First Results with the Superconducting Source for Ions (SuSI) at 24 GHz

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National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, USA

Outline

- ❖ Motivations/Context
  - ❖ FRIB update
- ❖ GYCOM 24 GHz gyrotron system
- ❖ SuSI Features /Upgrade/Shielding
- ❖ Commissioning result at 24 GHz
  - ❖ Oxygen, Argon
- ❖ Metallic beam work
- ❖ Summary

Coupled Cyclotron Facility (CCF)

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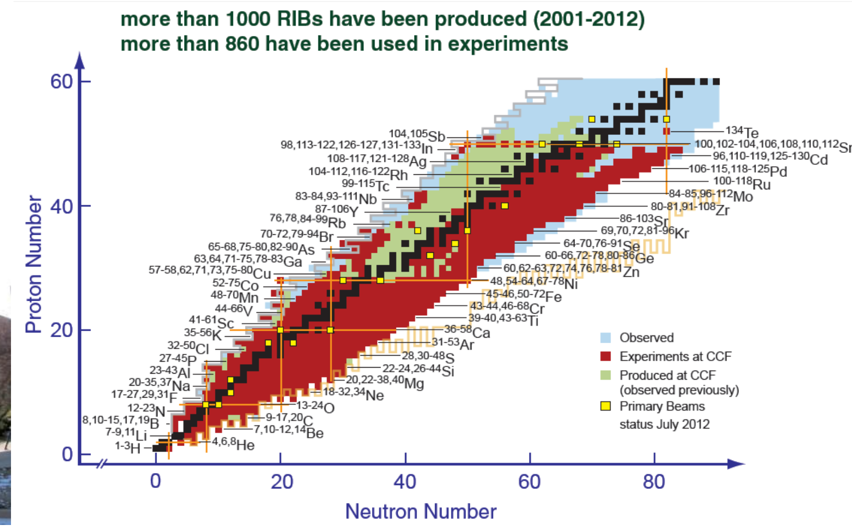

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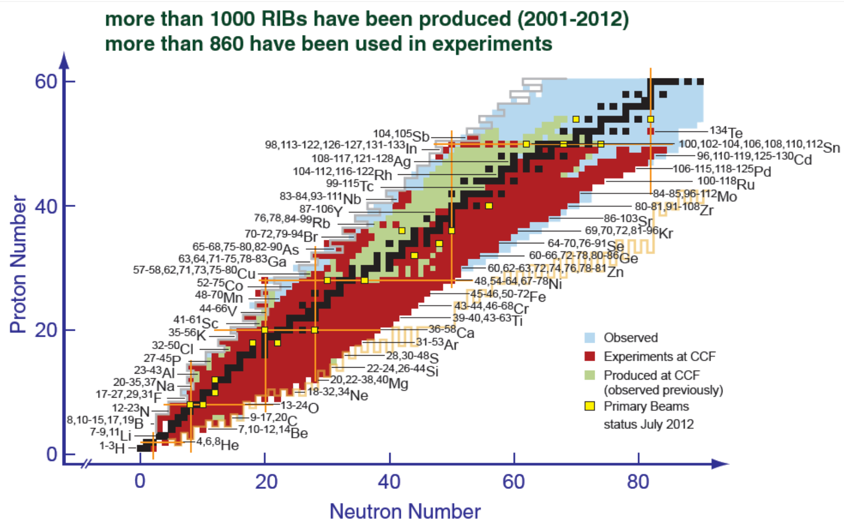

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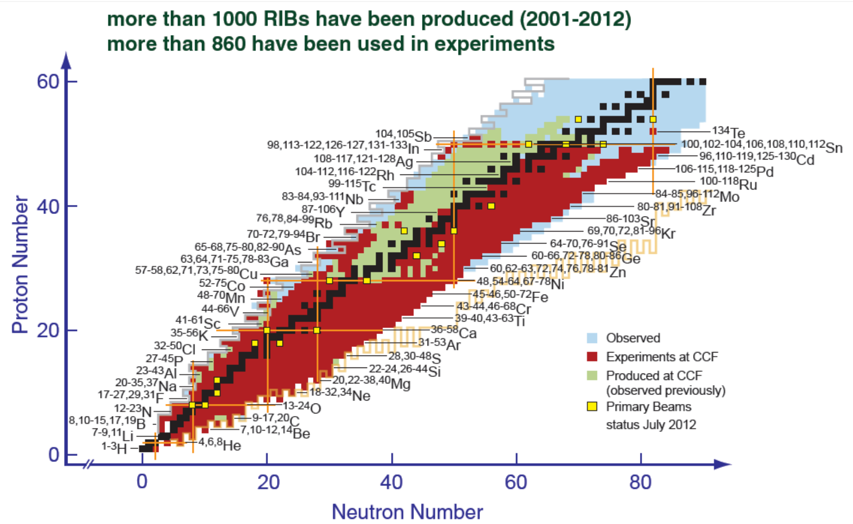

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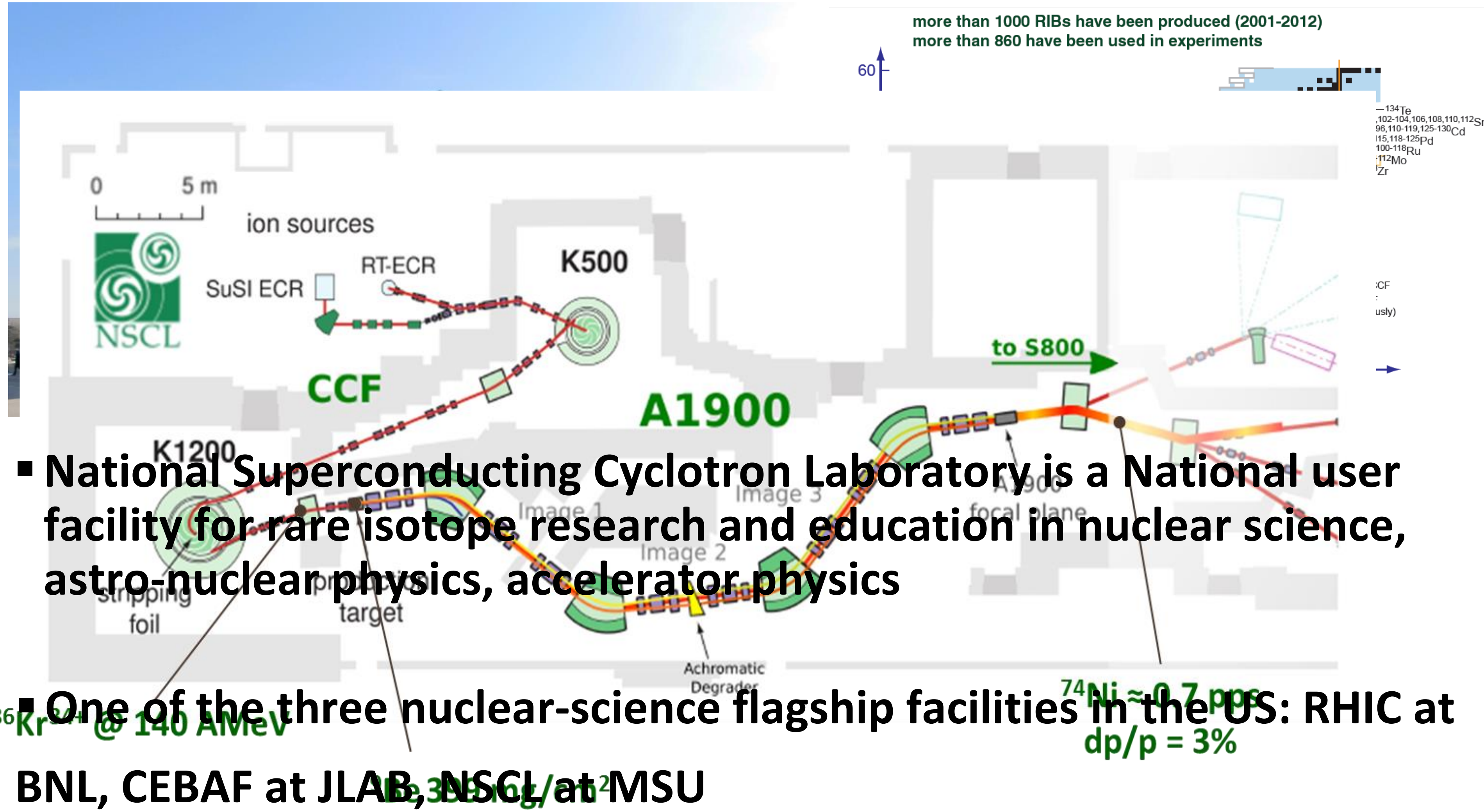

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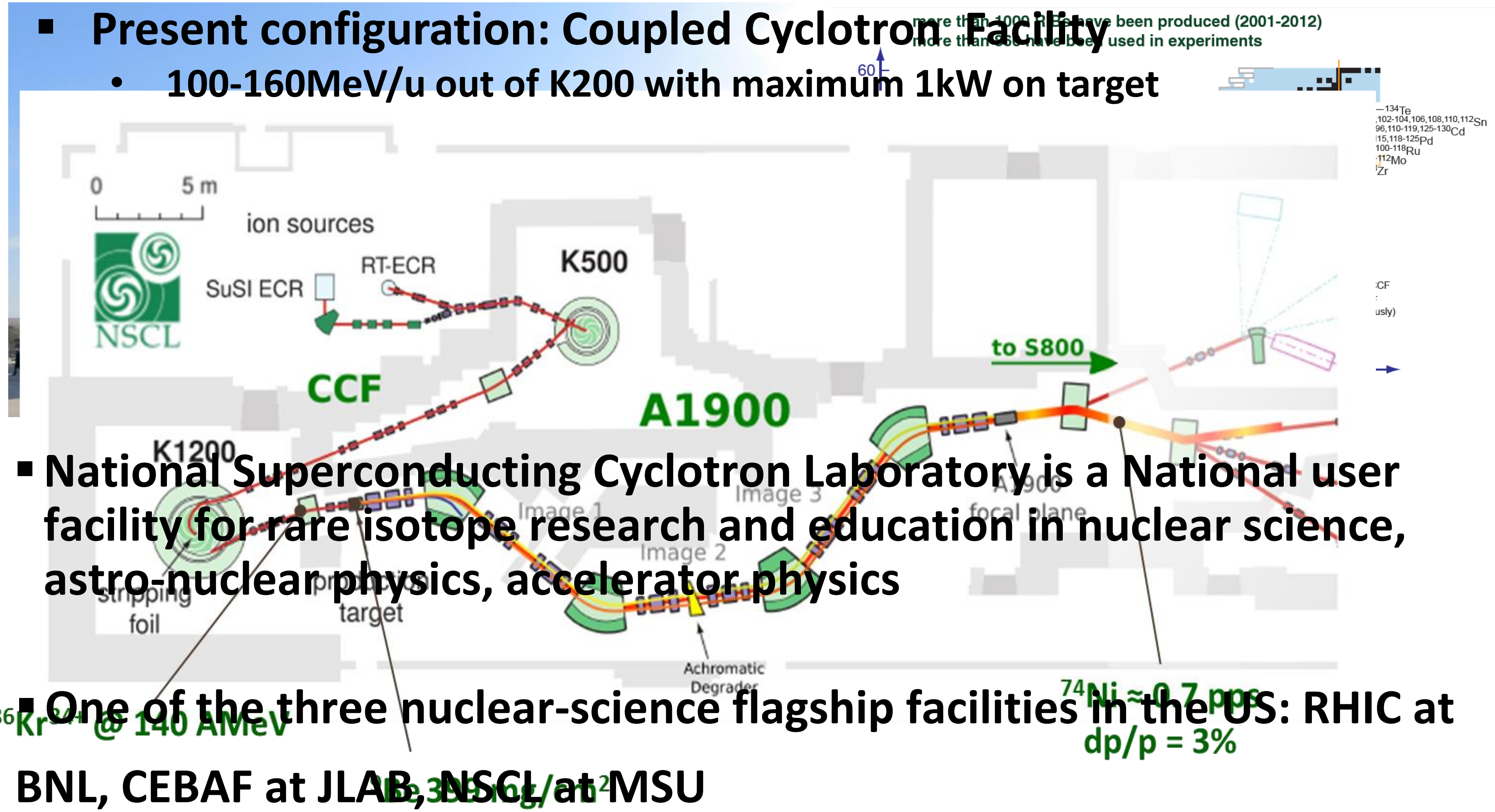
  - **100-160MeV/u out of K200 with maximum 1kW on target**



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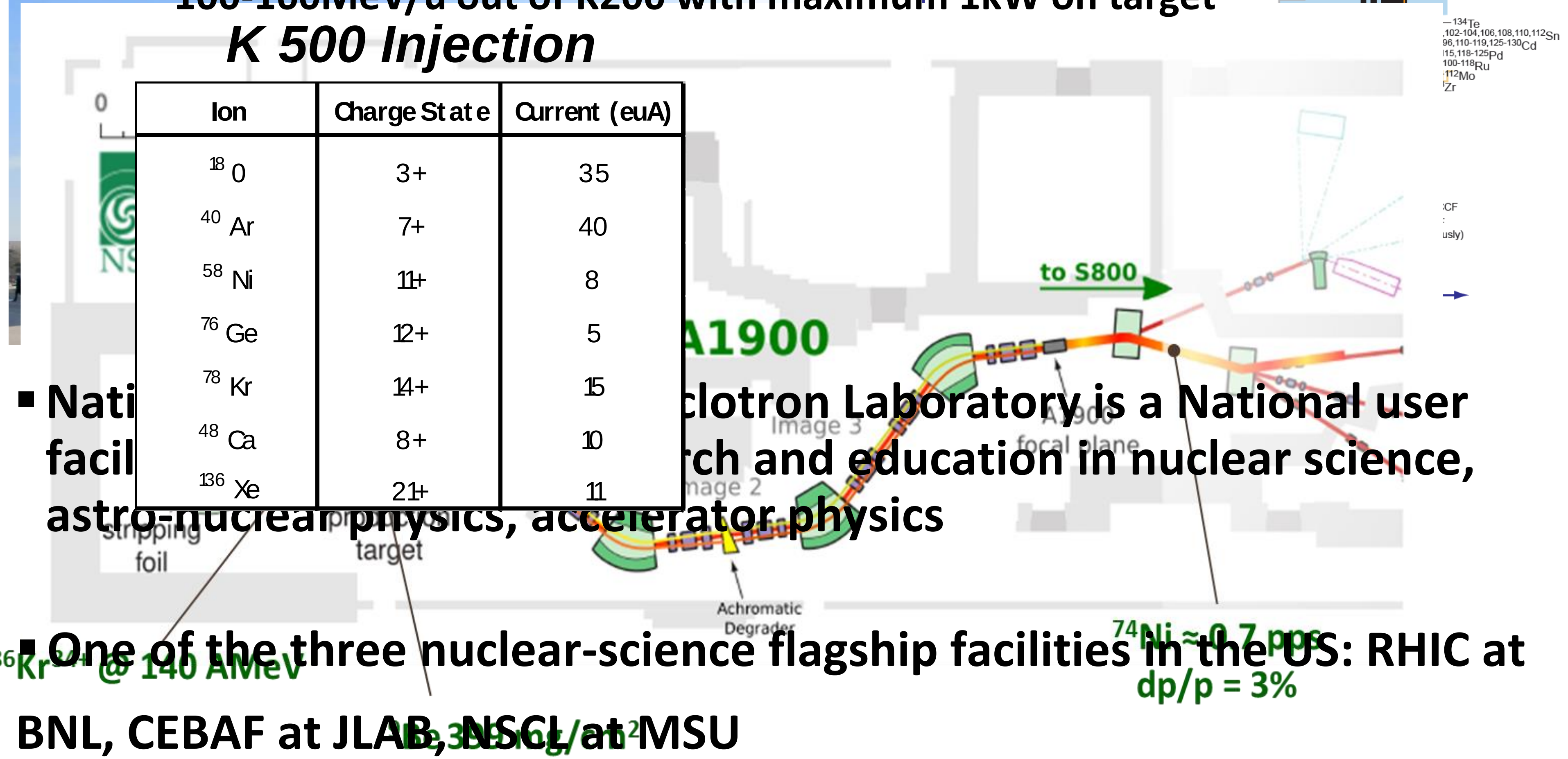
K 500 Injection

Ion	Charge State	Current (euA)
^{18}O	3+	35
^{40}Ar	7+	40
^{58}Ni	11+	8
^{76}Ge	12+	5
^{78}Kr	14+	15
^{48}Ca	8+	10
^{136}Xe	21+	11



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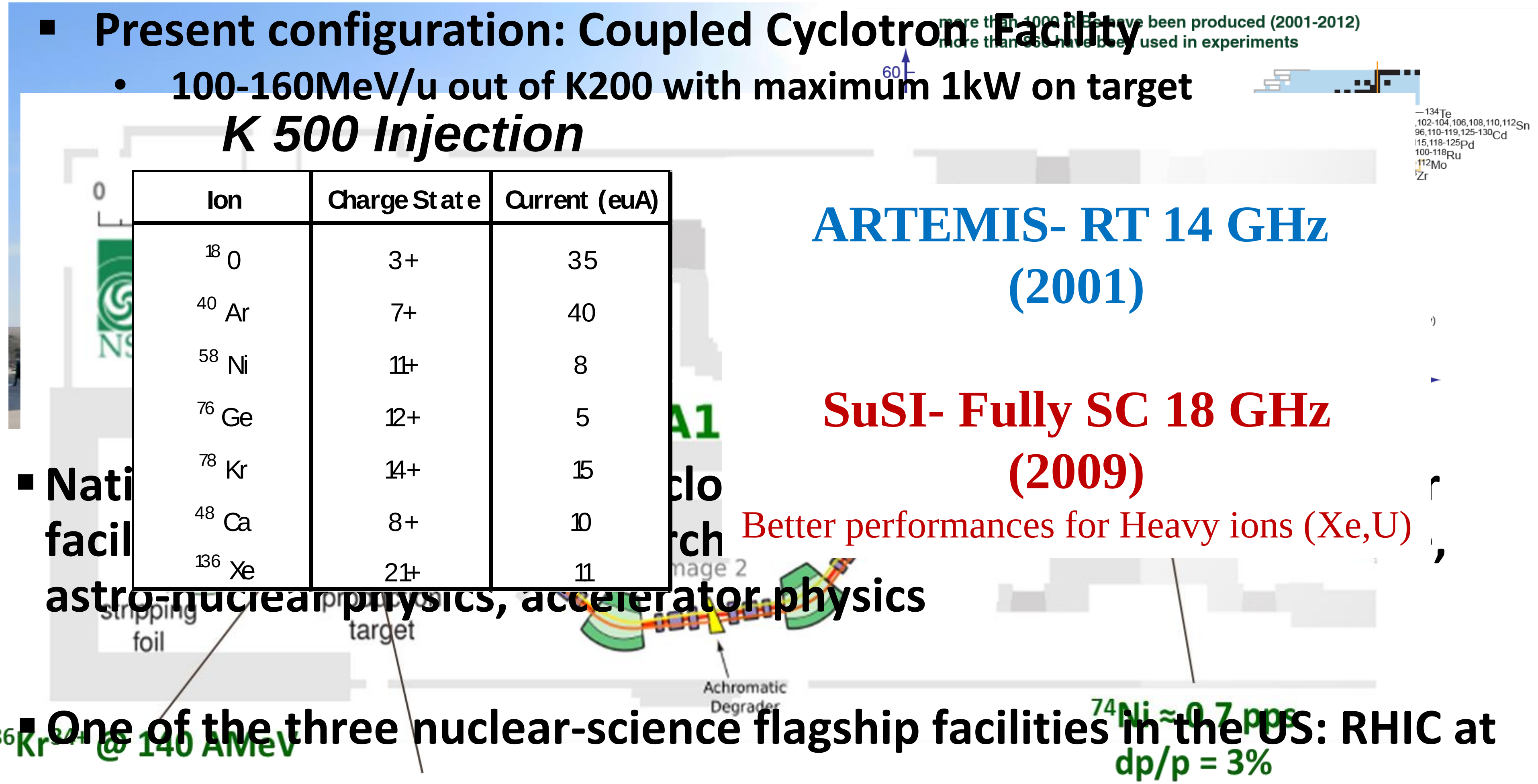
SuSI- Fully SC 18 GHz (2009)

Better performances for Heavy ions (Xe,U)

- **Nati... clo... facil... rch... astro-nuclear physics, accelerator physics**



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more than 1000 RIBs have been produced (2001-2012)
more than 850 have been used in experiments

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stripping foil

target

Achromatic Degrader

$^{86}Kr^{34+}$ @ 140 AMeV

Facility for Rare Isotope Beams (FRIB)

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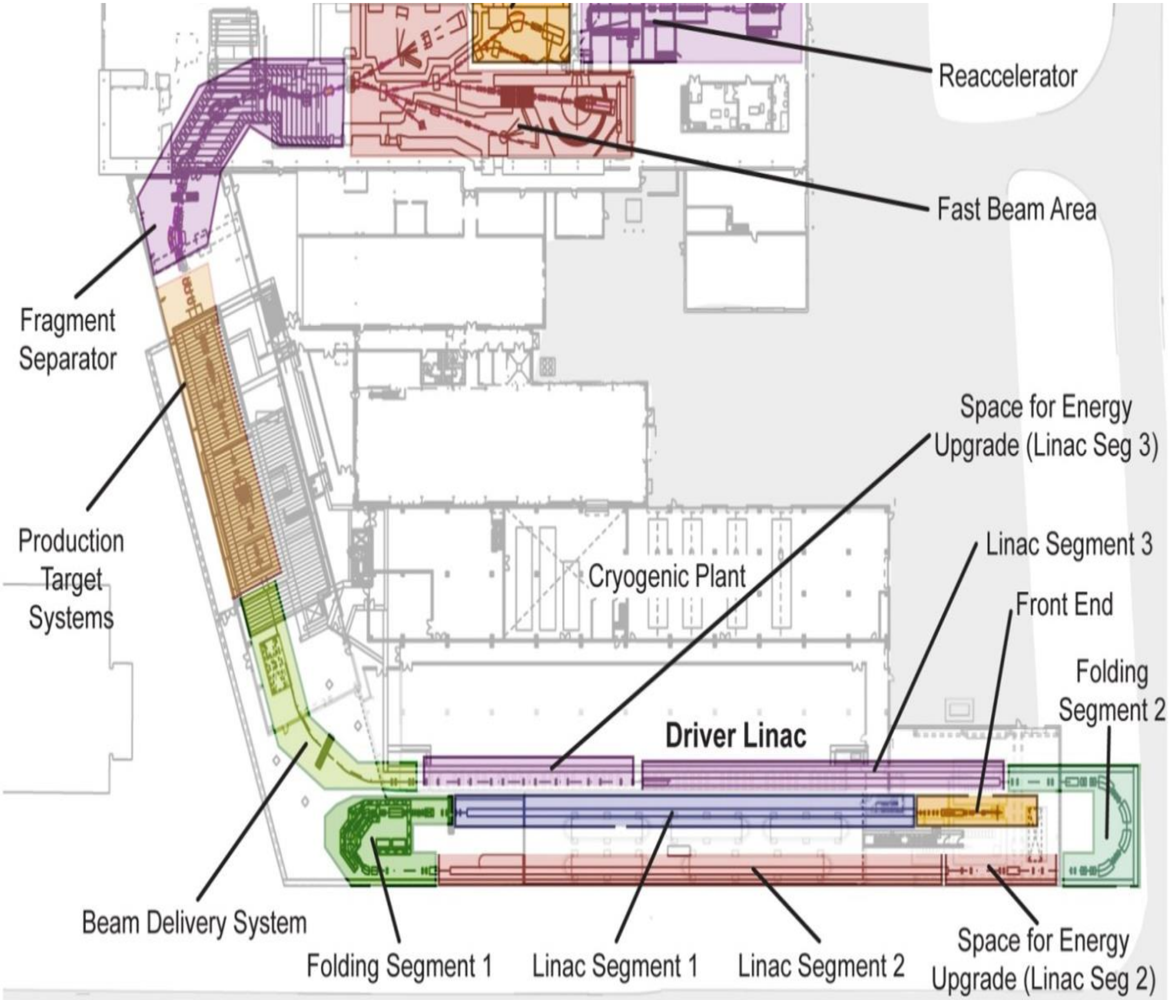

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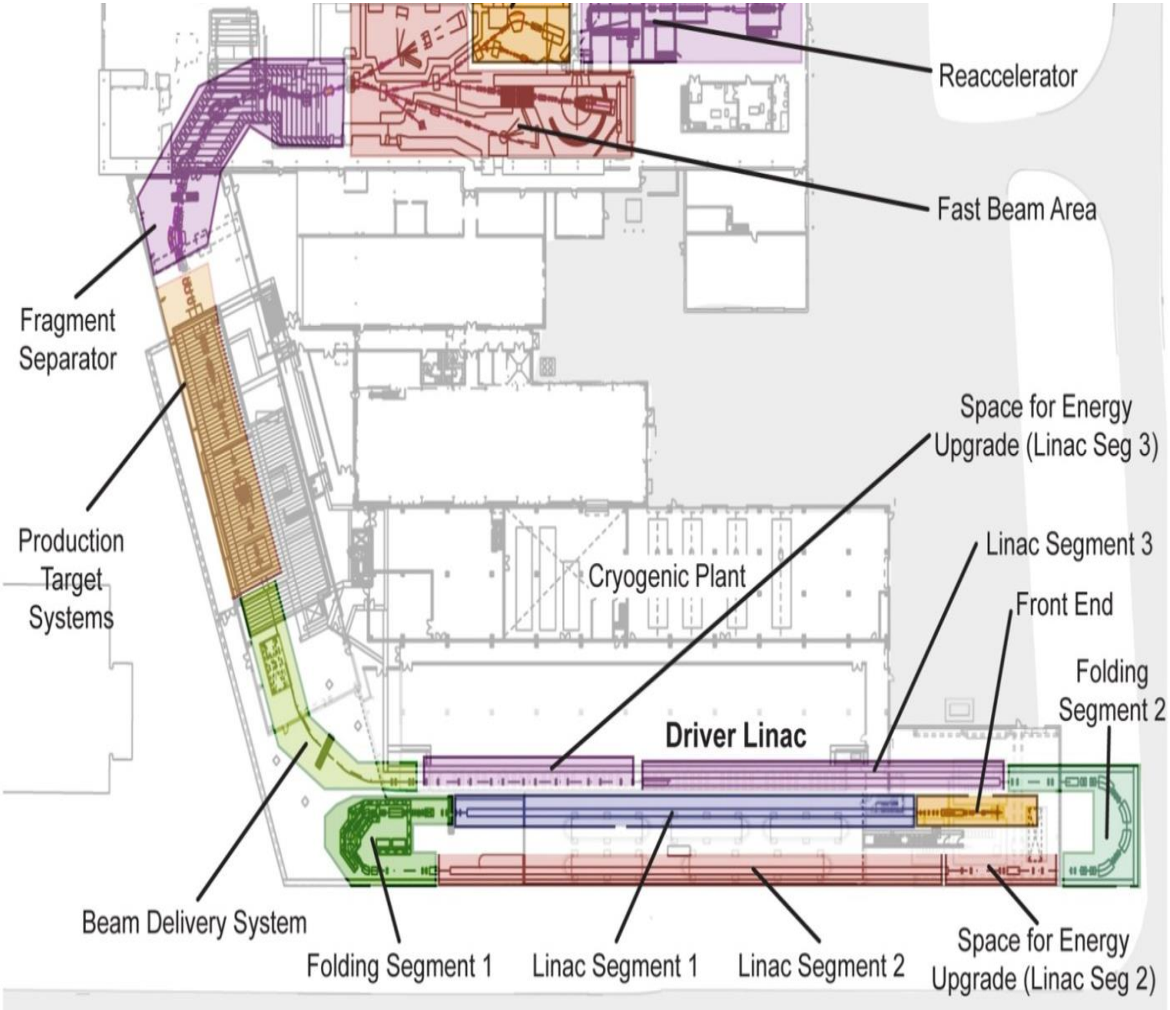

- **Facility for Rare Isotope Beam (FRIB)**
  - Accelerate ion species up to ^{238}U with energies of no less than 200 MeV/u
  - Provide beam power up to 400 kW
  - Energy upgrade to >400 MeV/u by filling vacant slots with 12 cryomodules

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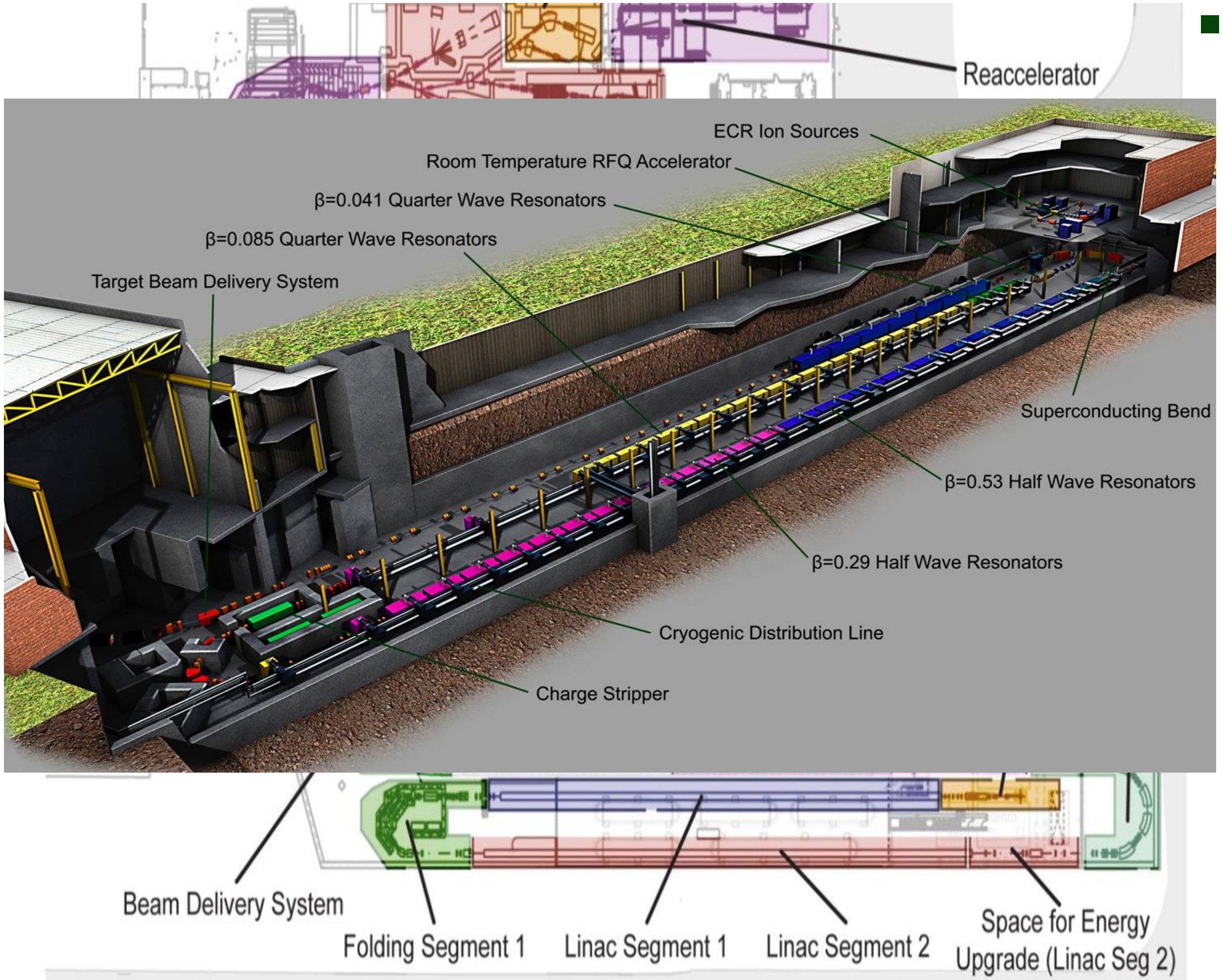

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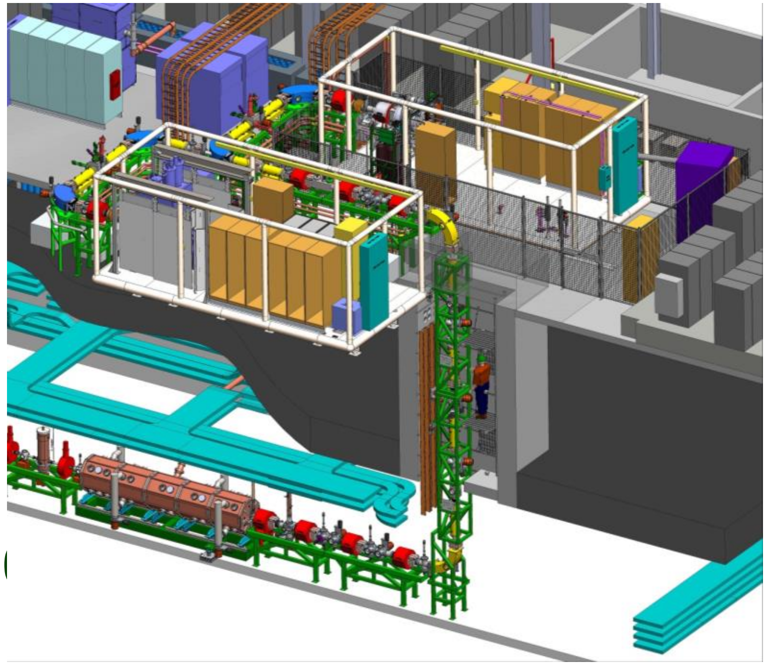
- June 2016: Linac Tunnel
- November 2016: Cryoplant Area
- March 2017: Target High Bay
- March 2017-November 2017: Ion source &LEBT Installation
- Early 2018 Ion source commissioning

ECR Ion Sources Requirement for FRIB

- Energy of 12 keV/U for injection into RFQ (87kV for U)
  - Ion source 30-40kV + HV platform

- Intensity needed (For 400 kW on target)

Argon	40	18	8	378	47.3
Calcium	48	20	11	468	42.5
Krypton	86	36	14	331	23.6
Xenon	124	54	18	334	18.5
Uranium	238	92	33, 34	438	13.1



- Q/A= 1/3 to 1/7
- Transverse emittance (per charge state, 1
  - Single charge state beam 0.9 pi.mm.mrad
  - Dual charge state beam 0.6 pi.mm.mrad
- Project will start with two ion sources
  - One commissioning ion source (14 GHz ARTEMIS) to be ready early
  - One High performance ECR meeting requirement for 400 kW on target

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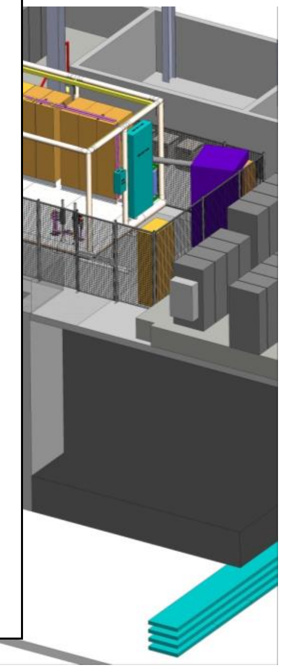
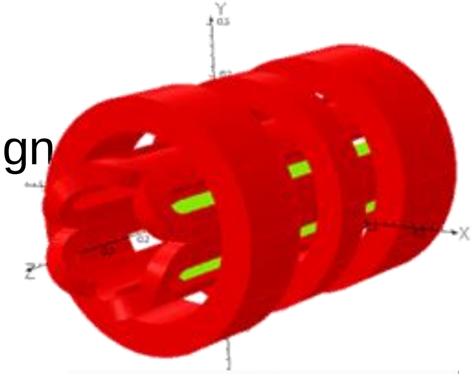
Plan for FRIB

- **1. Develop One SC-ECR Based on VENUS (LBNL)**
  - » Capable to operate up to 28 Ghz (magnet)
- **2. Use SuSI used as development source**
  - » Gain experience with Gyrotron operation
  - » Push performances for Gases and Solid beams
  - » Beam charaterizations (emittance, stability..)

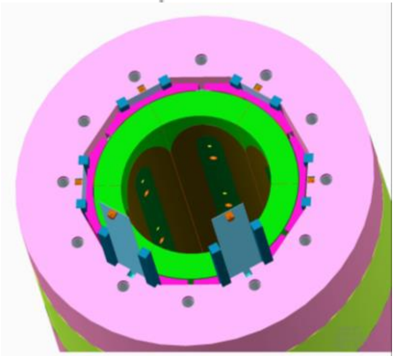


▪Collaboration with SUPERCON group from LBNL for designing FRIB ion source cold mass

- Magnetic and Mechanical Analysis
  - Parameters of the solenoids and sextupole follow VENUS design
  - Sextupole conductor temperature margin 1 K



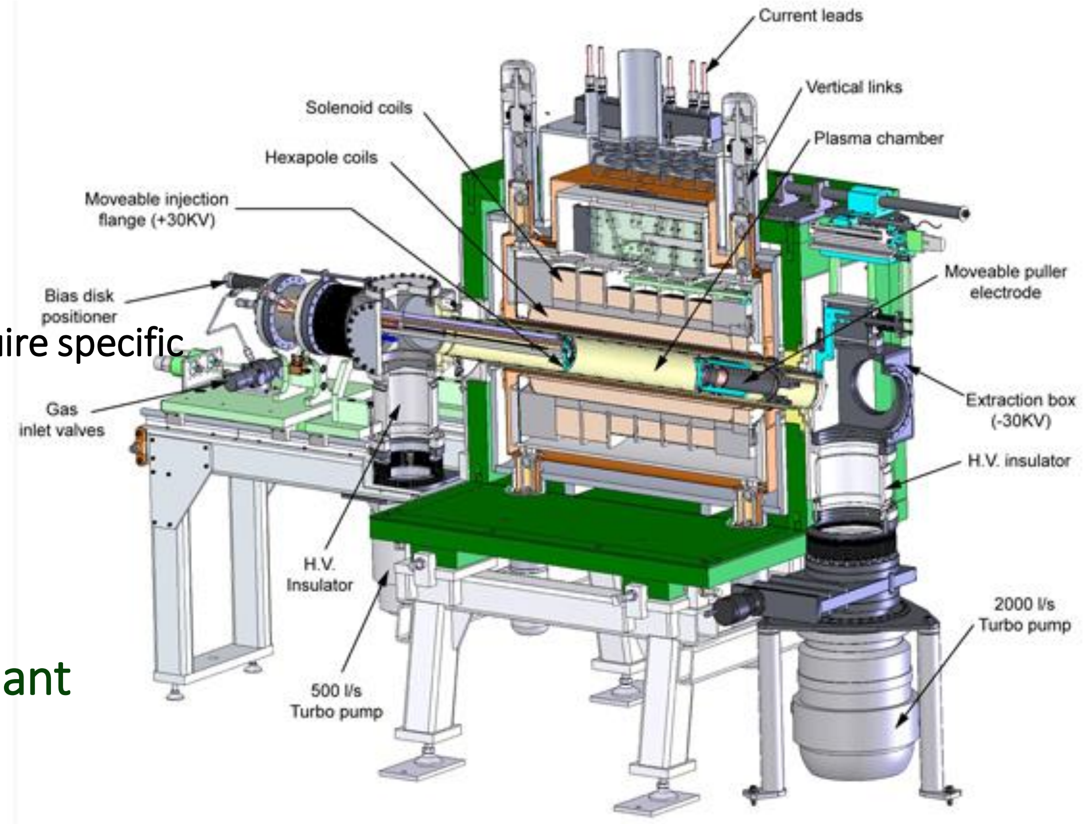
- Shell based Support structure
  - Allows for easy assembly, disassembly, and stress tuning
  - Radial keys and water-inflatable, removable bladders provide radial pre-stress
  - Bladders removed, keys provide preload at Room temperature
  - During cool-down solenoid mandrel used as a compression shell



- Test coil completed successfully ready for vacuum impregnation
  - » Dry wound approach

SuSI ECR ion source

- Completed and operational since 2007
  - Used for injection to CCF since 2009
- Fully Superconducting coils
  - 6 Solenoids
  - Solenoid /Sextupole interaction forces require specific ramp sequenced
    - » Eliminate "random quenches" at field
  - Demonstrated nominal 24 GHz field
- Cold mass cooled with 2kW powerplant
  - Advantages/disadventages
- Al Plasma chamber of ∅101 mm ID
  - 3.5 l overall volume



SuSI modifications to operate at 24 GHz

- Injection assembly rebuilt
  - Oversized waveguide (1.284”)
  - Added cooling
  - 1 oven port remains
  - 1-18 GHz port
- Tantalum liner installed in 2010
  - PEEK used as insulator
- New plasma electrode
  - 5/16” (7.9 mm diameter)

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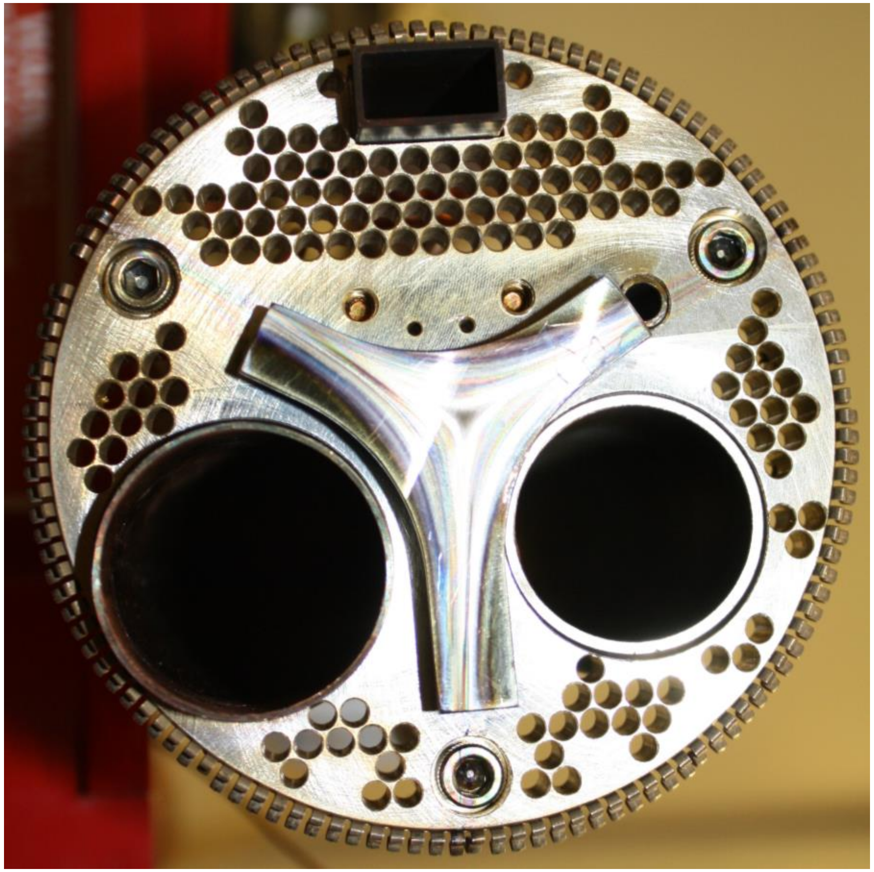

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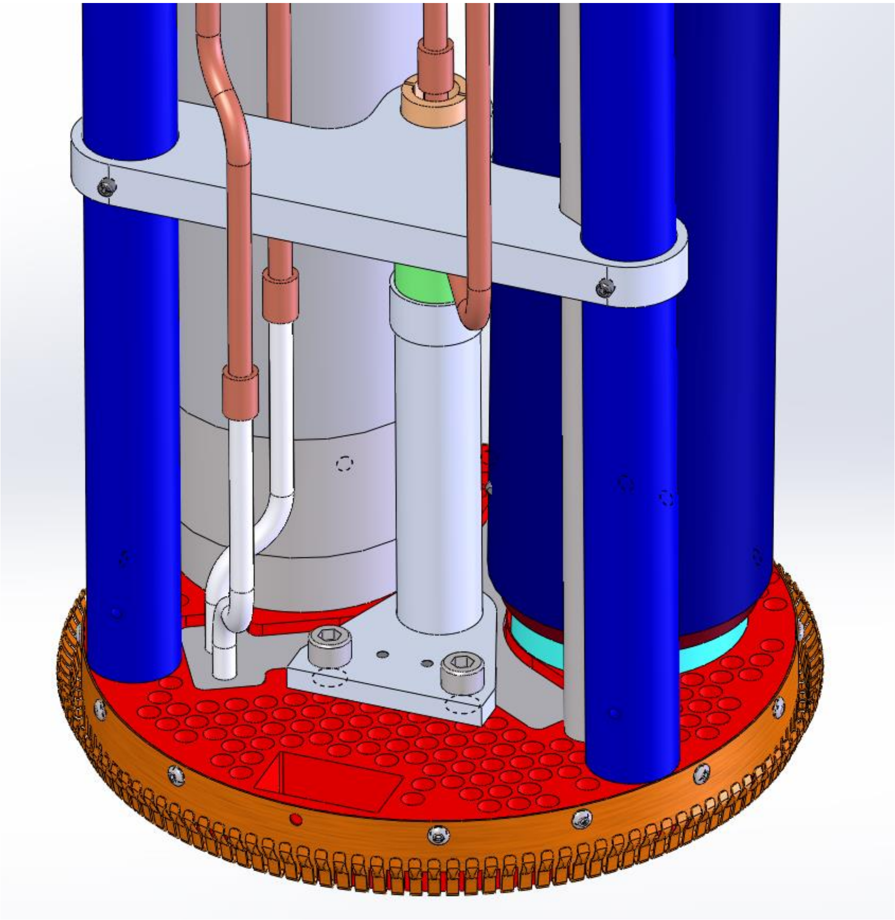

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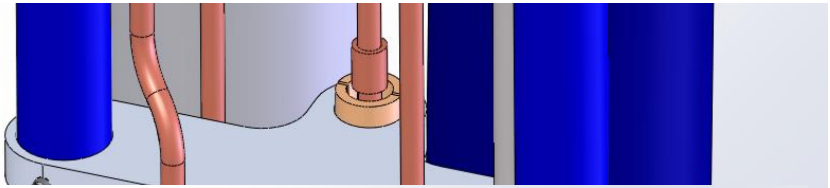

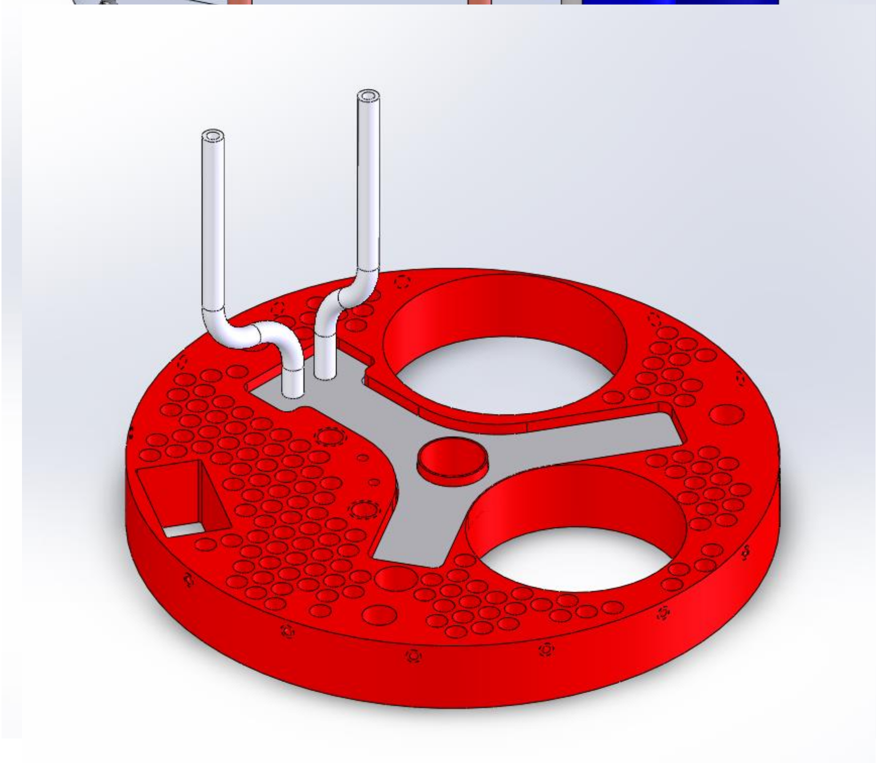

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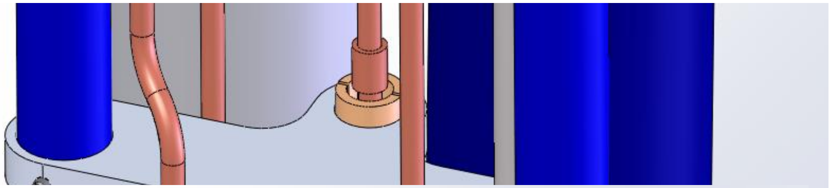

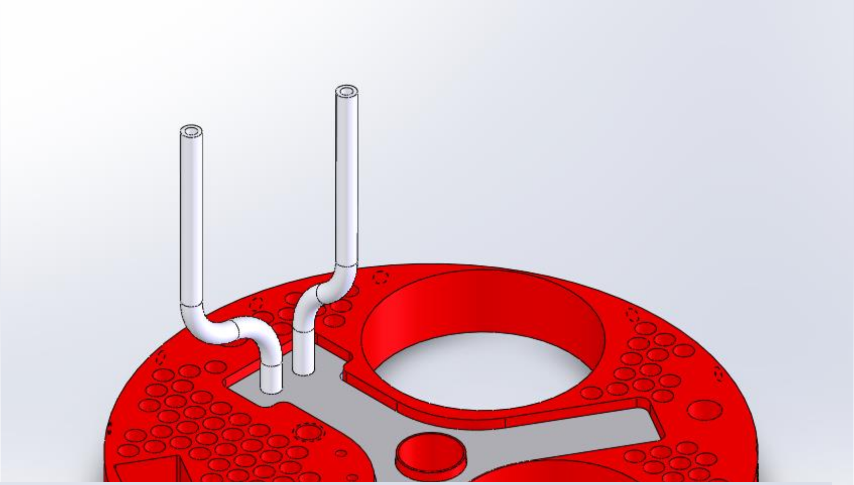

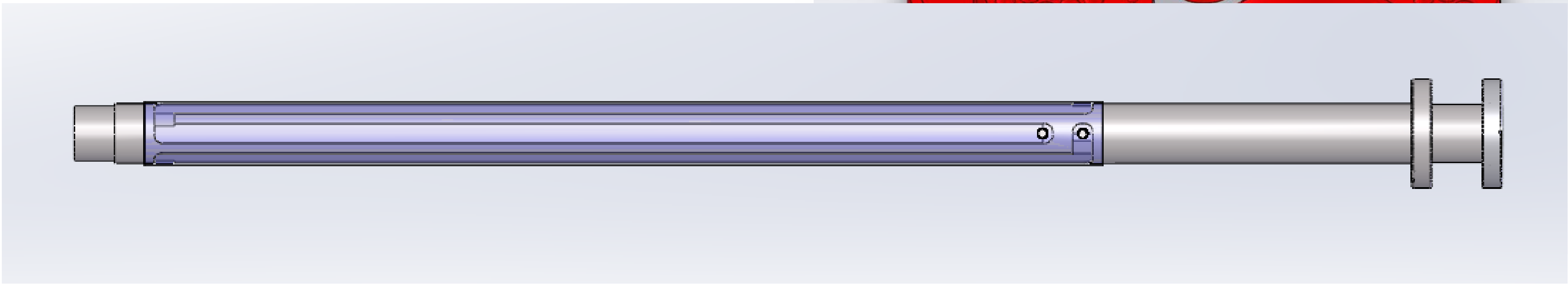

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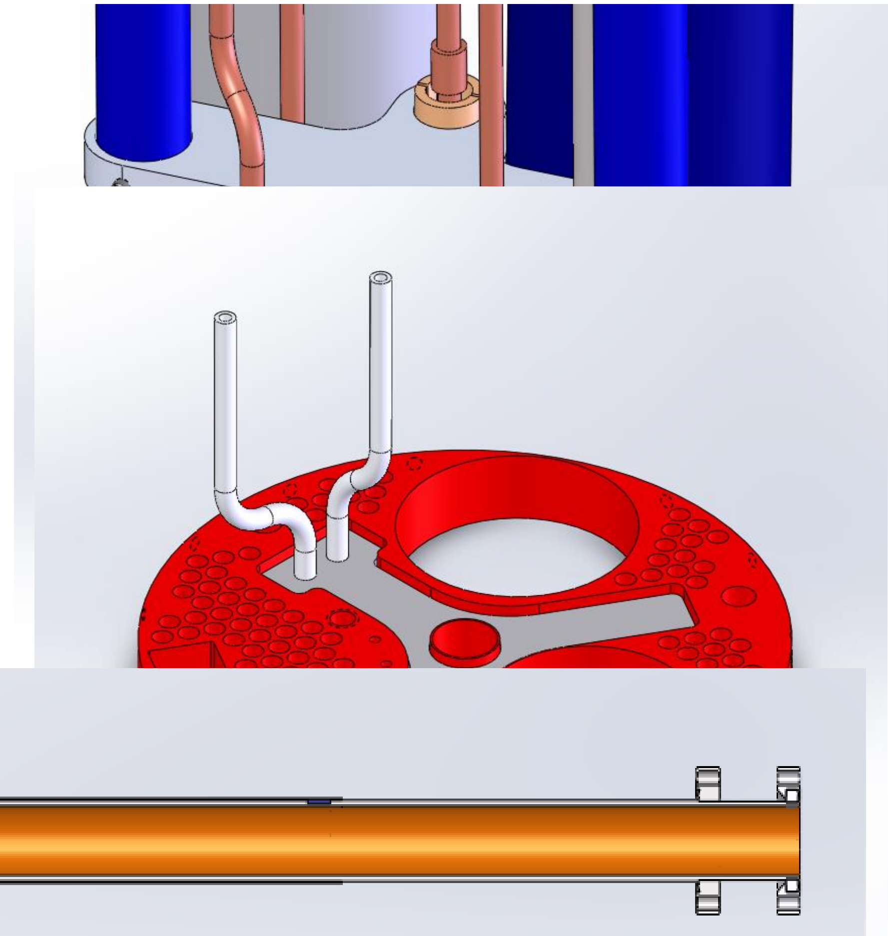

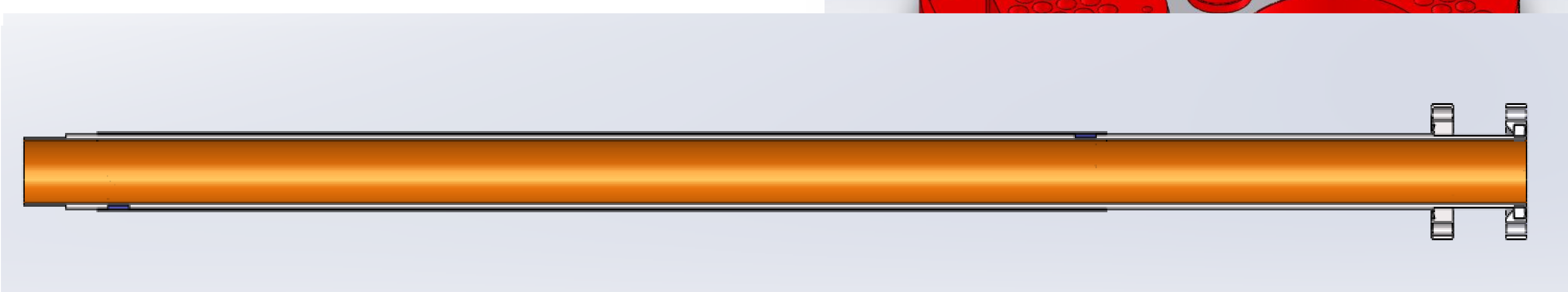

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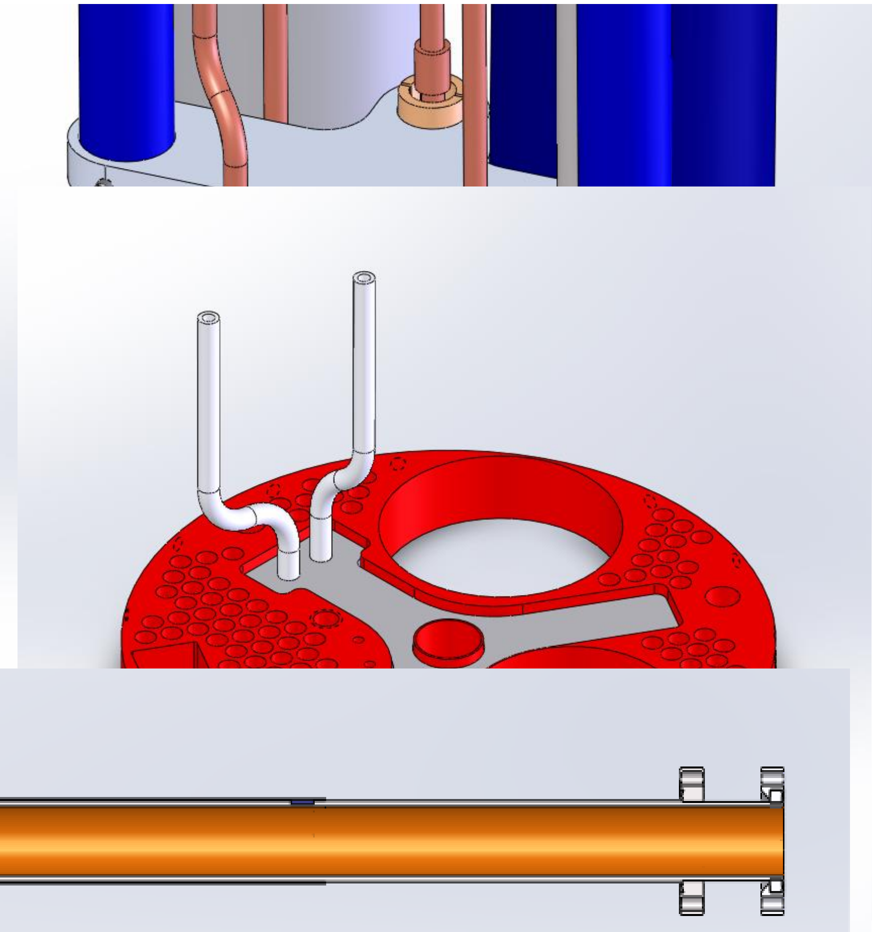
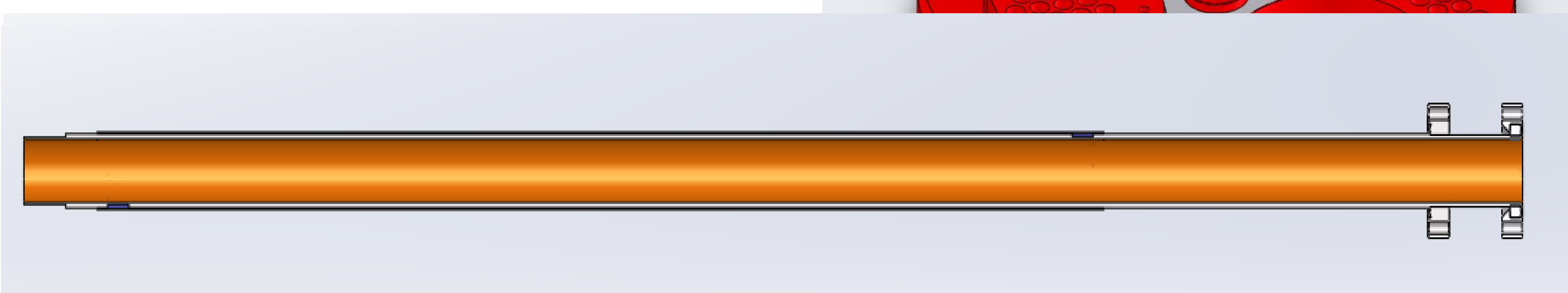
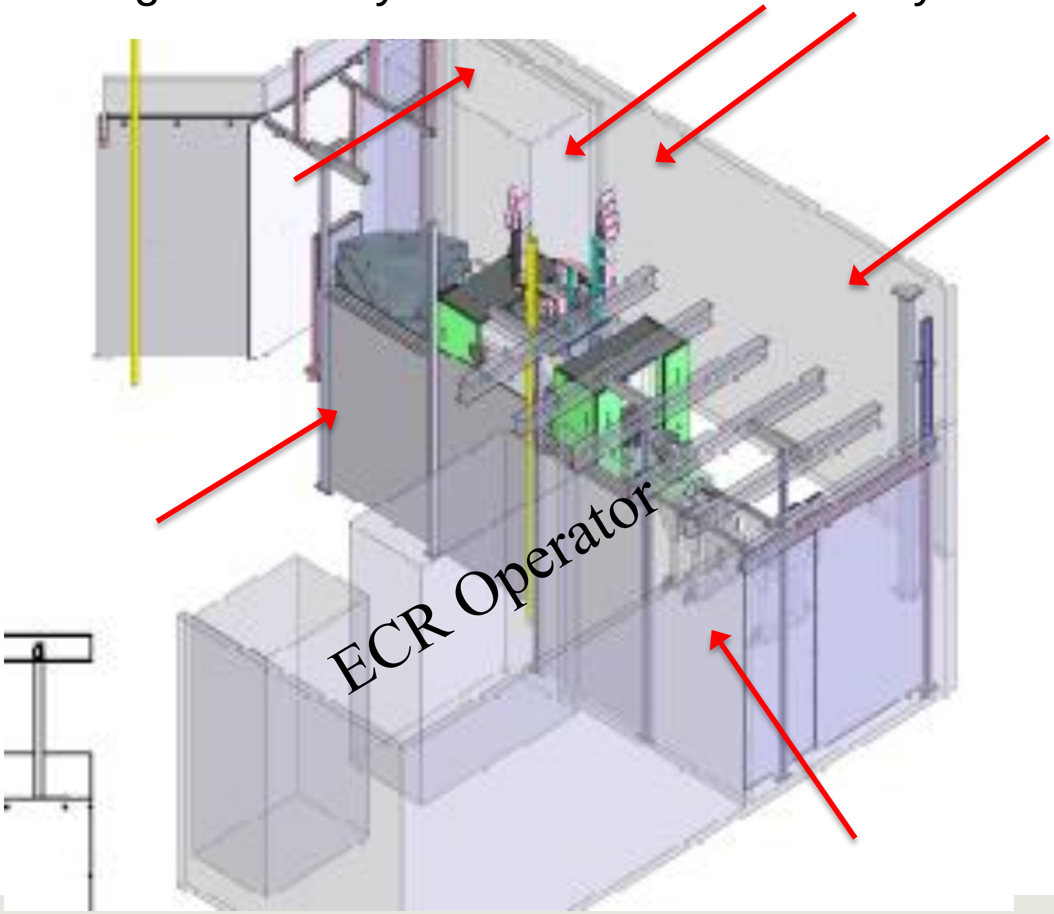


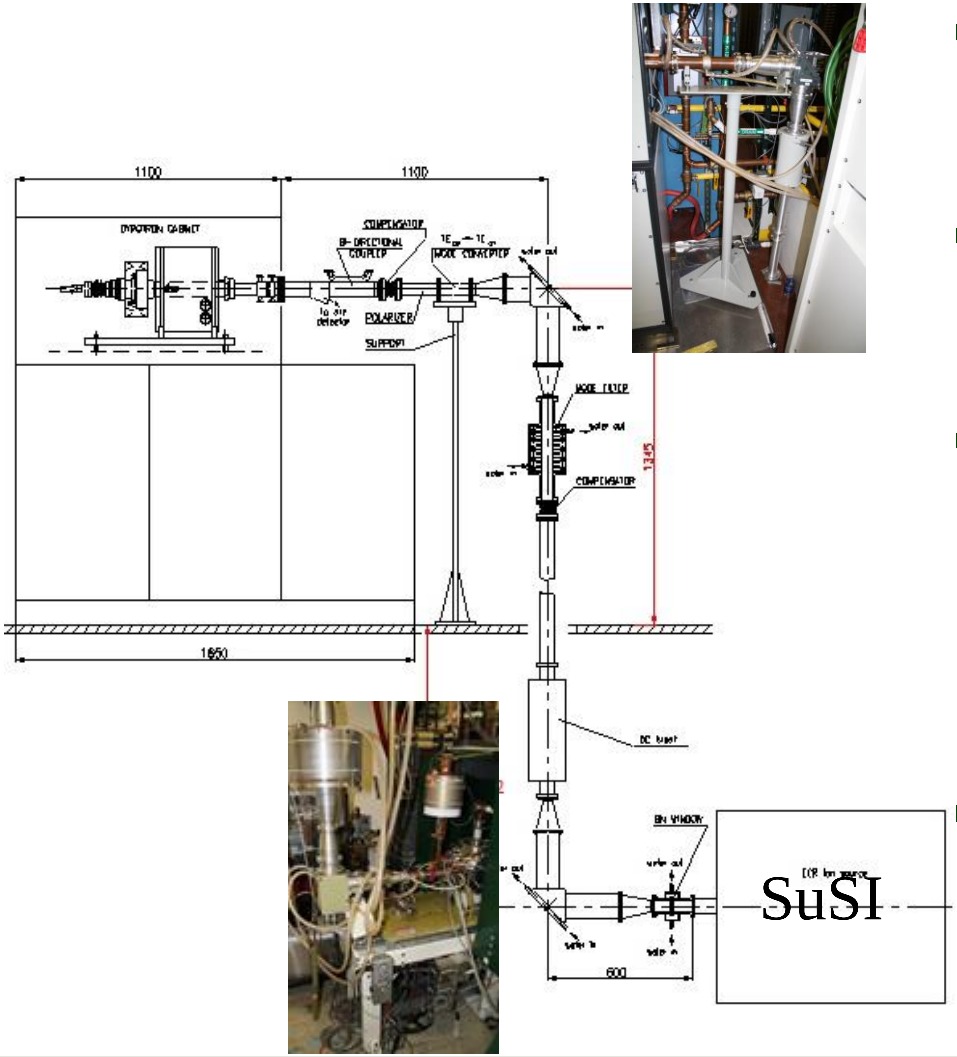


Radiation shielding upgrade

- Goal to keep exposure lower than 0.1 mR/h
  - ½" panel added all around SuSI Room
  - Additional shielding around Gyrotron cabinet on balcony



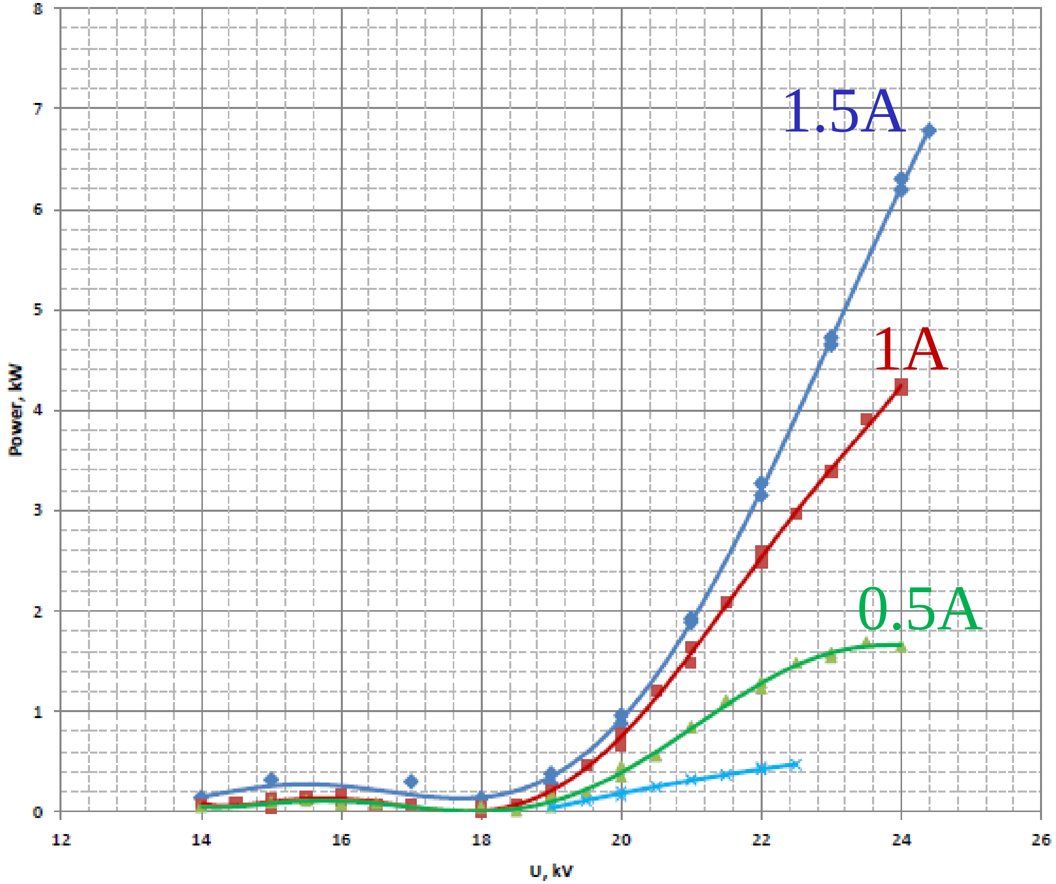
24 GHz Gyrotron System



- Reason for choice of 24GHz:
  - Cant go higher with SuSI
  - 24+18GHz better than 28+18GHz?
- 24GHz RF coupling to SuSI similar to that of SECRAL, VENUS
  - TE_{02} to TE_{01}
- All transmission line components at 24GHz provided by GYCOM
  - Rigid coupling to ion source (No corrugated bend)
  - 50kV Rated DC break
  - 10 kW rated window
- High Voltage and Solenoid power supply purchased separately to Domestic Suppliers

24 GHz Gyrotron System

Power output vs voltage

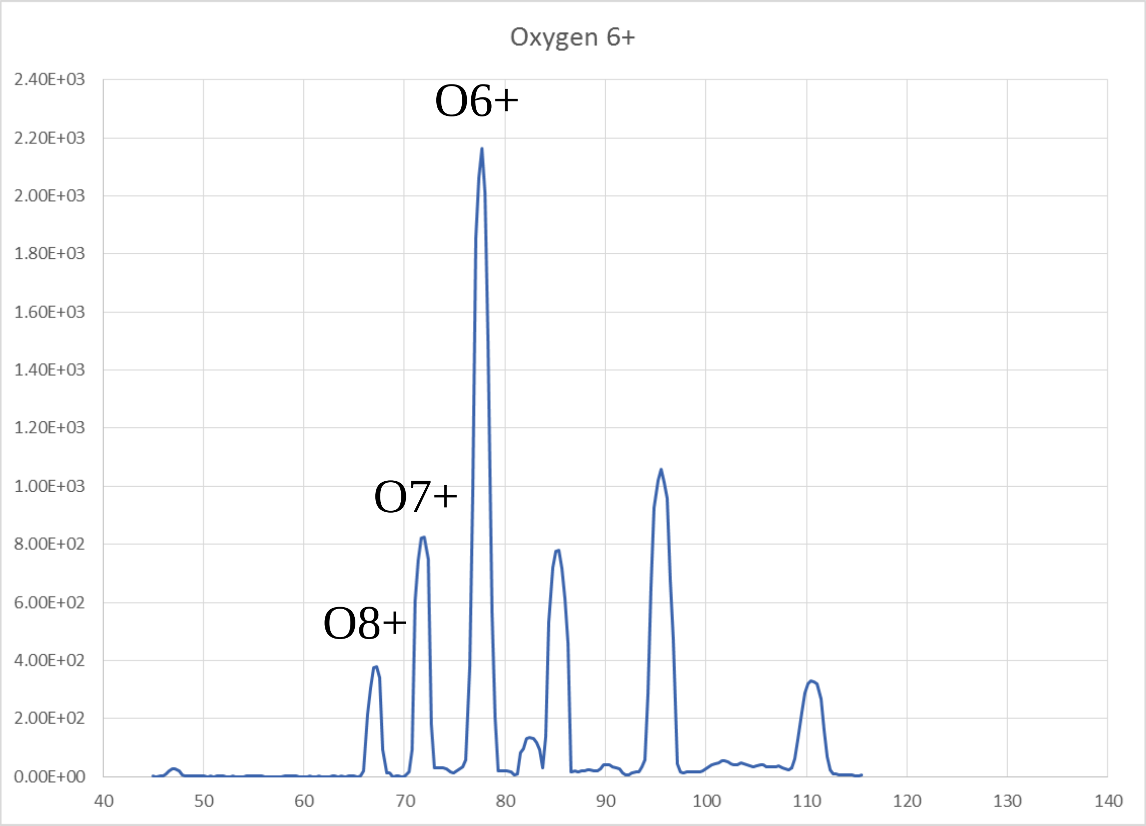


- Maximum power output on dummy load 8.8kW
  - Ibeam=1.95A
  - Maintained 5kW +/- 1% output for 6 hours during testing
- Gyrotron parameters
  - Filament power>200W
  - Solenoid 85A
  - Anode Voltage: up to 12kV
- No issue with equipment so far
  - 350 hours operation
- Maximum power send to ion source ~5.6kW

Commissioning Results: Timeline

- Installation and Tests of 24 GHz gyrotron completed in February 2014
  - Dummy load test
  - Injection assembly, Radiation shielding
- Initial conditioning with ion source in April 2014
  - Large outgassing for 2-3 weeks especially at injection
- Argon development in May 2014 for 1 ½ Week
  - Medium charge states results
  - Difficult optimization for Ar^{16+}
- Oxygen and Argon development for additional 1Week in July
  - Much less outgassing
  - Better performances especially for Ar^{16+}

24 GHz Commissioning Results: Oxygen 6+ and 7+



Bsext=1.49T; Binj=2.97T
Bmin=0.47T; Bext=1.53T
∇Inj=6.42 T/m; ∇Ext=5.79 T/m
Ecr length =111.2 mm
24 GHz Power = 5200W
18 GHz Power = 300W
Idrain=7.3emA
Pinj=3E-7Torr Pext=3.7E-8Torr

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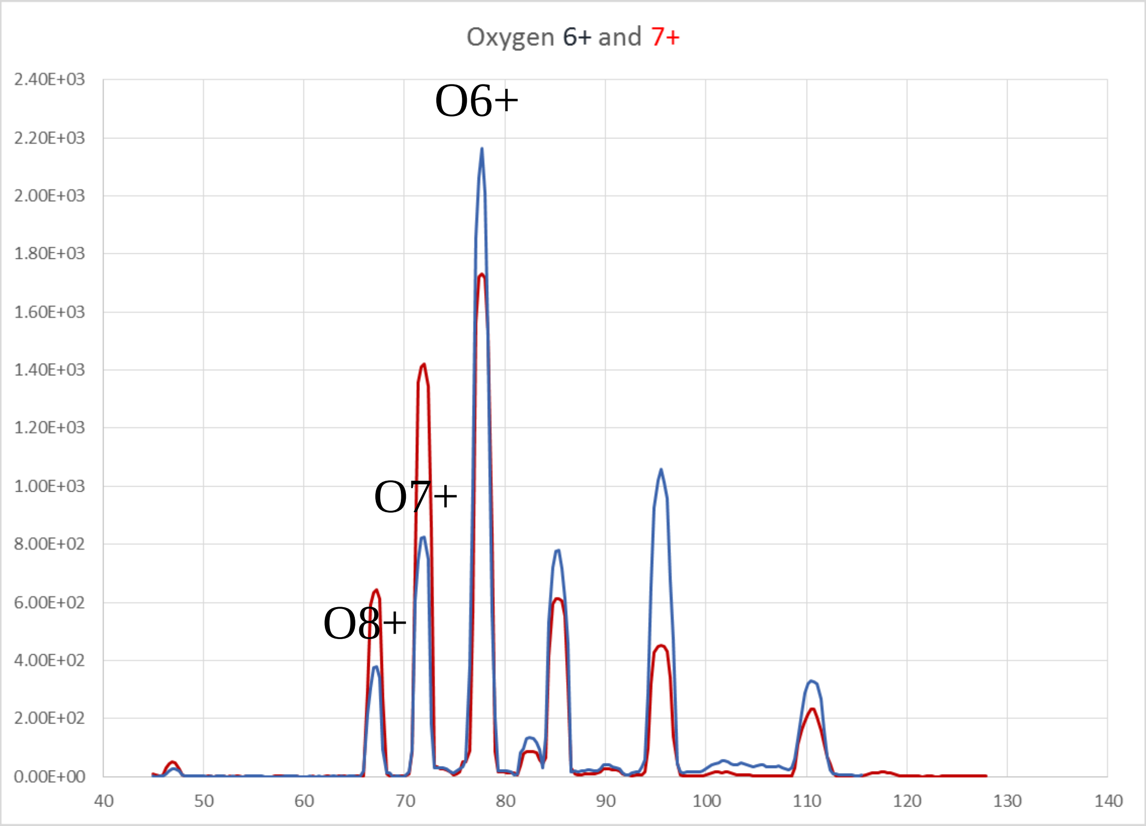

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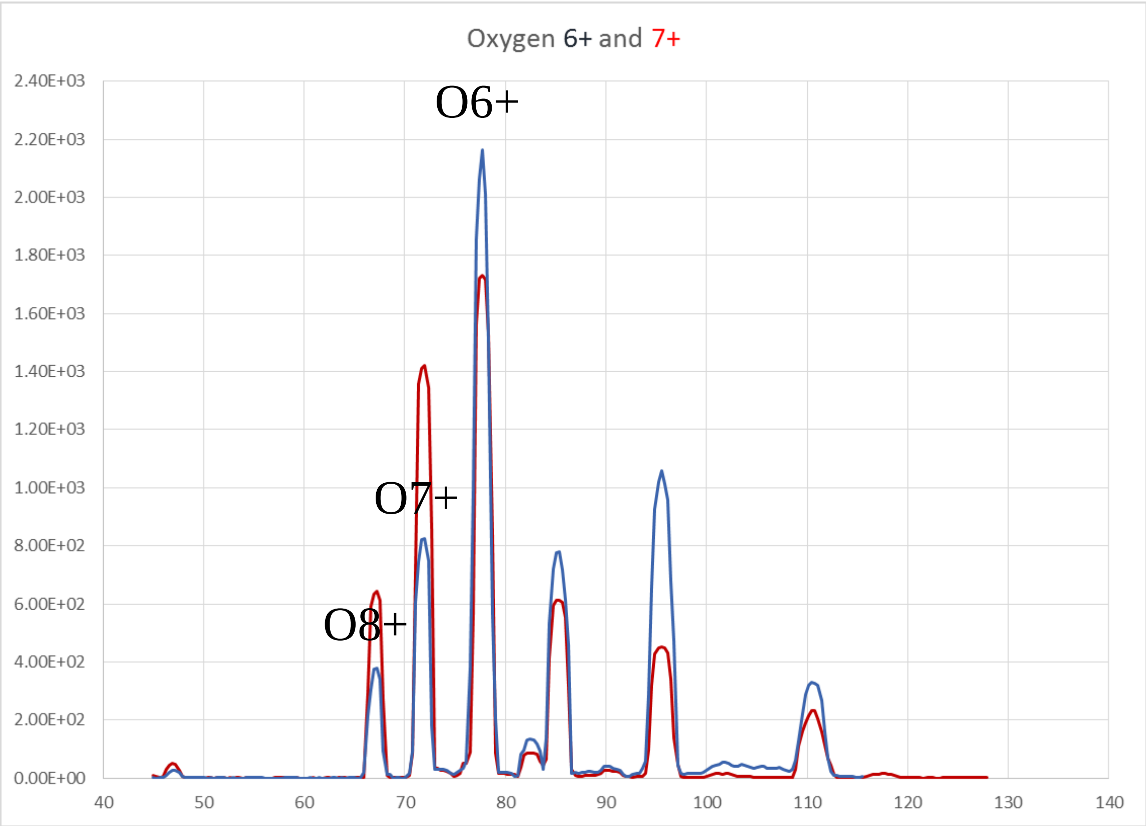

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Bmin=0.52T; Bext=1.57T
∇Inj=5.46 T/m; ∇Ext=4.95 T/m
Ecr length =93.1 mm
24 GHz Power = 5200W
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Idrain=3.9emA
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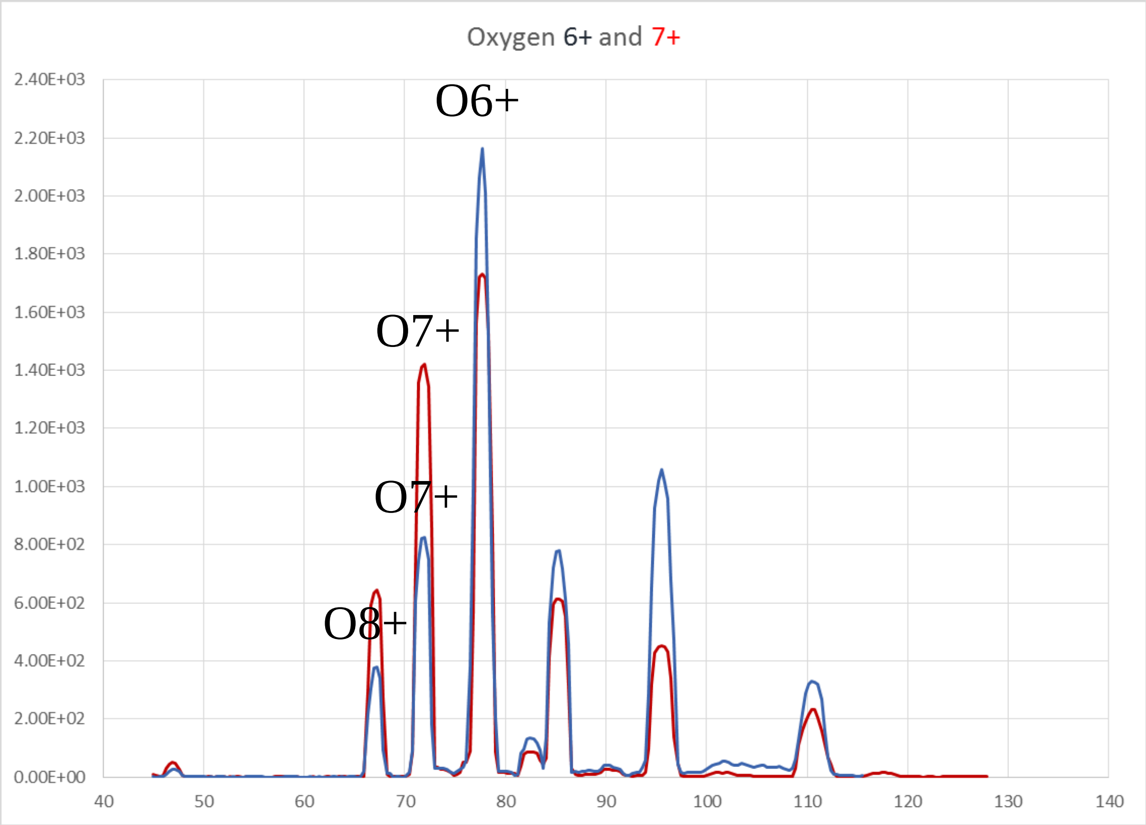

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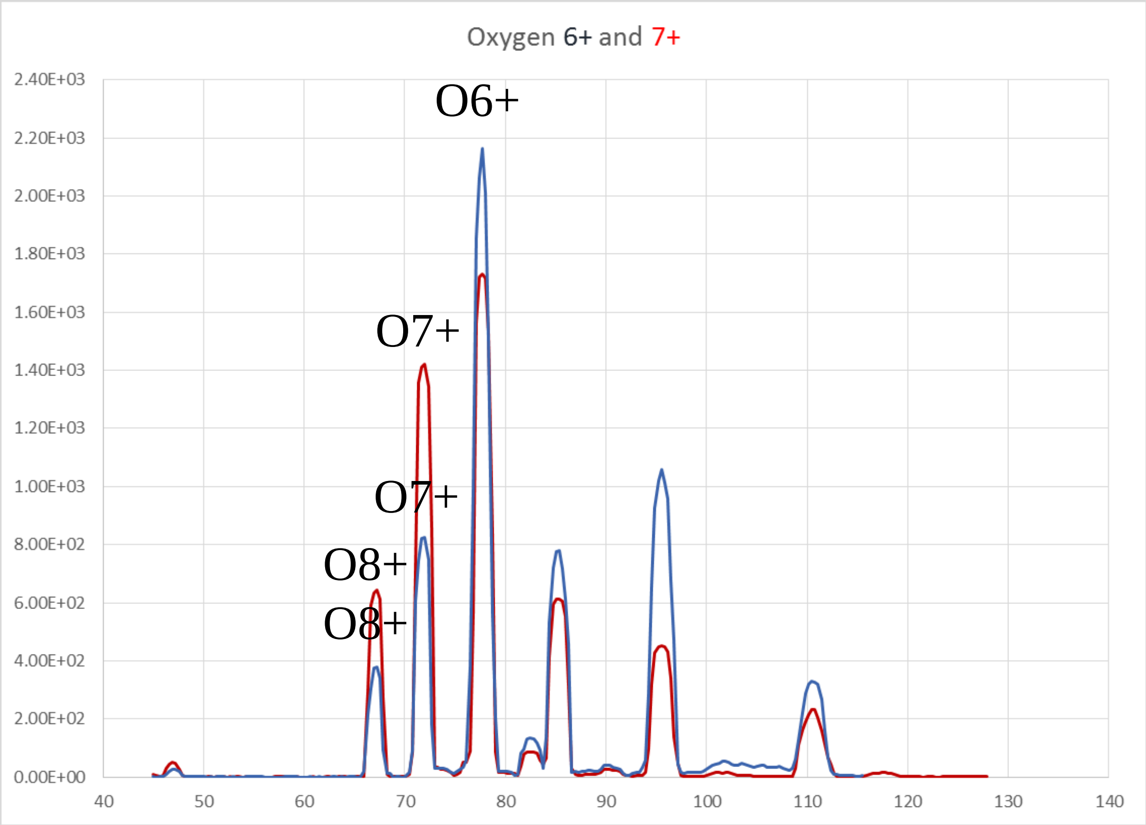
Pinj=3E-7Torr Pext=3.7E-8Torr

Bsext=1.46T; Binj=3.05T
Bmin=0.52T; Bext=1.57T
∇Inj=5.46 T/m; ∇Ext=4.95 T/m
Ecr length =93.1 mm
24 GHz Power = 5200W
18 GHz Power = 0W
Idrain=3.9emA
Pinj=7E-8Torr Pext=3.3E-8Torr

24 GHz Commissioning Results: Oxygen 6+ and 7+



Bsext=1.49T; Binj=2.97T
Bmin=0.47T; Bext=1.53T
∇Inj=6.42 T/m; ∇Ext=5.79 T/m
Ecr length =111.2 mm
24 GHz Power = 5200W
18 GHz Power = 300W
Idrain=7.3emA
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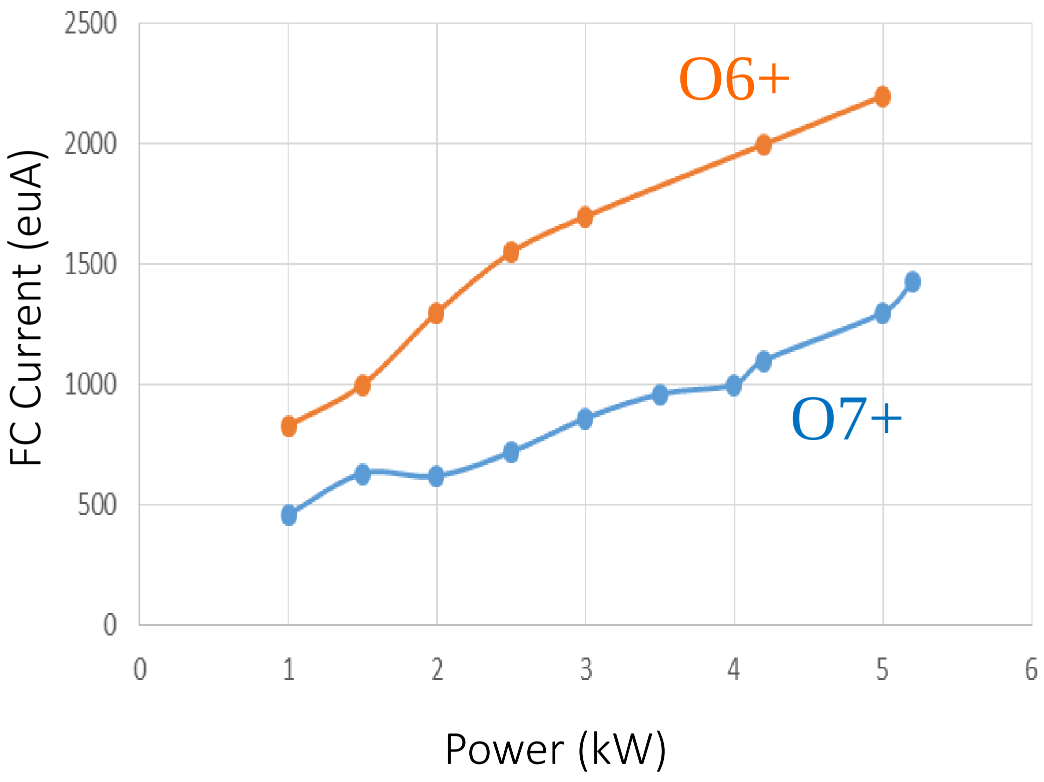
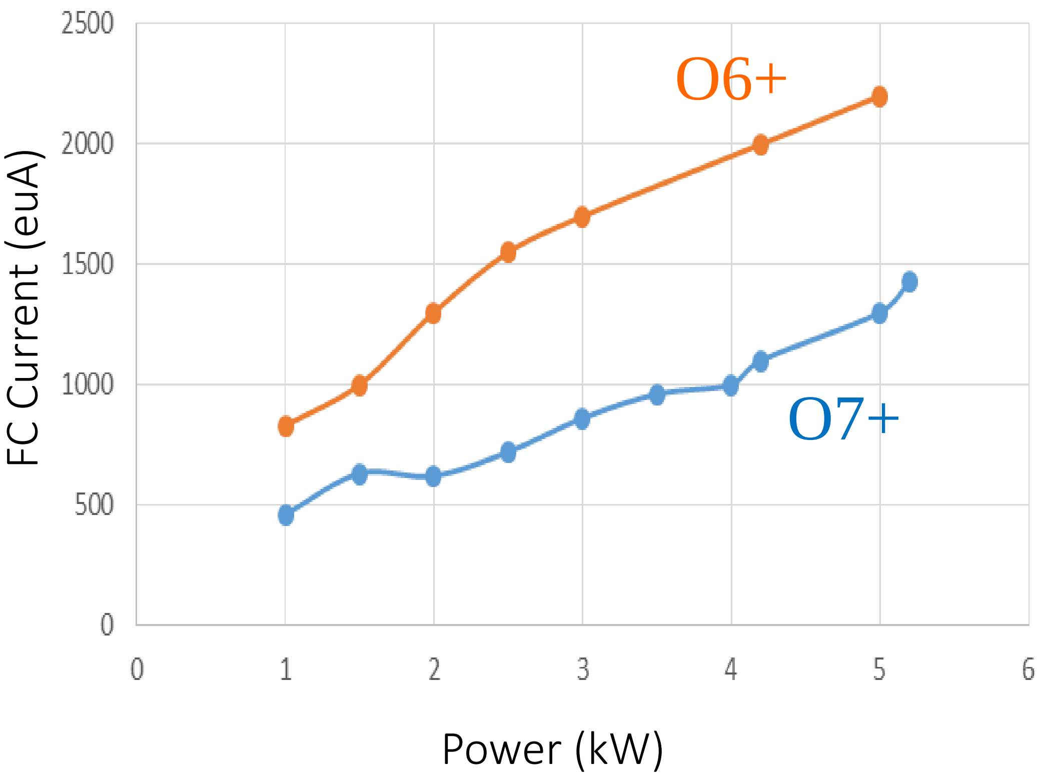


- **No Saturation with microwave power observed so far**
  - **Power density maximum of ~1.5 kW/l**
  - **Gas and field optimized for each case**

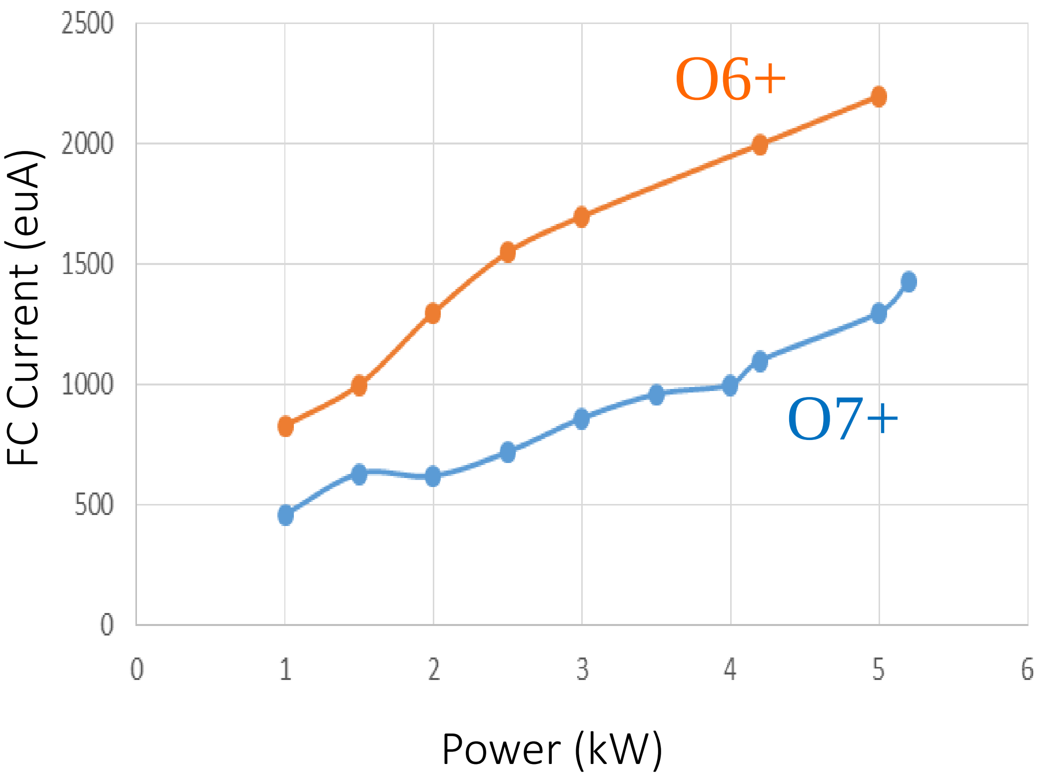
24 GHz Commissioning Results: Oxygen 6+ and 7+



- No Saturation with microwave power observed so far
  - Power density maximum of ~1.5 kW/l
  - Gas and field optimized for each case

	6+	7+
SuSI	2200	1400
VENUS	2900	850

24 GHz Commissioning Results: Oxygen 6+ and 7+

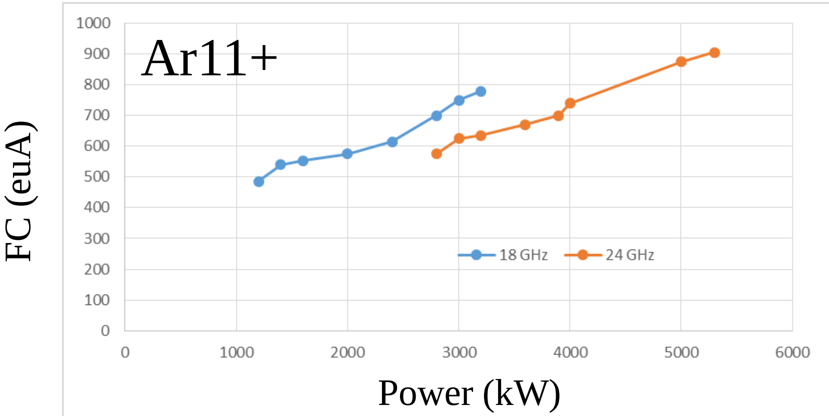


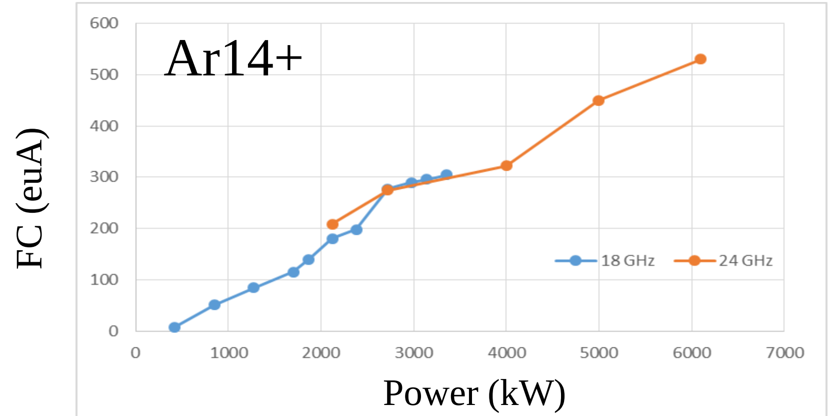
- **No Saturation with microwave power observed so far**
  - **Power density maximum of ~1.5 kW/l**
  - **Gas and field optimized for each case**

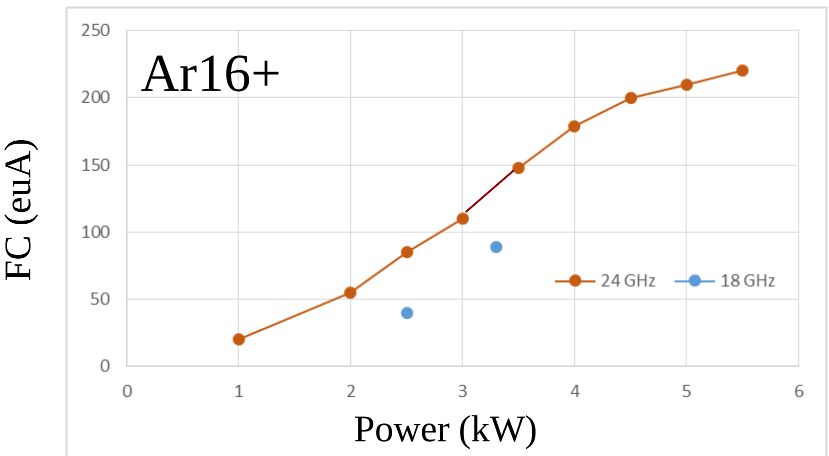
- **Comparison with VENUS (for similar power)**

	6+	7+
SuSI	2200	1400
VENUS	2900	850

24 GHz commissioning Results: Argon



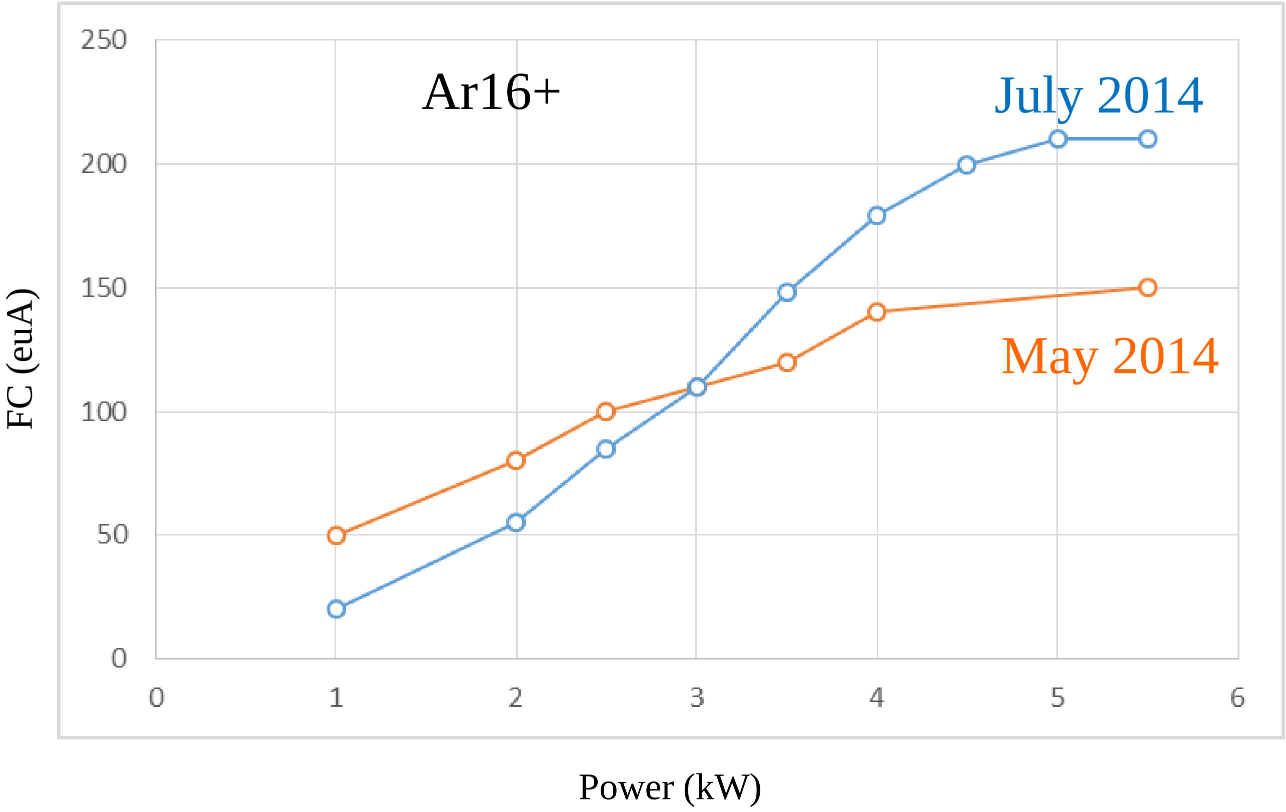




- **Continuing increase of current with power at 24 GHz**
  - No or very little 18 GHz injected despite Bmin~0.5T
- **Impact of frequency not so clear for medium charge states**
  - Field still not at optimum value for use with 24 GHz

24 GHz commissioning Results: Argon

- Conditioning takes time to optimize performances at 24 GHz



24 GHz commissioning Results: Argon

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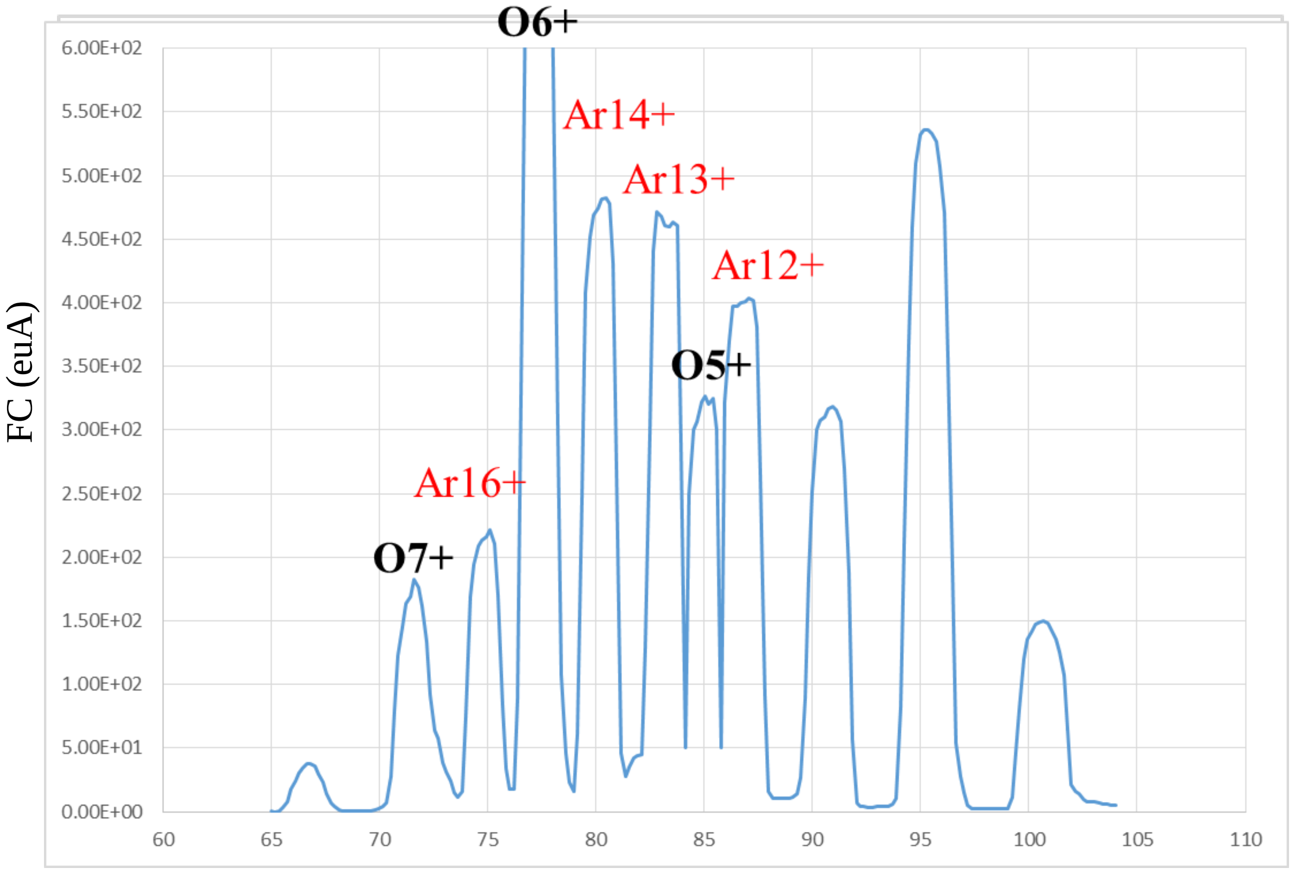

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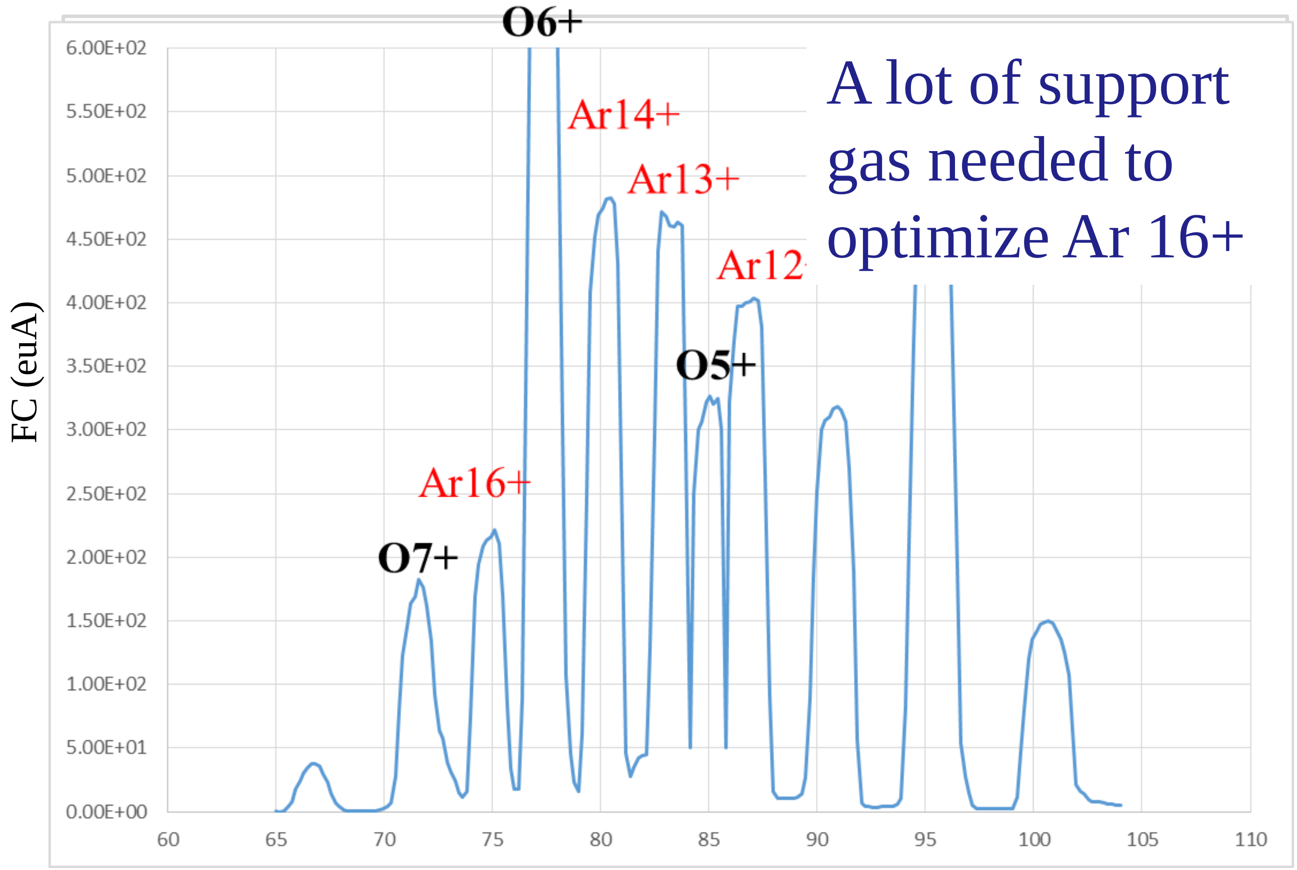

A lot of support gas needed to optimize Ar 16+

24 GHz commissioning Results: Argon

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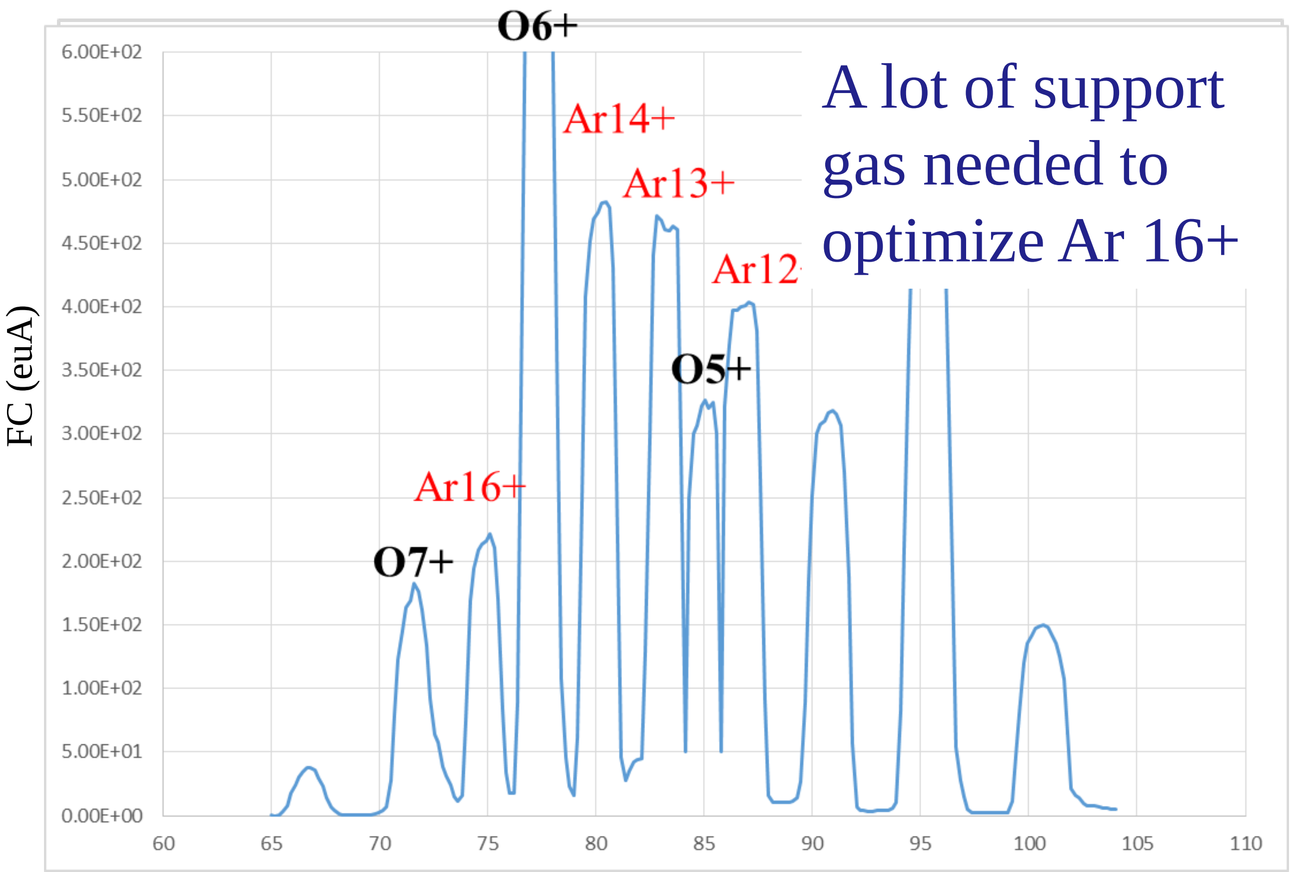

Comparison Venus- SuSI
(All current in eμA)

24 GHz commissioning Results: Argon

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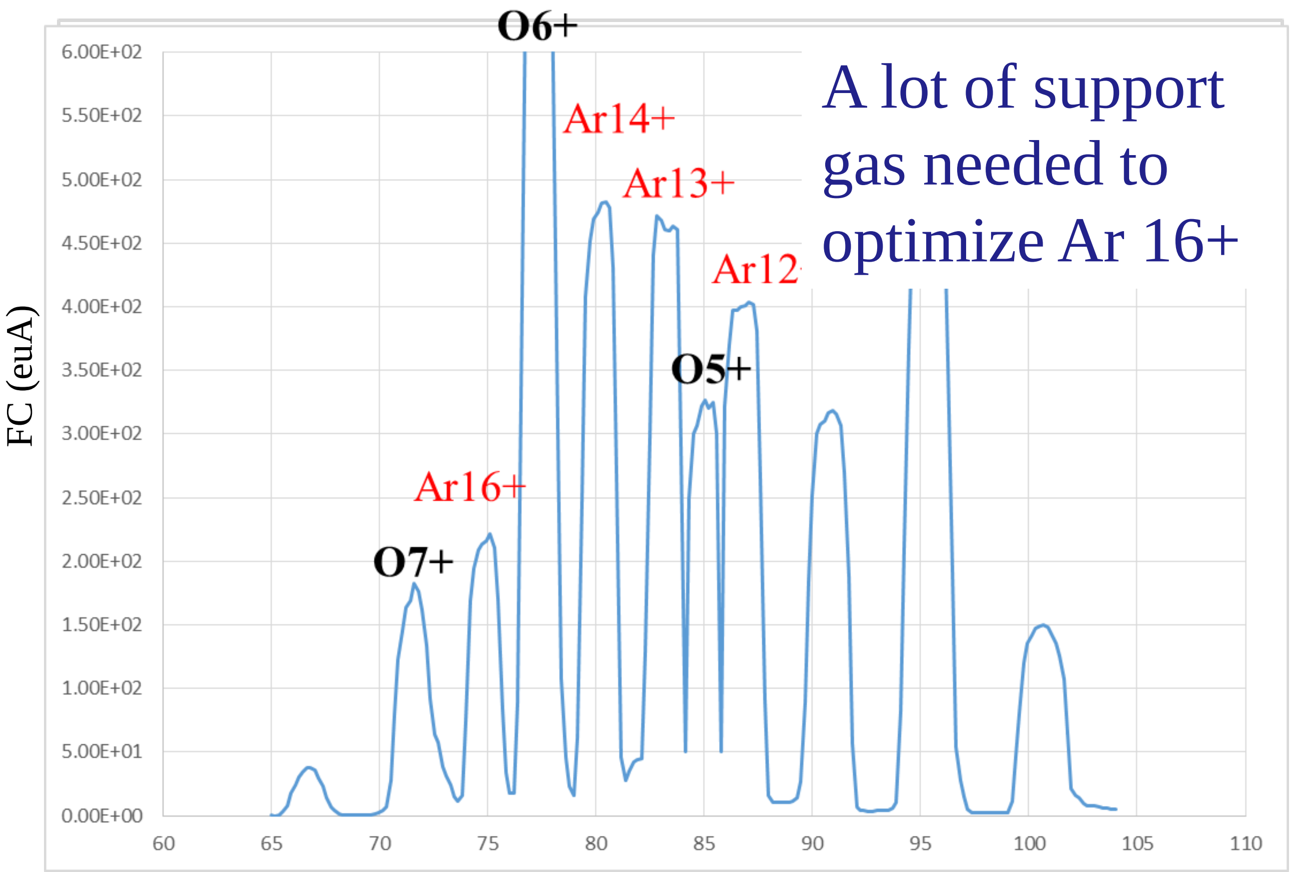

Comparison Venus- SuSI
(All current in eμA)

	VENUS-28 (1)	SuSI-24
11+	850	905
12+	860	860
13+	720	650
14+	514	530
16+	270	220

24 GHz commissioning Results: Argon

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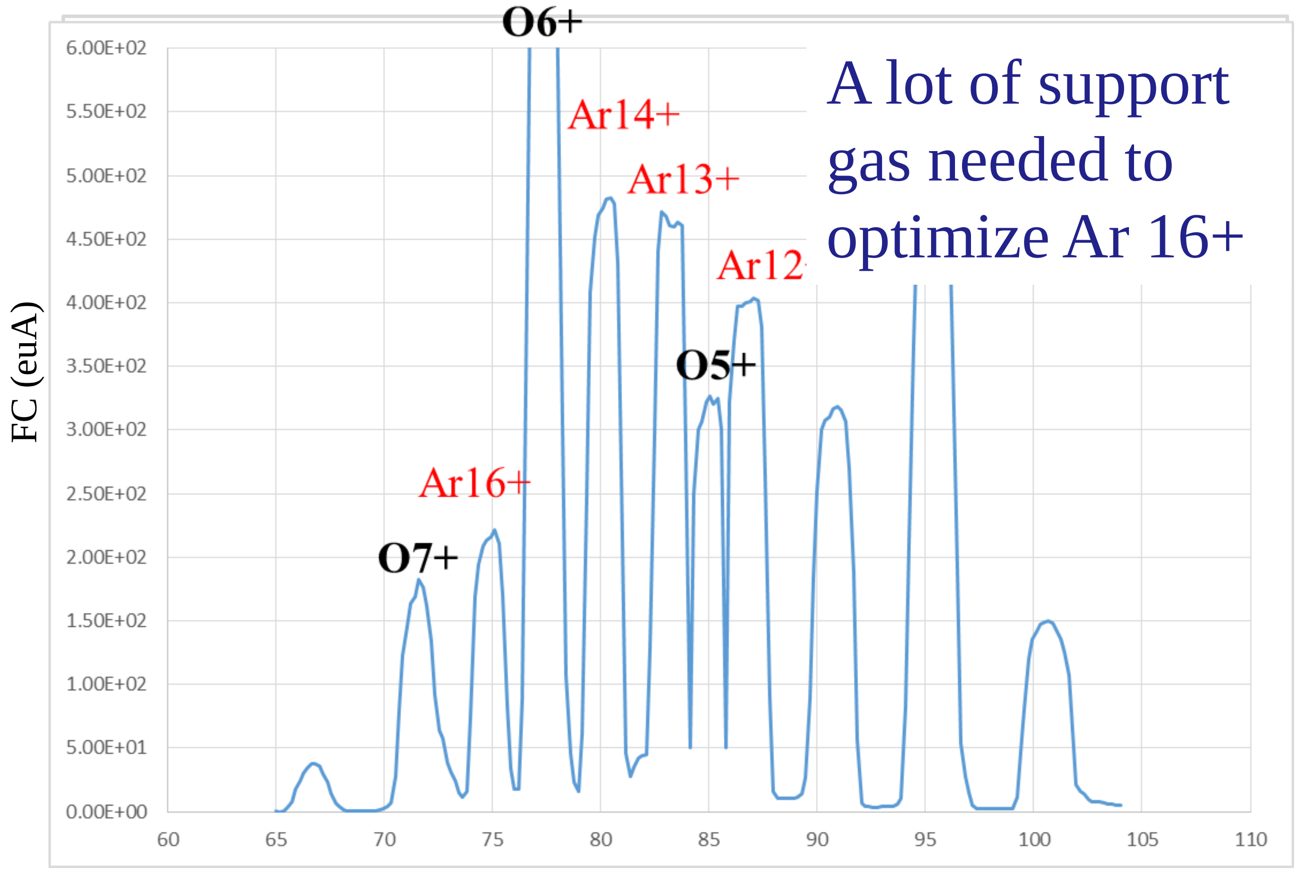

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(1) ECRIS 2006 IMP, China

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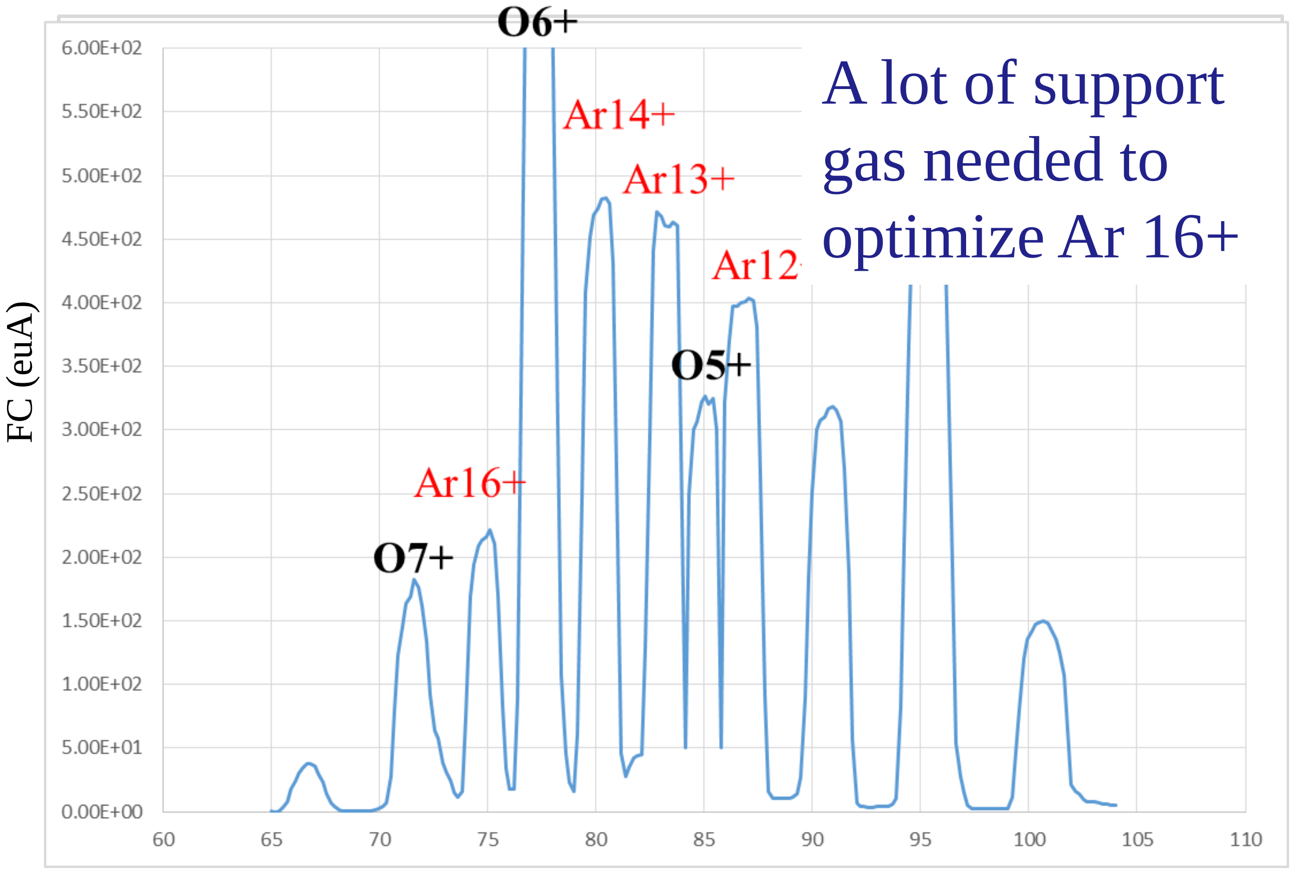

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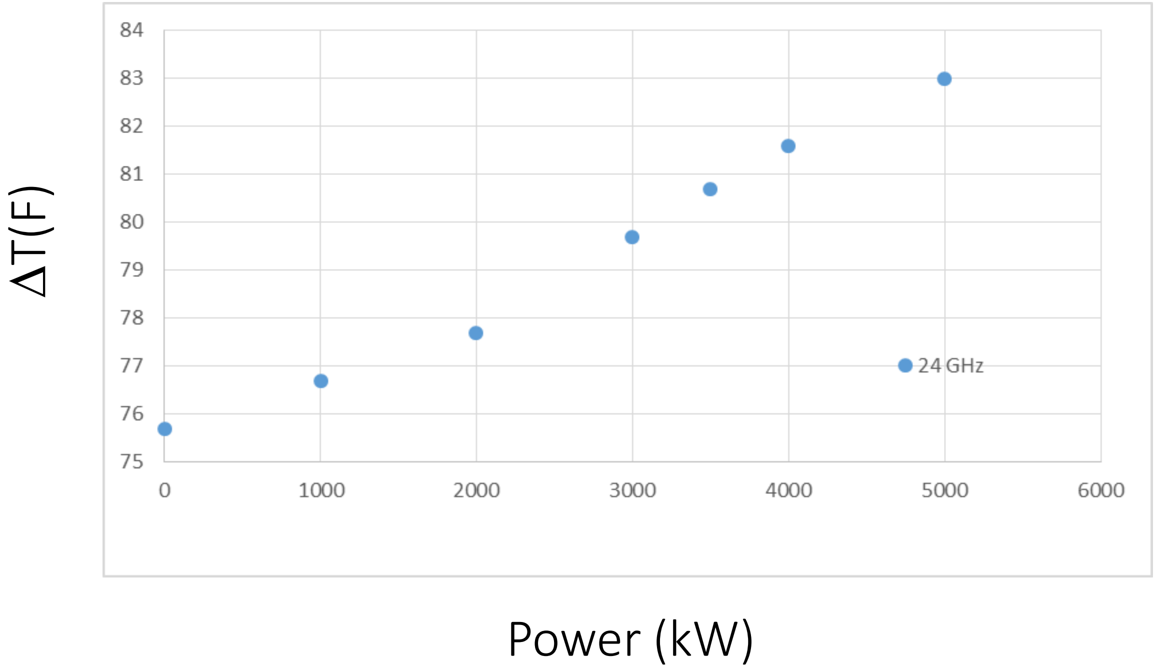
(1) ECRIS 2006 IMP, China

Very similar power level~5.5kW

Plasma chamber cooling

- **No direct way to measure forward or reflected power inside source for 24 GHz through waveguide**
  - **Monitoring of plasma chamber return temperature**



- **Temperature increase match ANSYS simulation**

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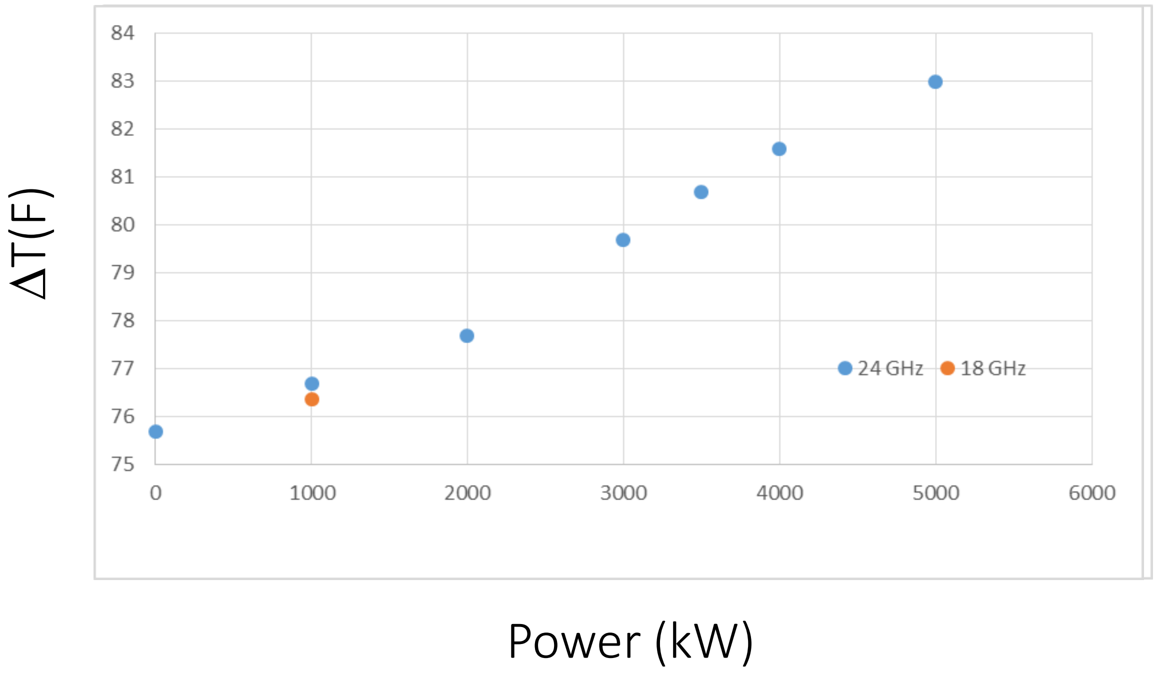

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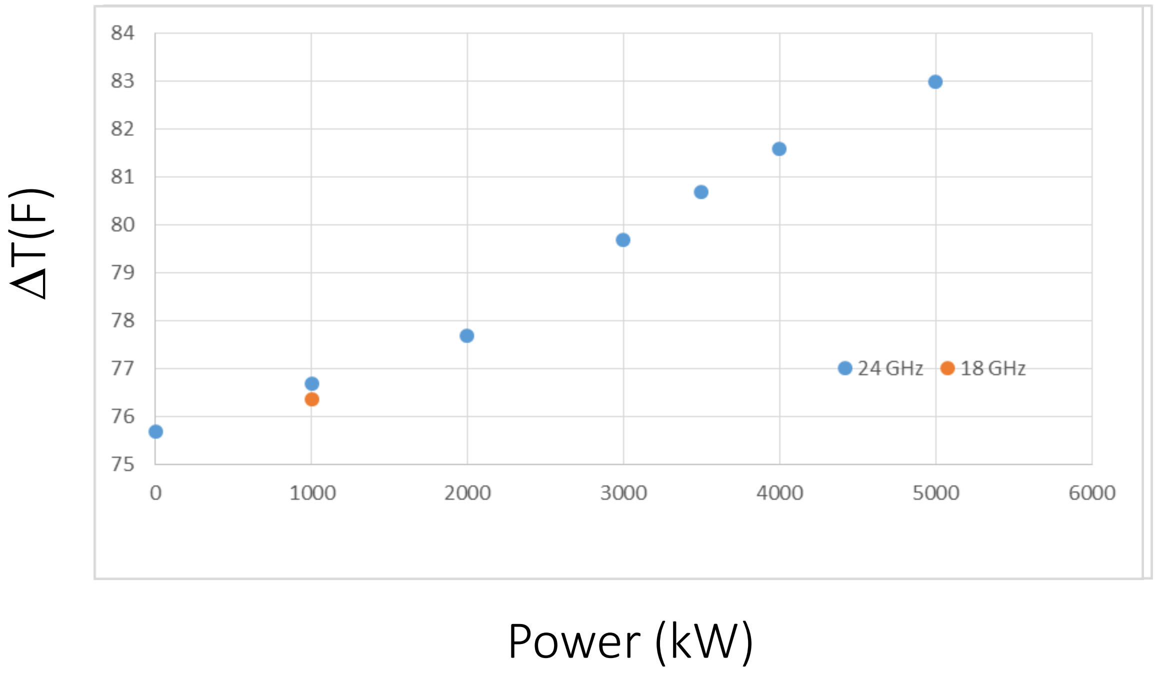


- Temperature increase match ANSYS simulation
- 1kW of 18 GHz lead to a lower increase in water temperature than 24 GHz
  - Added radial losses at 24 GHz?

24 GHz commissioning Results: Summary table

	FC (euA)	Drain current (emA)	Power (kW)	Power density (kW/l)	Bhex (T)	Binj (T)	Bmin (T)	Bext (T)
^{40}Ar								
11+	**905**	8	5.3	1.51	1.33	3.00	0.47	1.43
12+	**860**	8.2	5.9	1.69	1.48	3.11	0.48	1.51
14+	**530**	7.1	6.1	1.74	1.46	3.12	0.58	1.56
16+	**220**	4.5	5.7	1.63	1.46	3.02	0.50	1.54
^{16}O								
6	**2200**	7.3	5.2	1.49	1.49	2.97	0.47	1.53
7	**1430**	3.9	5.2	1.49	1.46	3.06	0.52	1.57
					1.71	3.43	0.51-0.69	1.71

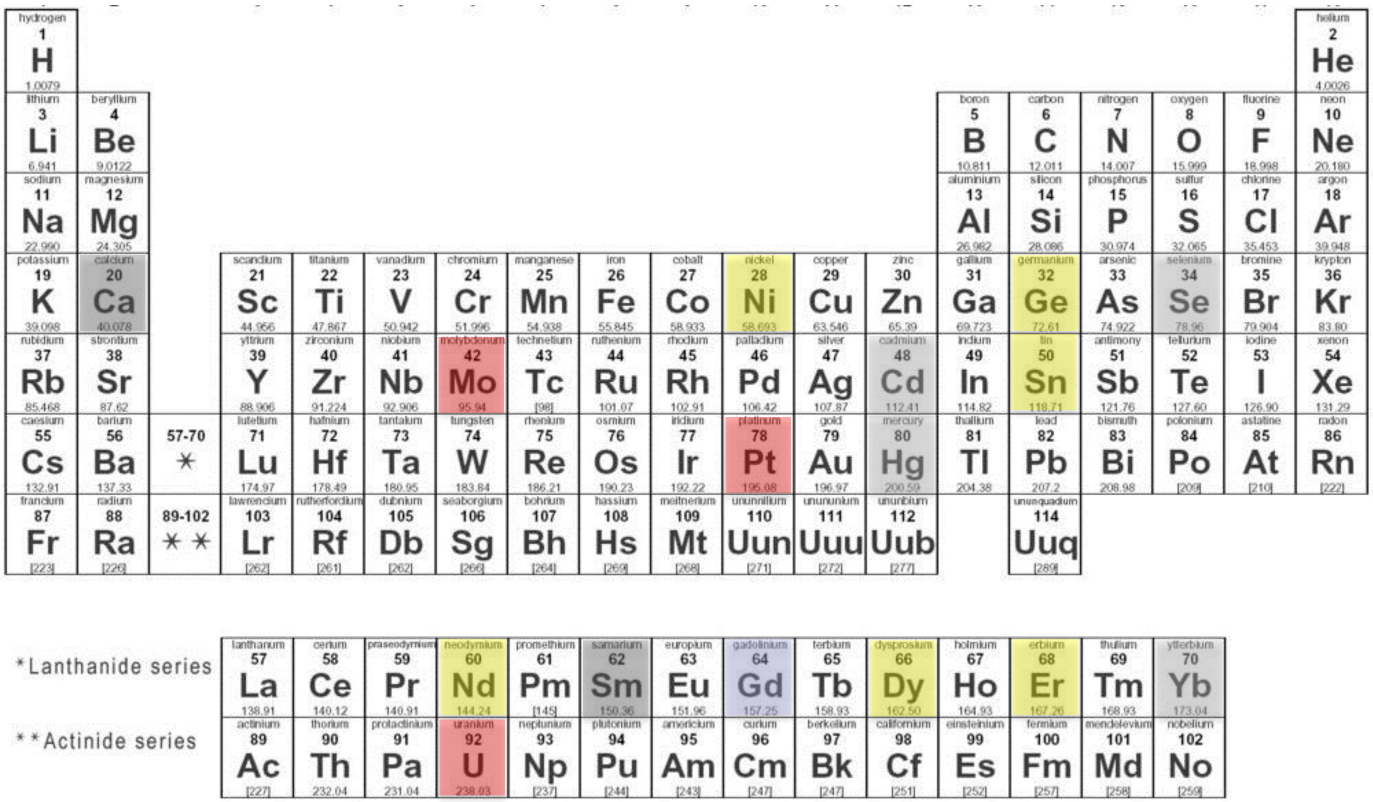
24 GHz commissioning Results: Summary table

▪Few Observations so far:

- Surprising that 18 GHz did not coupled well
- Did not expect SUSI would do so well for very high charge states (Ar16+, O7+)
- 5kW level was kept up 1-2 hour each time (chamber still intact yet!!)
- Tried briefly Xenon in May but source performed very poorly
  - » Conditioning long and demanding at 24 GHz

40 A
11+
12+
14+
16+
16 C
6
7

Metallic beam development for CCF and FRIB



Ranking

Beam	abundance	number of beams
238U	99.30%	1750
204Hg	6.90%	308
82Se	8.70%	156
144Sm	3.10%	139
58Ni	68.10%	130
176Yb	12.80%	129
198Pt	7.20%	122
48Ca	0.19%	104
106Cd	1.25%	101
92Mo	14.80%	98

- Temperature for a vapor pressure of 10^{-2} mmHg

T < 500 °C

T < 1000 °C

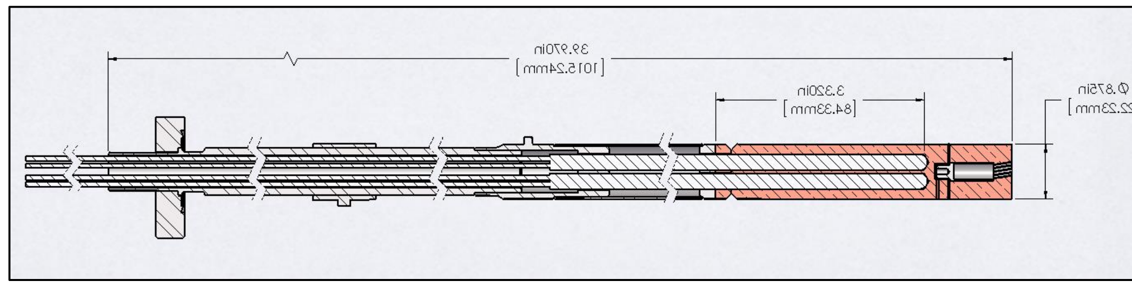
T < 1500 °C

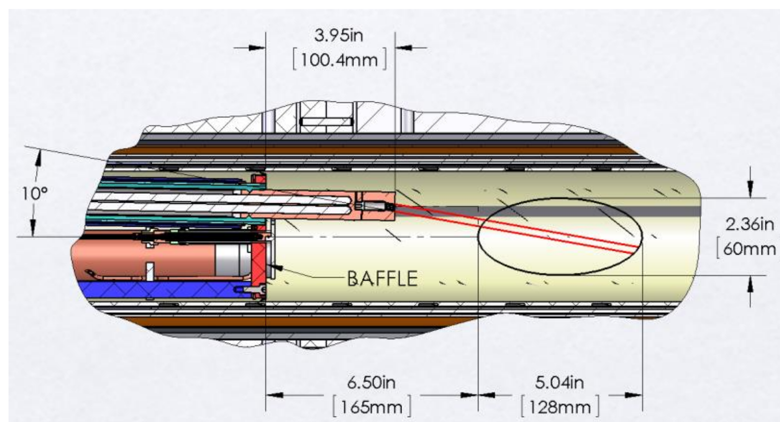
T < 2000 °C

T >2000 °C

Low temperature oven development

- Low temperature Oven similar to LBNL developed at MSU
  - Design to operate up to 800 °C
  - First tested this summer for 40 Ca experiment. 25euA No problem !
  - ~1% efficiency for 40Ca8+





Challenges for metallic beams

1. Develop high intensity metallic beams (> 400 eμA)

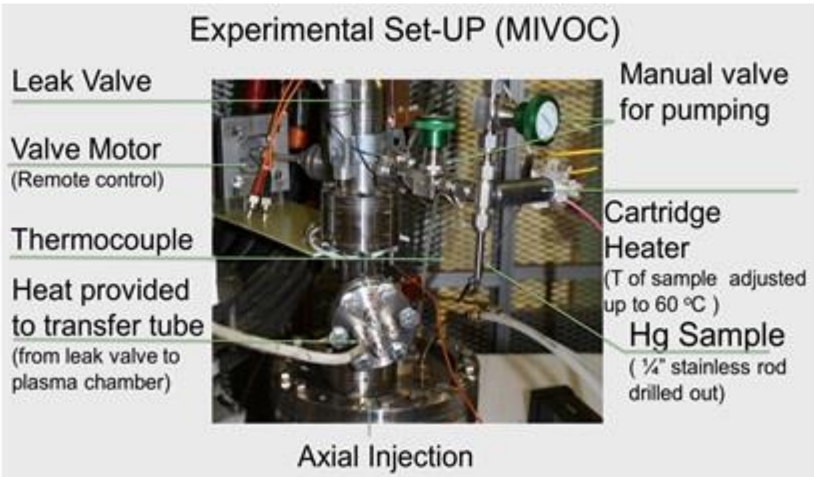
2. Optimize production efficiency
   - Expensive isotope
   - Support operation without interruption for long period of time (Larger oven, capture efficiency)

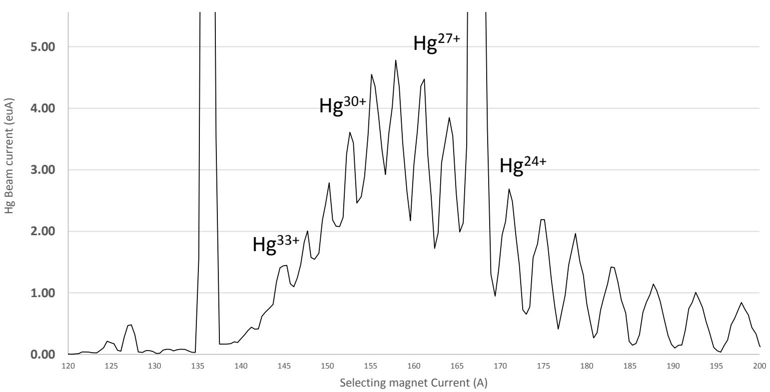
3. Develop targeted production technique
   - MIVOC chamber for element such as : Hg, Se, Cd
   - Sputtering (U, Pt, Zr)
   - High temperature oven (>2000 °C)

4. Material preparation
   - Conversion of Rare earth element to metal forms (Poster MOPPH019)

Recent results with Mercury and Molybdenum

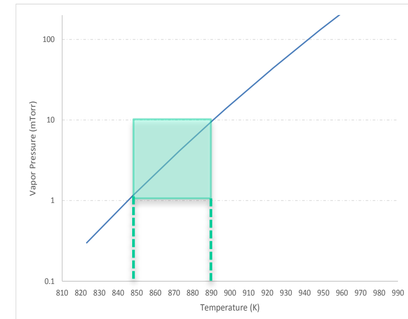
Natural Hg

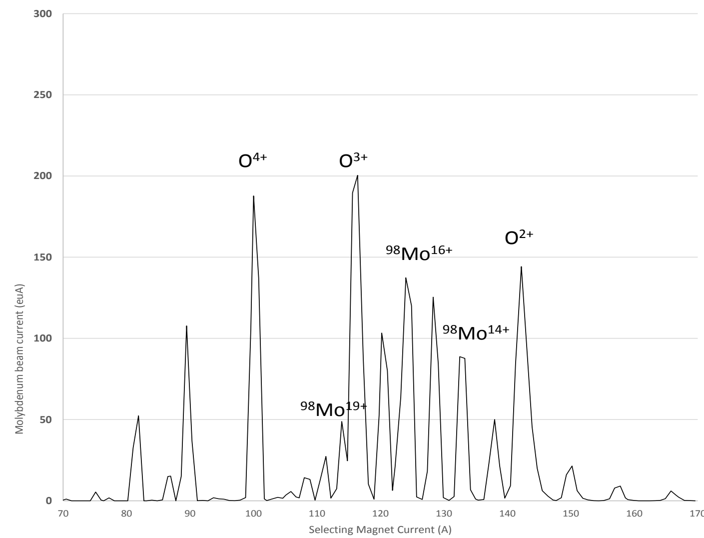




Molybdenum Trioxyde (MoO_3)

- Pure Molybdenum has a Vapor pressure of a few mTorr ~2400 °C
- Molybdenum Trioxide (MoO3) has a similar vapor pressure favorable around 800 °C





Outlook/Summary

- **24 GHz gyrotron coupled to SuSI**
  - Gyrotron operates well so far
  - Very good performance for Oxygen and Argon beam
  - Able to couple up to 5.5 kW microwave power to SuSI
- **Next step includes**
  - Xenon and metallic beam: Bismuth, Calcium
  - Systematic study to see impact of field, pressure, measure efficiencies and compare to 18 GHz
    - » Field not at optimum yet
    - » 18 Ghz not helping performance,Why?
  - **Beam characterization (emittance, stability)**
- **Installation of 24 GHz Gyrotron on FRIB HV platform**

Thank you