# Intense Beam Production of HCIs by the SC-ECRIS SECRAL for heavy ion Linacs

L Sun

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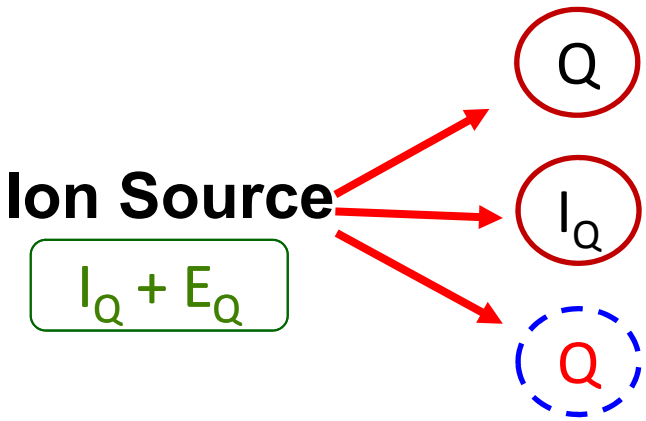
# Outline

- High Charge State Ion Sources
- Intense HCI Beams Production with SECRAL
  - ~emA HCI beams
  - Metallic ion beams
  - Beam quality
- SECRAL II
- Scope of 4th G. ECRIS

# HCI Sources

**Heavy ion Linac inquires ion sources of highly charged ions and intense beams**



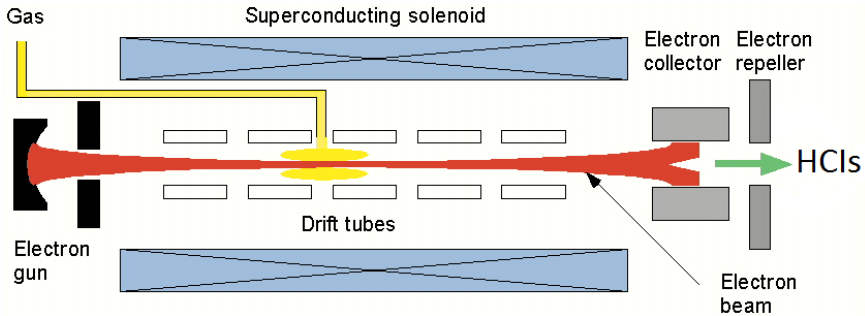

**E～Q for linac**

- **Higher power**
- **Simpler acceleration strategy**

**Beam quality, reliability, availability…**

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

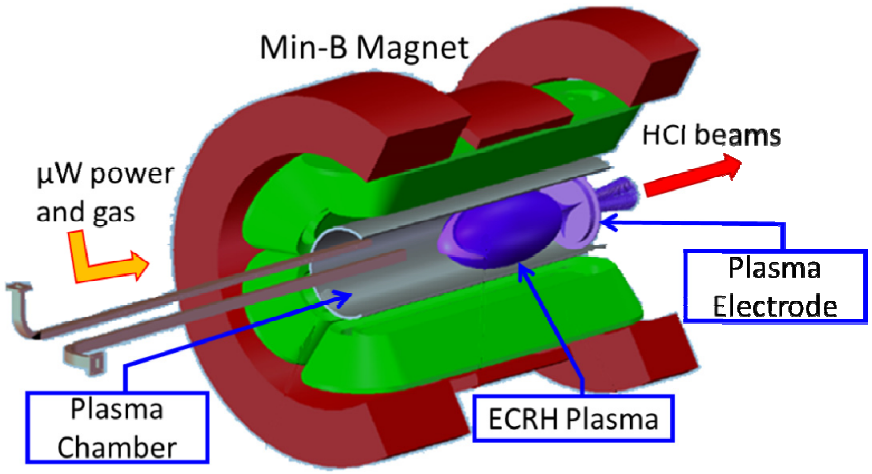
# HCI Sources




## Electron Beam Ion Source

$$C^{+} = 3.36 \times 10^{11}\, I_e L E_e$$

- Easily produces high intensity low duty factor HCI beams
- Very high charge state ions (from EBITs):
  - ✓ SuperEBIT (LLNL)→~100 $U^{90+}$ ions/s
  - ✓ Tokyo EBIT→ $Bi^{81+}$
- Narrow charge state distribution, peaked on interested charge state
- Beam production of any species and intensity independent of species
- Low background contamination (charge breeder)
- Fast beam species switching (~1 second)



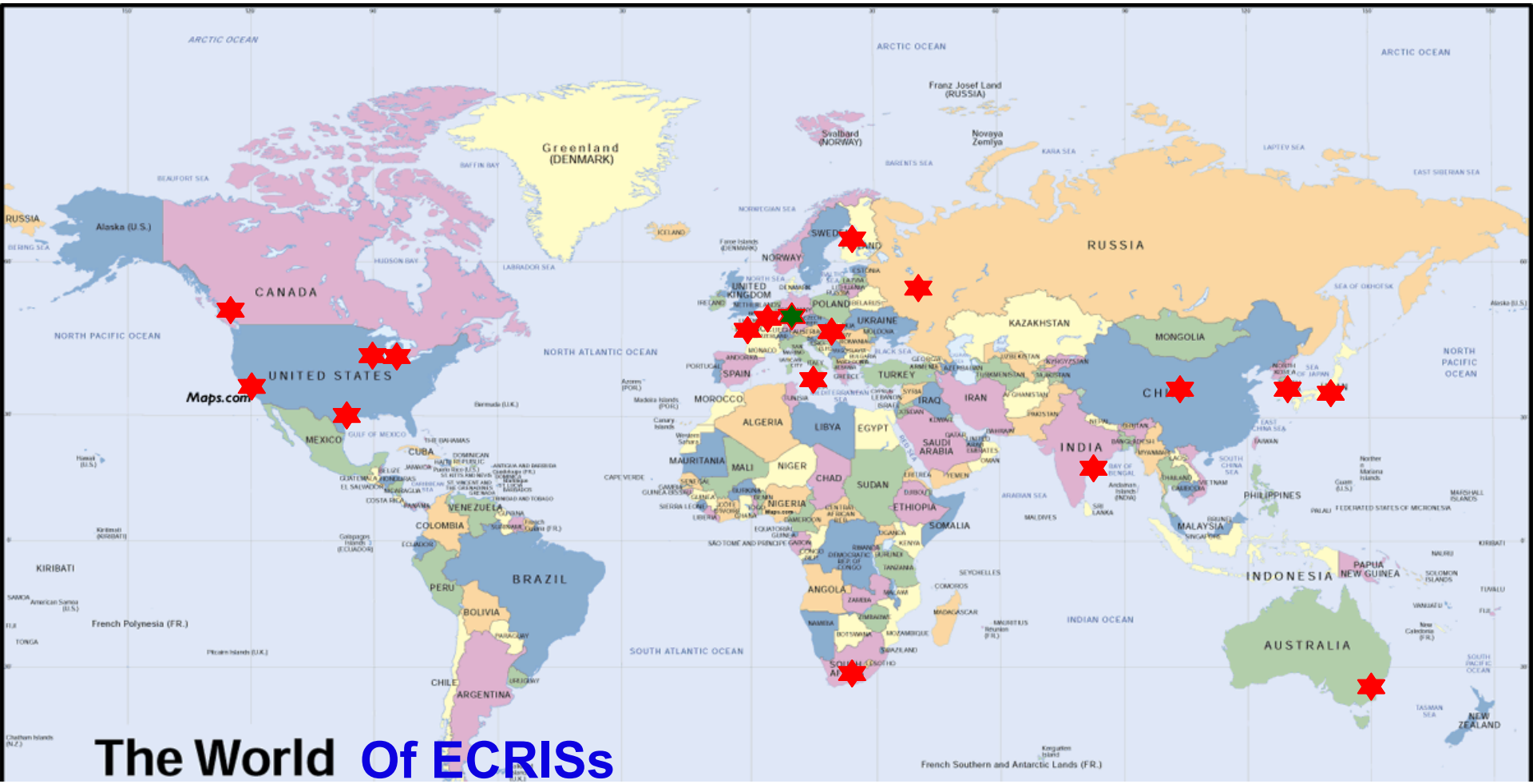

## Electron Cyclotron Resonance Ion Source

$$I_i^q = \frac{1}{2}\frac{n_i^q\, q\, e\, V_{ex}}{\tau_i^q} \propto \omega_{ecr}^2$$

- Irreplaceable machine for CW and high duty factor highly charged ion beams
- Long term stability reliability
- No life span issue
- Technology and physics advancing

# ECRIS: as HCI beam injectors

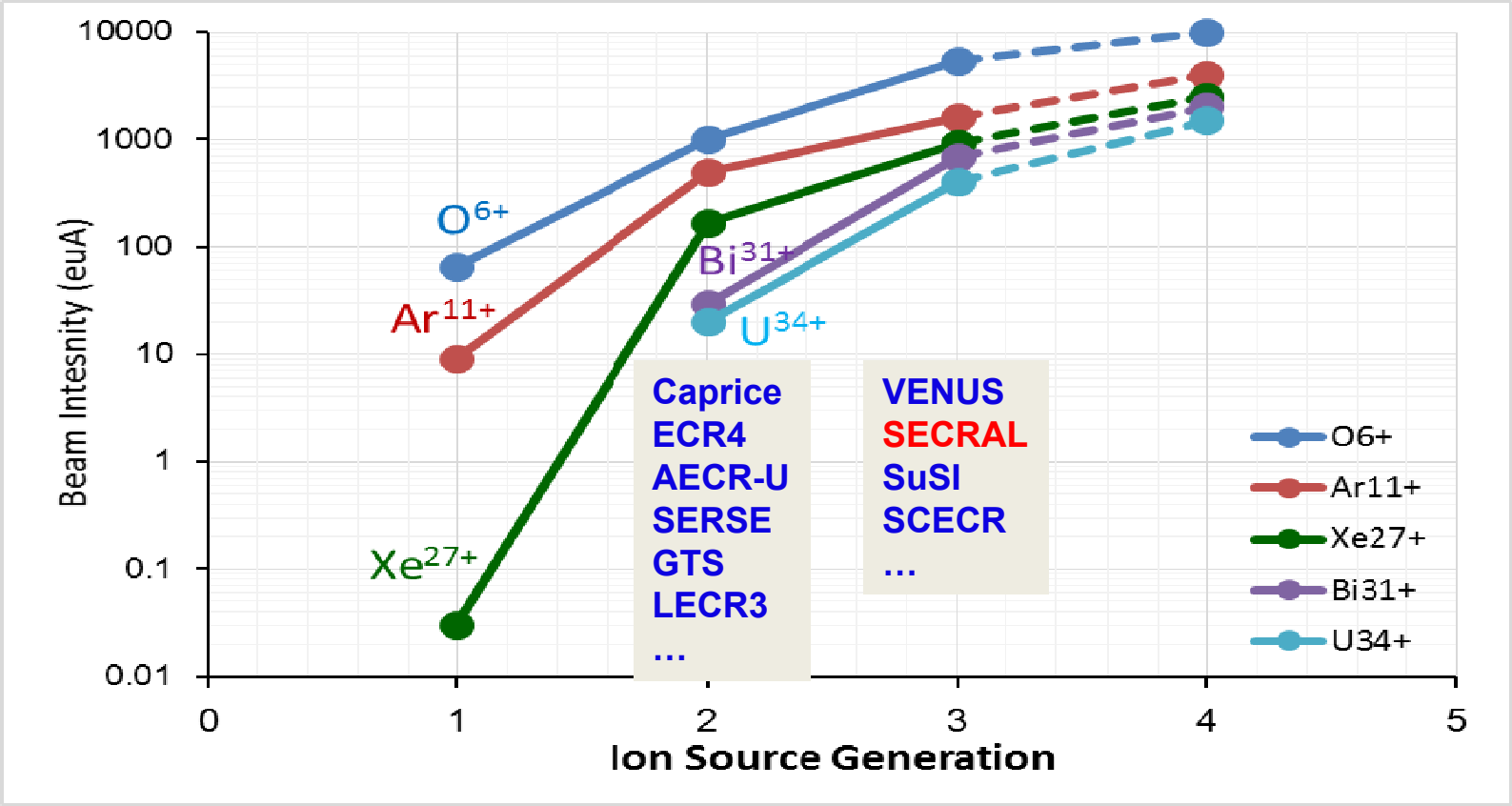
## World wide ECRISs and Applications



# ECRIS: State of the Art

| Cyclotrons | NC Linacs | SRF Linacs |
|---|---|---|

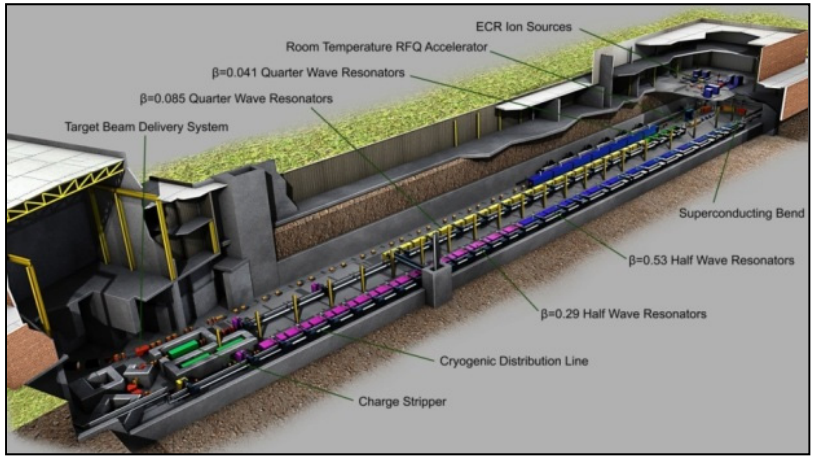
10 eμA — 100 eμA — 1 emA



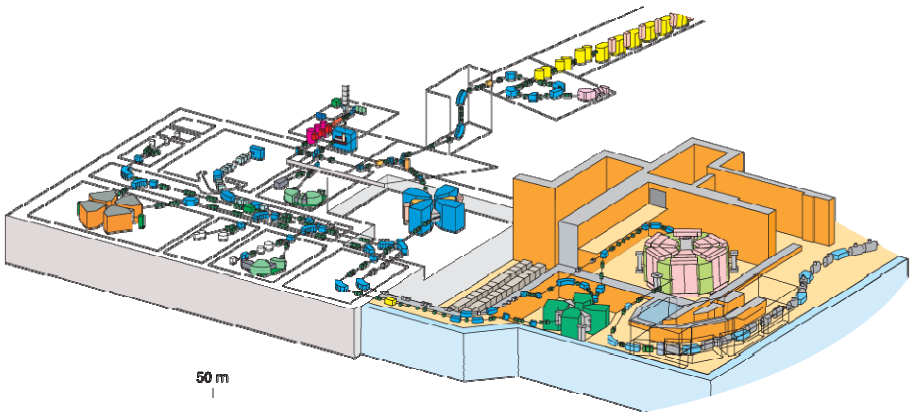

6.4~18 GHz — 18~28 GHz — 40~60 GHz

# ECRIS: as HCI beam injectors

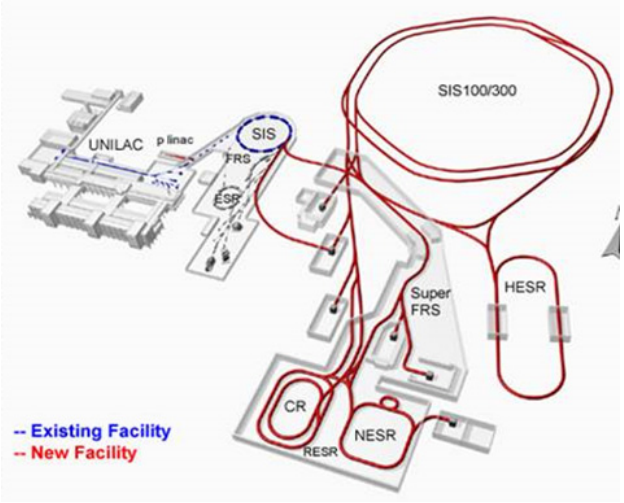
## Worldwide needs…



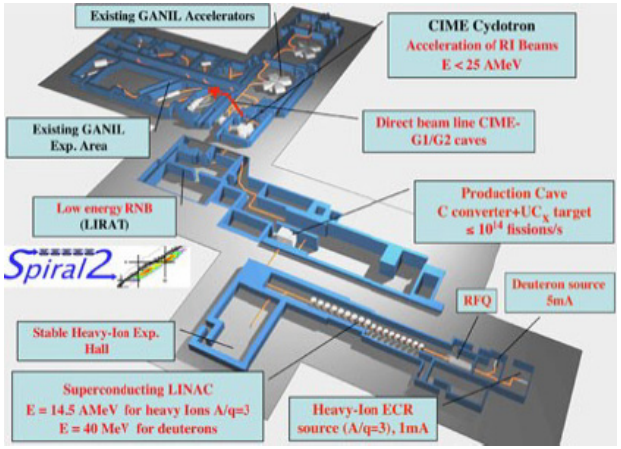

**MSU FRIB $U^{33+}$ + $U^{34+}$ 13 pμA/ CW**




**RIKEN RIBF $U^{35+}$ 15 pμA/ CW**

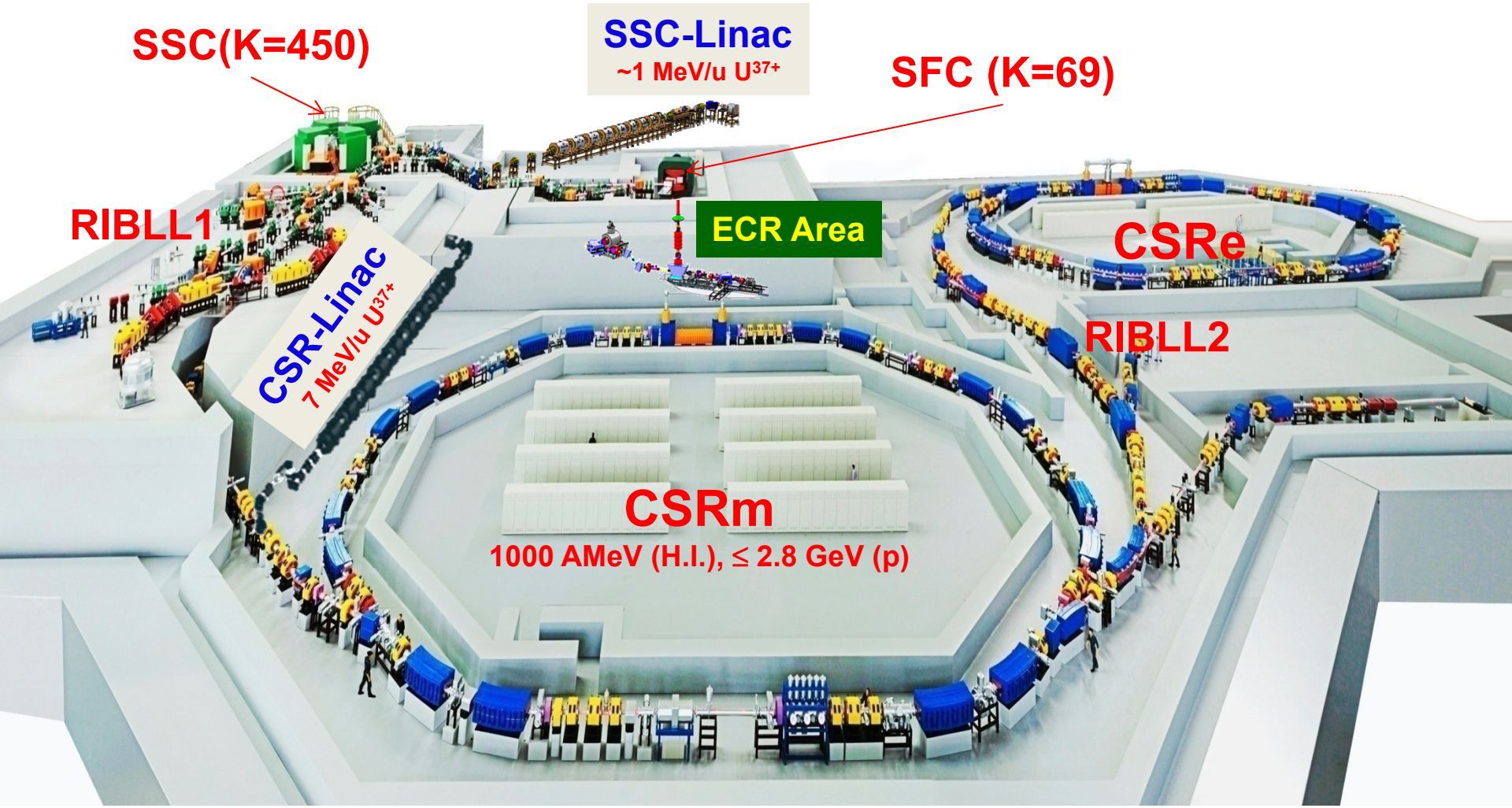



**GSI FAIR: intense HCI uranium beam**




**1.0 emA q/A=1/3 and intense heavy ion beams of q/A=1/6~1/7 (optional)**

# HCI Beam Production: HIRFL Introduction

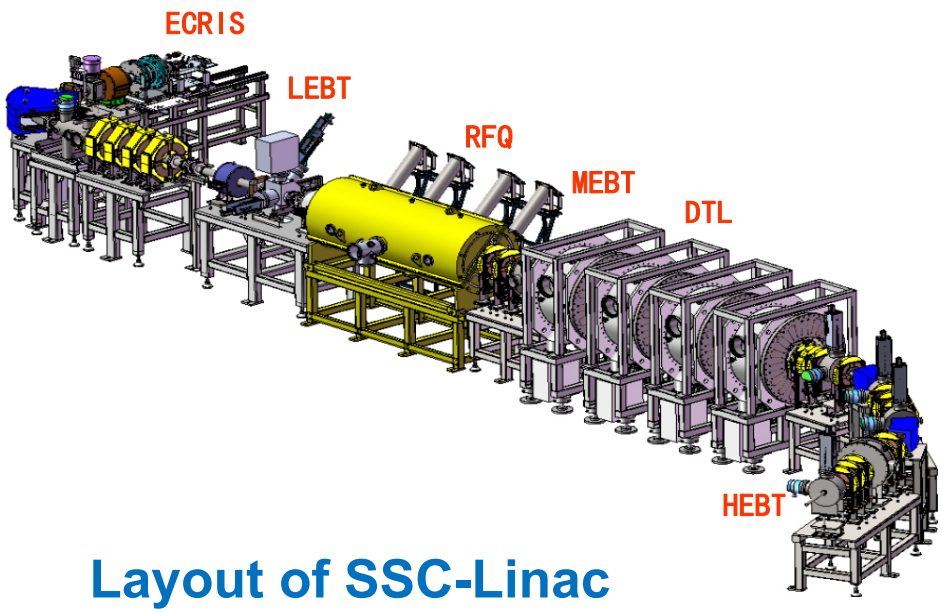



**Existing HIRFL**

# HCI Beam Production: SSC-Linac needs

**ECRIS:**

- **Intense heavy ion beams**
  - **A> 40**
- **High charge states**
  - **$Ni^{19+}$, $Bi^{36+}$, $U^{37+}$…**



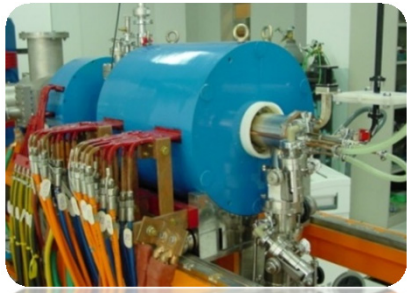

**Layout of SSC-Linac**

**Main parameters of SSC-Linac**

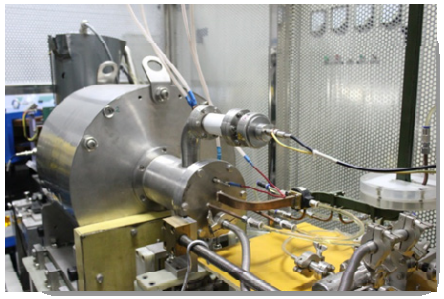
| Parameters | Values |
|---|---|
| **Designed ion** | $^{238}U^{34+}$ |
| **Preferred ion** | $^{238}U^{37+}$ |
| **RFQ** | 4-rod |
| Frequency | 53.667 MHz |
| Input energy | 3.728 keV/u |
| Output energy | 143 keV/u |
| Inter-electrode voltage | 70 kV |
| RF power | 35 kW |
| Max. current | 0.5 emA |
| **IH-DTL** | KONUS |
| Frequency | 53.667MHz |
| Input energy | 0.143 MeV/u |
| Output energy | 1.025 MeV/u |

# HCI Beam Production: HCI ECRISs at IMP

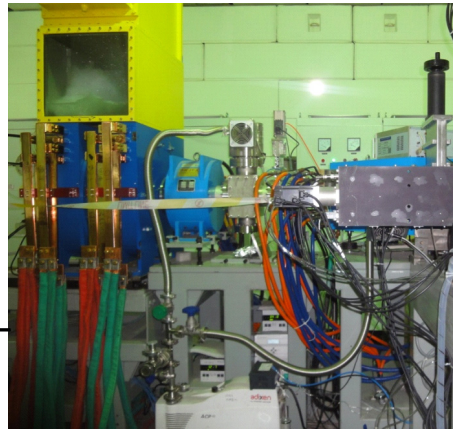
## HCI ECRIS Family @ IMP



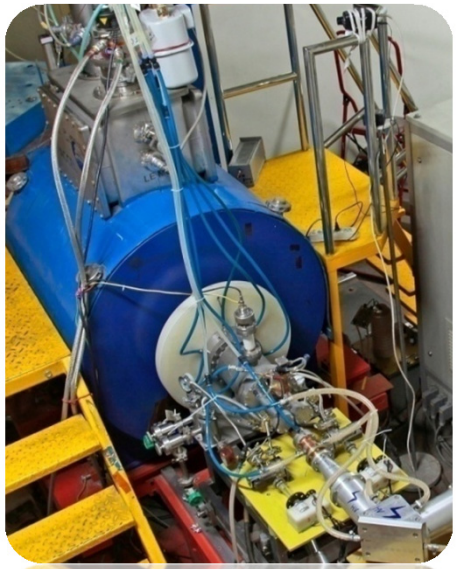
LECR3 1999-2002—



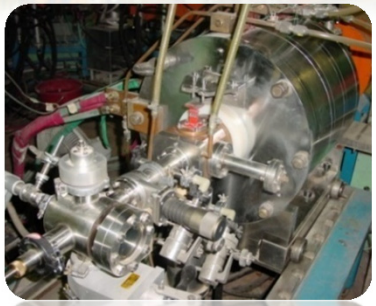
LAPECR3 2009-2012—



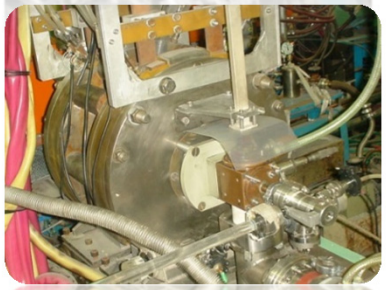
LECR4
2010-2014—



SECRAL
2002-2005—



LECR2 1996-1999—

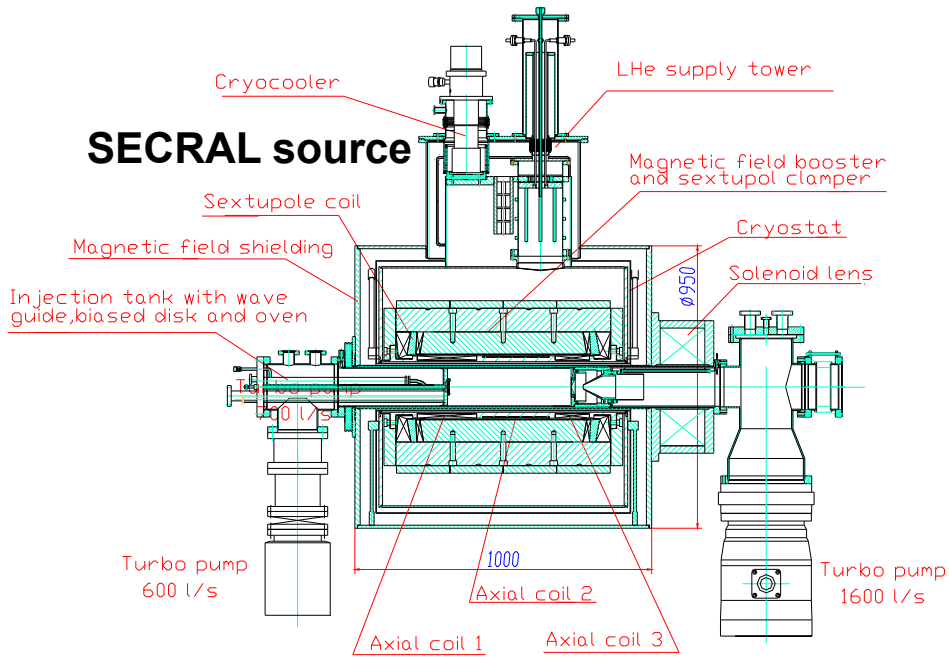


LECR1 1990-1995—

LAPECR2 2003-2006—

- Room temperature ECRIS
- Permanent magnet ECRIS
- Evaporative cooling ECRIS
- SC-ECRIS

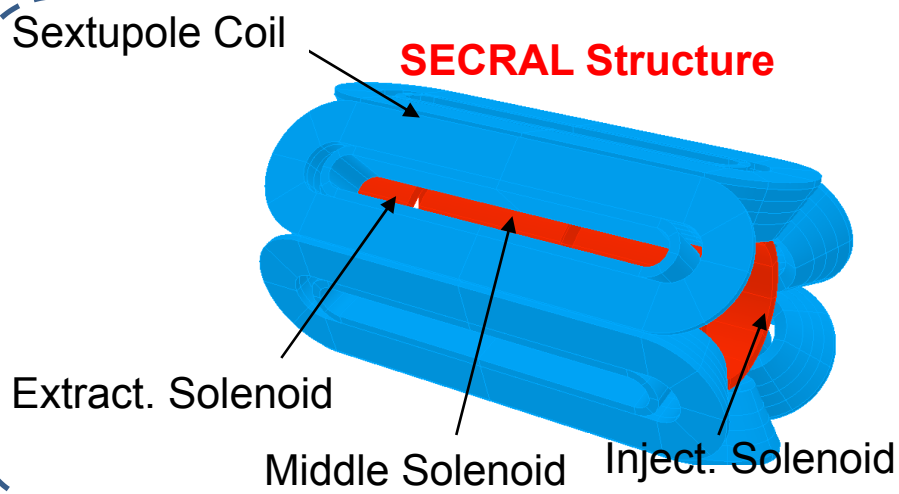
# HCI Beam Production: SECRAL Design

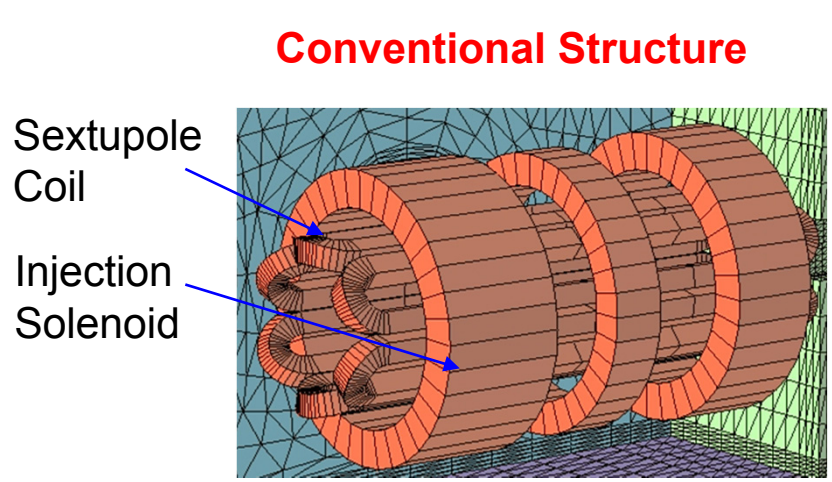



**SECRAL magnet**
**Unique Design with**
**Reversed structure**

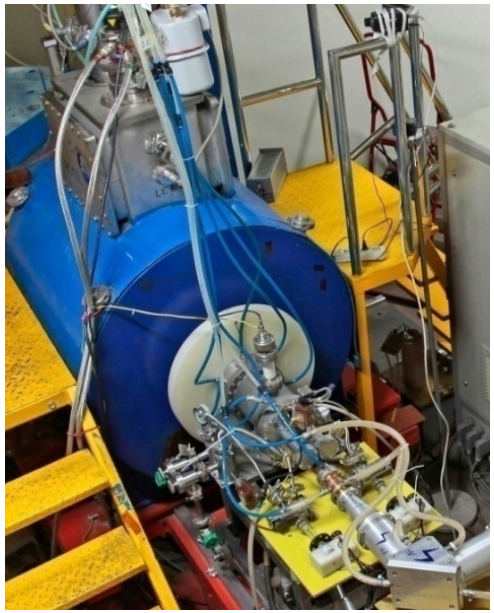
Advantages

- Lower/simpler interaction forces
- compact magnet size and cryostat
- Simpler fabrication and lower cost
- Low stray field



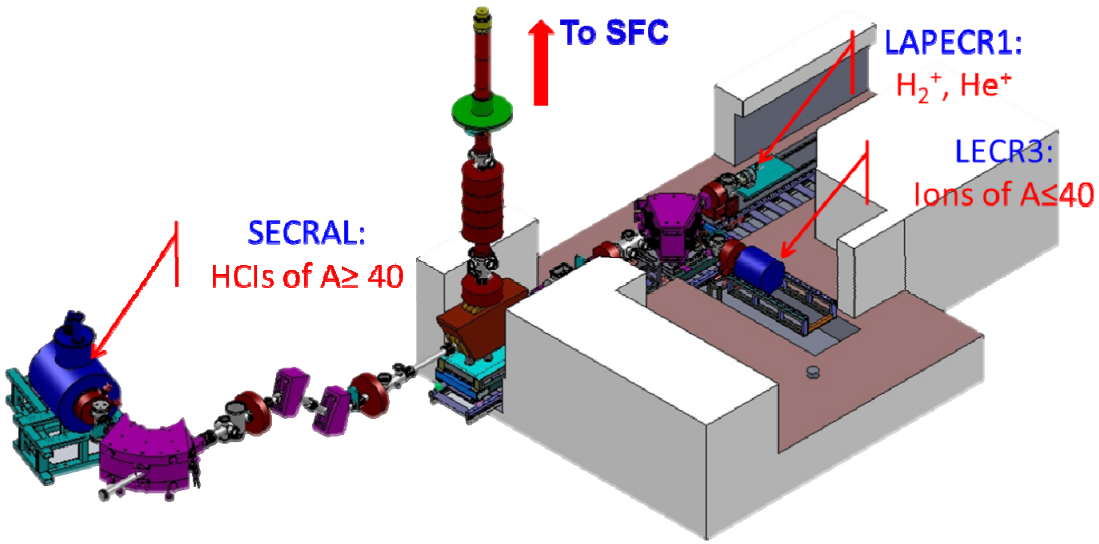
# HCI Beam Production: SECRAL Specs.



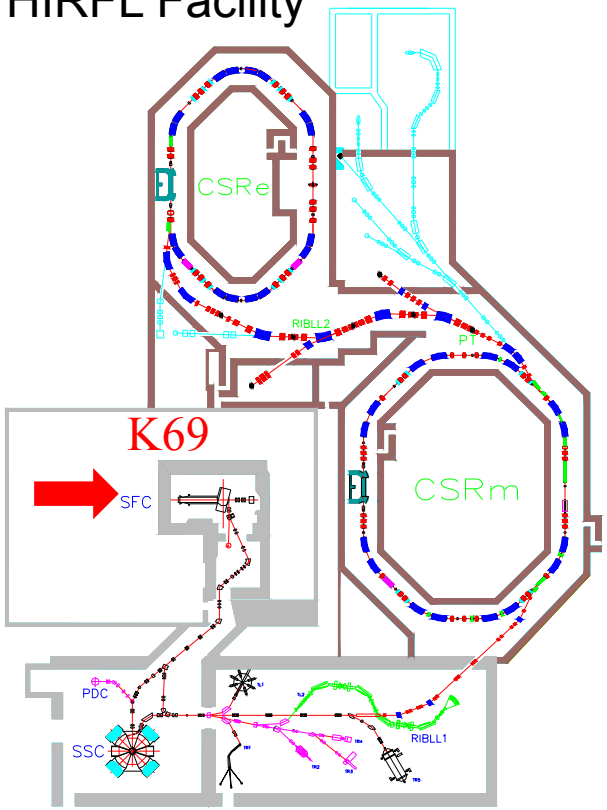
**SECRAL ion source**
**(since 2005)**

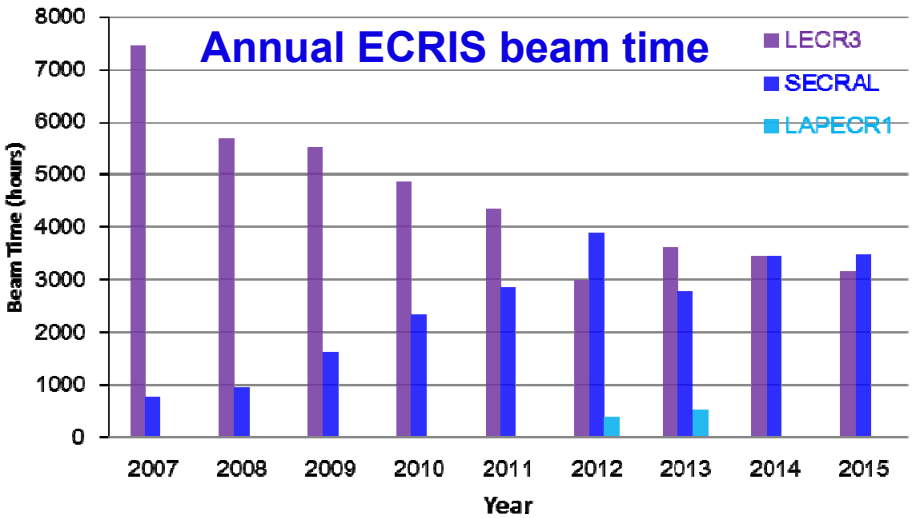
| Parameters | SECRAL |
|---|---|
| $\omega_{rf}$ (GHz) | 18-24 |
| Microwave power (kW) | 3 kW-18 GHz<br>7 kW-24 GHz |
| Axial Field Peaks (T) | 3.7 (Inj.), 2.2 (Ext.) |
| Mirror Length (mm) | 420 |
| No. of Axial SNs | 3 |
| $B_r$ at Chamber Inner Wall (T) | 1.7/ 1.83 |
| Coldmass Length (mm) | ~810 |
| SC-material | NbTi |
| Magnet Cooling | LHe bathing |
| Warm bore ID (mm) | 140.0 |
| Chamber ID (mm) | 116.0/120.5 |
| 4.2 K cooling power with external recondenser (W) | ~1.5 |

# HCI Beam Production: SECRAL Status




HIRFL Facility




- Averagely 7,000 hours beam time from all ECRISs
- Total beam time of SECRAL up to 25,000 hours as of summer 2016

# HCI Beam Production: SECRAL Status

## Beam List for HIRFL

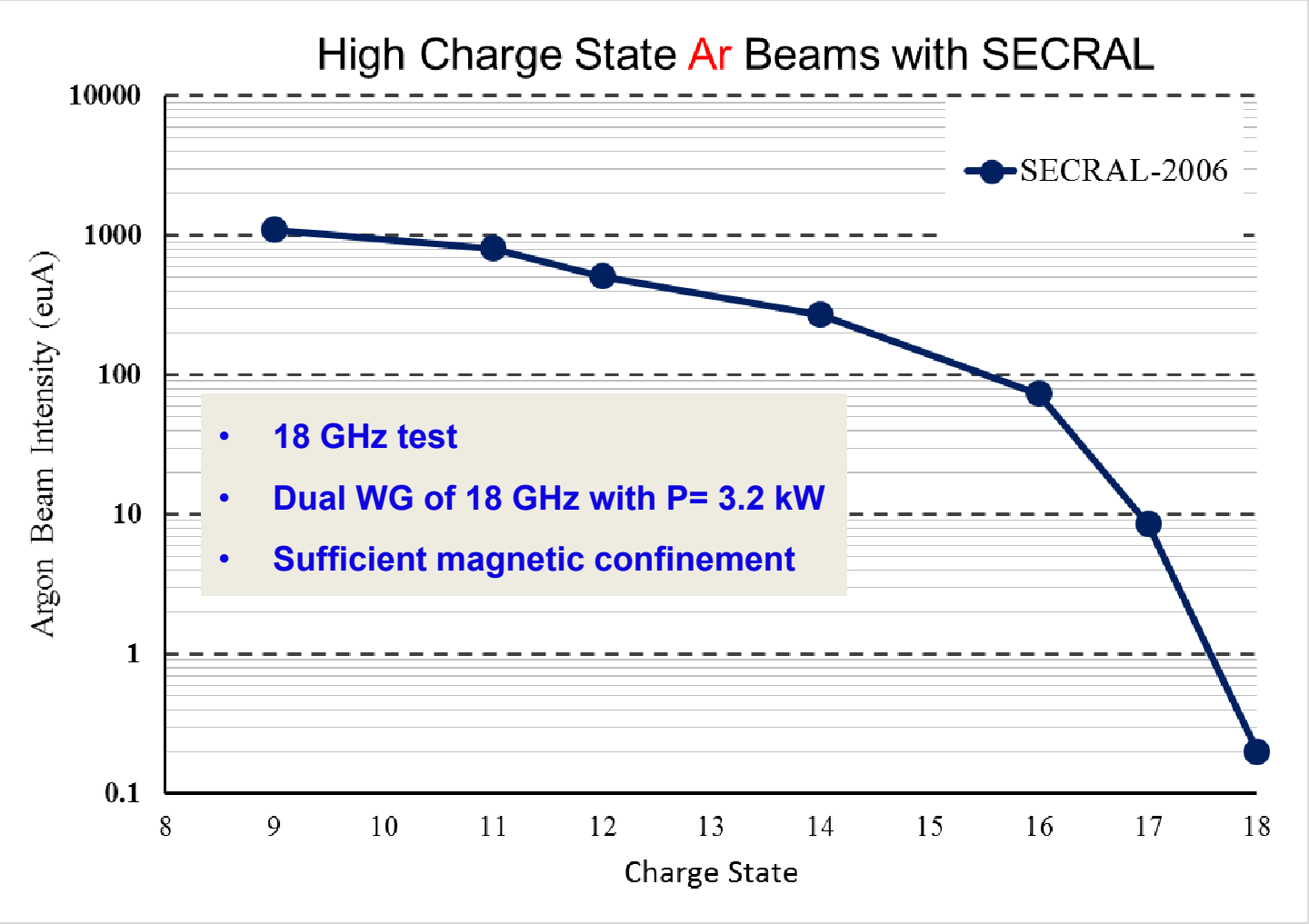
Beams Delivered for HIRFL

Beams Available

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| hydrogen 1 H 1.0079 | | | | | | | | | | | | | | | | | | helium 2 He 4.0026 |
| lithium 3 Li 6.941 | beryllium 4 Be 9.0122 | | | | | | | | | | | | boron 5 B 10.811 | carbon 6 C 12.011 | nitrogen 7 N 14.007 | oxygen 8 O 15.999 | fluorine 9 F 18.998 | neon 10 Ne 20.180 |
| sodium 11 Na 22.989 | magnesium 12 Mg 24.305 | | | | | | | | | | | | aluminium 13 Al 26.982 | silicon 14 Si 28.086 | phosphorus 15 P 30.974 | sulfur 16 S 32.065 | chlorine 17 Cl 35.453 | argon 18 Ar 39.948 |
| potassium 19 K 39.098 | calcium 20 Ca 40.078 | | scandium 21 Sc 44.956 | titanium 22 Ti 47.867 | vanadium 23 V 50.942 | chromium 24 Cr 51.996 | manganese 25 Mn 54.938 | iron 26 Fe 55.845 | cobalt 27 Co 58.933 | nickel 28 Ni 58.693 | copper 29 Cu 63.546 | zinc 30 Zn 65.39 | gallium 31 Ga 69.723 | germanium 32 Ge 72.61 | arsenic 33 As 74.922 | selenium 34 Se 78.96 | bromine 35 Br 79.904 | krypton 36 Kr 83.80 |
| rubidium 37 Rb 85.468 | strontium 38 Sr 87.62 | | yttrium 39 Y 88.906 | zirconium 40 Zr 91.224 | niobium 41 Nb 92.906 | molybdenum 42 Mo 95.94 | technetium 43 Tc [98] | ruthenium 44 Ru 101.07 | rhodium 45 Rh 102.91 | palladium 46 Pd 106.42 | silver 47 Ag 107.87 | cadmium 48 Cd 112.41 | indium 49 In 114.82 | tin 50 Sn 118.71 | antimony 51 Sb 121.76 | tellurium 52 Te 127.60 | iodine 53 I 126.90 | xenon 54 Xe 131.29 |
| caesium 55 Cs 132.91 | barium 56 Ba 137.33 | 57-70 * | lutetium 71 Lu 174.97 | hafnium 72 Hf 178.49 | tantalum 73 Ta 180.95 | tungsten 74 W 183.84 | rhenium 75 Re 186.21 | osmium 76 Os 190.23 | iridium 77 Ir 192.22 | platinum 78 Pt 195.08 | gold 79 Au 196.97 | mercury 80 Hg 200.59 | thallium 81 Tl 204.38 | lead 82 Pb 207.2 | bismuth 83 Bi 208.98 | polonium 84 Po [209] | astatine 85 At [210] | radon 86 Rn [222] |
| francium 87 Fr [223] | radium 88 Ra [226] | 89-102 * * | lawrencium 103 Lr [262] | rutherfordium 104 Rf [261] | dubnium 105 Db [262] | seaborgium 106 Sg [266] | bohrium 107 Bh [264] | hassium 108 Hs [269] | meitnerium 109 Mt [268] | ununnilium 110 Uun [271] | unununium 111 Uuu [272] | ununbium 112 Uub [277] | | ununquadium 114 Uuq [289] | | | | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Lanthanide series | lanthanum 57 La 138.91 | cerium 58 Ce 140.12 | praseodymium 59 Pr 140.91 | neodymium 60 Nd 144.24 | promethium 61 Pm [145] | samarium 62 Sm 150.36 | europium 63 Eu 151.96 | gadolinium 64 Gd 157.25 | terbium 65 Tb 158.93 | dysprosium 66 Dy 162.50 | holmium 67 Ho 164.93 | erbium 68 Er 167.26 | thulium 69 Tm 168.93 | ytterbium 70 Yb 173.04 |
| **Actinide series | actinium 89 Ac [227] | thorium 90 Th 232.04 | protactinium 91 Pa 231.04 | uranium 92 U 238.03 | neptunium 93 Np [237] | plutonium 94 Pu [244] | americium 95 Am [243] | curium 96 Cm [247] | berkelium 97 Bk [247] | californium 98 Cf [251] | einsteinium 99 Es [252] | fermium 100 Fm [257] | mendelevium 101 Md [258] | nobelium 102 No [259] |

# HCI Beam Production: SECRAL Status



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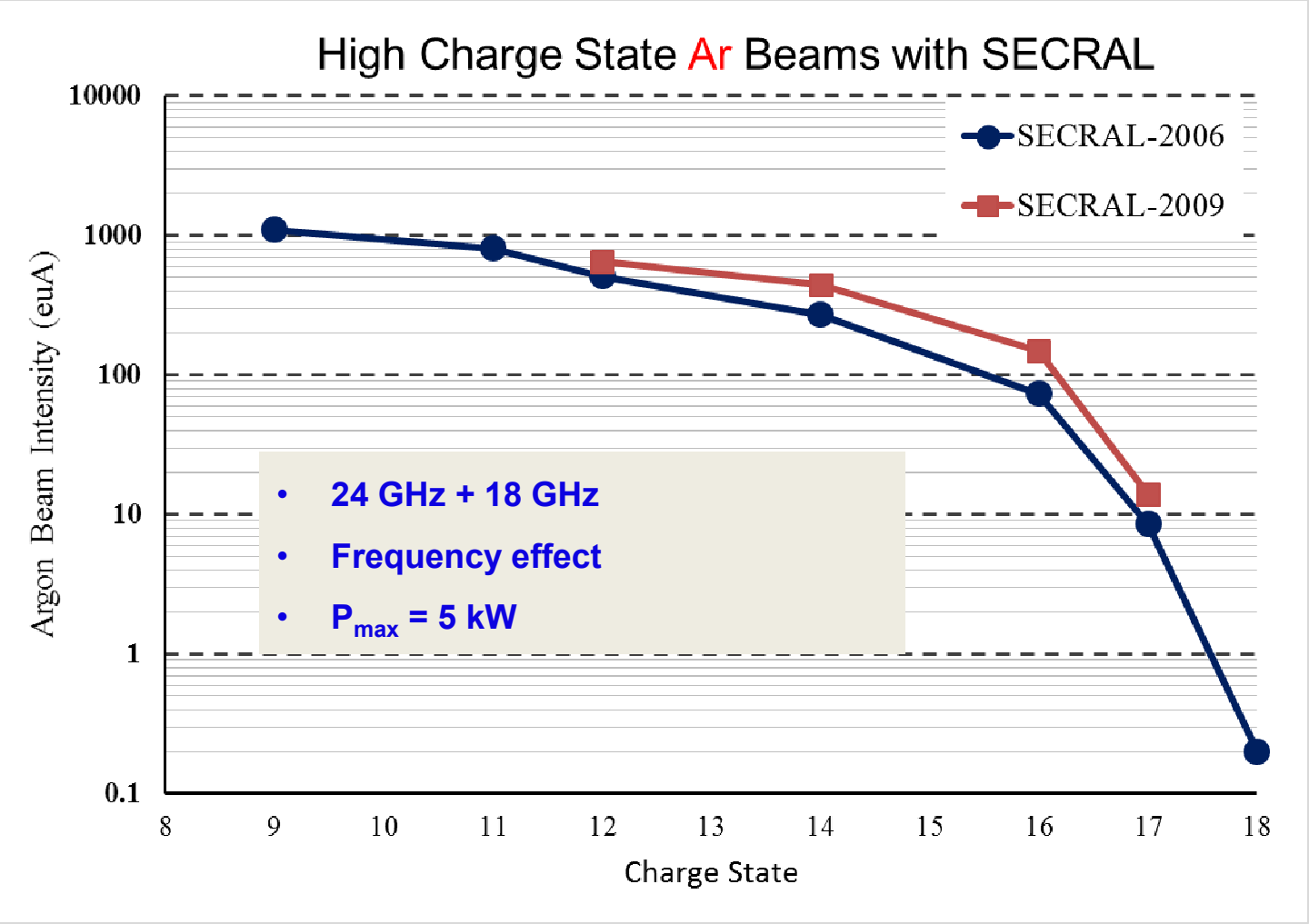

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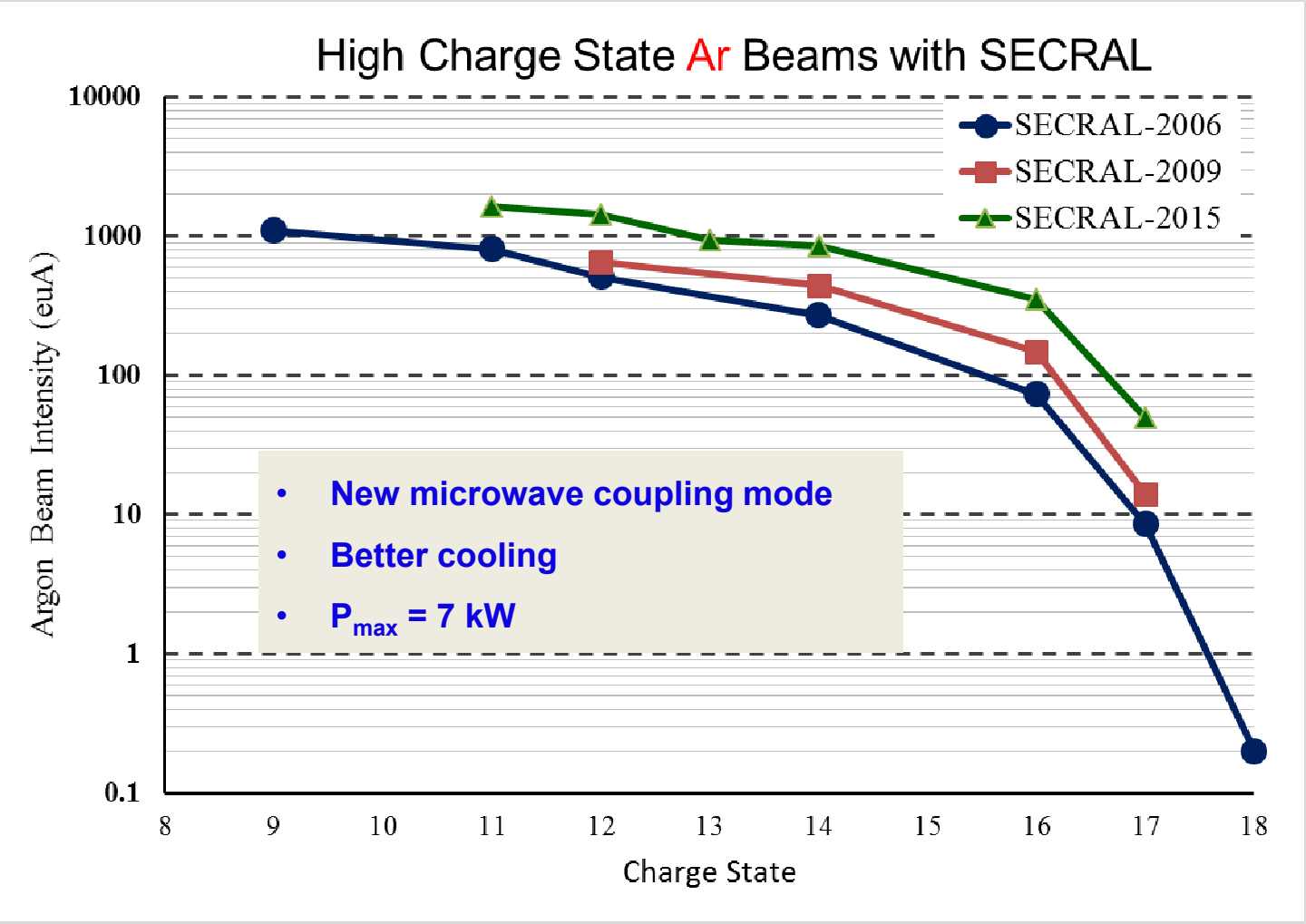
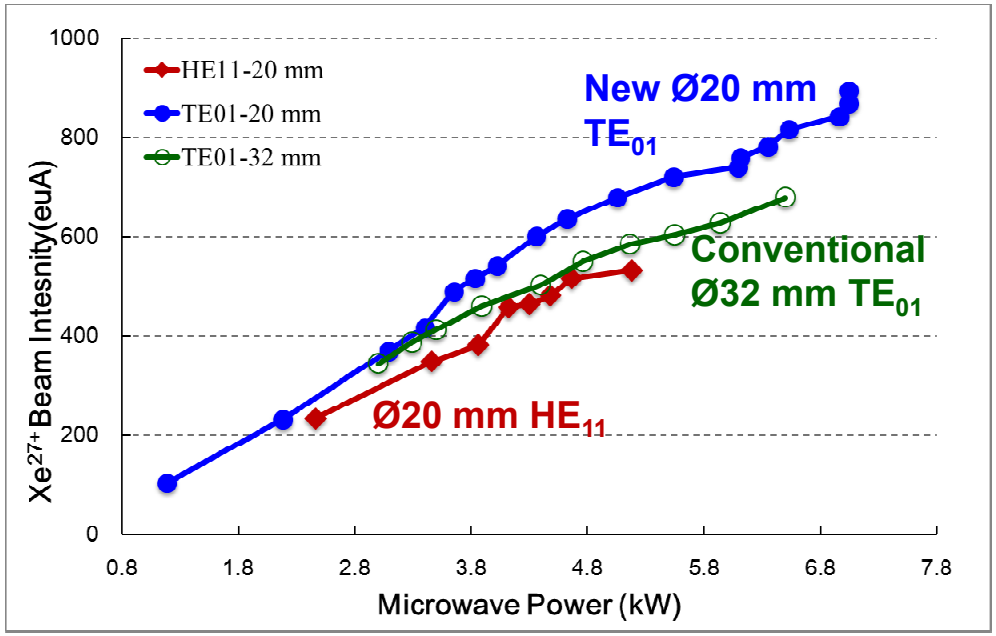
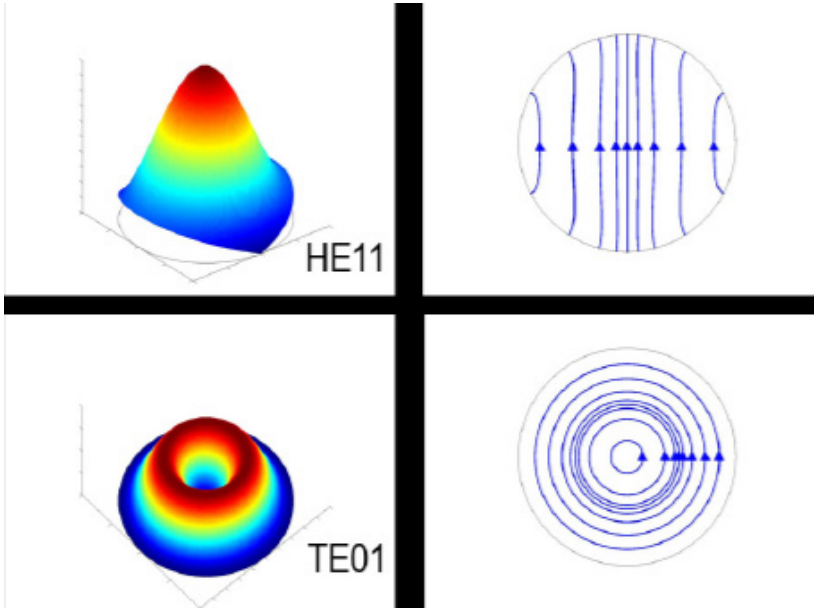


# HCI Beam Production: SECRAL Status

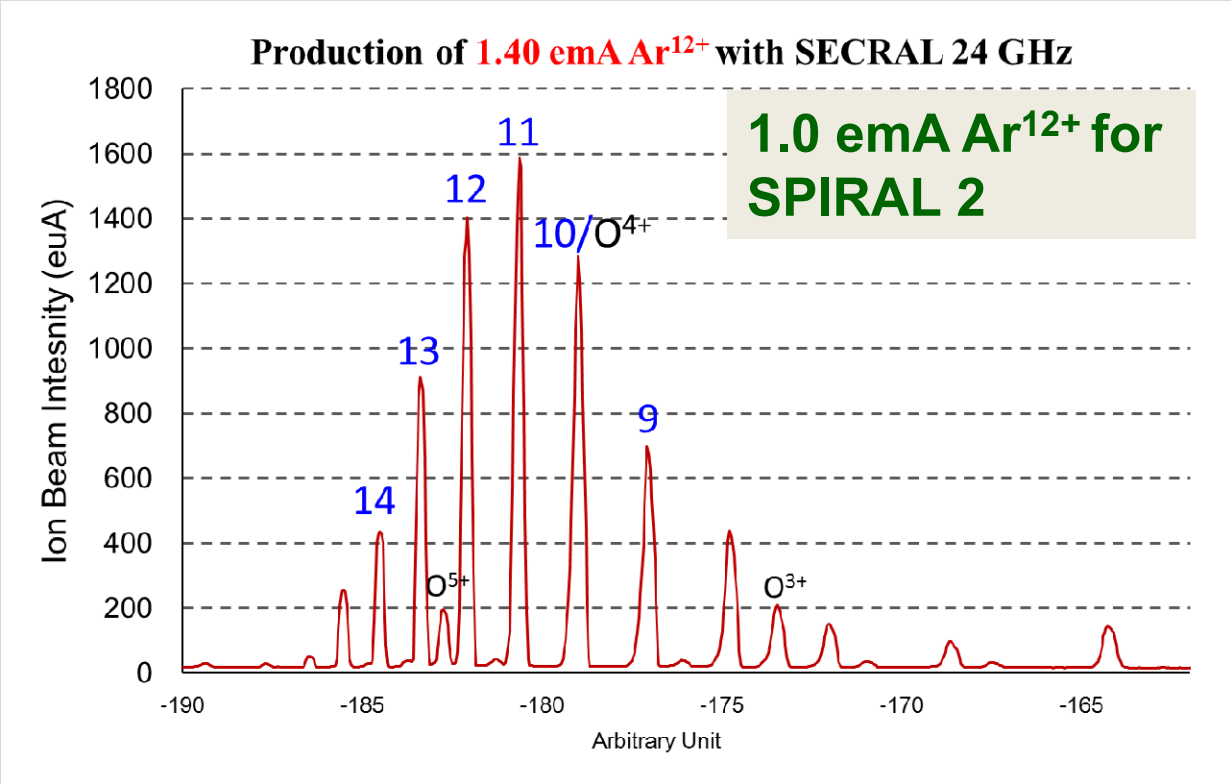



J. W. Guo, MOEO01, ECRIS'16

- Better microwave coupling efficiency
- Higher ECRH efficiency in terms of HCI production

# HCI Beam Production: SECRAL Status




| Ion | *Intensity (euA) |
|---|---|
| $Ar^{11+}$ | 1620 |
| $Ar^{12+}$ | 1420 |
| $Ar^{13+}$ | 930 |
| $Ar^{14+}$ | 846 |
| $Ar^{16+}$ | 350 |
| $Ar^{17+}$ | 50 |
| $Xe^{26+}$ | 1100 |
| $Xe^{27+}$ | 920 |
| $Xe^{30+}$ | 322 |
| $Xe^{34+}$ | 90 |

**Recent test of tapered waveguide Ø20 mm with VENUS/LBNL gave very promising performance improvement, see D. Xie, THAO01, ECRIS'16**

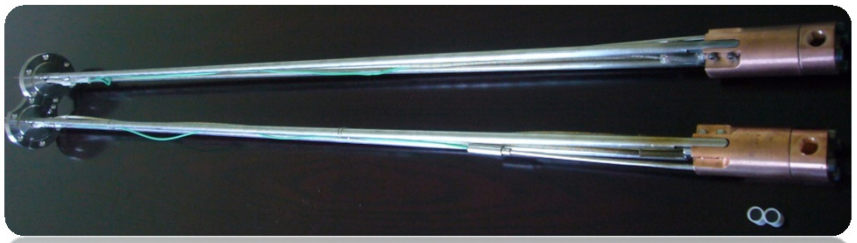
***Based on Ø20 mm $TE_{01}$**

L. Sun, R.S.I. 87, 02A707 (2016)

# HCI Beam Production: Metallic ion beams

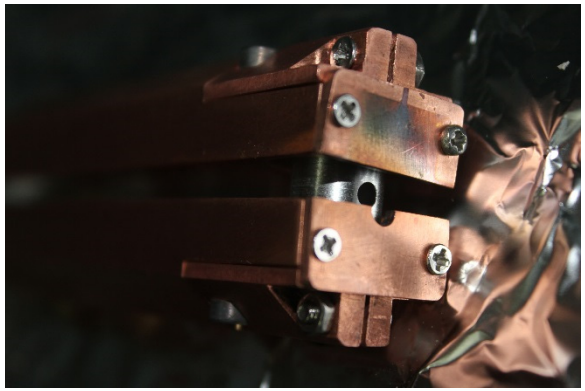
Resister oven
(500℃- 1500℃)

- Matured technique
- Low loading capacity
- ~100 euA metal ion beams



Cartridge Heater oven
(100℃- 700℃)

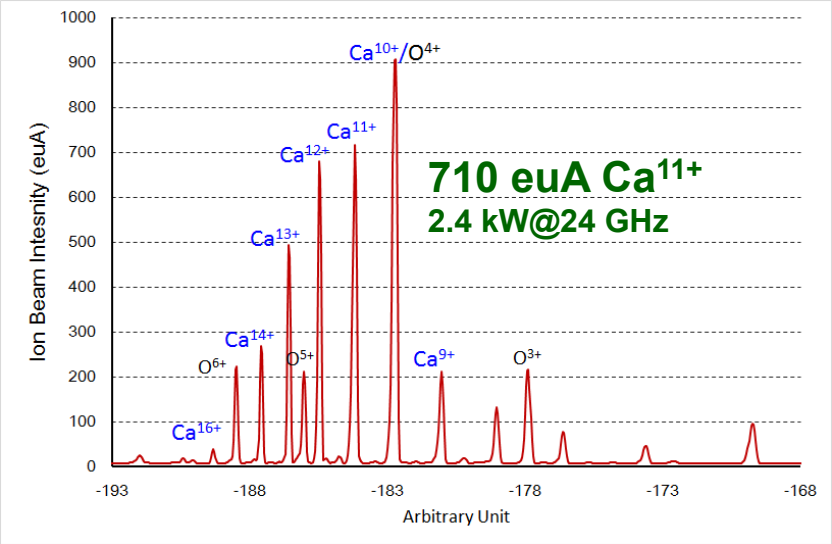
- Allows precise control
- High loading capacity
- Good for emA metal ion beams

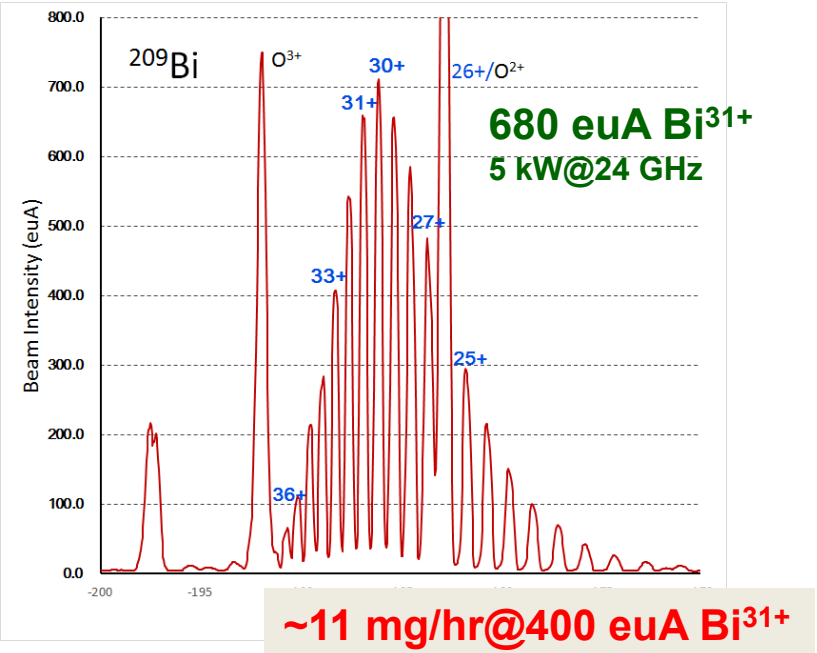


High Temp. oven
(500℃- 1900℃)

- For ion beams of very refractory metals, i.e. U
- High loading capacity
- Limited operation life span
- Under R&D phase

# HCI Beam Production: Metallic ion beams



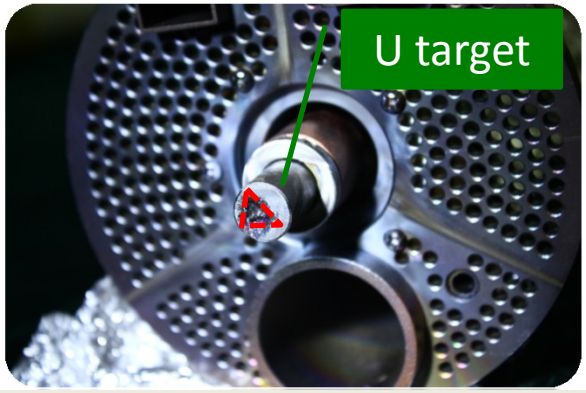




**~11 mg/hr@400 euA $Bi^{31+}$**

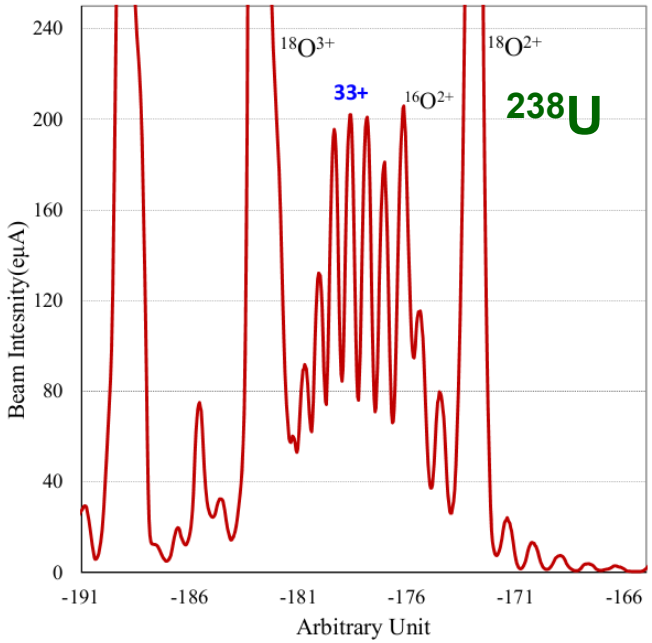
| | Q | I (euA) |
|---|---|---|
| Bi | 30 | 710 |
| | 31 | 680 |
| | 32 | 610 |
| | 33 | 500 |
| | 34 | 424 |
| | 36 | 320 |
| | 38 | 160 |
| | 41 | 100 |
| | 45 | 49 |
| | 48 | 16.6 |
| | 50 | 10.7 |
| | 51 | 7 |
| | 54 | 3.4 |
| Ca | 11 | 710 |
| | 12 | 670 |
| | 13 | 480 |
| | 14 | 270 |

L. Sun, R.S.I. 87, 02A707 (2016)

# HCI Beam Production: Refractory metallic ion beams



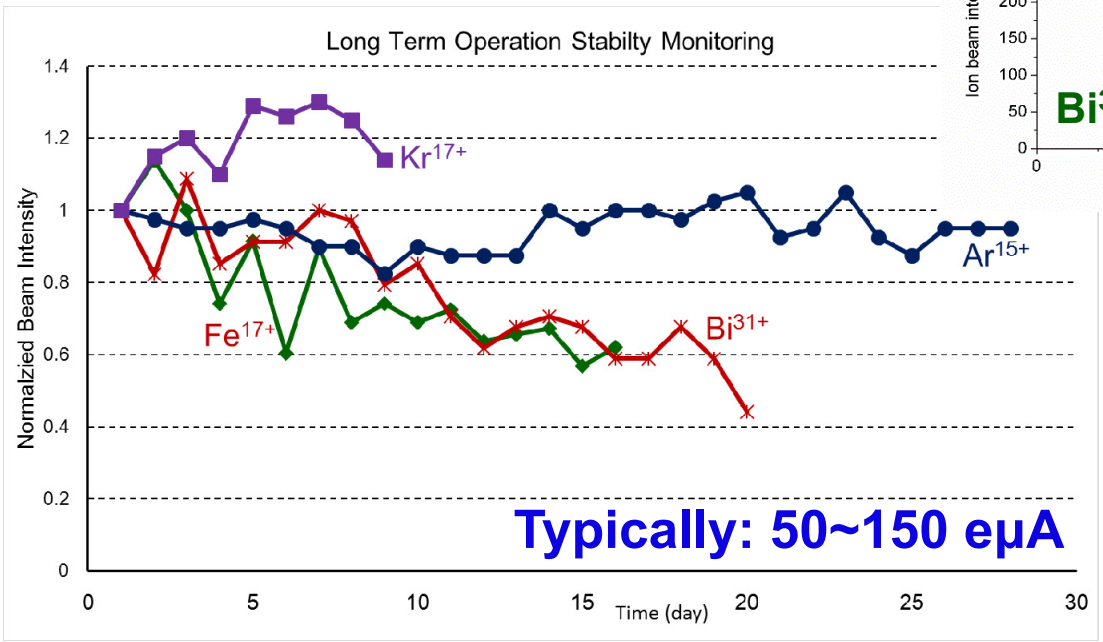

**Sputtering method for intense U beams**

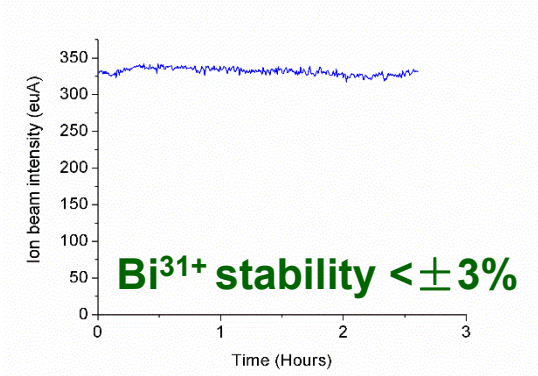



**For more reliable intense U ion beams:**

- **Resister HTO oven**
- **Inductive heating oven**
- **Electron beam heating oven**
- **Laser ablation tech.**

# HCI Beam Production: Metallic ion beams



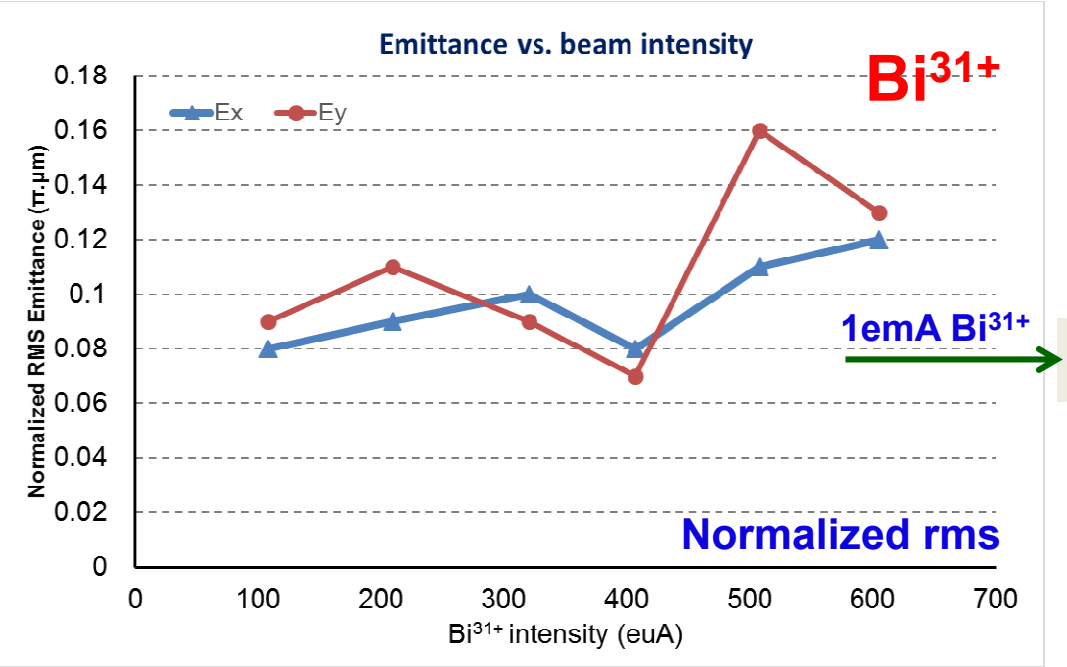

## Gaseous beams:

- Fairly reasonable stabilities

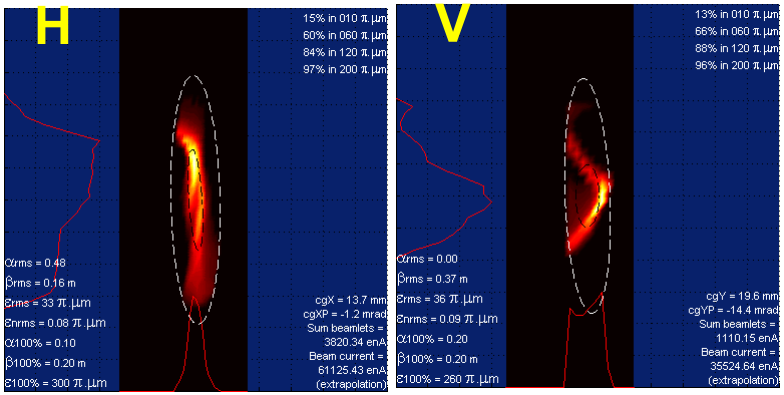
## Metal beams:

- Source conditioning
- Oven stability
- Material dissipation
- On-call tuning

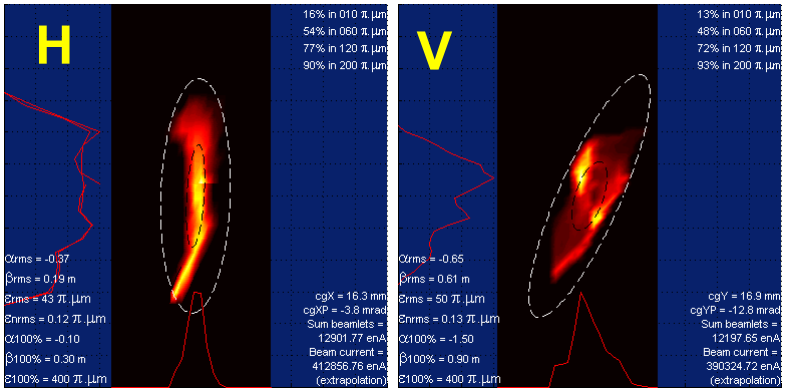
# HCI Beam Production: Intense HCI beam quality




~0.2 π.mm.mrad



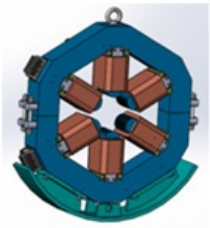

100 eμA $Bi^{31+}$



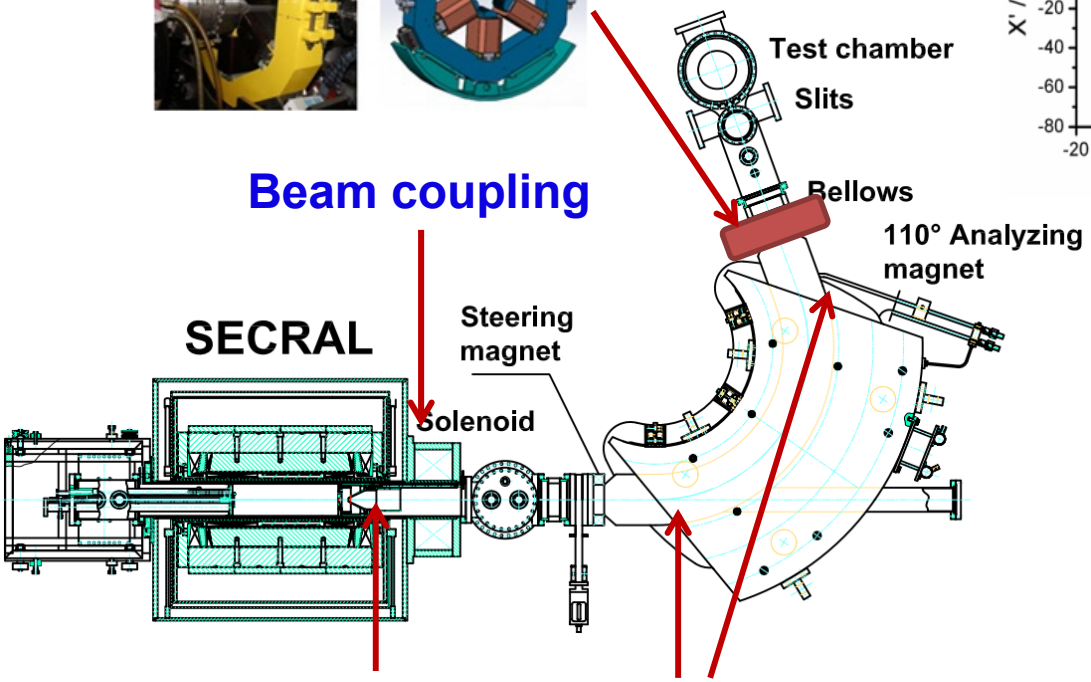

600 eμA $Bi^{31+}$

# HCI Beam Production: Intense HCI beam quality

**High order aberration compensation**



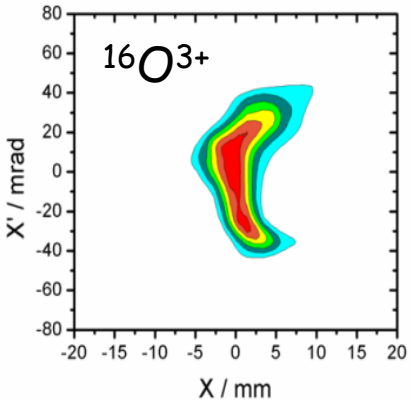
**Beam coupling**



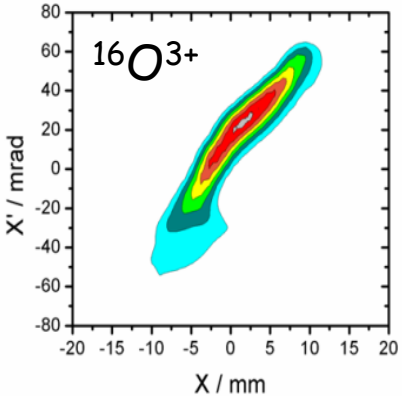

**High order aberration**

**High order aberration**

**Before compensation**




**After compensation**




## Conclusions:

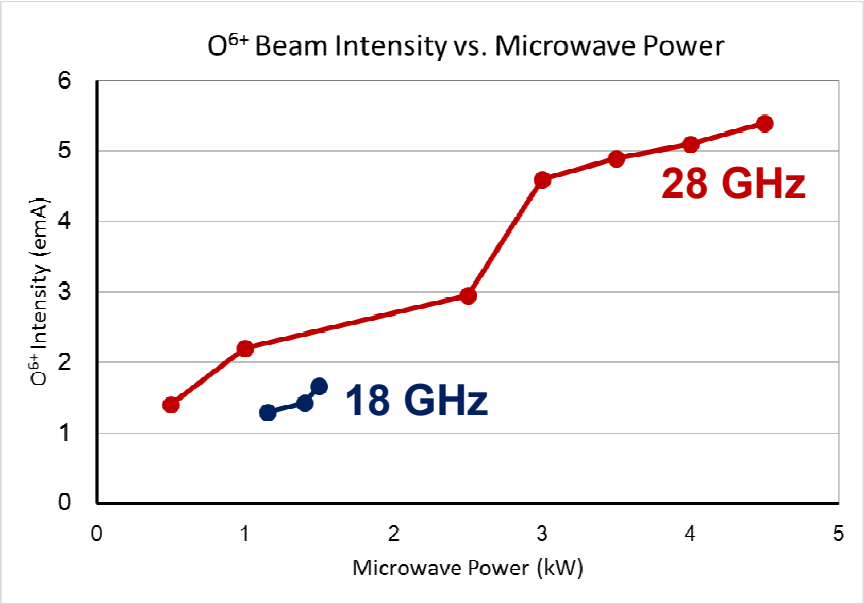
- Ion beams from high charge state ECRIS are transversely coupled
- High order aberration mostly comes from sextupole component of ion source
- High order aberration can be compensated

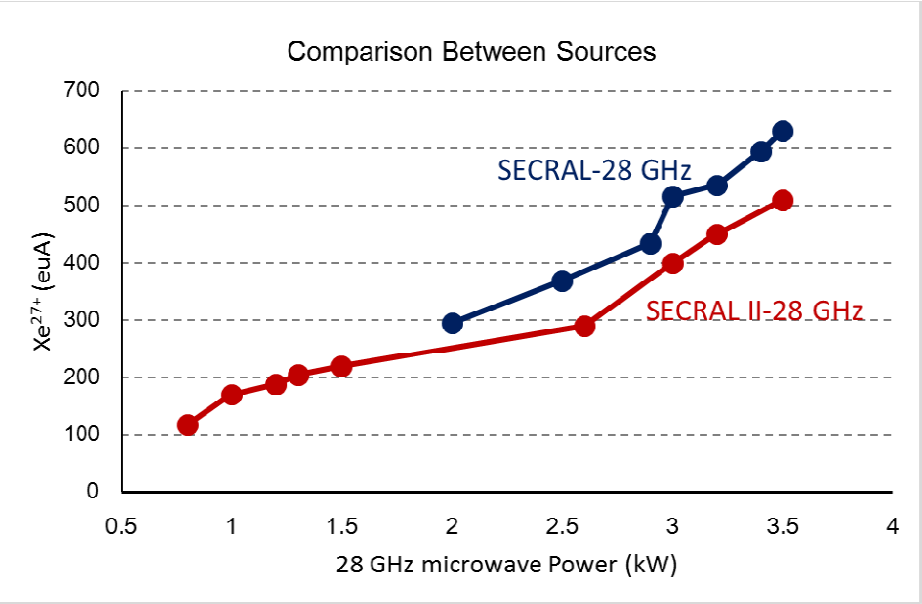
# SECRAL II: Magnet Design

| Parameters | SECRAL II | SECRAL |
|---|---|---|
| $\omega_{rf}$ (GHz) | 18-28 | 18-24 |
| Axial Field Peaks (T) | 3.7 (Inj.), 2.2 (Ext.) | 3.7 (Inj.), 2.2 (Ext.) |
| Mirror Length (mm) | 420 | 420 |
| No. of Axial SNs | 3 | 3 |
| $B_r$ at Chamber Inner Wall (T) | 2.0 | 1.7/ 1.83 |
| Coldmass Length (mm) | ~810 | ~810 |
| SC-material | NbTi | NbTi |
| Magnet Cooling | LHe bathing | LHe bathing |
| Warm bore ID (mm) | ~142 .0 | 140.0 |
| Chamber ID (mm) | 125.0 | 116.0/120.5 |
| Dynamic cooling power (W) | ~5 | 0 |

# SECRAL II: Test Bench Layout

# Beam Commissioning: Oxygen & Xenon



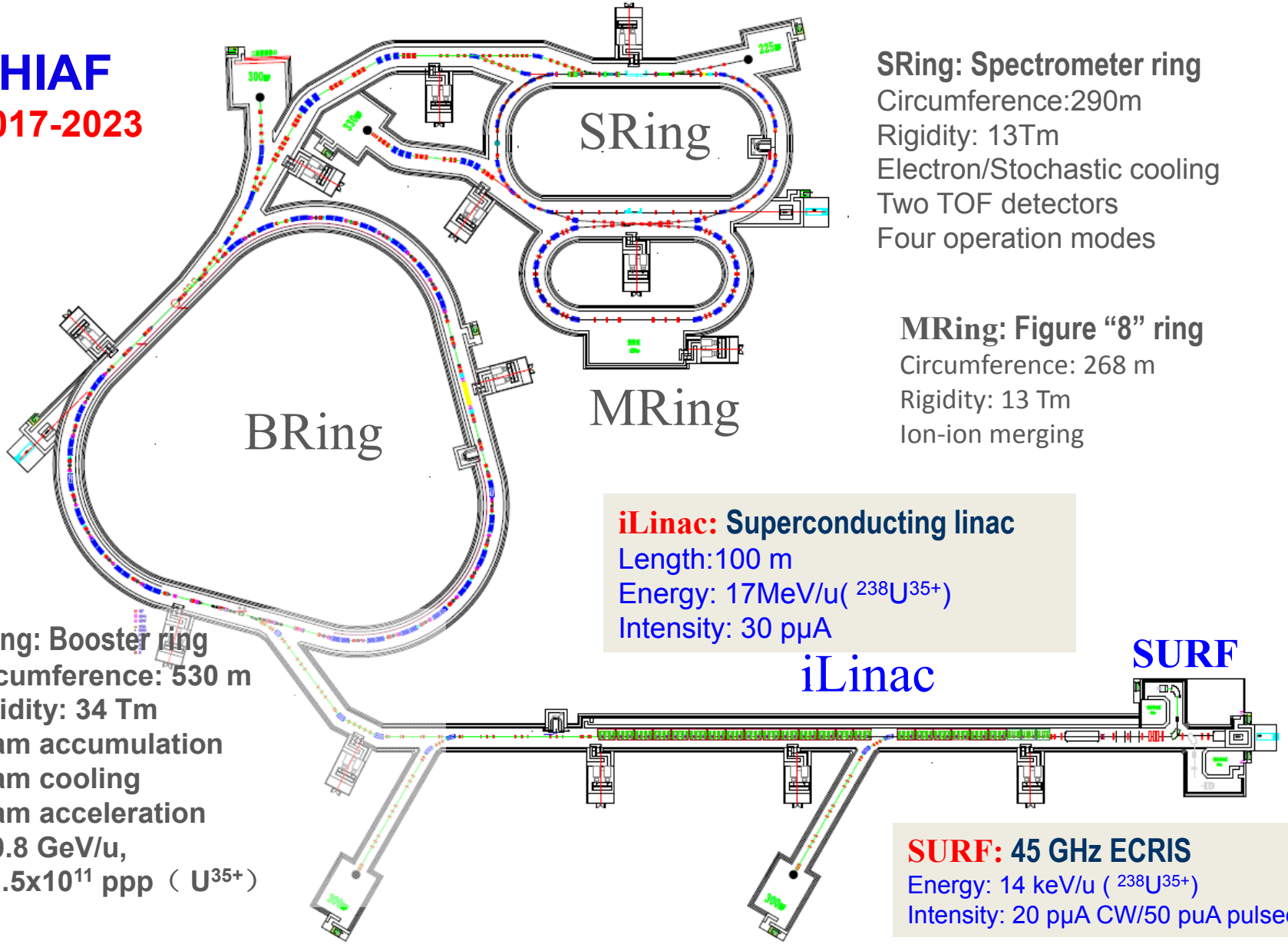




| Ion | $P_{28\ GHz}$ (kW) | $I_{drain}$ (emA) | $I_q$ (emA) |
|---|---|---|---|
| $O^{6+}$ | 4.5 | 20.0 | 5.4 |
| $O^{7+}$ | 3.5 | 13.0 | 1.57 |
| $Xe^{27+}$ | 3.5 | 8.0 | 0.51 |

- **Total beam transmission efficiency is 84% for 1.8 emA $O^{6+}$/8.0 emA drain current, and 86% for 450 euA $Xe^{27+}$/7.0 emA drain current**
- **~10 days conditioning to produce 510 euA $Xe^{27+}$**

# Scope: Future development

**HIAF**
**2017-2023**




**SRing: Spectrometer ring**
Circumference:290m
Rigidity: 13Tm
Electron/Stochastic cooling
Two TOF detectors
Four operation modes

**MRing: Figure "8" ring**
Circumference: 268 m
Rigidity: 13 Tm
Ion-ion merging

**iLinac: Superconducting linac**
Length:100 m
Energy: 17MeV/u( $^{238}U^{35+}$)
Intensity: 30 pμA

**BRing: Booster ring**
**Circumference: 530 m**
**Rigidity: 34 Tm**
**Beam accumulation**
**Beam cooling**
**Beam acceleration**
**E=0.8 GeV/u,**
**I= 1.5x10$^{11}$ ppp（ $U^{35+}$）**

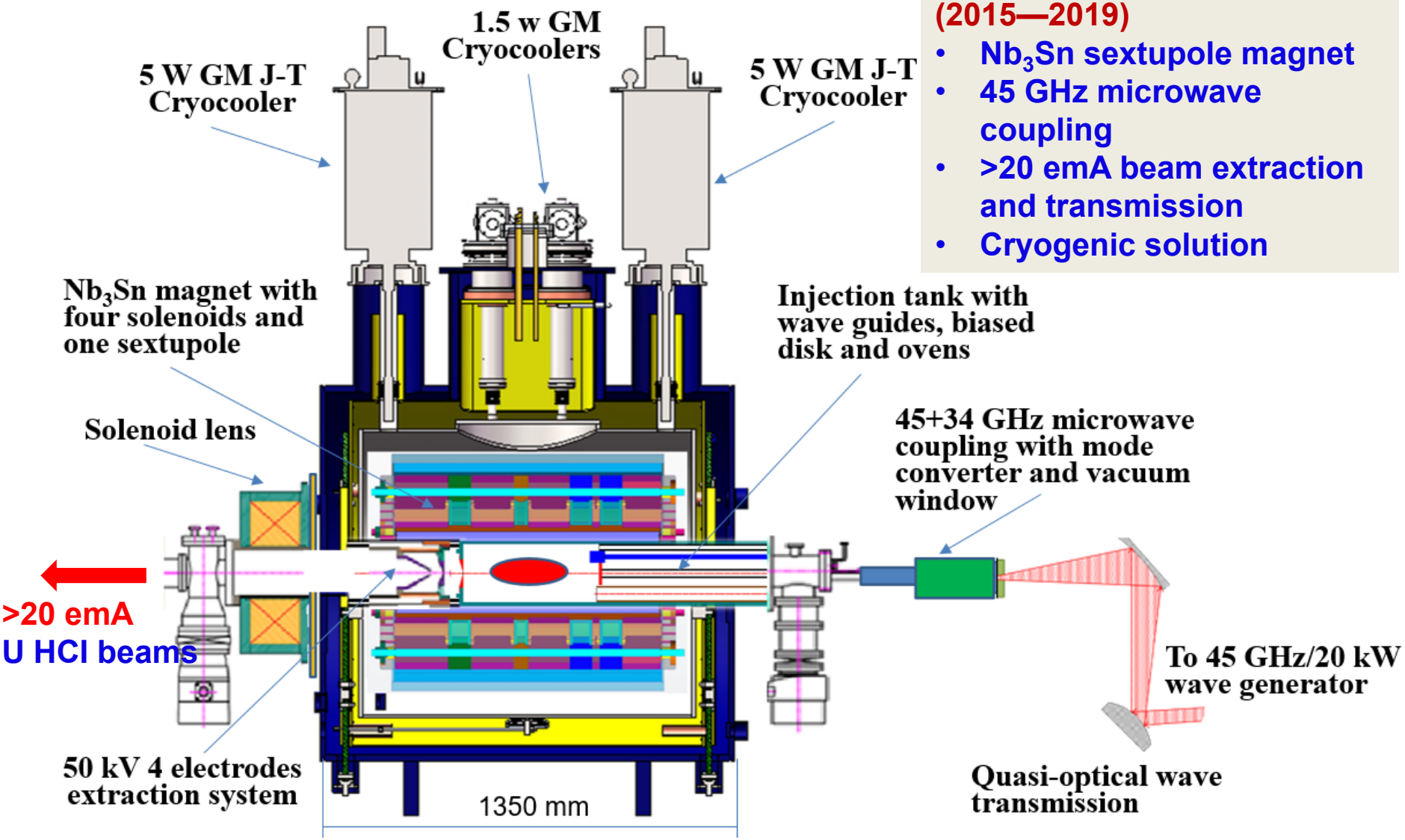
**SURF: 45 GHz ECRIS**
Energy: 14 keV/u ( $^{238}U^{35+}$)
Intensity: 20 pμA CW/50 puA pulsed

# Scope: Future development

H. W. Zhao, MOBO01, ECRIS'16

**Challenges: (2015—2019)**

- $Nb_3Sn$ sextupole magnet
- 45 GHz microwave coupling
- >20 emA beam extraction and transmission
- Cryogenic solution



# Summary

- State of the art ECRISs can produce HCI beams of emA currents
- High performance SC-ECR ion sources are reproduceable
- Challenges lie in the production of high current, high quality reliable metallic ion beams
- 4th generation ECRIS is under development for next generation heavy ion Linacs

Thanks for your attention

谢谢！