FRIB

Recent Advance in ECR Heavy Ion Sources,

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Facility for Rare Isotope Beams,

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U.S. DEPARTMENT OF ENERGY | Office of Science

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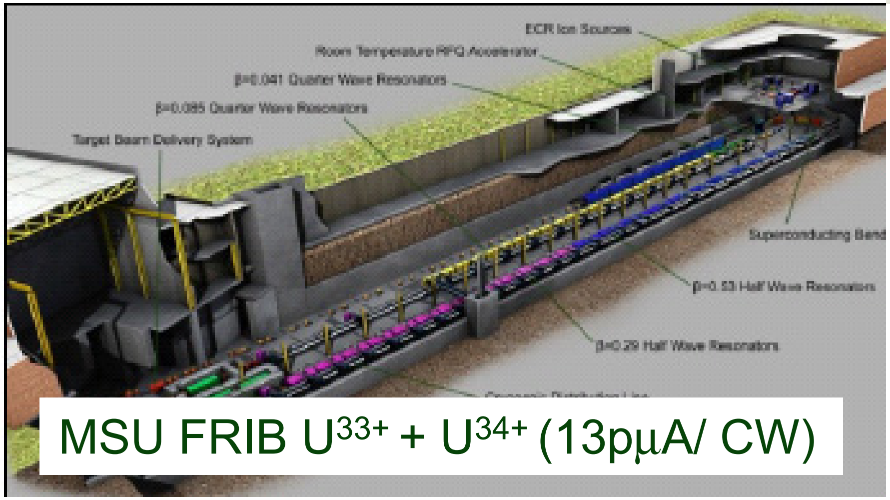
Outline

- Introduction
- Electron Cyclotron Resonance (ECR) Design Features and Parameters
- Challenges of ECR Magnet
- Development and Status of 28 GHz ECR ion sources for the facility for Rare Isotope Beams
- Concept and Challenges for next Generation ECR ion sources

Many New Projects Requires High Current of Highly Charged Ions

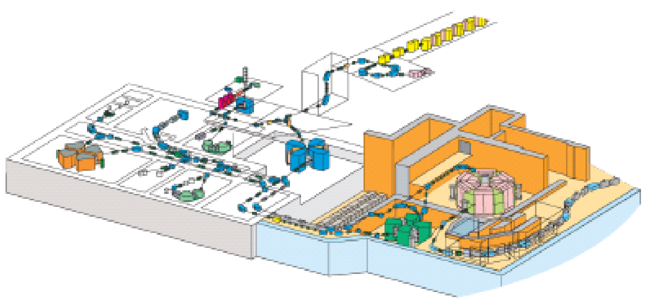


MSU FRIB U^{33+} + U^{34+} (13pμA/ CW)

HIAF China,

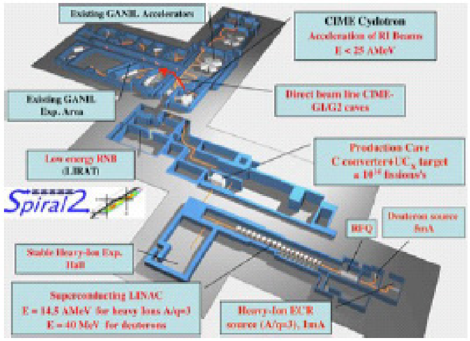
$$U^{35+}\ 20p\mu A\ CW, 50\ p\mu A\ Pulsed$$

Most Challenging for ECR!



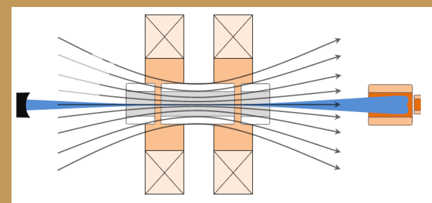
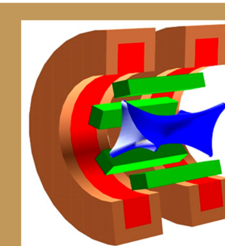
RIKEN RIBF U^{35+} 15 pμA/ CW

- Higher Charge State from Ion Source helps reach higher energy
  $E \propto Q_{ECR}^2$ for Cyclotrons
  $E \propto Q_{ECR}$ for Linac
- Higher Intensity from Ion Source leads to higher Beam power



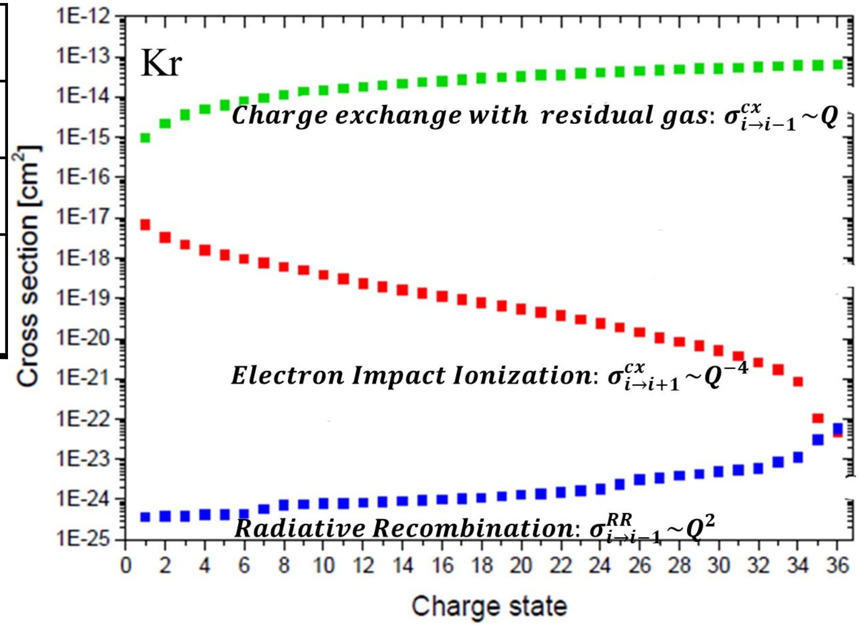
1emA of Ar 12+

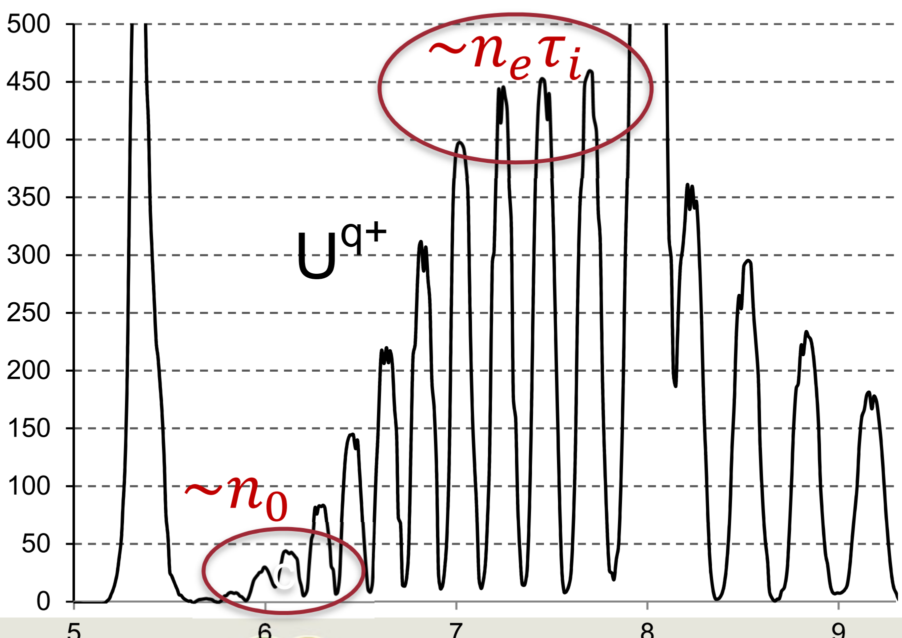
Ion Sources for Highly Charged Ions (HCI)

	Electron Beam Ion Source 	Electron Cyclotron Resonance Ion Source 
Advantages	• High intensity low duty cycle • Highest Charge state Ions • Fast switching operation • Low contamination • Narrow Charge State Distribution • Well controlled EEDF	• **High intensity cw beams** • Long life span • Low maintenance/High reliability • Wide range of elements • Development and performances keeps improving
Disadvantages	• Low CW current • Complex and intensive operation • Total charge limited by Length and electron current	• Contamination can be issue • Significant X-Ray production • Extraction in a high B field (Beam Quality)

Key Criterias to Reach High Charge States

Ion confinement times τ_i	$few\ ms\ to\ 10's\ ms$
Plasma densities n_e	$10^{11} - 10^{13}\ cm^{-3}$
Electron temperature T_e	$100s\ eV\ to\ 10s\ keV$
Charge exchange/ neutral gas density n_0	$\sigma^{cx} \propto . q^{1.17} . E_I^{-2.76}$



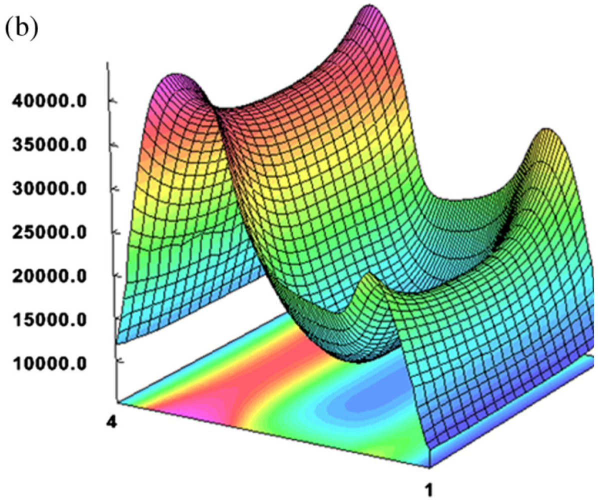


$$\boxed{n_e \tau_i \geq 5\ 10^4\ T_e^{3/2}}$$

Golovanivsky criteria for fully stripped ions

ECR Principle of Operation

- Confinement times achieved with a magnetic trap = Solenoids + Sextupole

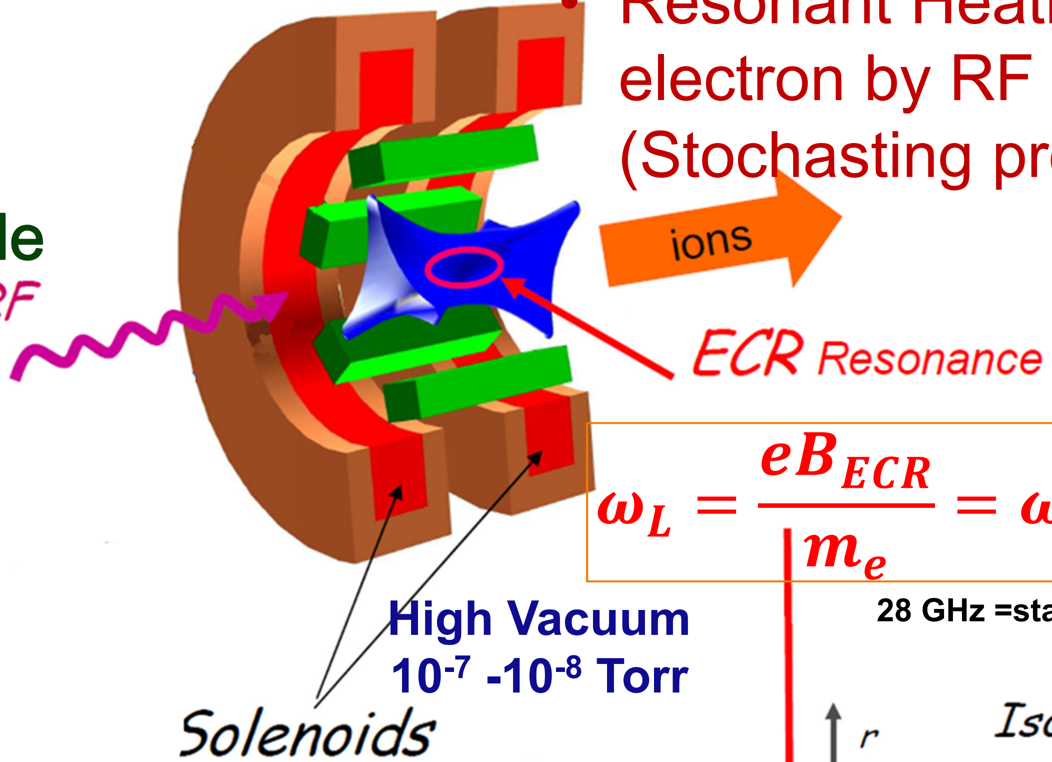


$B_{injection}$ ~ 3 - 4 B_{ecr} (T)

$B_{extraction\ ,radial}$ ~ 2 B_{ecr} (T)

$B_{minimum}$ ~ 0.6 -0.8 B_{ecr} (T)

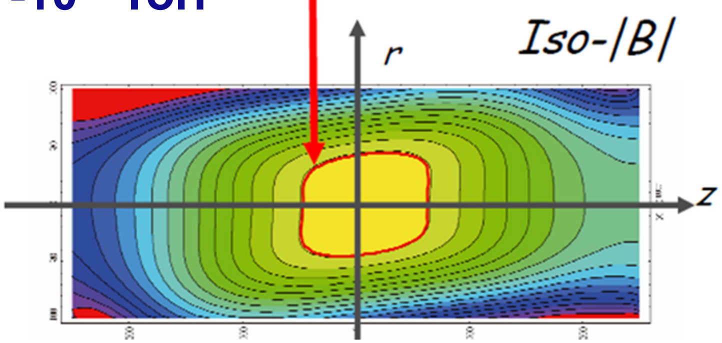
- Resonant Heating of electron by RF power (Stochasting process)



$$\omega_L = \frac{eB_{ECR}}{m_e} = \omega_{RF}$$

28 GHz =state of the art

High Vacuum
10^{-7} -10^{-8} Torr



Performances of ECR Ions Sources Rely on Scaling of Magnetic Field and RF Frequency

$$I_i^q = \frac{1}{2}\frac{n_i^q qeV_{ecr}}{\tau_i^q}$$

$$\sum_{i,q} n_i^q q_i = n_e$$

(Plasma neutrality)

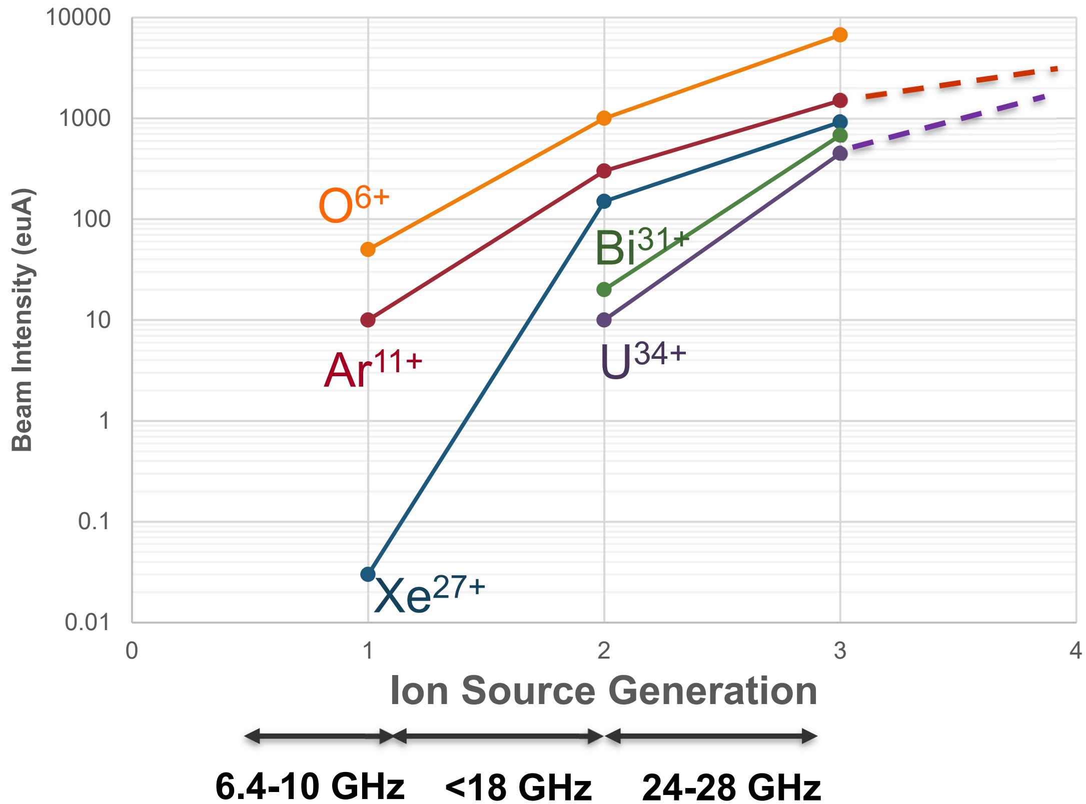
$$\boxed{I_Q \propto n_e \propto RF\ Power}$$

$$\boxed{n_e \propto B^2}$$

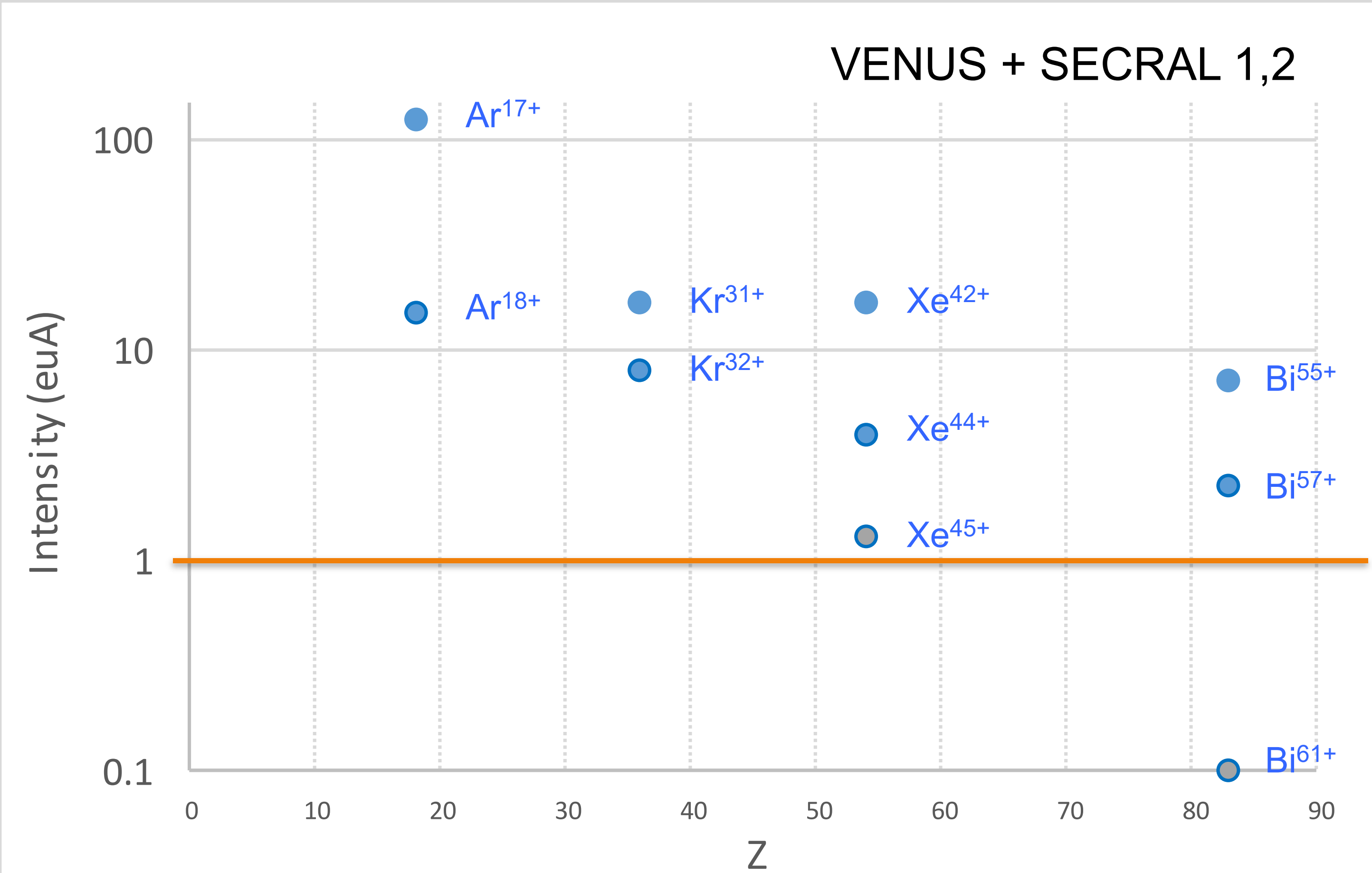
$$and\ B \propto f_{rf} \quad (\omega_{RF} = \omega = \frac{eB}{m_e})$$

Scaling Magnetic trap allow to couple more microwave power and increase confinement time

$$\boxed{I_Q \propto f_{rf}^2}$$

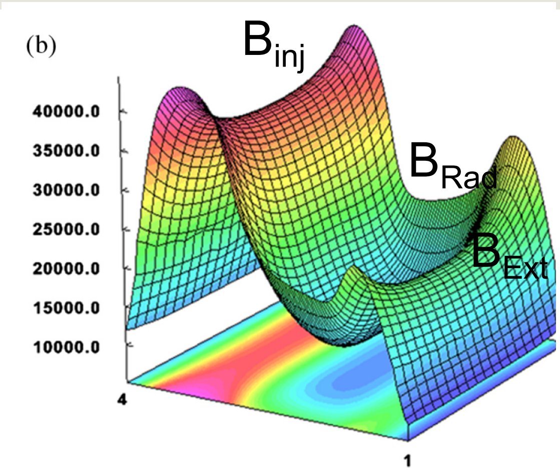


State of the Art for Very High Charge States



4th Generation ECR Bare Krypton and Xenon?

ECR Ion Source Development Timeline



f_{ECR} (GHz)	B_{ECR} (T)	B_{inj} (T)	B_{ext} (T)	B_{radial} (T)
14	0.5	2	1	1
18	0.64	2.5	1.2	1.3
28	1	4	2	2
56	2	8	4	4

1980 — 1985 — 1995 — 2002 — t

G1
SUPERMAFIOS
MINIMAFIOS
ECREVIS*
LBL ECR
MSU ECR
ORNL ECR
OCTOPUS
ISIS
…

G2
CAPRICE (CEA)
ECR4 (GANIL)
A-ECR (LBL) → MSU ARTEMIS
RIKEN 18 GHz
PHOENIX (LPSC)
SERSE* (LNS/CEA)
GTS (CEA)
…
Cost ~ 0.5-0.75M$

G3
VENUS (LBL) -2003
SECRAL (IMP CAS)-2005
SuSI (MSU)-2008
RIKEN SC-2010
SECRAL-2 (IMP CAS)-2016
FRIB-VENUS (MSU)-2020
Cost ~1-5M$

G4
FE-ECR 45 GHz (IMP CAS) - 202?
Cost ??

*Superconducting ECRIS

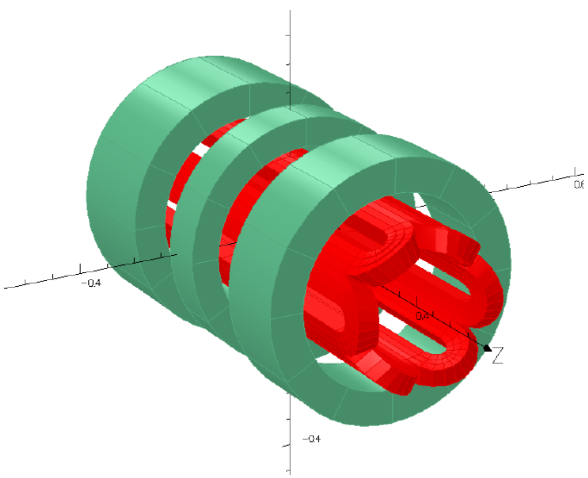
Magnets for ECR Ion Sources are Difficult to Build and Operate

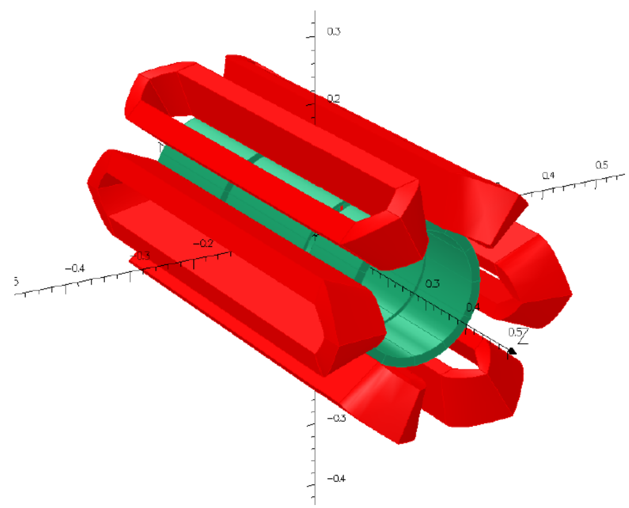
- Issue of interaction forces between solenoid and Sextupole (Slippage) for Superconducting Magnets
  - The construction of MS-ECRIS (GSI, LNS., EU) Sextupole Failed
    - » Project was abandoned
  - Quenches occurred in MSU SUSI ion source after reaching the required field. Source of quenches traced to Sextupole but root cause never identified
    - » Ramping procedure developed that provided safe operation of the magnet
- De-magnetization of some A-PHOENIX ECR magnets (LPSC, FRA) in the sextupole (Permanent Magnet) for SPIRAL 2 project
  - Water flow Interlock issue
- Unexpected quench of VENUS (LBNL,USA) near to a HTS current lead feedthrough in 2008
  - 1.5 year of work to investigate, fix the problem and have the ion source operational

Design of an Superconducting ECR ion Source

- **VENUS:Sextupole in Solenoid Design**
  - Minimizes the peak field in the sextupole by extending it
  - Solenoid field causes strong asymmetric forces on the sextupole coil ends

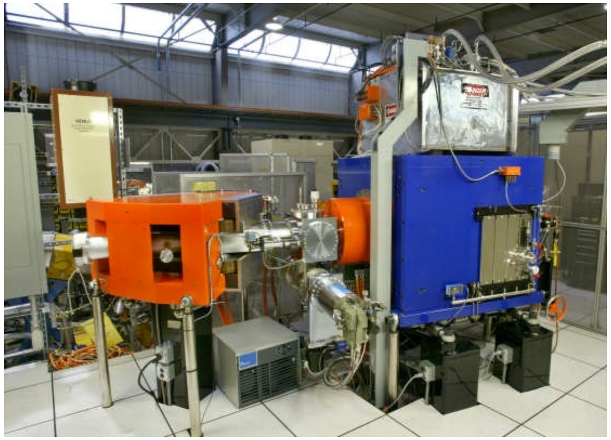
- **SECRAL: Solenoid in sextupole Design**
  - Minimizes the influence of the solenoid on the sextupole coil field and forces
  - More compact
  - Higher field in the sextupole coil (larger radius)
  - Strong forces on the solenoid coils

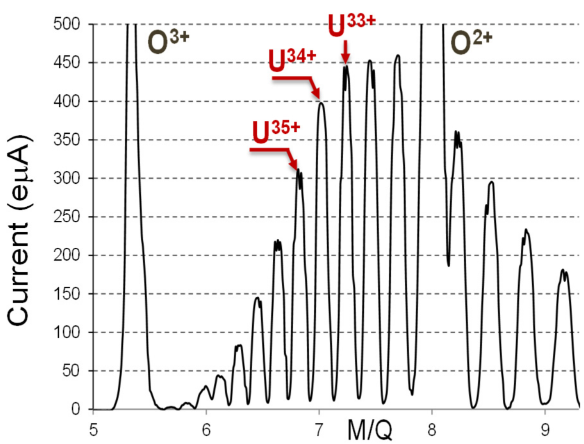




State of the Art ECR Ion Sources

VENUS (LBNL)

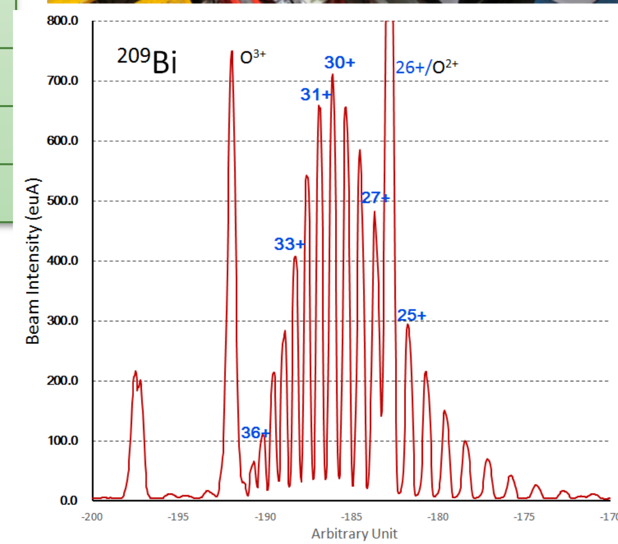




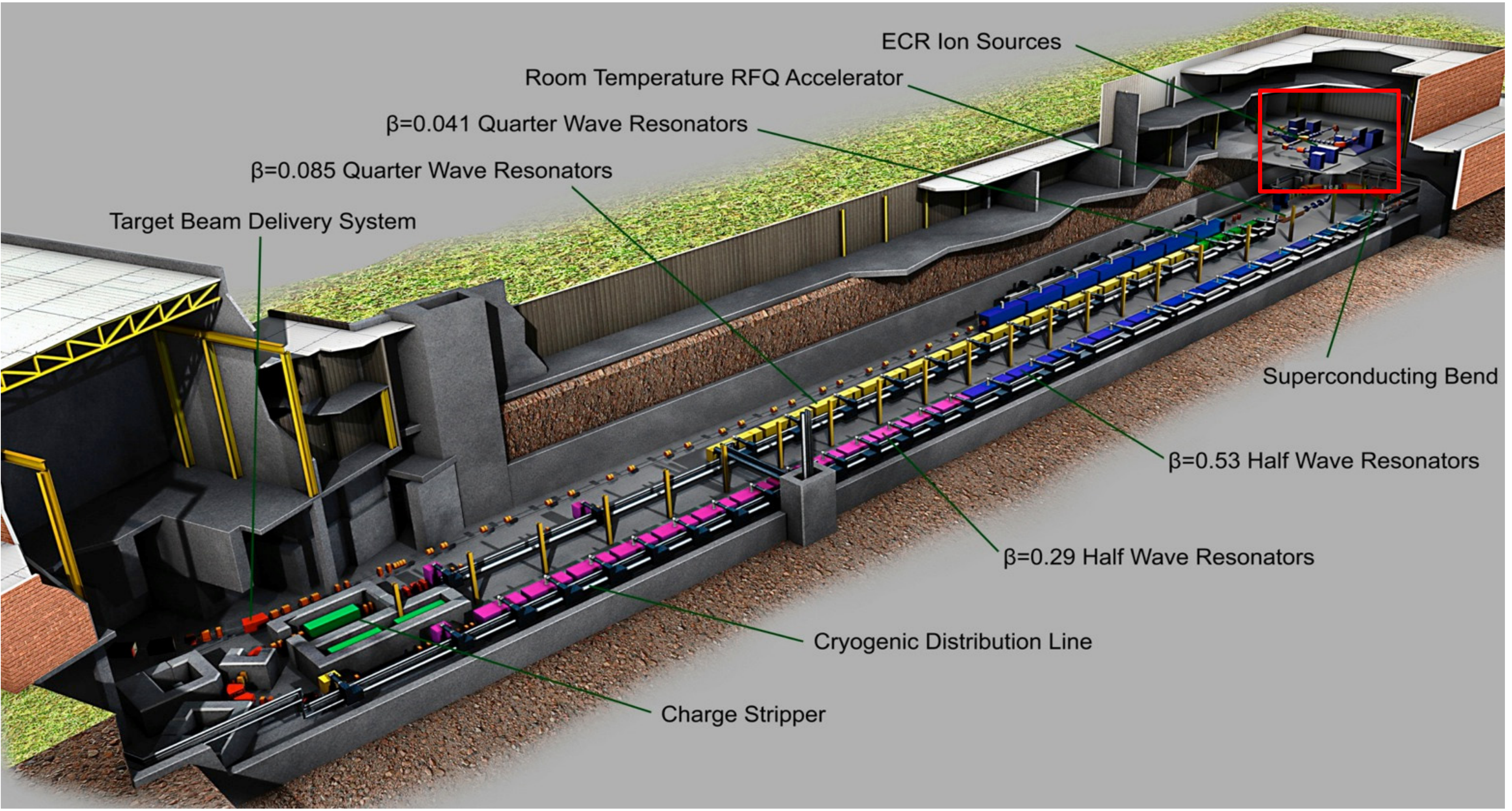
	VENUS 28+18GHz (euA)	SECRAL1,2 (24-28 GHz) (euA)	FRIB Requirement (euA)
O^{6+}	4750	6800	730
Ar^{12+}	1060	1420	660
Ar^{14+}	840	1040	770
Ca^{11+}	400	710	550
Kr^{18+}	770	1020	510
Xe^{27+}	705	920	540
Bi^{31+}	300	680	
Bi^{36+}	90	320	
U^{33+}	450	202	433
U^{35+}	300		460

Both VENUS and SECRAL meet FRIB Requirements for most Beams!

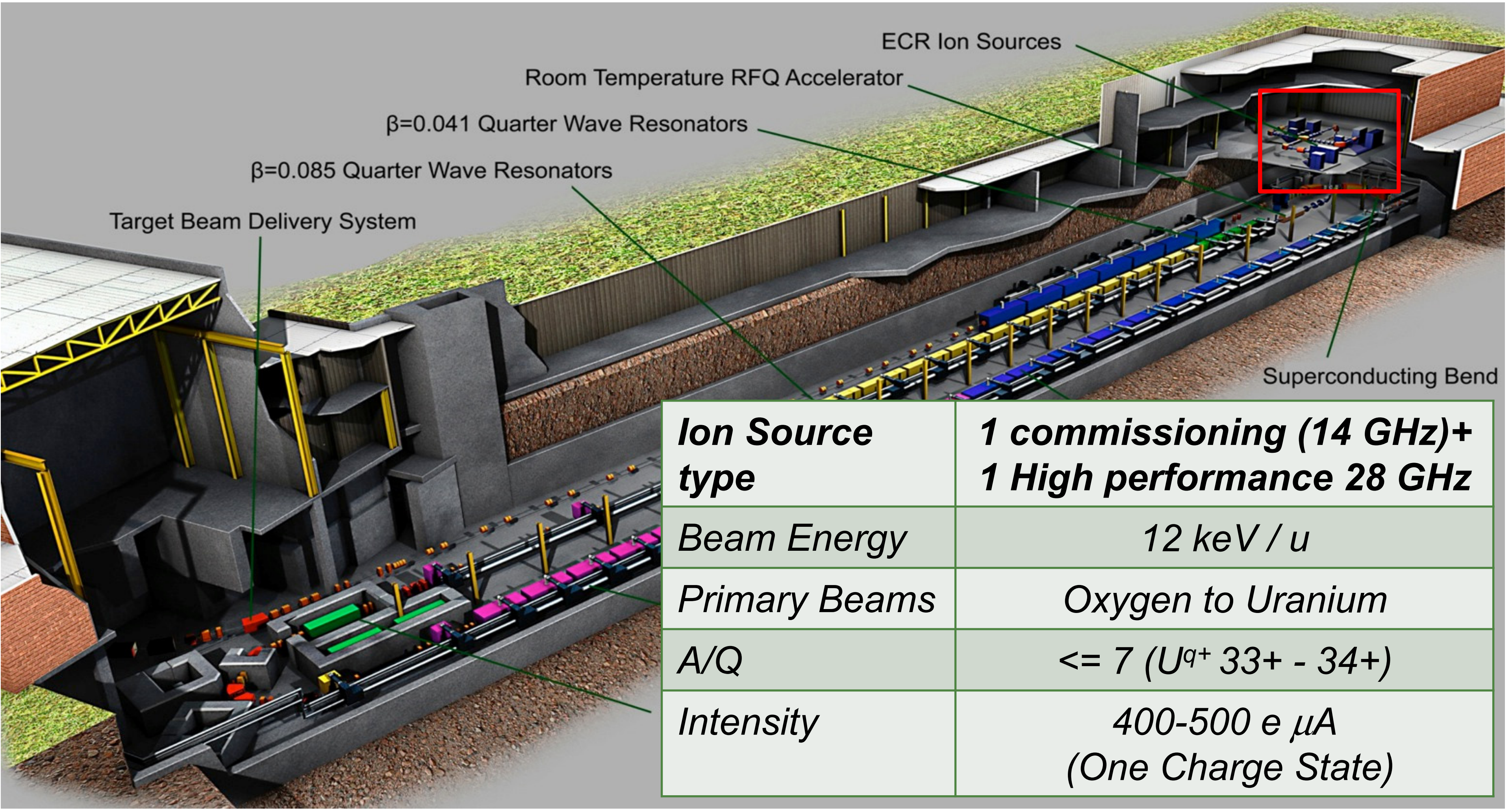
SECRAL I,II (IMP)



FRIB Accelerator

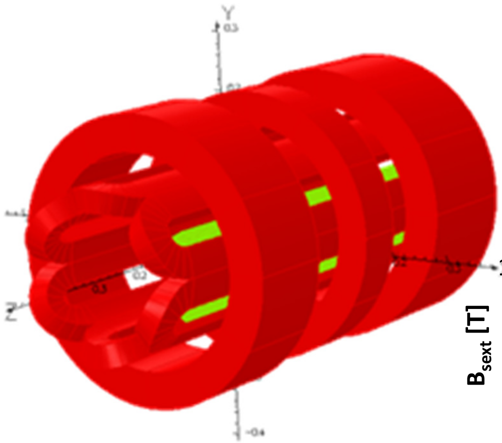


FRIB Accelerator

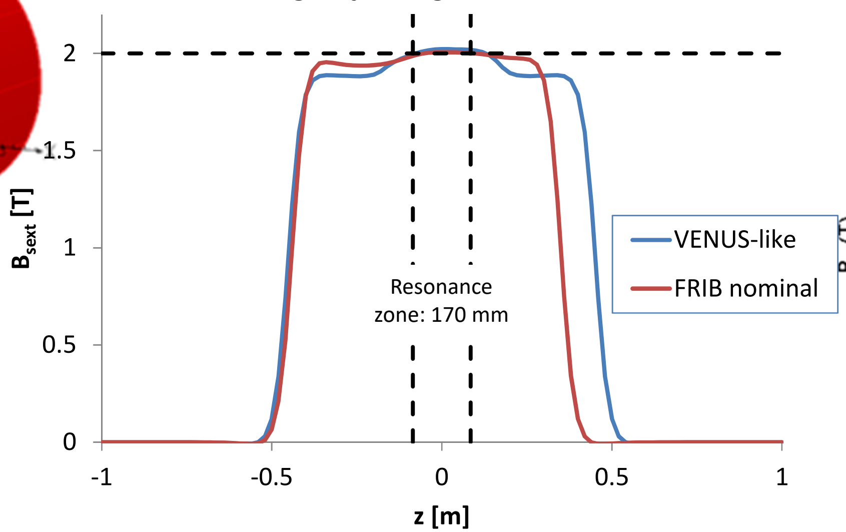


Ion Source type	***1 commissioning (14 GHz)+ 1 High performance 28 GHz***
Beam Energy	*12 keV / u*
Primary Beams	*Oxygen to Uranium*
A/Q	*<= 7 (U^{q+} 33+ - 34+)*
Intensity	*400-500 e μA (One Charge State)*

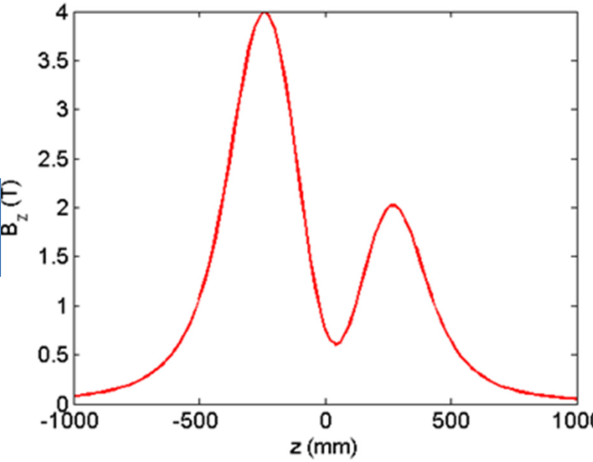
FRIB ECR Cold Mass Magnet based on VENUS
Designed and Fabricated by BCMT (LBNL)



Longitudinal profile slightly longer for FRIB



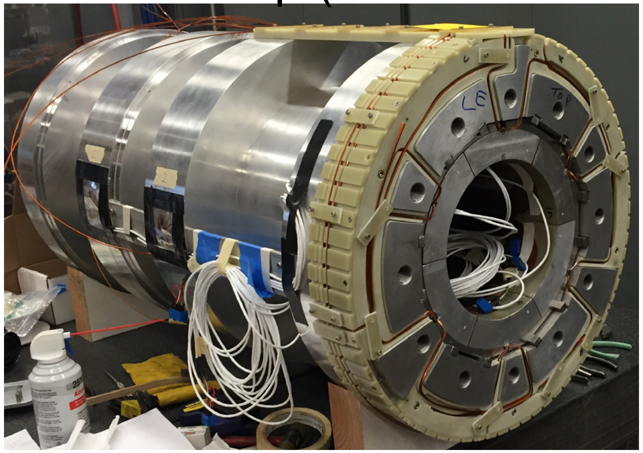
VENUS and FRIB ECR solenoid fields are near indistinguishable

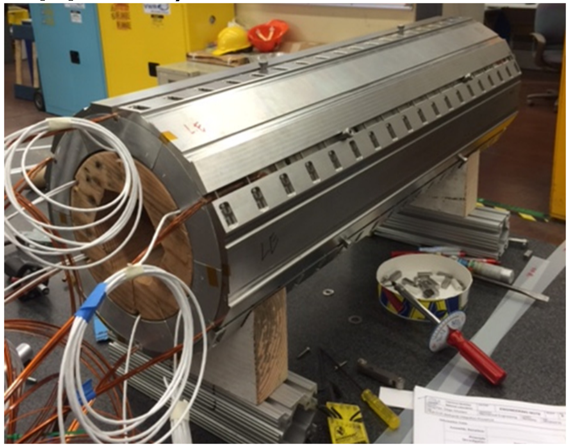


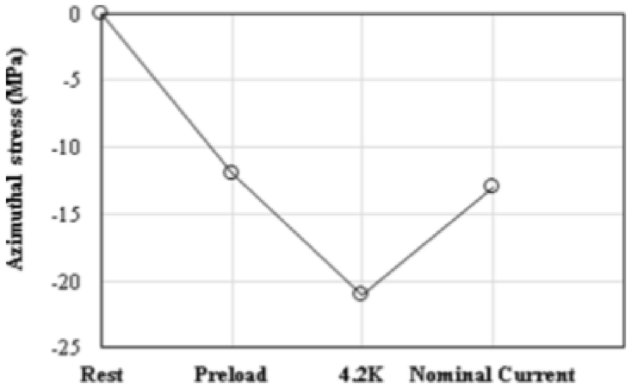
- Resonance zone 170 mm long
- Last Iso-B surface inside the plasma at 1.86T
- Sextupole Field at Plasma Chamber Wall (R=71.85mm): 2.03T with 450A excitation
- Sextupole conductor temperature margin close to 1 K- Max Current 500A
- Peak field on sextupole conductor of 6.6T (Lower than original VENUS)

Shell-Based Support Structure Applied to FRIB SC ECR Cold mass

- LBNL Magnet Group Adapted radial-key design developed for LARP for FRIB ECR ion source
  - Key-bladder technology allows for assembly-disassembly and fine tuning of preload
- Detailed mechanical study to define pre-load, contact pressures and stress*
  - Pre-load (Room Temperature)
  - Maximum Stress (Cool Down) caused by Aluminum Shell contraction
  - Final Step (Lorentz forces applied)







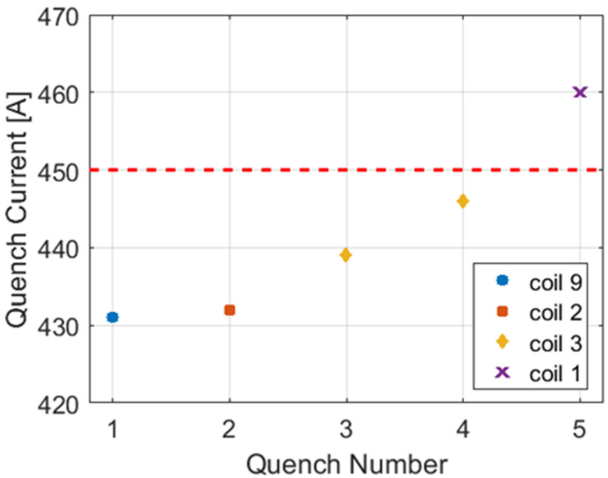
Azimuthal Stress coil/pole interface

* Heng Pan et al.; IEEE Transactions on Applied Superconductivity, Vol 29, Issue 5 (2019).

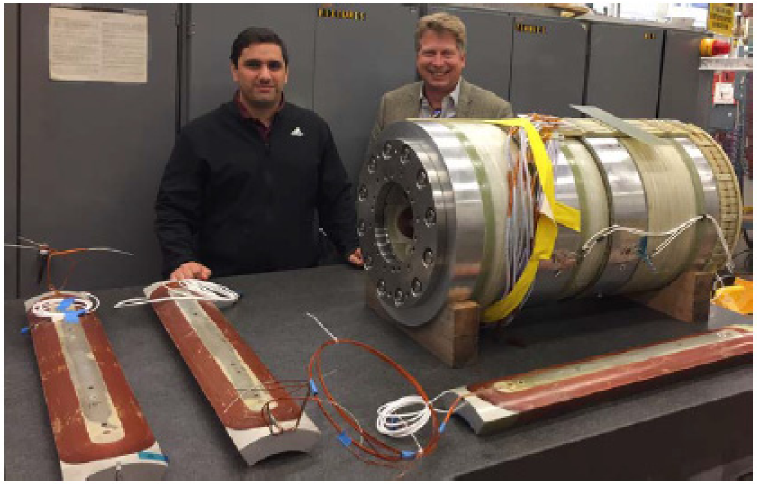
SC ECR Magnet Completed at Berkeley Met Performance Requirements

Delivered to FRIB January 2018

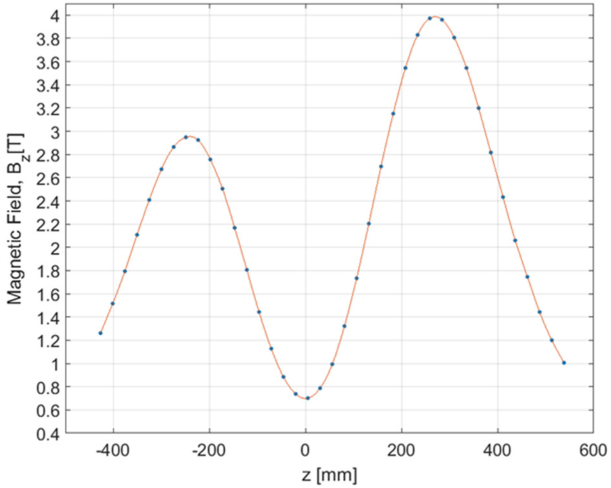
Quenches of sextupole magnet with new coil #9.Required current 450A

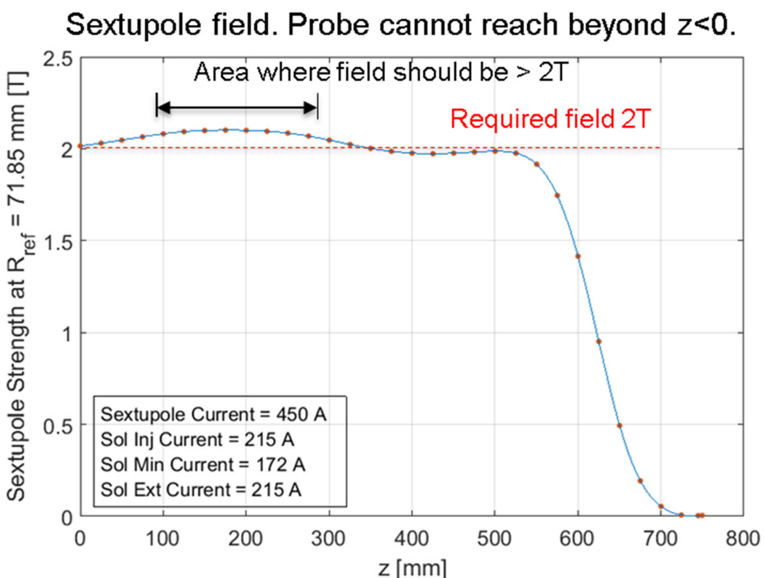


SC FRIB ECR magnet at Berkeley in November 2017



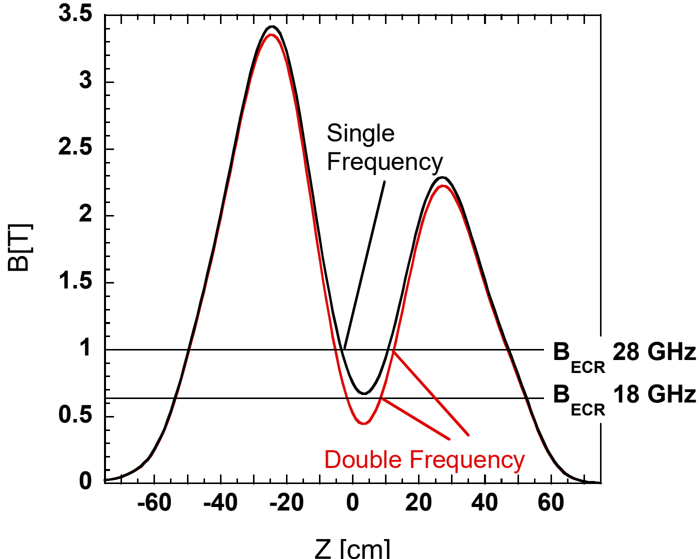
Measured solenoid magnetic field. Required fields 3 T at extraction and 4T at injection

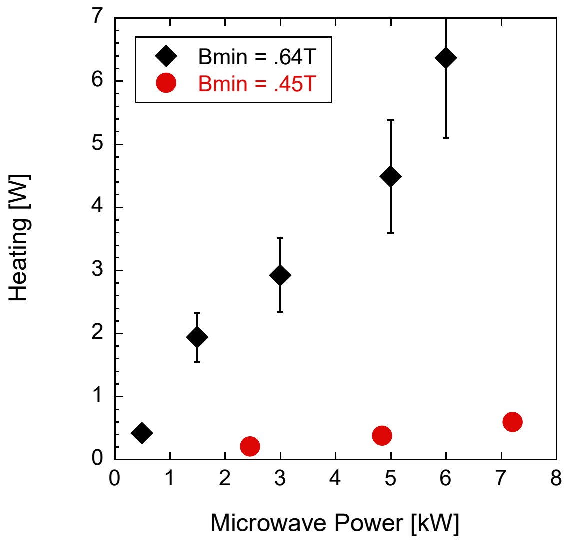




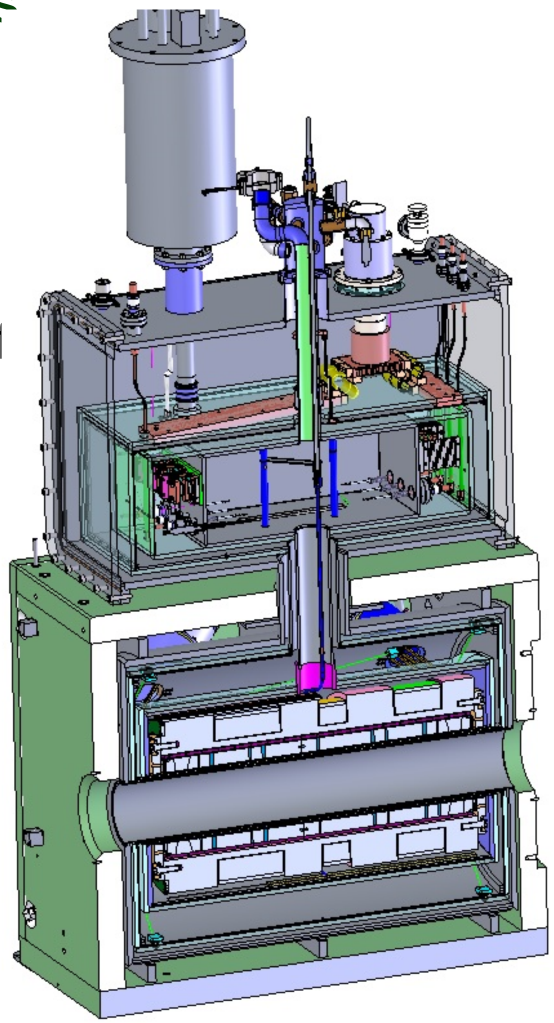
FRIB-VENUS Cryostat

- Design departed from VENUS for several aspects
  - Heat Shield cooled with 2X CH-110 crycoolers (X2)
  - 4K vessel cooled with 2X GM-JT cryocoolers (5W)
- Heat Load
  - Static Head load expected to be ~1.3W.
  - Dynamic heat load will depend on the optimization of the magnetic field minimum



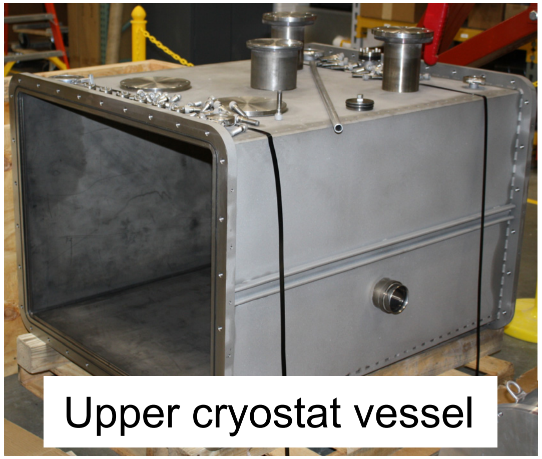


Courtesy D.Leitner (LBNL)

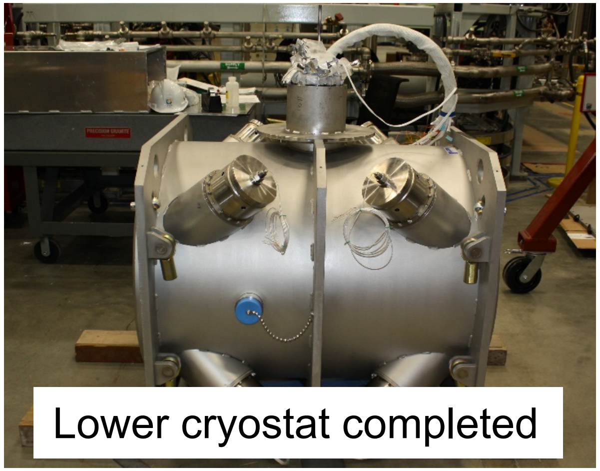


FRIB ECR Cryostat Assembly is progressing

- Lower cryostat has been completed
  - Magnet integrated in Helium vessel (leak checked)
  - Multi Layer Insulations installed
  - Final leak check of vacuum vessel underway
- Integration of upper cryostat assembly to start next
  - Most parts fabricated or procured
- Test of GM-JT Crocooler in the fall
- Full magnet excitation in cryostat by early 2020


Upper cryostat vessel

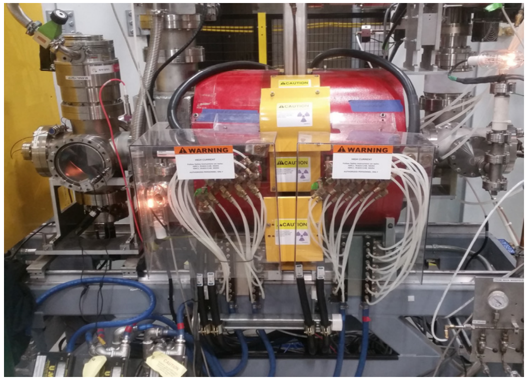

GM-JT Crocooler


Lower cryostat completed

FRIB From Commissioning to Operation

- Commissioning done with 14 GHz ECR ion source
  - Commissioning beams: ^{86}Kr, ^{36}Ar (^{129}Xe and ^{20}Ne)
  - Routine Operation at 900W .Up to 300euA obtained of Ar^{9+}
- Primary beams chosen to best produce key nuclides for operation

- 14 GHz ARTEMIS ECR



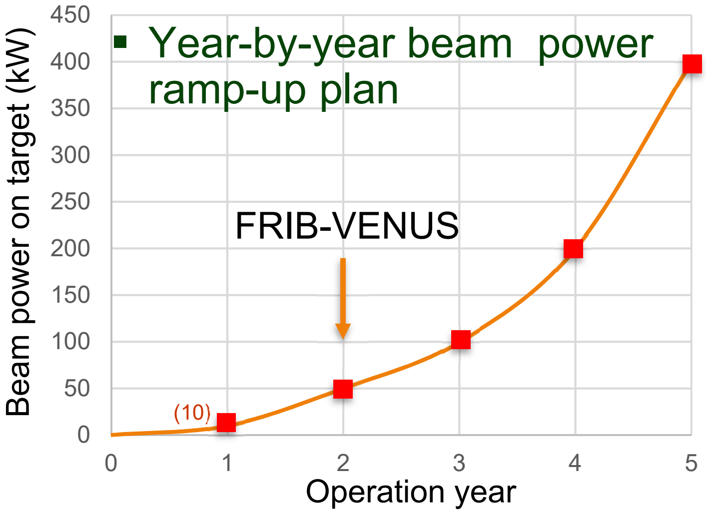
Year One (+6)

Beam	Weeks/Year
^{238}U	12
^{48}Ca	6.34
^{78}Kr	2.21
^{124}Xe	1.3
^{18}O	0.86
^{16}O	0.44

Year Two (+5)

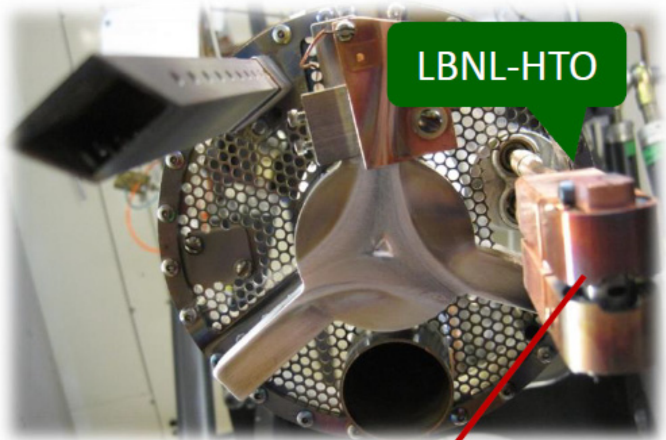
Beam	Weeks/Year
^{82}Se	5.25
^{92}Mo	2.45
^{58}Ni	1.64
^{22}Ne	0.54
^{64}Ni	0.5

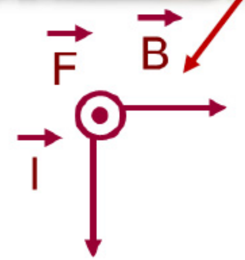
- Year-by-year beam power ramp-up plan



High intensity Metallic beam production

- For 450euA U33+ produced at LBNL with VENUS
  - Oven was damaged under Lorentz forces
    - » RF Inductive Oven
  - U02 is easy to handle and inert but need to reach Higher temperature (2000-2100C) to get more vapor
  - Outgassing/Conditioning and operational stability at high temperature (>2000C)





- For Low temperature elements (Ca, Se) Material Consumption (680 euA Bi^{31+} ~11 mg/hr for SECRAL) is concern
  - Development of Large capacity oven
  - Cost of material
  - Plasma chamber contamination after beam time
- High intensity from Sputtering? (Mo, Zr..)

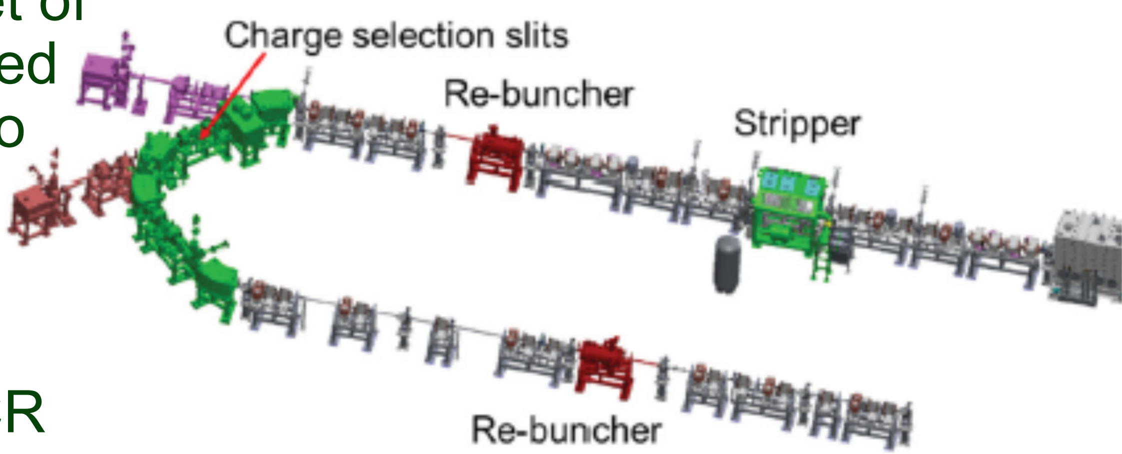
Contaminants from ECR

- Contaminants from ECR accelerated through Linac segment 1 could result in **uncontrolled losses** after charge striper:

N^{2+} Q/A =1/7 → N^{7+} Q/A =1/2

U^{34+} Q/A =1/7 Striper U^{78+} Q/A =78/238=0.328

- After linac segment 1 Uranium Beam ~40kW (Full power)
  - 1 -2% contaminant ~0.5-1kW!!
- Problem largely mitigated Set of collimators have been installed in Folding Segment 1 (x10) to intercept losses from contaminant

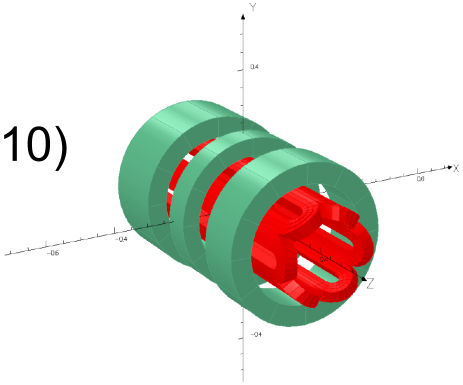


- But there is a strong need to reduce contaminant from ECR as much as possible
  - Learn techniques used in ECR-CB

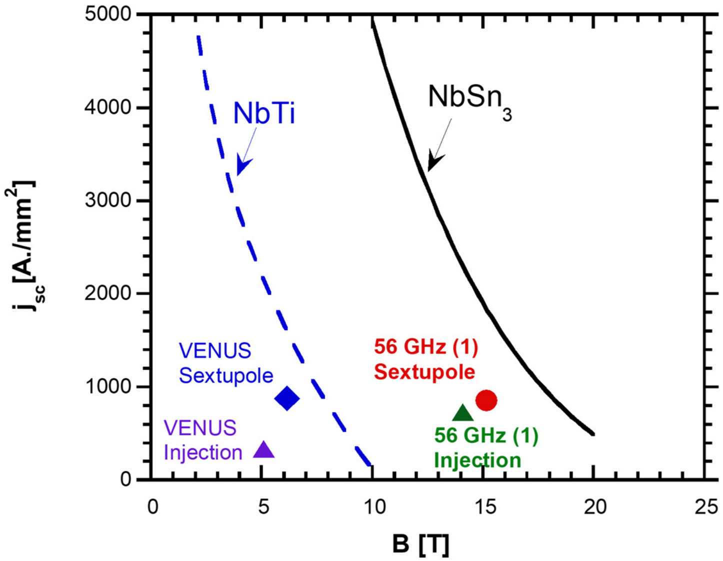
Beyond 28 GHz Operation

- Critical Field for NbTi wire exceeded for an ECR Magnet beyond 30-35 GHz. Need to use Nb3sN
  - First design Study in 2010 for 56 Ghz structure

    P. Ferracin et al.,Rev. Sci. Instrum., vol.81, 02A309 (2010)



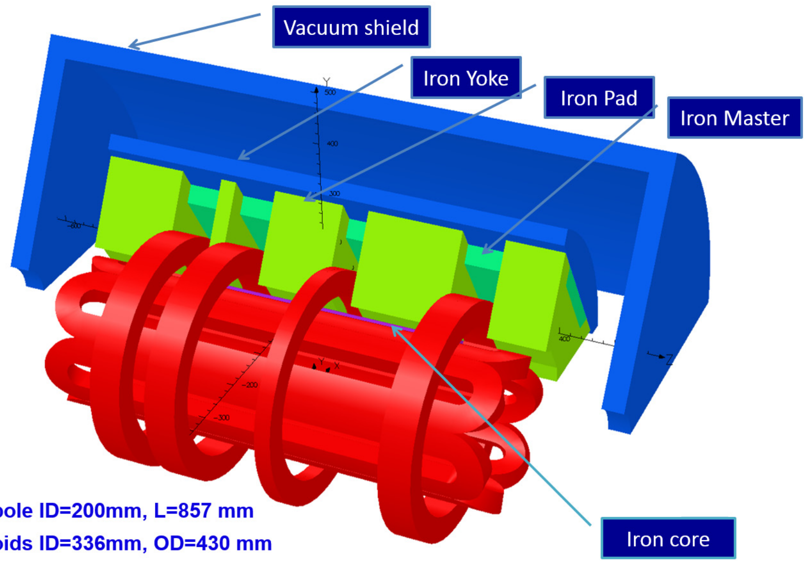
Magnetic Design		28 GHz	56 GHz
Max solenoid field	on the coil	6 T	12 T
	on axis	4 T	8 T
Max sextupole field	on the coil	7 T	15 T
	on plasma wall	2.1 T	4.2 T
Superconductor		NbTi	Nb_3Sn



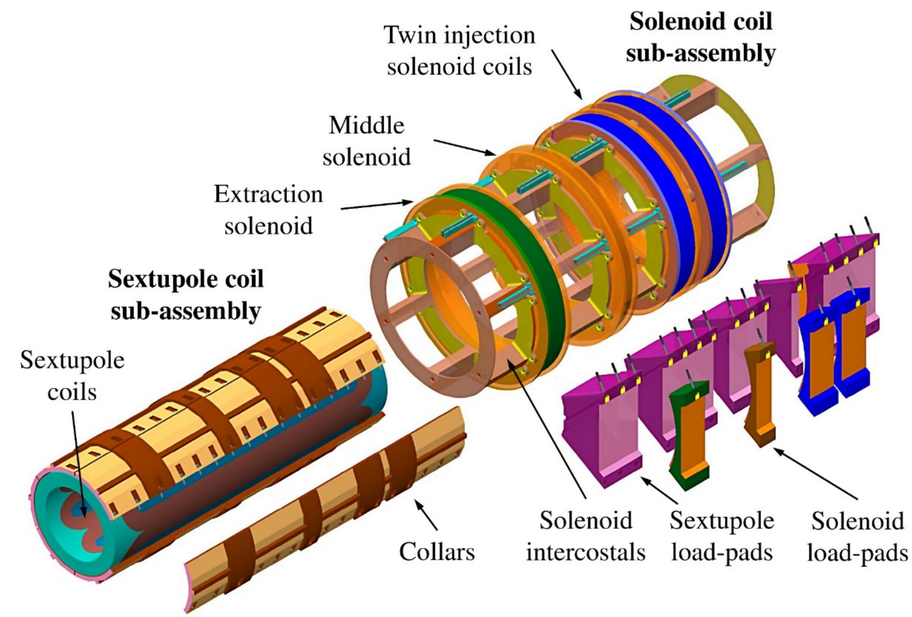
Courtesy D. Leitner

FE-ECR First 45 GHz FECR for HIAF (IMP, China)

- Design of a mechanical structure for 45 GHz ion source (Collaboration between IMP, China and LBNL)



Sextupole ID=200mm, L=857 mm
Solenoids ID=336mm, OD=430 mm



*H.W. Zhao et.al ECRIS2018, Catania, Italy, 2018
*H.W. Zhao et. al.,Rev. Sci. Instrum., vol.89, 052301 (2018)
**M. Juchno et al.,IEEE Trans.Appl.Supercond., 28, 4602806(2018)

Courtesy D. Leitner

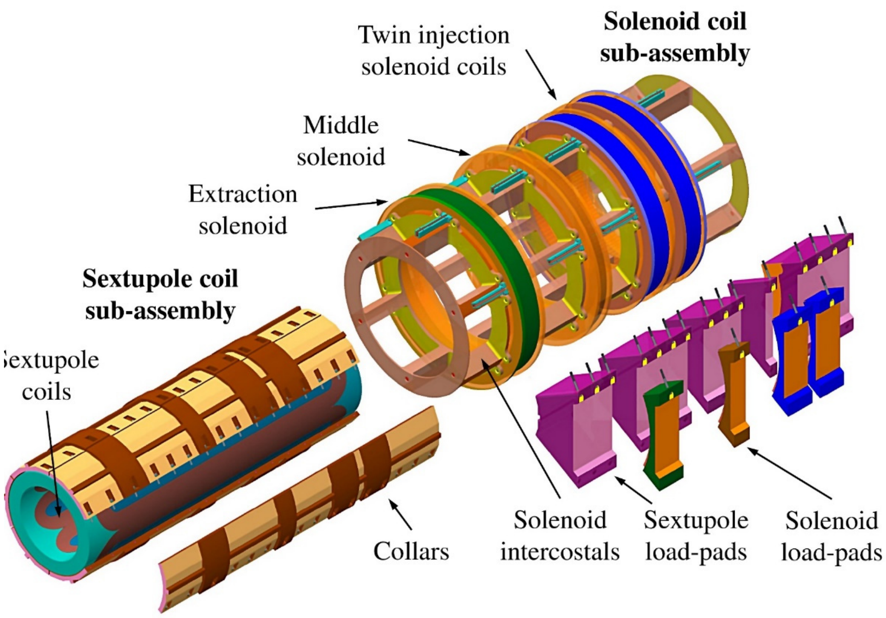
FE-ECR First 45 GHz FECR for HIAF (IMP, China)

- Design of a mechanical structure for 45 GHz ion source (Collaboration between IMP, China and LBNL)

Design is based on several years of experience with the design and fabrication Nb^3Sn at LBNL within the LARP program and the HILUMI project to develop high field quadrupoles (Rutherford Cables) for the LHC upgrade.

Challenges:

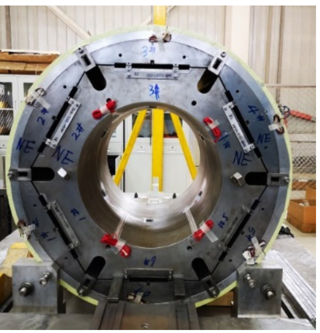
- Combined magnet functionality (Solenoid_Sextupole)
- Single Strand SC Wire

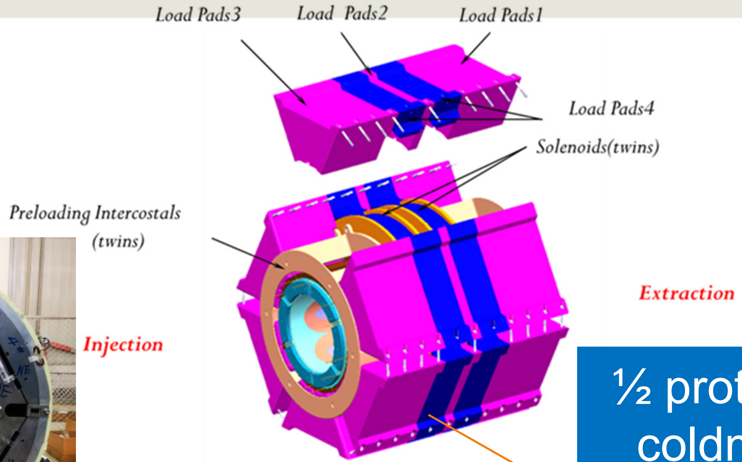


*H.W. Zhao et.al ECRIS2018, Catania, Italy, 2018
*H.W. Zhao et. al.,Rev. Sci. Instrum., vol.89, 052301 (2018)
**M. Juchno et al.,IEEE Trans.Appl.Supercond., 28, 4602806(2018)

Courtesy D. Leitner

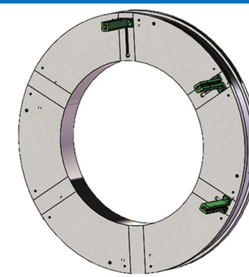
FE-ECR (IMP, China) magnet Prototyping underway



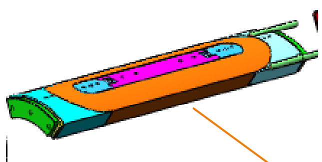


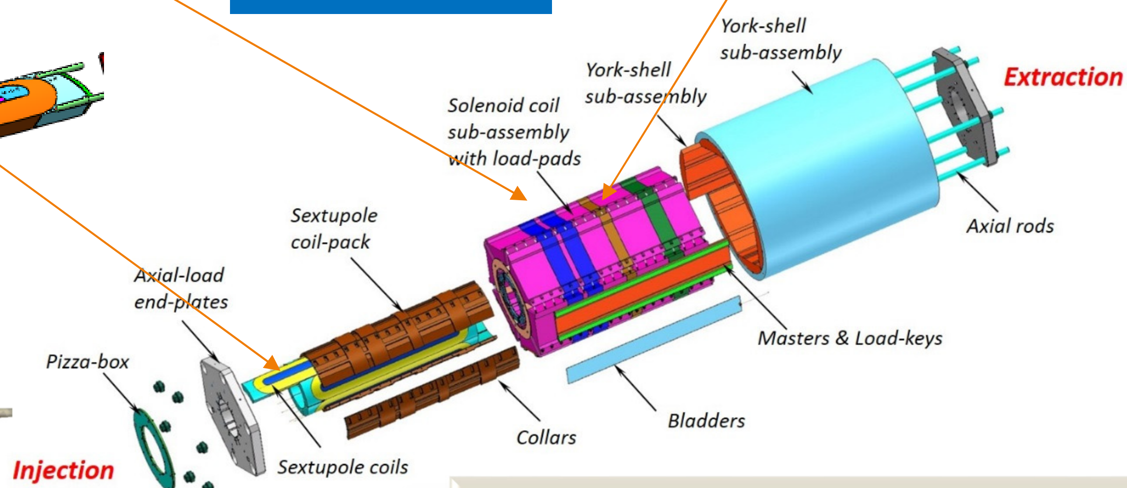
½ prototype coldmass

prototype solenoid



800 A no quench





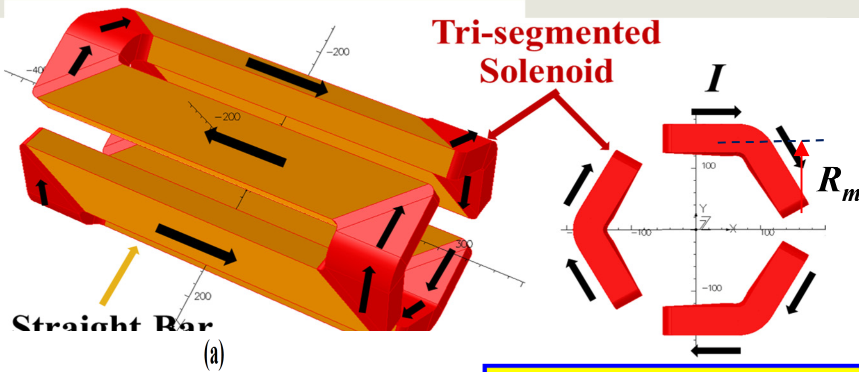
½ prototype sextupole

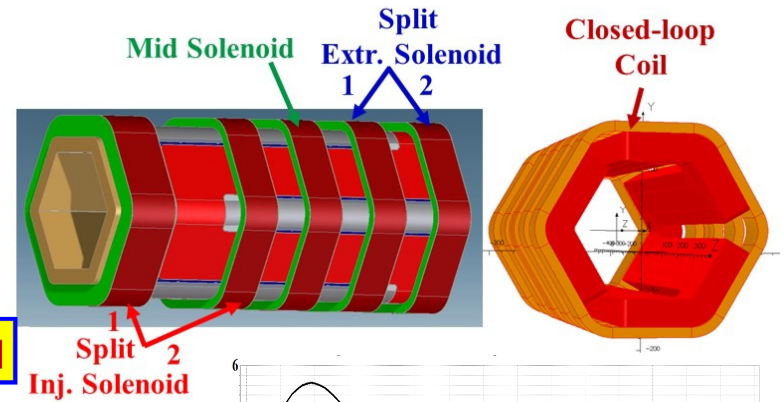
800 A no quench

Courtesy L.T Sun

- ☐ Full sized coldmass is to be started

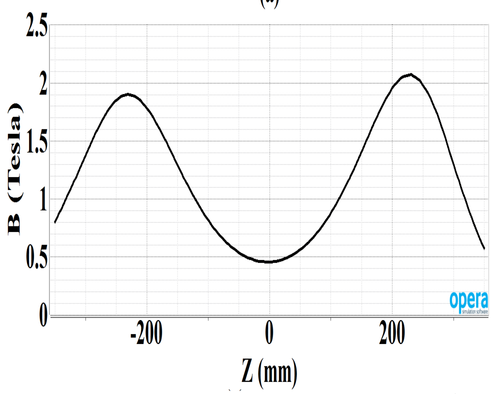
Closed-Loop Coil Concept (MARS-D, LBNL)

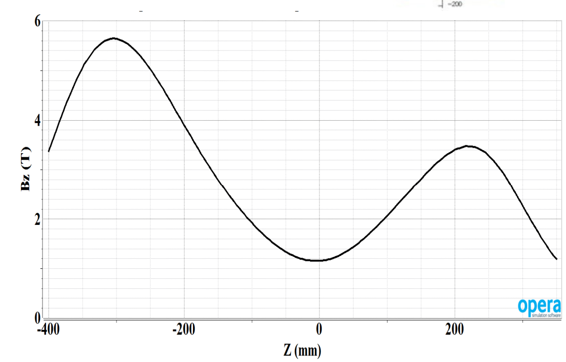


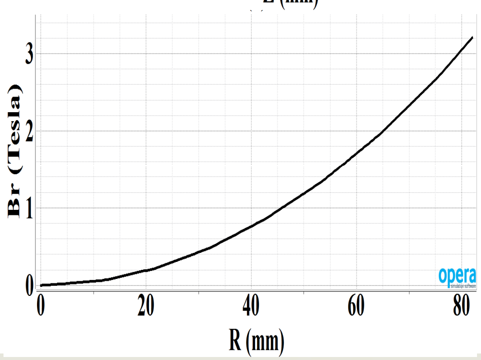


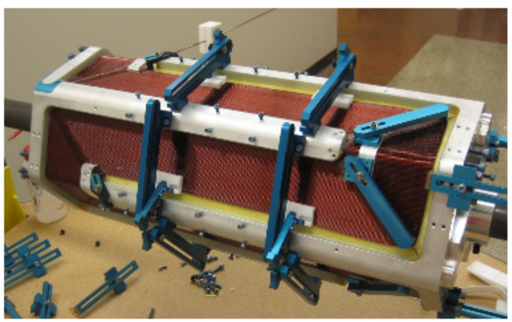
A closed-loop hexagon coil

The Closed-loop Coil (ClC) generates a minimum-B configuration by itself, except the axial mirrors are not high enough for applications in ECRIS.







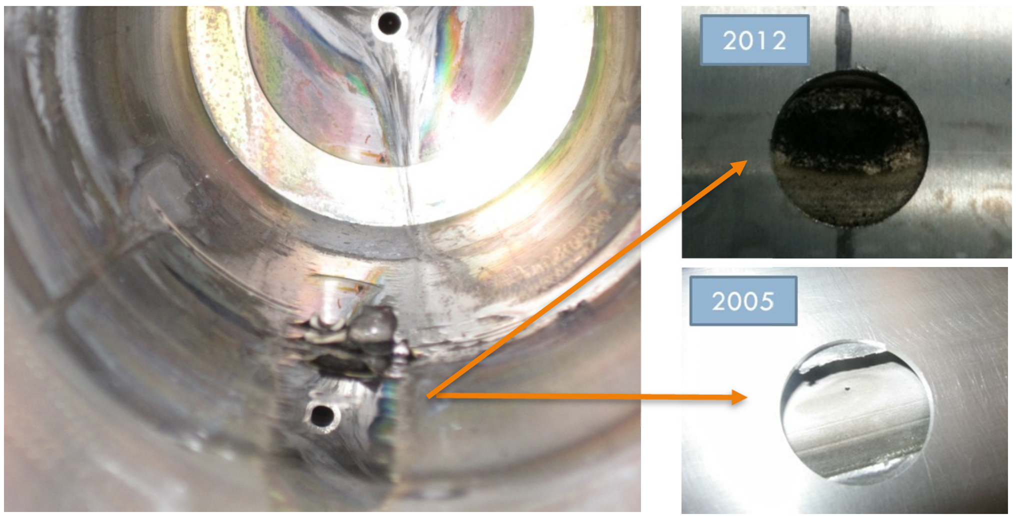


Courtesy D.Xie

- **Demonstration Project Mars-D Proposed for operation at 18 GHz**
- **Could be extended beyond 28 GHz**

Impact of High Power Operation On the Plasma Chamber

- Plasma Losses (Flutes) lead to localized very high heat Load
  - VENUS running at 8-10kW made a hole in plasma chamber twice (2005-2012)
  - SECRAL 1,2 also made a hole in plasma chamber several times



MYLAR Electrical Insulator damaged at flute location

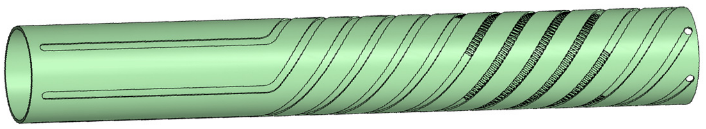
- Plasma Chamber normally as thin as possible (maximize plasma volume and optimize field at chamber radius

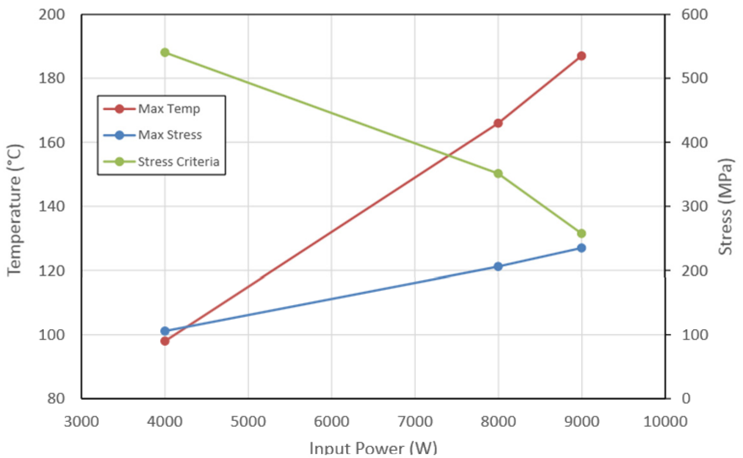
How to operate reliably at 10kW to 20 kW or more of microwave Power?

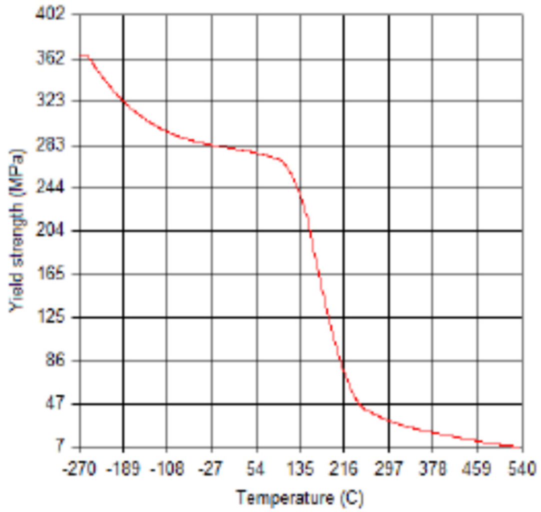
Plasma Chamber for FRIB-VENUS ECR

- Plasma chamber optimized for high power operation
  - Thermal Analysis conducted to maximize power injected
  - Can cool 9kW for a temperature increase to of ~180 C

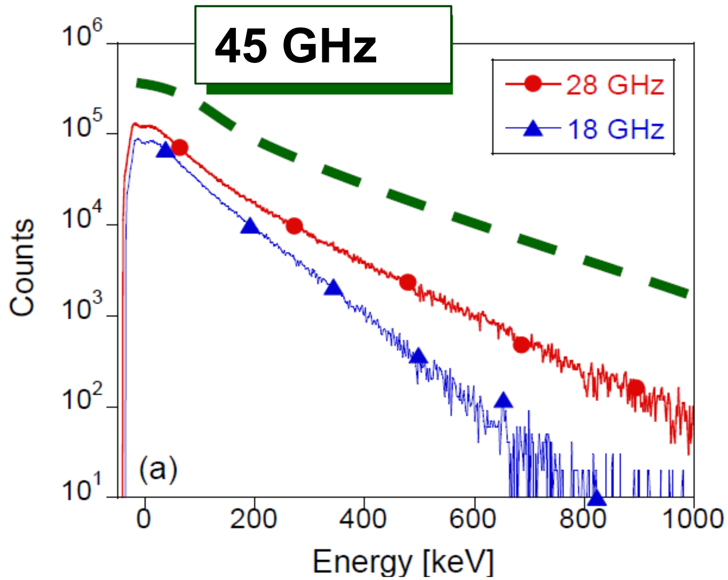
Cooling Parameters	
Material, thickness	Al-6061, 1.83mmm thinnest
Water channel Geometry, angle, width, depth	Spiral shape, 68º,15mm, 2mm
Water velocity	9 m/s
Water flow rate	5gpm/ channel (x3)
Inlet water pressure, drop	120 psig, 60 psi



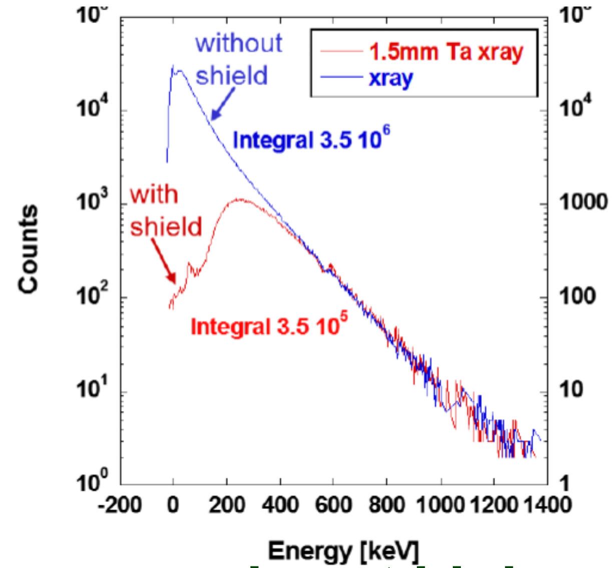




Bremsstrahlung Radiation and Cryogenics



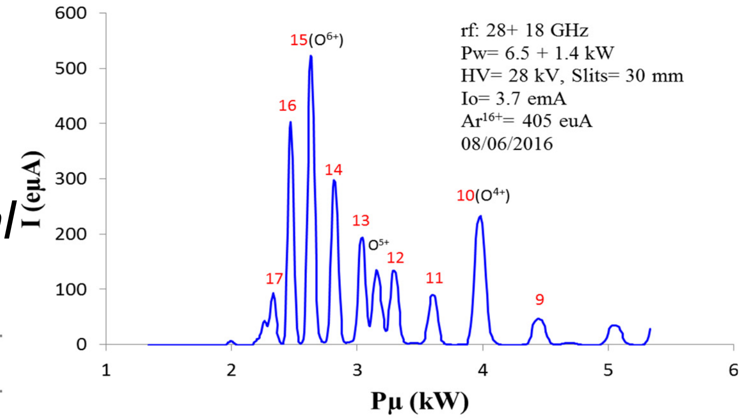
D. Leitner FRIB ECR Workshop (2009)

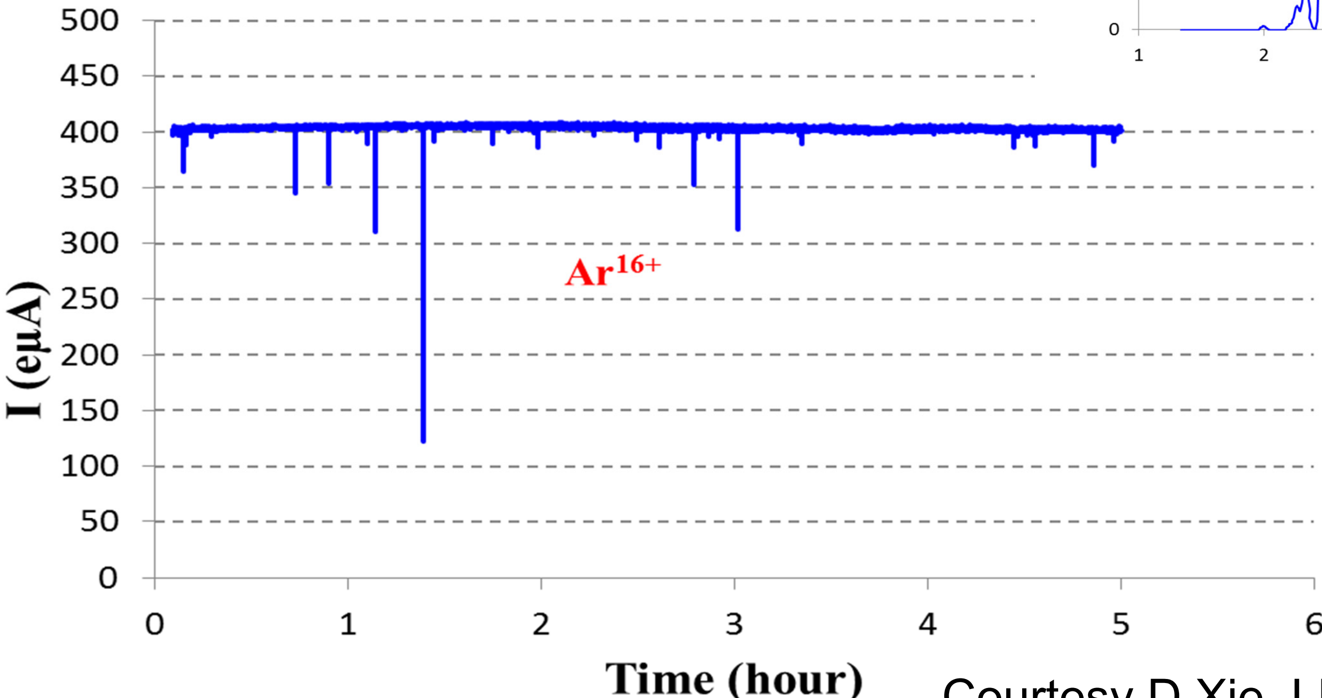


- **Higher X-ray flux and higher X-ray energies at higher frequency:**
  - High 4.2 K cooling capacity
    - » >10 W@4.2 K ?
  - Plasma chamber electrical insulator life span
    - » Heavy metal shielding can work, thickness?
    - » How fast insulator material degrades?
  - Will superconducting magnet epoxy be affected?

Long Term Stability with ECRs at High microwave power operation

- Example of VENUS Operation at high power optimized for Ar^{16+} production
  - *HV discharge, plasma instability, neutral flow issue*

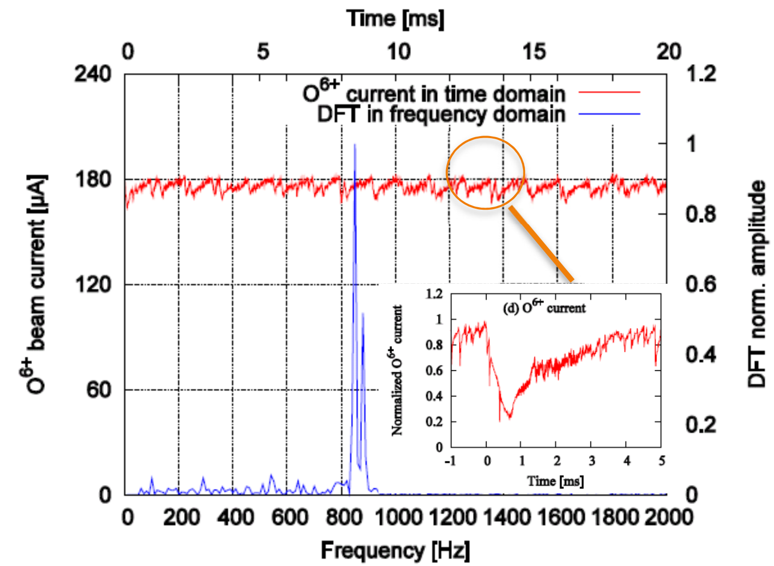




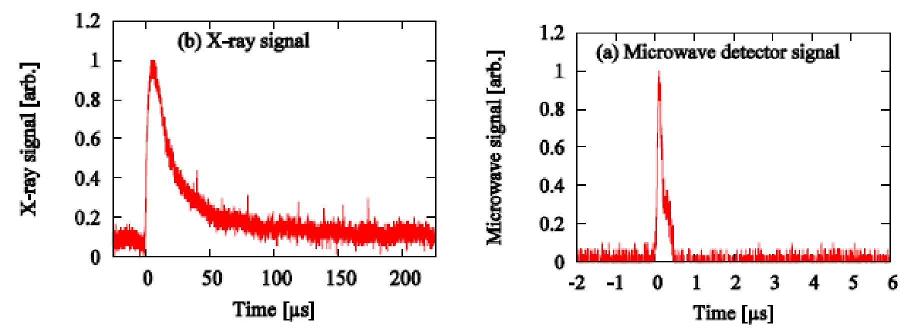
Courtesy D.Xie, LBNL

Short term stability: Beam current oscillation driven by plasmas instabilitiies

- Observations of beam current oscillations driven by instabilities generated by the hot electron population of the ECR plasma
  - Instability characterized by emission of microwave and burst of bremsstrahlung X-rays as well as reduction in beam intensity
  - Observed frequencies typically range few Hundreds of Hz to kHz
  - Plasma Parameters involved in the electron heating rate and source optimization (magnetic field, power, gas) impact the onset of these instabilities
  - May limit performances achievable for a given ECR



O6+ current oscillations



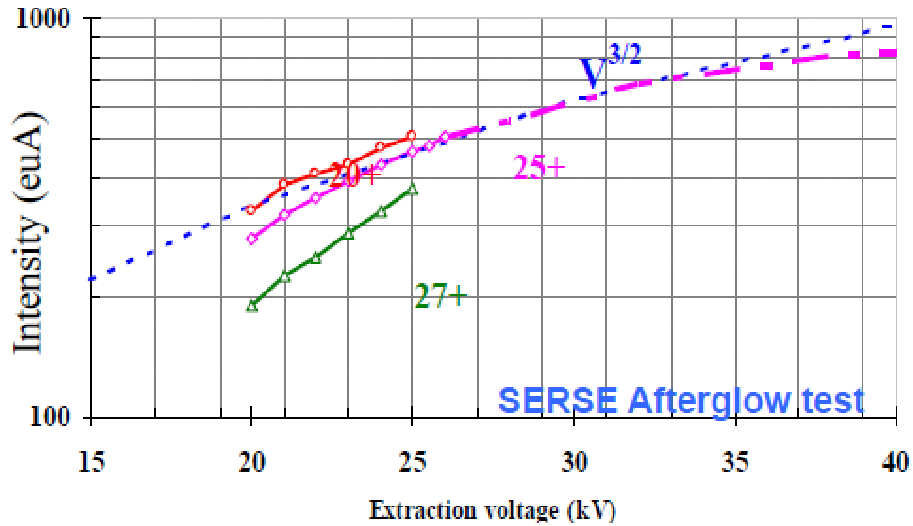
Diagnostics signal:X-ray emission and Microwave burst

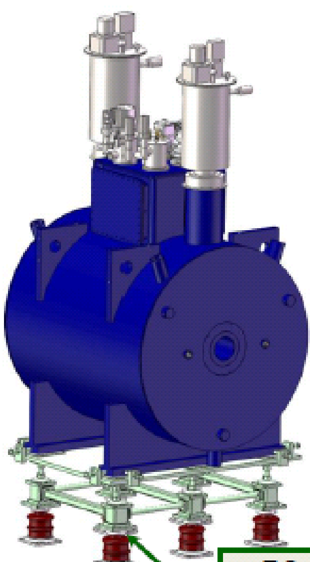
O. Tarvainen ECRIS 2014

Intense Beam Extraction

Child-Langmuir Law:

$$j = \frac{4}{9}\varepsilon_0\left(\frac{2q}{m_i}\right)^{0.5} U^{1.5}/d^2$$





50 kV insulation columns

	O6+	Ar12+	Xe27+	Bi31+
I_q (euA)	5400	1460	920	680
I_{drain} (emA)	20	12.3	14.1	13.0
$I_{drain\text{-}45\ GHz}$ (emA)	30~40	~30	~30	~30

When more ions produced, higher extraction voltage is desired, i.e. 40~50 kV

Courtesy L.T Sun

Conclusion

- Performances of ECR ion sources have increased several orders of magnitudes over the last 40 years
  - Increasing frequency and microwave power coupled still the main roadmap to increase performance
- Physics of ECR ion sources better understood but still many unknown and more effort for modelisation needed
  - Coupling of microwave power
  - Optimization of ion source to minimize Instabilities
  - High intensity metallic beams and capture efficiencies
  - Long term operation at high power
- Design of Magnet is biggest challenge for 4th generation ECR ion source
  - New exciting projects to operate beyond 28 GHz

Thank you for your attention