ECRIS Developments Towards Intense High Brightness Highly-charged Ion Beams

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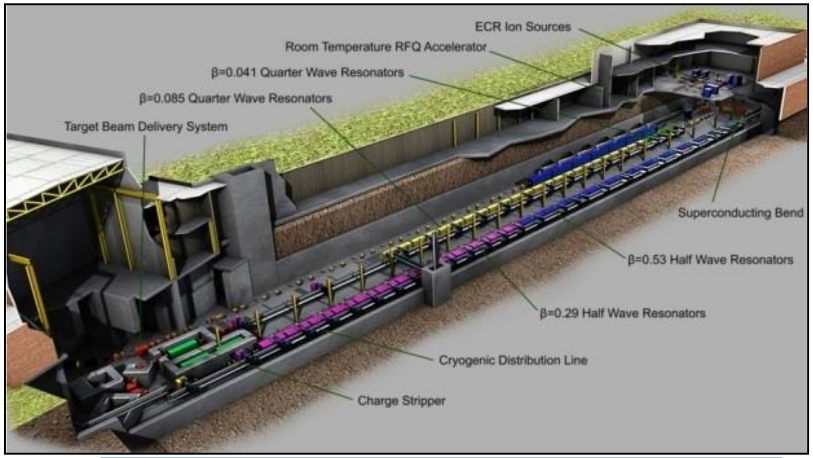
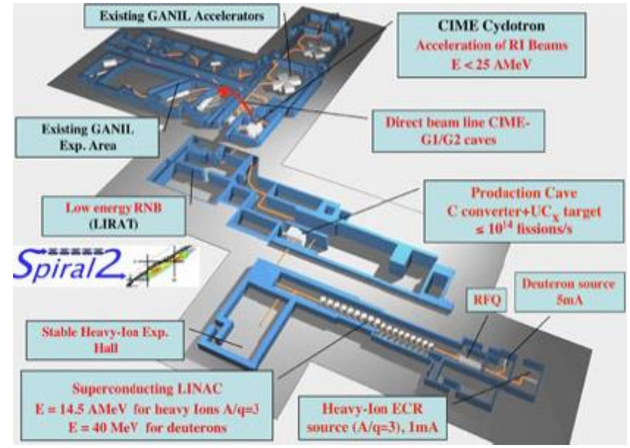
Outline

- Intense HCI Beam Needs
- HCI Production with ECRISs
  - Intense Beam Production
  - Ion Source Development
  - Beam Quality Development
- Summary

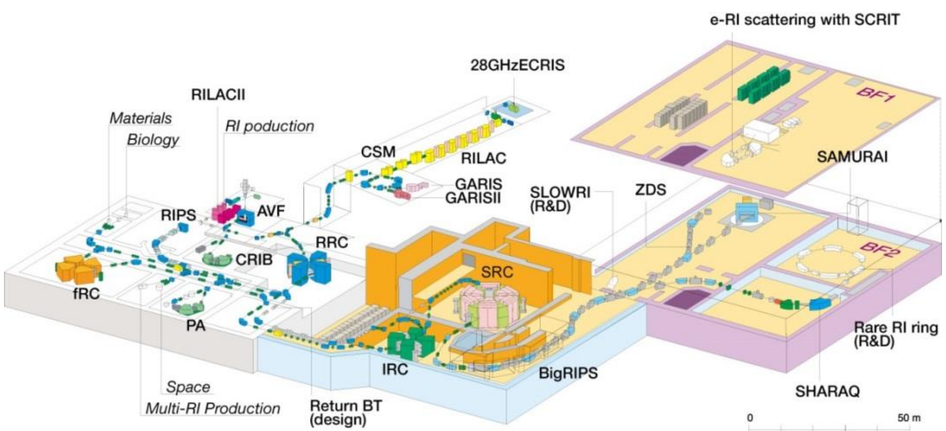
Intense HCI Beam Needs



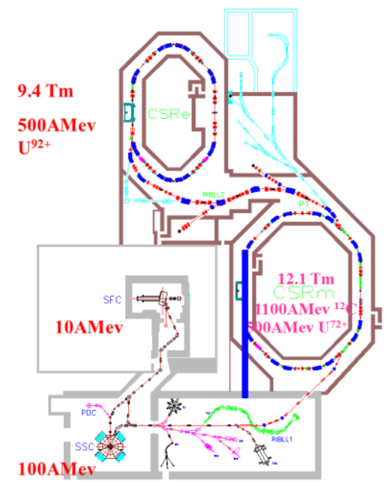
FRIB/ MSU: 13pμA $U^{34+ \& 33+}$/CW



SPIRAL2/ GANIL: 1emA Ar^{12+}/CW

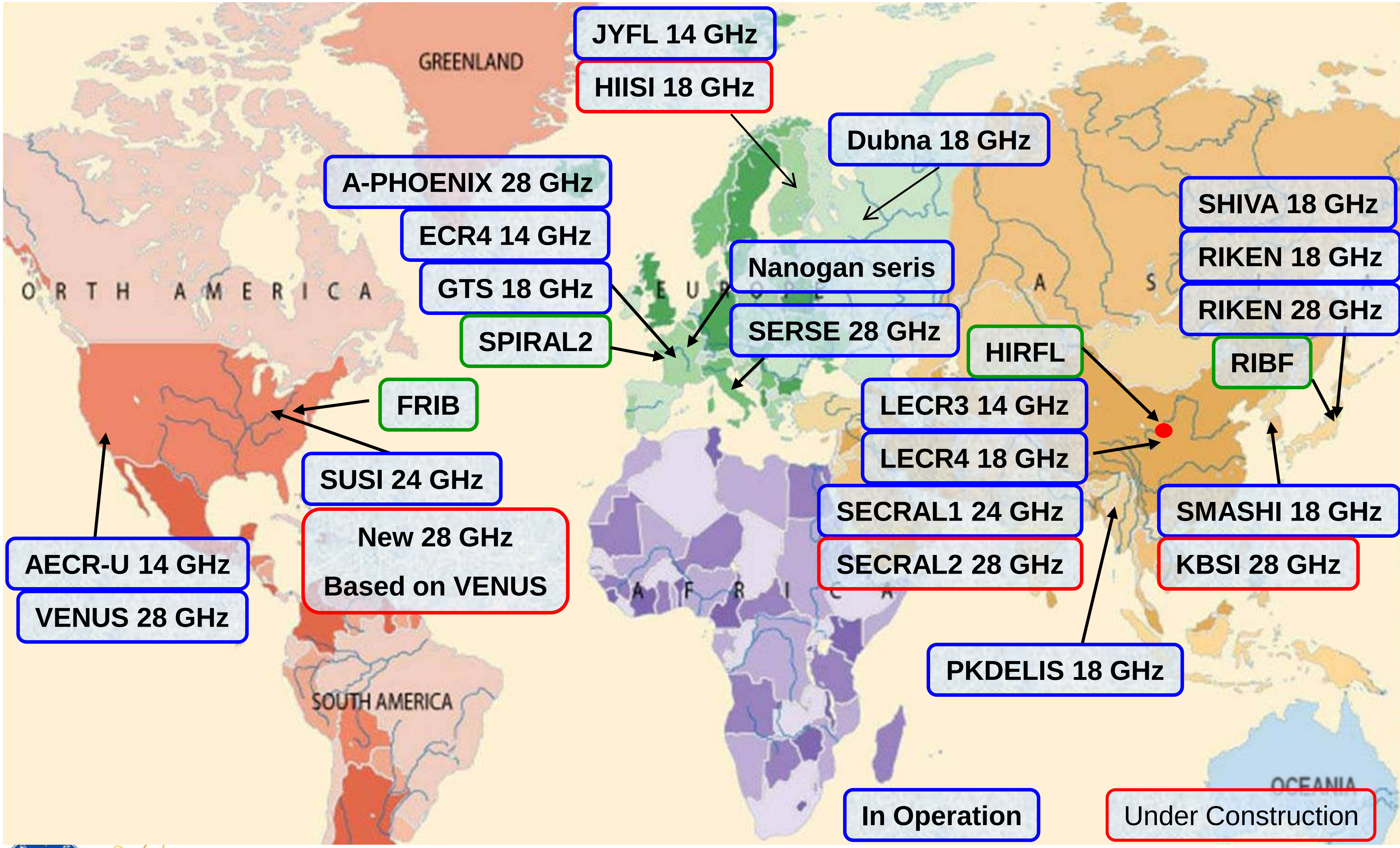


RIBF/ RIKEN: 15pμA U^{35+}/CW

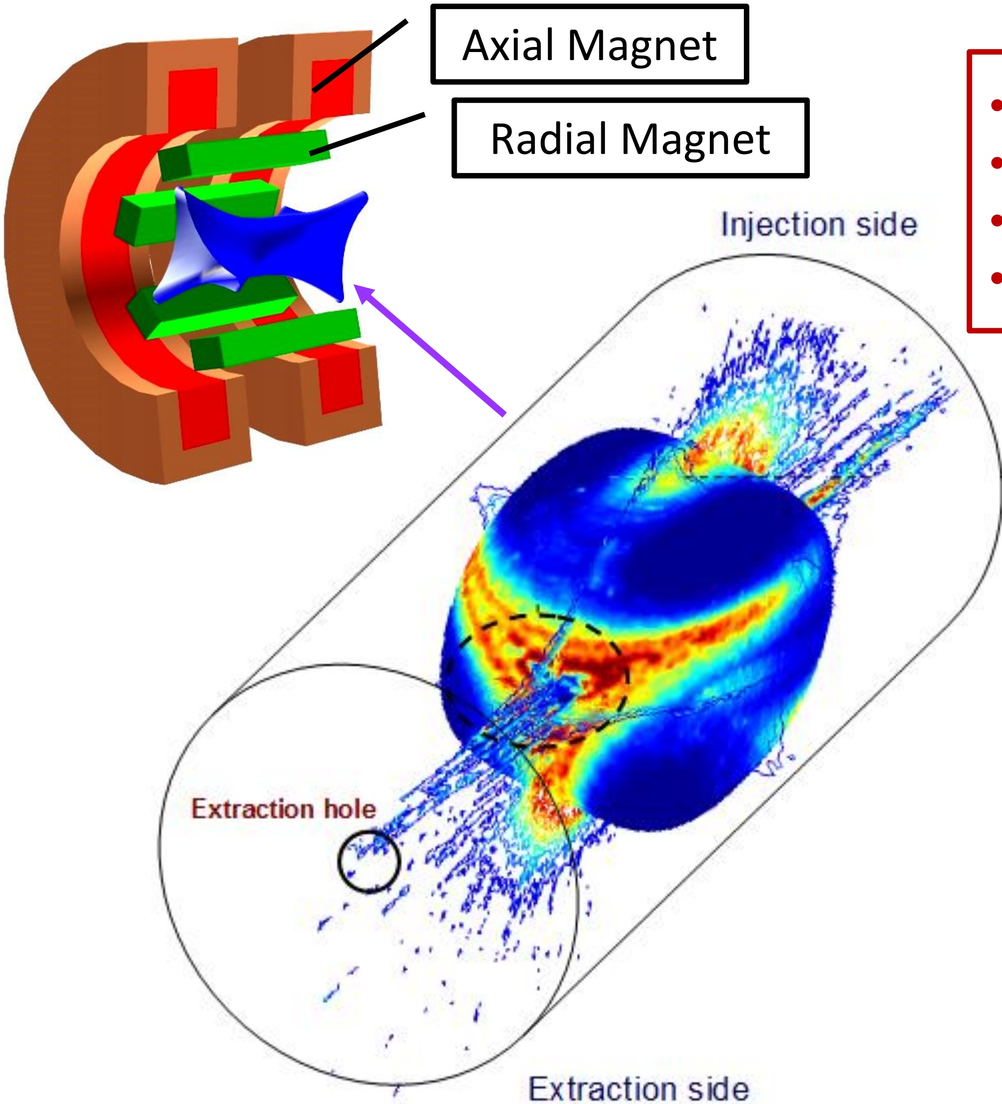


HIRFL/IMP: 100 eμA Xe^{31+}, U^{41+}/CW

Global ECRIS Development



ECR Ion Source



- B_{inj} ~ 3 - 4 B_{ecr} on axis
- B_{ext} ~ 2.2 B_{ecr} on axis (T)
- B_{rad} ~ $2B_{ecr}$
- $|B_{last}|$~2 B_{ecr}

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

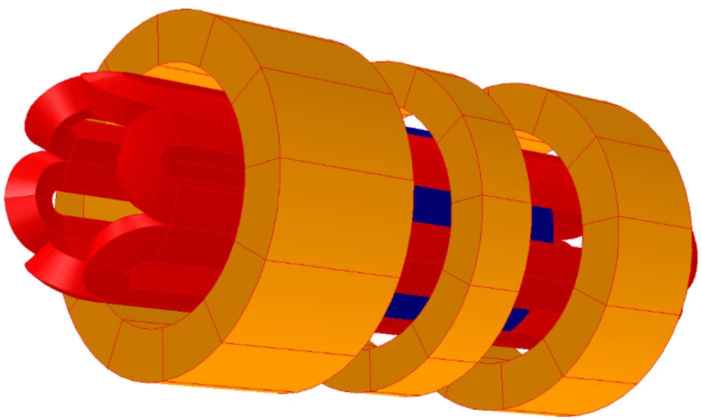
$$I^q \propto \omega^2_{ECR}$$

$$\omega_{ECR} = eB/m_e$$

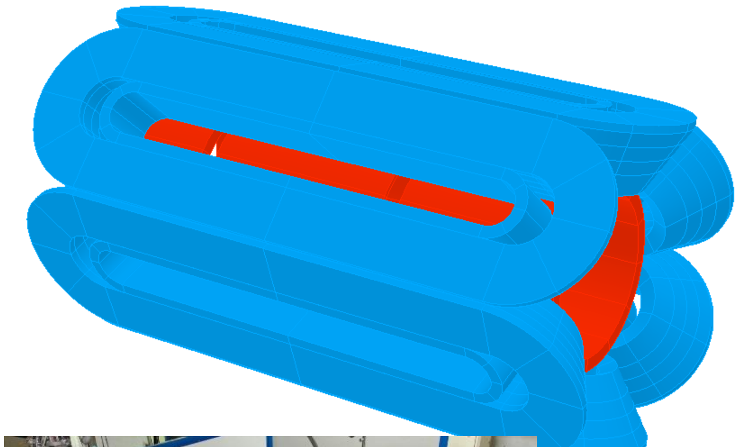
SC-ECRISs

Conventional Structure

Non-conventional Structure



VS

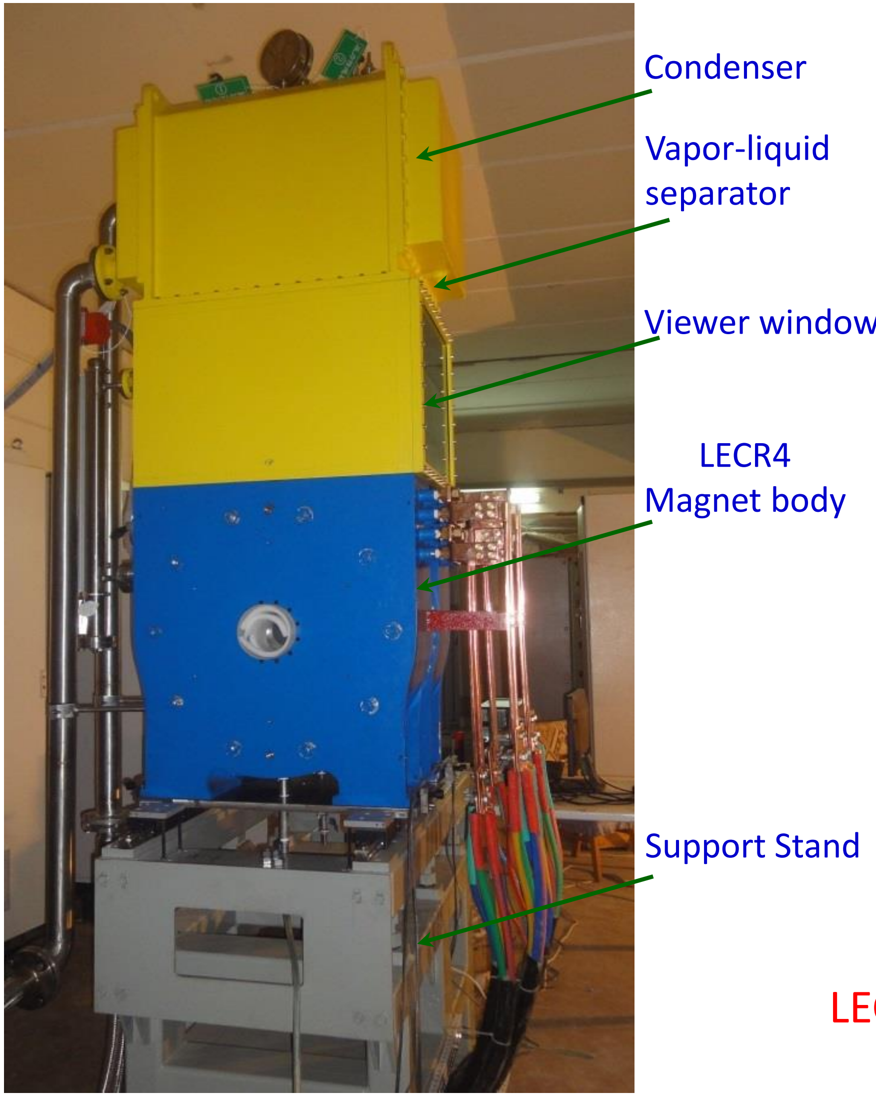


VENUS in LBNL (18-28 GHz)

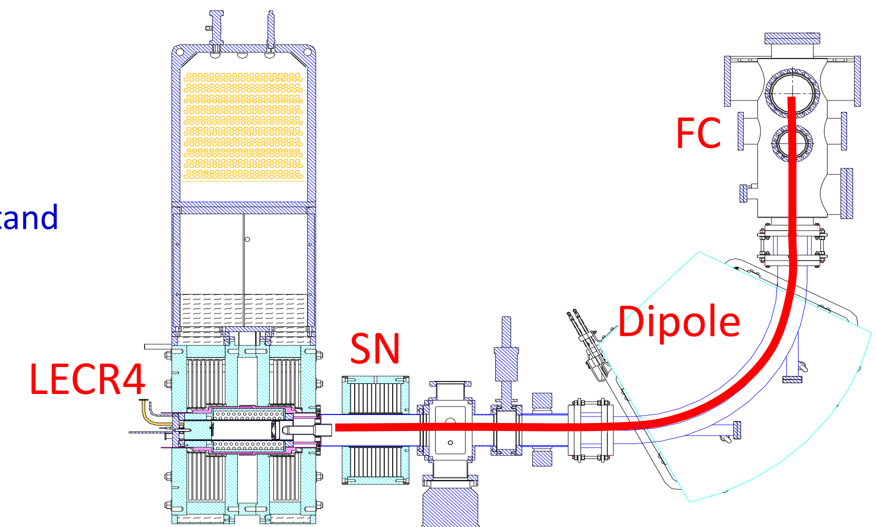
SECRAL in IMP (18-24 GHz)

SERSE and VENUS are pioneers, MS-ECRIS, RIKEN SC-ECR, SuSI…

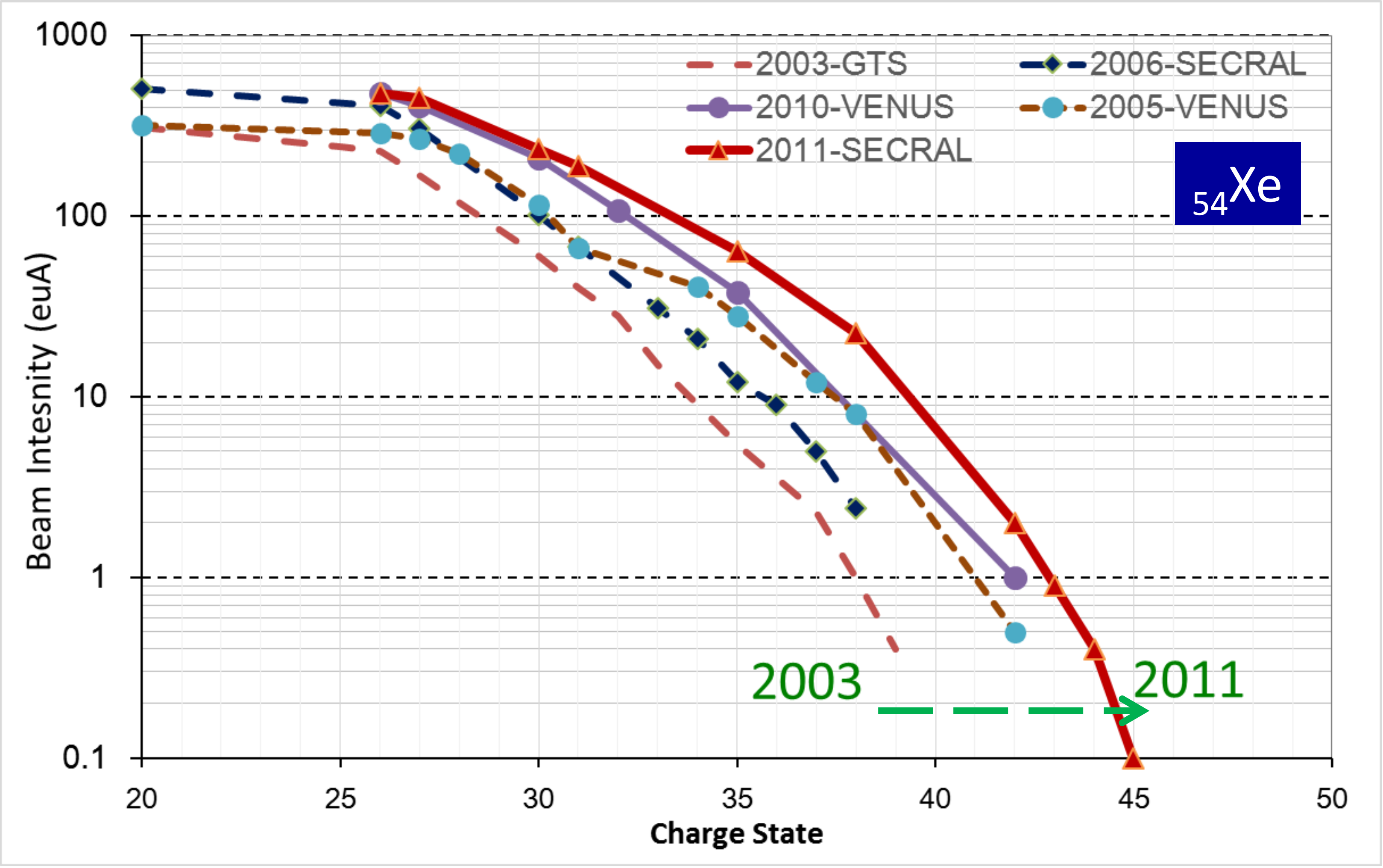
LECR4-an Evaporative Cooling Tech.



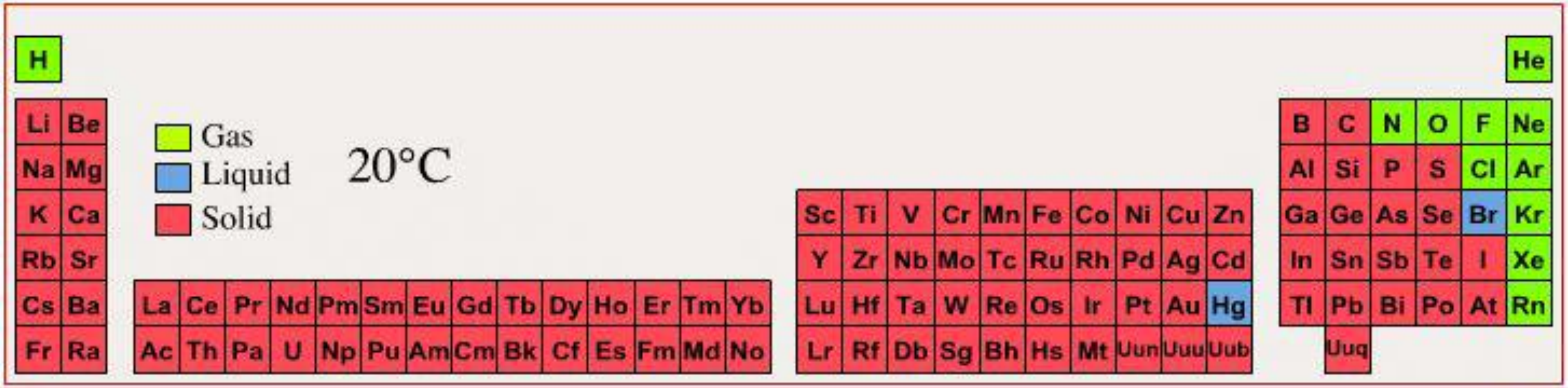
		SECRAL	GTS	LECR3	LECR4
f (GHz)		*18*	*18*	14	18
^{16}O	6^+	2300	1950	780	1970
	7^+	810		235	438
^{40}Ar	8+		1100	1100	1717
	9^+	1100	920	720	1075
	11+	810	510	325	503
^{129}Xe	20+	505	310	160	293
	23+			130	143
^{209}Bi	28+	214			118
	30+	191			78
	32+				51.5

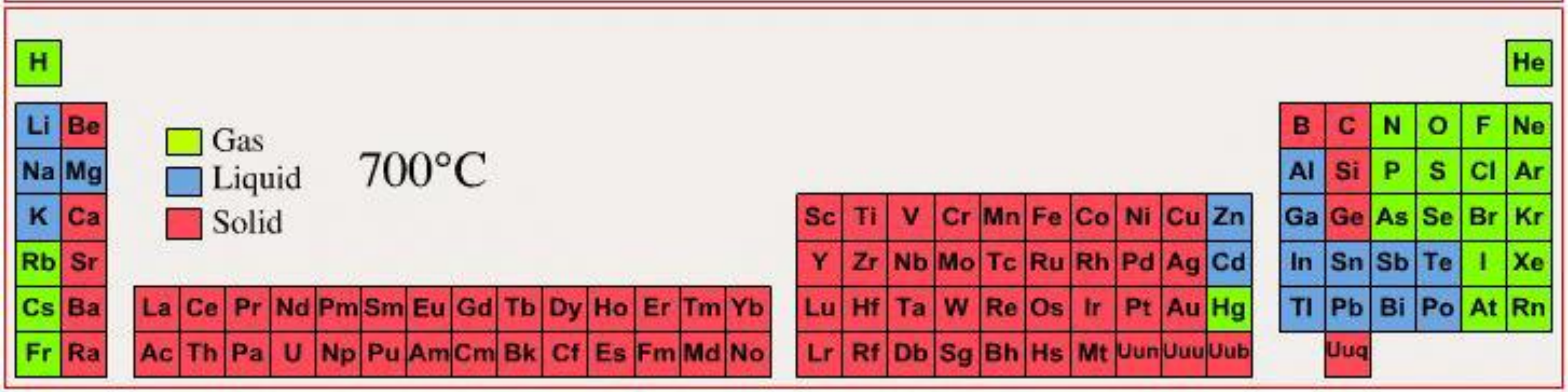


HCI Production



Metallic Beam



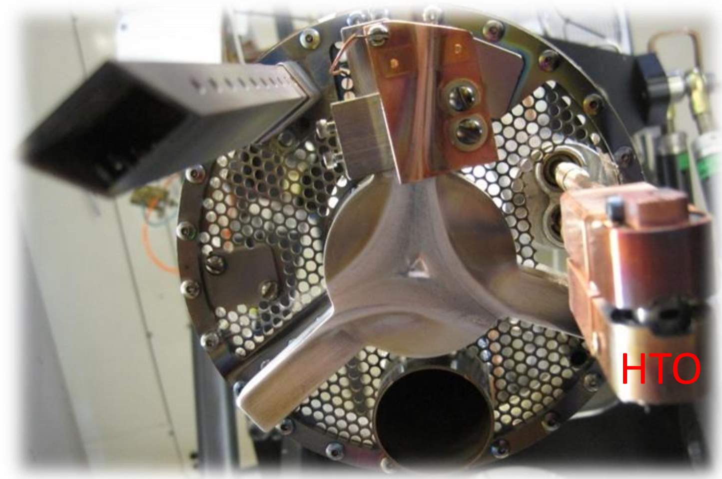


Oven Solution: <700℃--LTO, <1500 ℃--RHO, <2200 ℃--HTO

MIVOC and Sputtering are alternative method for refractory solids

Uranium Beam Production

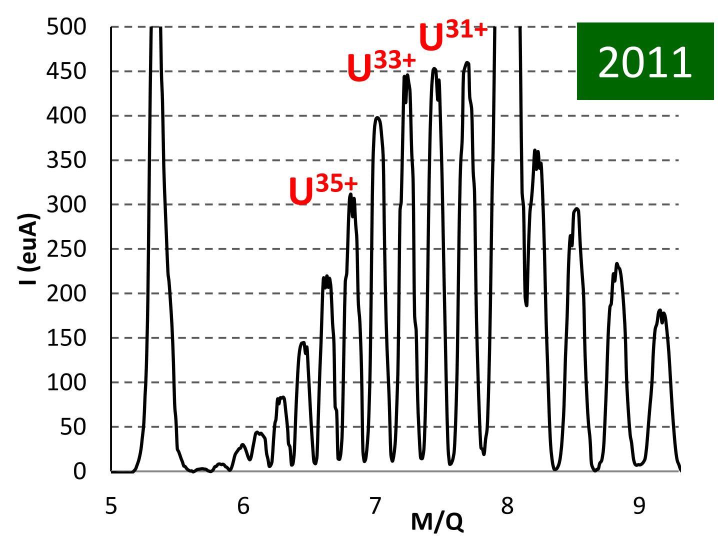
- Operates 650°C-2300°C to vaporize metals
- Improved cooling
- Expands VENUS' metal production capability



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

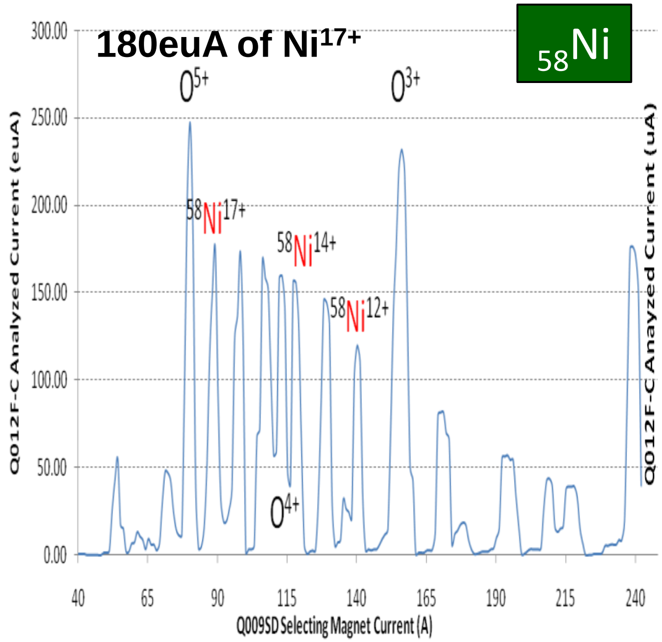
$^{238}U^{33+}$	450eμA
$^{238}U^{34+}$	400eμA
$^{238}U^{50+}$	13eμA

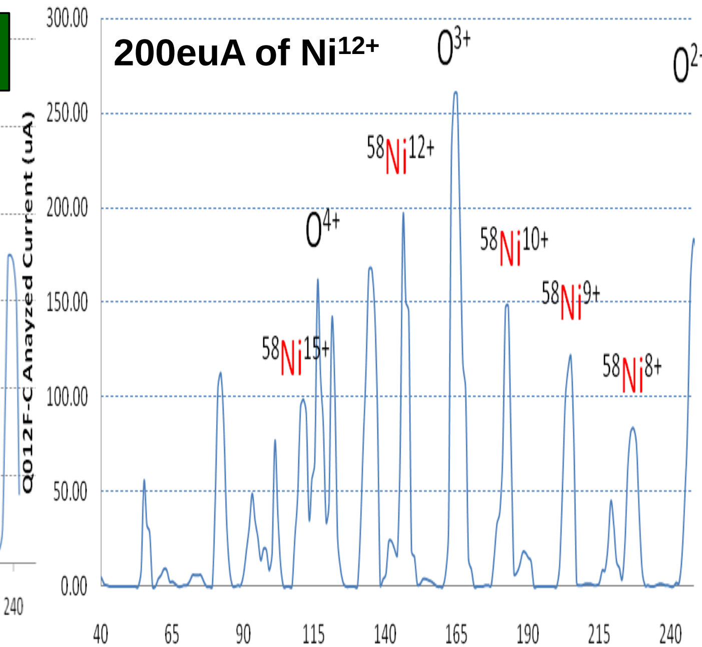


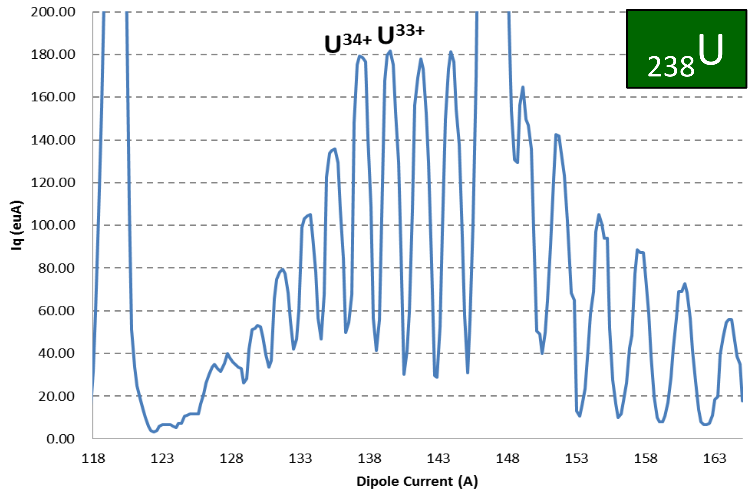
Courtesy of J. Benitez

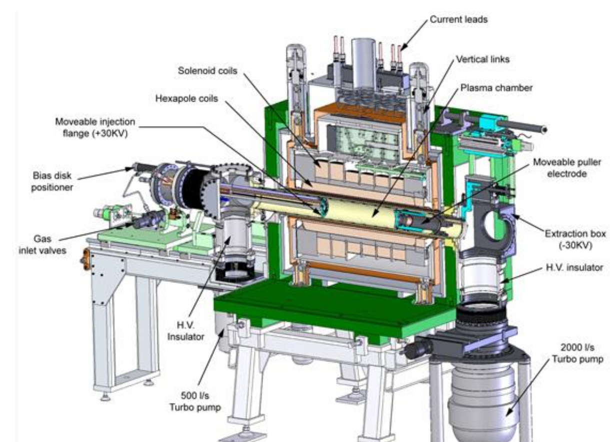
Nickel Beams with IHO

Stable inductive heating oven for refractory metal vapor production: Ni, Ge…





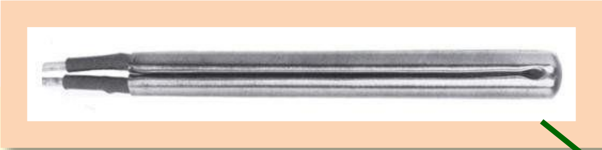


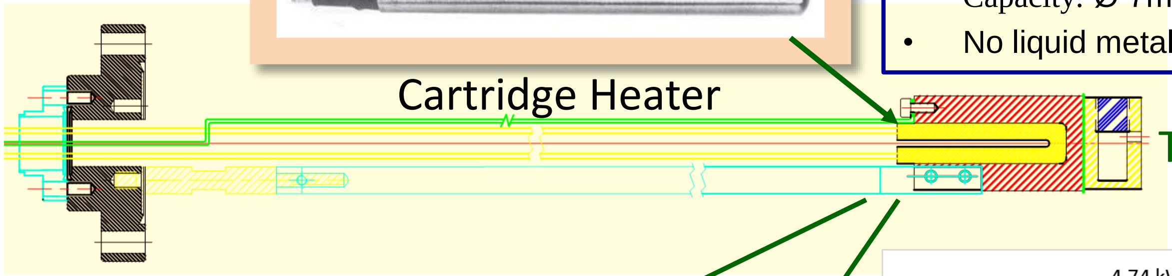


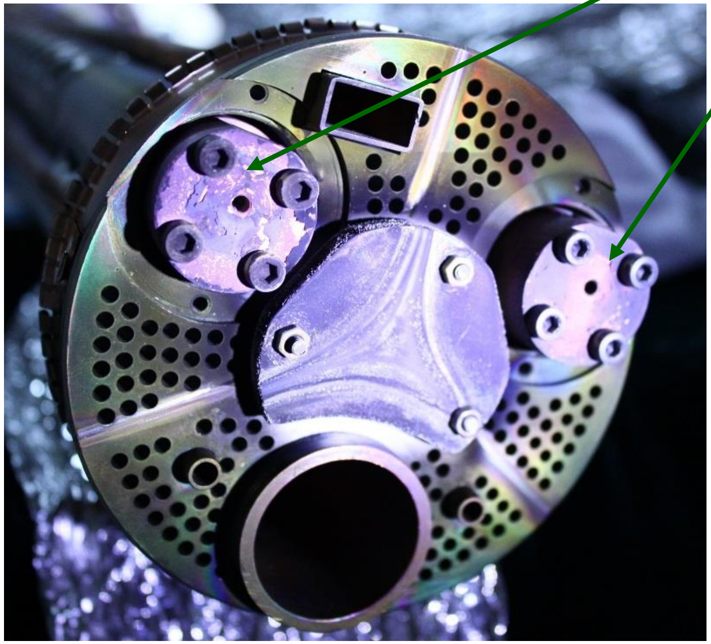
Courtesy of G. Machicoane

Bi Beams With LTO

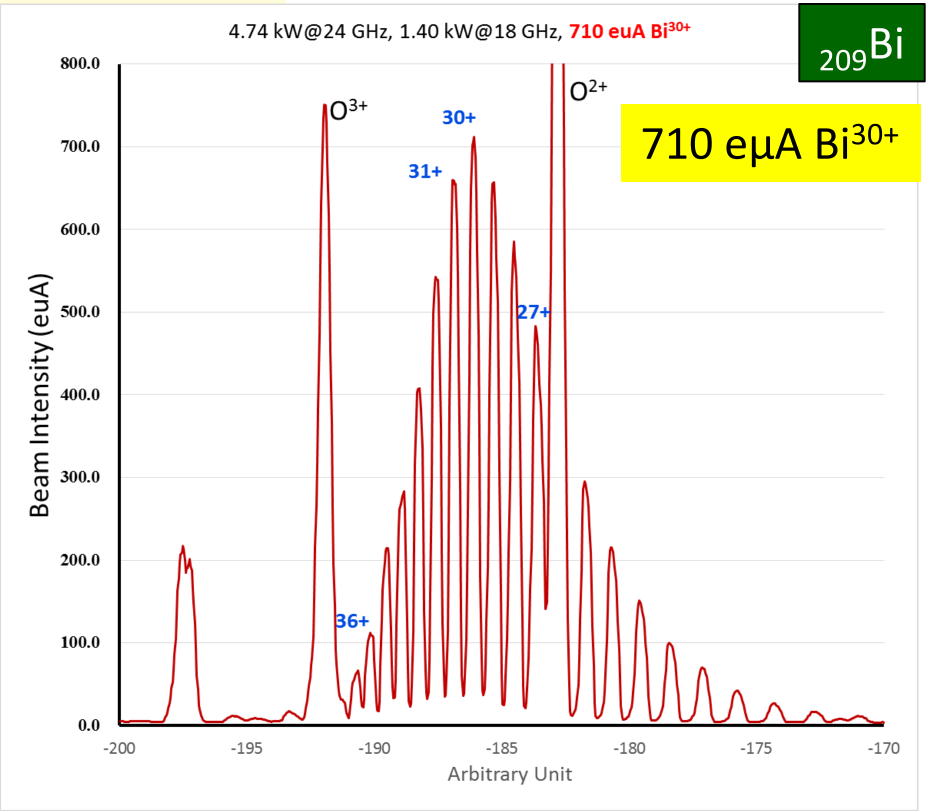
- Temp.: 650^{0}C Max., continuous control
- Capacity: Ø 7mmX12 mm crucible→>2 g Max. for Bi grains
- No liquid metal spilling



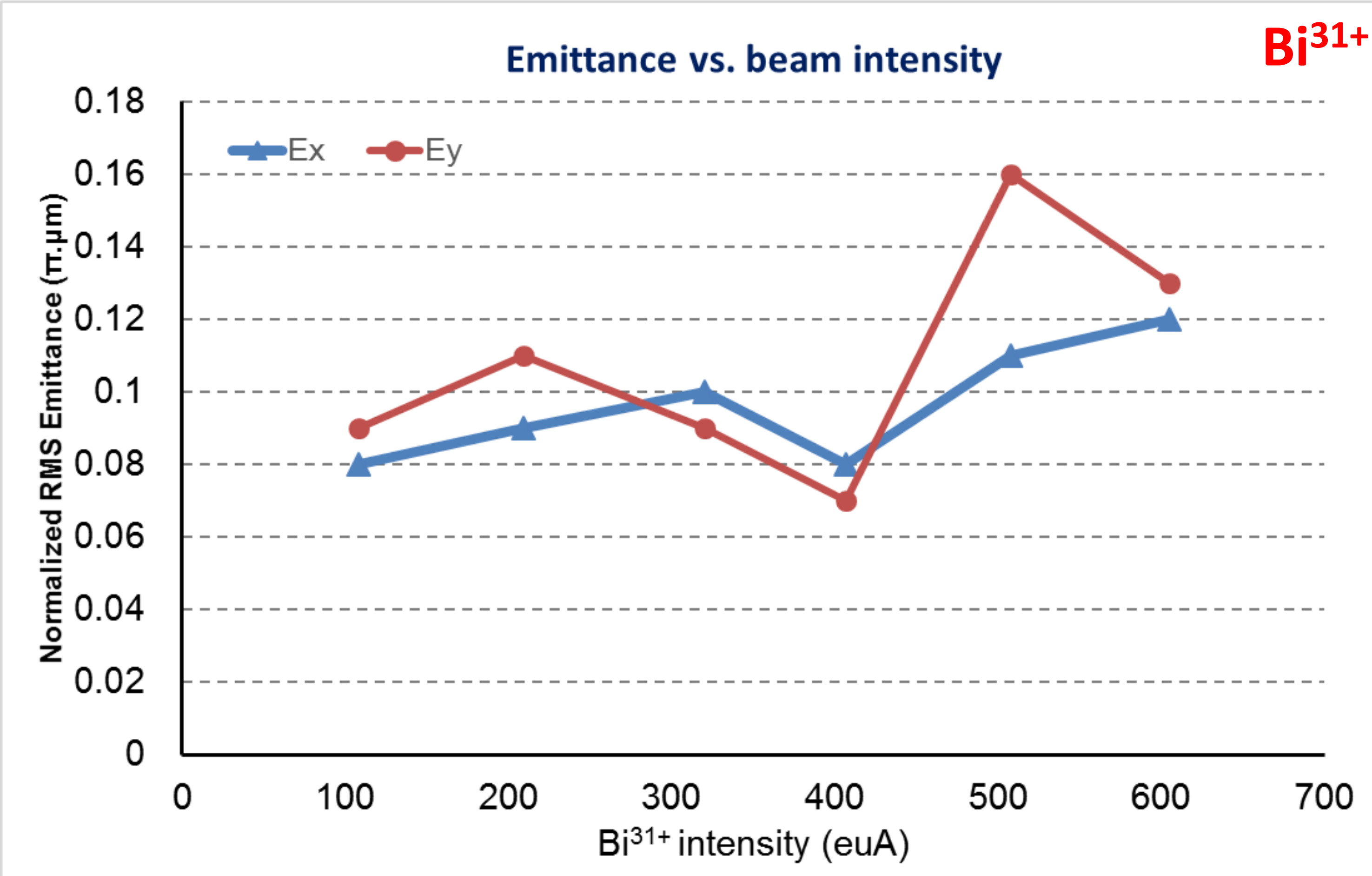




SECRAL 2014

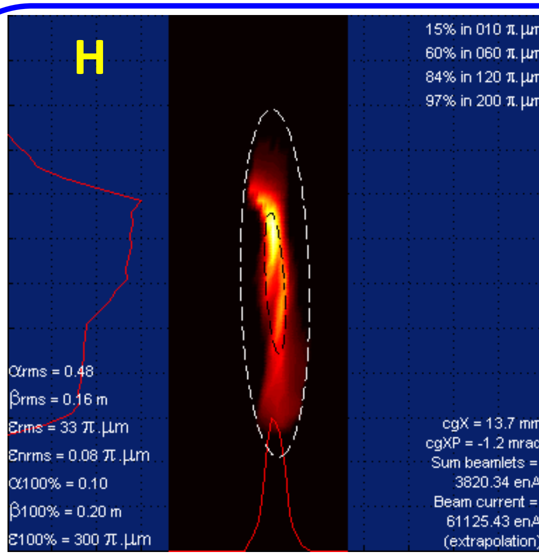


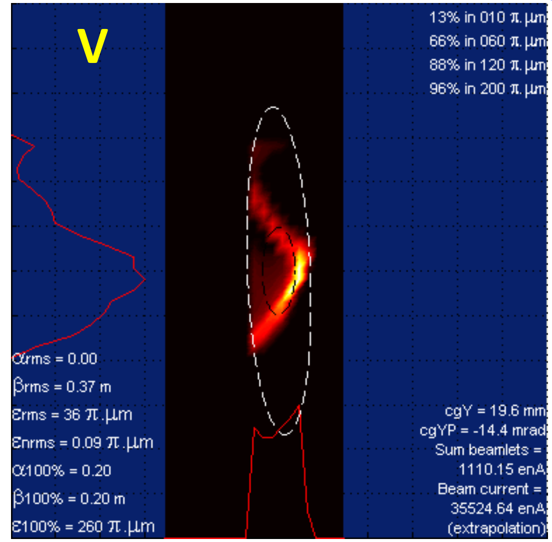
Beam Intensity and Emittance



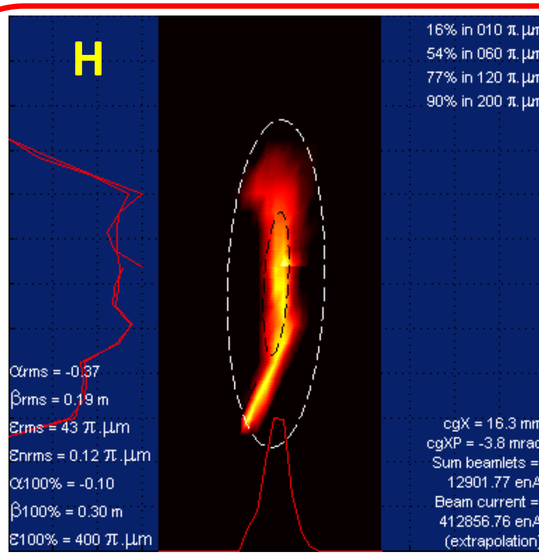
Intense Beam Quality

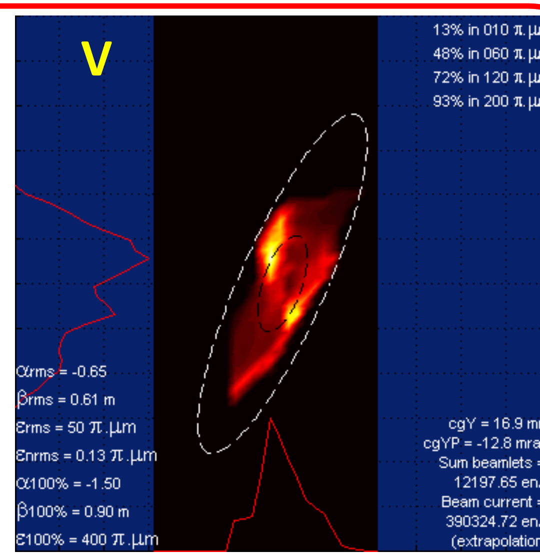
100 eμA Bi^{31+}





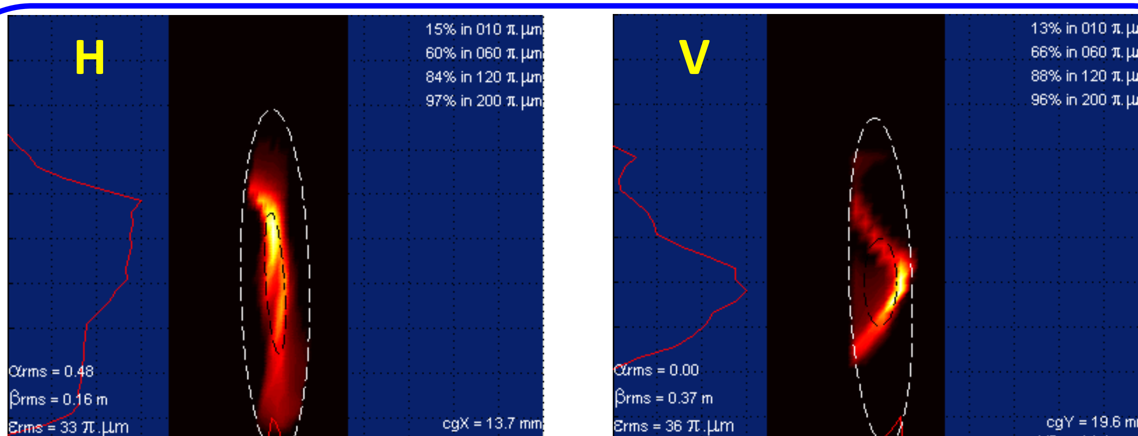
600 eμA Bi^{31+}





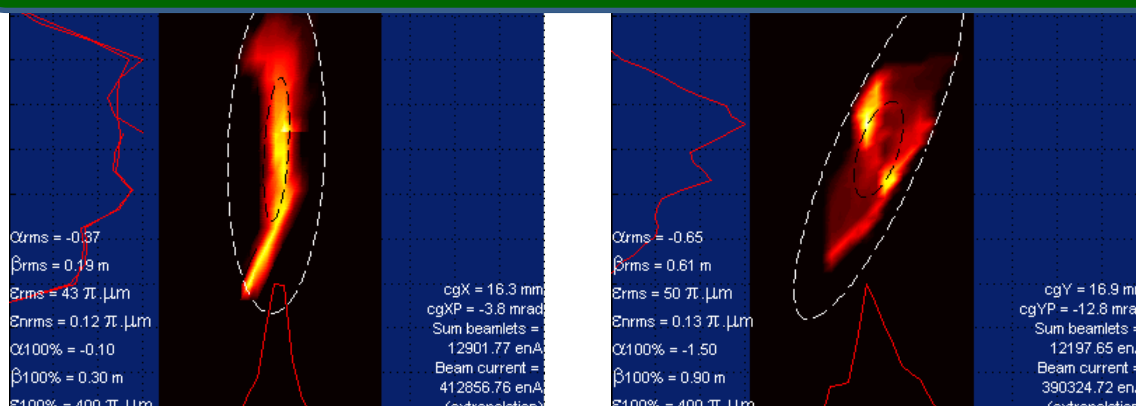
Intense Beam Quality

100 eμA
Bi^{31+}



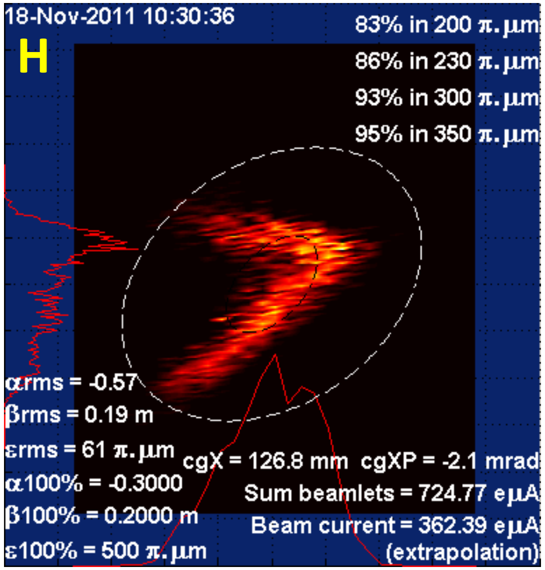
- ? High order aberration
- ? Nonsymmetrical beam in H/V directions

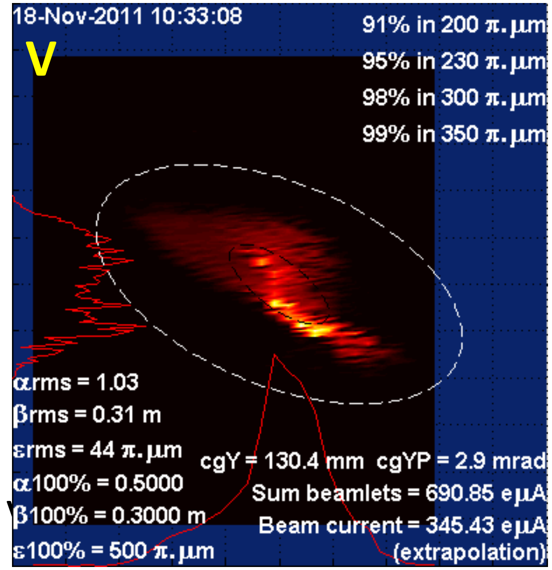
600 eμA
Bi^{31+}



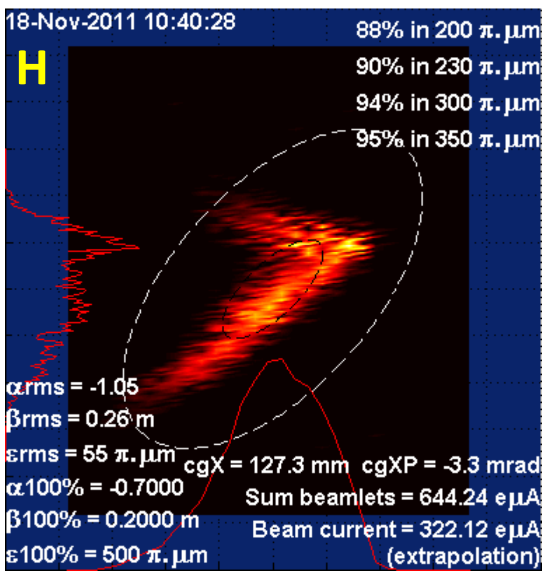
Uranium Beams from VENUS

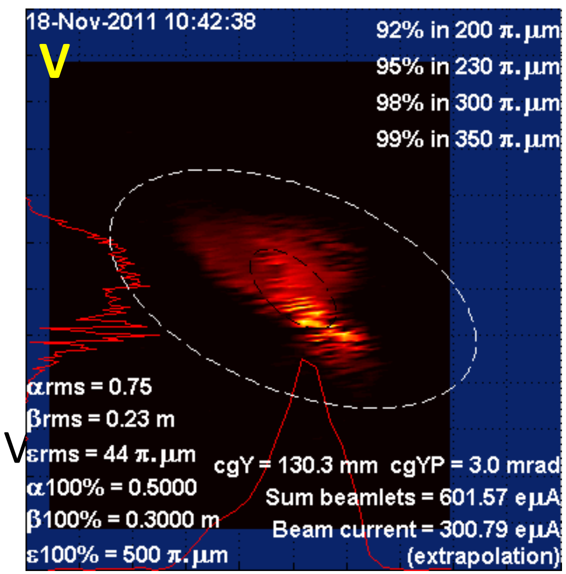
I_{U33+}=365eμA



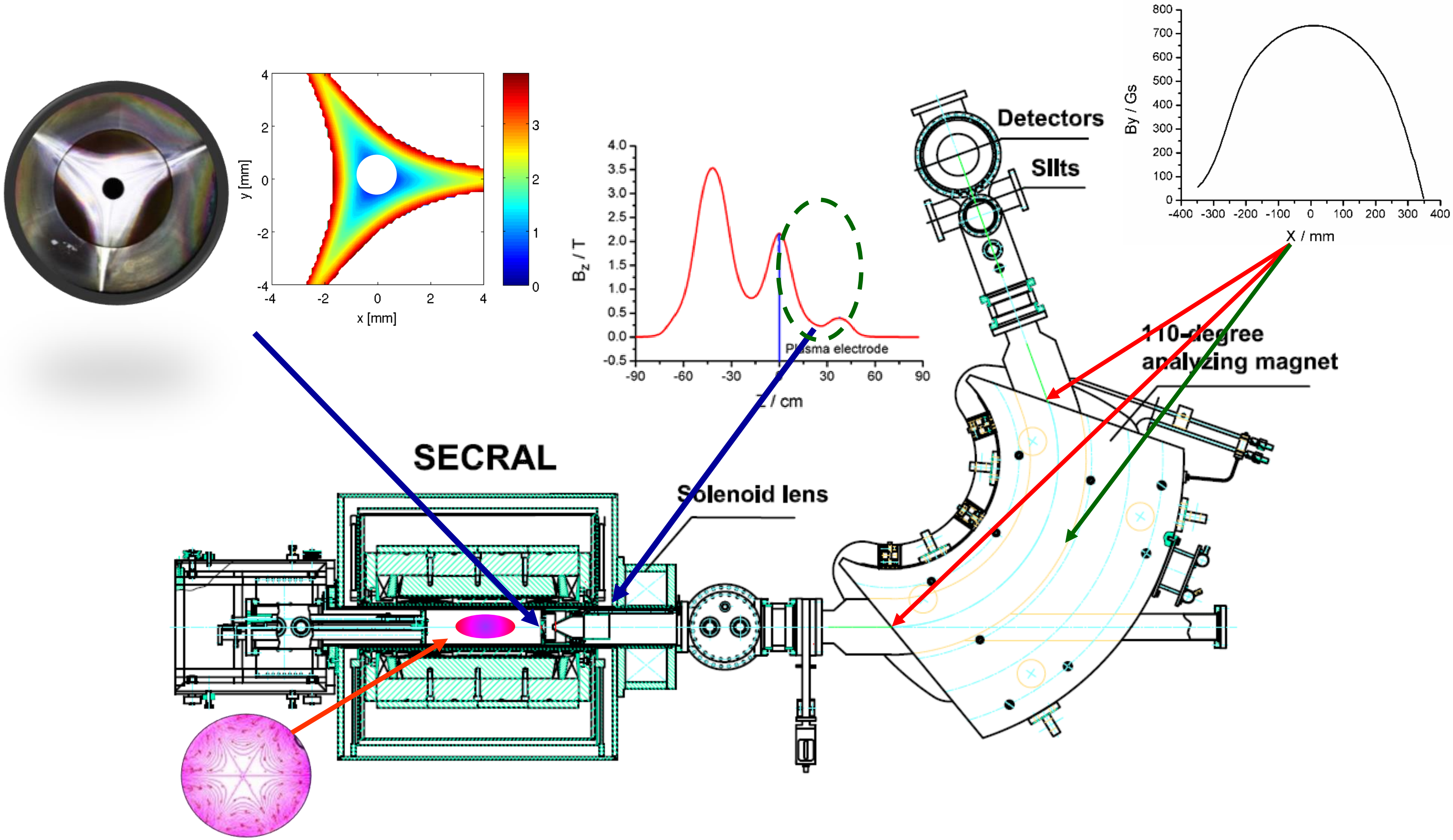


I_{U34+}=311eμA

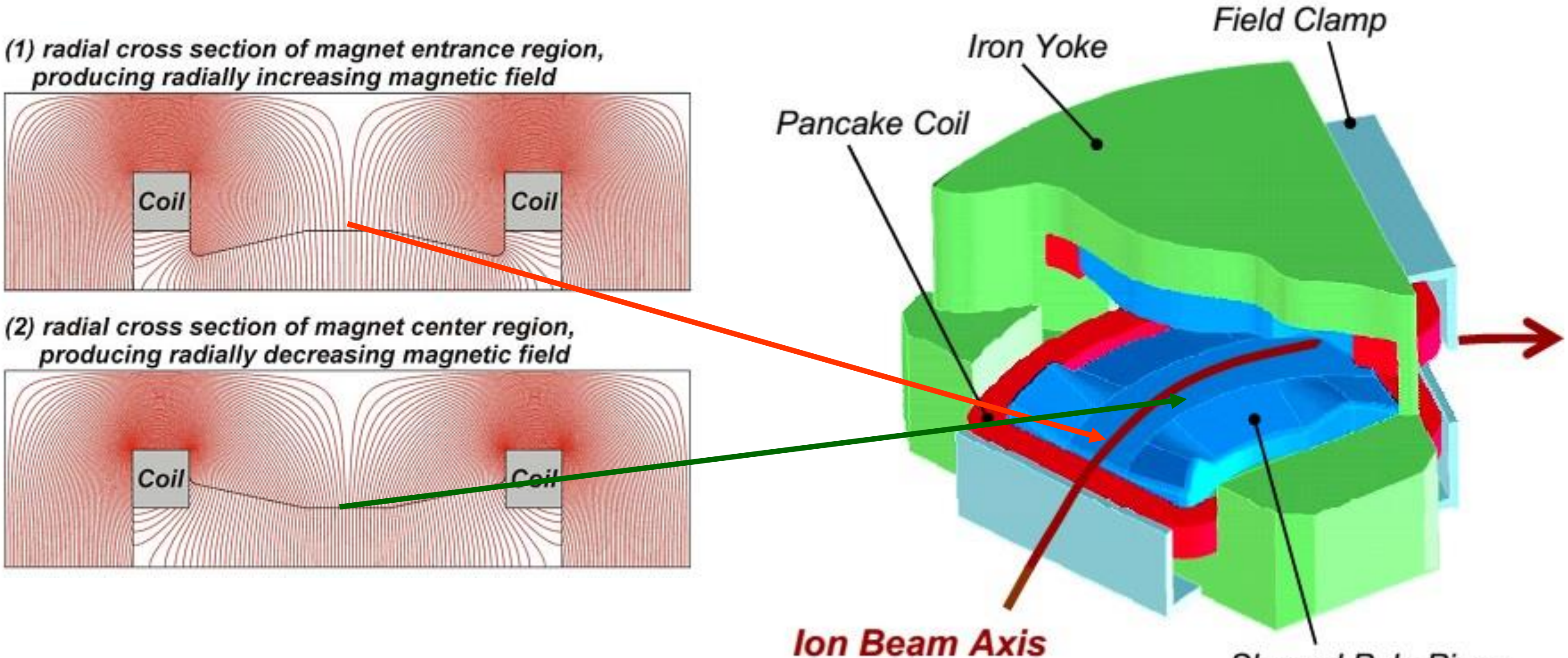


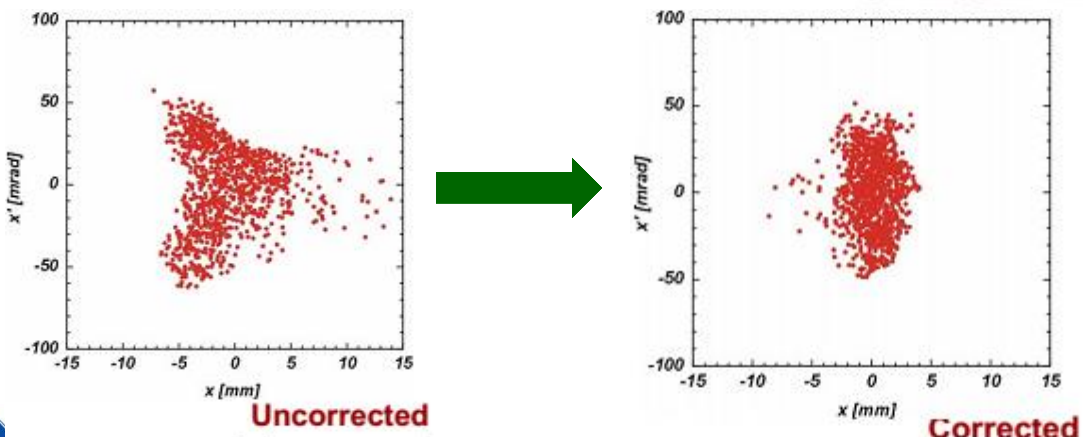


Beam Extraction and Transmission



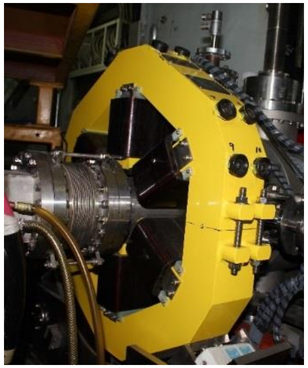
Magnet Trimming

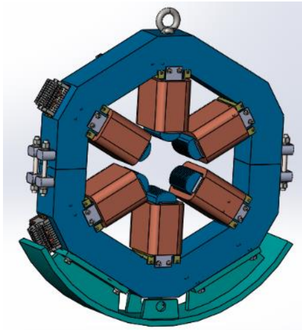


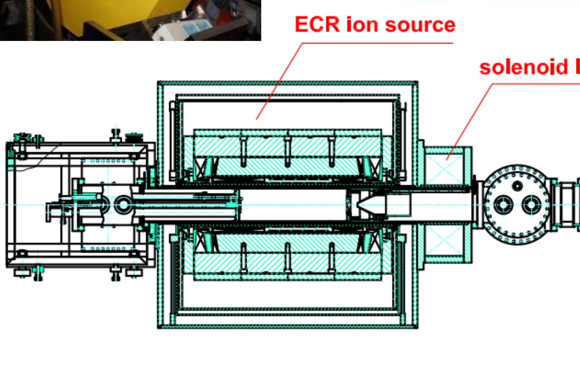


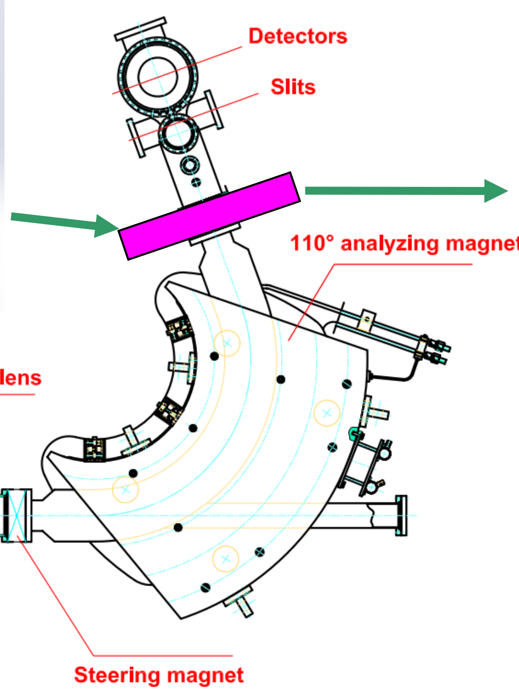
VENUS/LBNL, SuSI/MSU

Correction Magnet

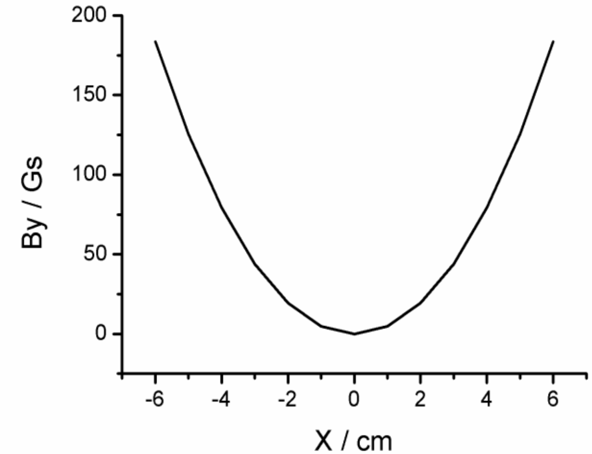




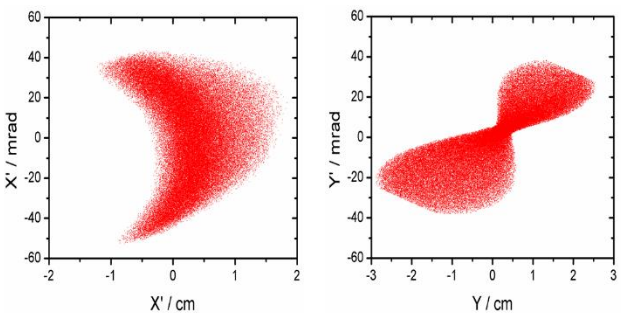




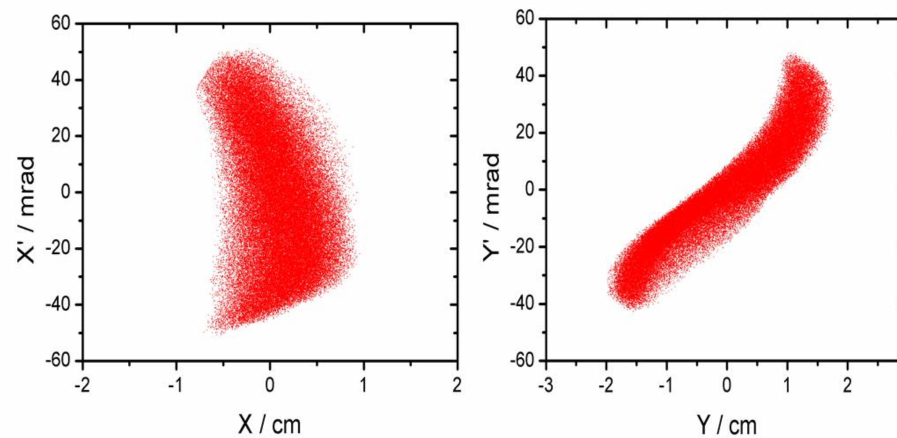
Opposite hexapole field



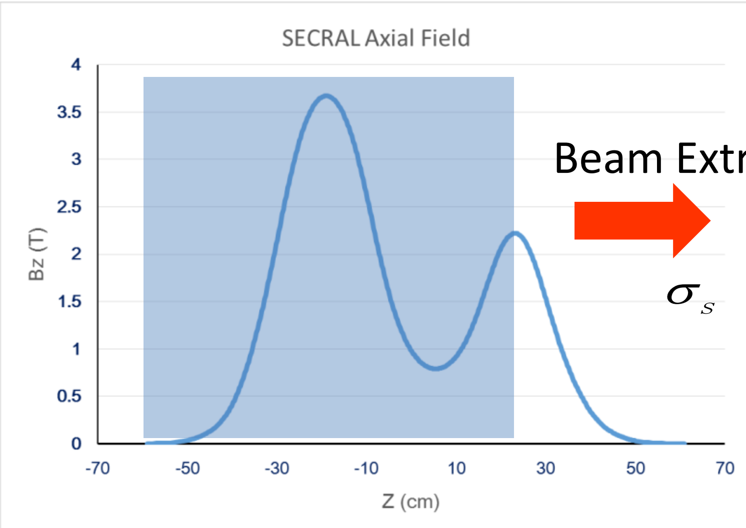
Uncorrected



Corrected



Extraction Field Impact



Beam Extraction

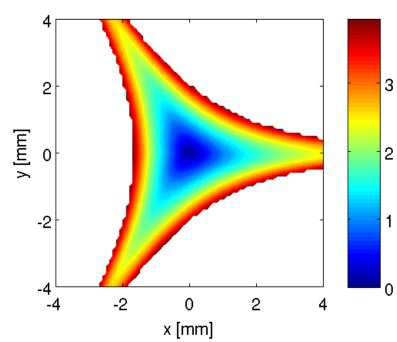
$$\sigma_s = R\sigma_0 R^T = \varepsilon \begin{pmatrix} \beta & -\alpha & 0 & k\beta \\ -\alpha & k^2\beta + \gamma & -k\beta & 0 \\ 0 & -k\beta & \beta & -\alpha \\ k\beta & 0 & -\alpha & k^2\beta + \gamma \end{pmatrix}$$

- Beam coupling in phase space
- Emittance growth

$$\sigma_0 = \varepsilon \begin{pmatrix} \beta & -\alpha & 0 & 0 \\ -\alpha & \gamma & 0 & 0 \\ 0 & 0 & \beta & -\alpha \\ 0 & 0 & -\alpha & \gamma \end{pmatrix}$$

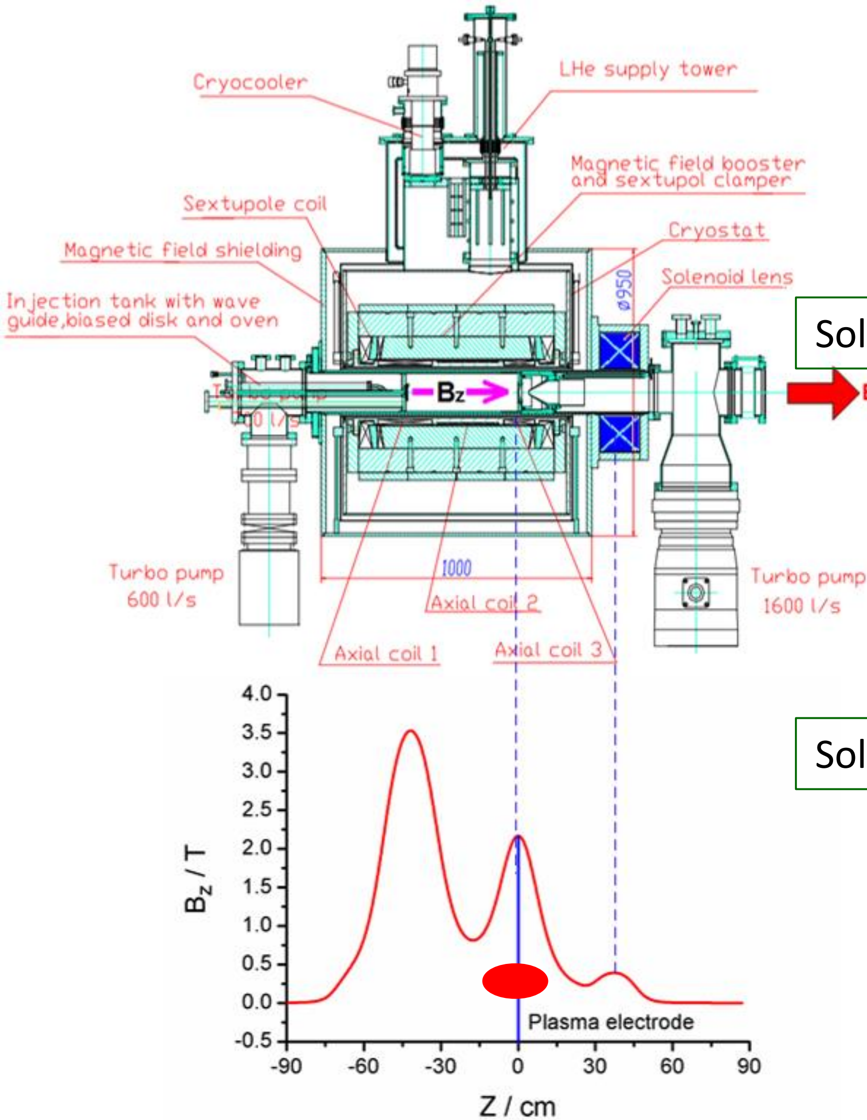
$$R_{exit} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ -k & 0 & 0 & 1 \end{pmatrix}$$

$K = B_{sol}/2B\rho$



Asymmetric beam will make it worse

Extraction SN



$$\sigma_s = \begin{bmatrix} 20 & 20 & 10 & 15 \\ 20 & 40 & 20 & 25 \\ 10 & 20 & 20 & 20 \\ 15 & 25 & 20 & 40 \end{bmatrix}$$

$\varepsilon_x = \varepsilon_y$ =20 π.mm.mrad

Solenoid has same field direction as Extraction field

$$\sigma_{+SN} = \begin{bmatrix} 8.3365 & -10.9968 & 3.6034 & -3.8789 \\ -10.9968 & 33.1551 & 1.1211 & -0.6289 \\ 3.6034 & 1.1211 & 33.8142 & -20.7461 \\ -3.8789 & -0.6289 & -20.7461 & 28.7088 \end{bmatrix}$$

ε_x =12.5 pi.mm.mrad
ε_y =23.2 pi.mm.mrad

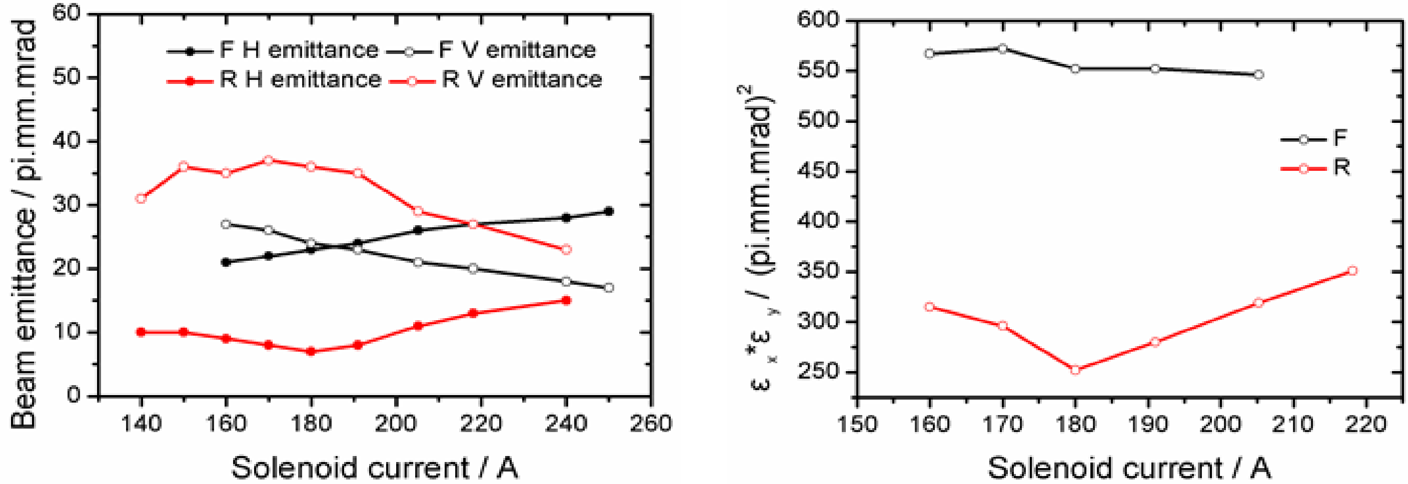
Solenoid has reversed field direction of Extraction field

$$\sigma_{-SN} = \begin{bmatrix} 33.8142 & -20.7461 & 3.6034 & -3.8789 \\ -20.7461 & 28.7088 & 1.1211 & -0.6289 \\ 3.6034 & 1.1211 & 8.3365 & -10.9968 \\ -3.8789 & -0.6289 & -10.9968 & 33.1551 \end{bmatrix}$$

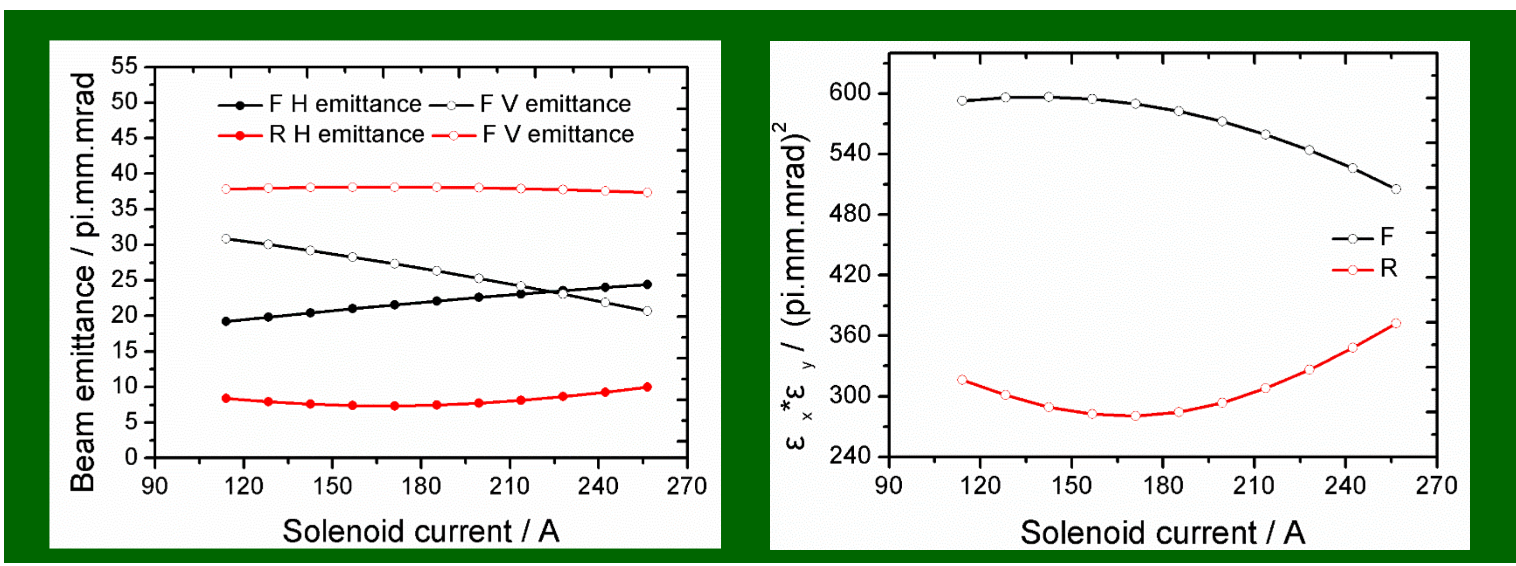
ε_x =23.2 pi.mm.mrad
ε_y =12.5 pi.mm.mrad

Emittance Coupling

Experiment



Simulation



Summary

- ECRIS still has very much intense HCI production capacity
- For intense beam production, it is essential to
  - Develop high reliability oven
  - Beam quality control
- Beam transmission in ECR beamline still needs better understanding.