



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

G.Machicoane, D.Cole, D.Leitner, D. Morris, E. Pozdeyev, L.Tobos



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

# Outline

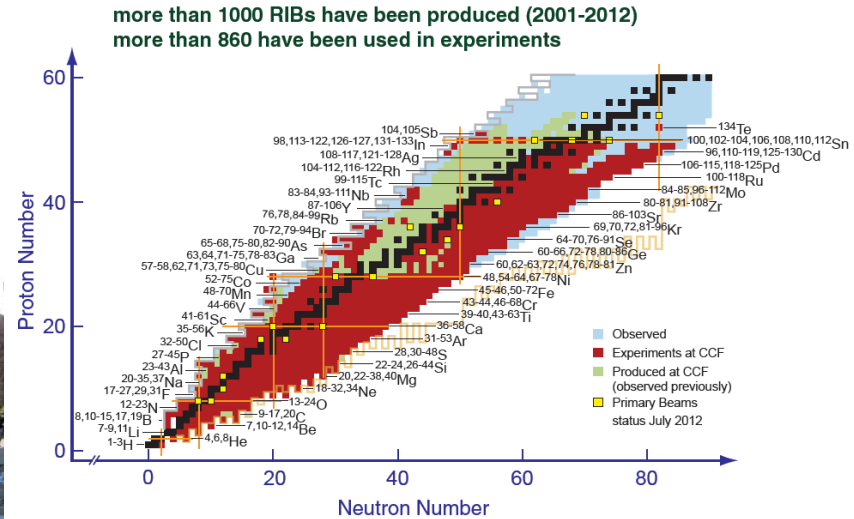
- ❖ Motivations/Context
  - ❖ FRIB update
- ❖ GYCOM 24 GHz gyrotron system
- ❖ SuSI Features /Upgrade/Shielding
- ❖ Commissioning result at 24 GHz
  - ❖ Oxygen, Argon
- ❖ Metallic beam work
- ❖ Summary

# Coupled Cyclotron Facility (CCF)

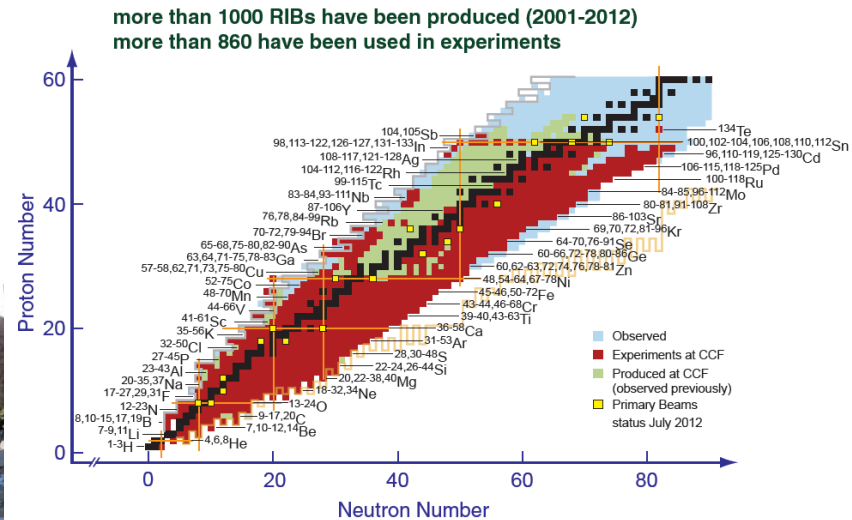
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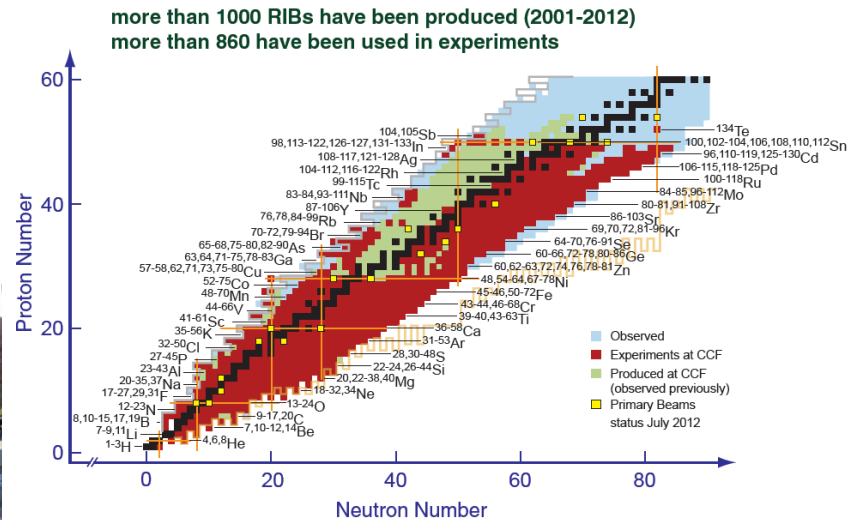


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# Coupled Cyclotron Facility (CCF)

more than 1000 RIBs have been produced (2001-2012)  
more than 860 have been used in experiments

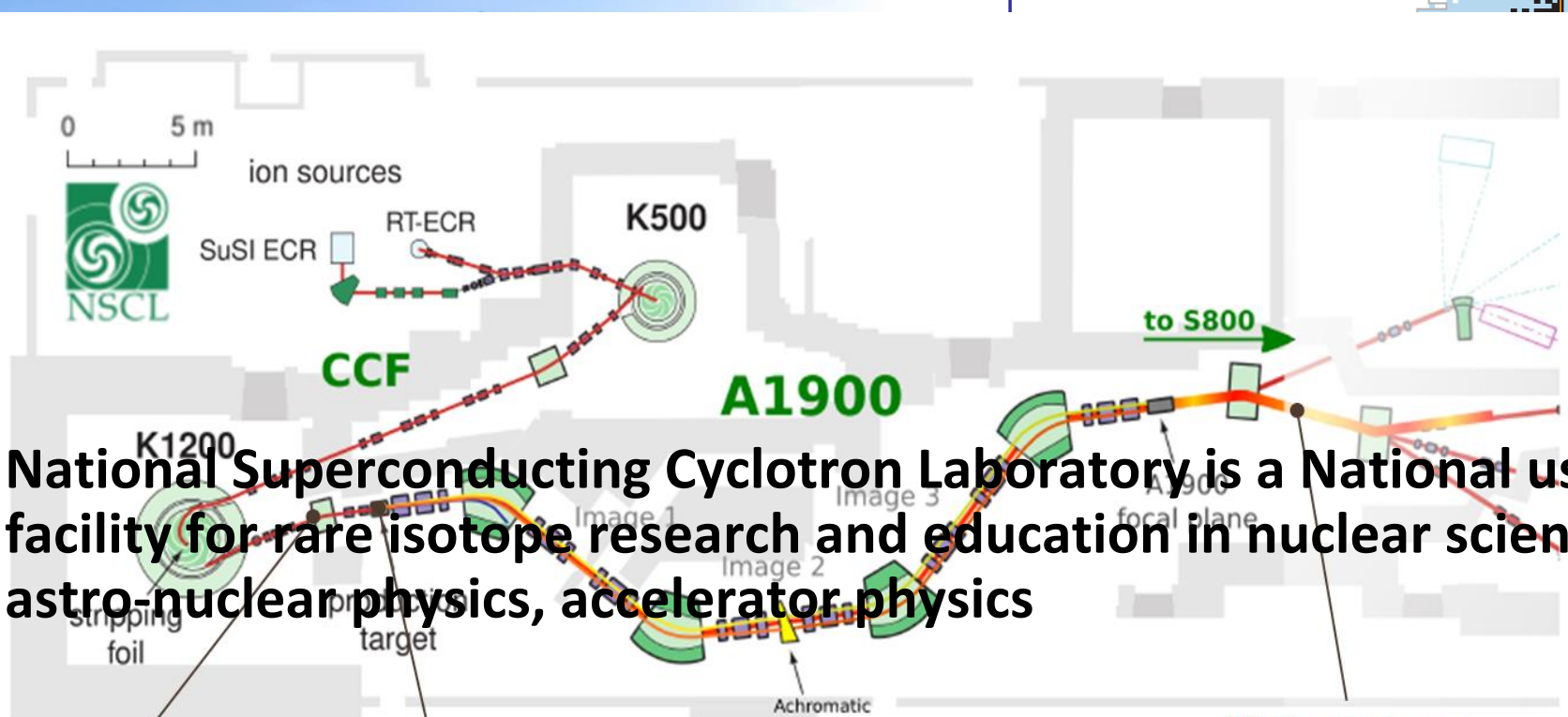
60°



-<sup>134</sup>Tb  
-<sup>102-104, 106, 108, 110, 112</sup>Sn  
-<sup>96, 110-119, 125-130</sup>Cd  
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-Zr

CF  
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→



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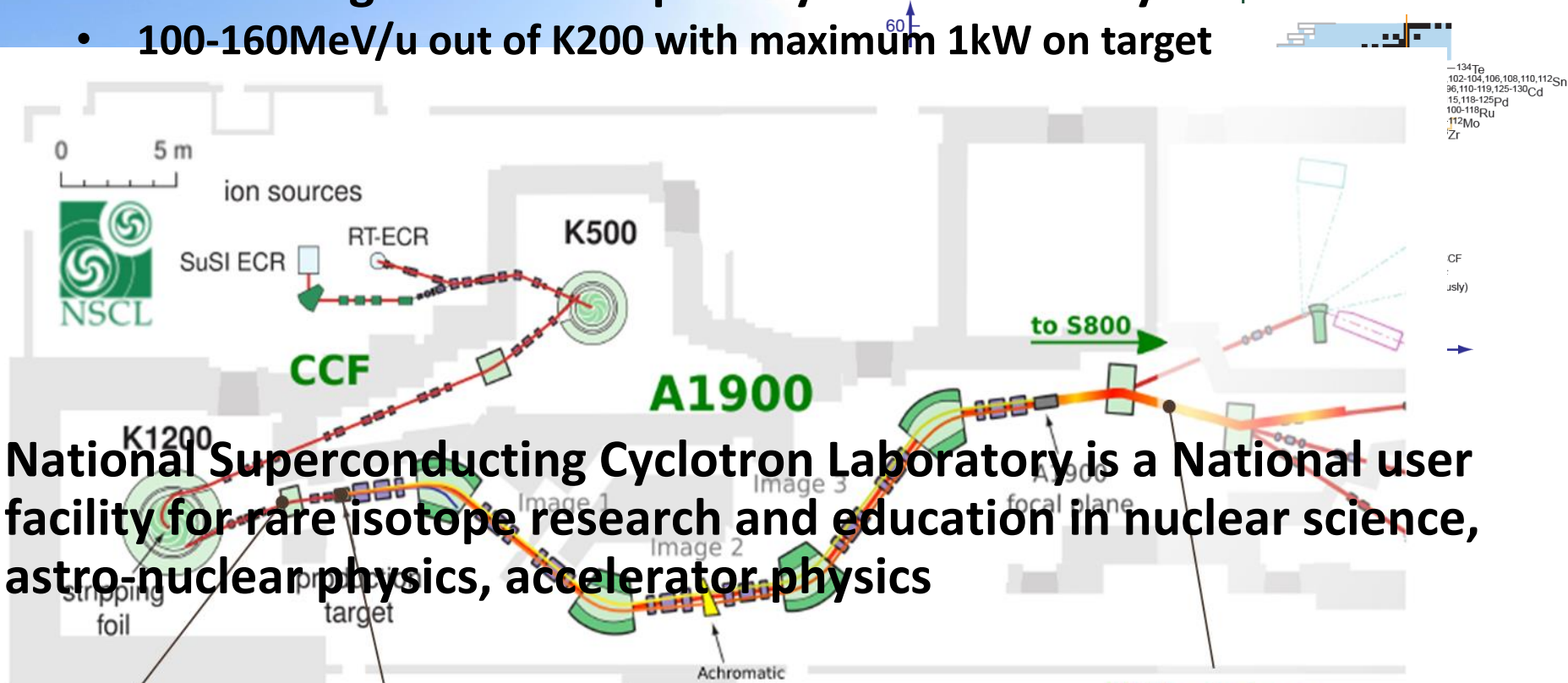
<sup>74</sup>Ni ≈ 0.7 pps  
dp/p = 3%



# Coupled Cyclotron Facility (CCF)

- Present configuration: Coupled Cyclotron Facility
  - 100-160 MeV/u out of K200 with maximum 1 kW on target

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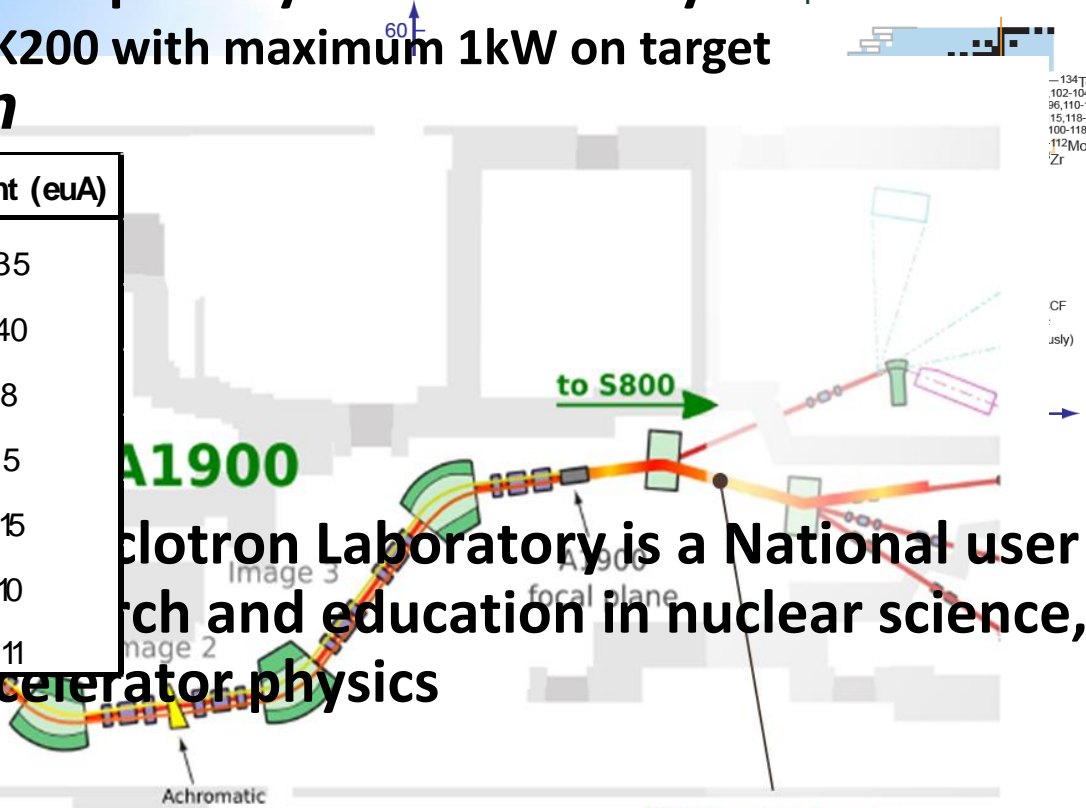
Ion	Charge State	Current (eUA)
<sup>18</sup> O	3+	35
<sup>40</sup> Ar	7+	40
<sup>58</sup> Ni	11+	8
<sup>76</sup> Ge	12+	5
<sup>78</sup> Kr	14+	15
<sup>48</sup> Ca	8+	10
<sup>136</sup> Xe	21+	11

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ARTEMIS- RT 14 GHz  
(2001)

SuSI- Fully SC 18 GHz  
(2009)

Better performances for Heavy ions (Xe,U)

astro-nuclear physics, accelerator physics

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60+

stripping foil

target

Achromatic Degraders

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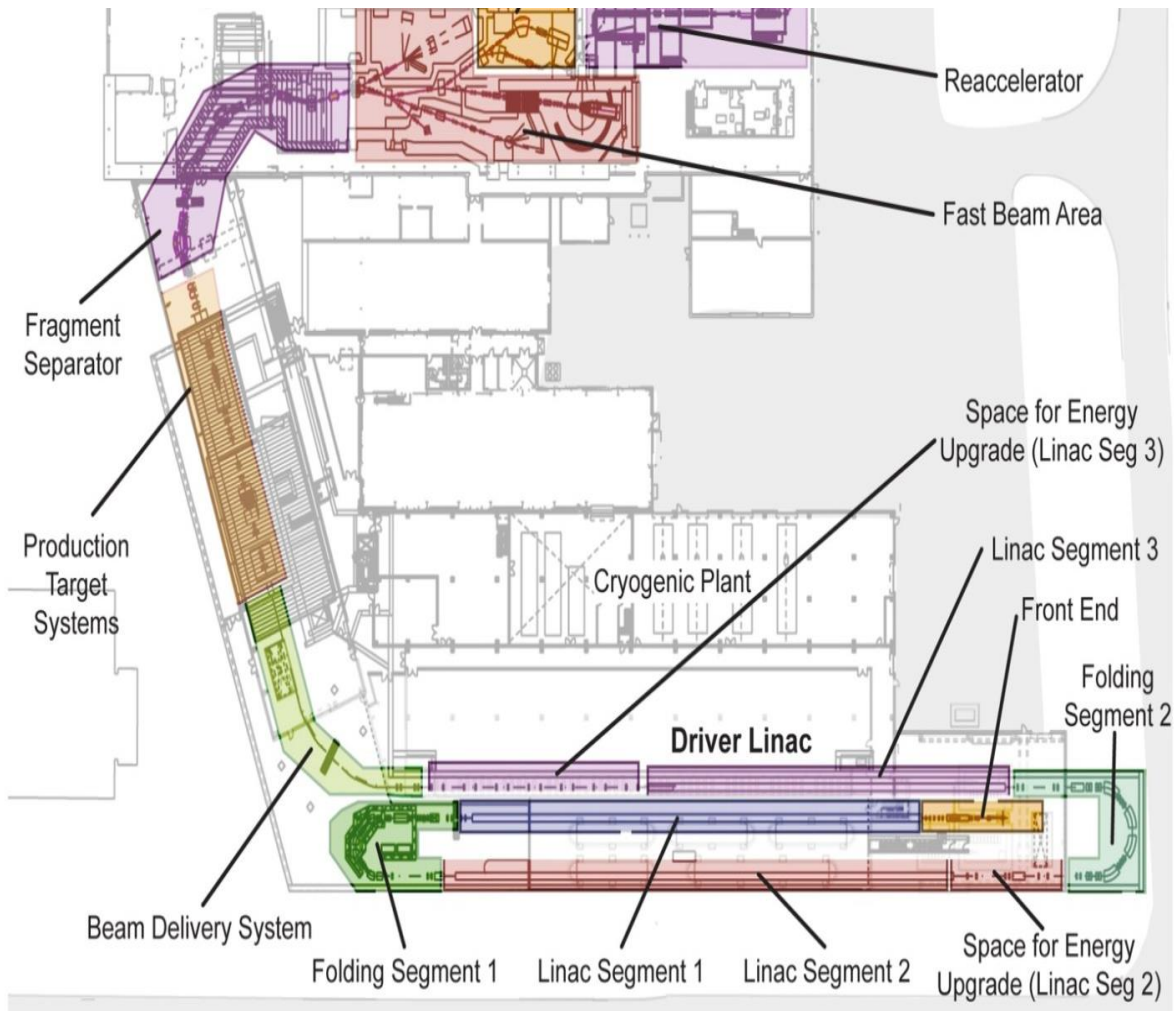
RHIC at

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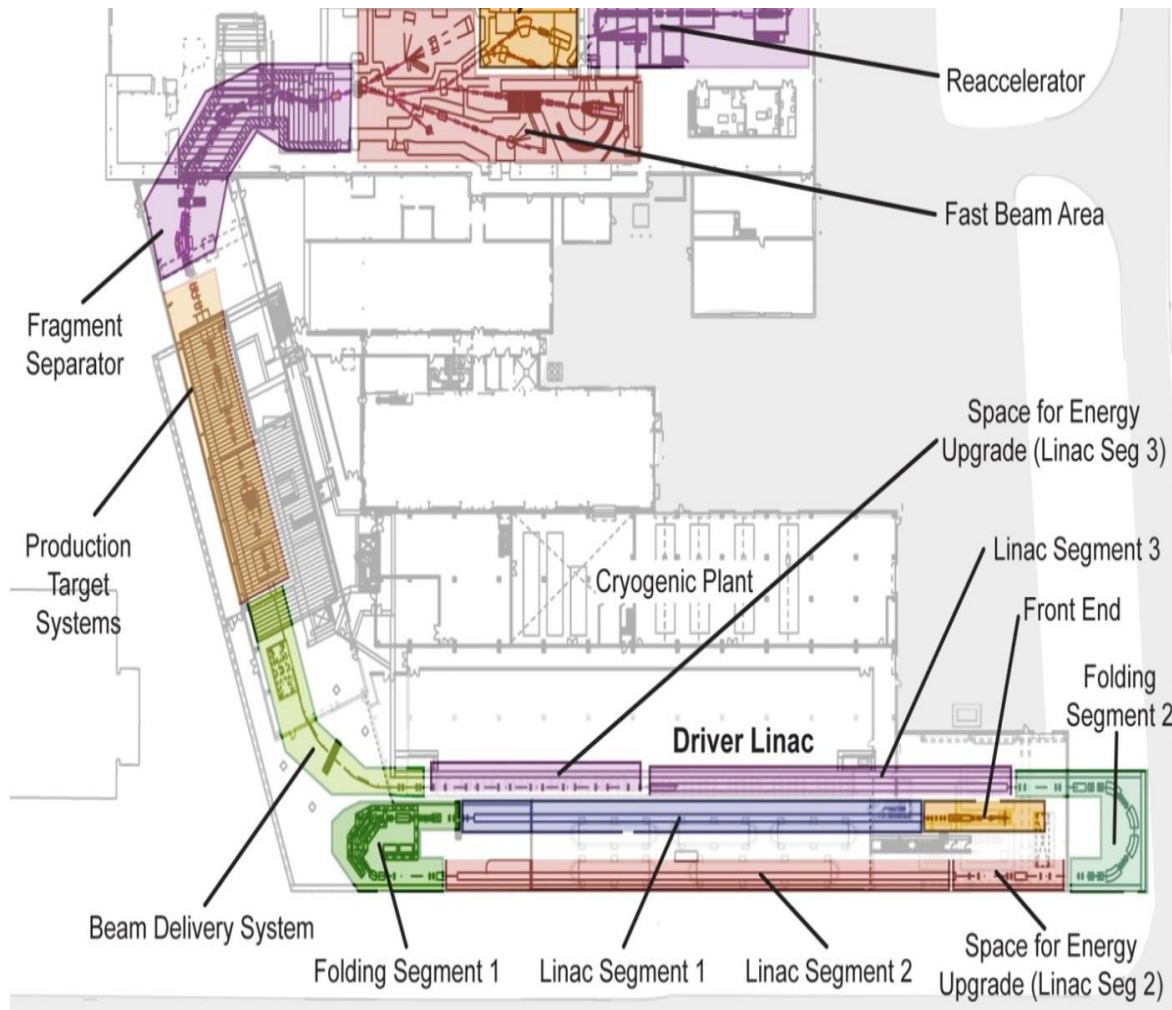
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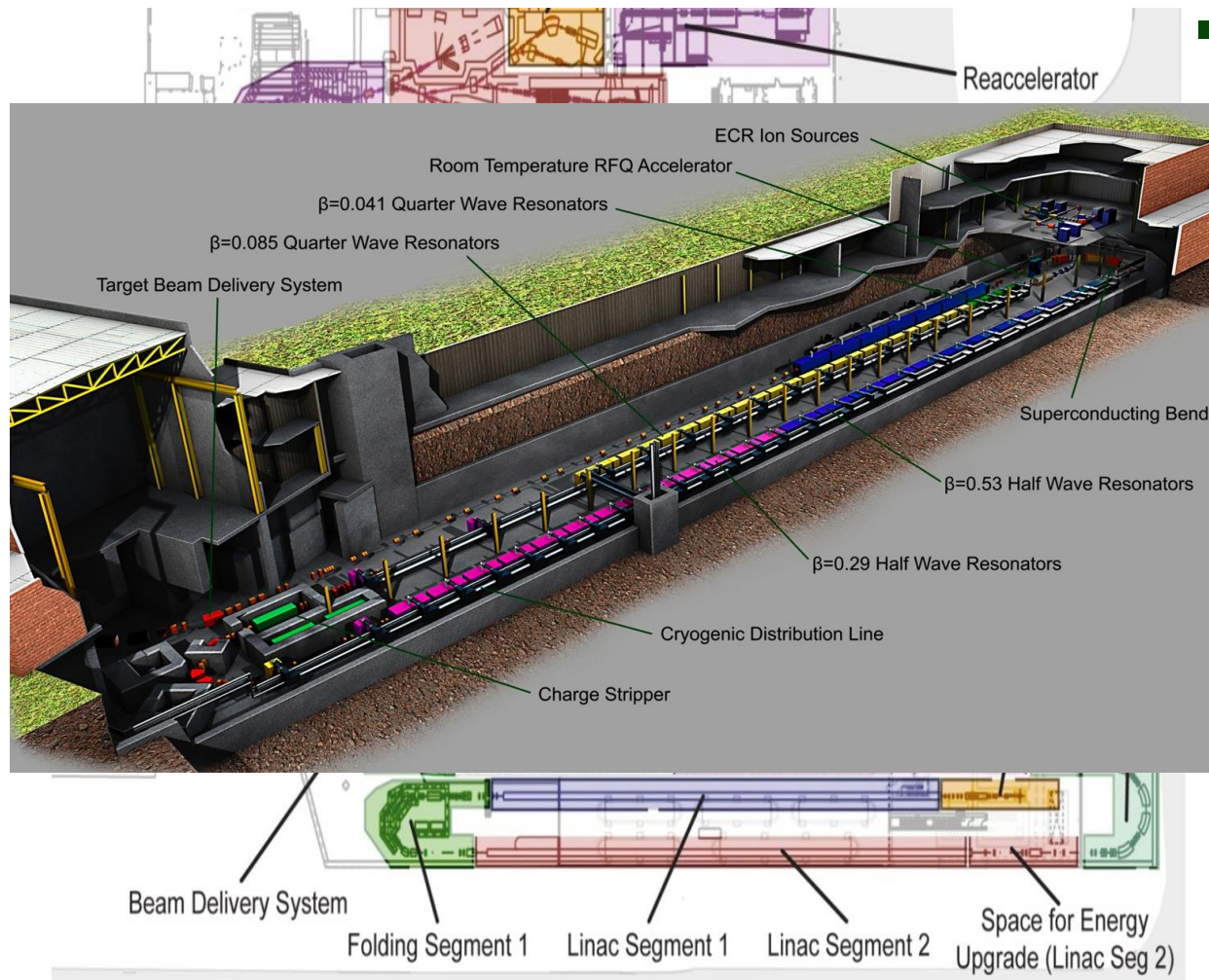
## Facility for Rare Isotope Beam (FRIB)

- Accelerate ion species up to  $^{238}\text{U}$  with energies of no less than 200 MeV/u
- Provide beam power up to 400 kW
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Beam Delivery System

Folding Segment 1

Linac Segment 1

Linac Segment 2

Space for Energy Upgrade (Linac Seg 2)

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Folding Segment 1    Linac Segment 1    Linac Segment 2    Upgrade (Linac Seg 2)

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# Facility for Rare Isotope Beams (FRIB)

2013

- Facility for Rare Isotope Beam (FRIB)

2014

- 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

Folding Segment 1   Linac Segment 1   Linac Segment 2   Upgrade (Linac Seg 2)



# 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

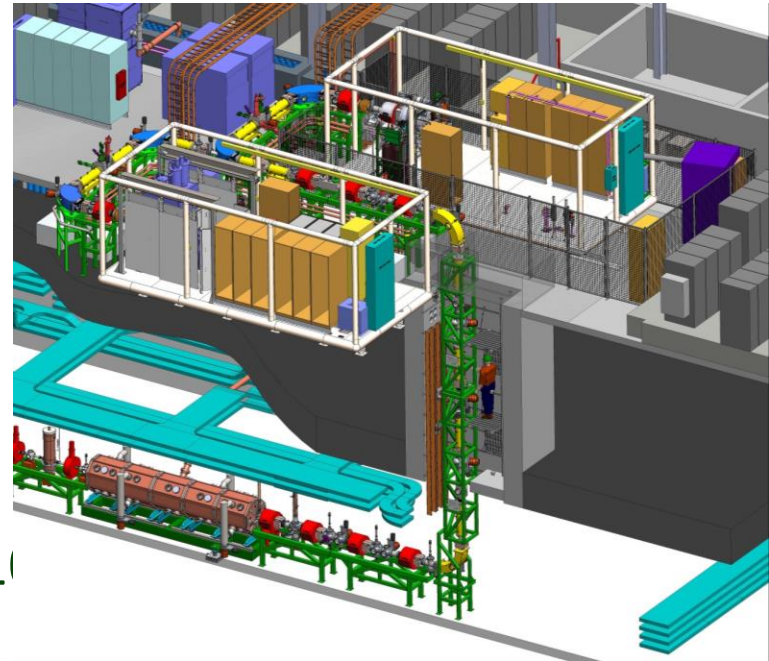
- $Q/A = 1/3$  to  $1/7$

## Transverse emittance (per charge state, 10)

- 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

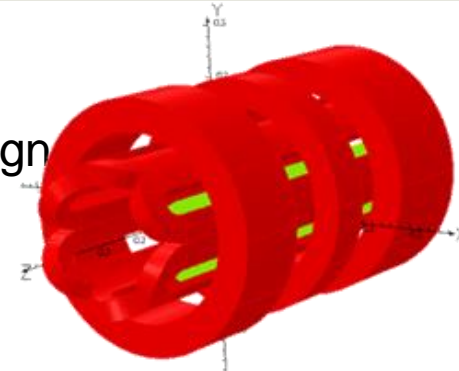
- » Gain experience with Gyrotron operation
- » Push performances for Gases and Solid beams
- » Beam characterizations (emittance, stability..)



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

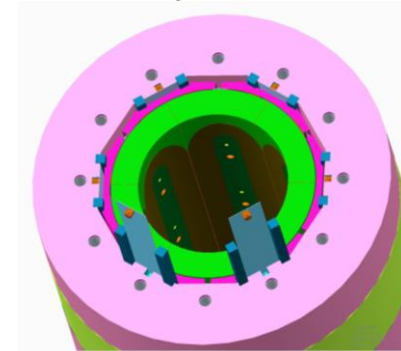
## ■ Magnetic and Mechanical Analysis

- 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

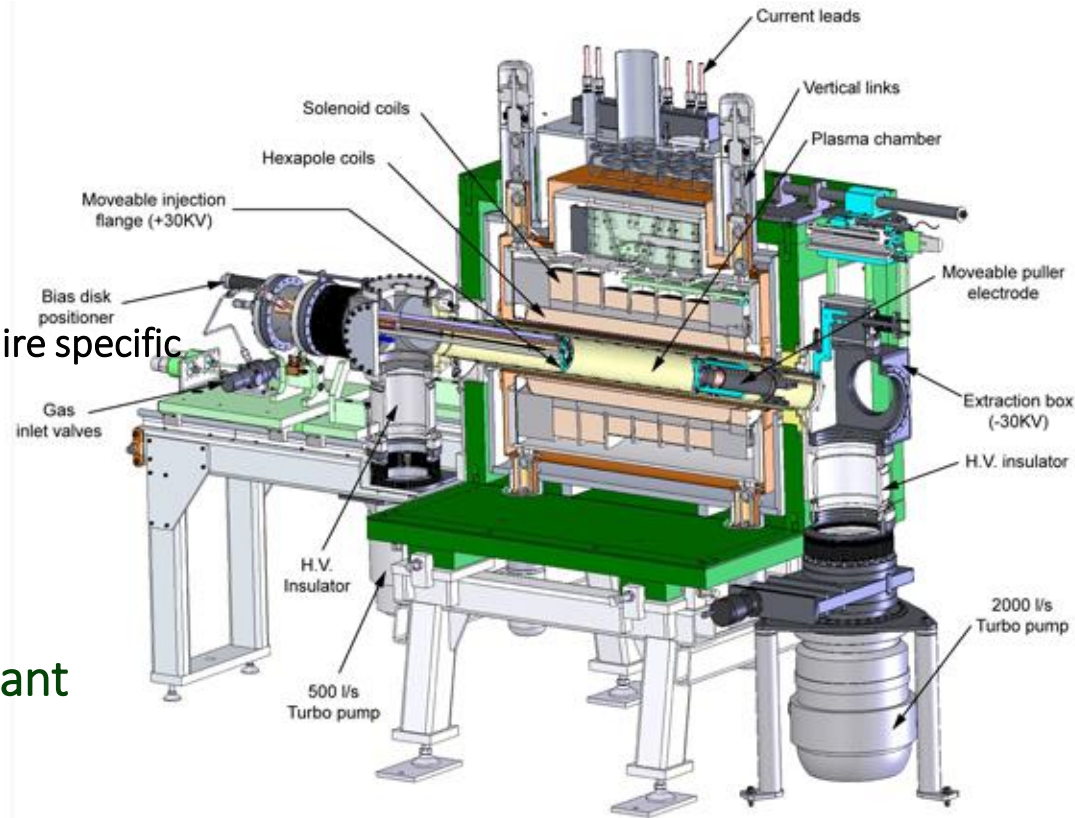
- 6 Solenoids
- Solenoid /Sextupole interaction forces require specific ramp sequenced
  - » Eliminate “random quenches” at field
- Demonstrated nominal 24 GHz field

- Cold mass cooled with 2kW powerplant

- Advantages/disadvantages

- Al Plasma chamber of  $\varnothing 101$  mm ID

- 3.5 l overall volume

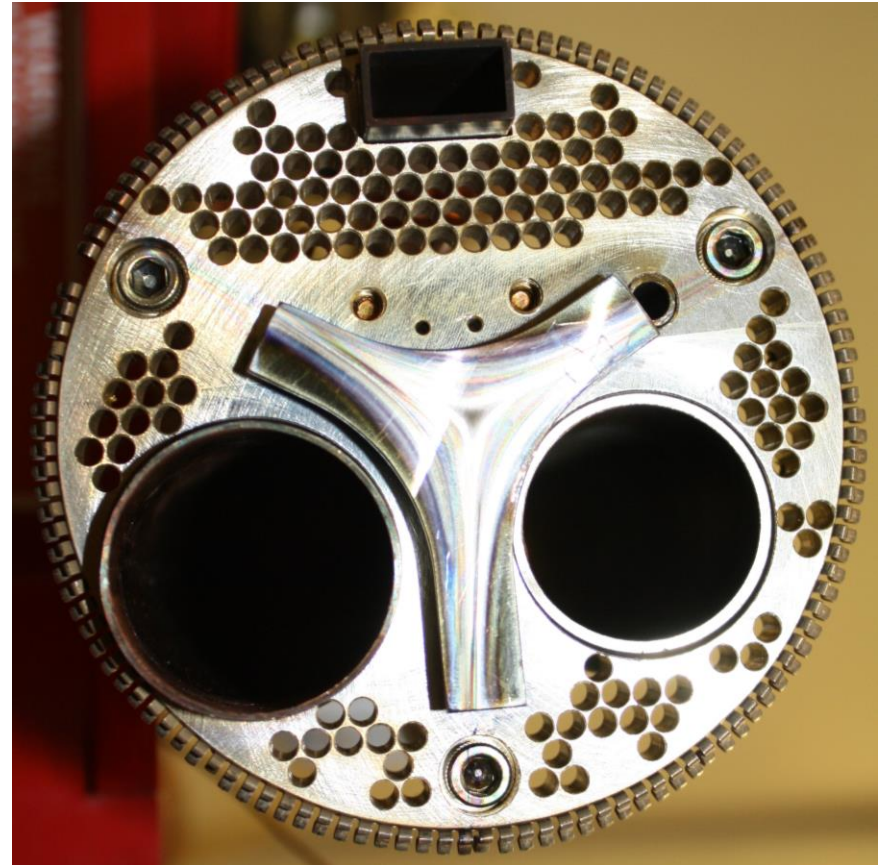


# SuSI modifications to operate at 24 GHz

- 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)

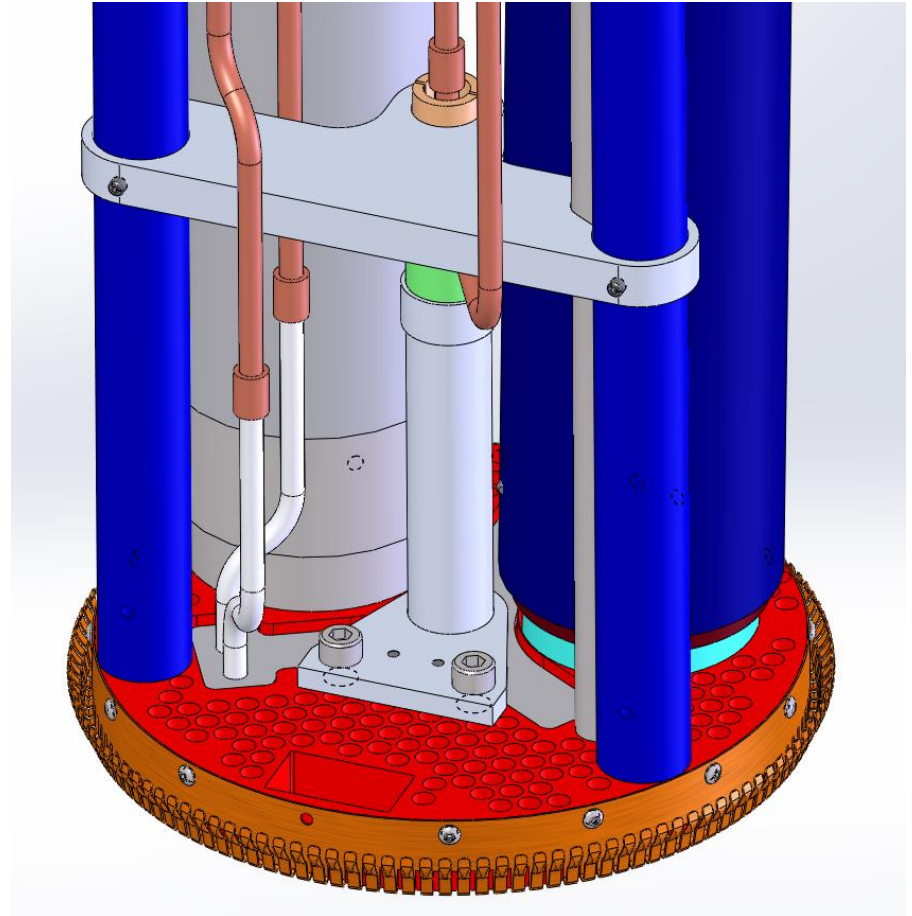
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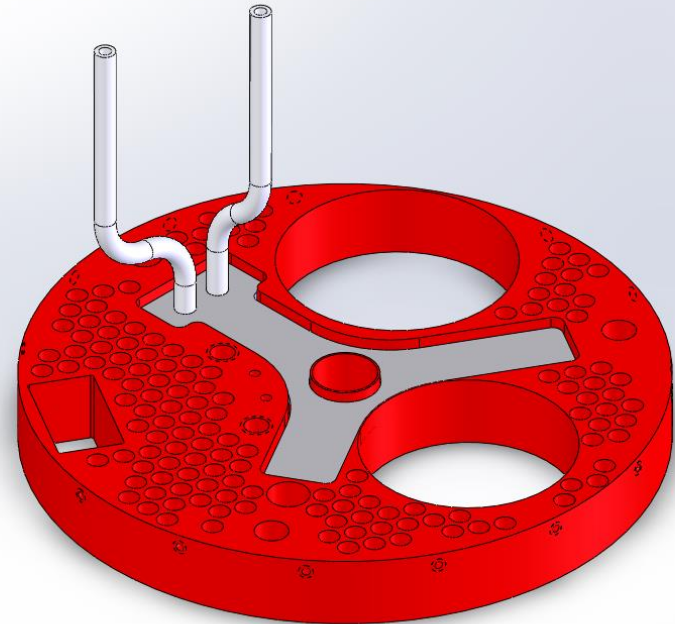
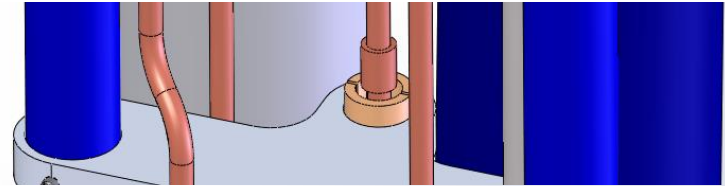
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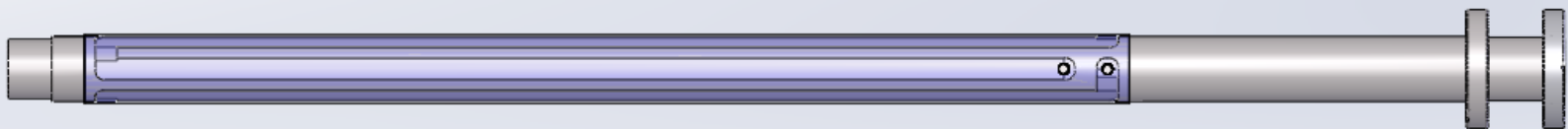
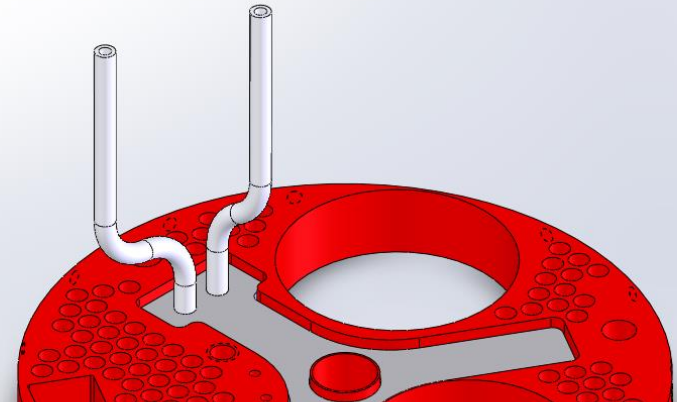
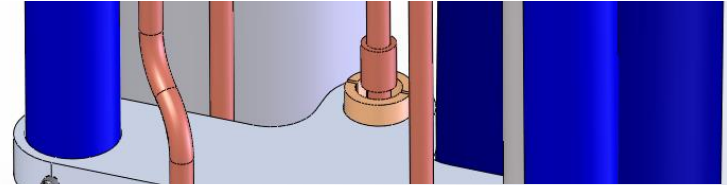
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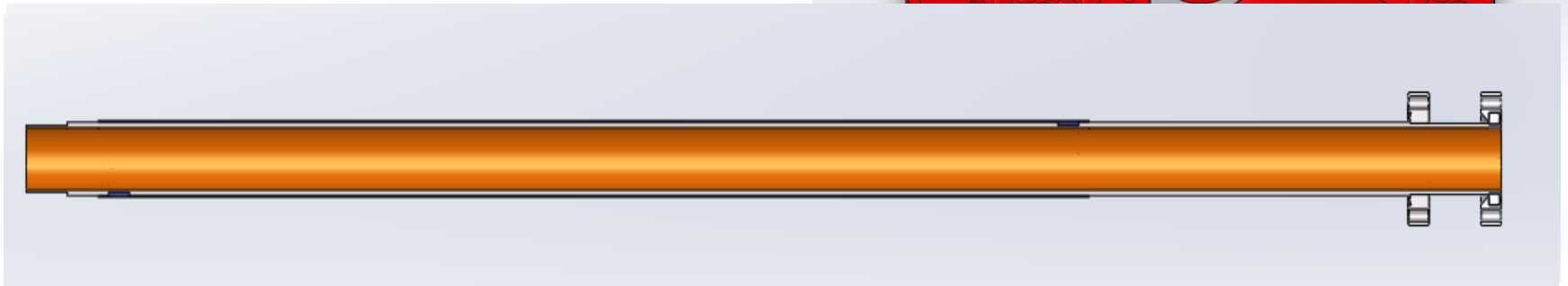
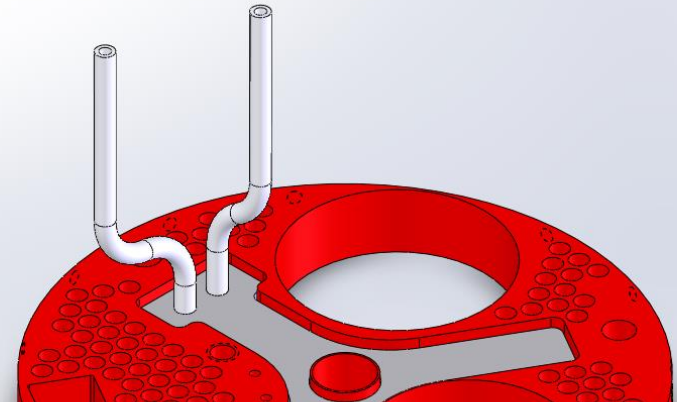
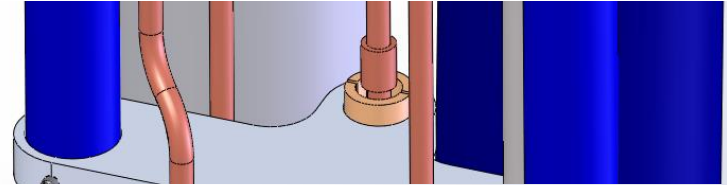
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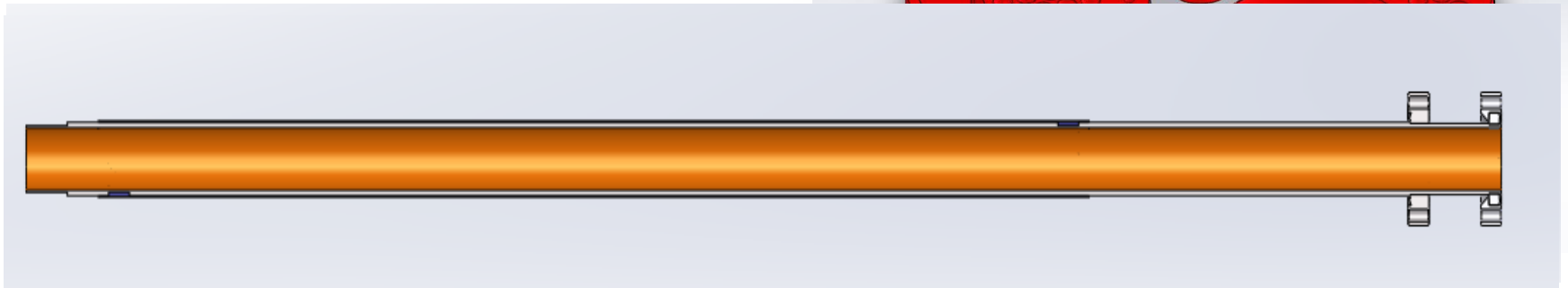
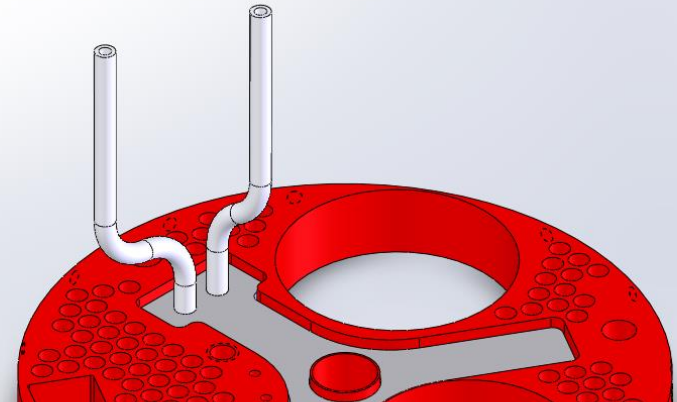
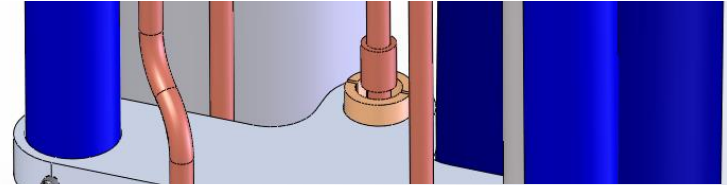
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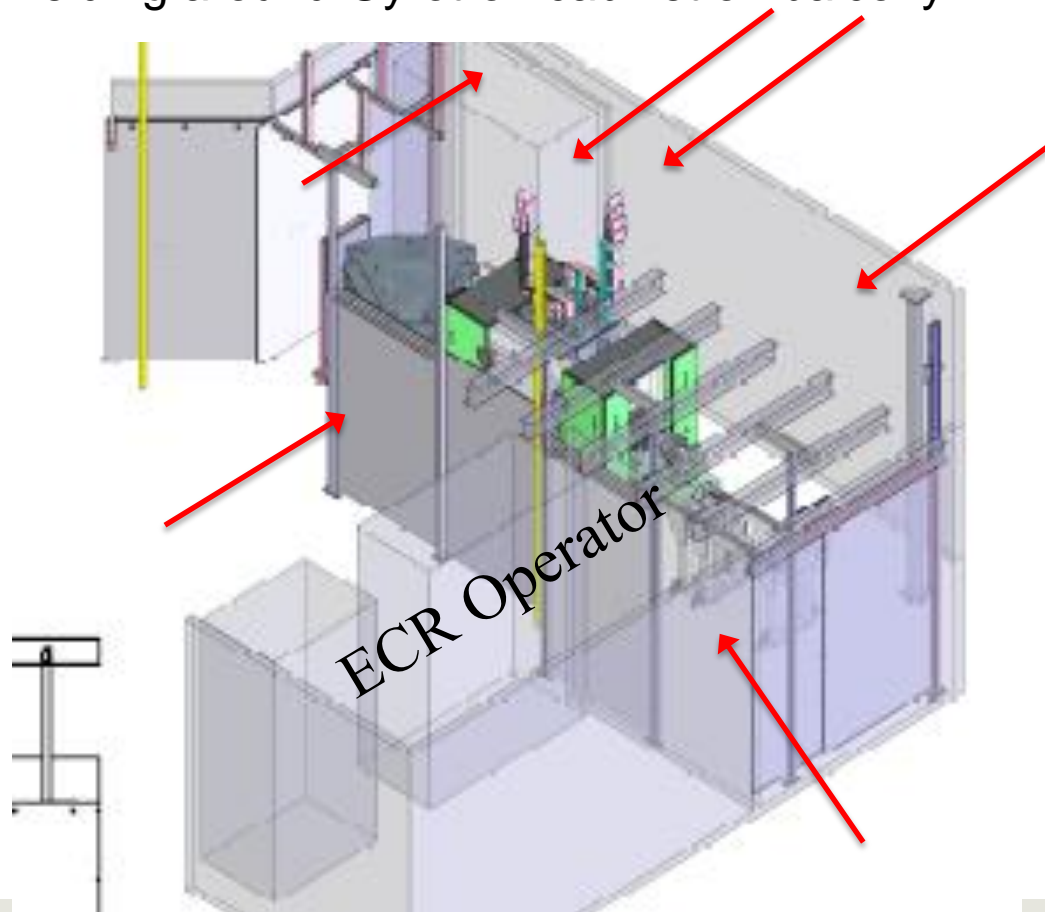
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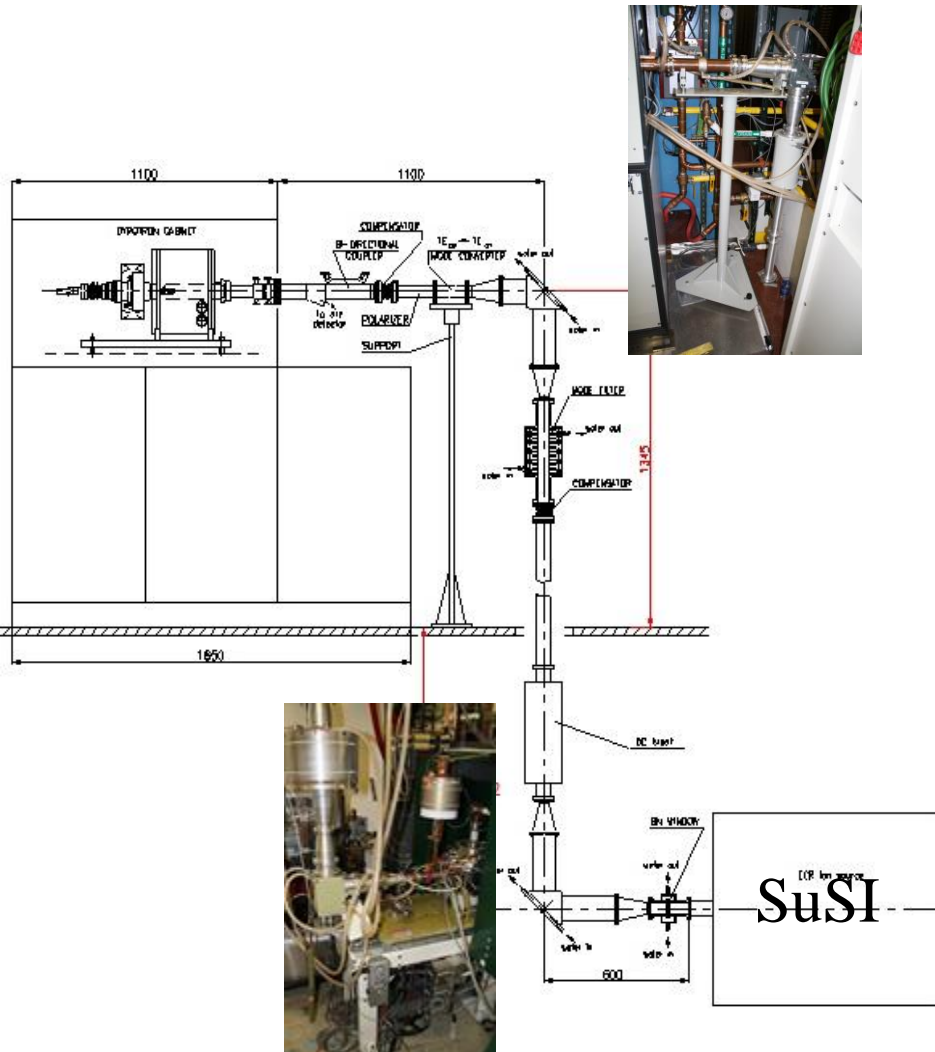


# Radiation shielding upgrade

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



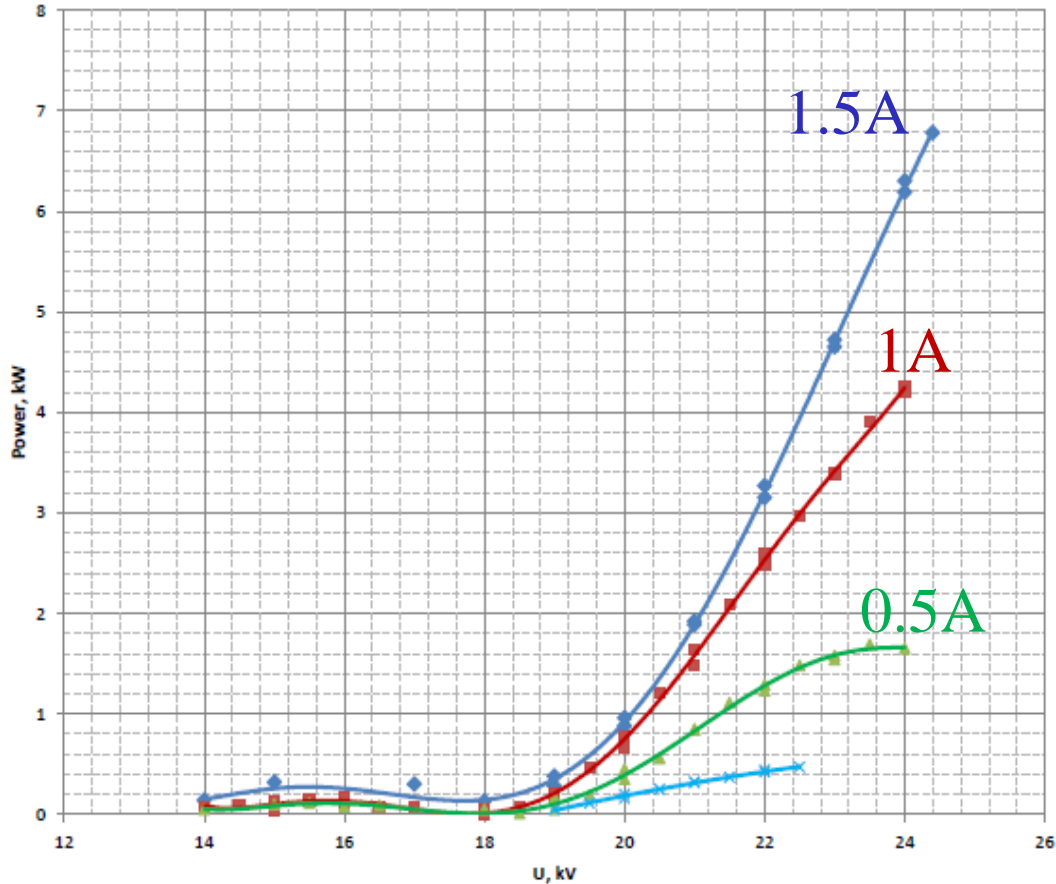
# 24 GHz Gyrotron System



- 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

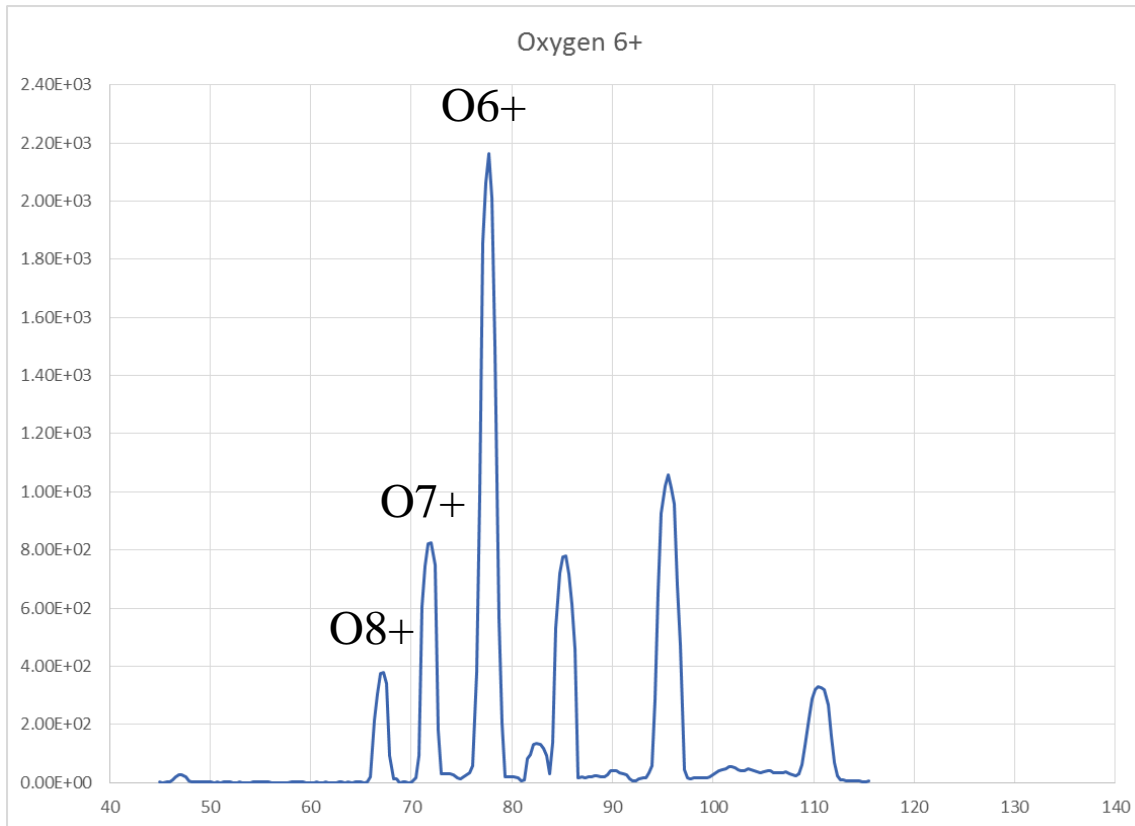


- Maximum power output on dummy load 8.8kW
  - Ibeam=1.95A
  - Maintained 5kW +/- 1% output for 6 hours during testing
- Gyrotron parameters
  - Filament power > 200W
  - Solenoid 85A
  - Anode Voltage: up to 12kV
- No issue with equipment so far
  - 350 hours operation
- Maximum power send to ion source ~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<sup>16+</sup>
- Oxygen and Argon development for additional 1Week in July
  - Much less outgassing
  - Better performances especially for Ar<sup>16+</sup>

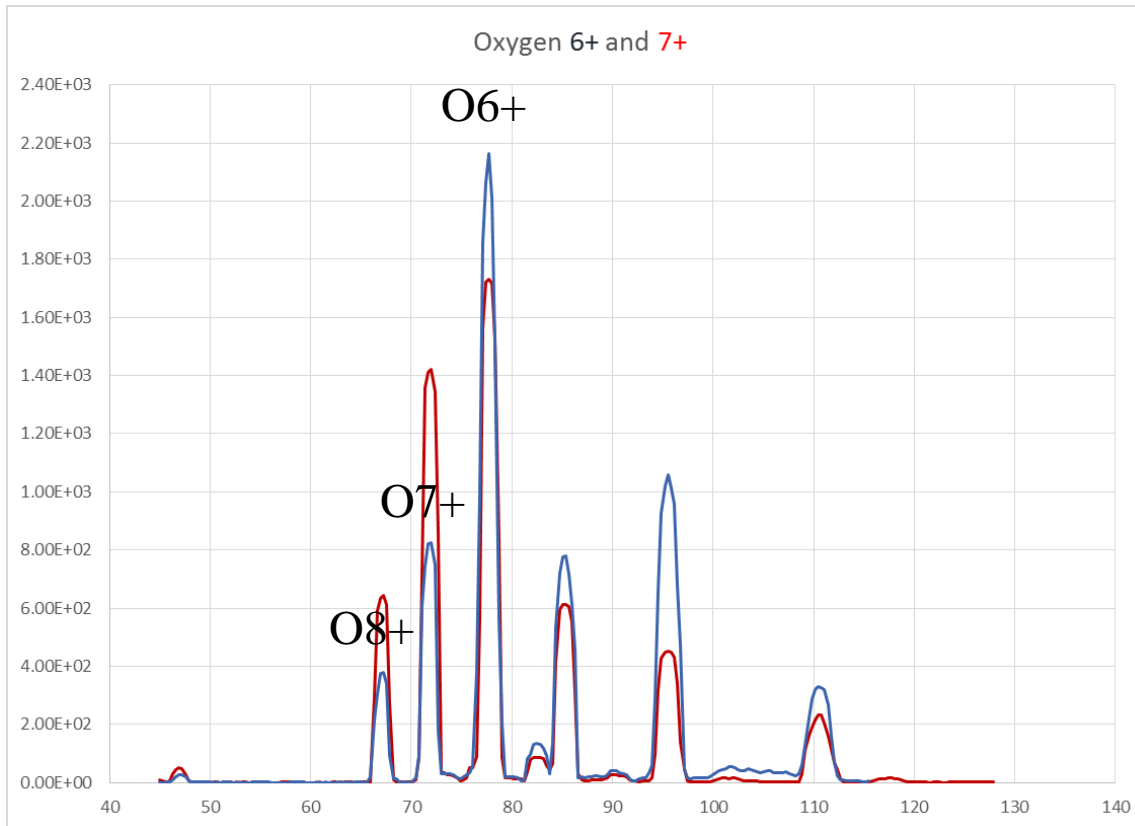
# 24 GHz Commissioning Results: Oxygen 6+ and 7+



$B_{\text{sext}}=1.49\text{T}$ ;  $B_{\text{inj}}=2.97\text{T}$   
 $B_{\text{min}}=0.47\text{T}$ ;  $B_{\text{ext}}=1.53\text{T}$   
 $\nabla_{\text{Inj}}=6.42\text{ T/m}$ ;  $\nabla_{\text{Ext}}=5.79\text{ T/m}$   
Ecr length = 111.2 mm  
24 GHz Power = 5200W  
18 GHz Power = 300W  
 $I_{\text{drain}}=7.3\text{eA}$   
 $P_{\text{inj}}=3\text{E-}7\text{Torr}$   $P_{\text{ext}}=3.7\text{E-}8\text{Torr}$

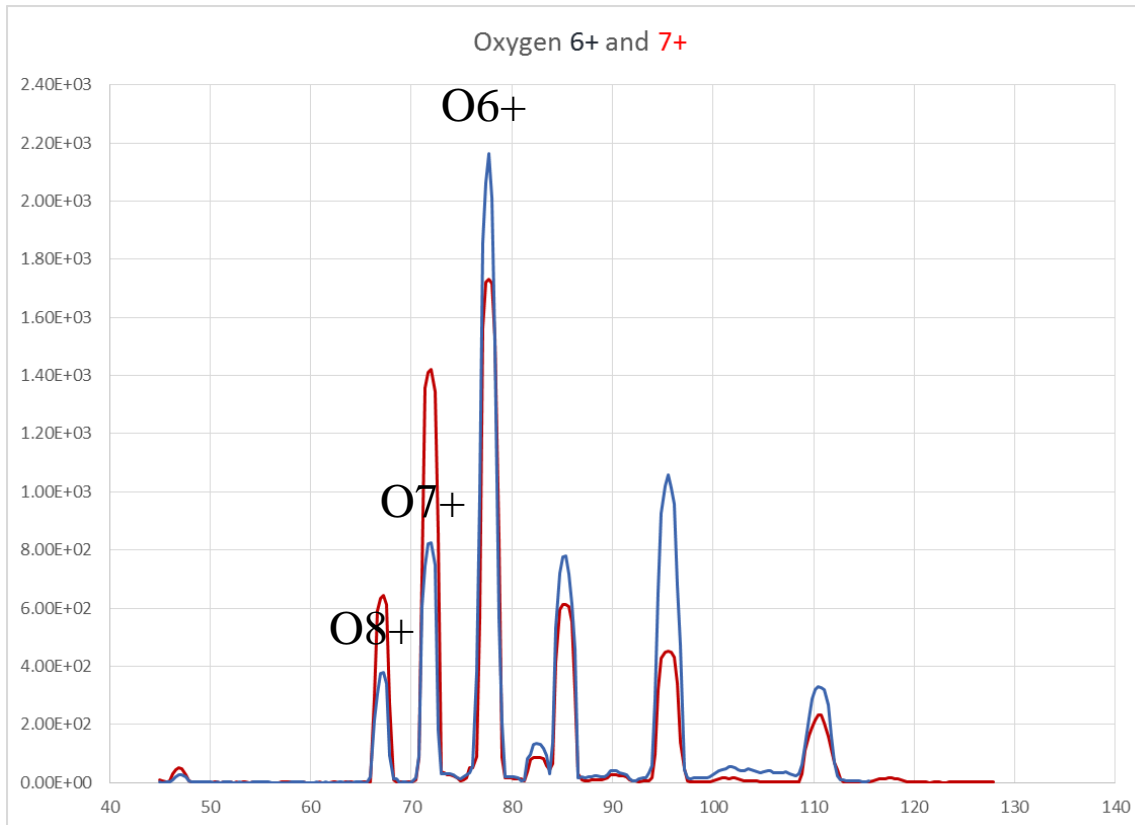


# 24 GHz Commissioning Results: Oxygen 6+ and 7+



B<sub>sext</sub>=1.49T; B<sub>inj</sub>=2.97T  
B<sub>min</sub>=0.47T; B<sub>ext</sub>=1.53T  
∇<sub>Inj</sub>=6.42 T/m; ∇<sub>Ext</sub>=5.79 T/m  
Ecr length = 111.2 mm  
24 GHz Power = 5200W  
18 GHz Power = 300W  
I<sub>drain</sub>=7.3eA  
P<sub>inj</sub>=3E-7Torr P<sub>ext</sub>=3.7E-8Torr

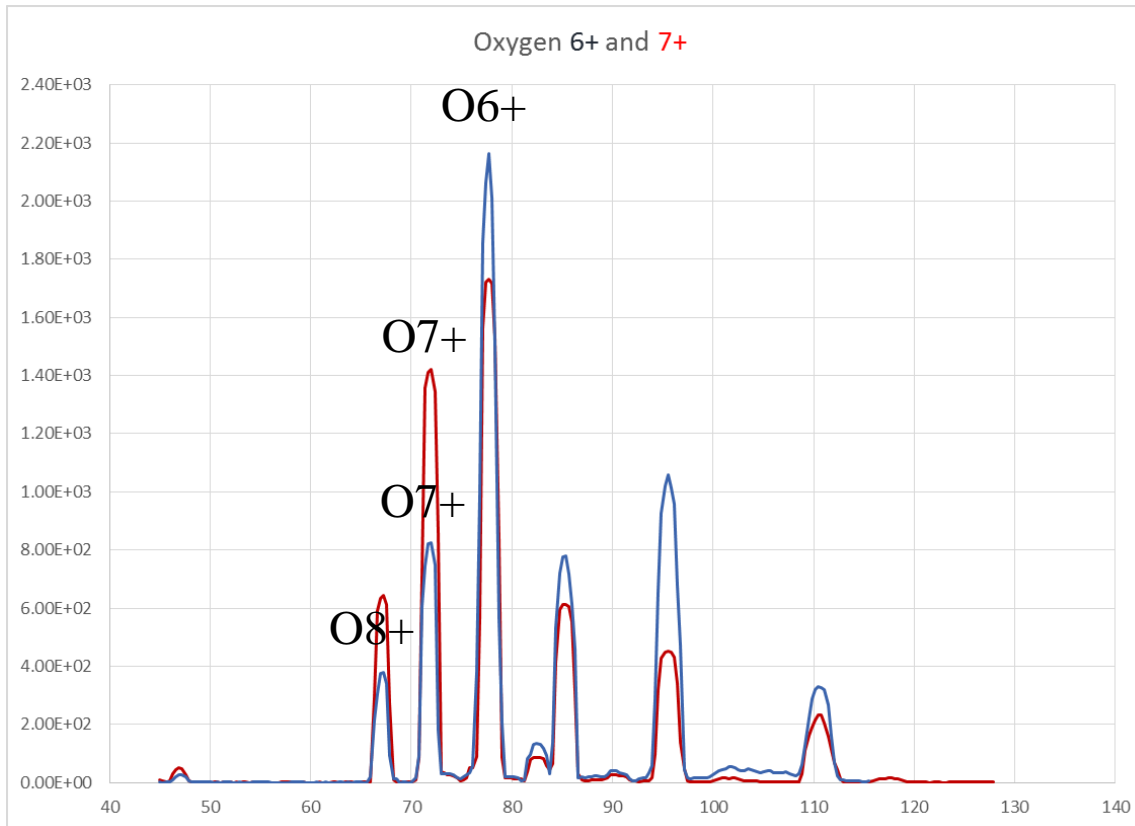
# 24 GHz Commissioning Results: Oxygen 6+ and 7+



$B_{\text{sext}}=1.49\text{T}$ ;  $B_{\text{inj}}=2.97\text{T}$   
 $B_{\text{min}}=0.47\text{T}$ ;  $B_{\text{ext}}=1.53\text{T}$   
 $\nabla_{\text{Inj}}=6.42\text{ T/m}$ ;  $\nabla_{\text{Ext}}=5.79\text{ T/m}$   
Ecr length = 111.2 mm  
24 GHz Power = 5200W  
18 GHz Power = 300W  
 $I_{\text{drain}}=7.3\text{eA}$   
 $P_{\text{inj}}=3\text{E-}7\text{Torr}$   $P_{\text{ext}}=3.7\text{E-}8\text{Torr}$

$B_{\text{sext}}=1.46\text{T}$ ;  $B_{\text{inj}}=3.05\text{T}$   
 $B_{\text{min}}=0.52\text{T}$ ;  $B_{\text{ext}}=1.57\text{T}$   
 $\nabla_{\text{Inj}}=5.46\text{ T/m}$ ;  $\nabla_{\text{Ext}}=4.95\text{ T/m}$   
Ecr length = 93.1 mm  
24 GHz Power = 5200W  
18 GHz Power = 0W  
 $I_{\text{drain}}=3.9\text{eA}$   
 $P_{\text{inj}}=7\text{E-}8\text{Torr}$   $P_{\text{ext}}=3.3\text{E-}8\text{Torr}$

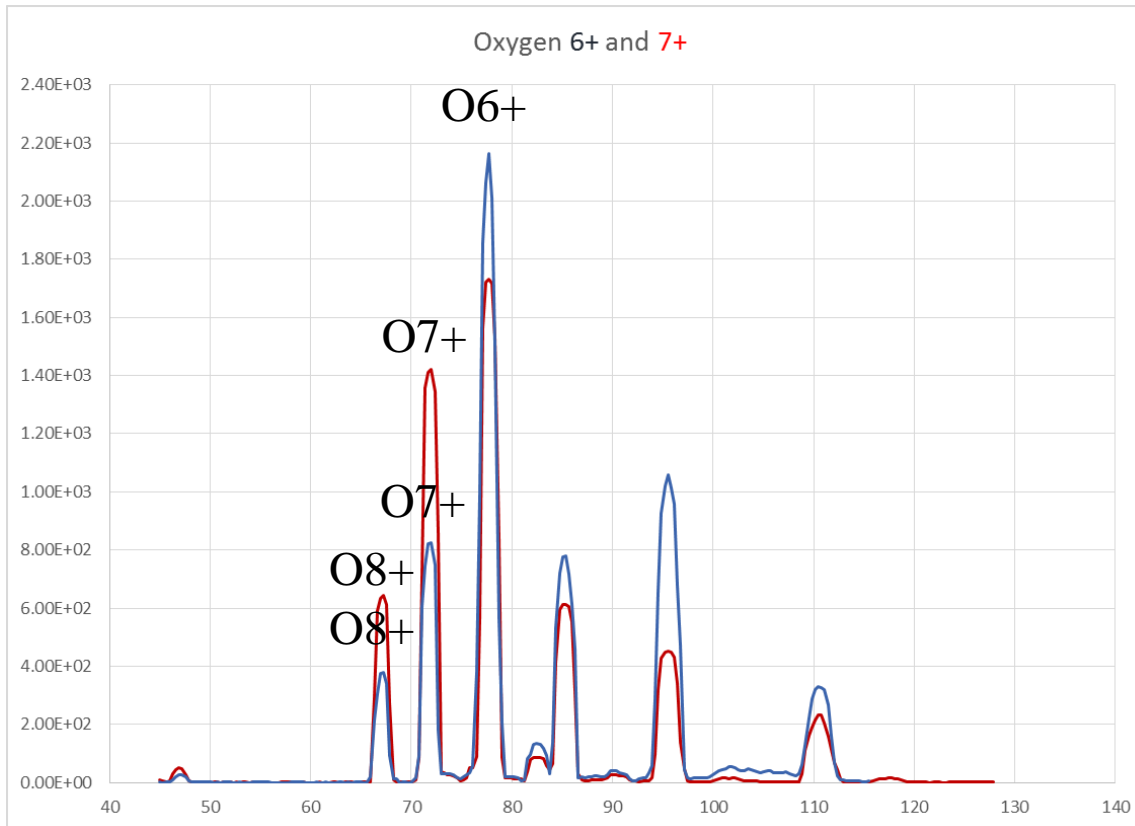
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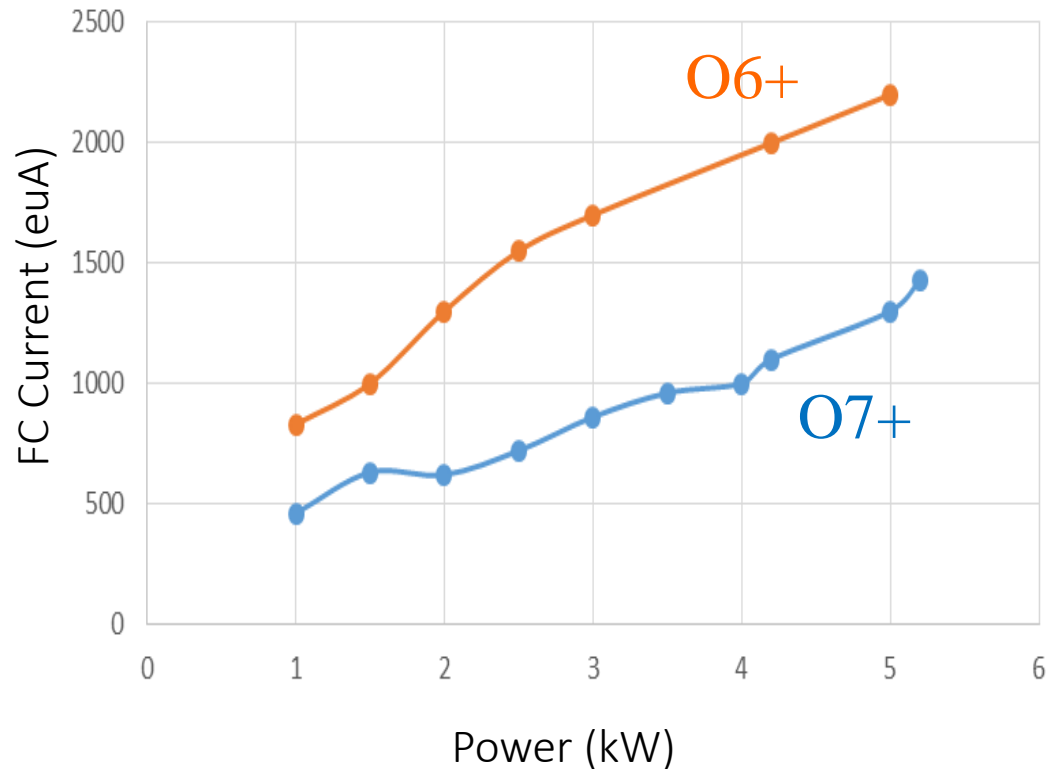
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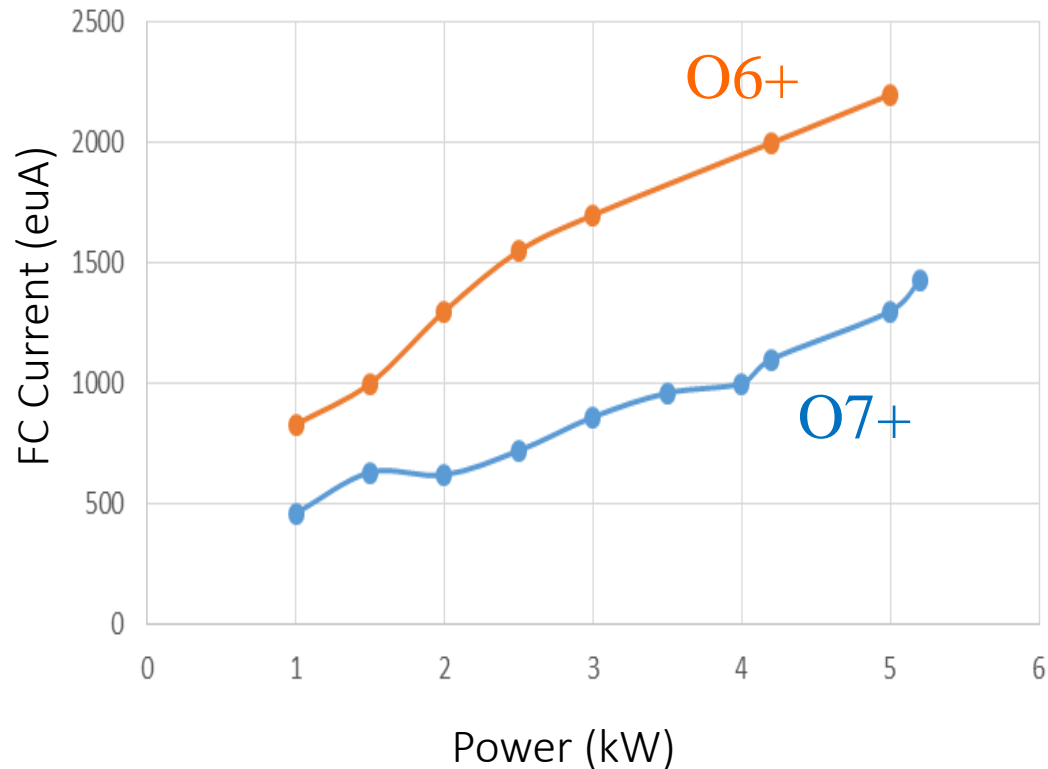
# 24 GHz Commissioning Results: Oxygen 6+ and 7+



■ **No Saturation with microwave power observed so far**

- **Power density maximum of ~1.5 kW/l**
- **Gas and field optimized for each case**

# 24 GHz Commissioning Results: Oxygen 6+ and 7+

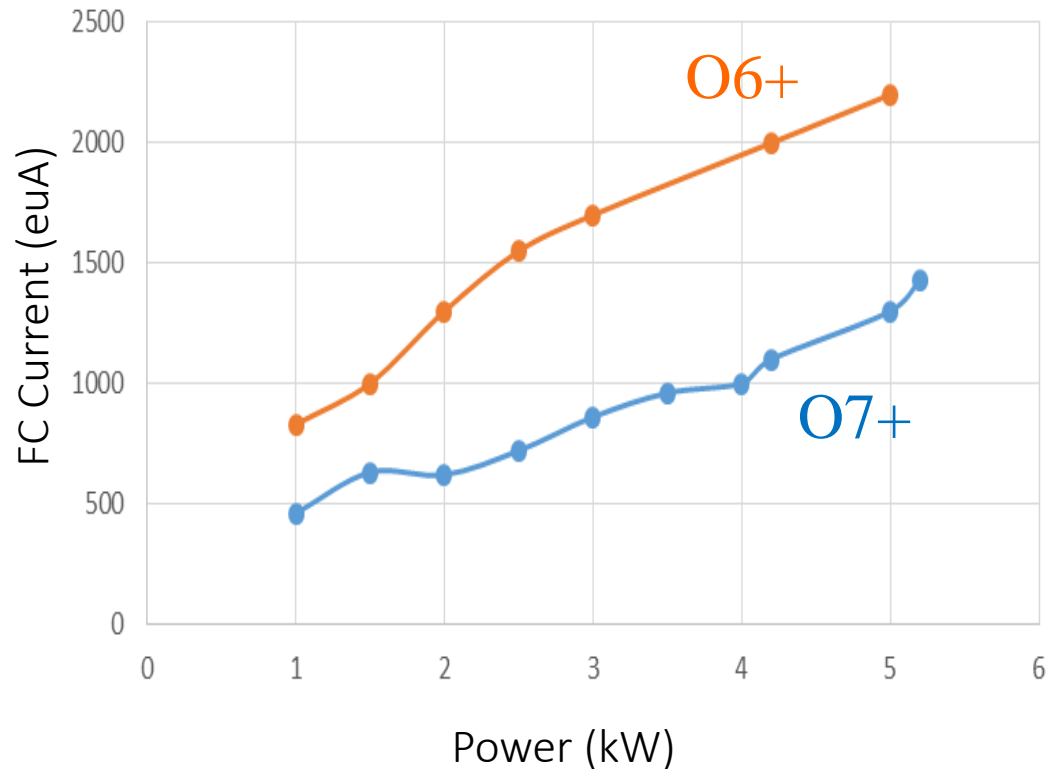


■ **No Saturation with microwave power observed so far**

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- **Gas and field optimized for each case**

	<b>6+</b>	<b>7+</b>
SuSI	2200	1400
VENUS	2900	850

# 24 GHz Commissioning Results: Oxygen 6+ and 7+



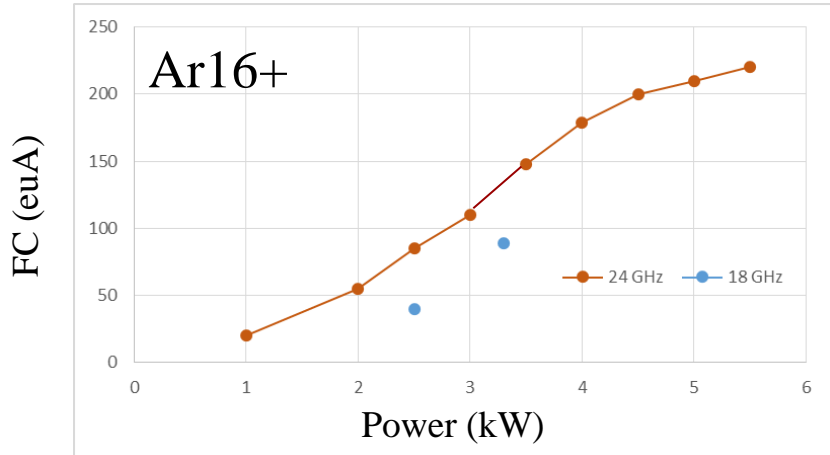
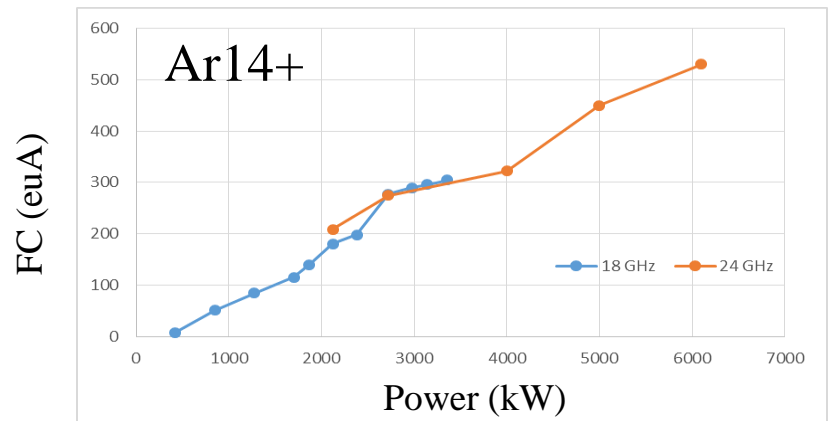
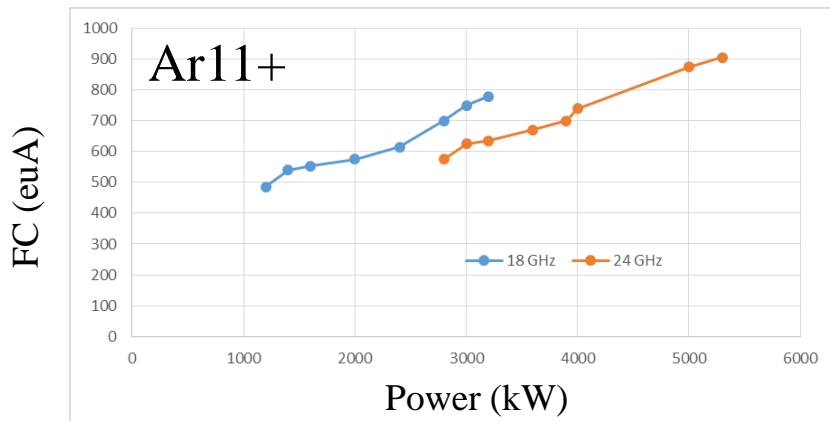
■ **No Saturation with microwave power observed so far**

- 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

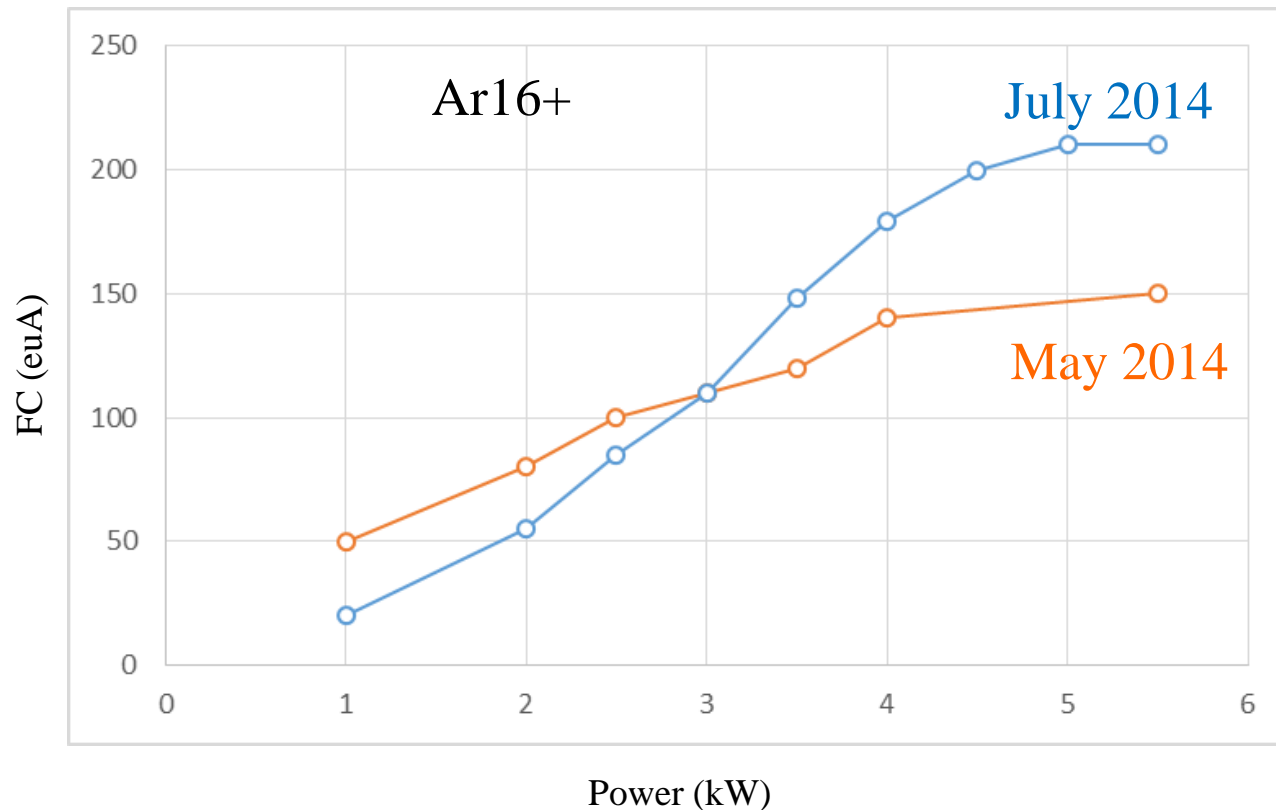


- **Continuing increase of current with power at 24 GHz**
  - No or very little 18 GHz injected despite  $B_{min} \sim 0.5T$
- **Impact of frequency not so clear for medium charge states**
  - Field still not at optimum value for use with 24 GHz



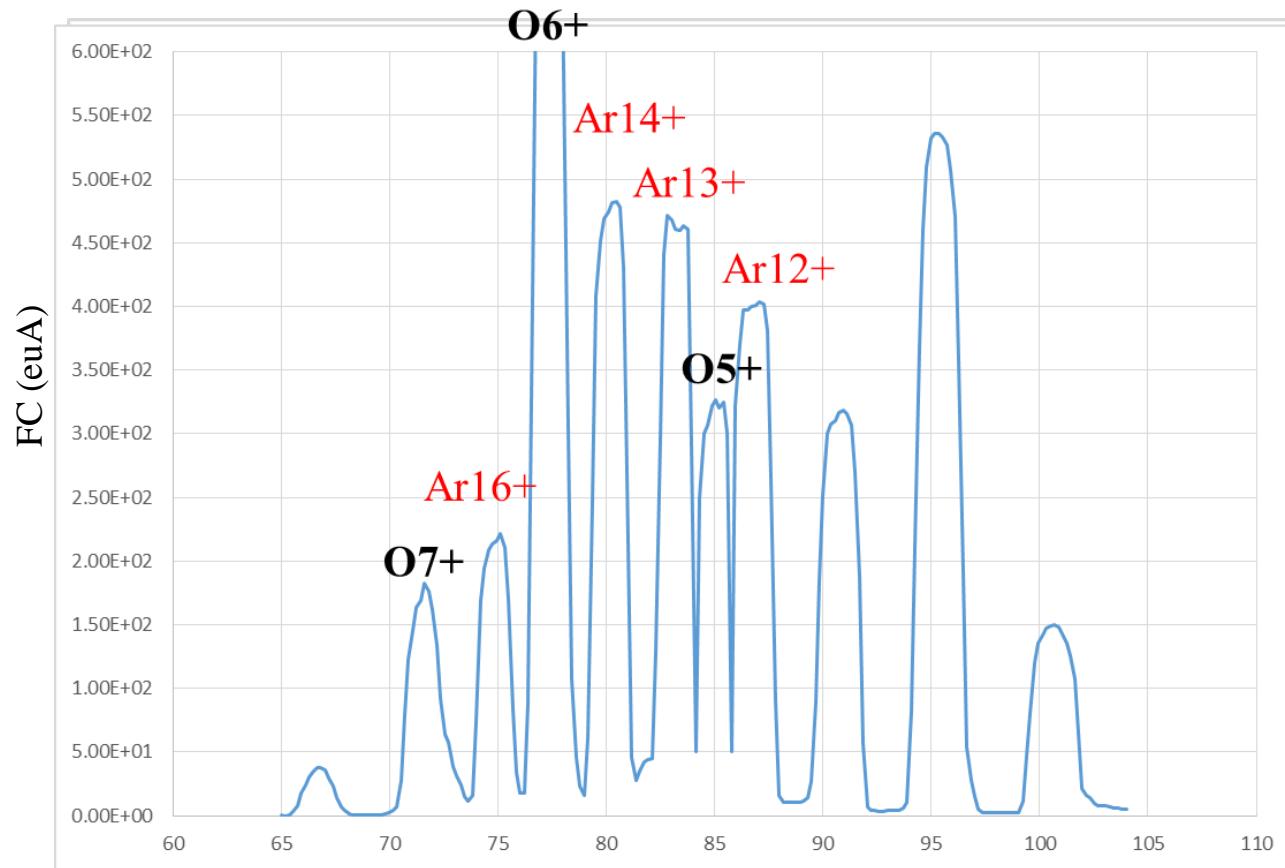
# 24 GHz commissioning Results: Argon

- Conditioning takes time to optimize performances at 24 GHz



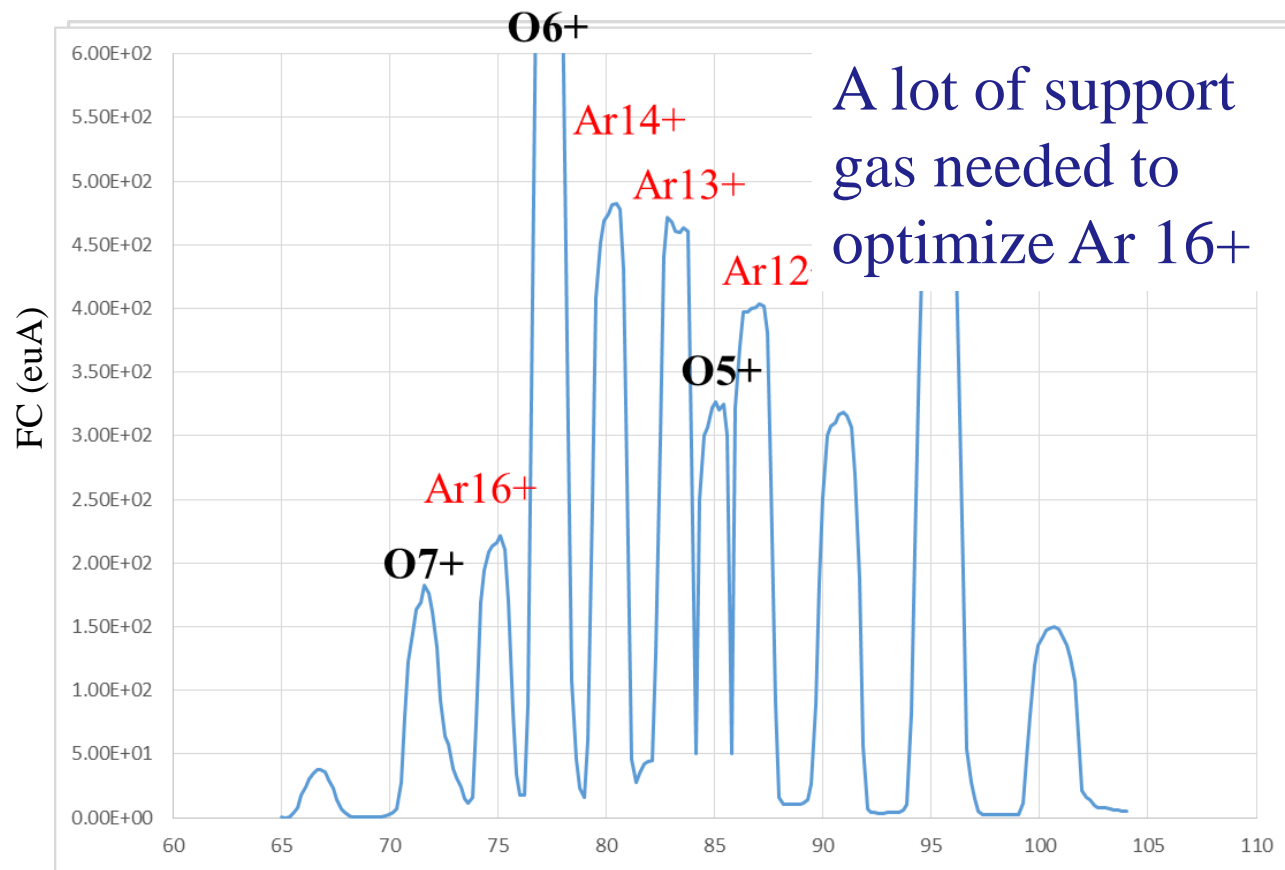
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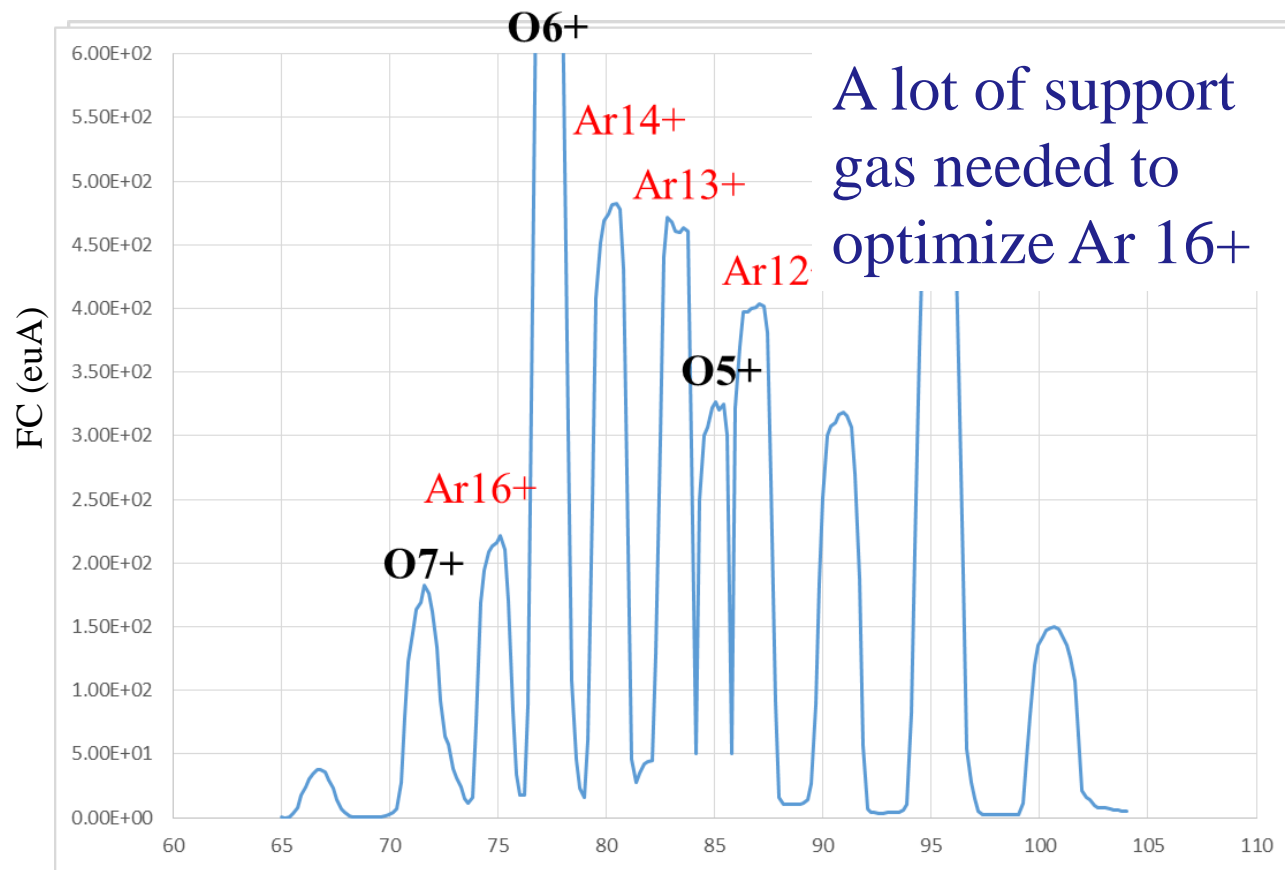
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# 24 GHz commissioning Results: Argon

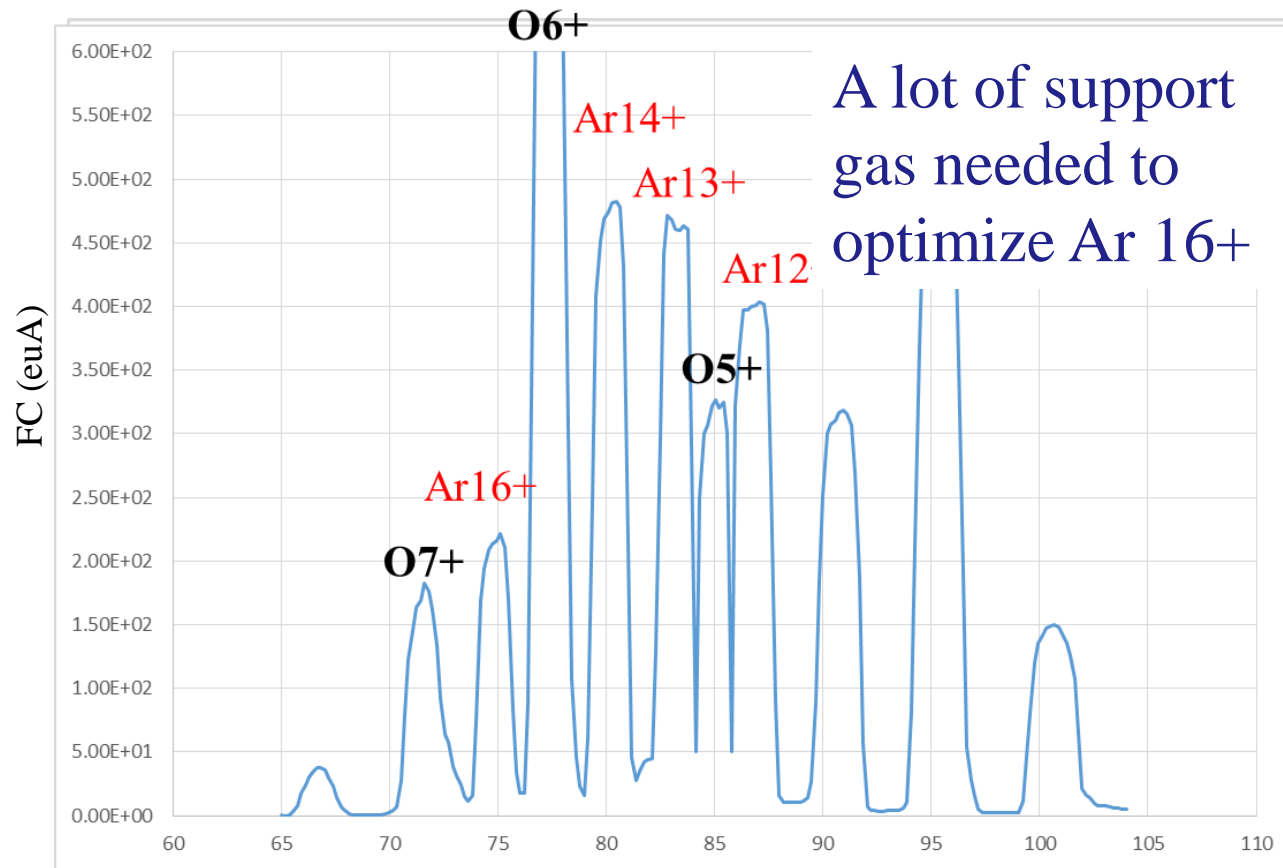
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Comparison Venus- SuSI  
(All current in e $\mu$ A)

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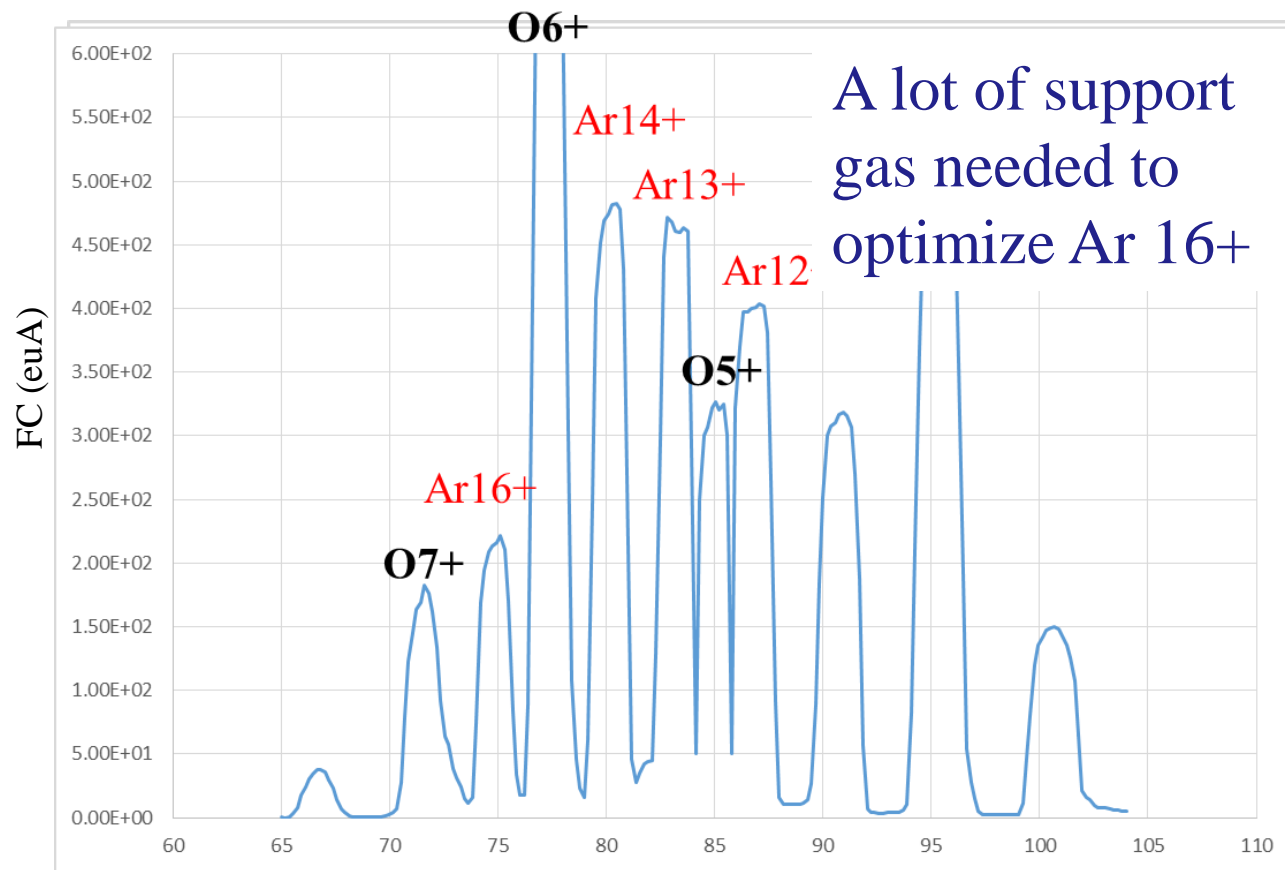


Comparison Venus- SuSI  
(All current in eμA)

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

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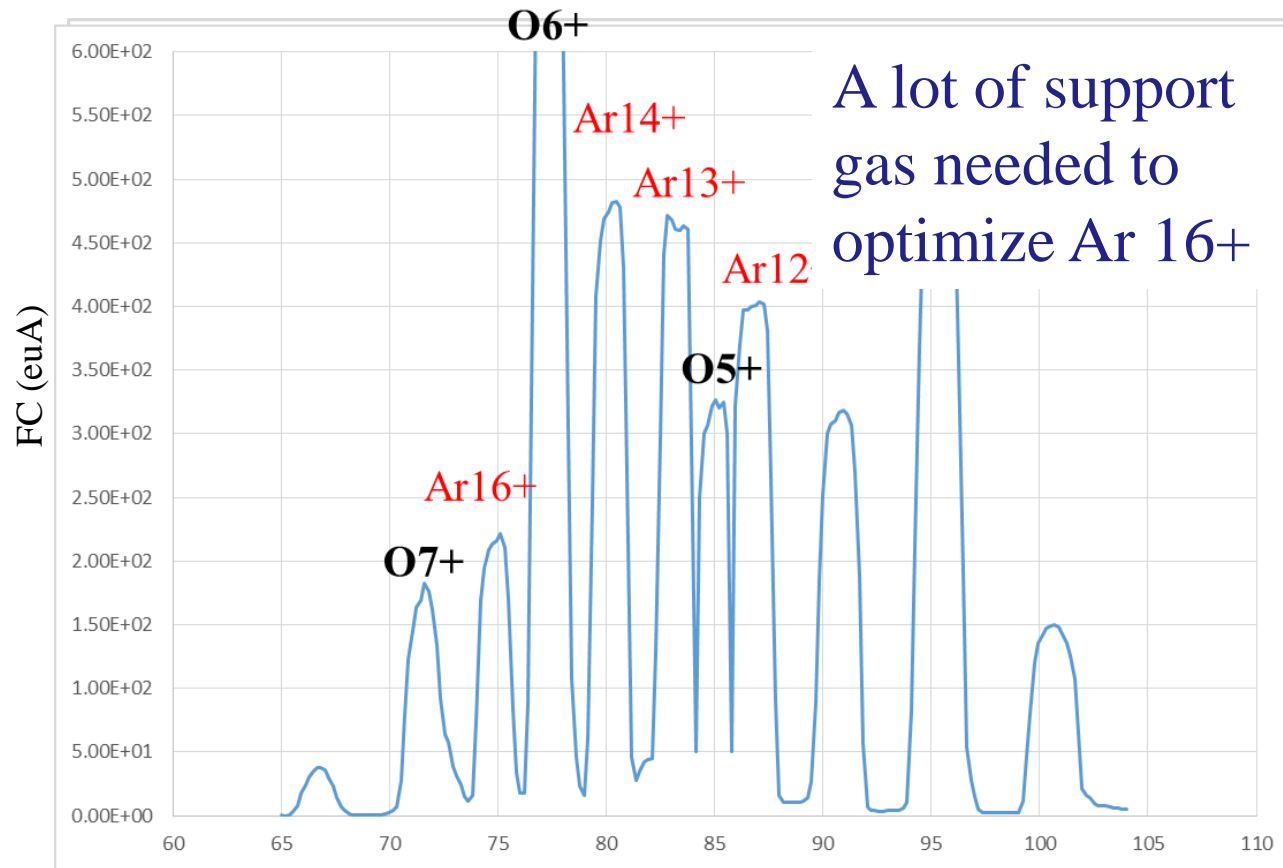
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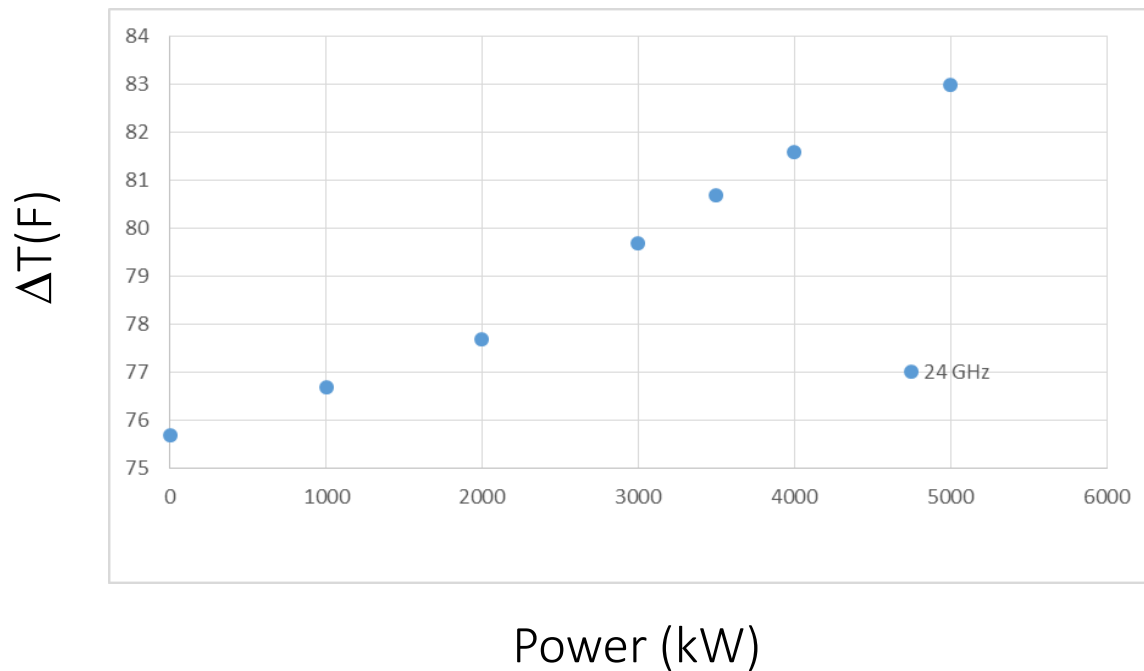
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(1) ECRIS 2006 IMP, China

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

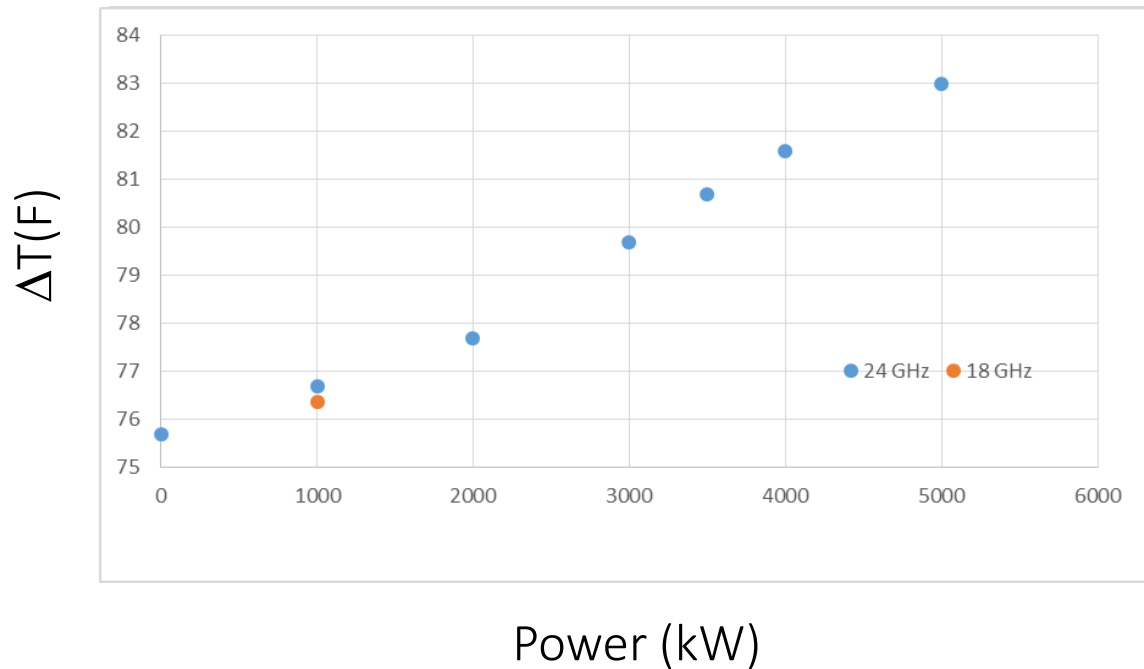


- Temperature increase match ANSYS simulation



# Plasma chamber cooling

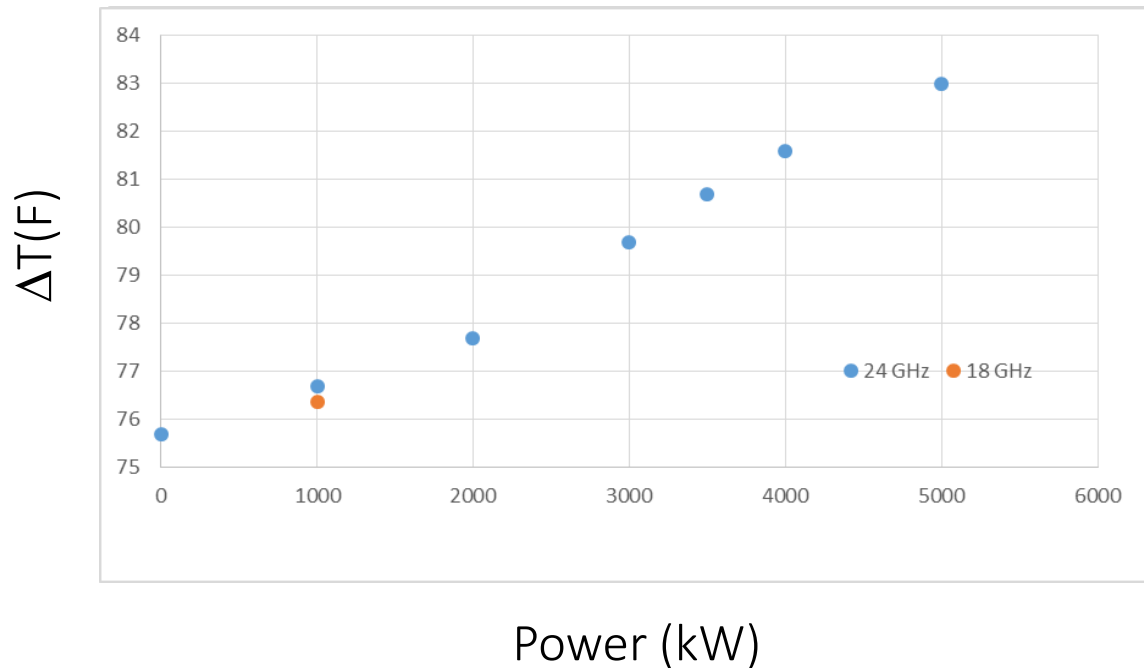
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- Temperature increase match ANSYS simulation

# 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
- 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)
<sup>40</sup> Ar								
11+	<b>905</b>	8	5.3	1.51	1.33	3.00	0.47	1.43
12+	<b>860</b>	8.2	5.9	1.69	1.48	3.11	0.48	1.51
14+	<b>530</b>	7.1	6.1	1.74	1.46	3.12	0.58	1.56
16+	<b>220</b>	4.5	5.7	1.63	1.46	3.02	0.50	1.54
<sup>16</sup> O								
6	<b>2200</b>	7.3	5.2	1.49	1.49	2.97	0.47	1.53
7	<b>1430</b>	3.9	5.2	1.49	1.46	3.06	0.52	1.57
					<b>1.71</b>	<b>3.43</b>	<b>0.51-0.69</b>	<b>1.71</b>

# 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




hydrogen 1 H 1.0079																	helium 2 He 4.0026				
lithium 3 Li 6.941	beryllium 4 Be 9.0122															boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305															aluminum 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80				
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29				
caesium 55 Cs 132.91	barium 56 Ba 137.33	lanthanum 57 La 138.91	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 196.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]				
francium 87 Fr [223]	radium 88 Ra [226]	actinium 89 Ac [227]	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	unnilium 110 Uun [271]	ununium 111 Uuu [272]	ununbium 112 Uub [277]	ununquadium 114 Uuq [289]								

\* Lanthanide series

\*\* Actinide series

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

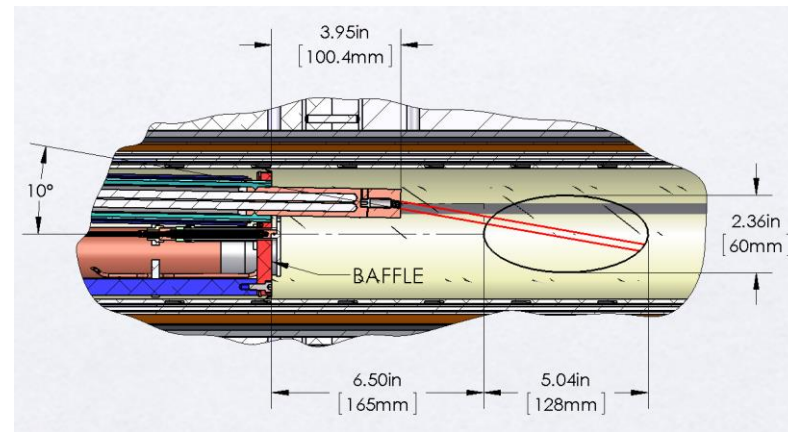
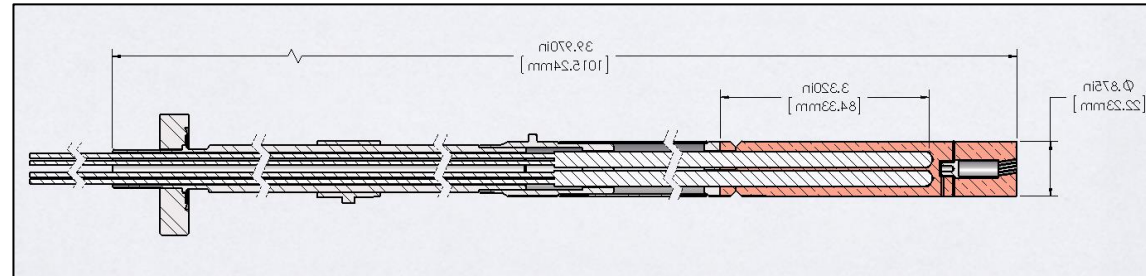
- Temperature for a vapor pressure of  $10^{-2}$  mmHg

  $T < 500$  °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+

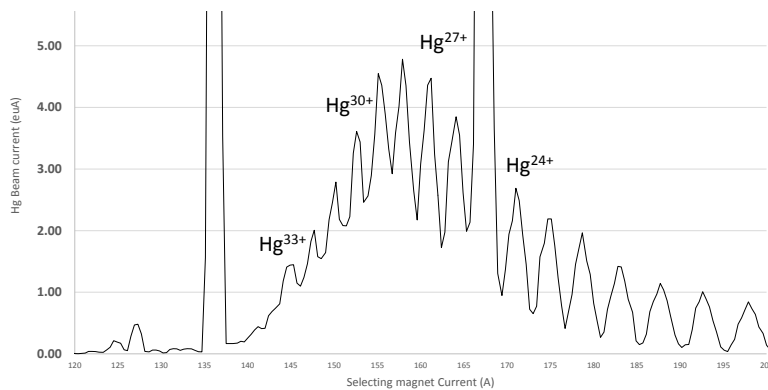
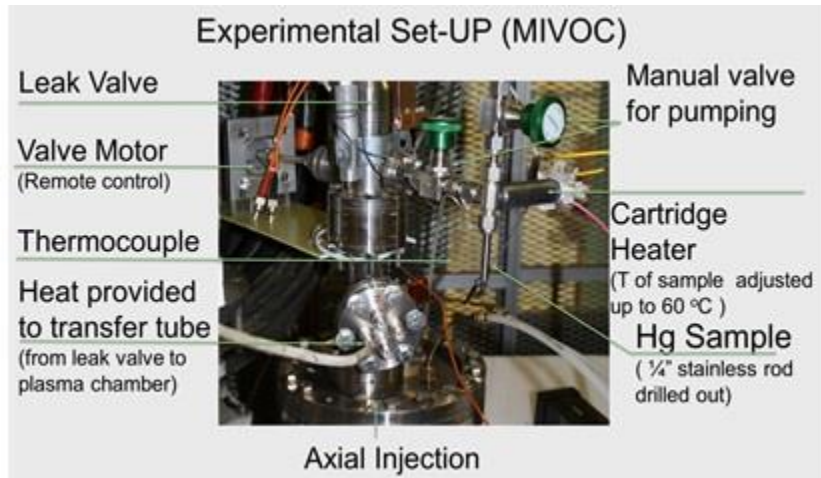


# Challenges for metallic beams

1. Develop high intensity metallic beams ( $> 400 \text{ e}\mu\text{A}$ )
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 ( $>2000 \text{ }^\circ\text{C}$ )
4. Material preparation
  - Conversion of Rare earth element to metal forms (Poster MOPPH019)

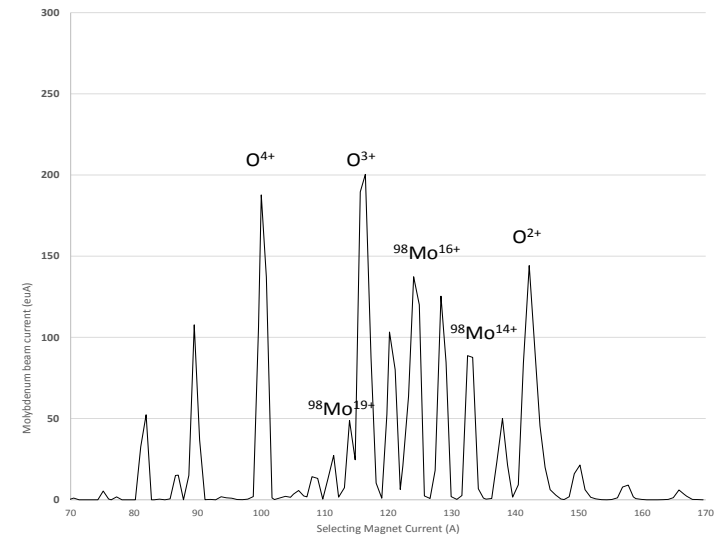
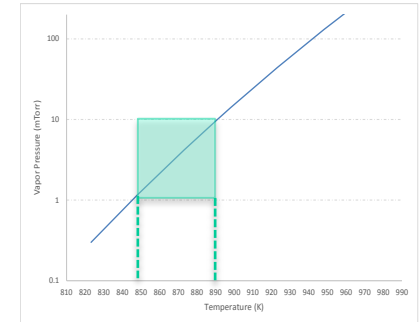
# Recent results with Mercury and Molybdenum

## Natural Hg



## Molybdenum Trioxide (MoO<sub>3</sub>)

- Pure Molybdenum has a Vapor pressure of a few mTorr ~2400 °C
- Molybdenum Trioxide (MoO<sub>3</sub>) 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