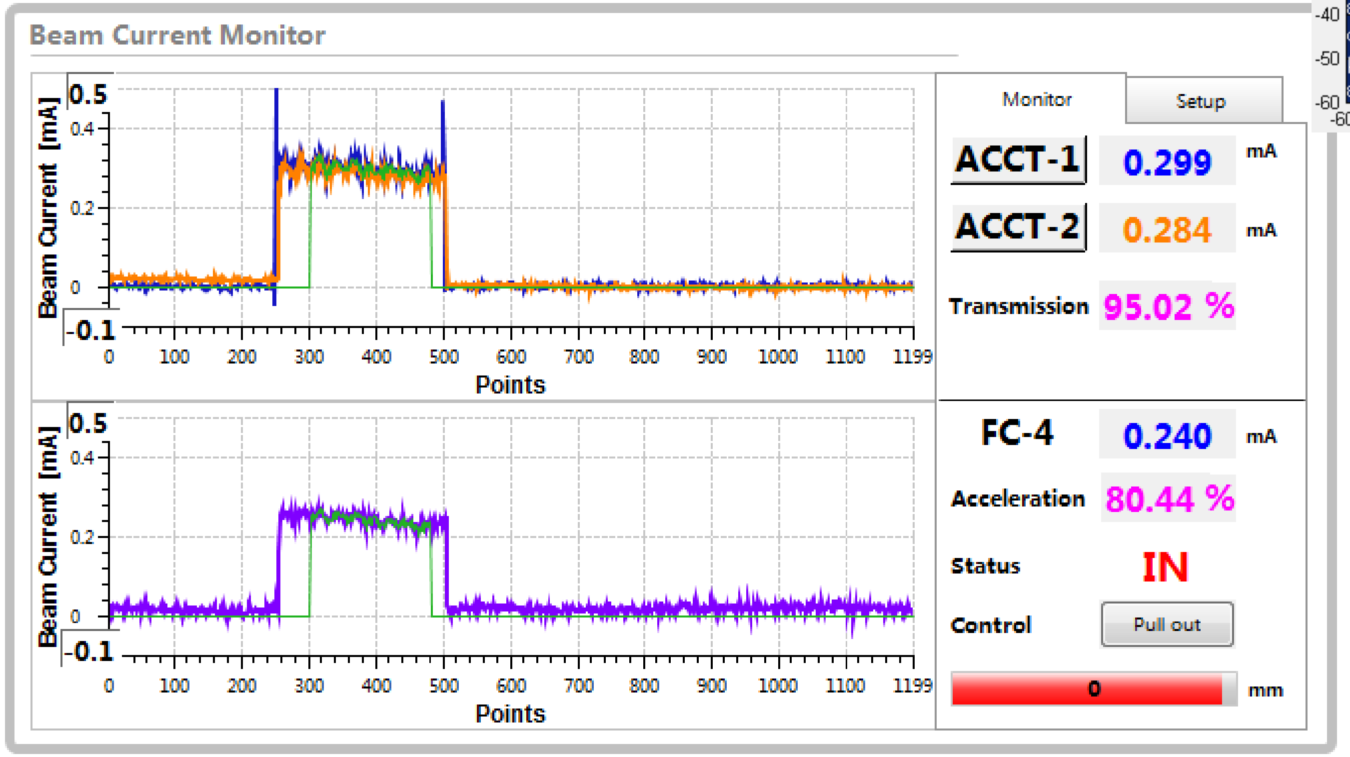
High-intensity beams produced by ECRIS and accelerated by LEAF-RFQ

- Current from ECR~330 eμA by FECR
- ε_x=0.16 π mm mrad
- ε_y=0.24 π mm mrad

$^{209}Bi^{35+}$

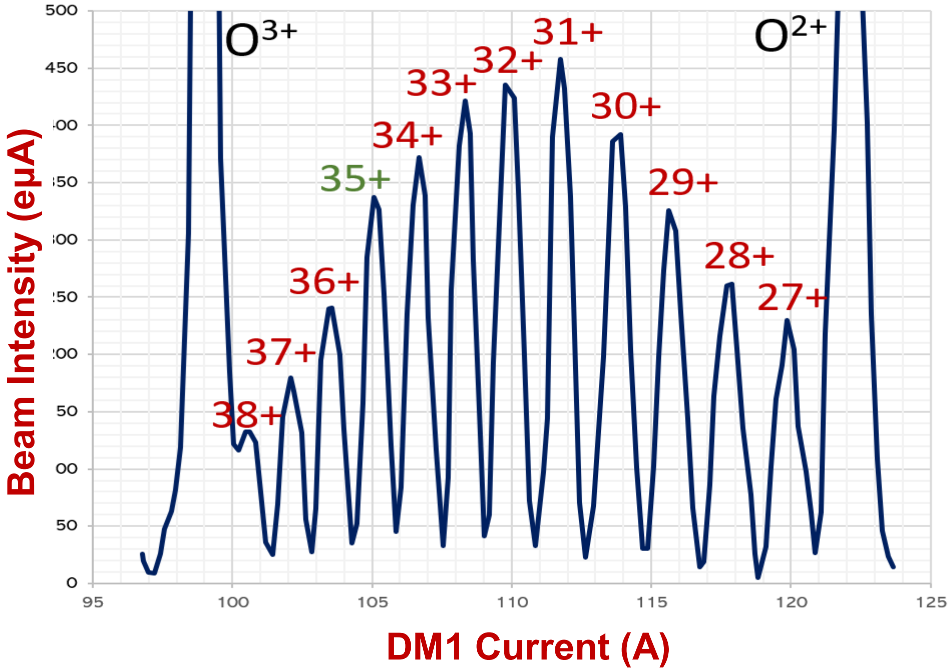






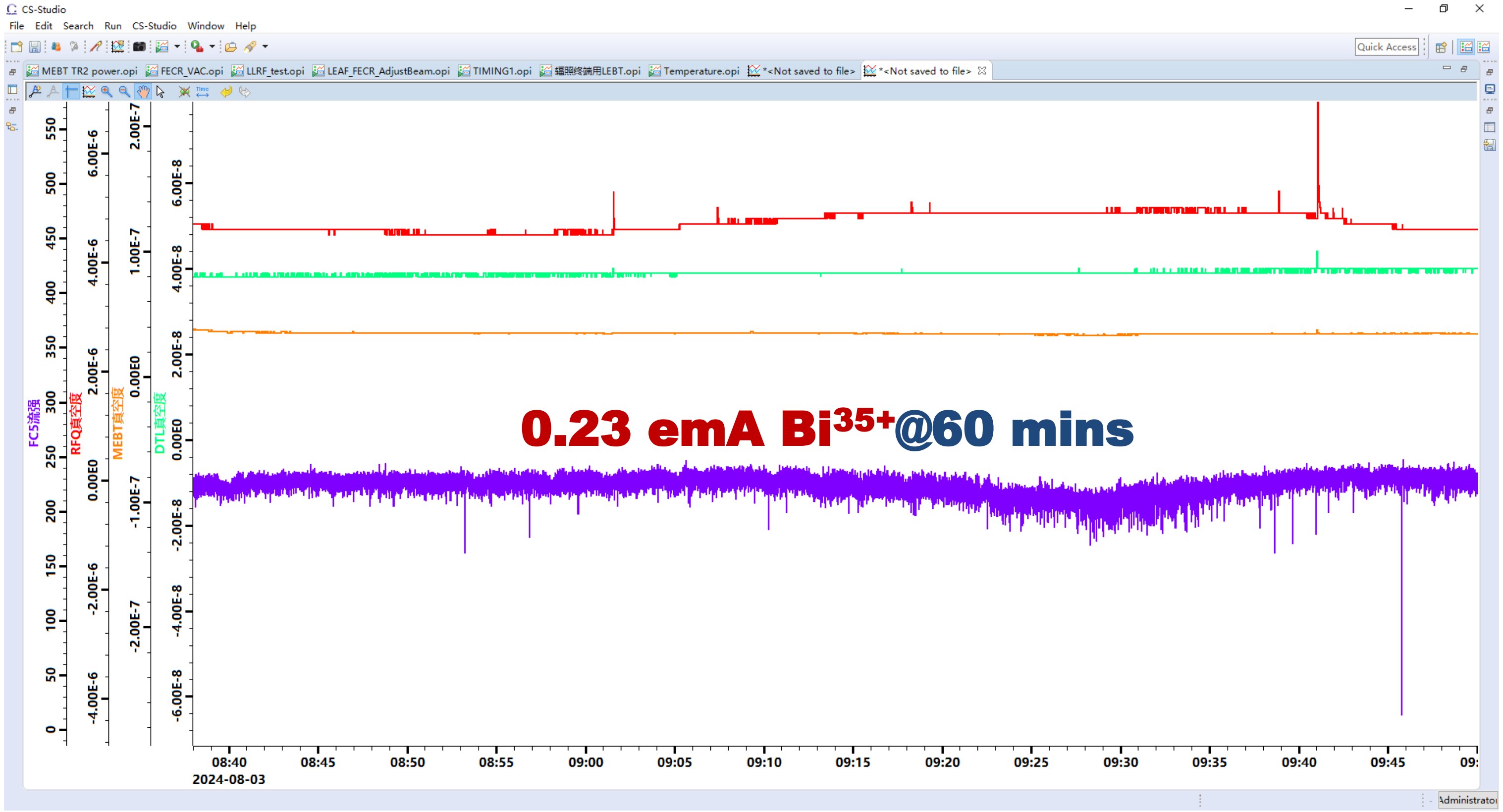
- RFQ input~ 300 eμA
- RFQ transmission efficiency ~95%
- RFQ acceleration efficiency ~80%
- Accelerated current~240 eμA

0.23 emA $^{209}Bi^{35+}$ CW beam acceleration by LEAF-RFQ



FECR: 330-350 eμA $^{209}Bi^{35+}$

6.5 kW 45GHz+5.5 kW 28GHz



1 hour stability demonstration of CW 230 eμA Bi^{35+} beam accelerated by the LEAF-RFQ

Beam quality from ECRIS at high intensity remains a big issue

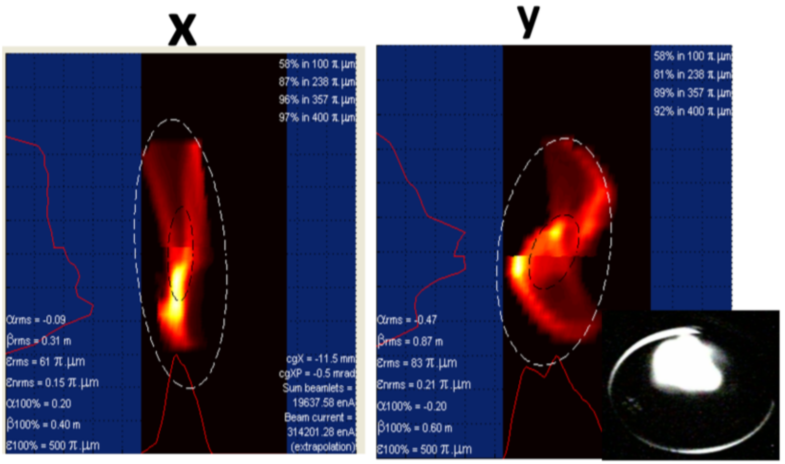
- Slide from my talk at ICIS2013.
- Beam intensities have been improved a lot in the past 10 years.
- But beam quality from ECRIS at high intensity has not been improved as expected and demanded.

Challenge No.5 — Beam Quality (Emittance)

SECRAL

24+18 GHz P= 3.5+0.3 kW
HV= 23 kV I_o= 10 emA,
Bi^{31+}= 330 eμA
Beam: 90%-95%

$\varepsilon_x \approx$ 200-350 ε_y= 350-450 πμm rad



VENUS

28+18 GHz P= 6+1.8 kW
HV= 22 kV I_{extr}= 7.5 emA,
U^{33+}= 365 eμA
Beam: 90%-95%

ε_x= 200-350 ε_y= 200- 230 πμm rad

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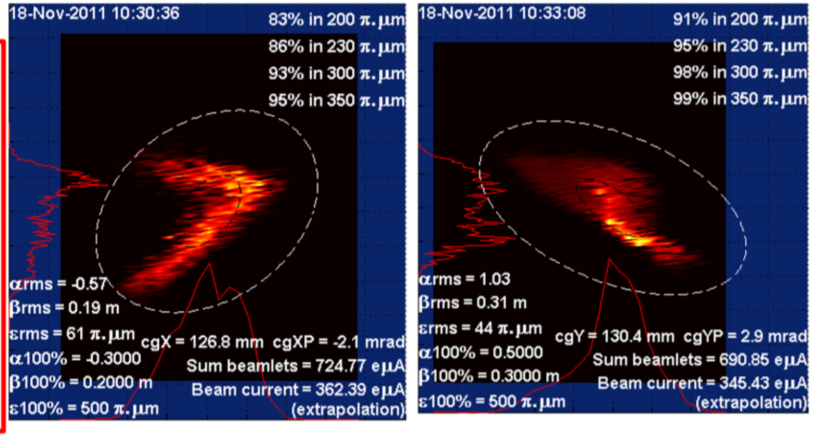
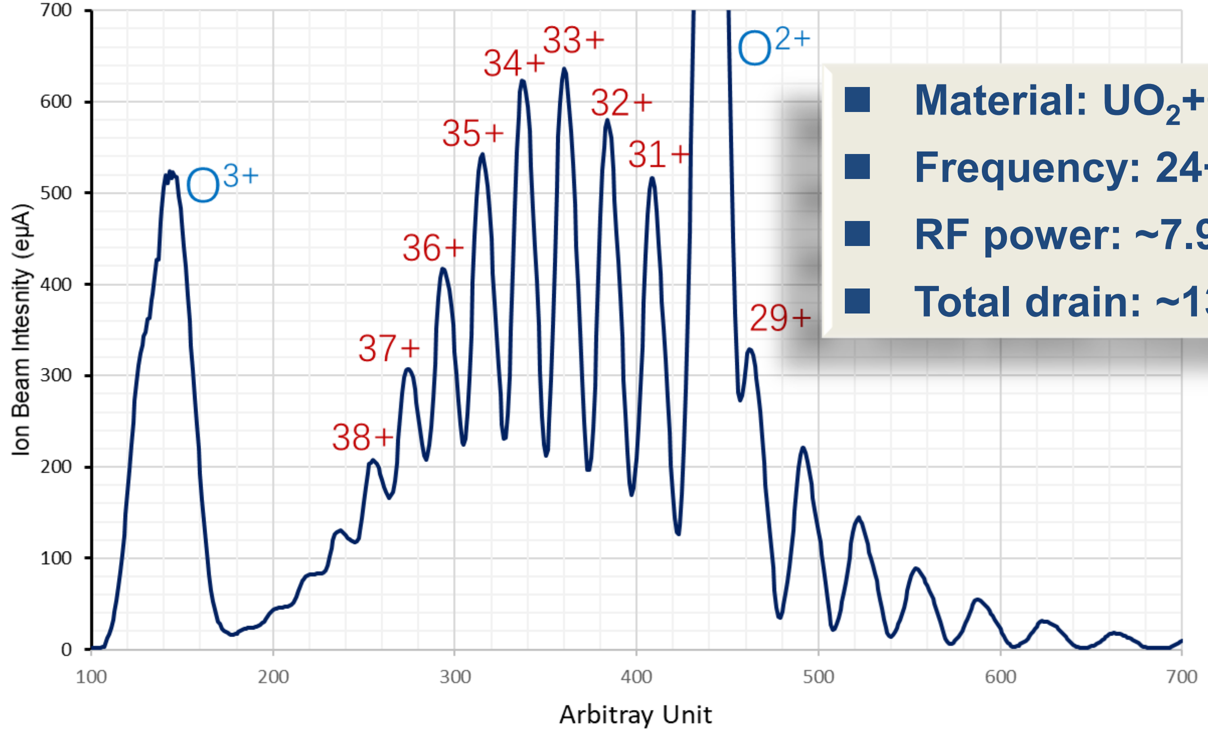


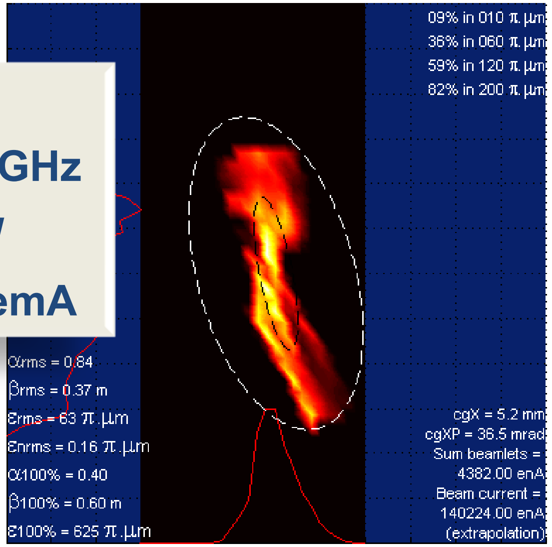
H.W.Zhao, ICIS2013, Japan, Sept.8-13, 2013

Challenging to produce and accelerate high-intensity HI beams

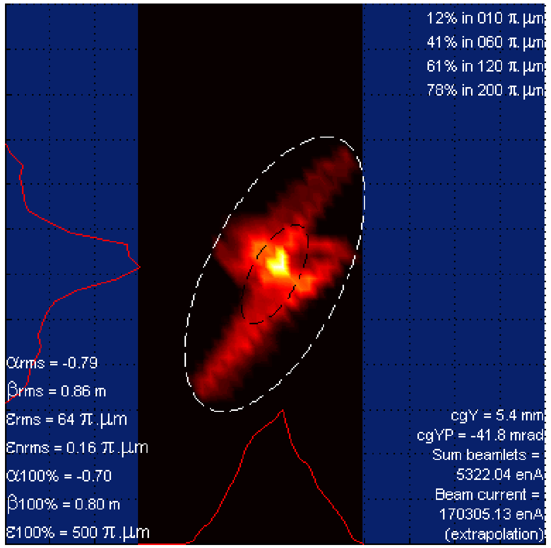
Production of 545 eμA $^{238}U^{35+}$ by SECRAL-II



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



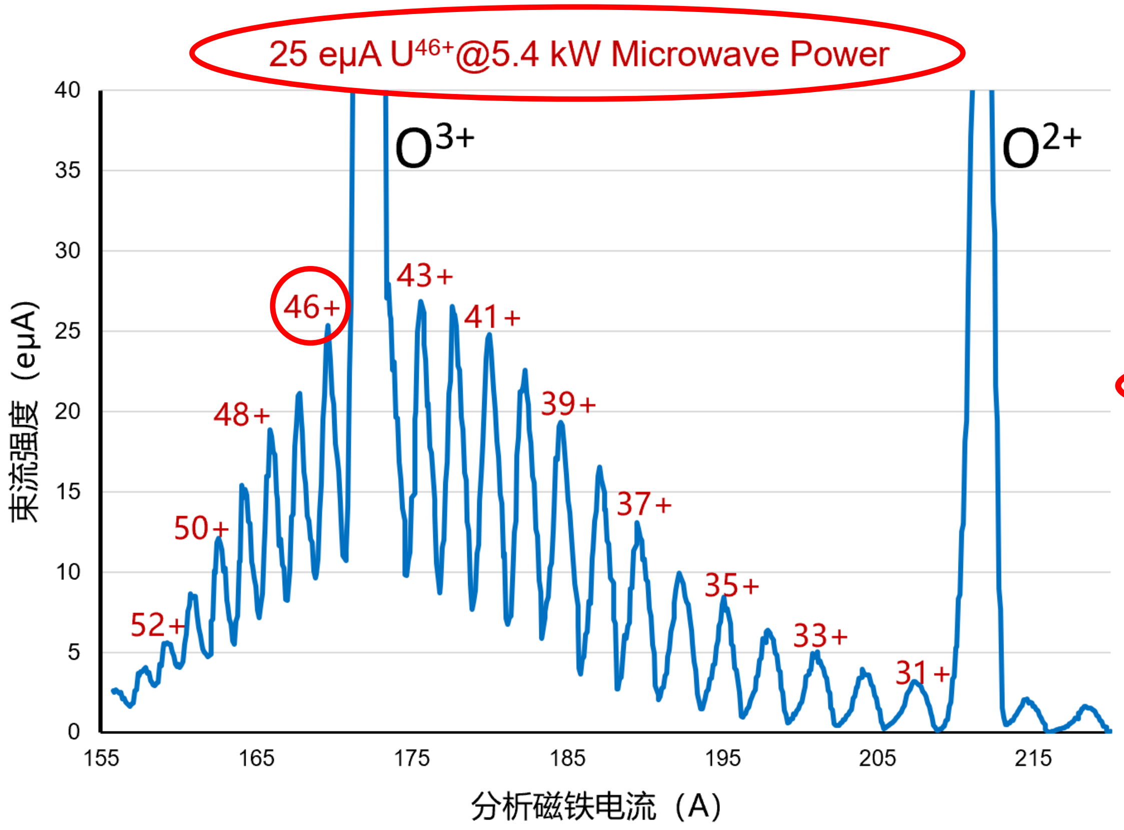
X-$\varepsilon_{n.rms}$: 0.16 π.mm.mrad



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

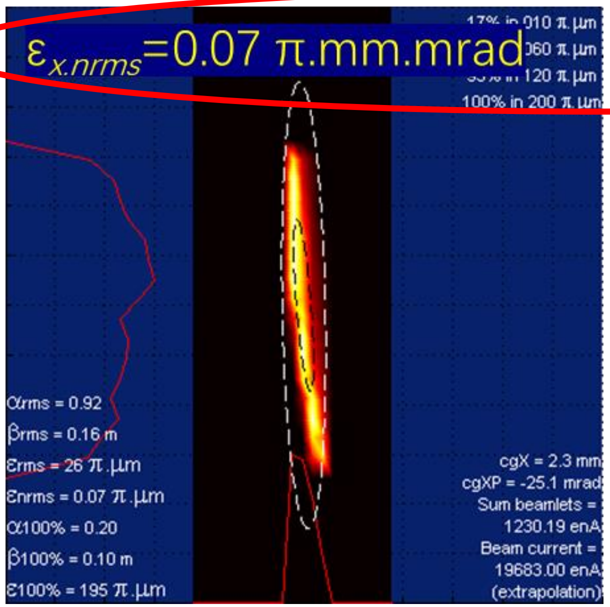
- Beam distribution in phase space and emittance are not so good.
- Beam emittance at high current ε_{nrms} < 0.1 πmm mrad for high efficiency acceleration

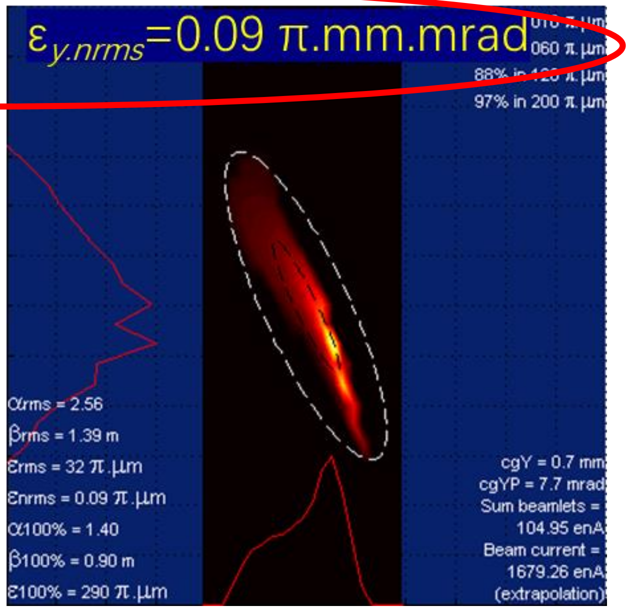
Higher charge state and lower intensity may achieve lower emittance



Production of 25 eμA $^{238}U^{46+}$ by SECRA-I

Lower emittance for higher charge state





With 25 eμA $^{238}U^{46+}$ beam intensity and low emittance, SSC-linac RFQ achieved 94% acceleration efficiency and 95% transmission efficiency.

But we need higher charge state、higher beam intensity and lower emittance

Conclusion

- **High performance ECRIS at 28-60 GHz not only increases beam intensity, charge state and energy, but also makes accelerator performance-cost more efficient.**
- **The biggest challenge for mA CW heavy ion beam acceleration by RFQ and SC linac is beam quality from ECRIS.**

Acknowledgement

Thanks for your attention !

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