Perspectives in High Intensity Heavy Ion Sources for Future Heavy Ion Accelerators

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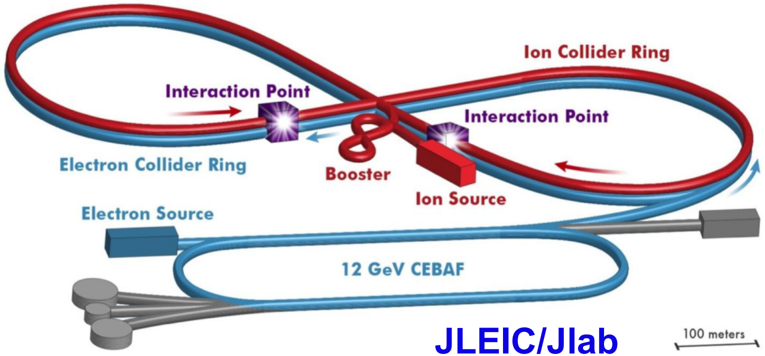
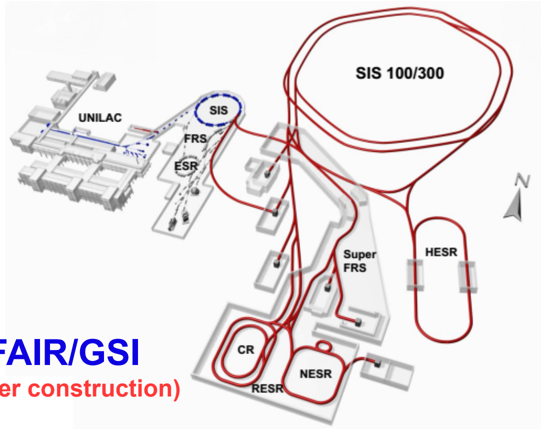
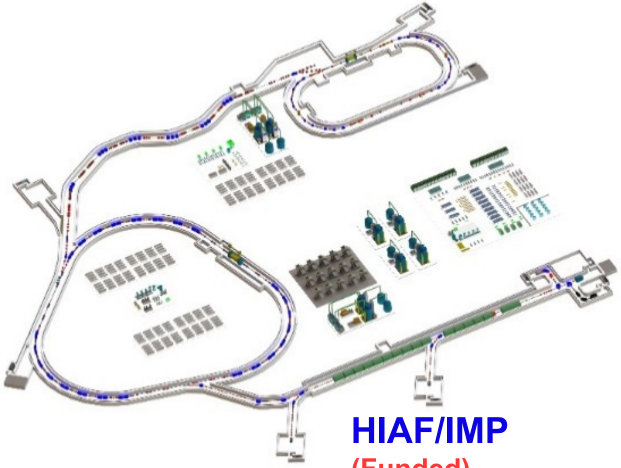
Preface



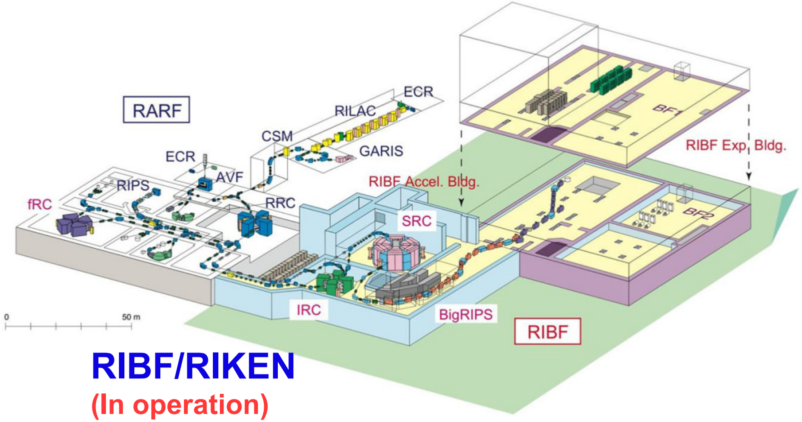
JLEIC/Jlab
(Proposal)



FAIR/GSI
(under construction)

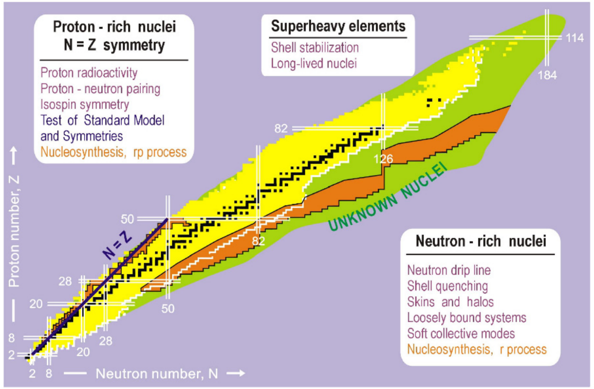


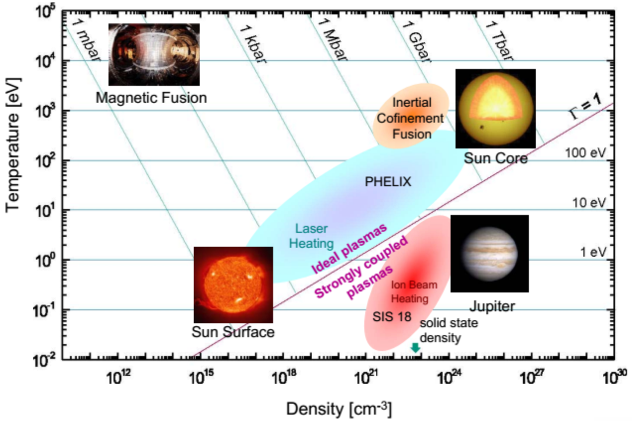
HIAF/IMP
(Funded)

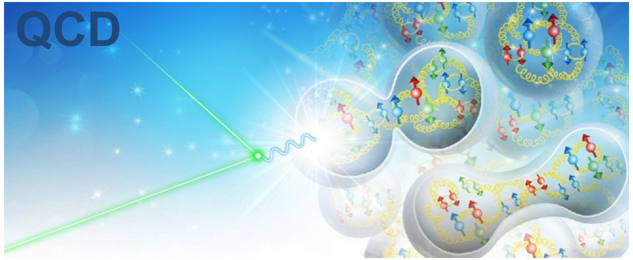


RIBF/RIKEN
(In operation)

Preface







Nuclear Physics

- Intense heavy ion beams
- High beam power

High Energy Density Physics

- High energy very heavy ion beams
- High power density

Electron Ion Collider

- High energy ion beams
- High Luminosity

Outline

- Accelerator Requirements
- High intensity HCI sources
- Future developments and perspectives

Typical requirements of high intensity heavy ions

Facility	Typical Ion	Required Intensity*	Pulse Length	Physics Goal	Status
FAIR/GSI	U^{28+}	2.75×10^{12}	82 μs	Nuclear Physics HEDP, ENC	Construction
HIAF/IMP	U^{35+}	20 pμA	CW	Nuclear Physics HEDP, ENC	Funded
		Pulsed 1.25×10^{11}	0.5 ms		
FRIB	$U^{33+, 34+}$	14 pμA	CW	Nuclear Physics	Construction
RHIC	Au^{32+}	3.4×10^{9}	10~40 μs	Nuclear Physics	Operation
JLEIC	Pb^{30+}	Pulsed $\sim 2.6 \times 10^{10}$	0.25 ms	EIC	Proposal

*** Particles per pulse**

Accelerator Requirements

Requirements of ion source for those high energy (GeV/u) high current heavy ion accelerators

Ion Source → Q

$E \sim Q^2$ for cyclotrons

$E \sim Q$ for linac

Ion Source → I_Q

Higher power

Simpler injection mode

Developing intense highly charged ion source is both performance-effective and cost-effective.

Accelerator Requirements

	$^{238}U^{34+}$	$^{238}U^{46+}$	$^{238}U^{55+}$
Injection E（MeV/u）	1.3	1.3	1.3
Output E（MeV/u）	100	100	100
Design I_{max}（emA）	1.0	1.0	1.0
SC cavity	HWR009+HWR015+ Spoke021	HWR009+HWR015+ Spoke021	HWR009+HWR015+ Spoke021
SC cavities	44+100+248=392	40+92+176=308	32+80+152=264
Solenoids	78	65	55
CRM Reduced		11	16
Total length（m）	288	225	197
Budget reduced		>70 M$ (MP not included)	>100 M$ (MP not included)

Courtesy of H. W. Zhao@ICIS'13 Talk

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Output E（MeV/u）	100	100	100
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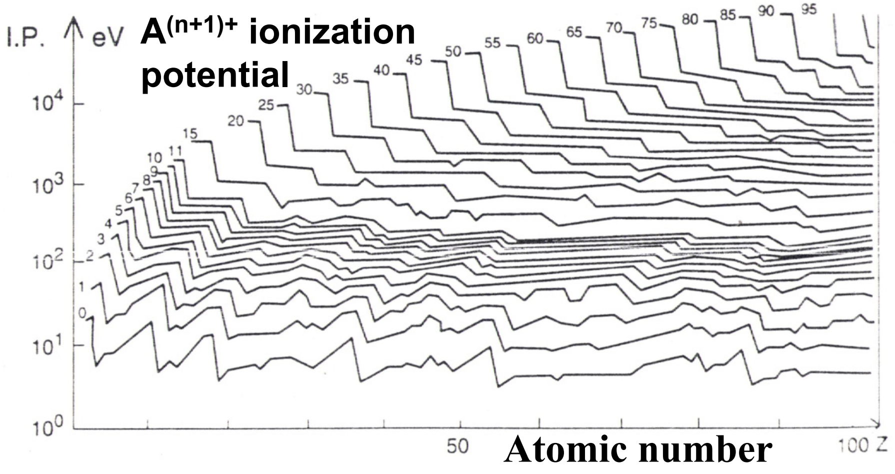
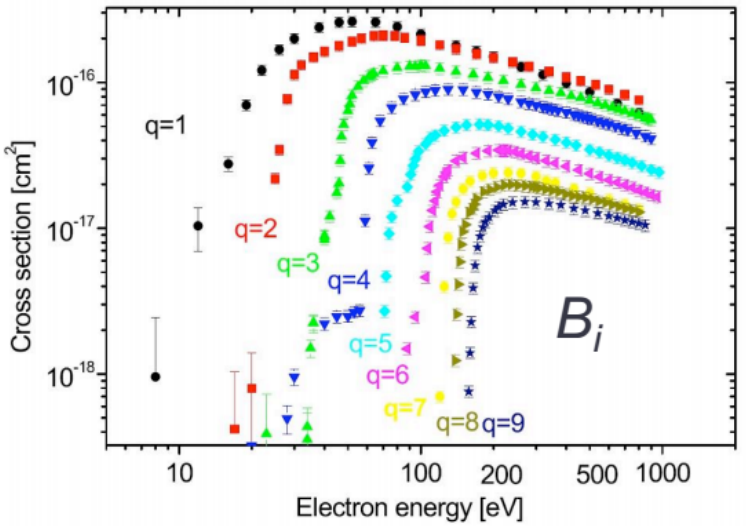
SC cavity	HWR009+HWR015+	HWR009+HWR015+	HWR009+HWR015+
SC	[illegible]	[illegible]	[illegible]
So[illegible]	[illegible]	[illegible]	[illegible]
CRM Reduced		11	16
Total length（m）	288	225	197
Budget reduced		>70 M$ (MP not included)	>100 M$ (MP not included)

It is very much worthy of developing highly charged ion source aiming at very high charge state!!

Courtesy of H. W. Zhao@ICIS'13 Talk

High intensity HCI sources





It is hard to produce intense HCI beams

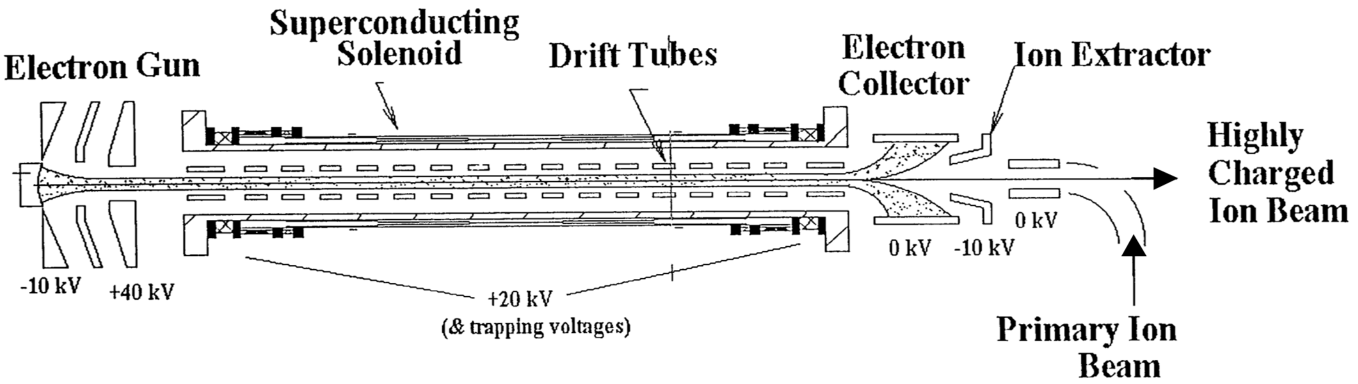
- **HCI production needs energetic electrons T_e**
- **HCI production cross sections is low**
  - » Long enough confinement time τ_i
  - » High enough electron density n_e

Charge State	I.P. (eV)	Cross Section (cm²)
1+	6.8	~2.4×10^{-16}
22+	660	~4.9×10^{-19}
54+	3,474	~1.4×10^{-20}
72+	9,321	~7.8×10^{-22}
82+	102,000	~1.5×10^{-24}

High intensity HCI sources

- EBIS or Electron Beam Ion Source
  - » Invented by Dr. Donets in 1965
  - » Control precisely and independently n_e, T_e and τ_i, **pulsed beam**
- LIS or Laser Ion Source
  - » Proposed by Dr. Bykovskii et al. and Peacock, Pease in 1969
  - » Laser irradiation on solid target induced plasma, **pulsed beam**
- ECRIS or Electron Cyclotron Resonance Ion Source
  - » proposed by Prof. Geller in late 1960s
  - » Reasonable control of the n_e, T_e and τ_i factors, **dc and pulsed beam**
- Charge Stripping Scheme
  - » In operation for GSI since 1990s
  - » HCI beams With high intensity low charge sate ion source + Linac + Stripper, **pulsed beam**

High intensity HCI sources: EBIS



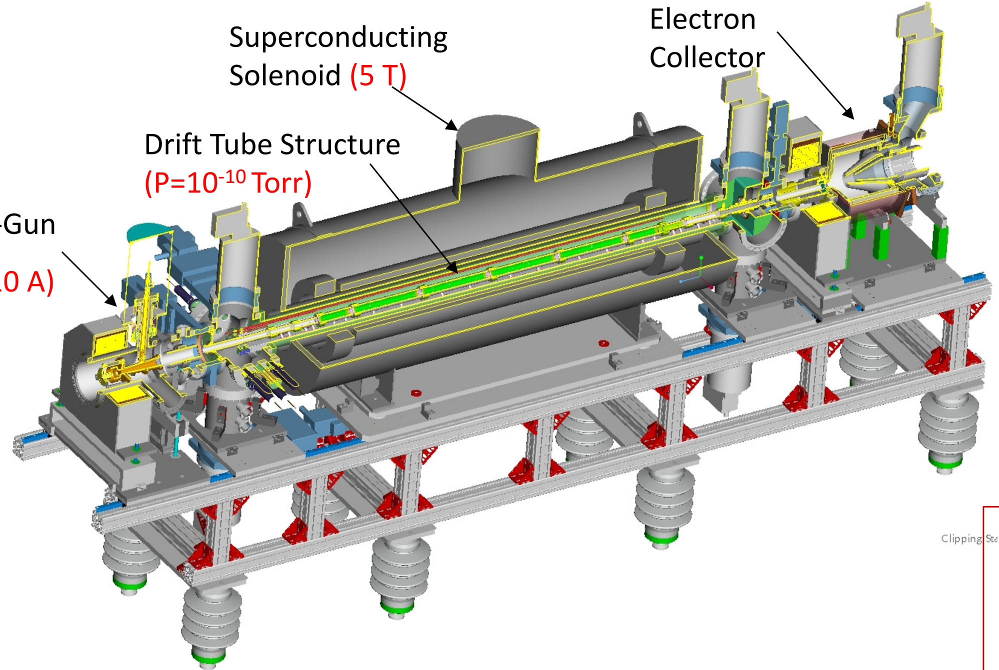
- Radial trapping of ions = space charge of the electron beam
- Axial trapping = electrostatic potentials at ends of trap

$$N_q = \frac{I_e \times L}{q \times \sqrt{U_e}} \times K_1 \times K_2$$

- Total charge of ions extracted per pulse: ~ (0.5 – 0.8) x (N_e in the trap)-K_1
- Ion output/pulse proportional to the trap length L, electron current I_e, Ion q fraction K_2
- Ion charge q increases with increasing confinement time
- Output current pulse almost independent of species or charge state

High intensity HCI sources: EBIS

RHIC-EBIS Source Assembly



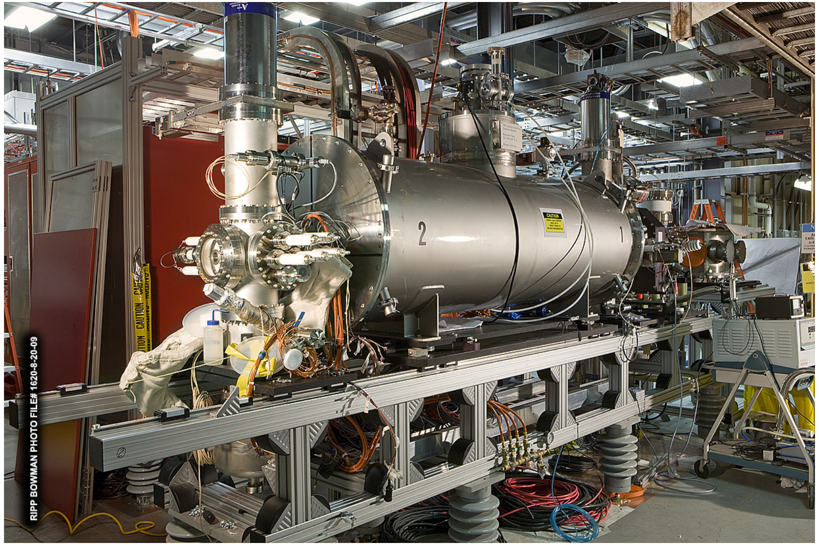
Parameter		RHIC EBIS
Max. electron current	I_{el}=	10 A
Electron energy	E_{el}=	20 keV
Electron density in trap	j_{el}=	575 A/cm^2
Length of ion trap	l_{trap}=	1.5 m
Ion trap capacity	Q_{el}=	1.1x10^{12}
Ion yield (charges)	Q_{ion}=	5.5x10^{11} (10 A)
Yield of ions Au^{32+}	N_{Au}^{32+}=	3.4x10^{9}

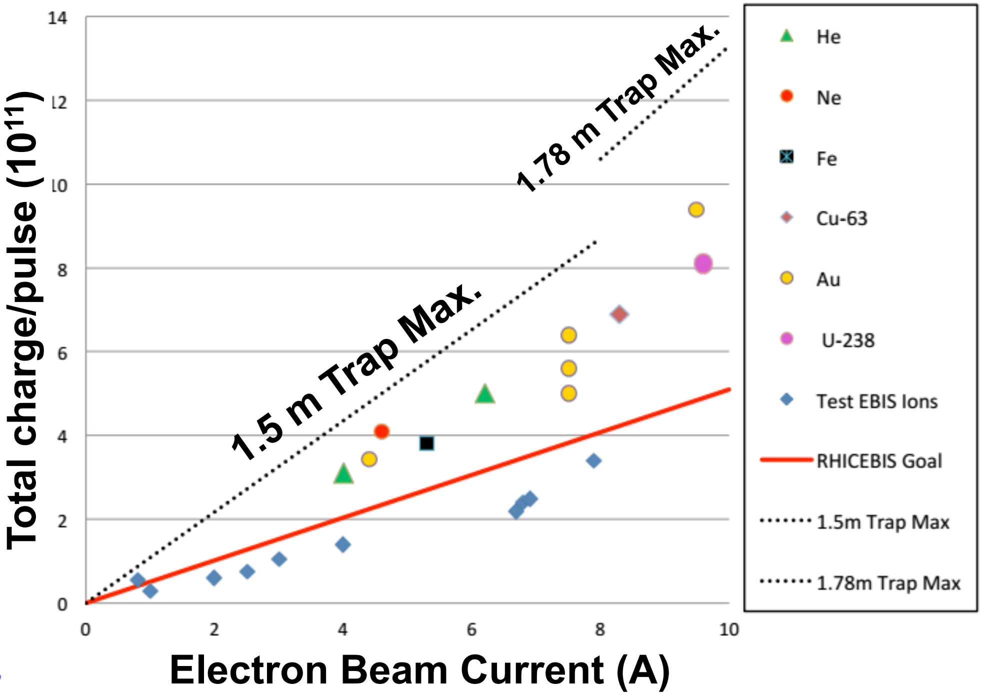
- ◆ Very high charge state
- ◆ Variable extraction pulse length
- ◆ Pure ion beams

Courtesy of E. Beebe@ICIS'17 Talk

High intensity HCI sources: EBIS

RHIC-EBIS in Operation

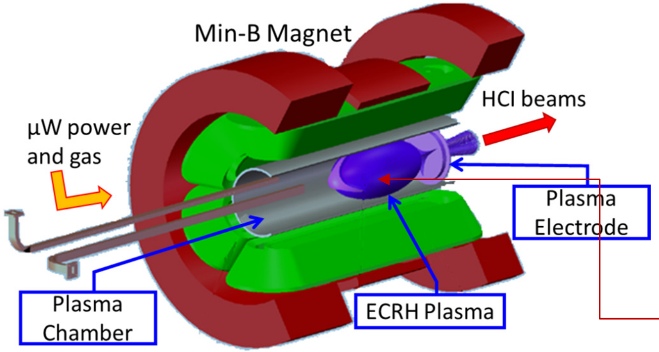




D, $^{3}He^{2+}$, $^{4}He^{1+,2+}$, Li^{3+}, $C^{5+,6+}$, O^{7+}, Ne^{5+}, Al^{5+}, $Si^{11+,12+}$, Ar^{11+}, Ca^{14+}, Ti^{18+}, $Fe^{20+,24+}$, Cu^{11+}, Kr^{18+}, **$^{90}Zr^{15+}$, $^{96}Zr^{16+}$, Nb^{16+}**, Xe^{27+}, Ta^{38+}, **$^{184}W^{31+}$**, Au^{32+}, Pb^{34+}, **$^{232}Th^{39+}$**, U^{39+}

Courtesy of E. Beebe@ICIS'17 Talk

High intensity HCI sources: ECRIS



Plasma Magnet Microwave

Electron Cyclotron Resonance
Ion Source

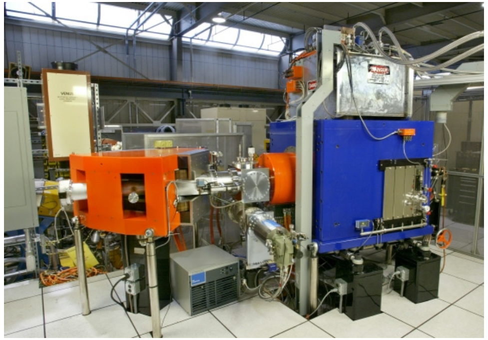
$$\omega_{ce} = \frac{e \cdot B_{ecr}}{m_e}$$

- $I_i^q = \frac{1}{2}\frac{n_i^q\, q\, e V_{ex}}{\tau_i^q}$ n_i^q ion density for species i charge q; τ_i^q Confinement time for species i charge q; $\sum_{i,q} n_i^q\, q_i = n_e$ (Plasma neutrality)

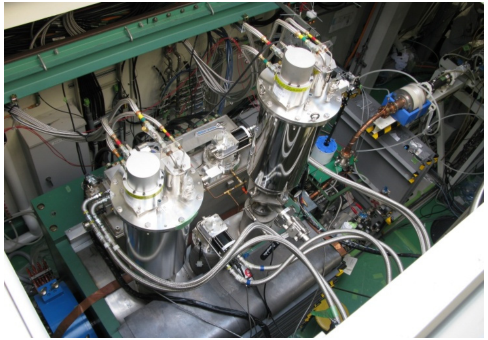
- RF dispersion equation at resonance : $(n_e T_e) \approx (\frac{m_e \varepsilon_0 \omega_{rf}^2}{e^2}) m_e c^2$ $I^q \propto \omega^2_{ECR}$

- Plasma Stability condition : $\beta = \frac{n_e k_b T_e}{(\frac{B^2}{2\mu_0})} < 1$ As $n_e \nearrow$ $B \nearrow$

High intensity HCI sources: ECRIS

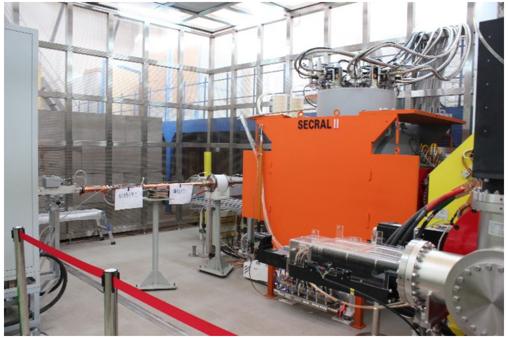


VENUS@LBNL



SCECRIS@RIKEN

SuSI@MSU

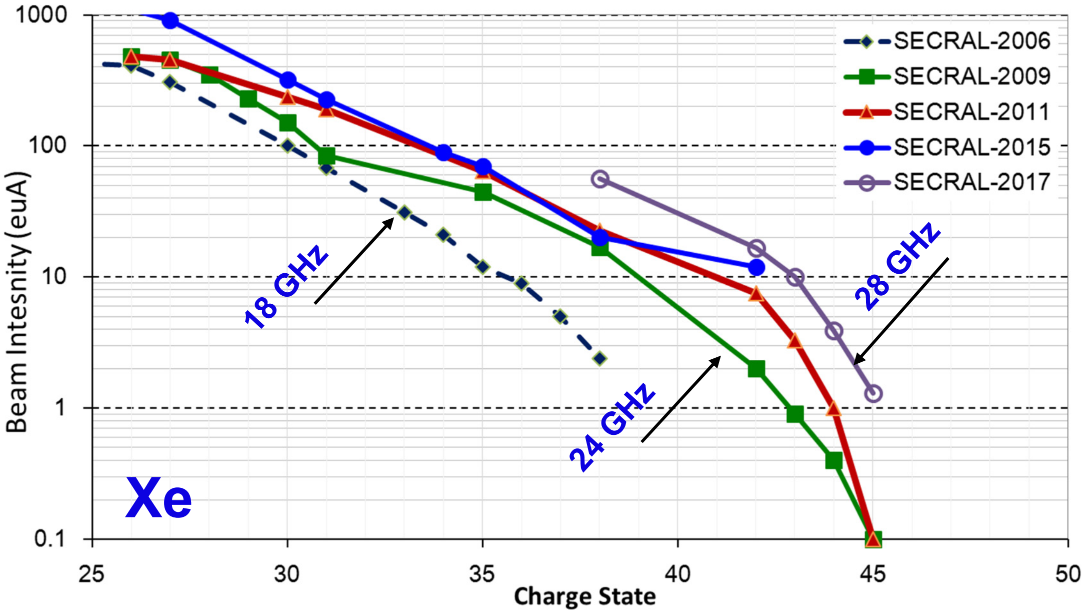


SECRAL, SECRAL-II@IMP

Parameters	Unit	State of the Art ECRISs
ω_{rf}	GHz	24~28
P_{rf}	kW	10.0
B_{mirror}	T	3.7~4.0/2.2~2.8
B_r	T	1.8~2.0
Chamber ID	mm	Ø100~150
Mirror Length	mm	400~500
HV	kV	30

- Very high charge state
- ~ms pulse to dc beam
- High beam intensity

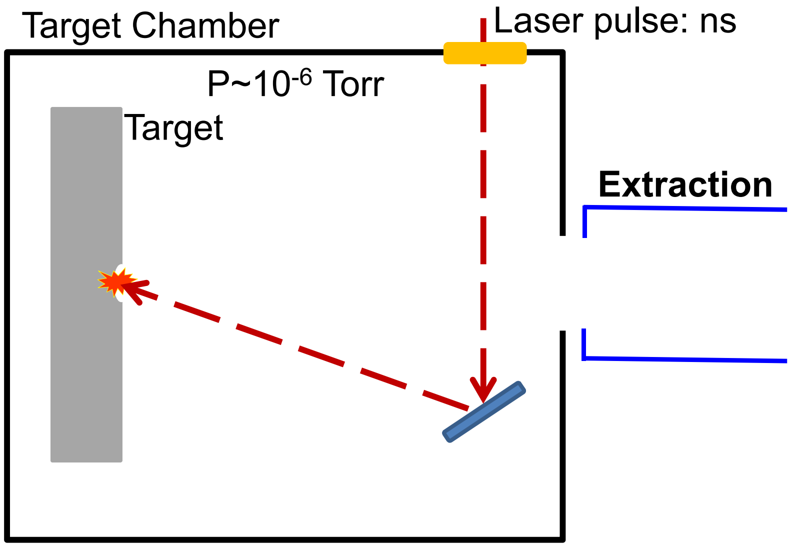
High intensity HCI sources: ECRIS



- ECRIS performances are keeping boosting in years
- ~emA order HCI beams available

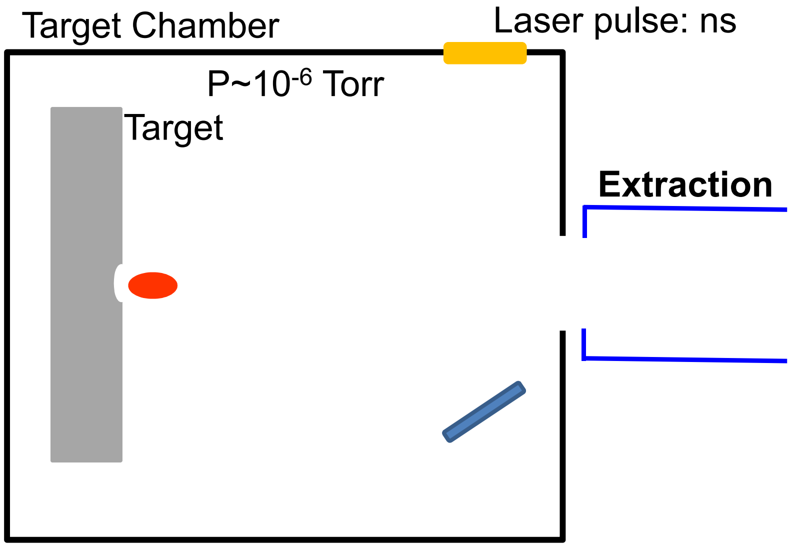
Ion beam	I (emA)	Frequency (GHz)
O^{6+}	6.7	28
Ar^{12+}	1.42	24
Ar^{14+}	1.04	28
Ar^{16+}	0.62	28
Ar^{18+}	0.015	28
Ca^{11+}	0.71	24
Kr^{18+}	1.02	28
Kr^{28+}	0.146	28
Xe^{26+}	1.1	24
Xe^{30+}	0.365	28
Xe^{38+}	0.053	28
Xe^{42+}	0.017	28
Ta^{30+}	0.375	28
Bi^{30+}	0.71	24
Bi^{50+}	0.01	24

High intensity HCI sources: LIS



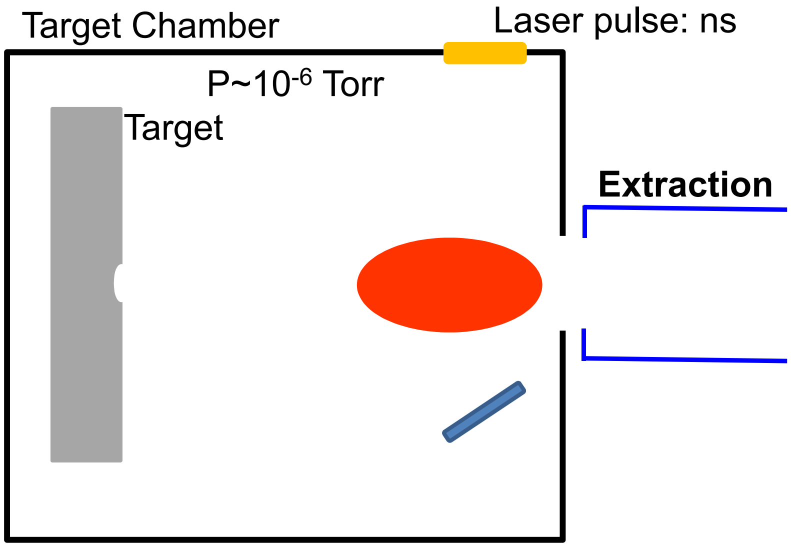
Courtesy of S. Kondrashev/BNL

High intensity HCI sources: LIS



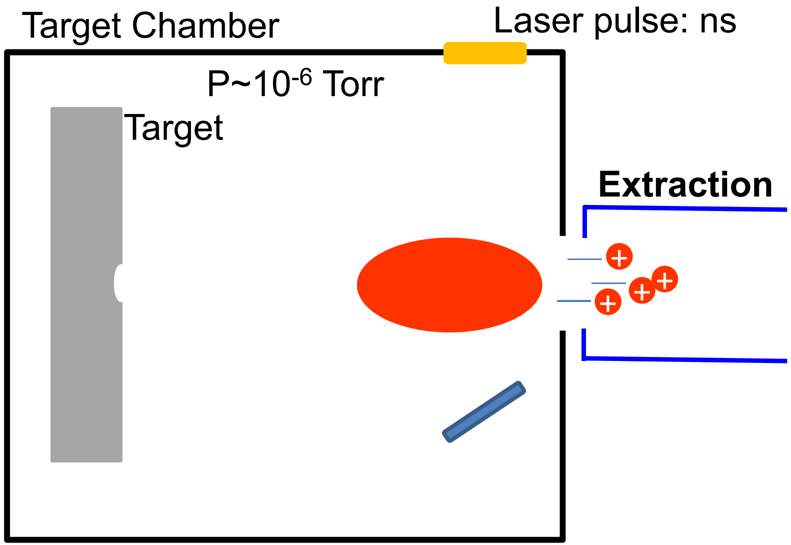
Courtesy of S. Kondrashev/BNL

High intensity HCI sources: LIS



Courtesy of S. Kondrashev/BNL

High intensity HCI sources: LIS



Courtesy of S. Kondrashev/BNL

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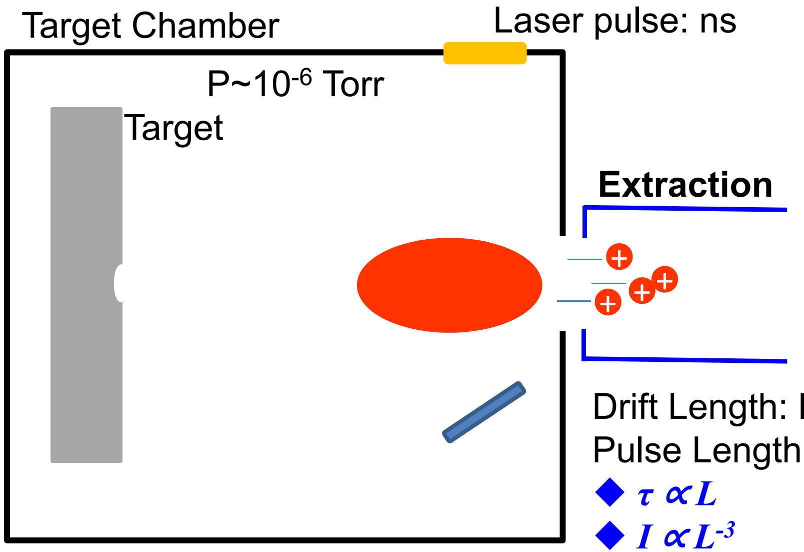


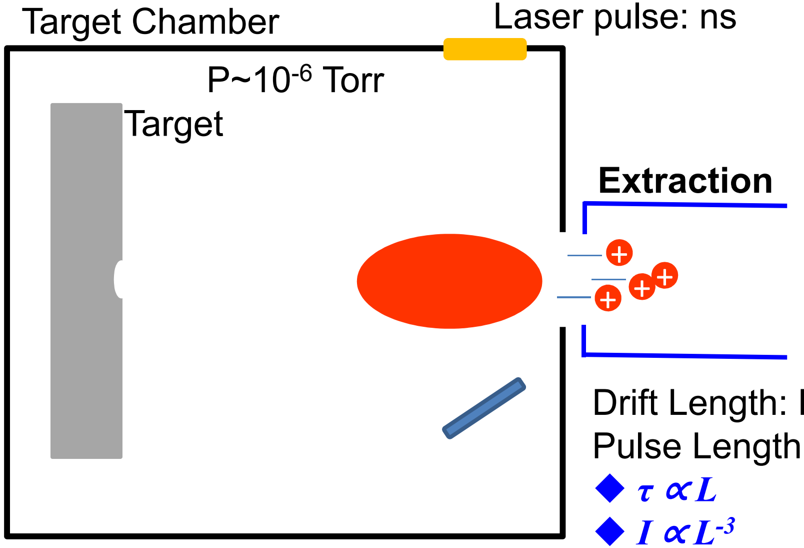
Drift Length: L

Pulse Length τ: 2-30 μs

- $\tau \propto L$
- $I \propto L^{-3}$

Courtesy of S. Kondrashev/BNL

High intensity HCI sources: LIS



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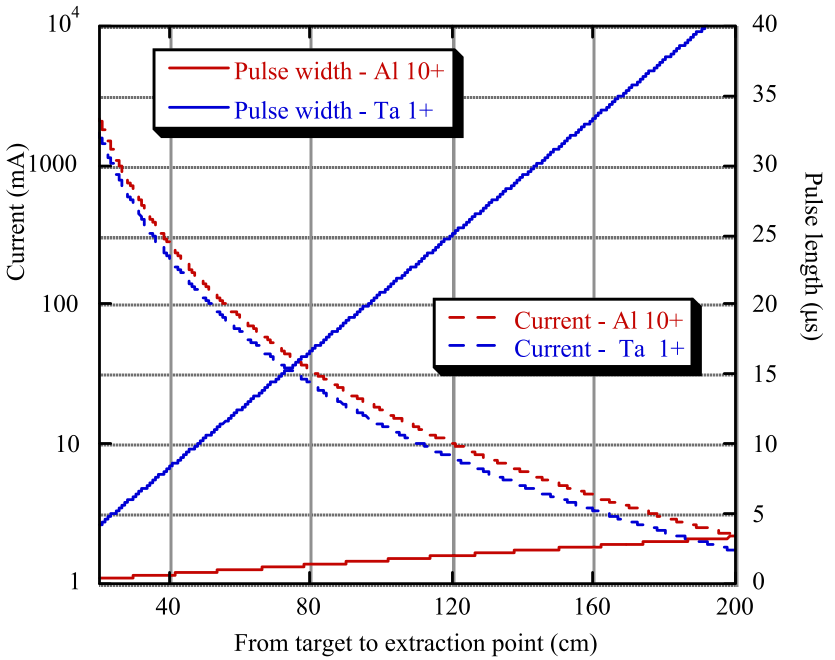
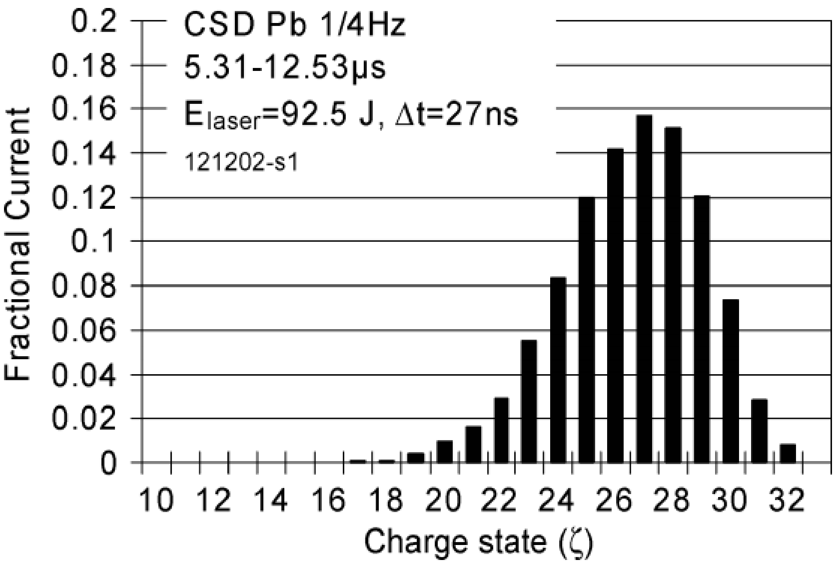


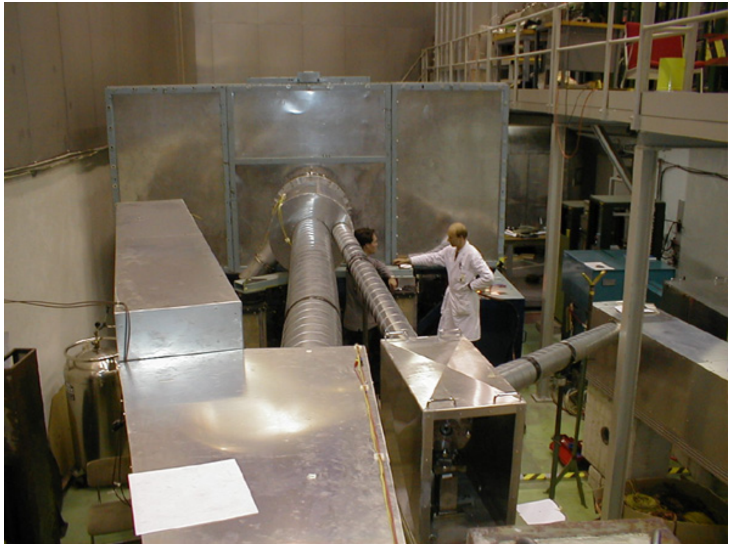
- Al - 3 J/30 ns Nd-glass 1062 nm laser (10^{11} W/cm²)
- Ta - 1 J/5 ns Nd-YAG 532 nm laser (10^{9} W/cm²)

Advantage：
- Simple structure: Laser, Vacuum, Target, Extraction
- Short pulse： μs
- High charge state
- high intensity, tens of emA, 10^{10}~10^{11}ppp
- Ion beams of any solid materials

Courtesy of S. Kondrashev/BNL

High intensity HCI sources: LIS





100 J/1 Hz MO-PA CO_2-laser system

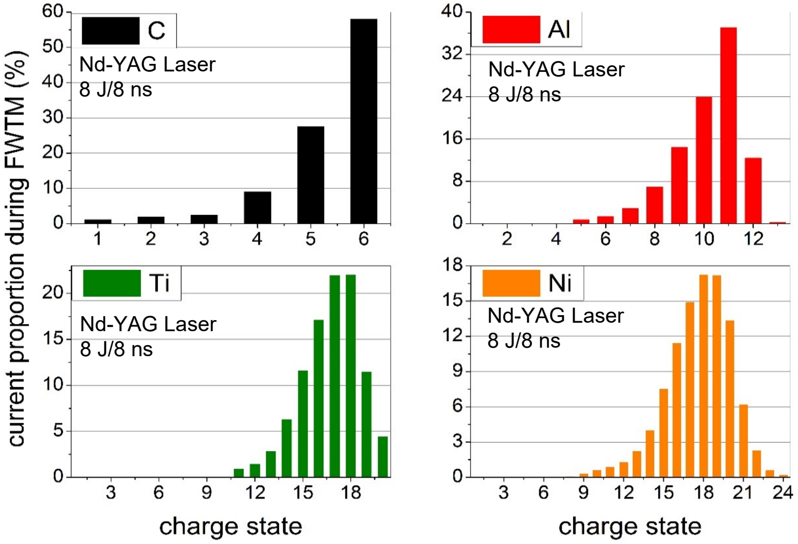
- **CSD of a lead ion beam generated by a CO_2 laser at a power density P~3×10^{13} W/cm^2**
- **Max. 3.5 emA or 2.8×10^{10} ppp Pb^{27+} with a pulse length of 3.6 μs**
- **16% Pb^{27+} in the extracted beam**

- CERN-ITEP-TRINITI collaboration on LIS
- Design study towards to LIS capable to meet LHC demand for Pb^{25+} ions

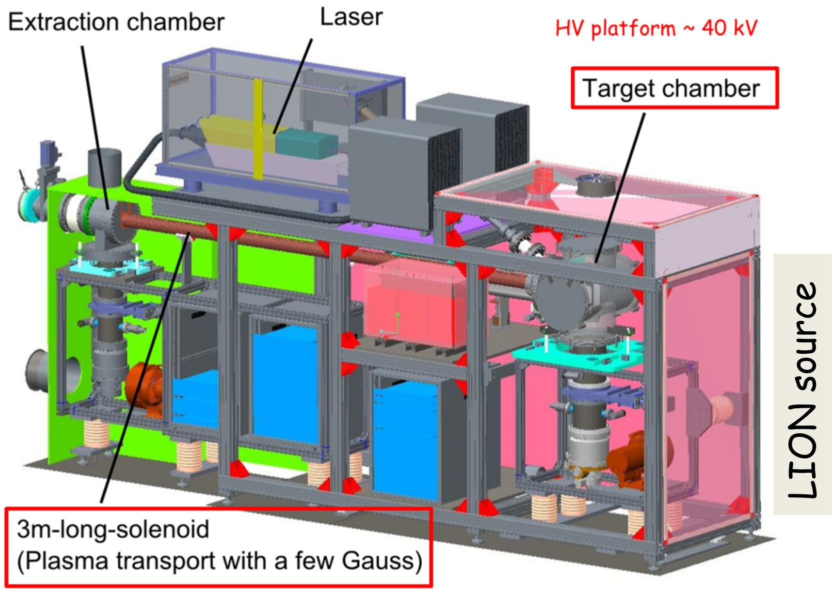
Courtesy of S. Kondrashev/BNL

B. Sharkov and R. Scrivens, IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 33, NO. 6, P.1778, DECEMBER 2005

High intensity HCI sources: LIS



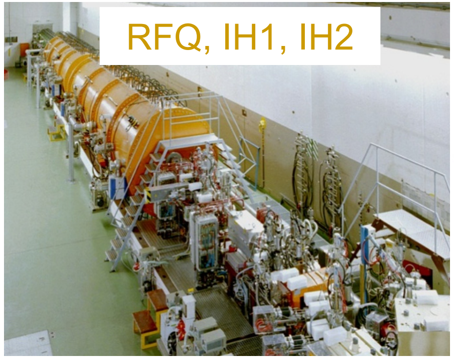
Ion Species	Specs.	Total Charge	Peak Current	Pulse length (FWHM)
C	Avg	1.38×10^{-7} C	46.5 emA	1.64 μs
	SD	**3.5%**	10%	6.7%
Ni	Avg	0.98×10^{-7} C	15.5 emA	2.24 μs
	SD	**2.6%**	5.9%	4.7%
Al	Avg	1.21×10^{-7} C	35.2 emA	2.22 μs
	SD	**2.6%**	7.6%	8.1%

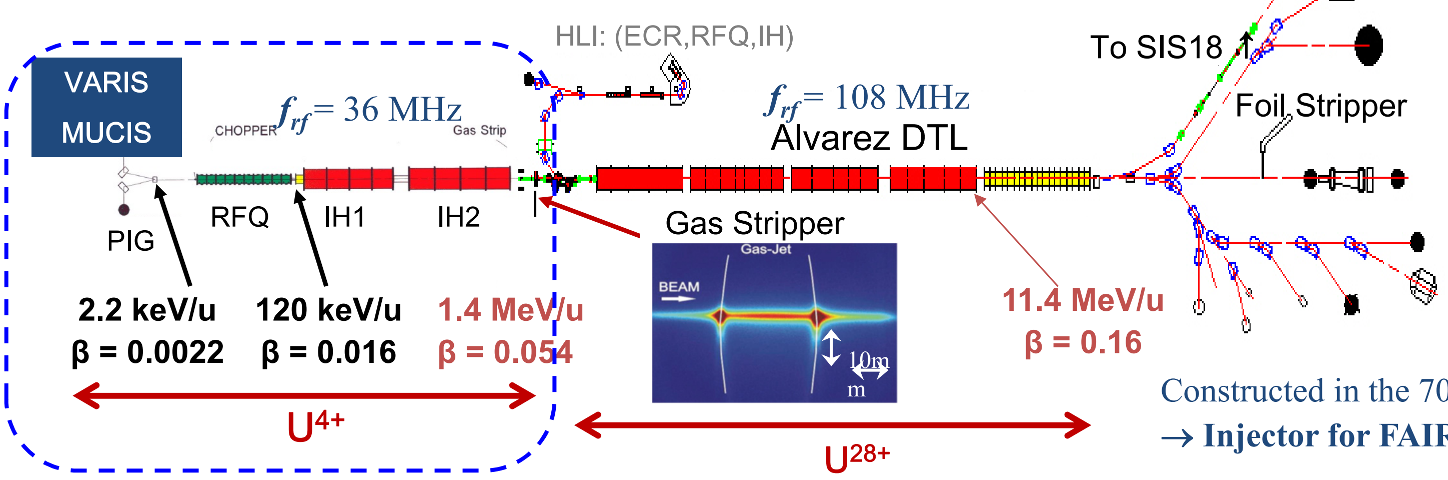


- Pulse to pulse stability: better than 10%
- Low Emittance: ~0.1 π. μm (n.rms)
- Routine operation (with):
  - » LION source for RHIC in BNL
  - » LIS source for NICA in JINR
  - » LIS source for ITEP-TWAC

Courtesy of H. Y. Zhao/IMP
Courtesy of M. Okamura/BNL

High intensity HCI sources: Charge Stripping



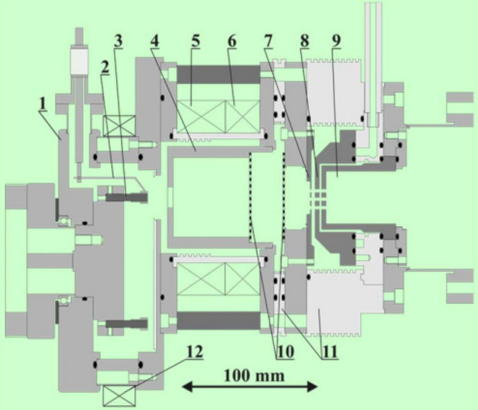


Constructed in the 70[th], Upgraded in 1999,

→ **Injector for FAIR ion operation**

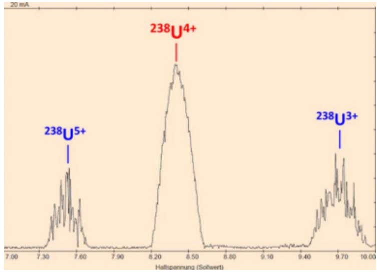
High intensity HCI sources: Charge Stripping

1 - Cathode
2 - Trigger
3 - Cathode
4 - Anode
5 - Coil I
6 - Coil II
7 - Plasma-Electrode
8 - Screening-Elect.
9 - Ground-Elect.
10 - Grid
11 - Isolator
12 - Coil III



Operational data of the ion source

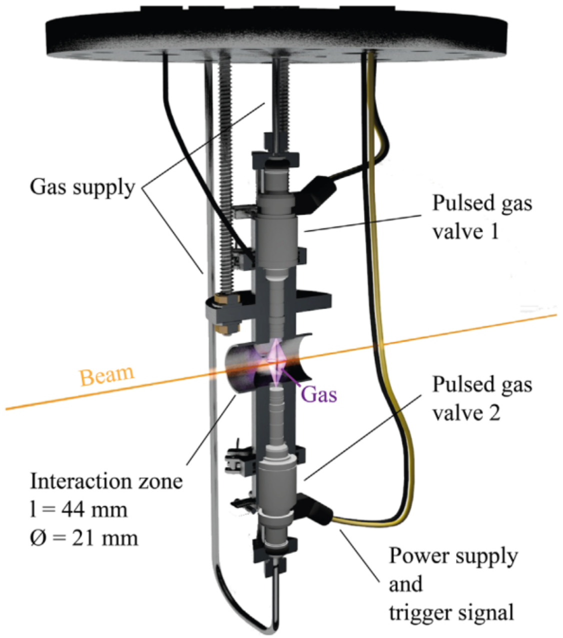
Ion fraction	U^{3+} = 16%, U^{4+} = 67% U^{5+} = 14%, U^{6+} = 3%
Arc current/arc power	600–700 A/up to 30 kW
Pulse length/rep. rate	0.6 ms/1 Hz
Flux densities solenoid I + II/III	40 mT/0–60 mT
Extraction system	13 × 3 mm, multi-aperture aspect ratio 0.5
Emission current density (for standard operation)	170 mA/cm^2 (150 mA/cm^2)
Full beam ion current, FC (for standard operation)	156 mA @ 35 kV (140 mA @ 32 kV)
DC accelerated ion current	55 mA @ 131 kV
Analysed U^{4+} current	25 mA
U^{4+} current for RFQ injection	15 mA
$\varepsilon_{effective}$ (156 mA @ 35 kV)	890 π mm mrad
$\varepsilon_{x,4rms}$ (156 mA @35 kV)	440 π mm mrad
$\varepsilon_{y,4rms}$ (156 mA @ 35 kV)	470 π mm rad
$\varepsilon_{x,y,4rms}$ (55 mA @ 131 kV)	400 π mm rad
$\varepsilon_{x,90\%}$ (after separation, 15 mA)	180 mm rad
$\varepsilon_{y,90\%}$ (after separation, 15 mA)	140 π mm rad
Noise full beam/after separation	< ± 4%/±5%
Pulse to pulse stability	Better than 80%
Voltage break downs	2 per day for standard operation
Cathode life time	12 h @ 0.6‰ duty cycle



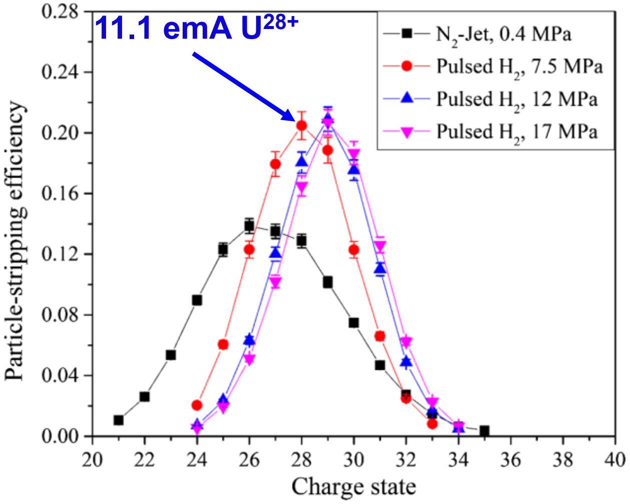
Courtesy of Aleksey Adonin@ICIS2017, Talk

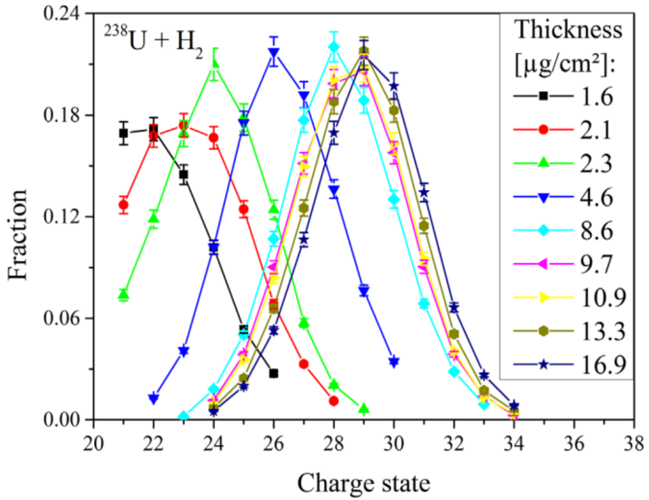
R. Hollinger, M. Galonska, Nucl. Instr. and Meth. in Phys. Res. **B 239**, p.227 (2005)

High intensity HCI sources: Charge Stripping



- **Pulsed gas valve synchronized with beam pulse timing**
- **Gas back-pressure up to 12 MPa**



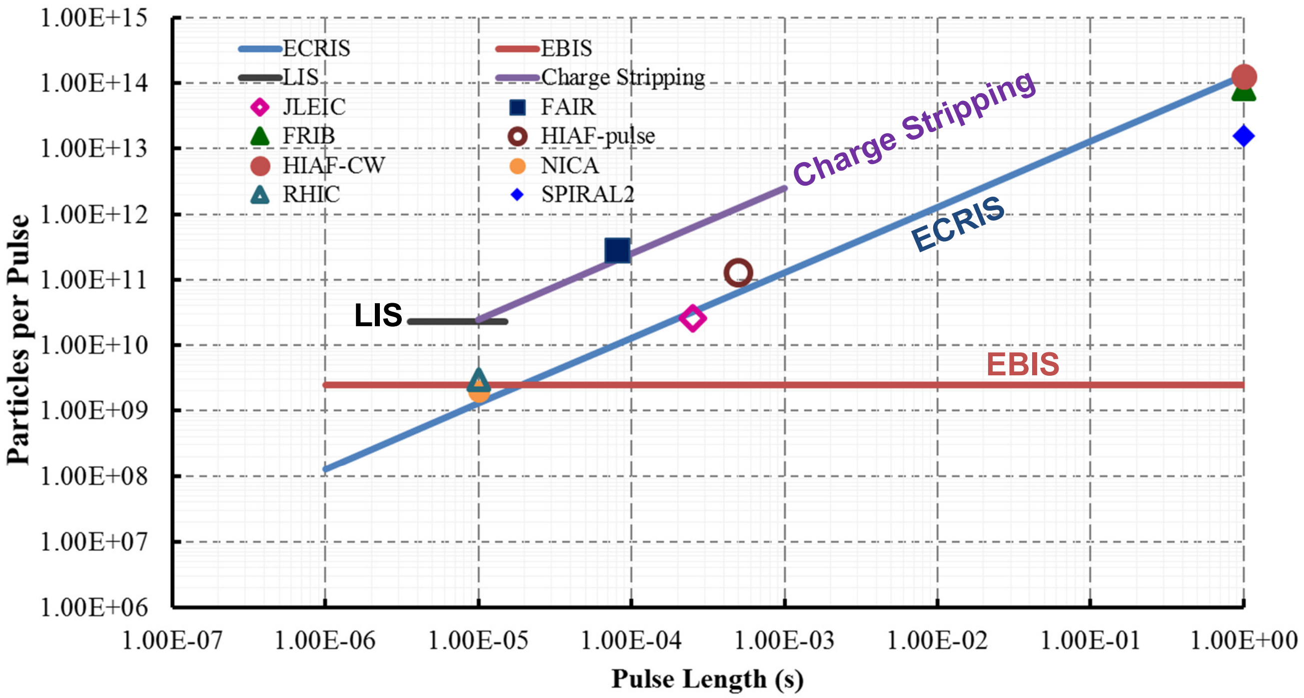


Charge distribution after stripping of U projectiles in a H_2 gas target for different target thickness in comparison with N_2 target

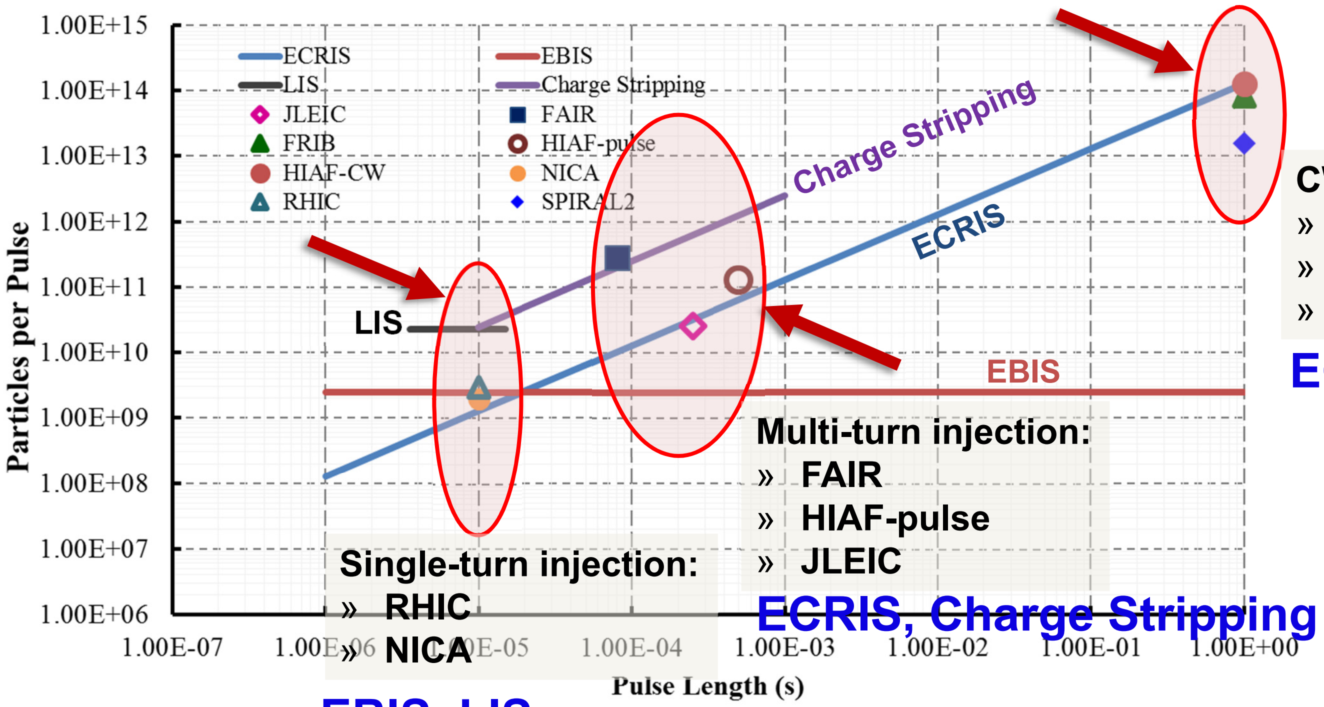
- *7.5 MPa gas cell → 11.1 emA U^{28+}*
- *12.0 MPa gas cell → 11.5 emA U^{29+}*
- *From formerly 7.6 emA (50% of FAIR requirement) → 74%*

W. Barth, et al., /Phys. Rev. Accel. Beams, **20**, 050101 (2017)
P. Scharrer, at al., Nucl. Instr. and Meth. in Phys. Res. **A 863,** P.20 (2017)

High intensity HCI sources: impact



High intensity HCI sources: impact



Single-turn injection:
» RHIC
» NICA

EBIS, LIS

Multi-turn injection:
» FAIR
» HIAF-pulse
» JLEIC

ECRIS, Charge Stripping

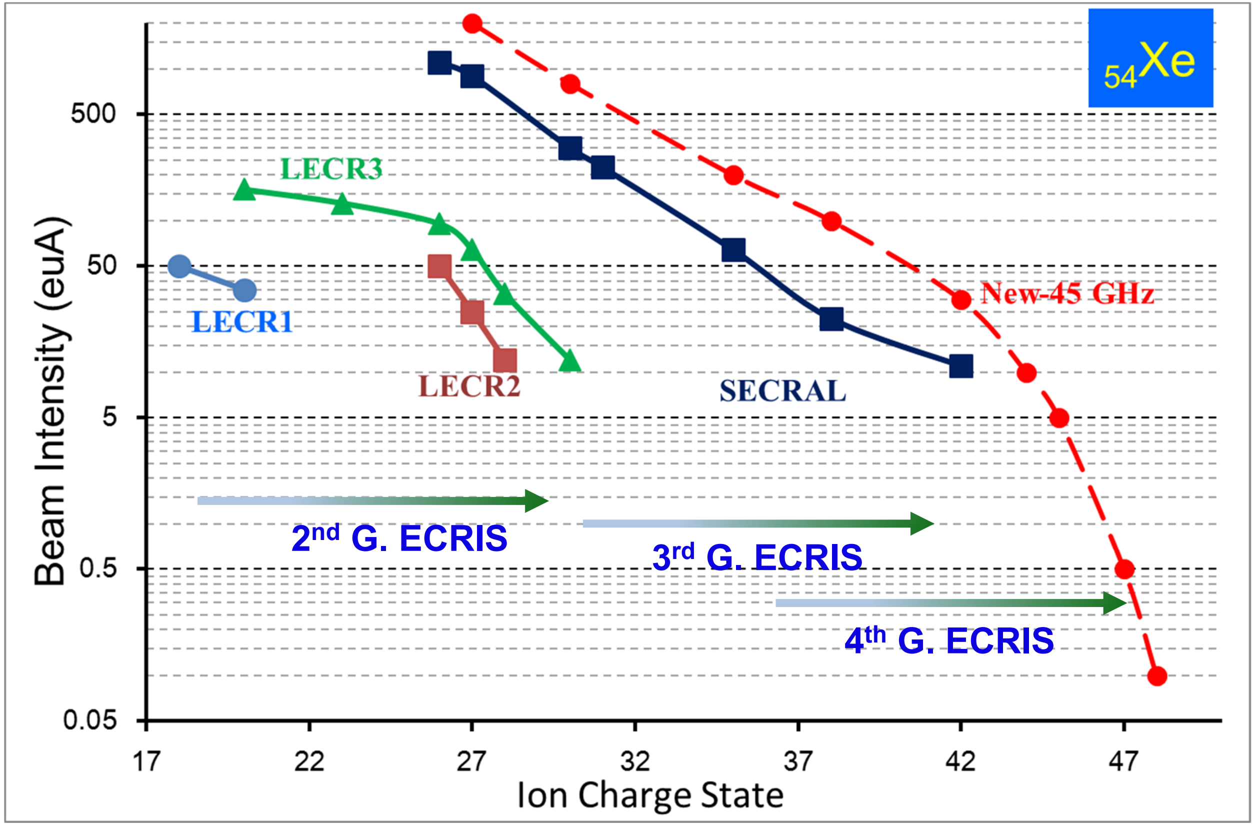
CW operation:
» FRIB
» HIAF-CW
» SPIRAL2

ECRIS

Future developments and perspectives

- Next Generation ECRIS
- Tandem EBIS
- Gasdynamic ECRIS (G-ECRIS)+Stripping

Next Generation ECRIS



$I^q \ \alpha \ \omega^2_{ECR}, G_q \sim (28/18)^2 = 2.4$

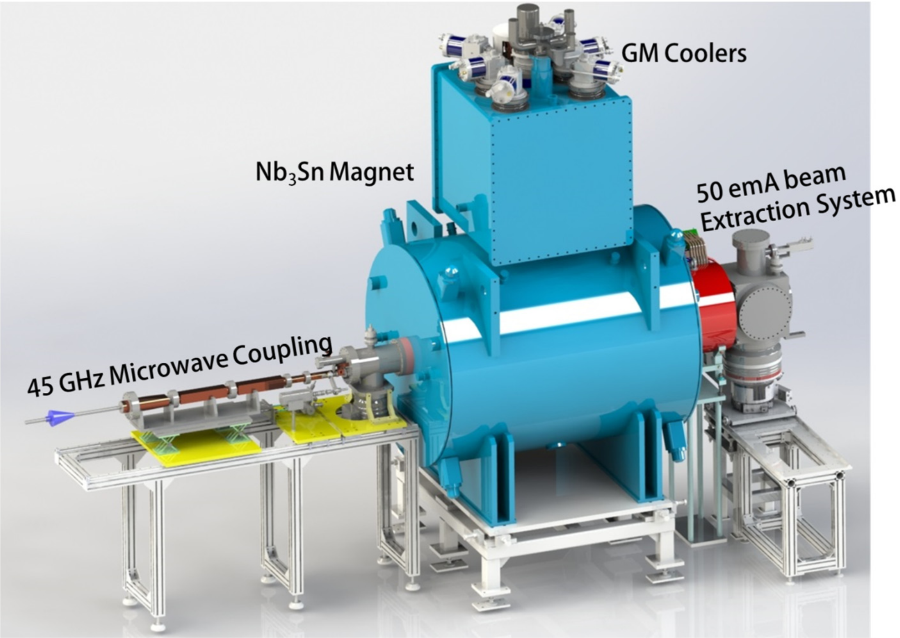
45 GHz~ G_q=2.6

>1.0 emA U^{34+}, dc

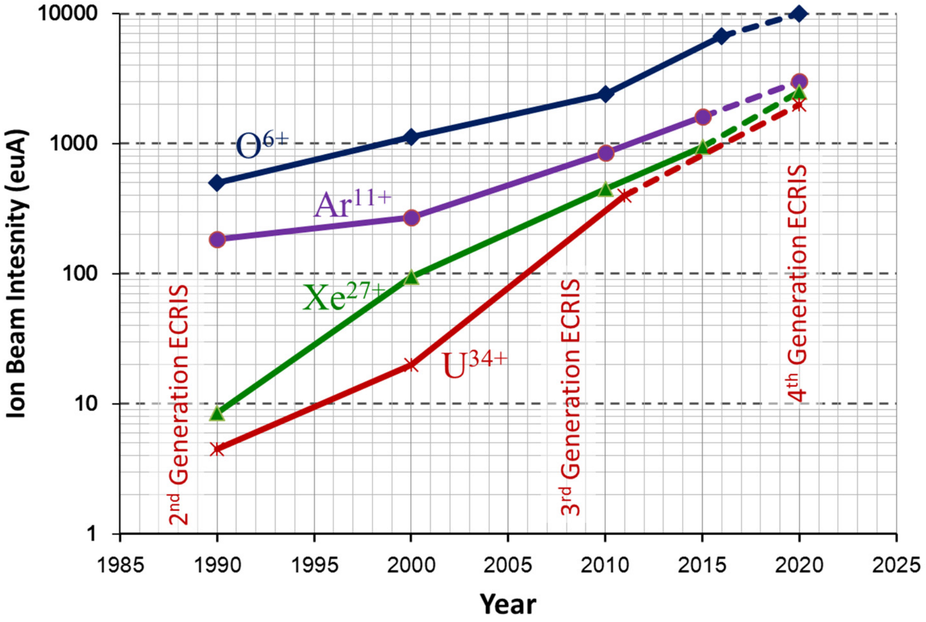
(>2.0 emA, pulsed)

Specs.	Unit	45 GHz ECRIS
Frequency	GHz	45
Mirror Fields	T	⩾6.4/3.2
B_{rad}	T	⩾3.2
Mirror Length	mm	~500
Magnet coils	/	Nb_3Sn
Conductor	J_c>1500 A/mm²@12T	
Cooling Capacity@4.2 K	W	⩾10.0

Next Generation ECRIS



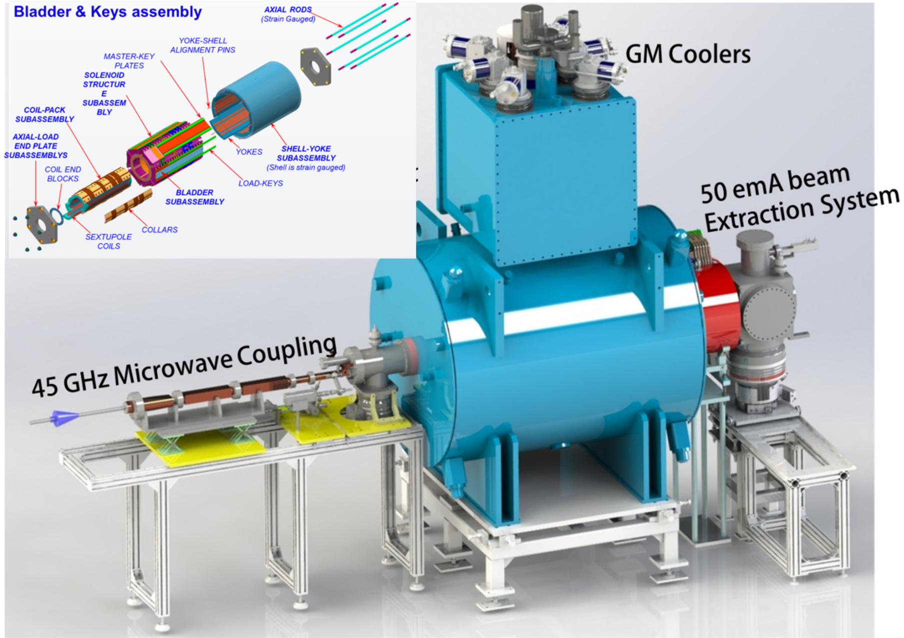
45 GHz FECR@IMP (2017~2020)



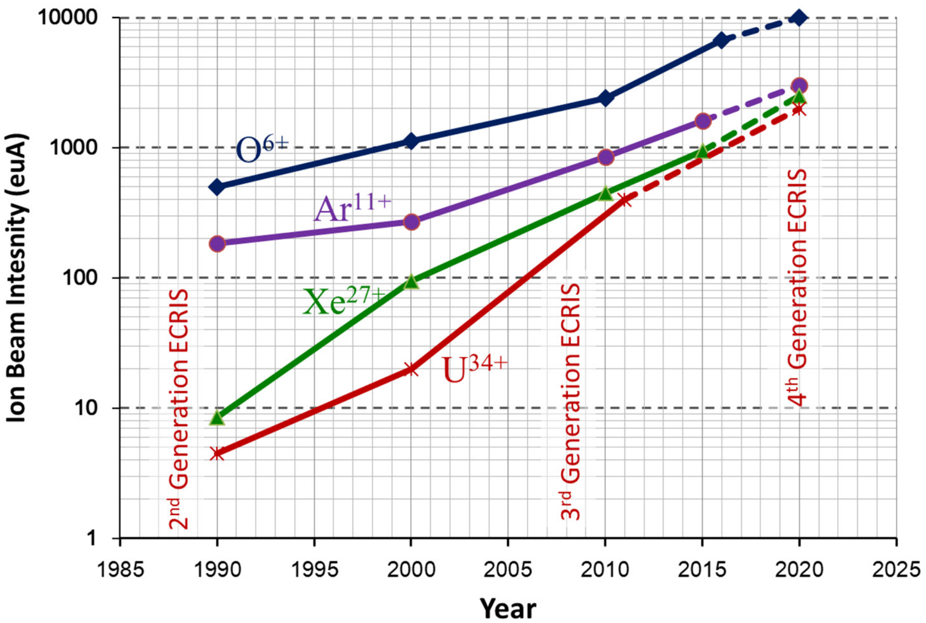
HCI currents with a 4th G. ECRIS:

- A=12~40 200 puA (dc)
- A=40~100 100 puA (dc)
- A=100~238 30 puA (dc), 50 puA (pulse)

Next Generation ECRIS



45 GHz **F**ECR@IMP (2017~2020)



HCI currents with a 4th G. ECRIS:

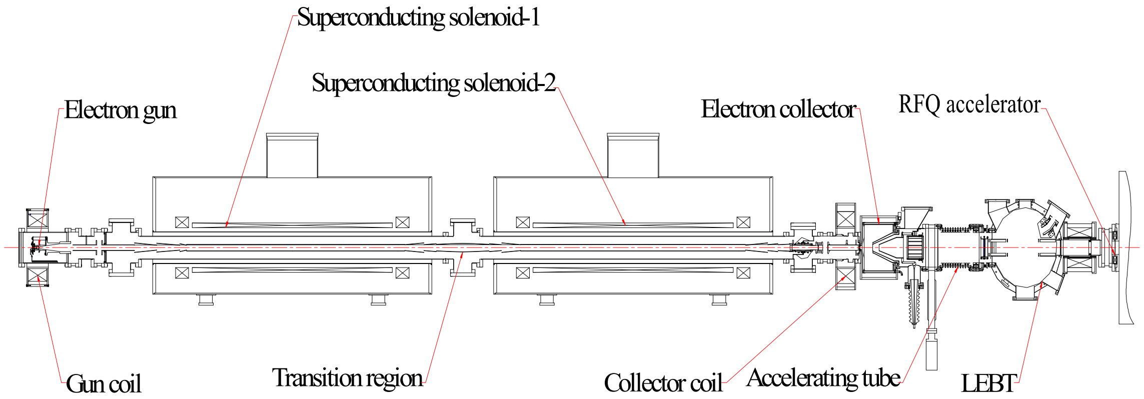
- ☐ A=12~40 200 puA (dc)
- ☐ A=40~100 100 puA (dc)
- ☐ A=100~238 30 puA (dc), 50 puA (pulse)

Tandem EBIS

Two Straightforward methods to increase EBIS charge:

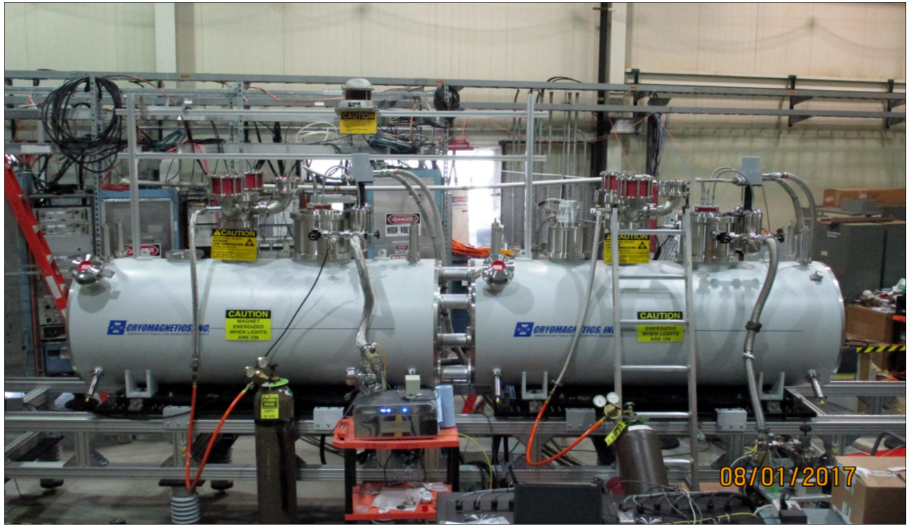
1) Increase the Electron Current I_e
2) Increase the ion trap length L

$$N_q = \frac{I_e \times L}{q \times \sqrt{U_e}} \times K_1 \times K_2$$



Courtesy of E. Beebe@ICIS2017, Talk

Tandem EBIS



Extended EBIS superconducting solenoids@BNL

$$N_q = \frac{I_e \times L}{q \times \sqrt{U_e}} \times K_1 \times K_2$$

RHIC-EBIS: Au^{32+} ~3.4×10^9 ions/pulse

Technical Approach:

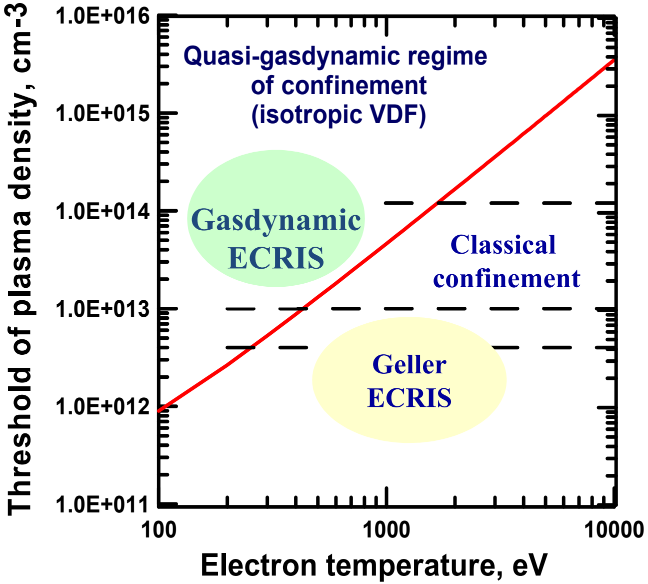
- ☐ I_e Increase from 10 A to 20 A (x~2.0)
- ☐ Regain optimal distribution $K_1 \times K_2$ (x~1.5)
- ☐ Tandem EBIS configuration (x~2.0)

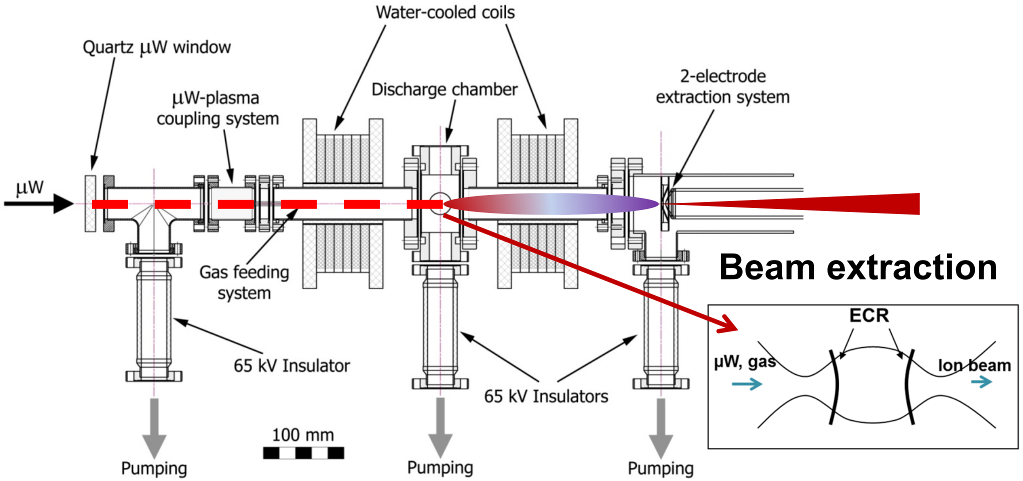
Tandem EBIS Output

- **Au^{32+} ~2×10^{10} ions/pulse**
- **U^{39+} >1×10^{10} ions/pulse**

Courtesy of A.Zelenski@IPAC'18, TUYGBE4
Courtesy of E. Beebe@HCI Sources Symposium 2014 in Lanzhou

G-ECRIS + Stripping

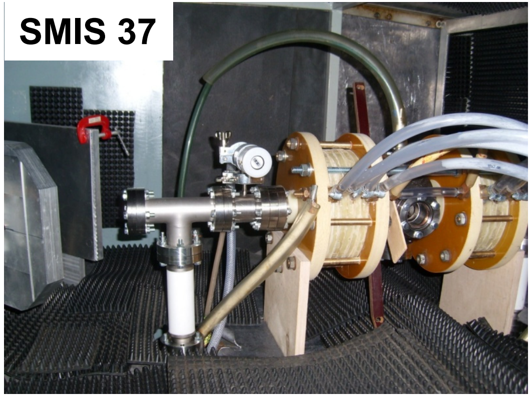




Features

- High current density: 1~10 A/cm^2
- Low emittance: ε_{rms}<0.1 π.um
- High ionization efficiency
- Simple scaling of performance

SMIS 37

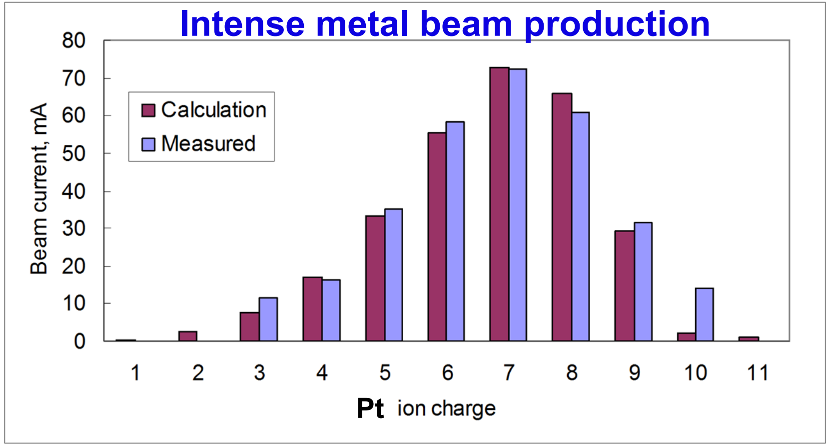


Scaled performance at 100 GHz

	$Q_{highest}$	Current Density
Carbon	+4	10 A/cm^2
Nitrogen	+5	10 A/cm^2
Oxygen	+6	10 A/cm^2
Argon	+11	6 A/cm^2
Xenon	+20	4 A/cm^2

Courtesy of Vadim Skalyga/IAP

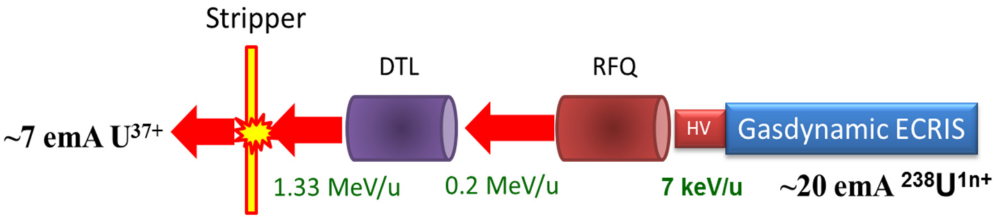
G-ECRIS + Stripping



- SMIS37: <Z>$_{Pt}$ = 4.5 @37.5 GHz/100 kW
- SMIS75: <Z>$_{Pt}$ = 7 @75 GHz/200 kW

- **Higher frequency: >100 GHz**
- **Better confinement: MHD stability**

~20 emA U^{1n+}

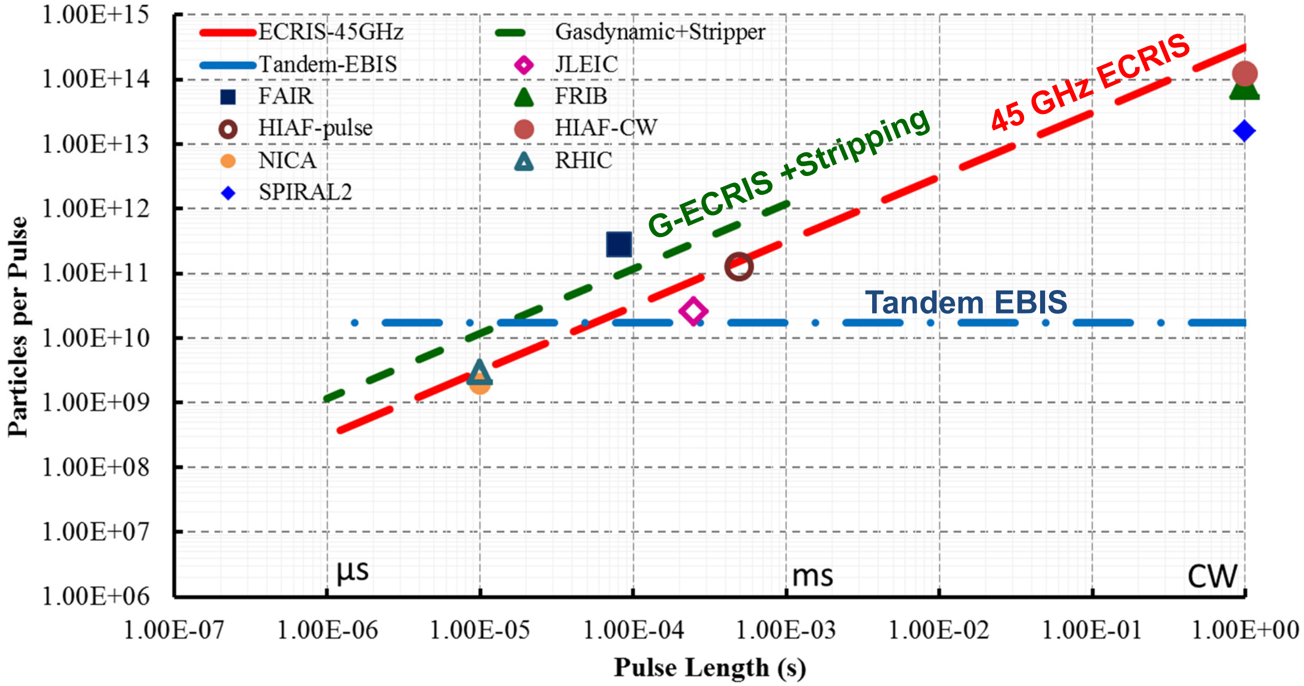


Advantages

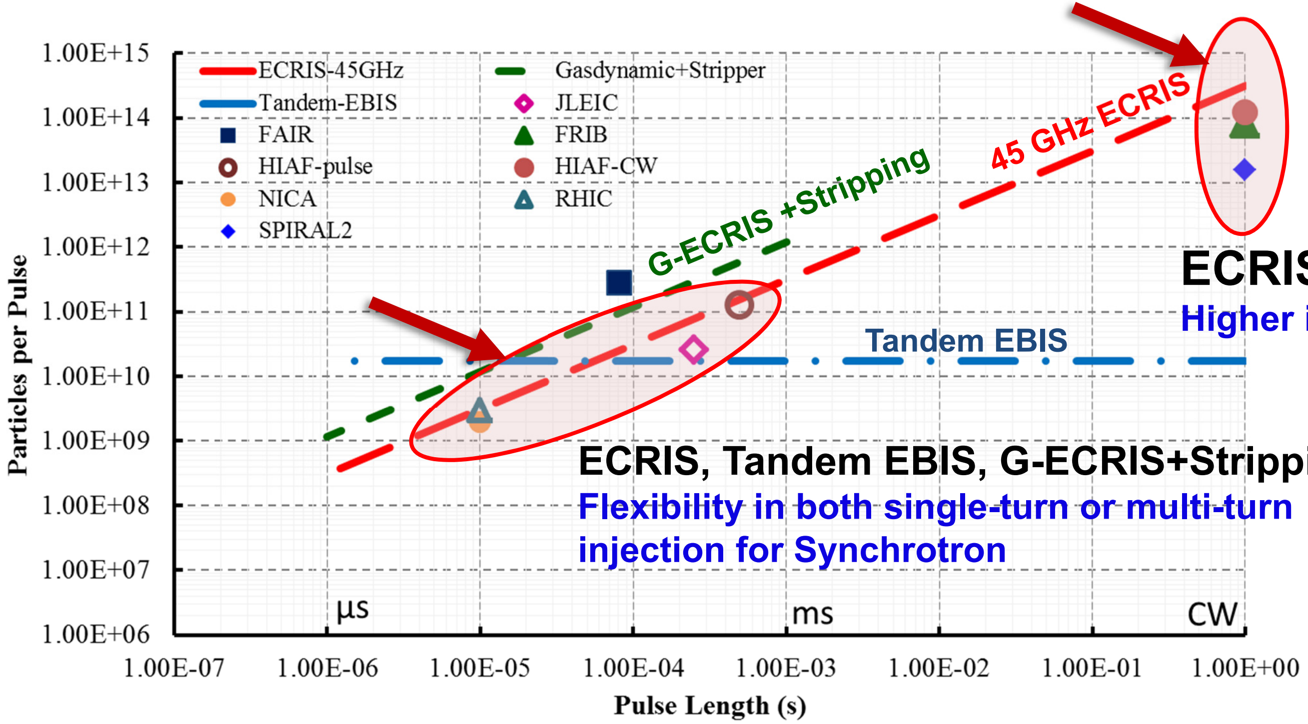
- **Efficient acceleration before stripper**
- **Low beam emittance**
- **No life span in principle**
- **Produce both gaseous and metal beams**

Courtesy of Alexander Vodopyanov/IAP

Next G. HCI sources: possibilities



Next G. HCI sources: possibilities



ECRIS

Higher intensity linac

ECRIS, Tandem EBIS, G-ECRIS+Stripping

Flexibility in both single-turn or multi-turn injection for Synchrotron

Conclusion

- ◆Remarkable progresses in high intensity high charge state heavy ion sources development in recent years
- ◆No all-purpose ion source available for exiting facilities and next generation heavy ion accelerators
- ◆Next generation accelerators need more powerful HCI sources
- ◆Next generation or future HCI sources provide more possibilities/flexibilities for next generation heavy ion facilities

Thanks for your attention!

HIAT 2018

Lanzhou, China

Oct. 22-26, 2018

http://hiat2018.csp.escience.cn