High Intensity Operation for Heavy Ion Cyclotron of Highly Charged ECR Ion Sources

L Sun

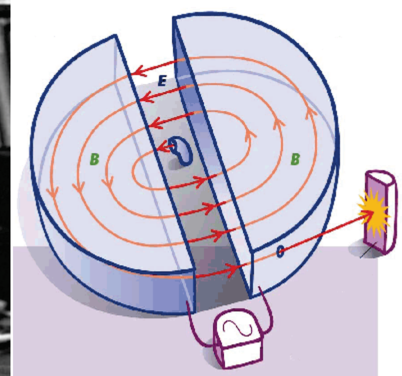
Institute of Modern Physics, CAS

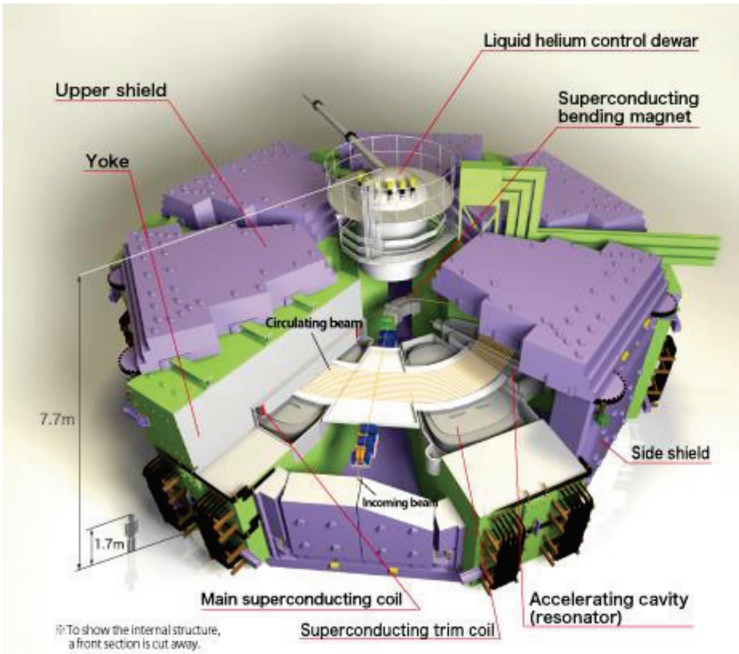
Outline

- Cyclotron and ECRIS
- HCI ECRISs operation status in several typical labs
  - GANIL
  - LNS/INFN
  - LBNL: 88-Inch
  - MSU: CCF in NSCL
  - RIKEN: RIBF
  - IMP: HIRFL
- The features and importance of ECRISs
- Summary

From Cyclotron to ECRIS

Ernest O. Lawrence

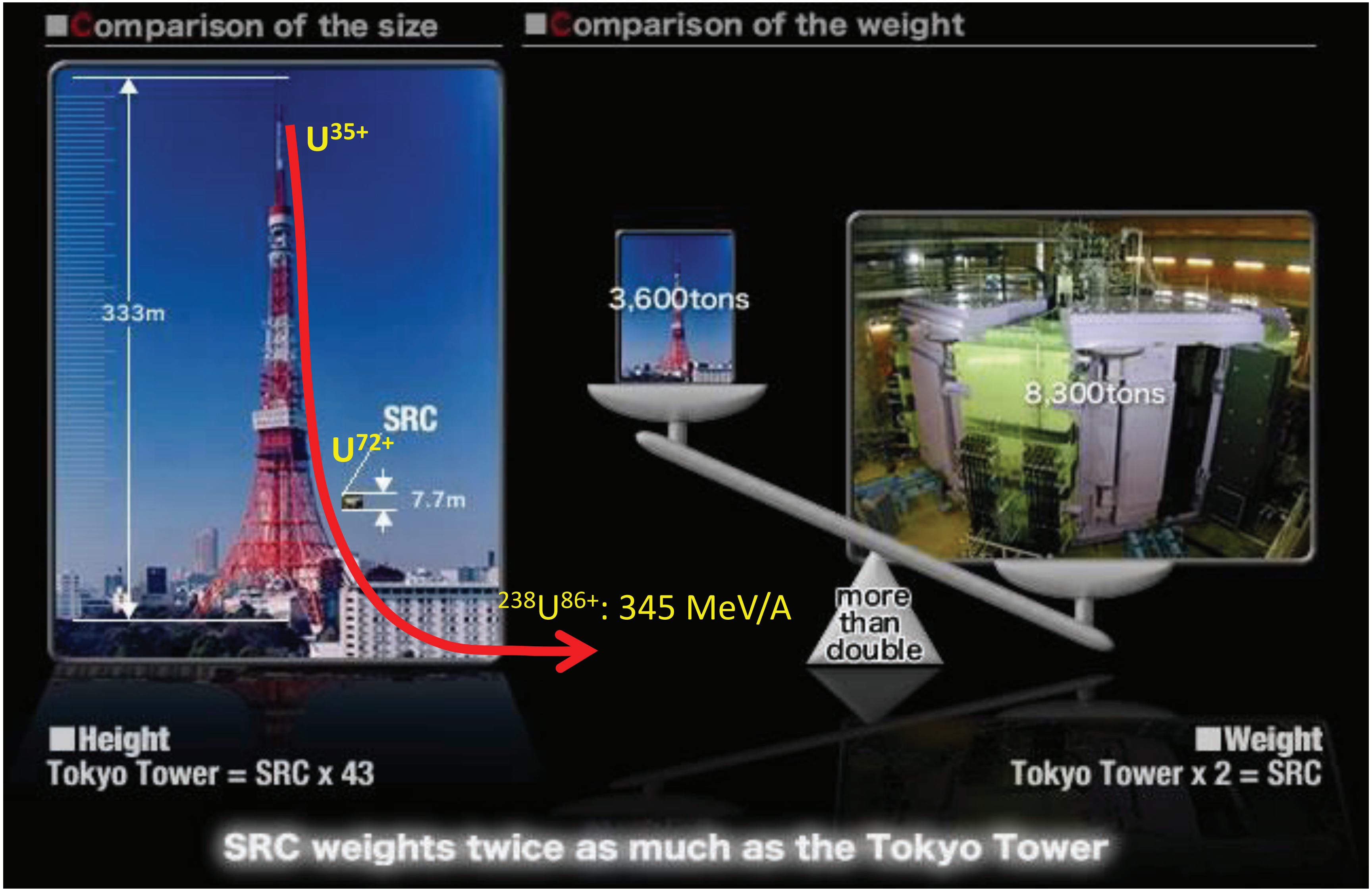




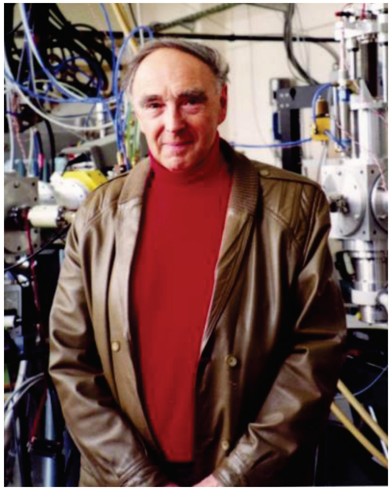
Factor of >60

12” Cyclotron → RIKEN/SRC

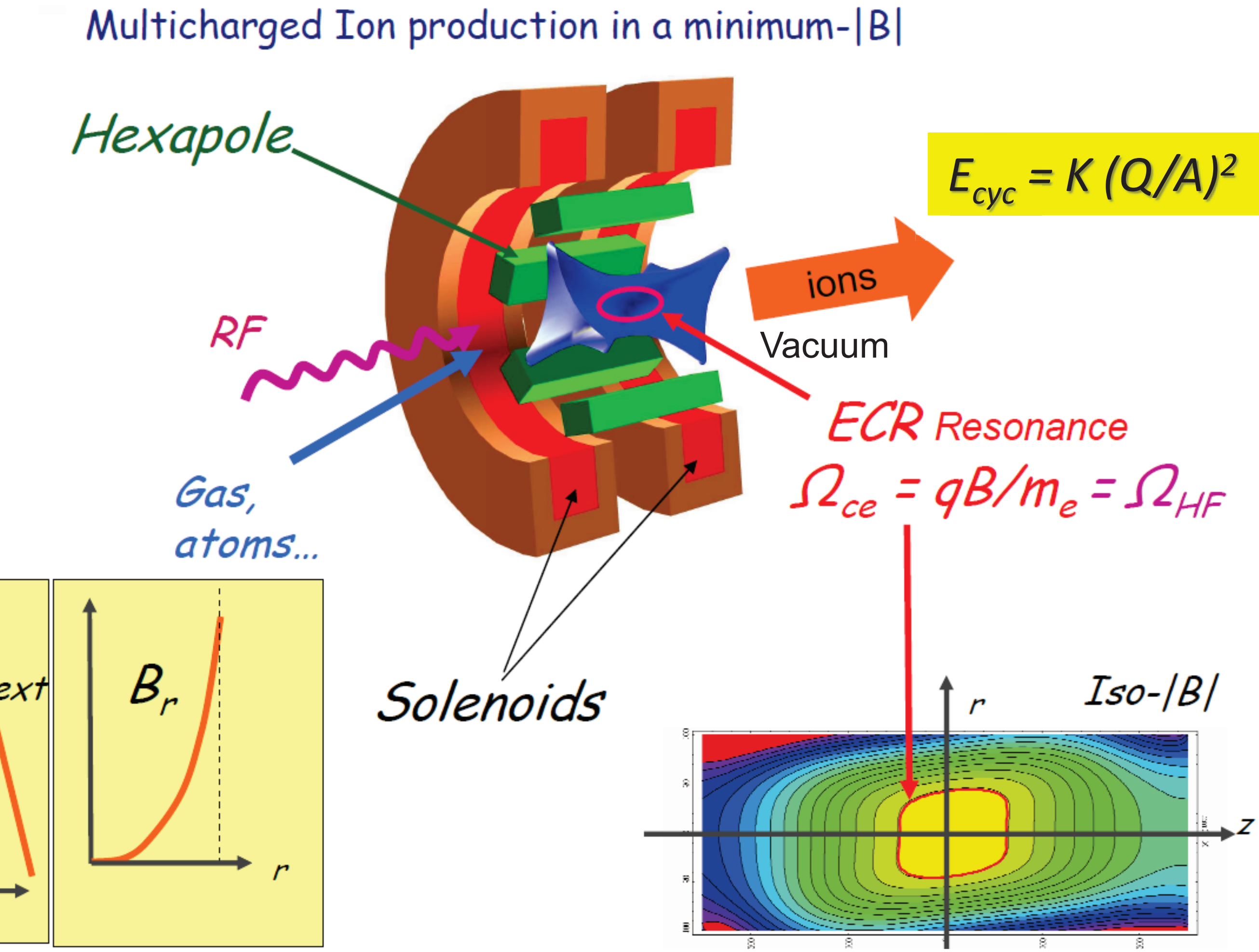
From Cyclotron to ECRIS



From ECRIS to Cyclotron



Richard Geller

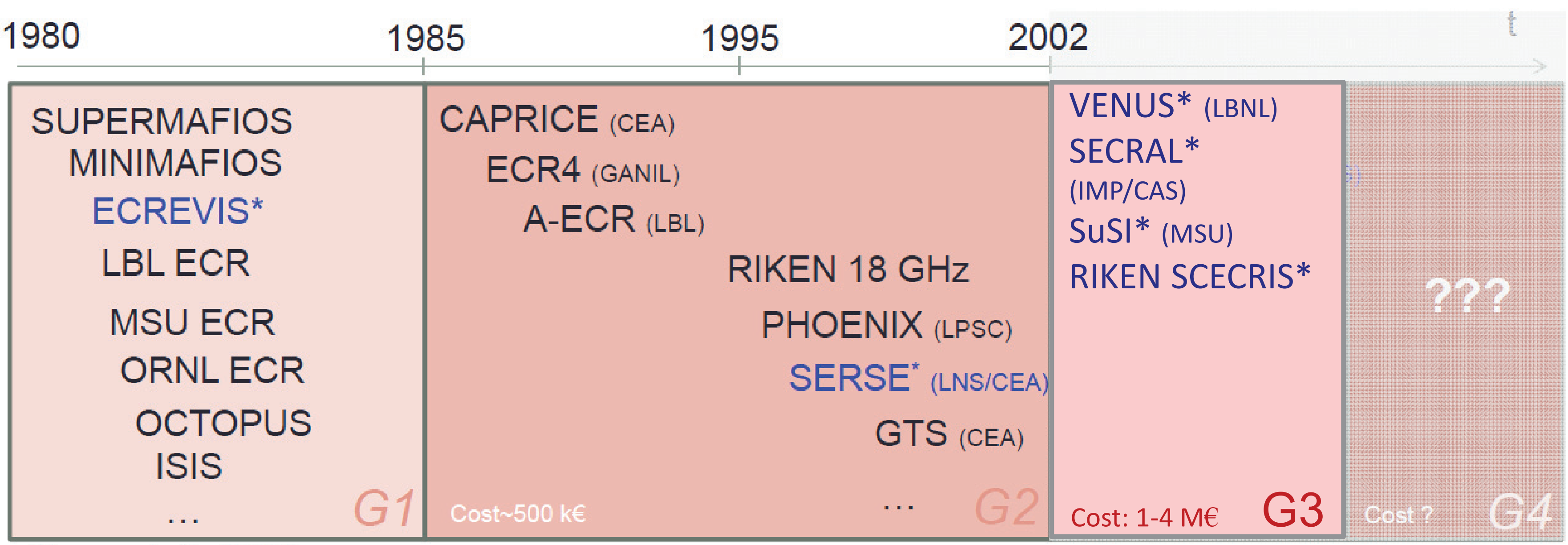


$E_{cyc} = K\,(Q/A)^2$

From ECRIS to Cyclotron (1980s)

Family Tree of ECRISs

All permanent magnet ECRIS	Classical RM ECRIS	Hybrid SC-ECRIS	Fully SC-ECRIS
Nanogan series ion sources	GTS source	RAMSE, SHIVA	SERSE 18 GHz
BIE series ion sources	AECR-U	A-PHOENIX	VENUS 28GHz
LAPECR1, LAPECR2	LECR2, LECR3	PKDELIS	SECRAL 18~28 GHz
Kei1, Kei2	RIKEN 18 GHz	Dubna 18 GHz	SUSI 18~24 GHz
SOPHIE	ECR4, Caprice		RIKEN SCECRIS 28 GHz
Operated 2.45 ~ 14 GHz	Operated 10 ~ 18 GHz	Operated 14 ~ 28 GHz	Operated 18 ~ 28 GHz



*Superconducting ECRIS

ECRIS Direction?

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

  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)

- From RF dispersion equation at resonance : $(n_e T_e) \approx (\frac{m_e \varepsilon_0 \omega_{rf}^2}{e^2}) m_e c^2$

  $I^q \;\alpha\; f^2_{ECR}$

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

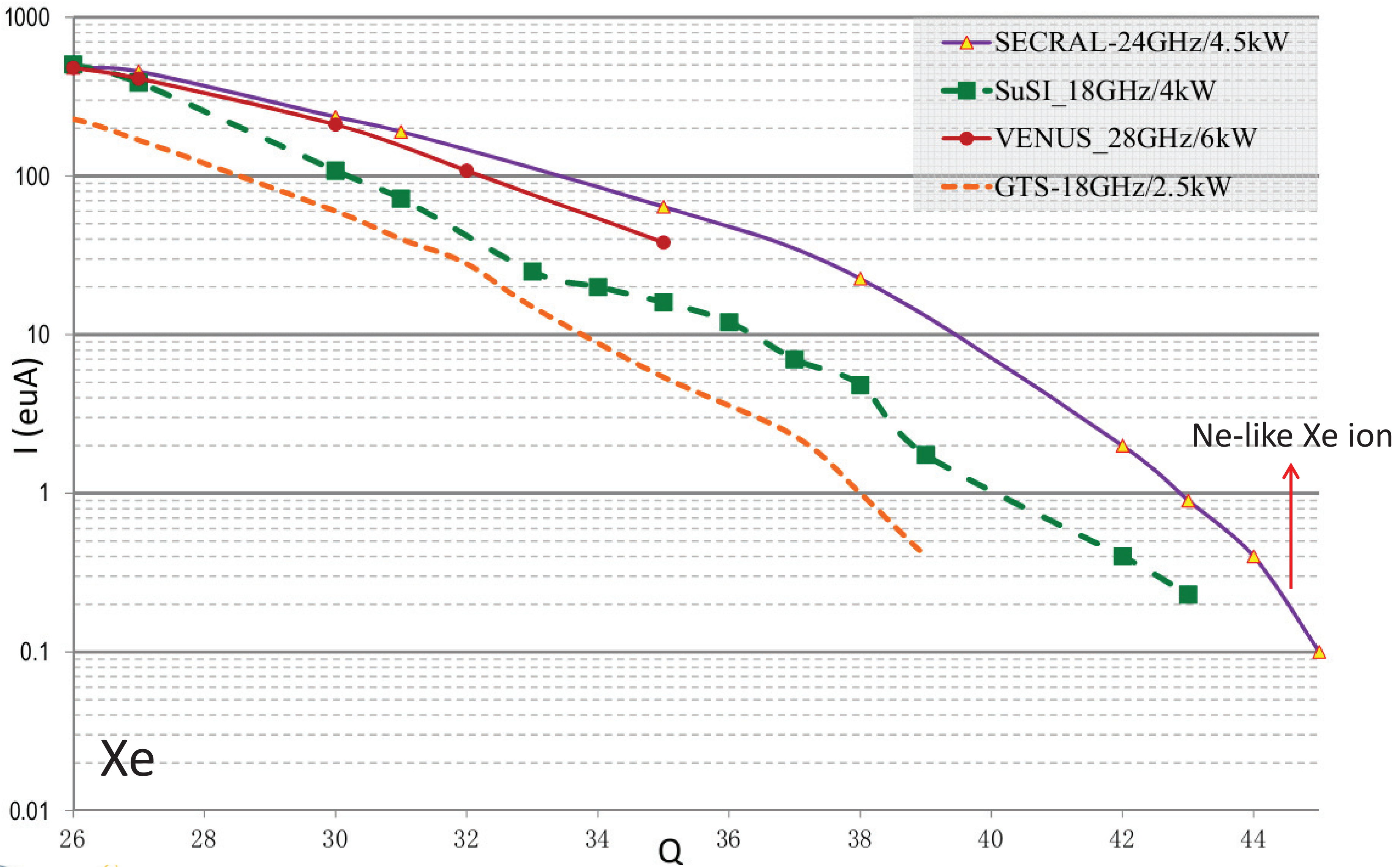
  As $n_e \nearrow$ $B \nearrow$

- B_{inj} ~ 3 - 4 B_{ecr} on axis
- B_{ext} ~ 2.2 B_{ecr} on axis (T)
- B_{rad} ~ $2B_{ecr}$ on plasma chamber wall
- Last closed Bmod inside chamber is ~2 B_{ecr}

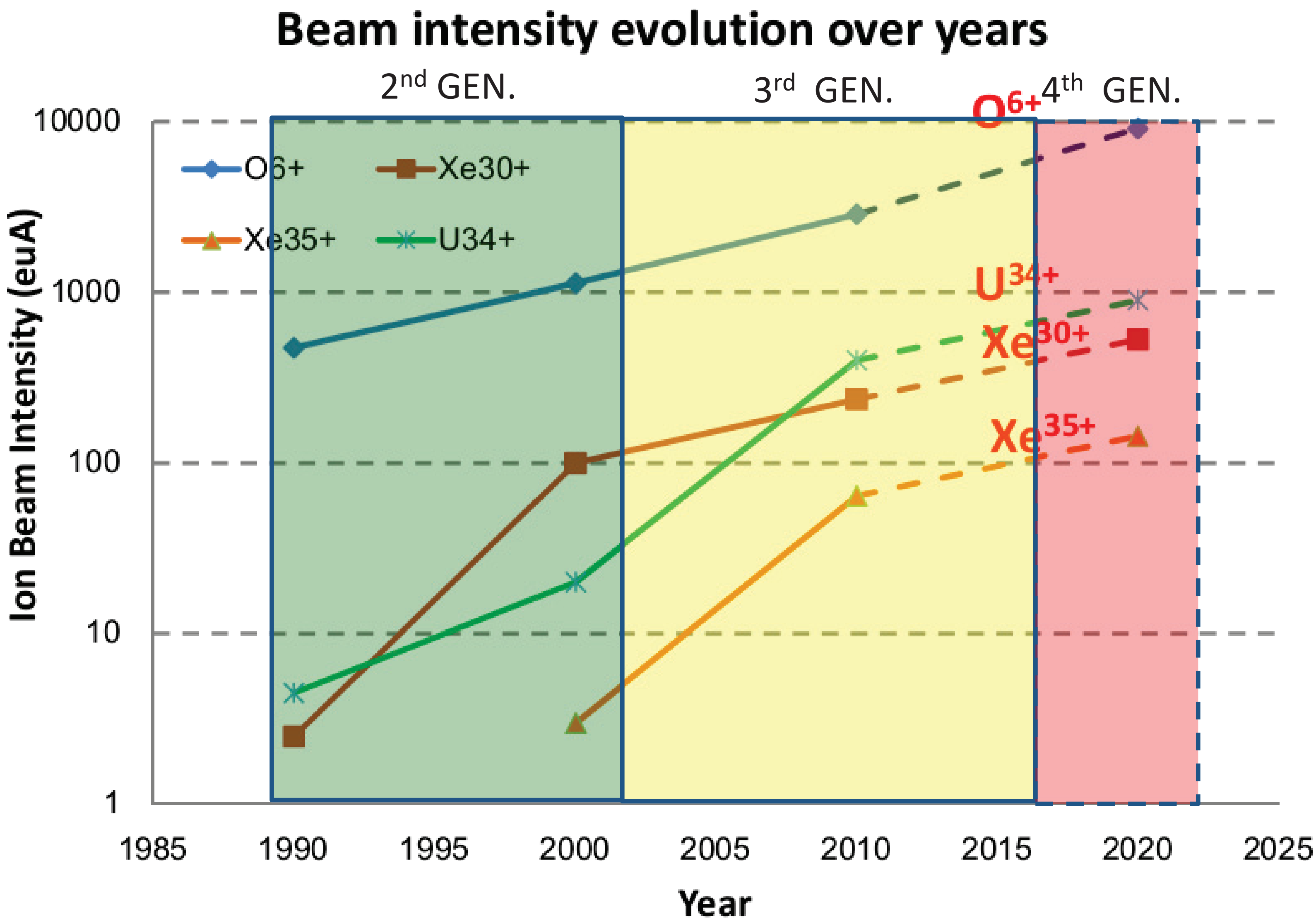
Semi-empirical rules

f_{ECR}	B_{ECR}	B_{inj}	B_{rad}
14 GHz	0.5 T	2 T	1 T
28 GHz	1 T	4 T	2 T

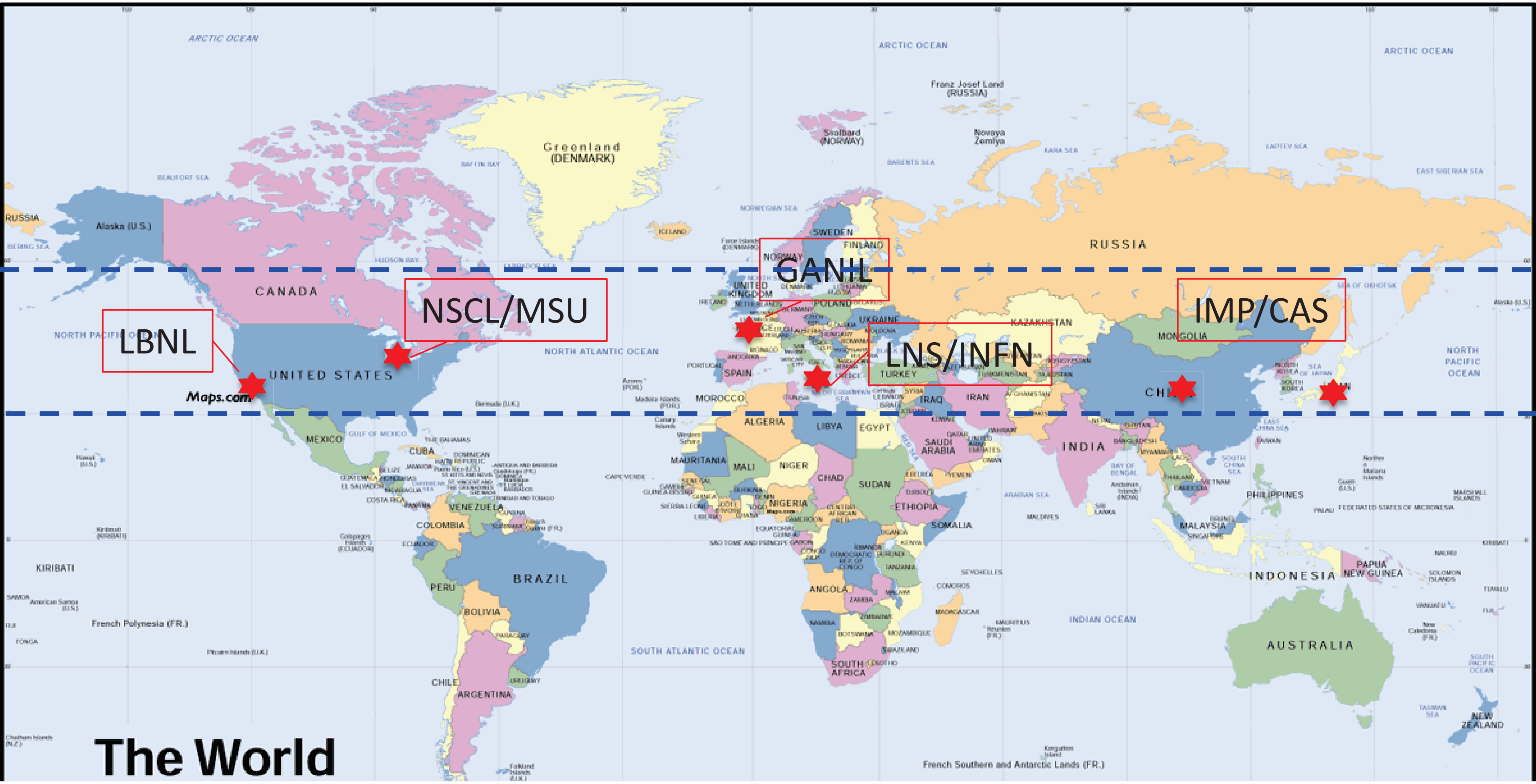
Performance of the 3rd Generation ECRISs



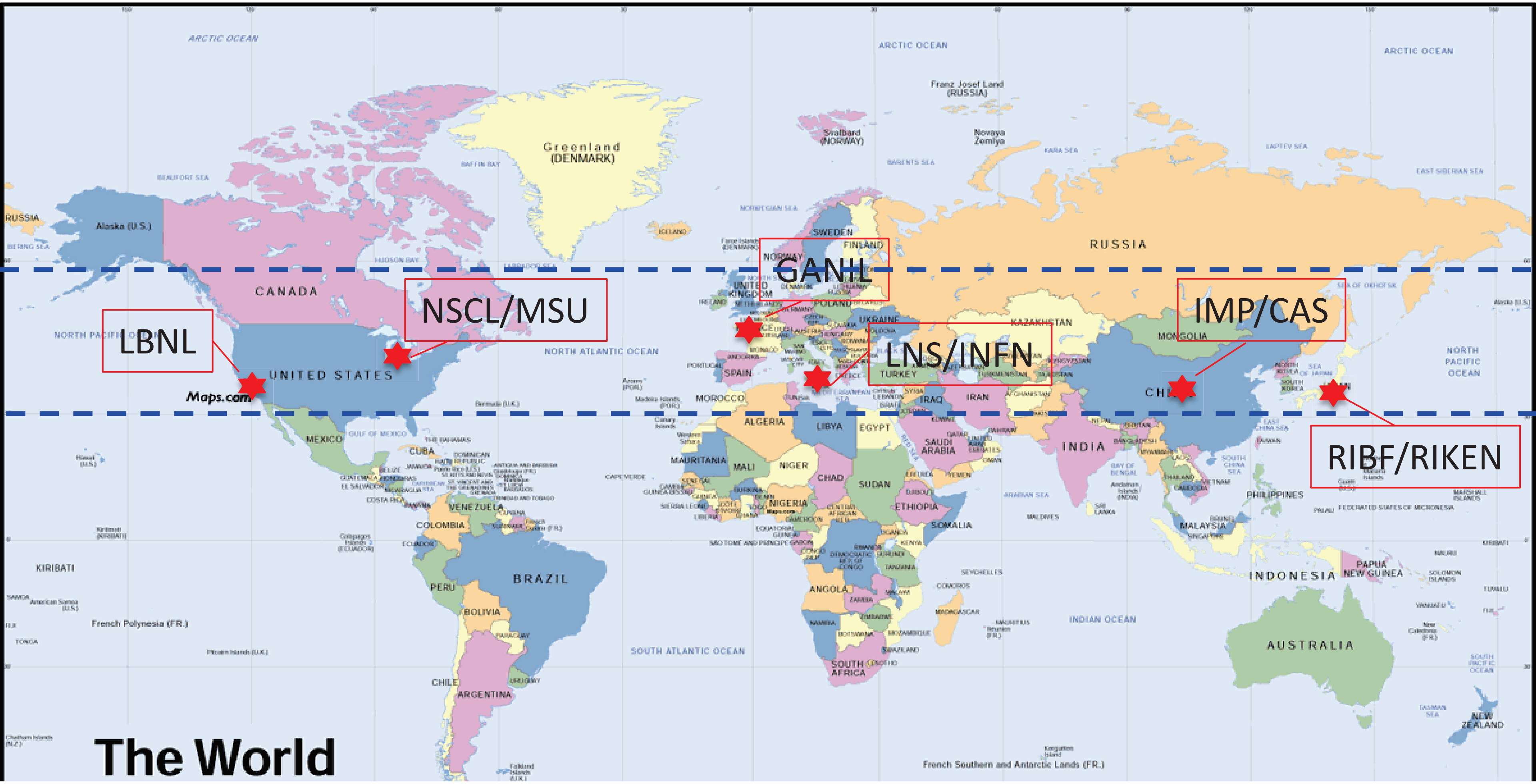
Performance Improvement



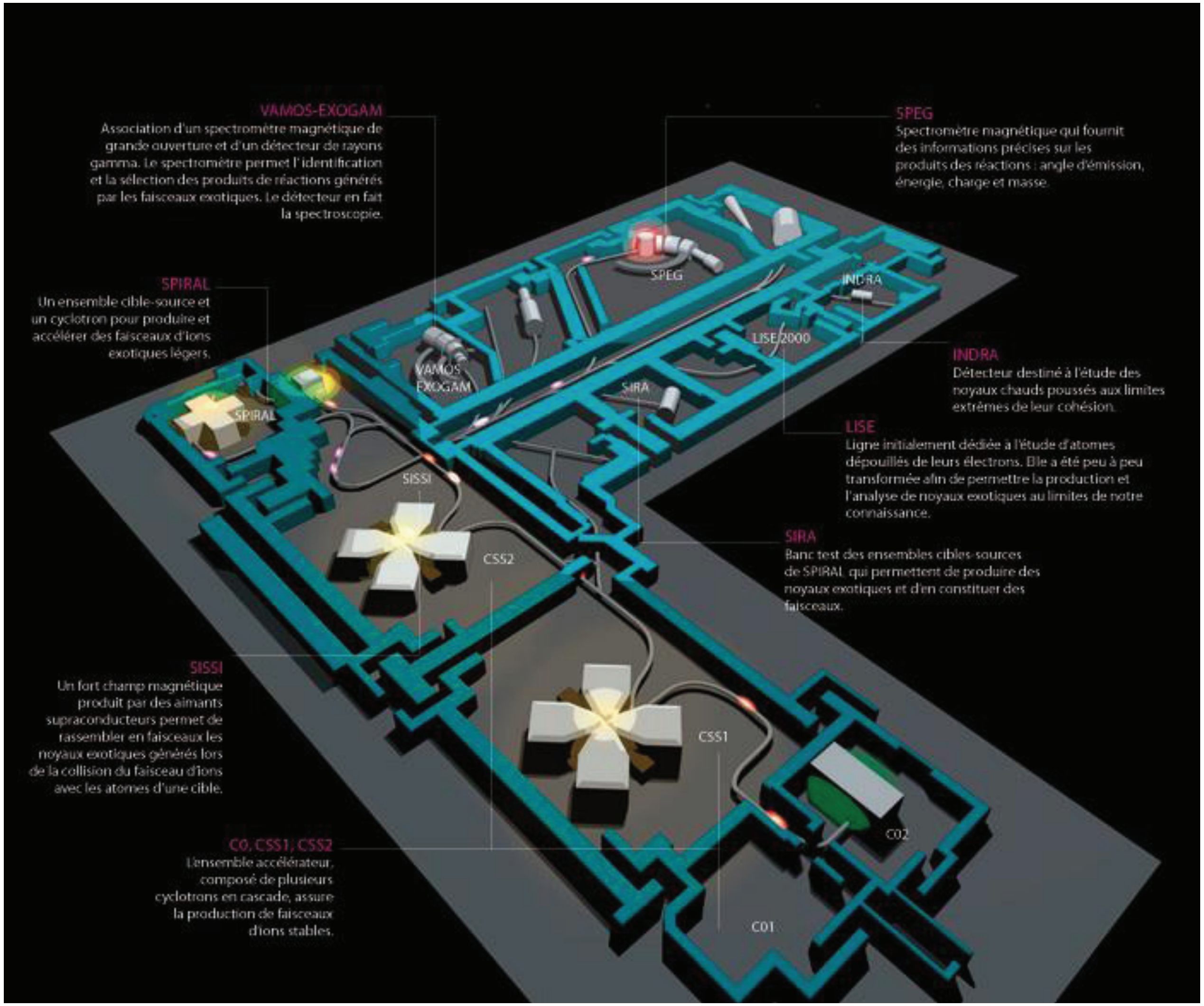
Status of HCI ECRISs for Cyclotron



Status of HCI ECRISs for Cyclotron



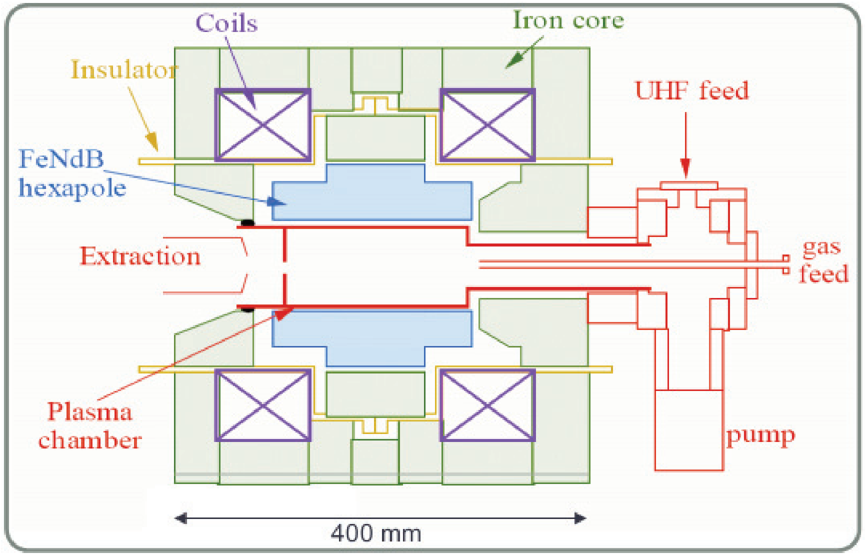
ECRISs in GANIL



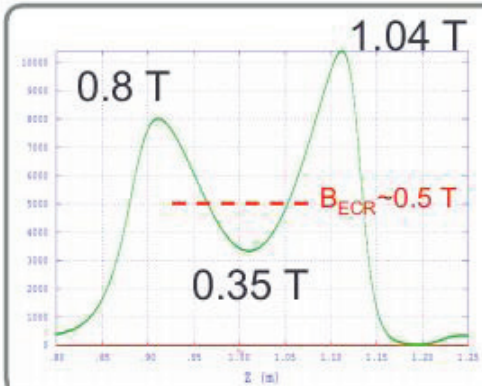
- One of first cyclotron labs used ECRIS for routines
- ECR4 & ECR4M operation for stable ion beams
- ECRISs used for radioactive ion beams

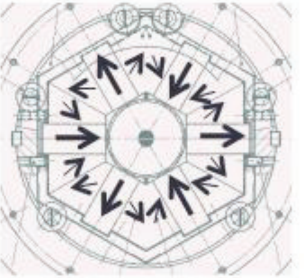
ECR4 & ECR4M

- f=14.5 GHz/1.5 kW (B_{ECR} = 0.64 T)
- Coaxial RF coupling to adapt RF impedance to the ECR cavity, inherited from CAPRICE source design.
- Big iron yoke
- Double-wall structure plasma chamber
- High B mode:
  - Axial Mirror: 1.04 T/0.35 T/0.8 T
  - Hexapole: 1 T **FeNdB Halbach** type
- Typical Ion Beam: ~650 μA Ar^{8+}
- Chamber volume (Ø64 mm×L200 mm) V~0.5 liter

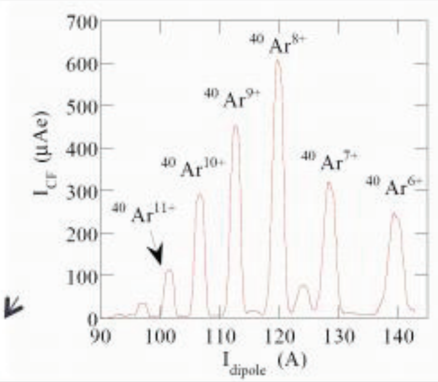


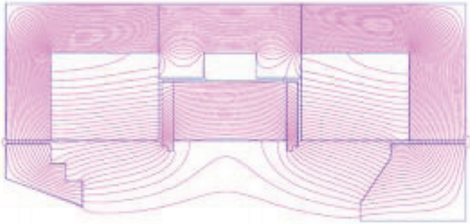
Courtesy of T. Thuillier





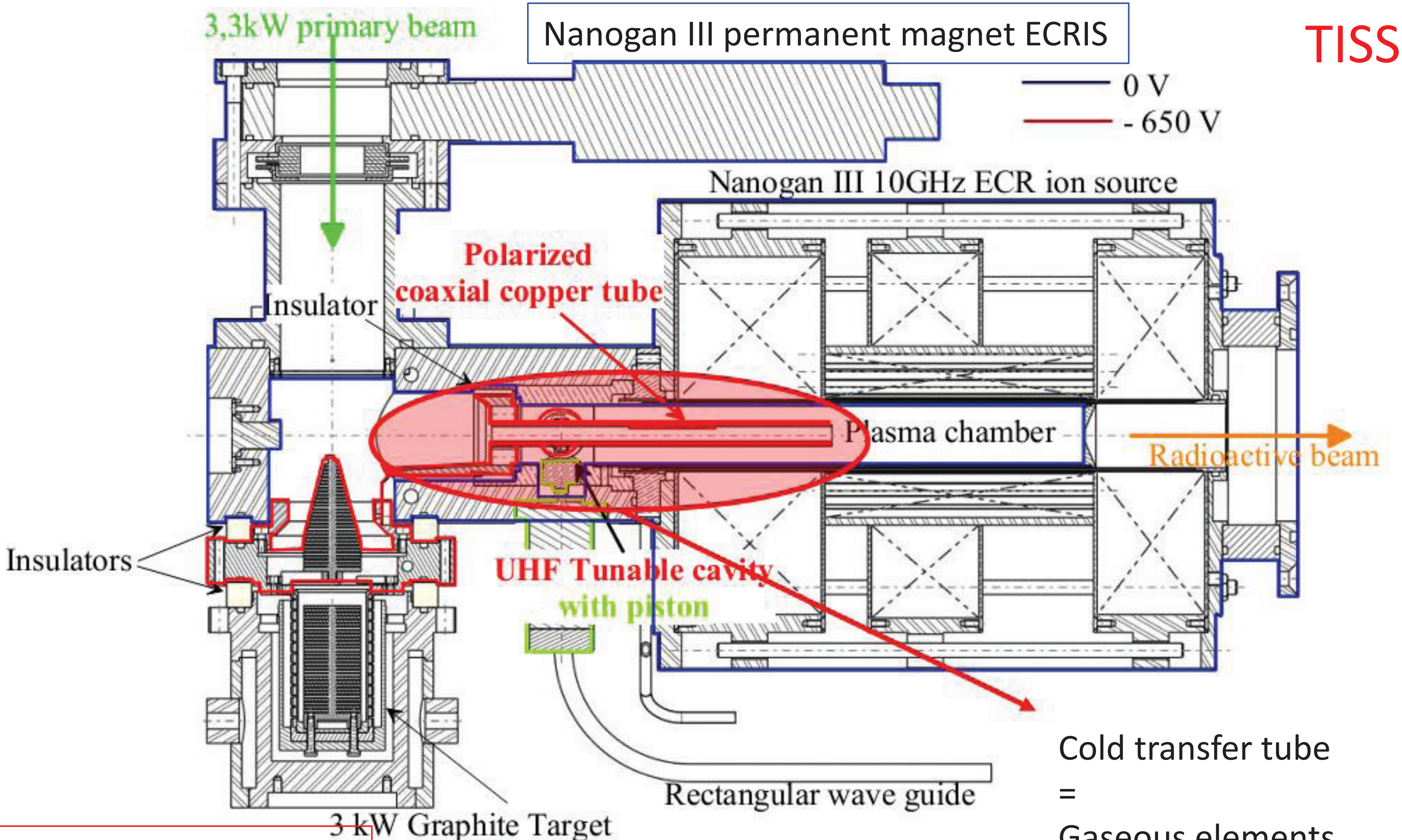
FeNdB hexapole





Axial Magnetic field lines (ECR4M)

ECRIS for Radioactive Beams



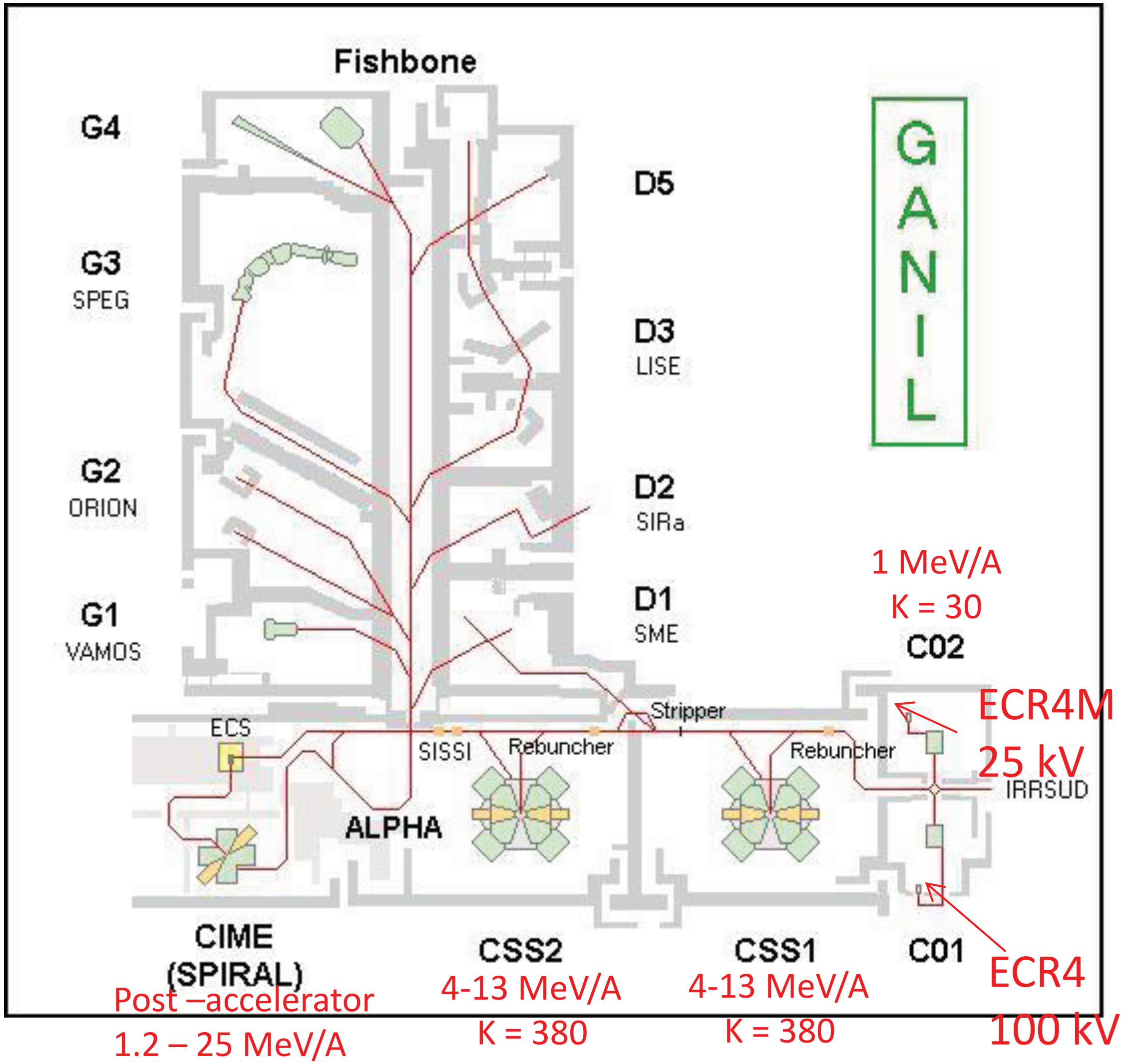
Cold transfer tube

=

Gaseous elements

F. Chautard, Cyclotrons'10

GANIL



- Stable ion beams: C – U
- Beams of more than 50 isotopes
- Maximum energy ~100 MeV/u
- Typical final beam power: 100 W—1000 W

ECRISs in LNS/INFN

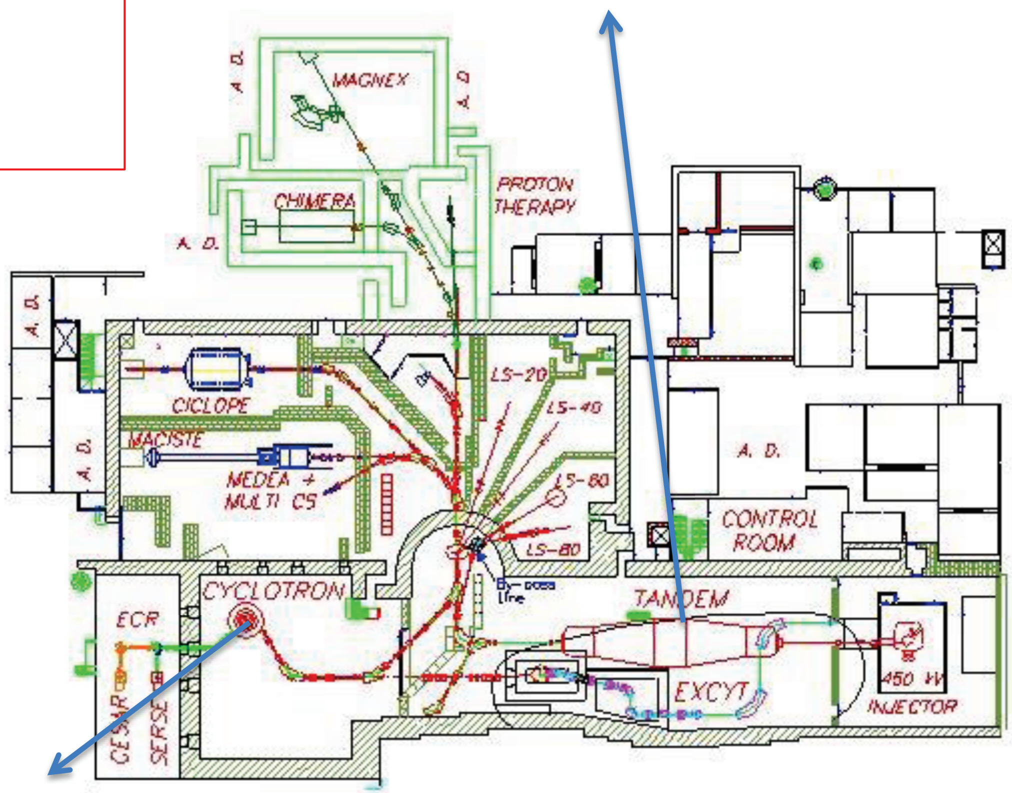
- 1st high performance superconducting ECRIS utilized for cyclotron routine operation
- Utilization of ECRIS makes the stand-alone operation of cyclotron CS possible

Operation Scheme in LNS

Coupling mode:

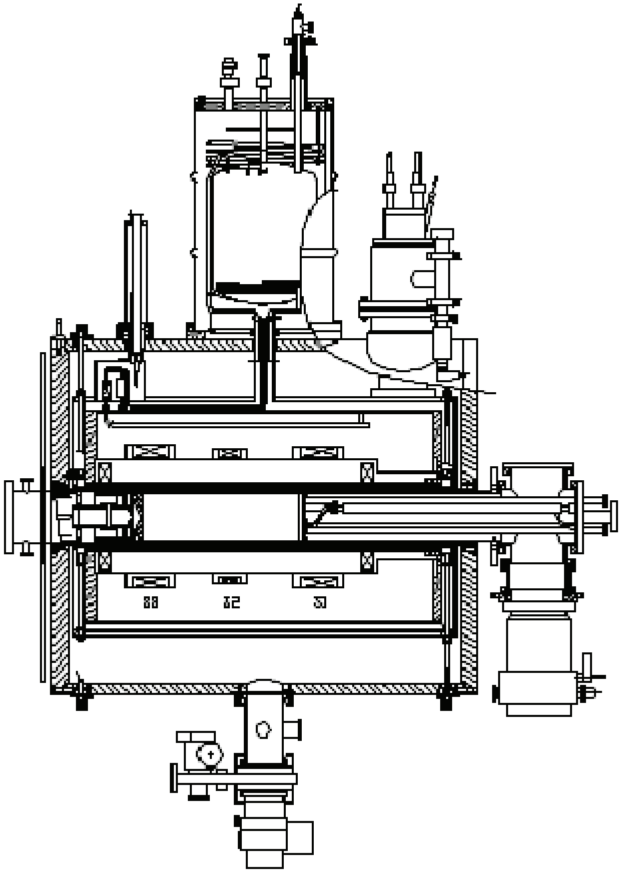
- Low efficiency
- No stable

Tandem Van De Graaff, 13 MV
Built in early 80s



K800 CS fully operational since 1996

SERSE Ion Source



Available in 1997

Frequency	18 + 14.5 GHz
Type of launching	WR62, off-axis
Mirror length	490 mm
B_{inj}	2.7 T
B_{min}	0.3-0.6 T
B_{ext}	1.6 T
L_{ecr}	< 100 mm
$L_{hexapole}$	700 mm
B_{rad}	1.55 T max.
Ø plasma electrode	8 mm
Ø puller	12 mm
Extraction voltage	30 kV Max.

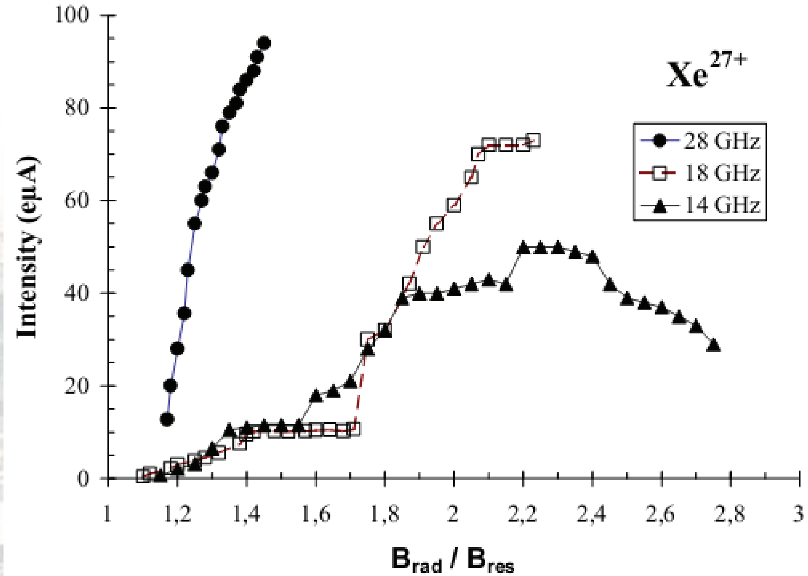
SERSE Achievements

- Demonstration of the state of art SC-techniques for ECRISs
- Refinement of scaling laws for ECRIS development
- Guidance of gyrotron generator microwave coupling method to ECRIS

SERSE Performance

SERSE typical currents at 18GHz

O6+	*540*	Kr22+	*66*	Au30+	*20*
O7+	*208*	Kr25+	*35*	Au31+	*17*
O8+	*62*	Kr27+	*7.8*	Au32+	*14*
Ar12+	*200*	Kr29+	*1.4*	Au33+	*12*
Ar14+	*84*	Kr31+	*0.2*	Au34+	*8*
Ar16+	*21*	Xe27+	*78*	Au35+	*5.5*
Ar17+	*2.6*	Xe30+	*38.5*	Au36+	*2.5*
Ar18+	*0.4*	Xe31+	*23.5*	Au38+	*1.1*
Kr17+	*160*	Xe33+	*9.1*	Au39+	*0.7*
Kr18+	*137*	Xe34+	*5.2*	Au40+	*0.5*
Kr19+	*107*	Xe36+	*2*	Au41+	*0.35*
Kr20+	*74*	Xe38+	*0.9*	Au42+	*0.03*



Scaling laws tested with SERSE

28 GHz operations:
1 μA Xe^{42+}, 8 μA Xe^{38+}, 100 μA Xe^{30+}

Courtesy of C. Luigi

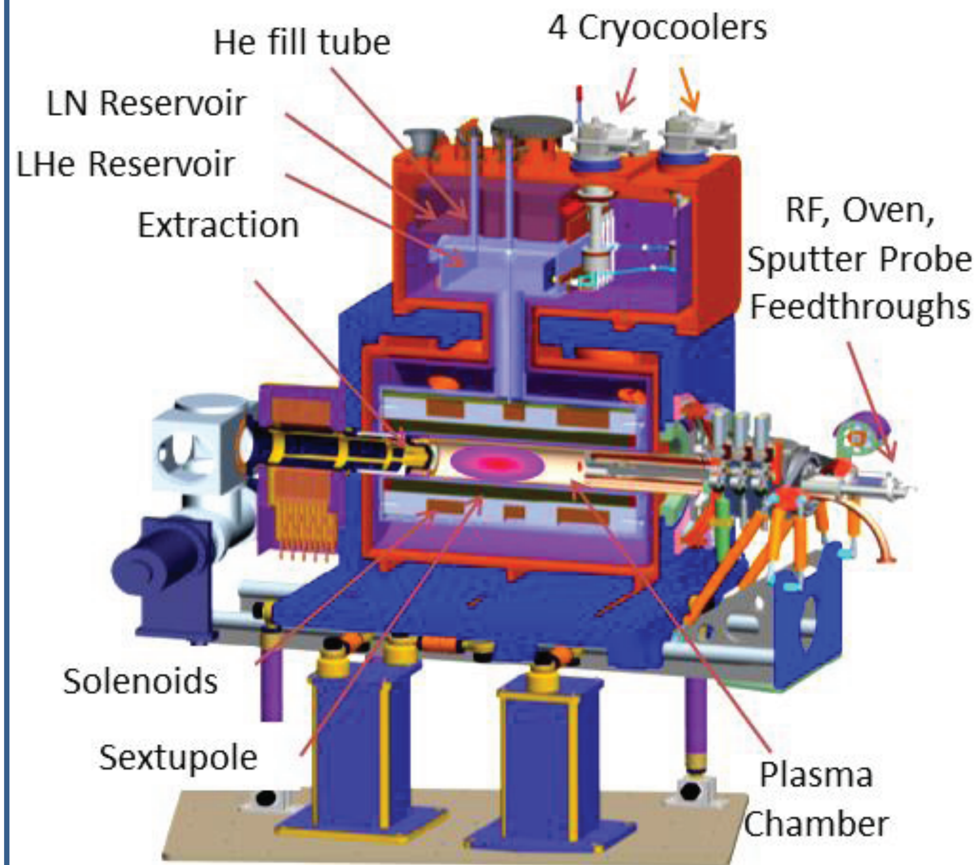
88-Inch Lab/LBNL

- The first 3rd Gen. ECRIS
- The only cyclotron lab having 3 generations of ECRISs in operation
- High performance ECRIS makes the 50 years old cyclotron still powerful and attractive

VENUS in LBNL

- **Fully superconducting**, Niobium-Titanium sextupole & 3 solenoids enclosed in LHe
- **LN Reservoir** : 70K, dissipates heat from normal conducting leads
- **LHe Reservoir**: 4.2K
- **Four two stage cryocoolers** which provide **6W total cooling power at 4.2K**, recondense evaporated He, 1st stage (45K) cools part of the Cu leads
- **Recently ran 22 months straight**

Maximum Injection Field, on axis	4.0T
Maximum Extraction Field, on axis	3.0T
Maximum Radial Field, at wall	2.2T
Chamber Diameter	14cm
Chamber Length	50cm
18 GHz Maximum Power	2kW
28 GHz Maximum Power	10kW
28 GHz Maximum Power Injected	6.5kW
18+28 GHz Maximum Power Injected	8.5kW

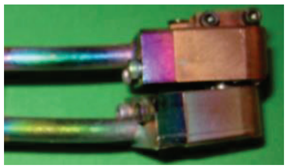


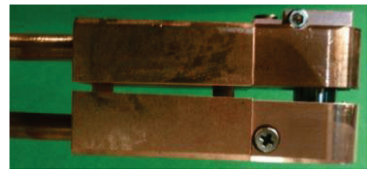
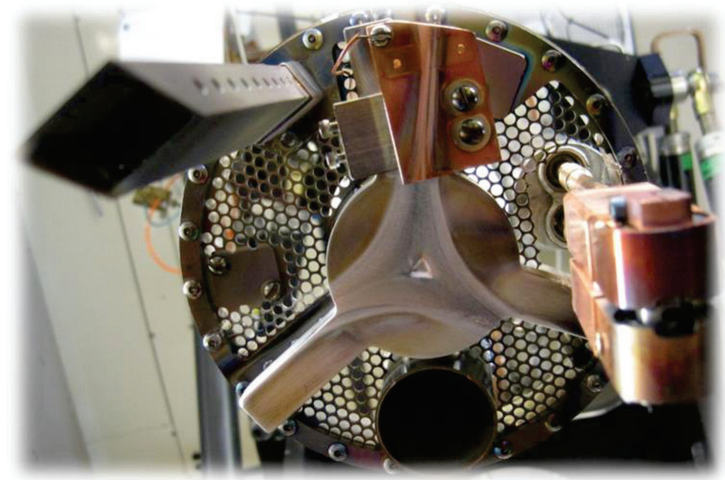
Available in 2002

Courtesy of J. Benitez

U Beam with VENUS

- Operates 650°C-2300°C to vaporize metals
- Improved cooling
- Expands VENUS' metal production capability

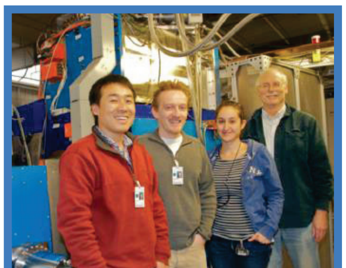



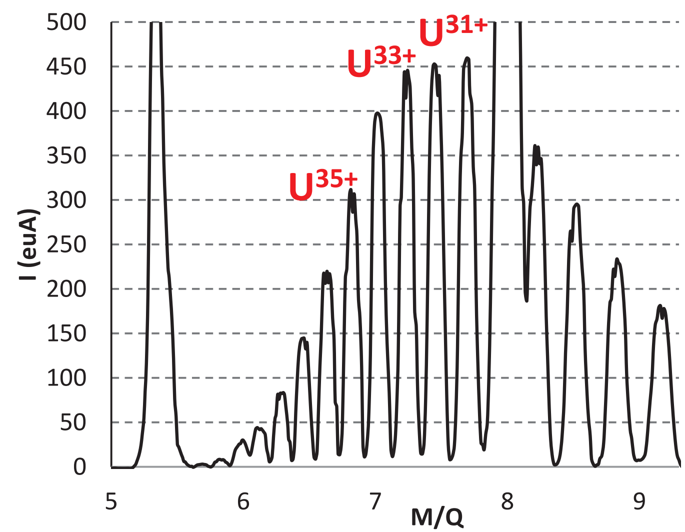



Uranium Development: High Intensity

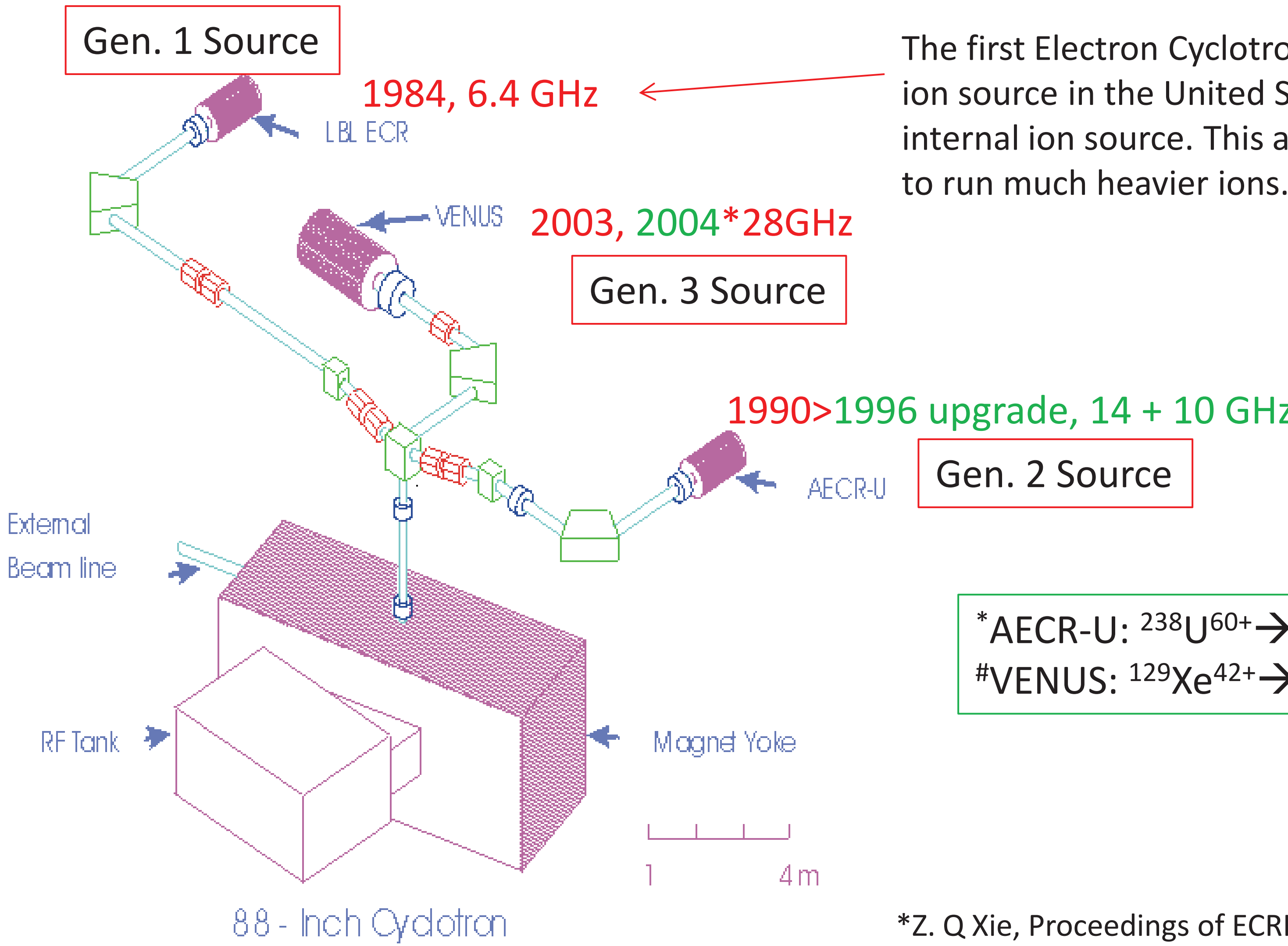
- Uranium beams will be one of the most important and challenging beams for projects like FRIB, RIBF, HIAF…
- U sublimes @ 2000°C, 1000W!
- FRIB needs 440eμA of $^{238}U^{33+,34+}$ combined

$^{238}U^{33+}$	450eμA
$^{238}U^{34+}$	400eμA
$^{238}U^{50+}$	13eμA





Operation Mode in 88-Inch



The first Electron Cyclotron Resonance (ECR) ion source in the United States replaced the internal ion source. This allowed the 88-Inch to run much heavier ions.

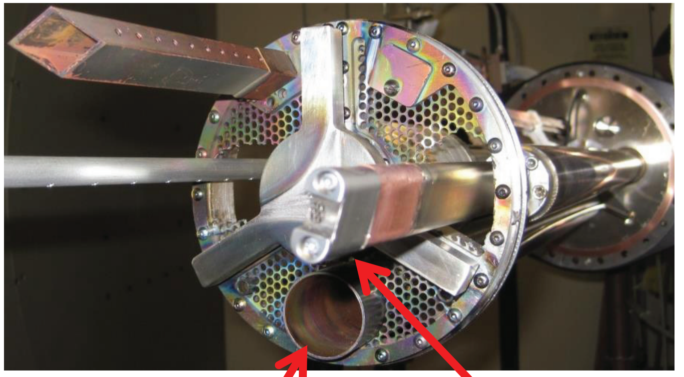
*AECR-U: $^{238}U^{60+}$ → 8.13 MeV/u
#VENUS: $^{129}Xe^{42+}$ → 14 MeV/u

*Z. Q Xie, Proceedings of ECRIS'97
#D. Leitner et al., Rev. Sci. Instrum. 79 (2008) 02C710

Operation Status: $^{48}Ca^{11+}$

- VENUS Low Temperature Oven completed July, 2011
- Successfully delivered ^{48}Ca to 88-Inch experimenters for 60 days straight from April-June 2013
- Summary of the operation:
  - ✓ average current of 78eμA of $^{48}Ca^{11+}$
  - ✓ consumption rate of 0.25mg/hr
  - ✓ Good news for high intensity ^{48}Ca runs where 1mg of ^{48}Ca~$250 (63mg~$15,750)
  - ✓ Good efficiency = No liner required = No interruption to cocktail runs

VENUS Injection



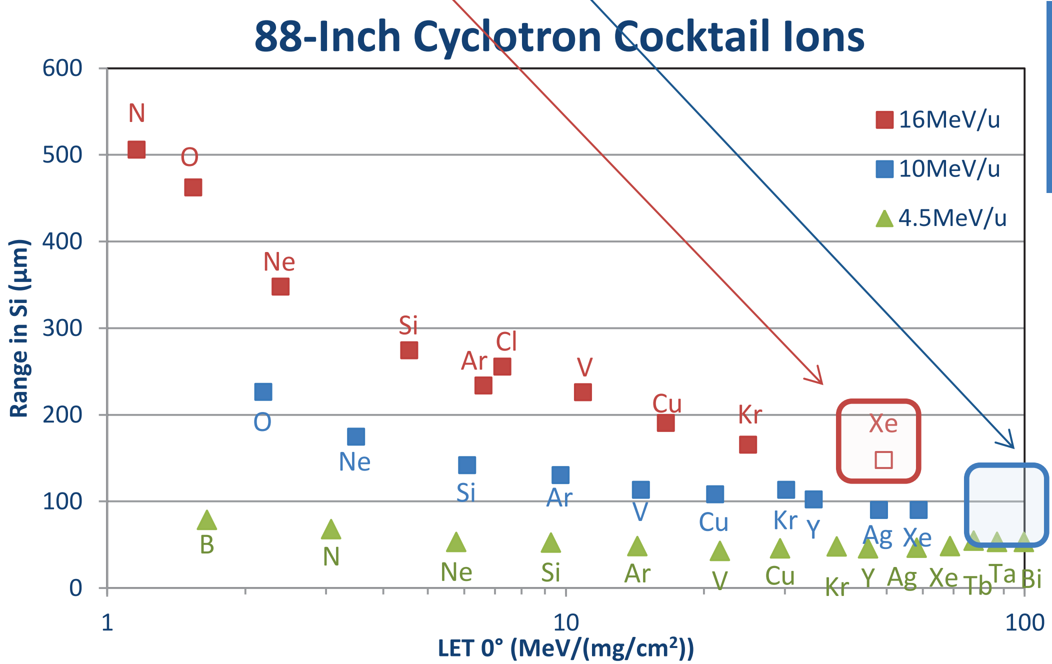
See D. Todd's talk MO2PB02 for details

Operation Status: Cocktail Beams

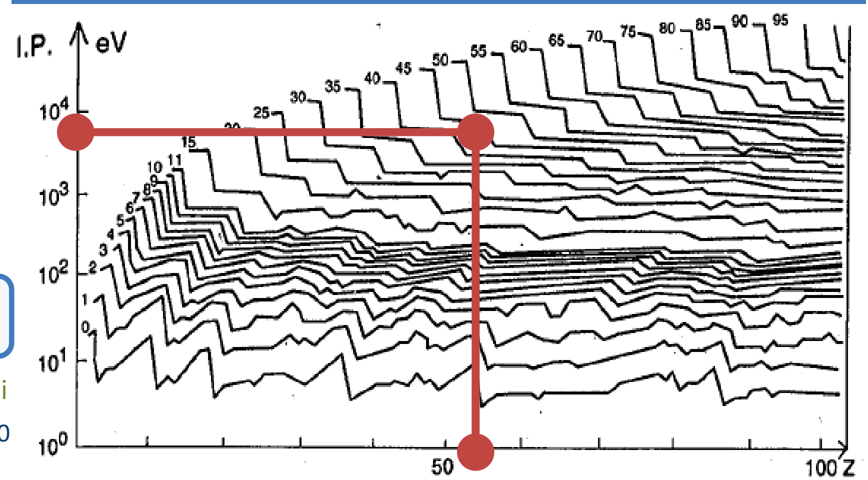
Development of new cocktail ions using VENUS to increase LET and range underway

$^{124}Xe^{43+}$ in 16MeV cocktail: extends LET from 25 to 50MeV/(mg/cm²)→ now regularly used

$^{209}Bi^{56+}$ in 10MeV cocktail: extends LET from 60to 91MeV/(mg/cm²)→ under development



- VENUS produces $^{124}Xe^{43+}$ for 16MeV users!
- For Z=54, to reach a Xe^{+43} charge state requires ~5×10^3eV electrons!

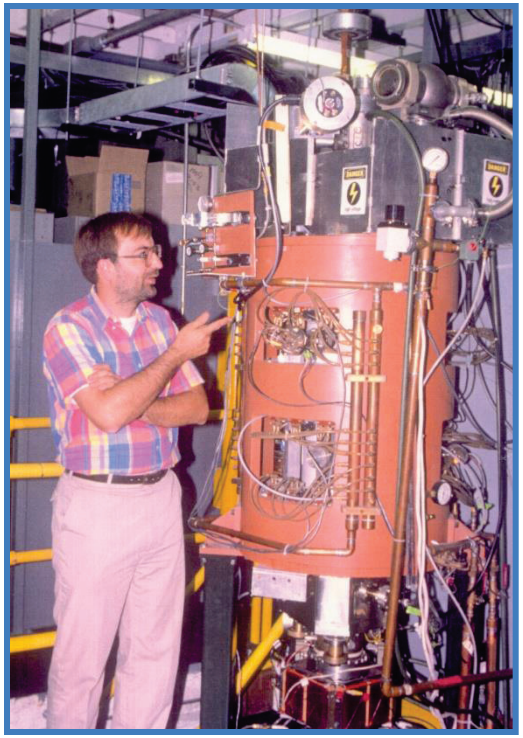


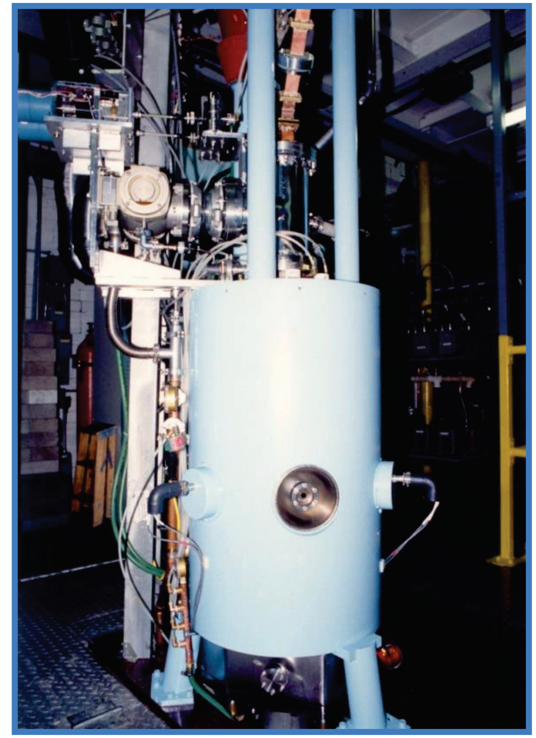
Courtesy of J. Benitez

NSCL/MSU

- 1st fully superconducting ECRIS built for operation
- SuSI sets high intensity beam records at 18 GHz
- Collimation beamline: the first ECRIS source beamline installed with collimation system for cyclotron operation

Early ECRISs in NSCL





RT-ECR (1985-)

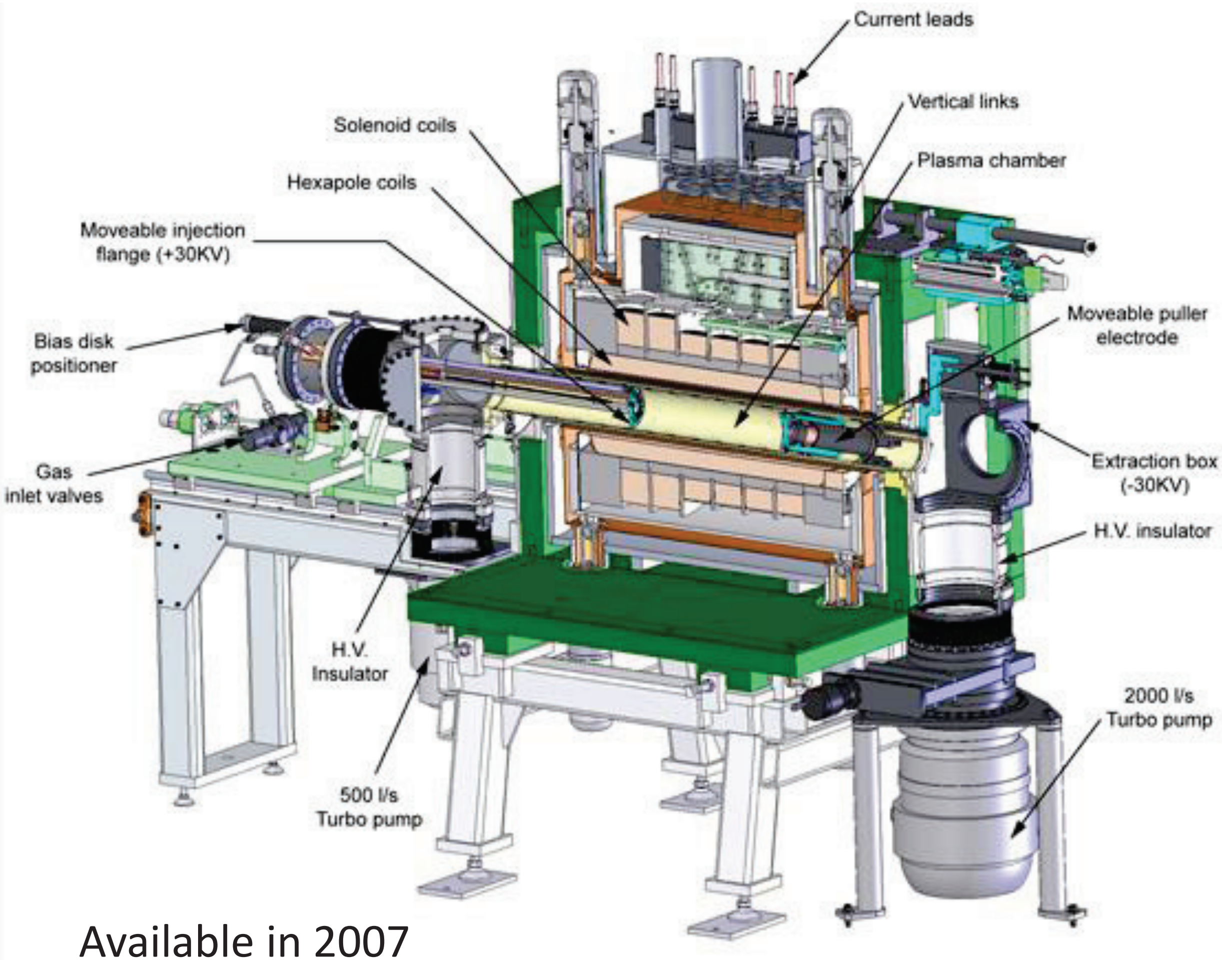
First ECRIS using iron return yoke

SC-ECR (1993)

- The first dynamically tunable SC ECRIS using the High-B mode at 6.4 GHz
- important for Geller's Scaling Laws

SuSI Source

SuSI – Superconducting Source for Ions



Available in 2007

- maximum magnetic fields:

Original Design:
- 2.6 T, 1.5 T axial field
- 1.5 T radial field

Tested (February 2006):
- 3.6 T, 2.2 T axial field
- 2 T radial field

- plasma chamber diameter:

101.6 mm (aluminum)
3.5 L plasma volume

- superconducting wire:
  - 2x1 mm NbTi
  - Cu/SC ratio 1.7
- operating frequency:

Phase I: 18 + 14.5 GHz
Phase II: 24-28 GHz

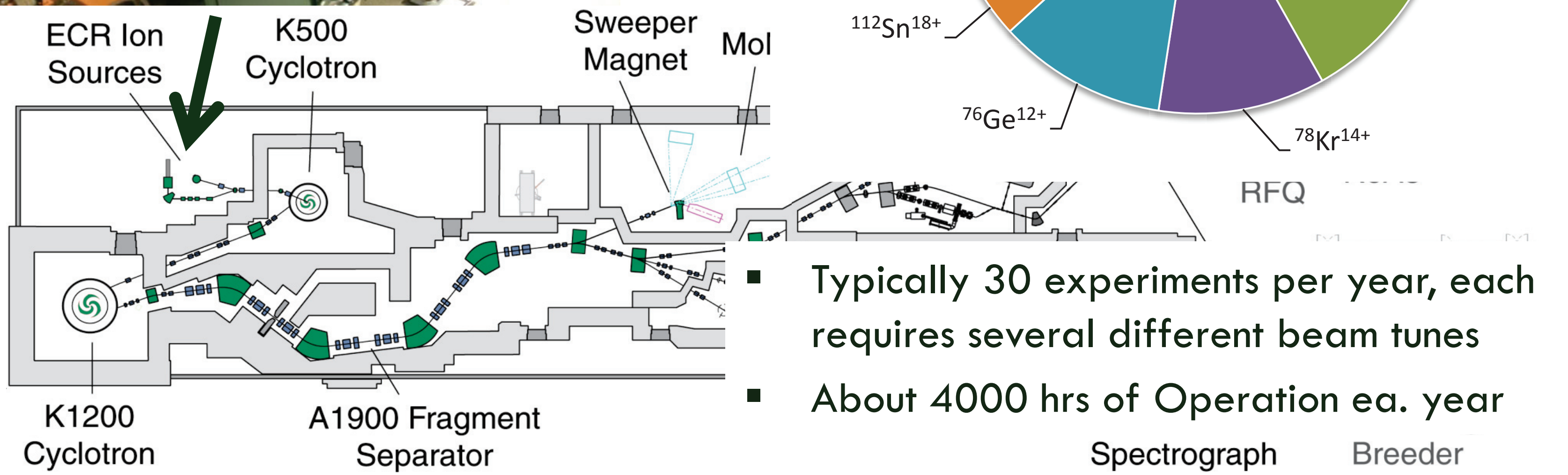
- tunable plasma chamber length and bias disc position

Performance at 18 GHz

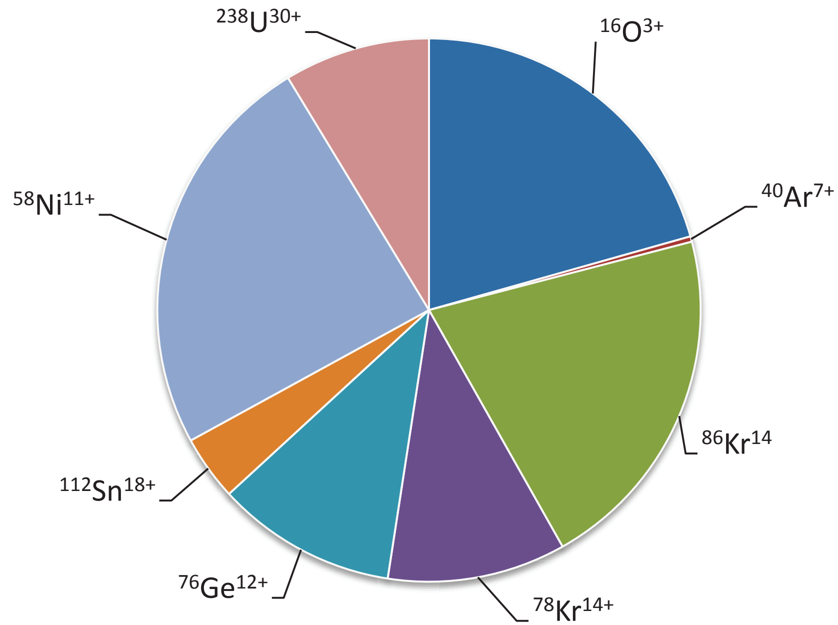
	SuSI (18 GHz/2kW)	SuSI (18 GHz/ 4kW)	SECRAL (18GHz 3kW)	SECRAL (24GHz)	VENUS (28 GHz)
$^{40}Ar^{11+}$	550	800	810		
$^{40}Ar^{12+}$	300	735			860
$^{40}Ar^{14+}$	145	308	270	440	514
$^{40}Ar^{16+}$	25	80	73	149	270
$^{129}Xe^{26+}$	350	500	410		
$^{129}Xe^{27+}$	276	385	306	455	411
$^{129}Xe^{30+}$	80	110	101	236	211
$^{209}Bi^{30+}$	190	320	205	422	310
$^{209}Bi^{31+}$	175	280	191	395	300
$^{238}U^{33+}$		196			430
$^{238}U^{34+}$		180			400
$^{238}U^{35+}$		140			300

Operation for CCF

ICIS 2009:
- Commissioning of SuSI
- Connection of of SuSI to CCF



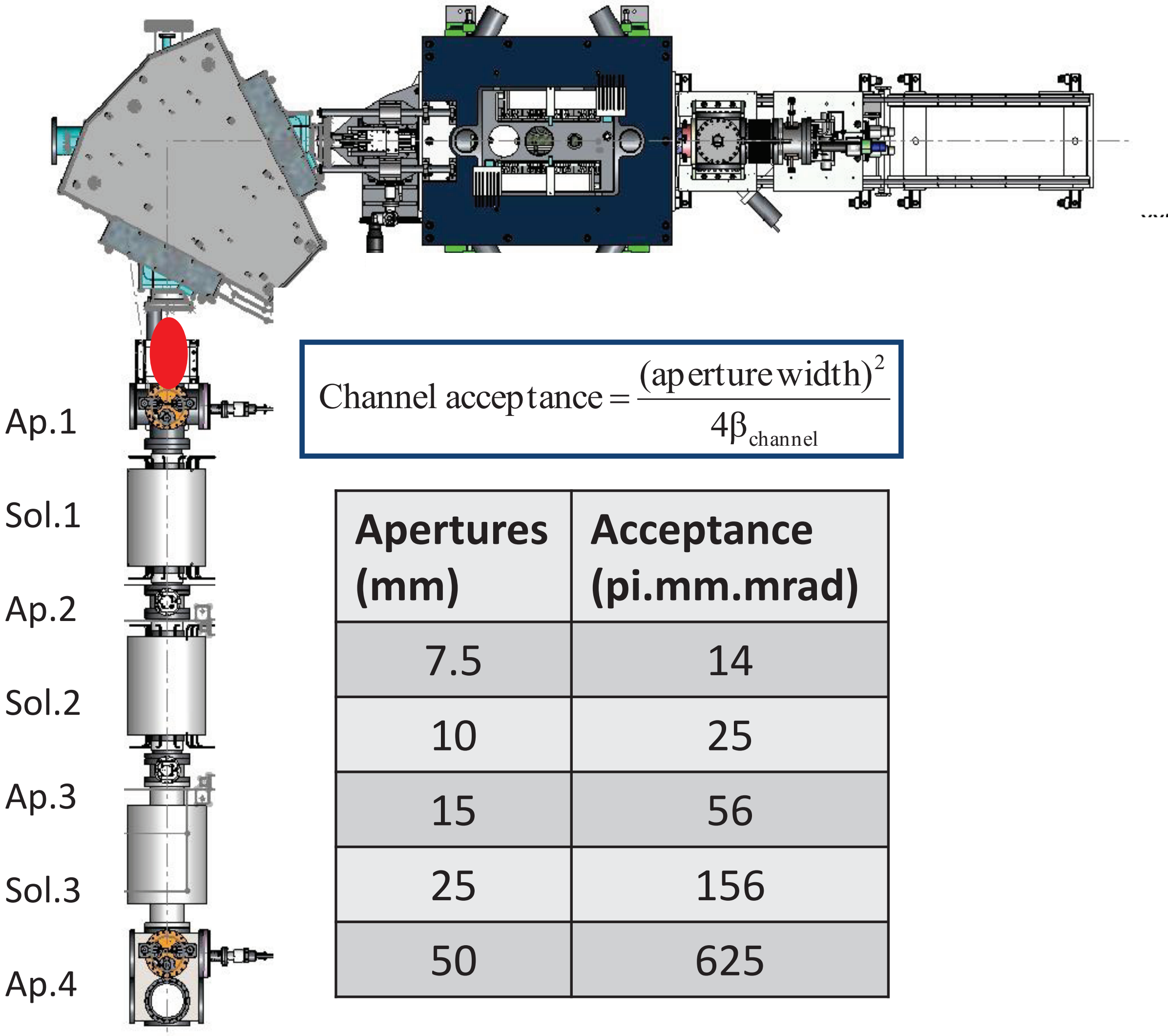
ICIS 2011:2500 Hrs operation for CCF



- Typically 30 experiments per year, each requires several different beam tunes
- About 4000 hrs of Operation ea. year

Courtesy of G. Machicoane

Collimation Channel

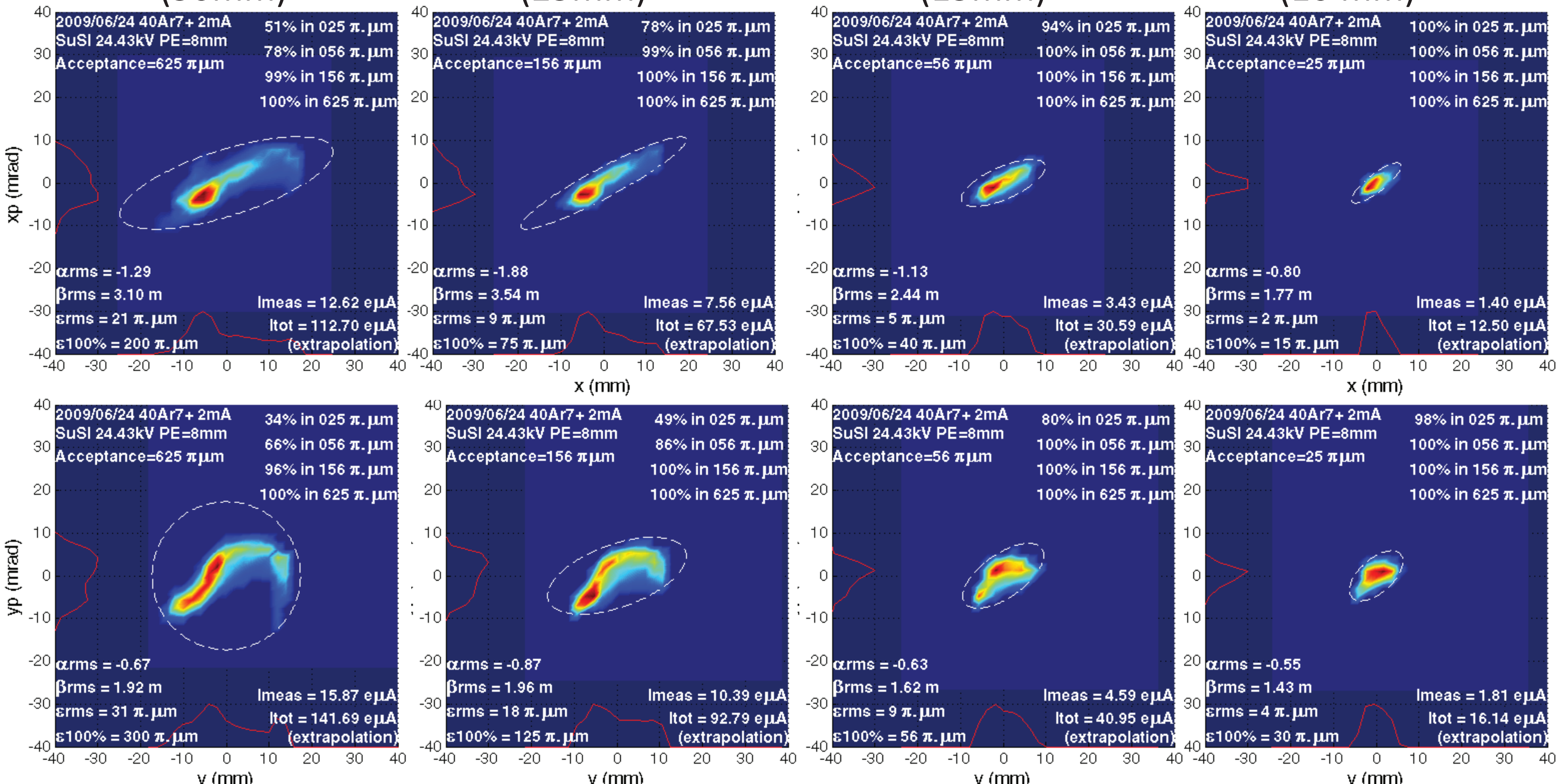


$$\text{Channel acceptance} = \frac{(\text{aperture width})^2}{4\beta_{\text{channel}}}$$

Apertures (mm)	Acceptance (pi.mm.mrad)
7.5	14
10	25
15	56
25	156
50	625

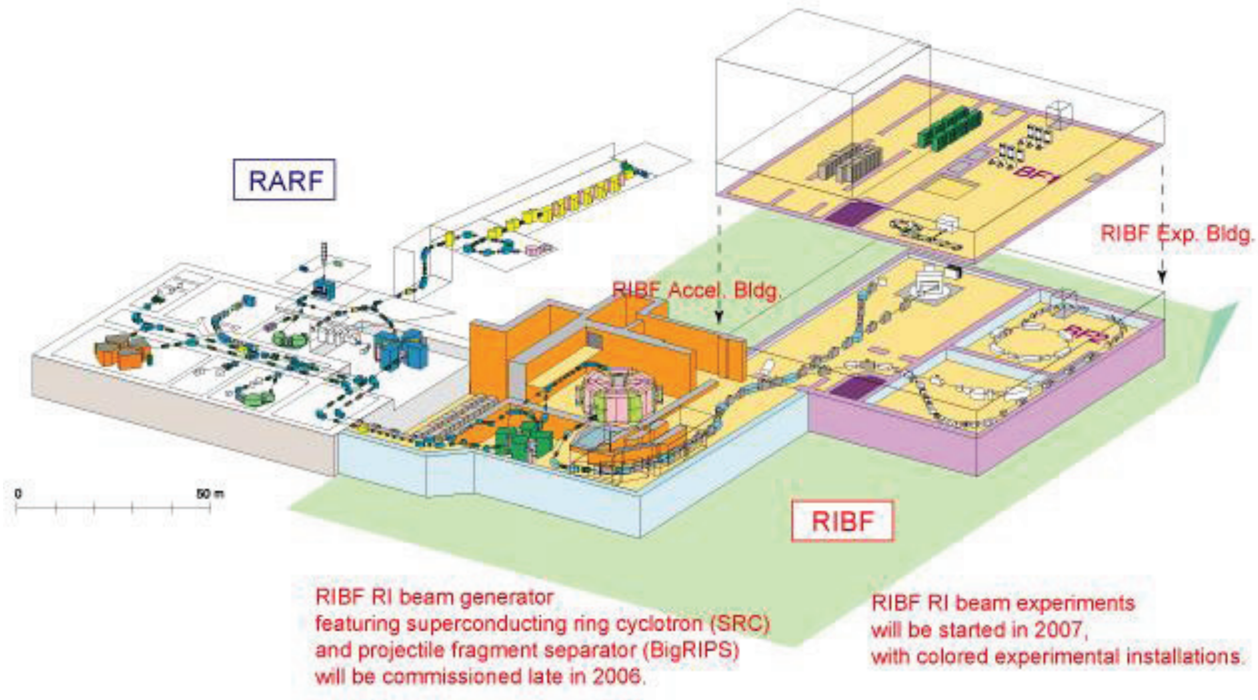
Collimation Effect

625 π.μm (50mm)	156 π.μm (25mm)	56 π.μm (15mm)	25 π.μm (10 mm)



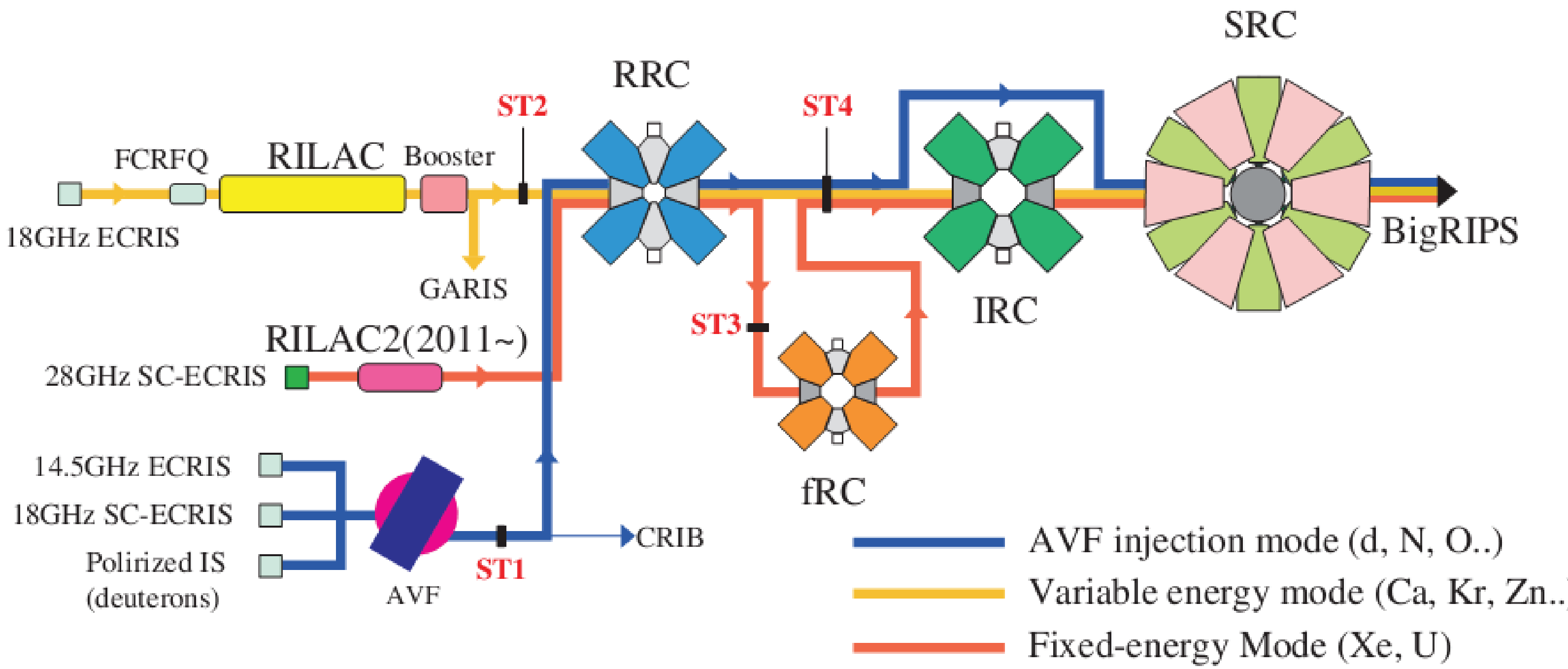
FC:	150 eμA	96 eμA	43 eμA	17 eμA

RIBF/RIKEN

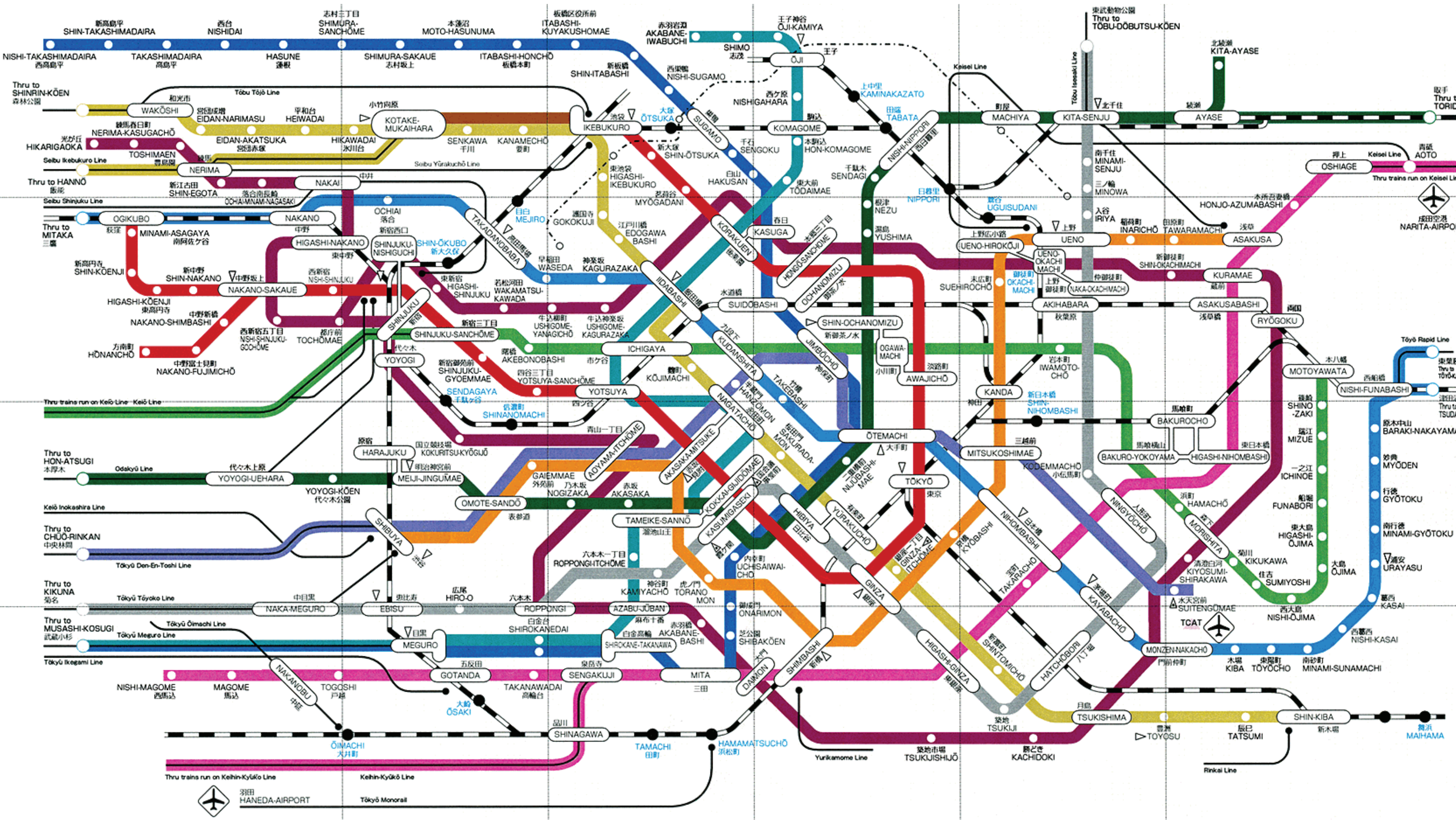


- Very flexible operation mode
- Powerful 3rd Gen. source RIKEN SC-ECRIS
- Very powerful ECRIS: the only solution to the RIBF project goal

Flexible Operation Modes



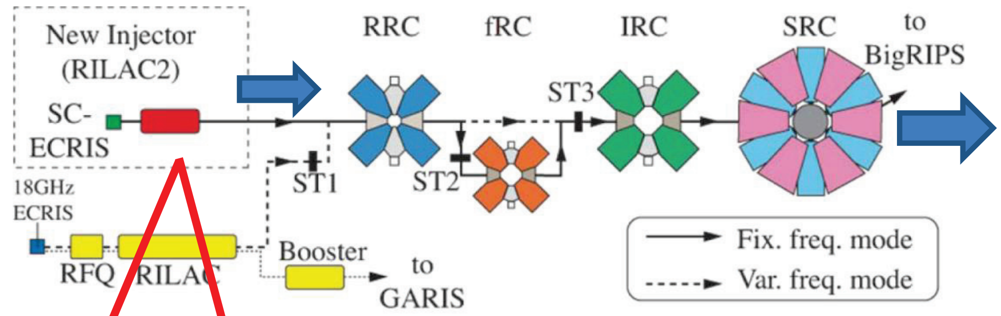
Flexible Operation Modes



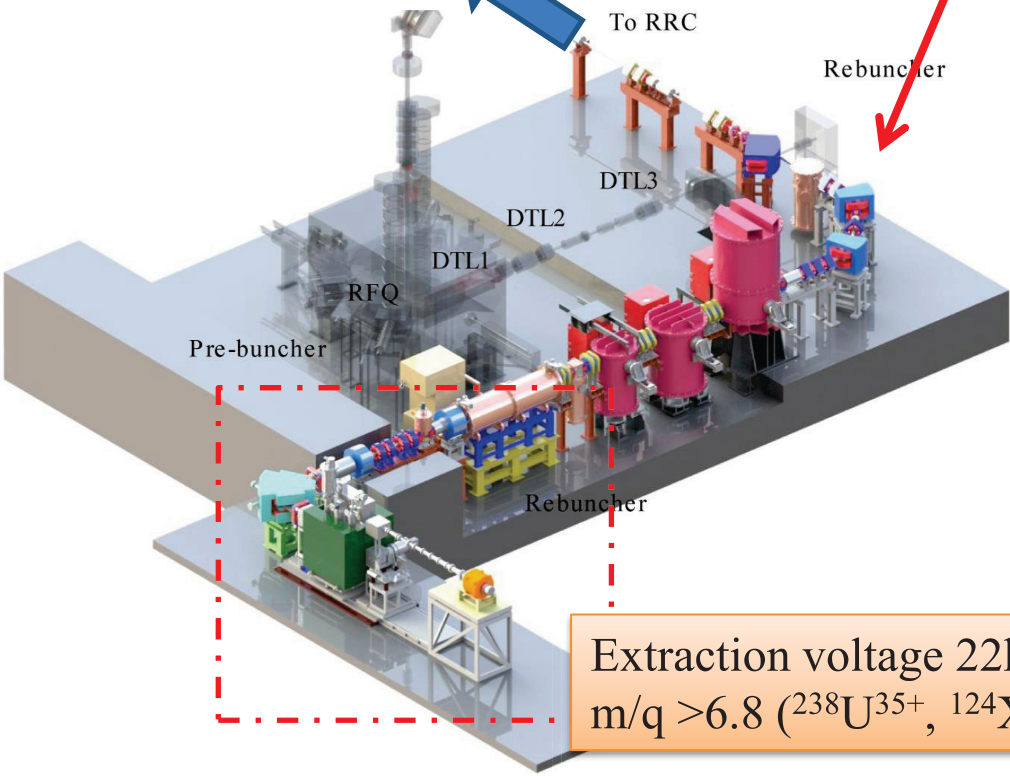
RILAC II

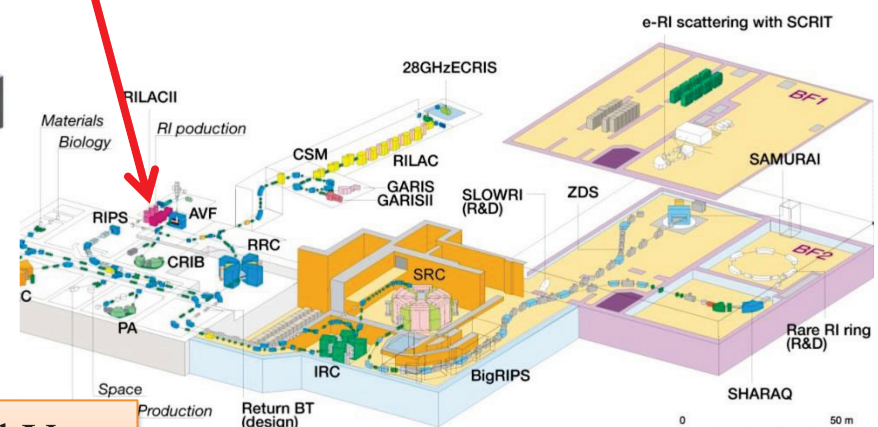
New injector system

~0.6MeV/u $^{238}U^{35+}$, $^{124}Xe^{19+}$



345MeV/u ^{238}U, ^{124}Xe

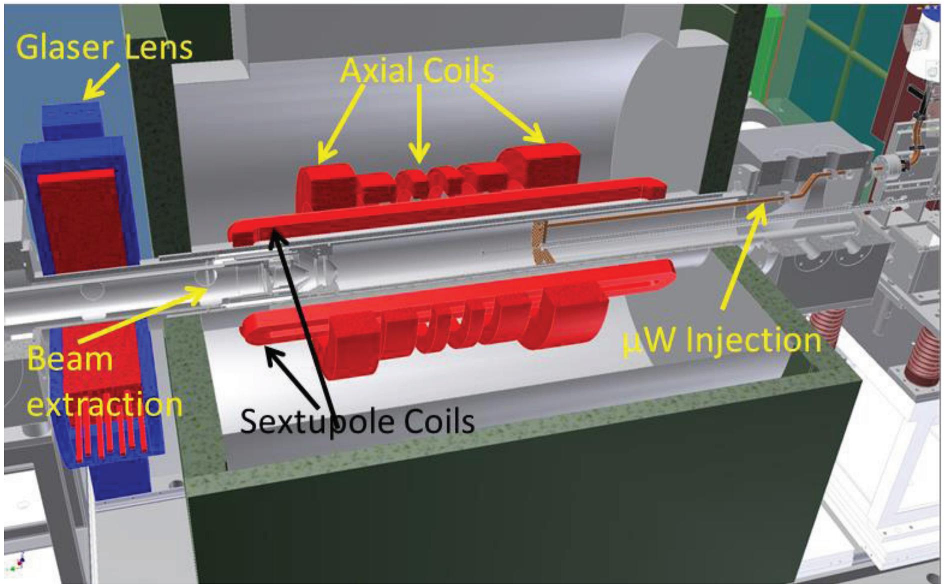


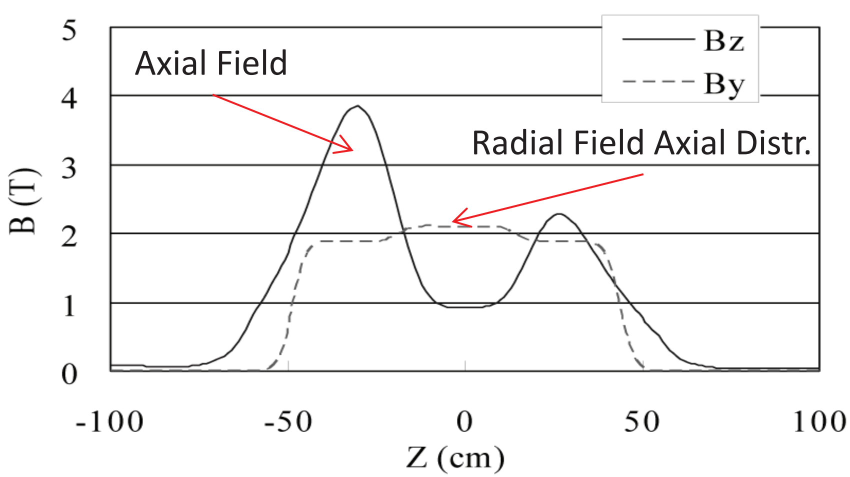


Extraction voltage 22kV
m/q >6.8 ($^{238}U^{35+}$, $^{124}Xe^{19+}$)

Courtesy of T. Nakagawa

SC-ECRIS





- Frequency: 28 GHz/10 kW
- Six axial solenoid coils:
  - Maximum flexibility of axial field configuration
  - B_{inj} = 3.8 T, B_{min} < 1.0 T, B_{ext} = 2.3 T
- Sextupole Coils: B_{rad} = 2.1 T
- Mirror length: 500 mm
- Al Plasma Chamber: Ø150 mm ID
- Plasma volume: >10 L
- Max. Extraction HV: 40 kV
- Cryogenics solution:
  - 3-stage design: 300 K-70 K-20K-4.2 K
  - 2 GM-JT + 4.2 K GM + 2 GM-45 K/10 K
  - A dynamic cooling power of 8W

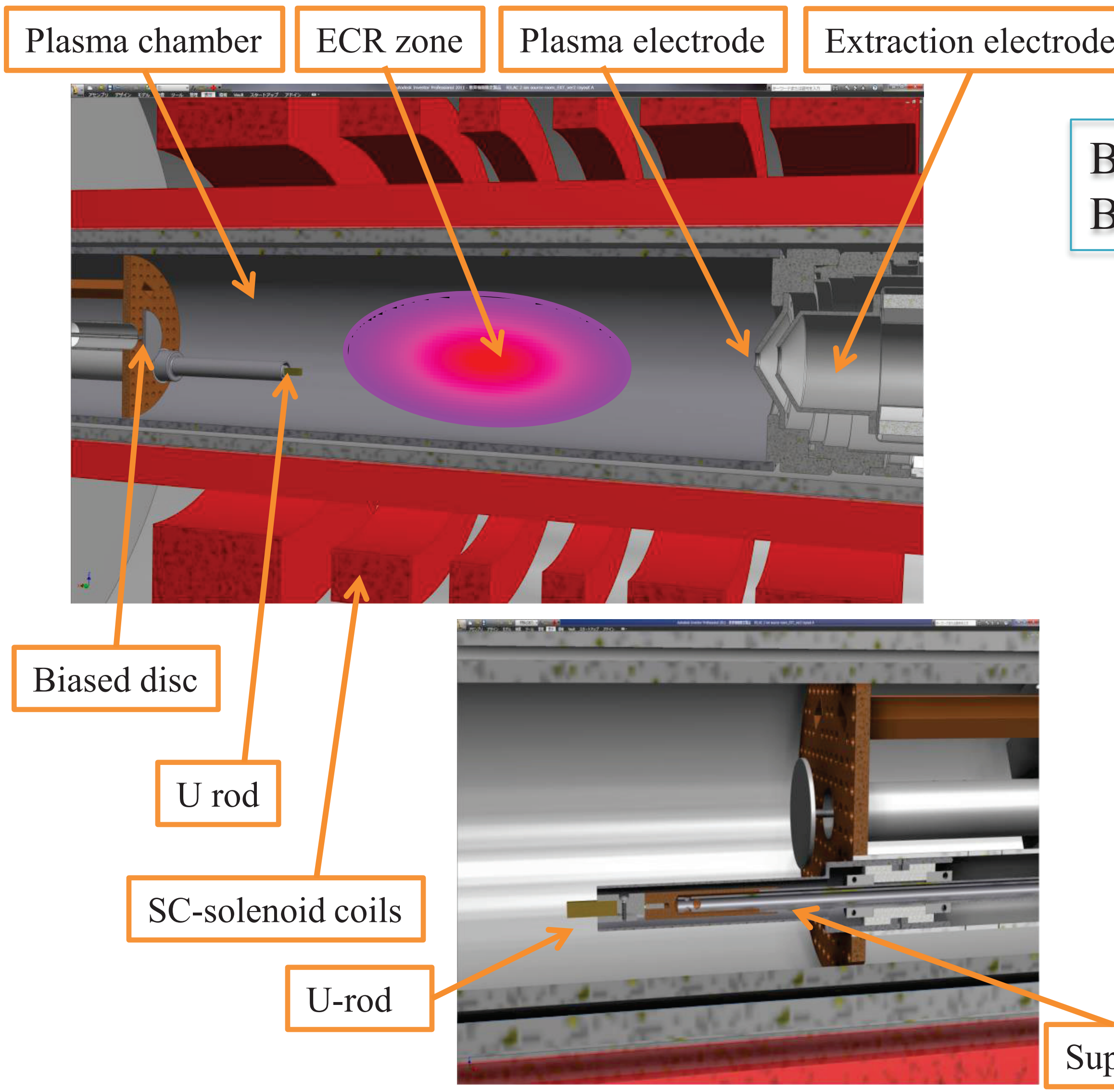
Available in 2009

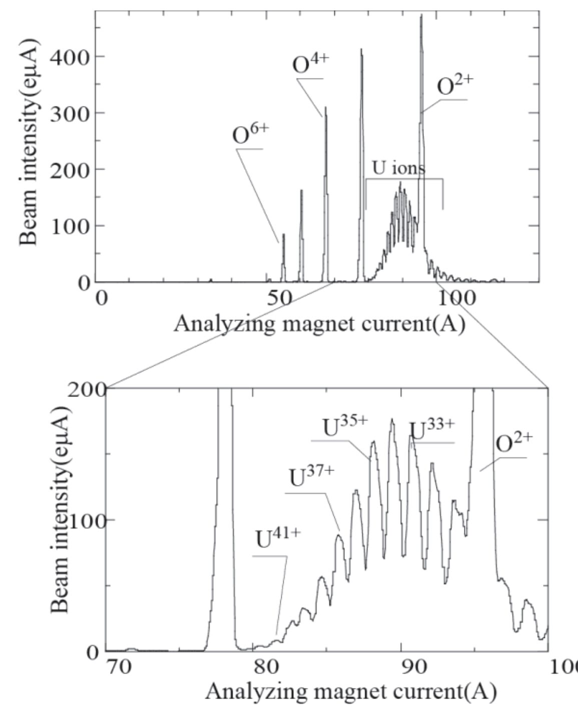
Goal: 15 puA U^{35+}

Uranium Beam Production

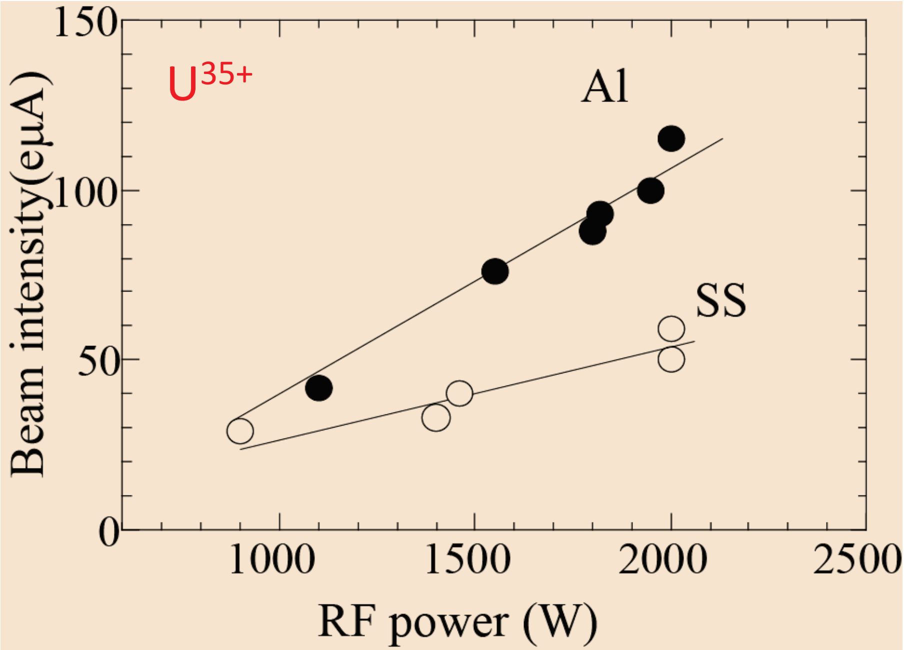
Y. Higurashi, TU1PB04

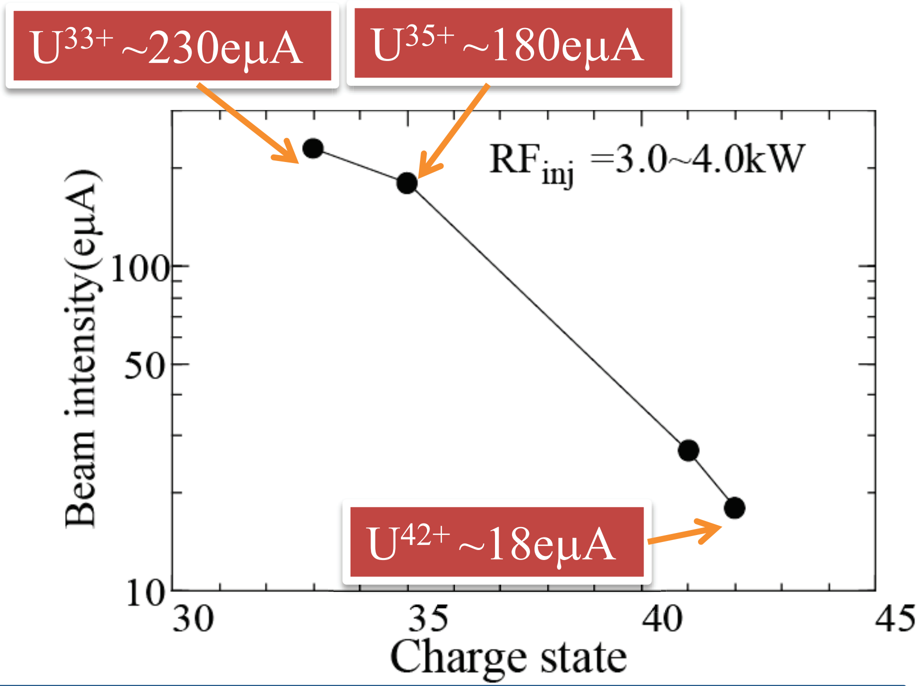
B_{inj}~3.2T, B_{min}~0.6T, B_{ext}~1.9T
B_r~1.9T

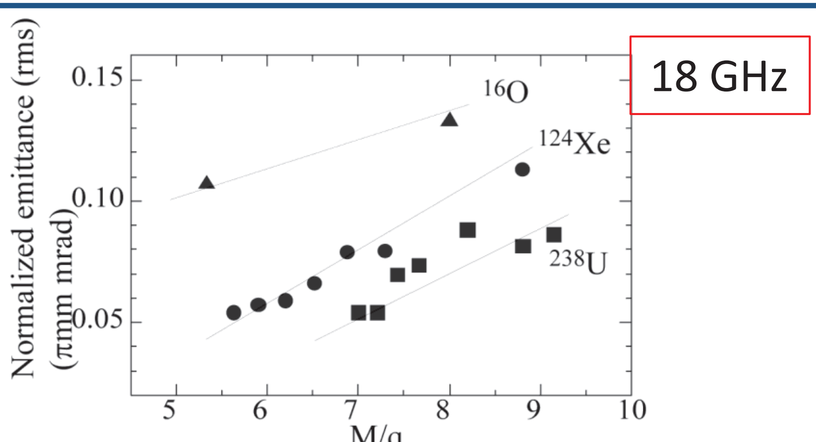


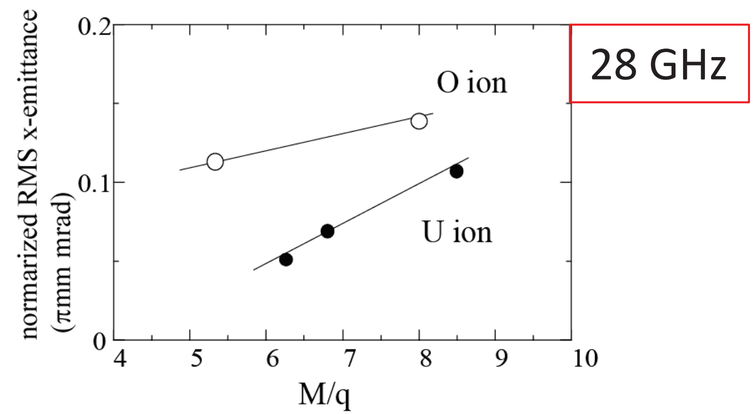


Intense U Beam





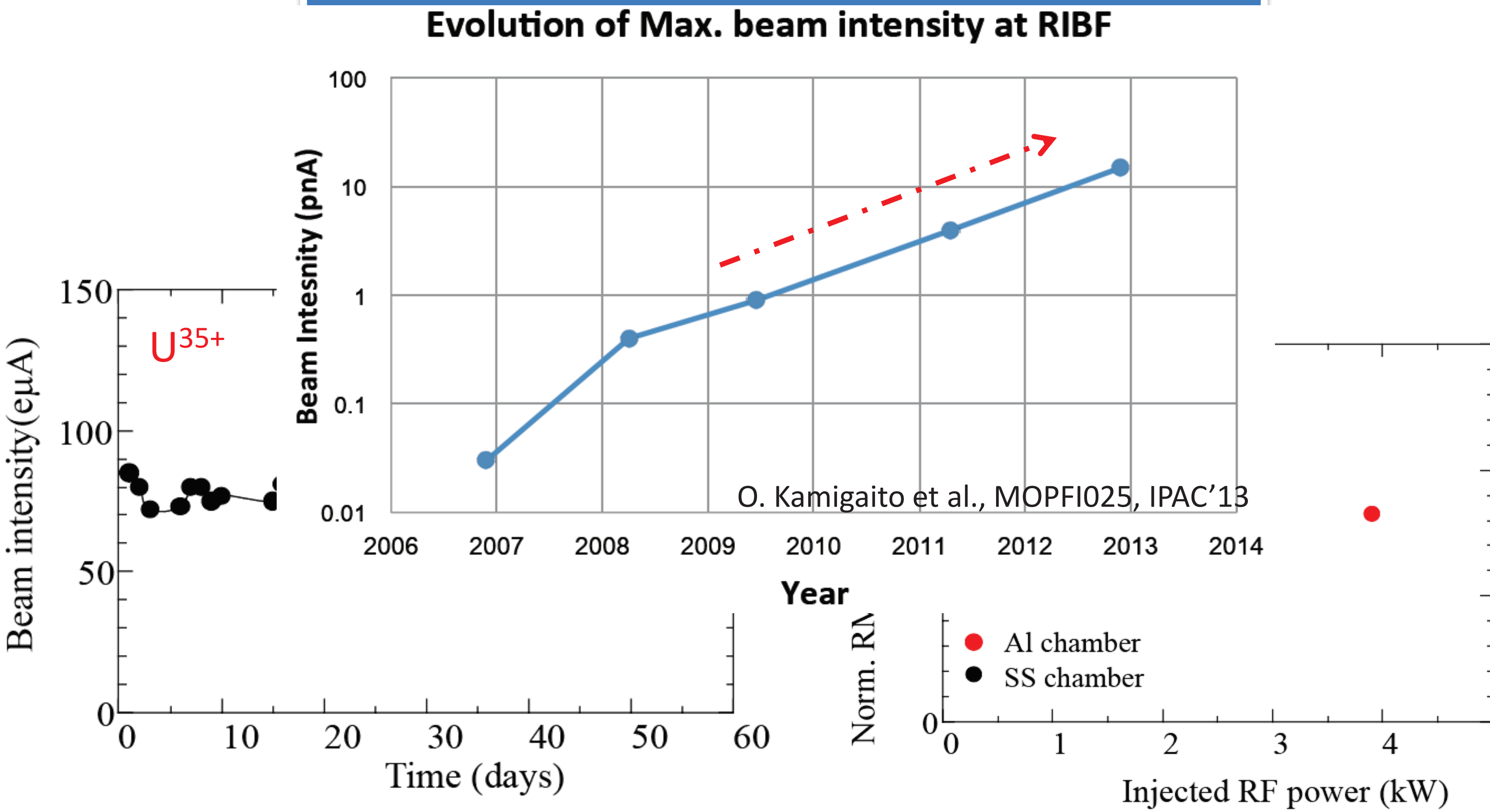




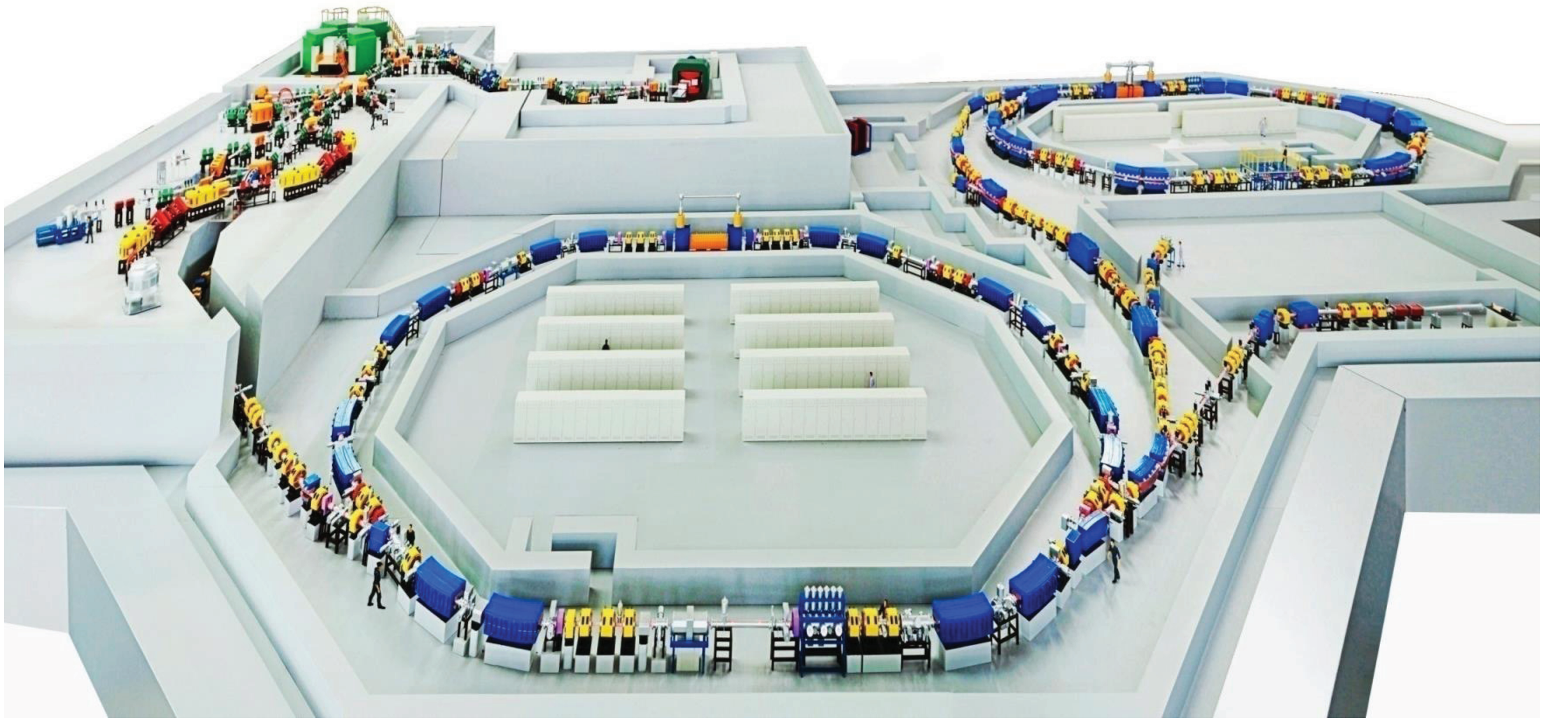
U^{35+} for Routines

U^{35+} beam production with sputtering method

RF power	~ 1.3kW
average beam intensity	~86 eμA

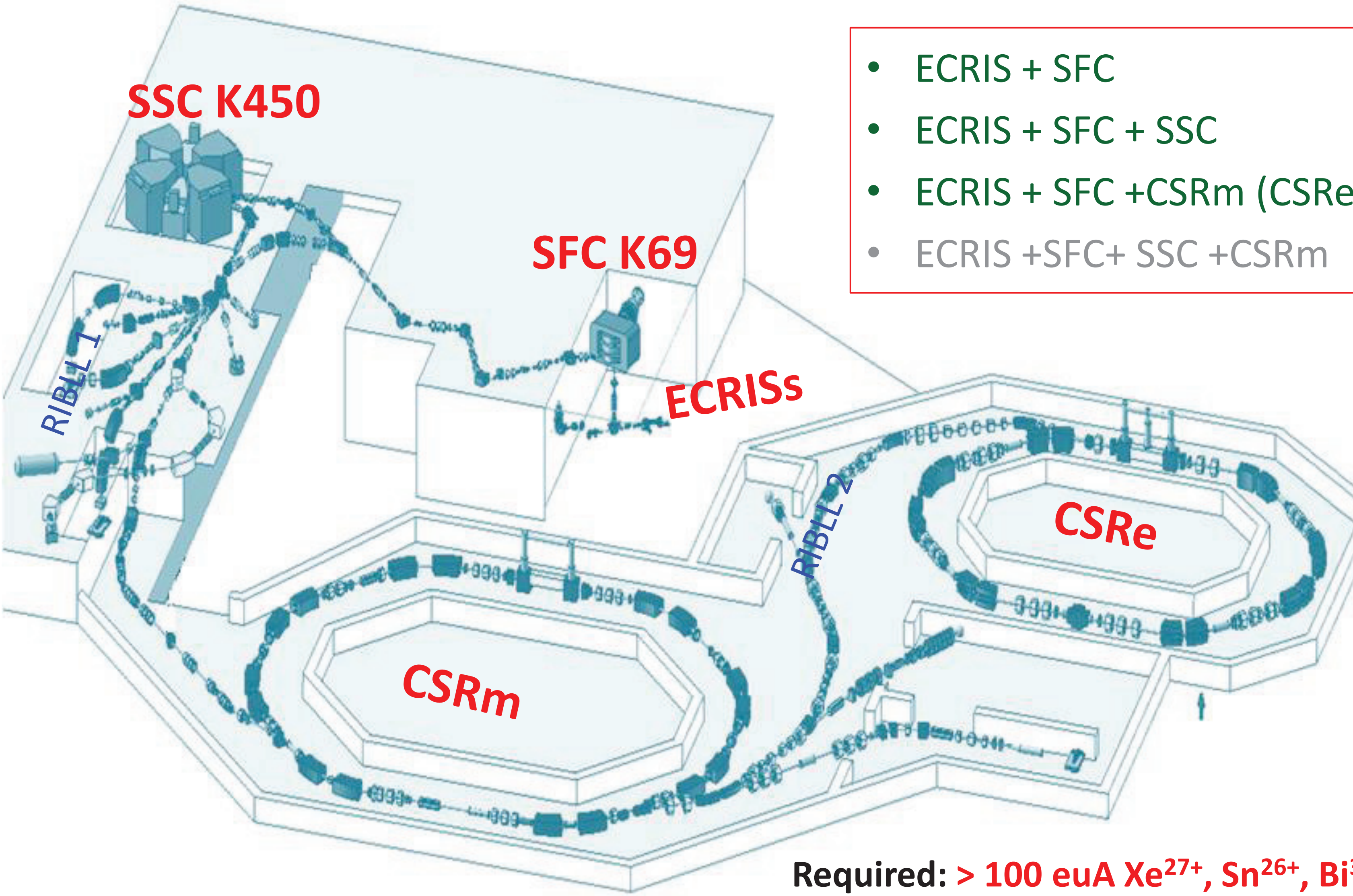


HIRFL/IMP



- More than 13,000 hours operation of a 3rd Gen. SECRAL for HIRFL
- High performance ECRIS: the only solution to make the facility efficient and more attractive to researchers

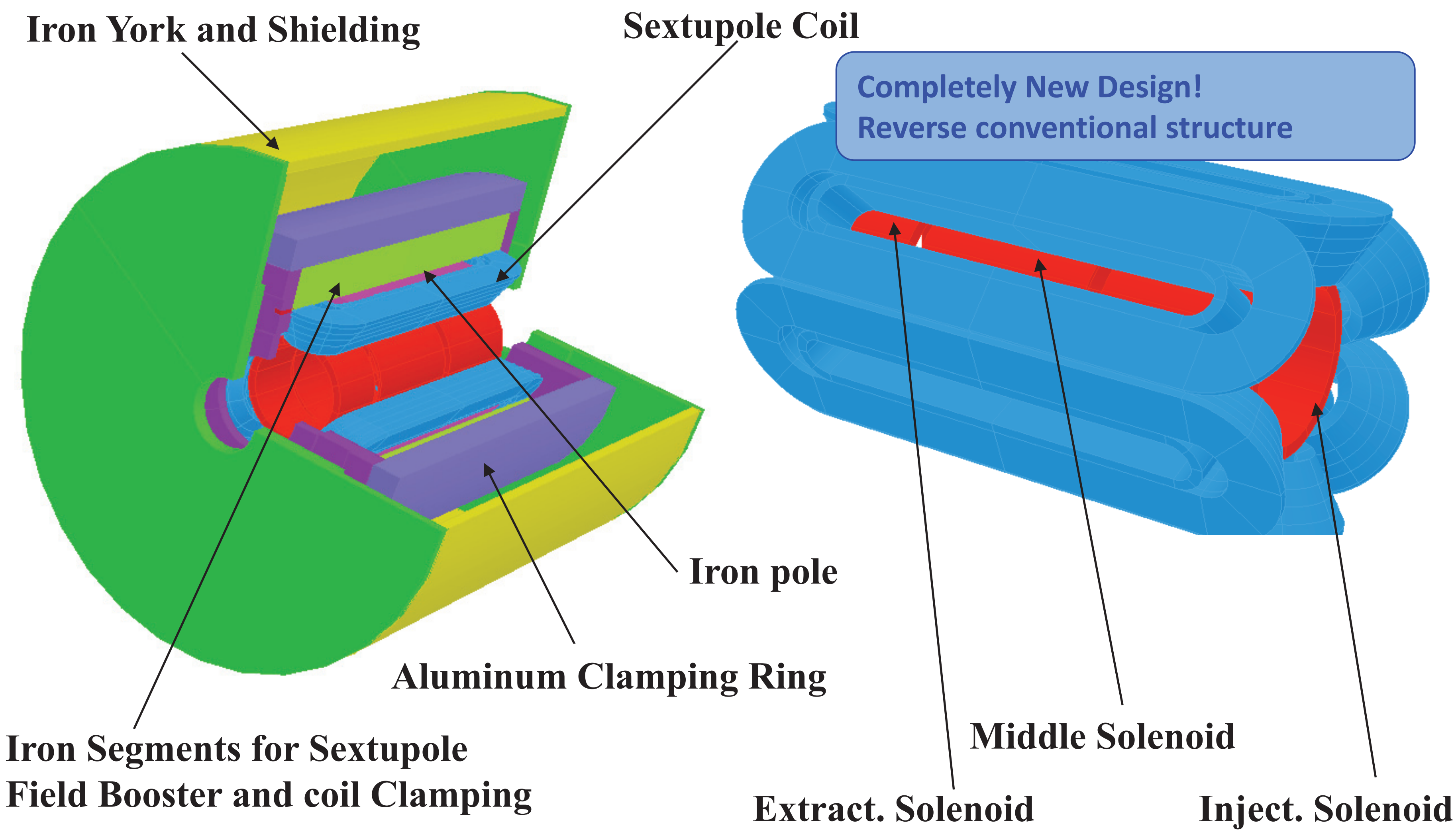
Operation Scheme



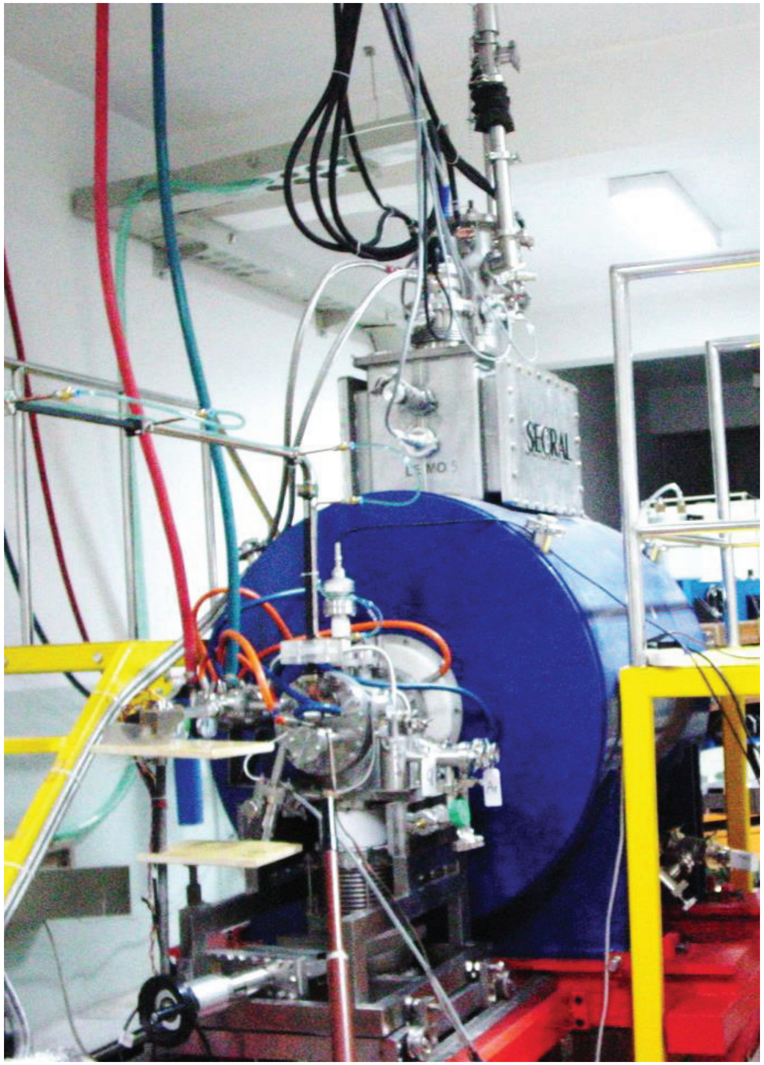
- ECRIS + SFC
- ECRIS + SFC + SSC
- ECRIS + SFC +CSRm (CSRe)
- ECRIS +SFC+ SSC +CSRm

Required: **> 100 euA Xe^{27+}, Sn^{26+}, Bi^{31+}...**

SECRAL Concept



SECRAL Source



Available in 2005

Main Features

Frequency: 18- 28 GHz

3 axial solenoids providing mirror fields:

3.7 T, 0.8 T, 2.2 T

Mirror length: 420 mm

Sextupole field at chamber inner wall: 2.0 T

Warm bore size: Ø140 mm

Plasma chamber: Max. Ø126 mm ID

Plasma volume: 5.2 L

Max. extraction HV: 25 kV

Ta shielding: 1.5 mm

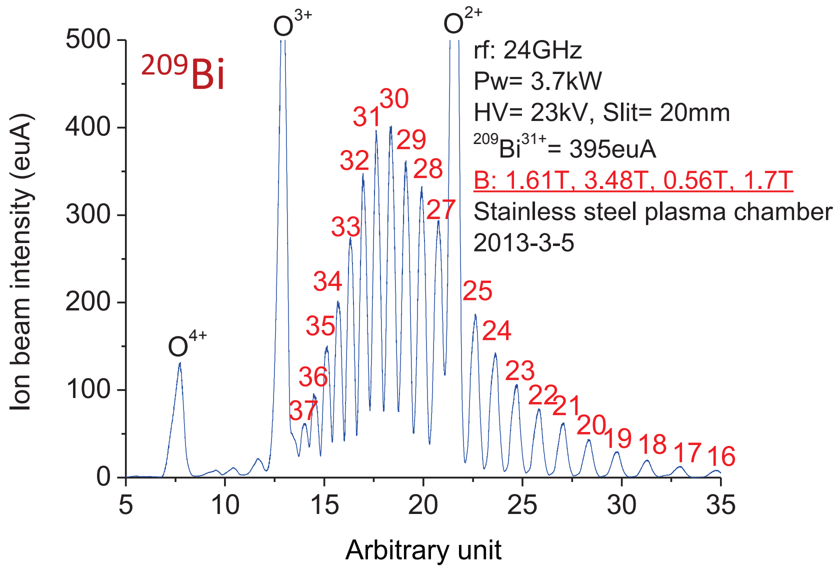
Insulator: PEEK

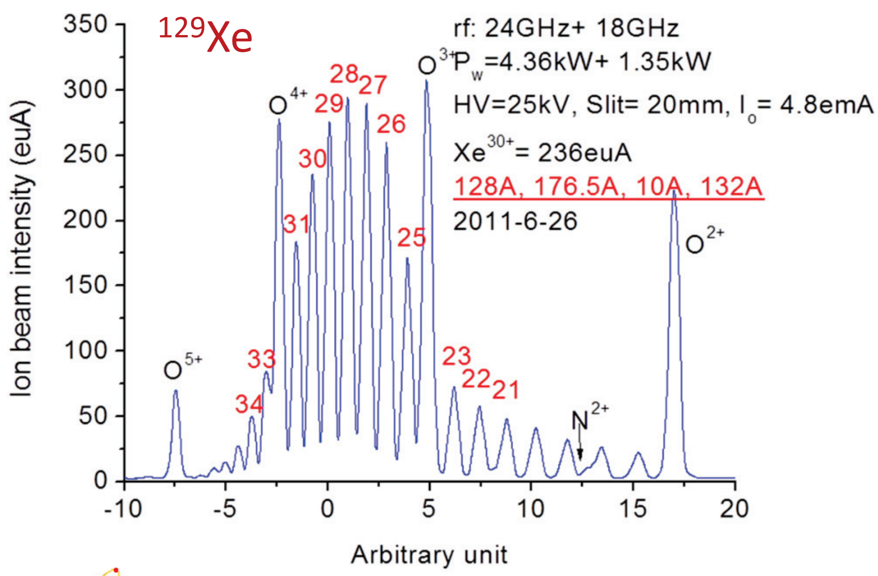
Microwave:

18 GHz: 3.0 kW Max. available

24 GHz: 7.0 kW Max. available

Intense HCI beams with SECRAL



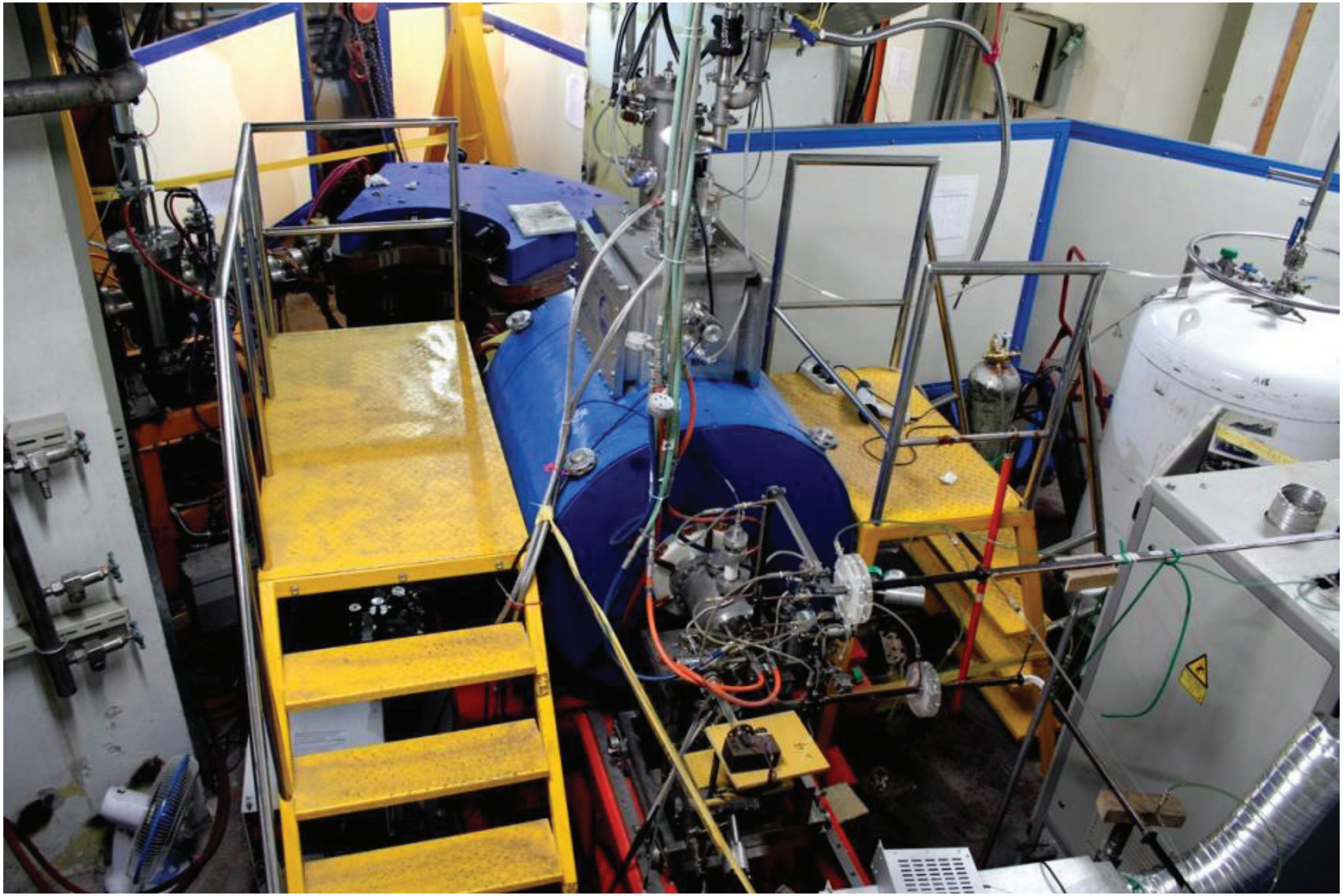


Intense HCI beams with SECRAL (euA)

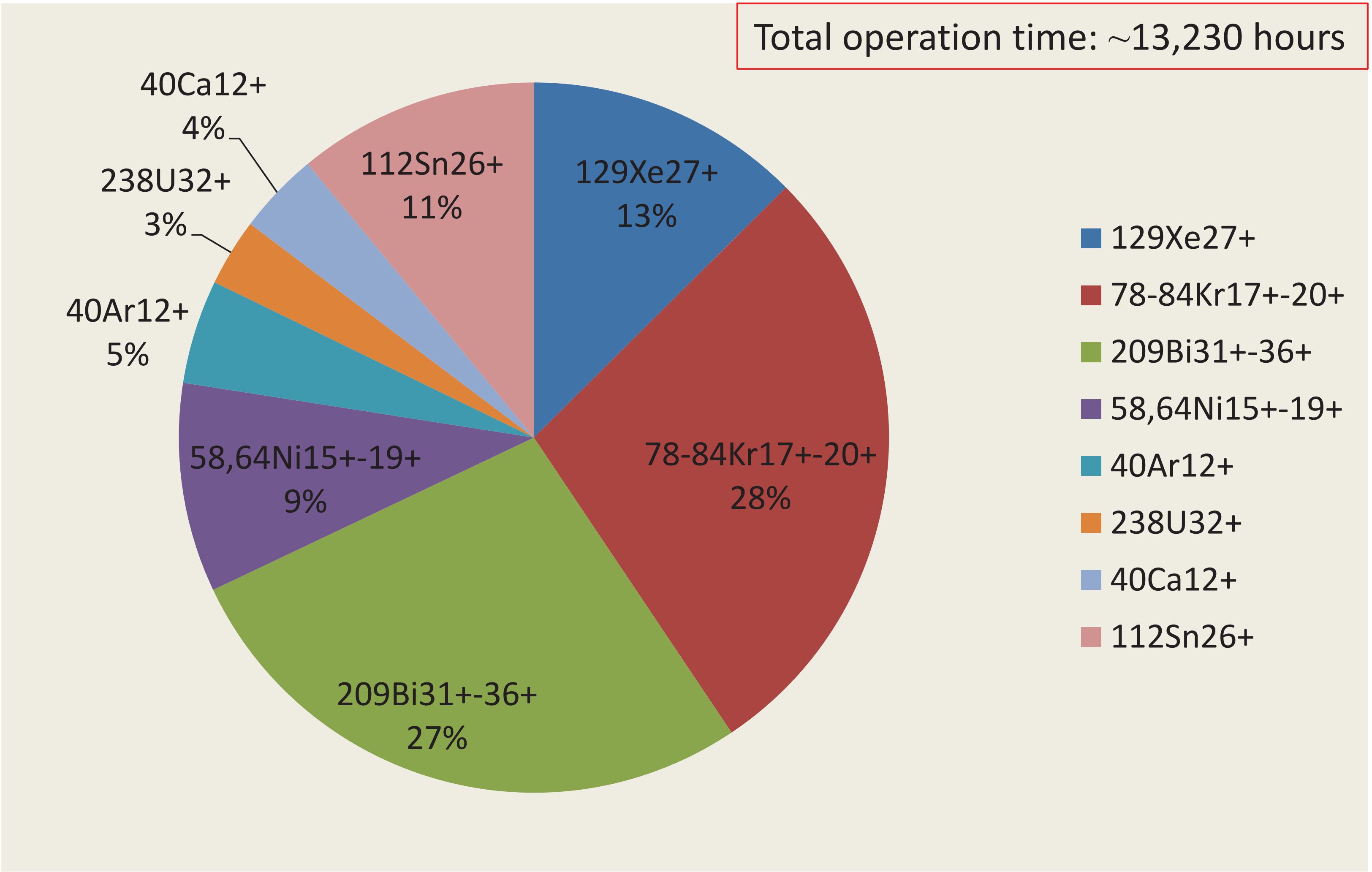
Xe	18GHz 2007	24GHz 2009	24GHz 2011
27+	306	455	
30+	101	152	236
31+	68	85	190
35+	16	45	64
38+	6.6	17	22.6
42+	1.5	3	

Bi	SECRAL 18 GHz	SECRAL 24+18GHz
30+	-	422
31+	150	396
36+	62	160
43+	17.3	38
48+	4.2	11.5
50+	1.5	4.3
51+	-	2.3
54+	-	0.2

SECRAL on-line operation (2007)



SECRAL Operation Status



Nuclear Physics Results

PRL **106,** 112501 (2011) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2011

Direct Mass Measuremen
Th

X. L. Tu,[1,2] H. S. Xu,[1,*] M. Wa
J. W. Xia,[1] G. Audi,[7] K. Blaum,[3]
R. S. Mao,[1] B. Mei,[1] P. Shuai,[8]
T. Yamaguchi,[10] Y. Yamagu

[1]*Institute of Modern P*
[2]*Graduate Universi*
[3]*Max-Planck-*
[4]*GSI Helmholtzze*
[5]*Department of Physi*
[6]*Department c*
and the Joint Institute for
[7]*CSN*
[8]*Department of Modern Physics*
[9]*Insi*
[10]*Dep*

Mass excesses of sh
to be −46 921(37), −
separation energy of −
burst model calculatic
passes through ^{64}Ge v

DOI: 10.1103/PhysRevL

PRL **109,** 102501 (2012) PHYSICAL REVIEW LETTERS week ending 7 SEPTEMBER 2012

Mass Measurements of the Neutron-Deficient ^{41}Ti, ^{45}Cr, ^{49}Fe, and ^{53}Ni Nuclides: First Test of the Isobaric Multiplet Mass Equation in *fp*-Shell Nuclei

Y. H. Zhang,[1] H. S. Xu,[1] Yu. A. Litvinov,[1,2] X. L. Tu,[1] X. L. Yan,[1,3] S. Typel,[2] K. Blaum,[4] M. Wang,[1,4,5] X. H. Zhou,[1]
Y. Sun,[6,1] B. A. Brown,[7]
R. S. Mao,[1] B. Mei,[1]

[1]*Institute of Mo*
[2]*GSI Heln*
[3]*Graduate U*
[4]*Max*
[6]*Department*
[7]*Department of Physic*
[8]*Department of Modern*

Isochronous
HIRFL-CSR f
^{41}Ti, ^{45}Cr, ^{49}F
test for the firs
IMME is inco

NUCLEAR ASTROPHYSICS

Star bursts pinned down

One of the main uncertainties in the burn-up of X-ray bursts from neutron stars has been removed with the weighing of a key nucleus, ^{65}As, at a new ion storage ring.

Philip Walker

Understanding how the chemical elements formed in stars, and how their formation is related to observable astrophysical phenomena, requires close cooperation between those astrophysicists who study the ways that stars burn and the nuclear physicists who study interactions between atomic nuclei. A fertile area of common interest is the nature of X-ray bursts — flashes of intense radiation that can last from tens to hundreds of seconds. These come from binary star systems, where material falls from the less dense companion star onto the surface of a collapsed neutron star.

Energy is generated by a rapid succession of proton captures by nuclei, but eventually any given nucleus can hold no more protons, and it must wait to beta-decay — a relatively slow process, because it depends on the weak nuclear interaction. Consequently, these 'waiting point' nuclei assume a key role in determining the time evolution of the radiation burst. Yet, in some cases, it is simply not known whether or not a nucleus can keep hold of another proton. By measuring the mass of the arsenic nucleus ^{65}As — a so-called proton-unbound nucleus, in which a captured proton remains unbound or only loosely bound to the nucleus — Xiaolin Tu and colleagues[1] have now shown that the germanium isotope ^{64}Ge is most likely not, after all, a waiting point in the evolution of X-ray bursts.

There is a long history of laboratory experiments being used to help understand

Figure 1 | A new facility for nuclear physics: the cooler storage ring, now in operation at the Institute of Modern Physics, Lanzhou, in western China.

PRL 106,112501 (2011)

PRL 109,102501 (2012)

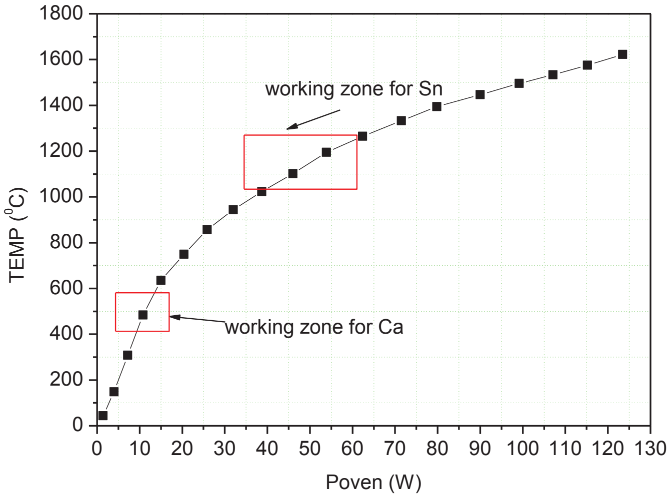
Nature Physics 7(2011) 281-282

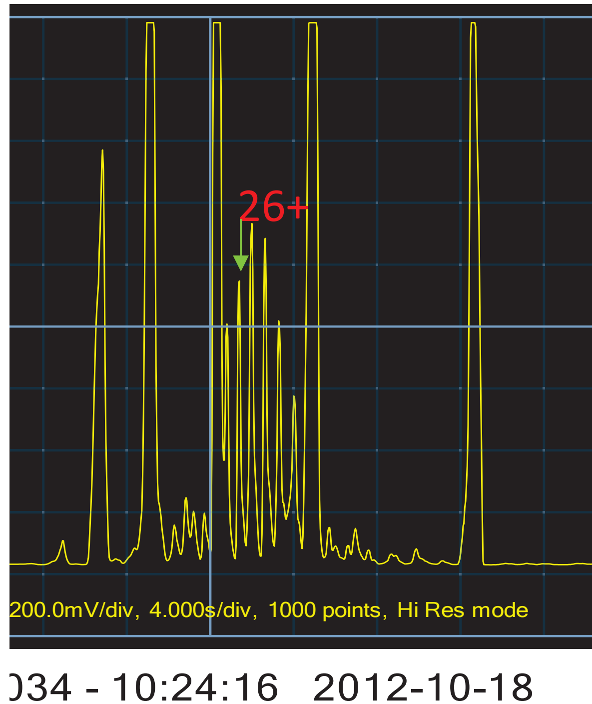
$^{112}Sn^{26+}$ Beam

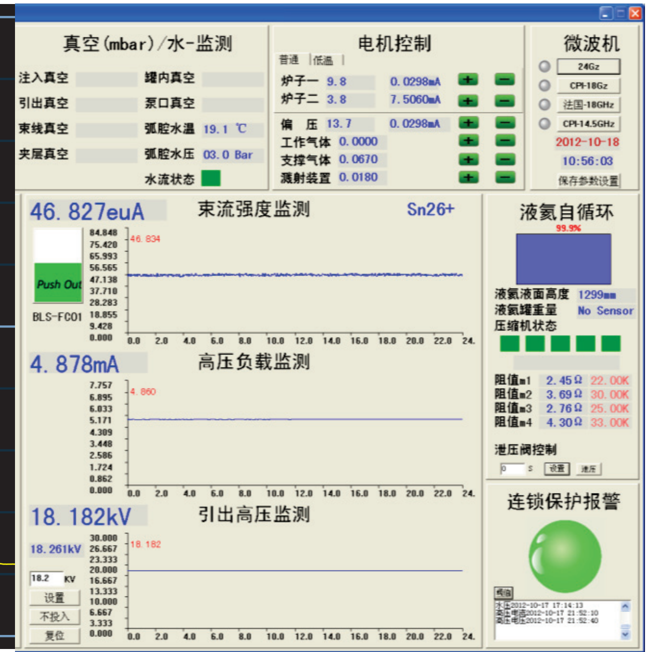
^{112}Sn MP：232 ^{0}C（505K）

Production Temp.:

9.8 V×4.5A≈ 1100 ^{0}C







- **$^{112}Sn^{26+}$:40~70 eμA, 61 days straight**
- **Average material consumption rate of 1.4 mg/h**

Summary

- Heavy ion cyclotrons need high performance ECRISs
  - all 5 SC-ECRISs are in service to cyclotrons
- High performance ECRISs are essential to heavy ion cyclotron:
  - performance enhancement
  - flexible operation modes
  - Produce attractive beams
- Combination of ECRIS + Cyclotron:
  - Still the most powerful CW heavy ion machine
  - 345 MeV/u CW uranium beam
- To improve operation efficiency:
  - Collimation system
  - Improve metallic beam production technique
  - May 4th Gen. ECRIS not necessary?

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T. Nakagawa	RIKEN, Japan
T. Thuillier	LPSC, France
H. W. Zhao	IMP/CAS, China

Thanks !!