Development of Key Technologies for 4th Generation ECRIS: Microwave Launching and Plasma Chamber Cooling

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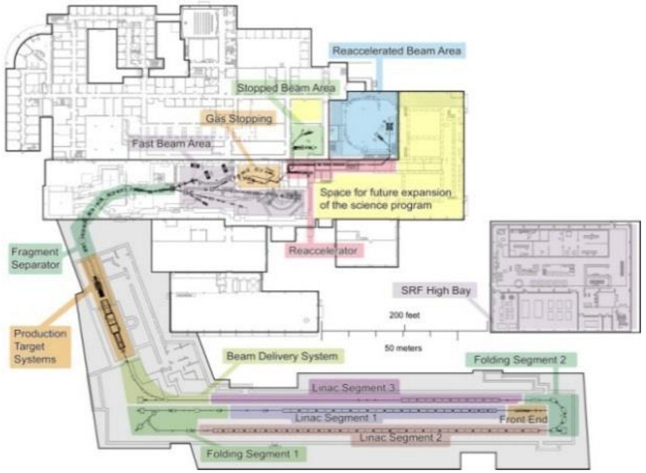
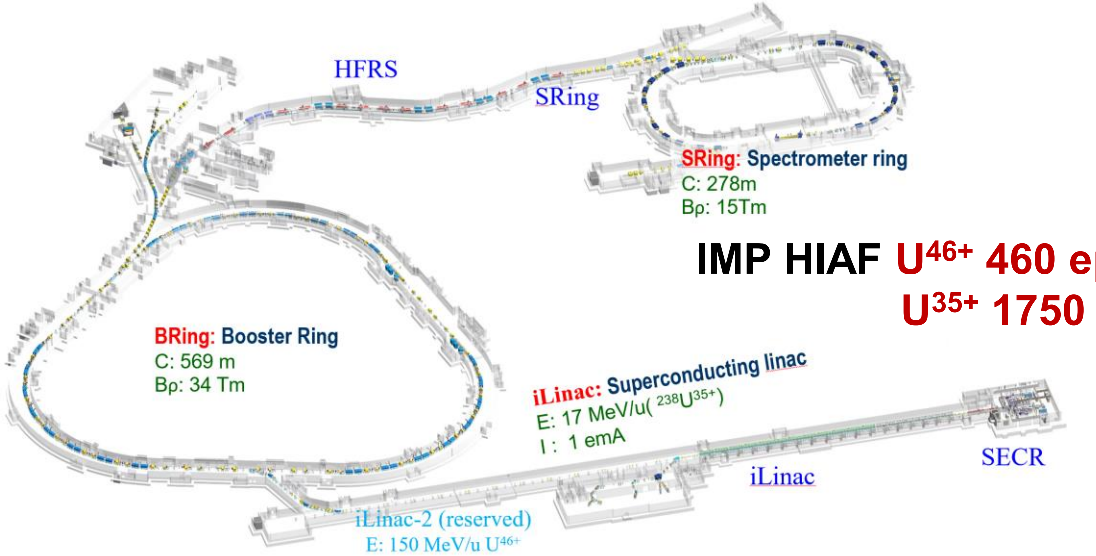
Outline

- Introduction
- Microwave launching
- Plasma chamber cooling
- Status of FRIB 28 GHz ECR ion source
- Summary

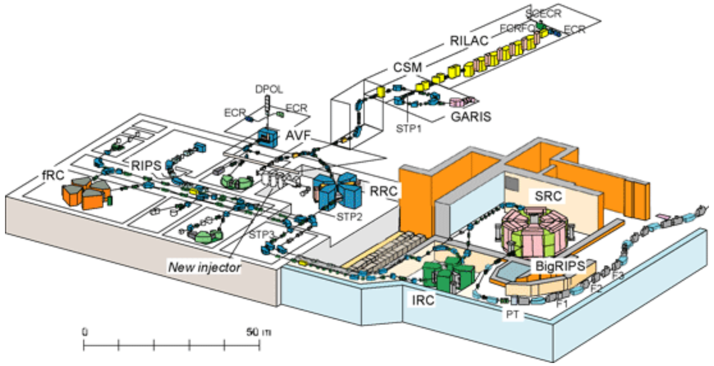
Accelerator Demands For High Charge State Ions Continue To Drive ECR Ion Source Development



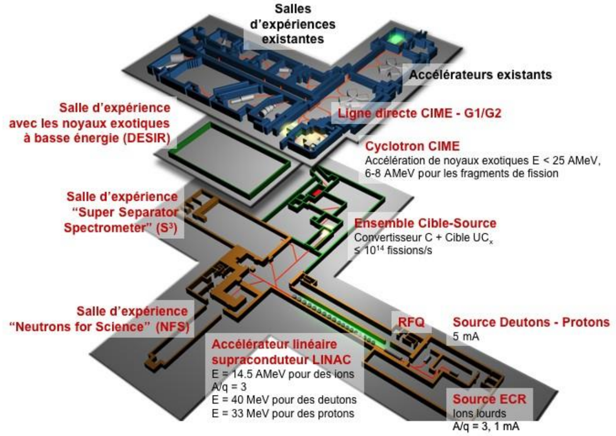
MSU FRIB U^{33+} + U^{34+} 440 eμA/CW



IMP HIAF U^{46+} 460 eμA/CW
U^{35+} 1750 eμA/Pulsed

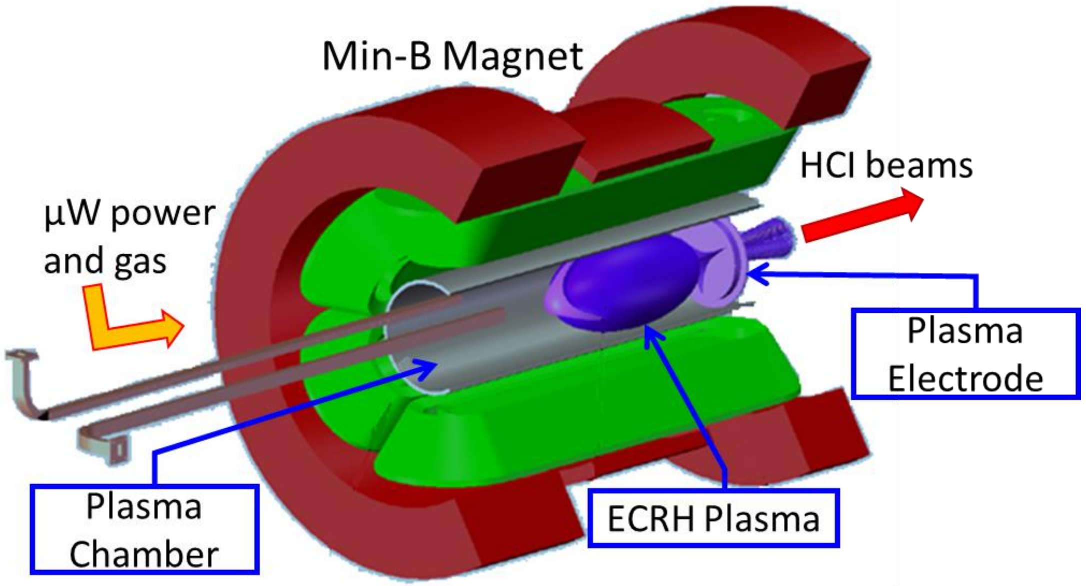


RIKEN RIBF U^{35+} 525 eμA/CW

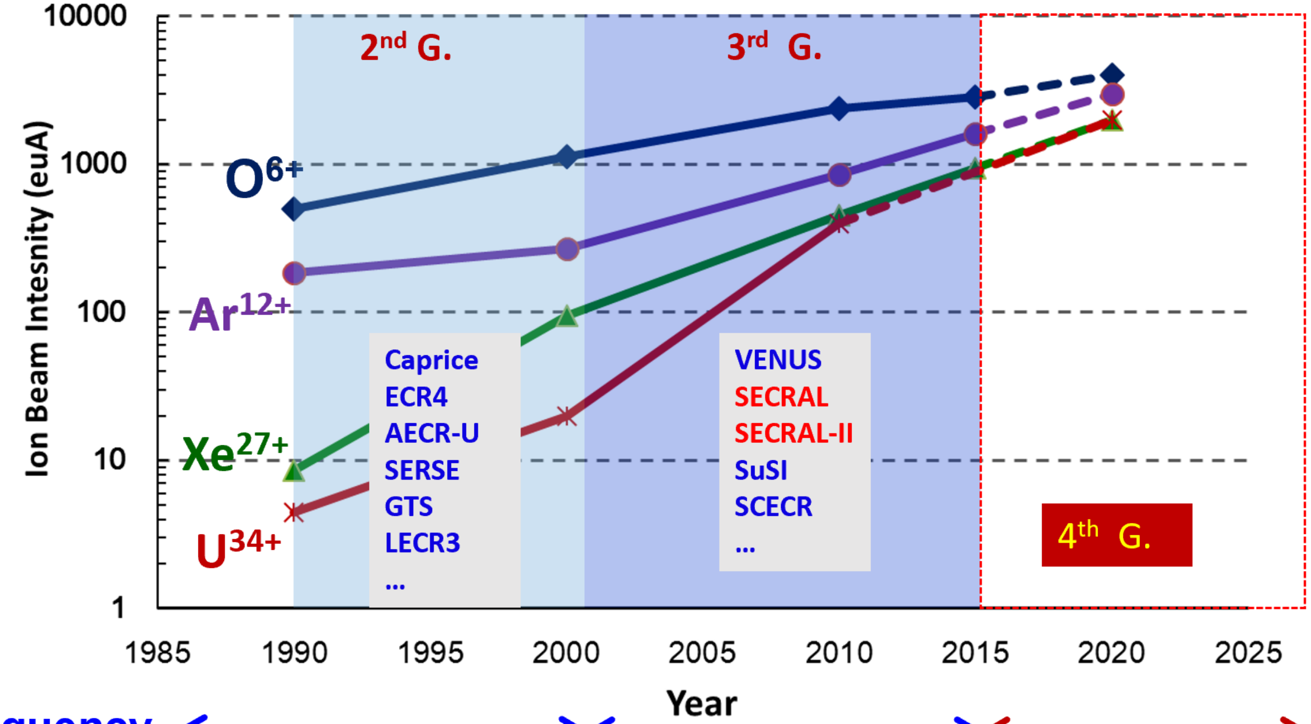


GANIL SPIRAL2 Ar^{12+} 1 emA/CW

ECR Ion Source Evolution



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



Frequency: 6.4~18 GHz | 24~28 GHz | 40~60 GHz

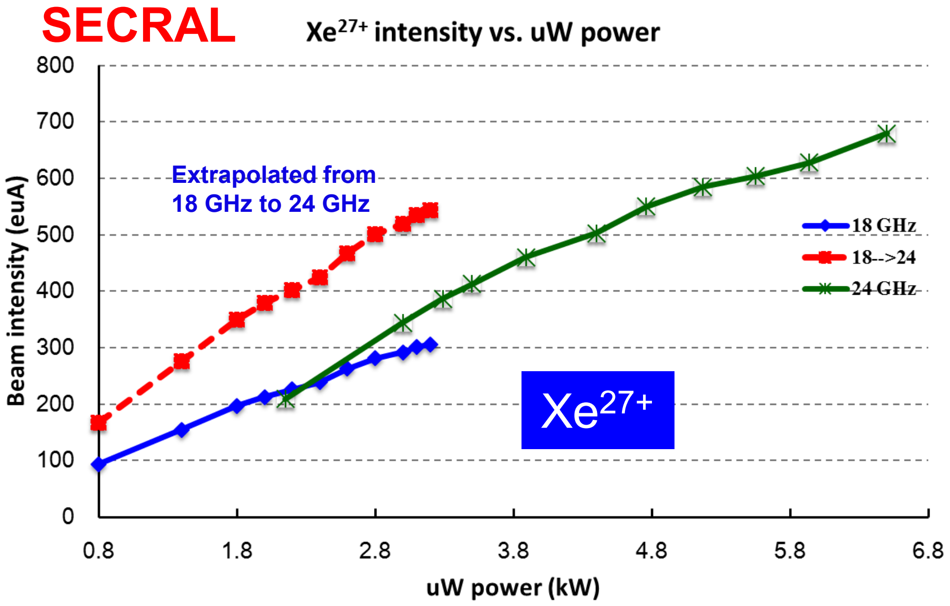
Power: 0.5-2 kW | 5-12 kW | 15-30 kW

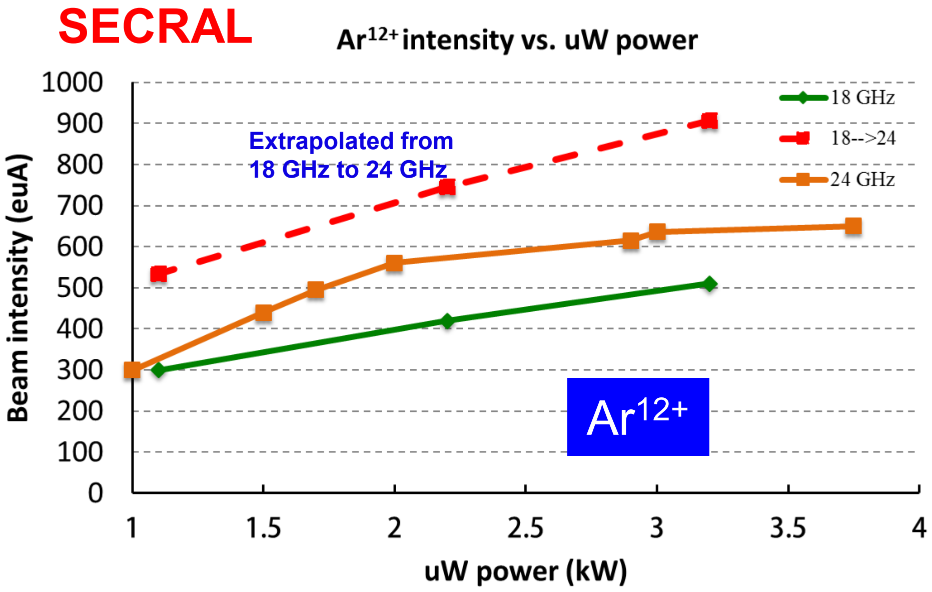
4^{th} Gen ECR Ion Source Challenges

Specs.	Unit	FECR	Challenges
Frequency	GHz	45	◆ High frequency high power microwave coupling ◆ High power chamber cooling
Operational RF Power	kW	20	
B_{ECR}	T	1.6	◆ Reliable high field Nb_3Sn magnet with min-B Field Configuration
B_{rad}	T	≥3.2	
B_{inj}	T	≥6.4	
B_{min}	T	0.5~1.1	
B_{ext}	T	≥3.4	
Plasma Chamber ID	mm	≥140	
Mirror Length	mm	500	
Cooling Capacity@4.2 K	W	≥10.0	◆ Radiation degradation and dynamic heat load
U^{35+}	mA	>1.0	◆ Intense solid material beam production ◆ High afterglow yield and pulse duration
Pulsed Beam Frequency	Hz	0.5~3	
Afterglow pulse width	ms	>2.0	

Liangting Sun, ICFA-Newsletter 73, p34.

3rd Gen ECRIS Microwave Heating Efficiency

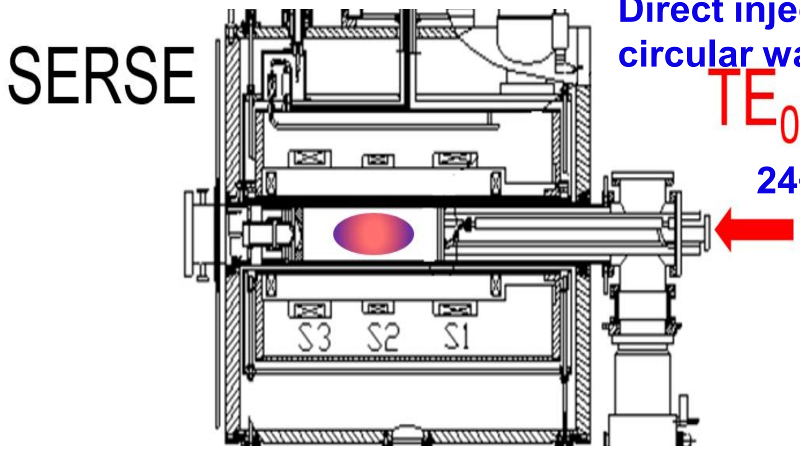




- Gyrotron frequency boosts beam intensities
- Beam intensity tends to saturation
- Frequency effect is limited by something

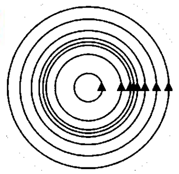
Microwave Coupling Schemes of ECR Ion Sources

Direct injection with circular waveguide



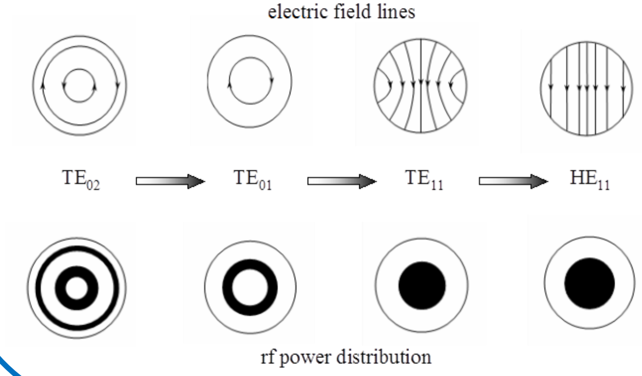
TE01

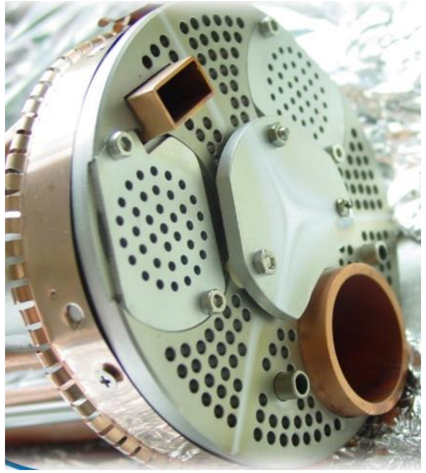
24~28 GHz @TE_{01}

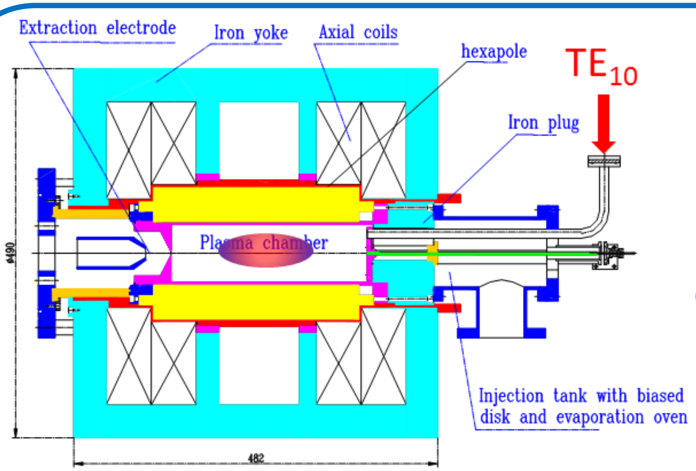


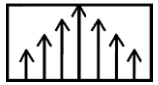
S. Gammino, et al, Rev. Sci. Instrum. 72, 4090 (2001)

D.Hitz ECRIS2006

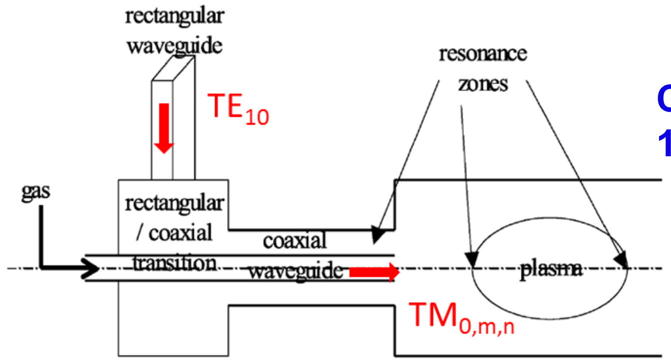








Direct injection with rectangular WG
6.4~18 GHz @TE_{10}

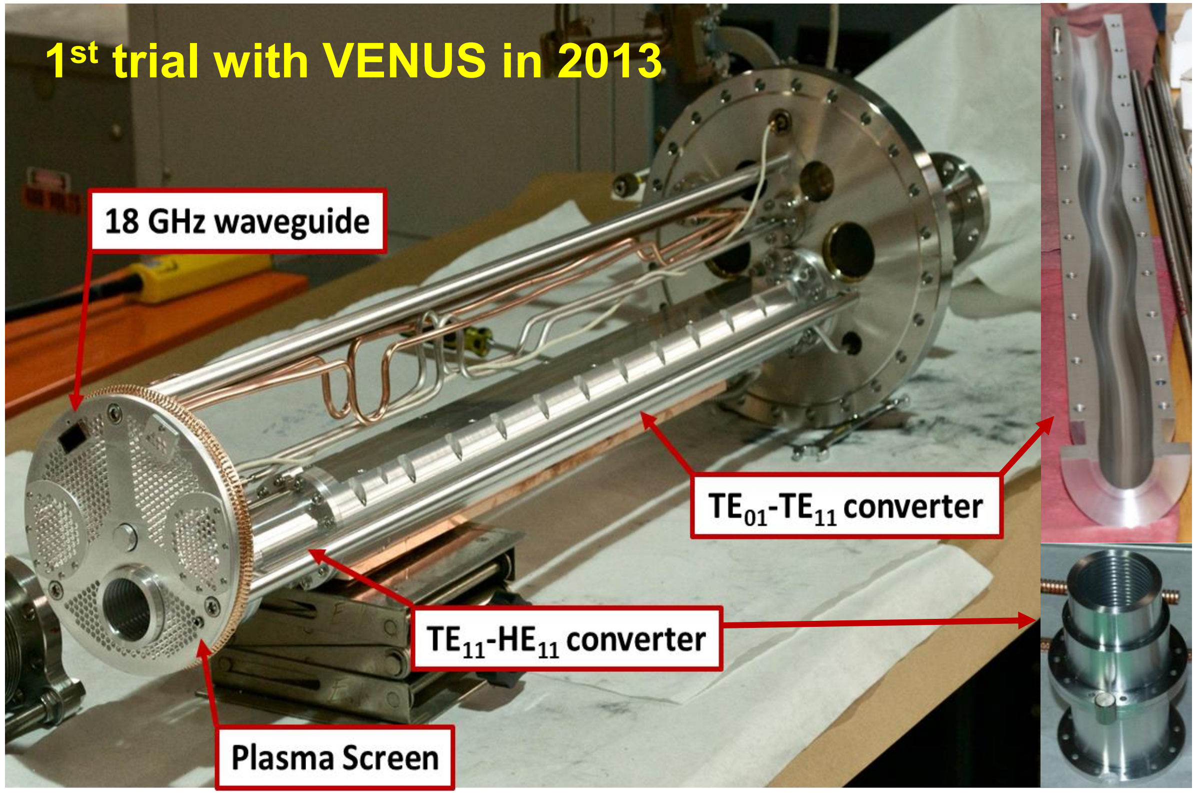


Coaxial coupling
10~14 GHz

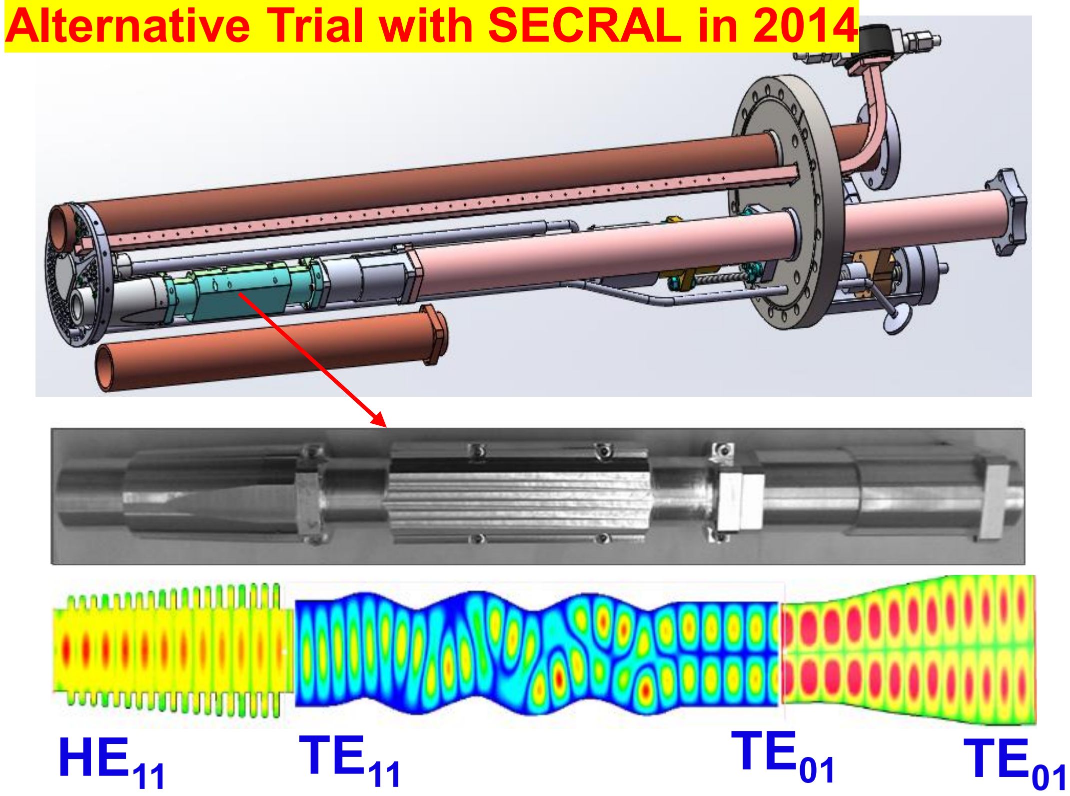
Denis HITZ, Advances in Imaging and Electron Physics, Vol. 144 (2006)

Exploration of Microwave Modes: HE_{11}

- SECRAL injection assembly with taper design, ⌀ 32.6 mm to ⌀ 20 mm
- Flexible choice of injection modes and waveguide diameters



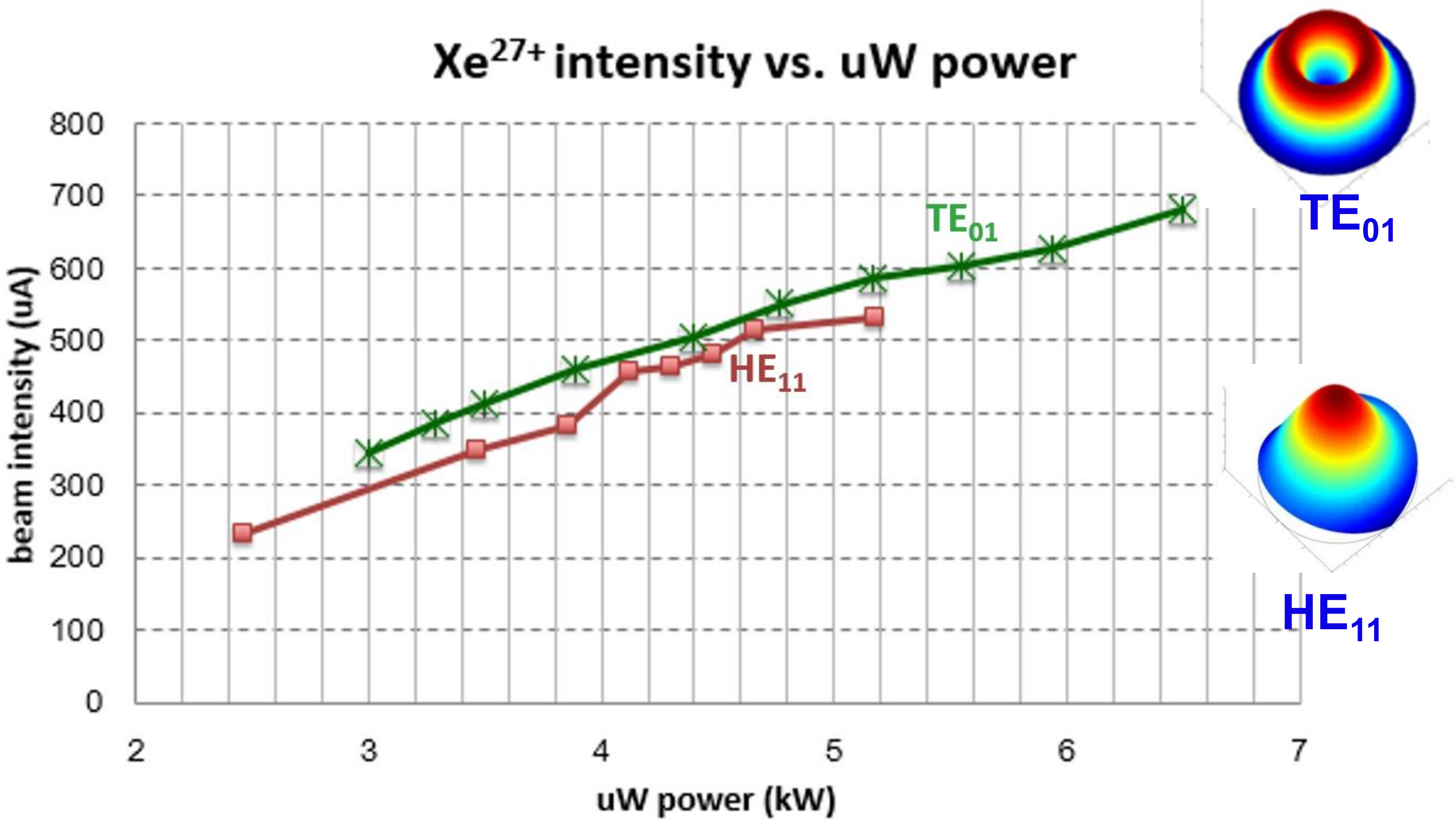
C. Lyneis, et al. Rev. Sci. Instrum. 85, 02A932 (2014).



L. Sun@ICIS'15 *J. W. Guo, et al., Rev. Sci. Instrum. 87 (2016) 02A708*

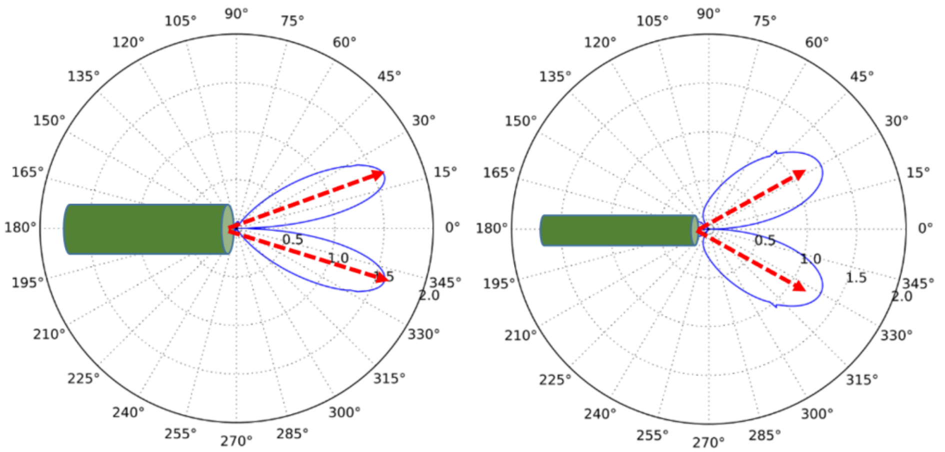
Results of HE_{11} Mode on SECRAL

- HE_{11} did not show any sign of advantage over TE_{01}
- The plasma shows instability and it is difficult to tune source stable when microwave power over 5 kW

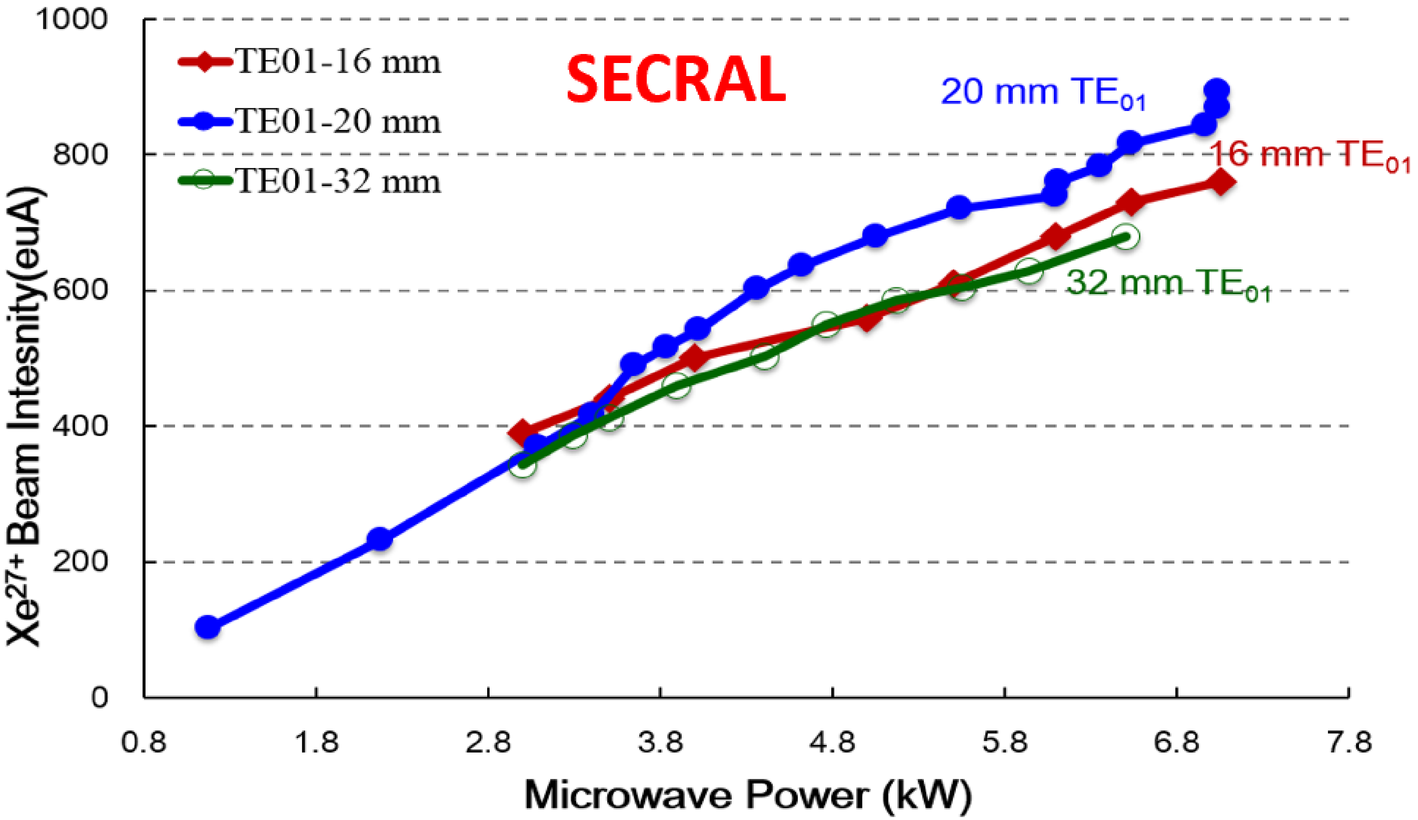


TE_{01} Mode with Different Launcher Diameters

- The key of microwave coupling might be the power distribution on the ECR surface
- Doesn't care about the microwave mode
- But the different modes directly affect the power distribution on the ECR surface



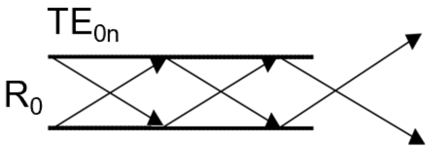
Ø32 mm radiation angle ~ 19 °   Ø20 mm radiation angle ~ 30 °

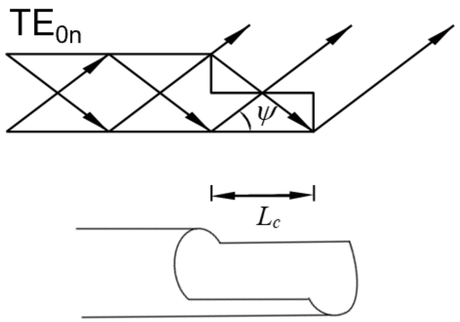


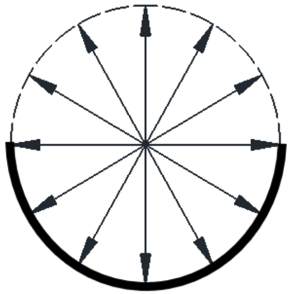
L. Sun, J. W. Guo, W. Lu et al., Rev. Sci. Instrum. 87 (2016) 02A707.

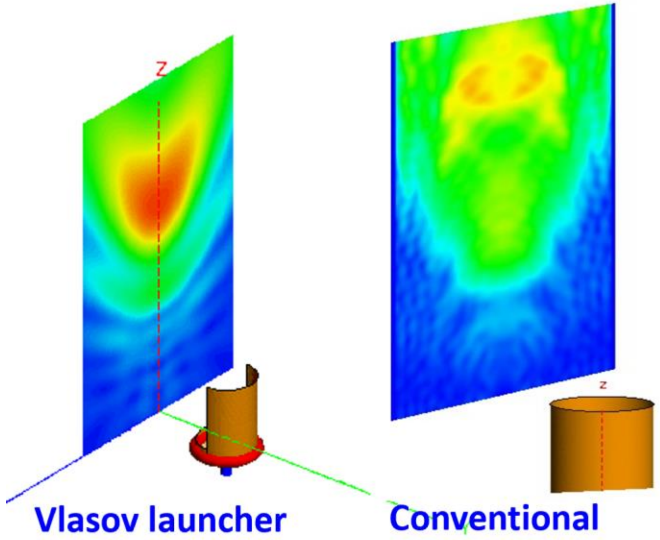
Vlasov Launcher

Geometric optics principles







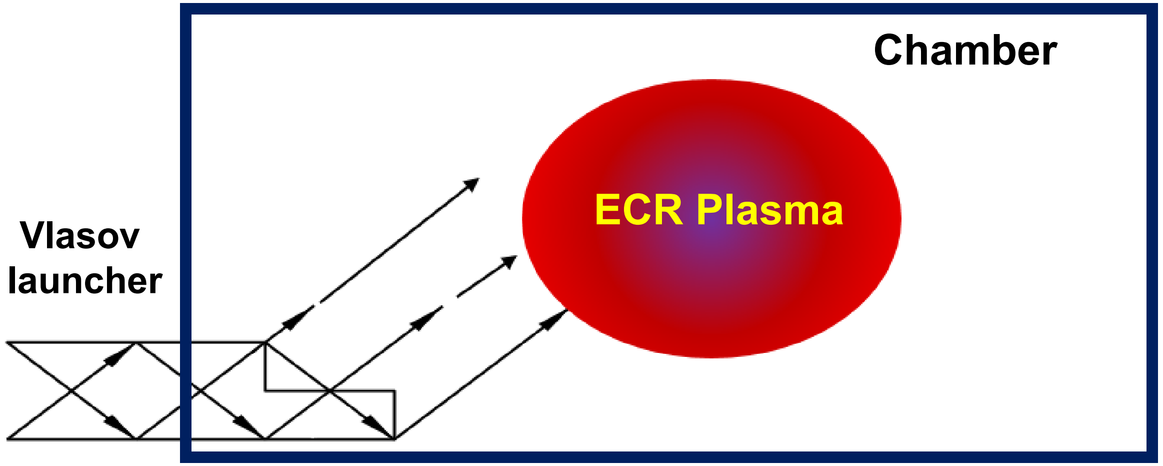


Brillouin Angle $\cos\psi = \frac{\vec{e}_z \bullet \vec{N}}{|e_z| \bullet |N|}$

$$L_c = 2R_0 \cot\psi$$

Advantages:

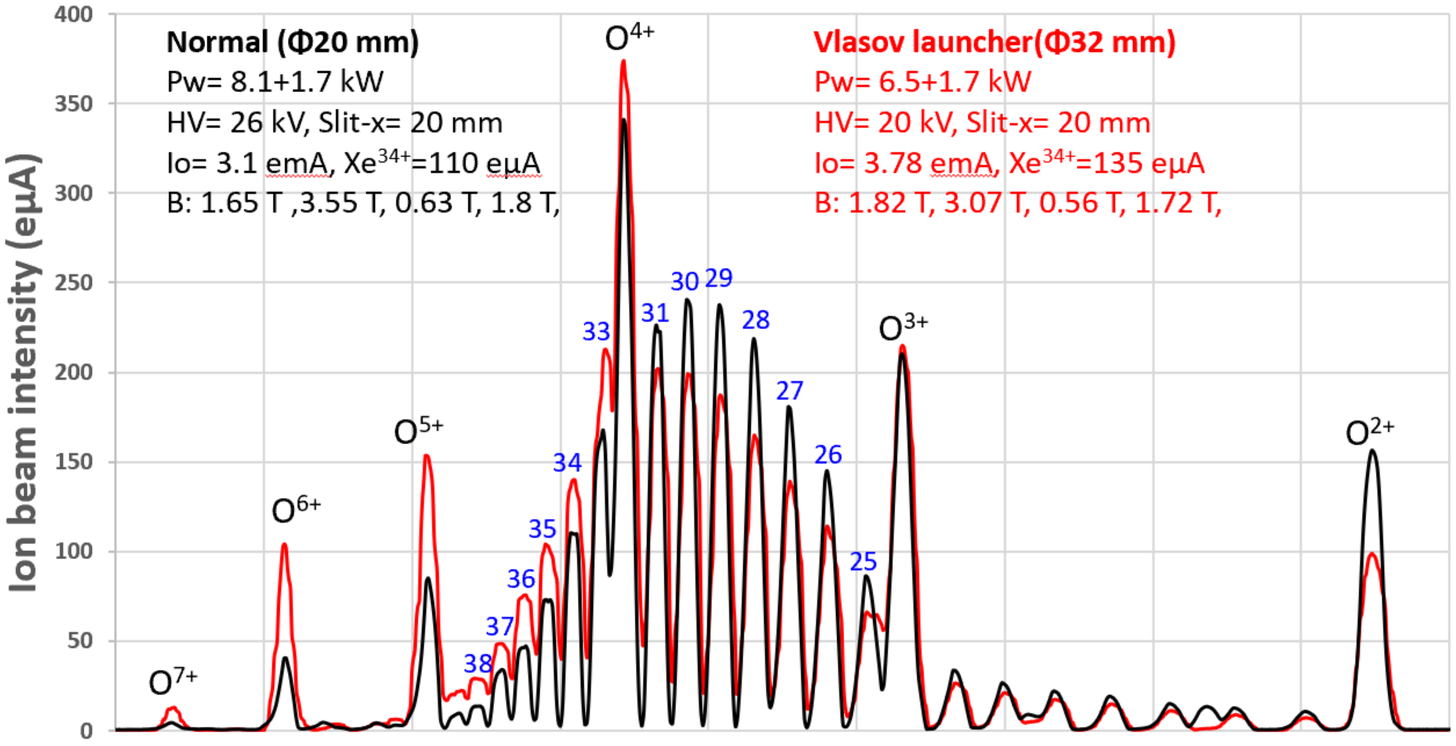
- Change the direction of radiation
- Optimized power distribution
- Low reflection
- Simple structure

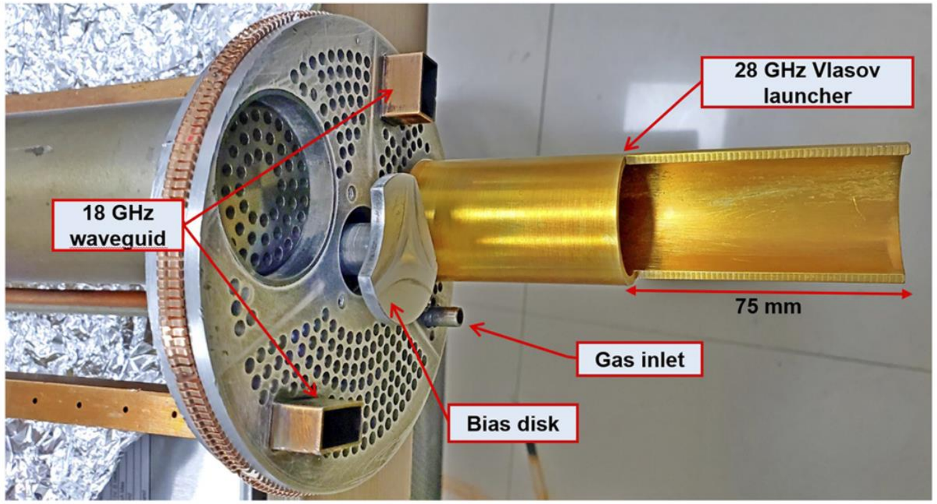


Vlasov S N. Radiophysics and Quantum Electronics,1975,Vol.17,No.1,115-119.
J. Guo, et al. Rev. Sci. Instrum. 91, 013322 (2020).

Source Performance with Vlasov launcher

	Normal (Φ20 mm)	Vlasov launcher (Φ32 mm)	Improvement
$^{129}Xe^{30+}$	322 eμA @(8+1.1 kW)	365 eμA @(7.5+1.7 kW)	**13.3 %**
$^{129}Xe^{34+}$	110 eμA @(8+1.7 kW)	135 eμA @(6.5+1.7 kW)	**22.7 %**

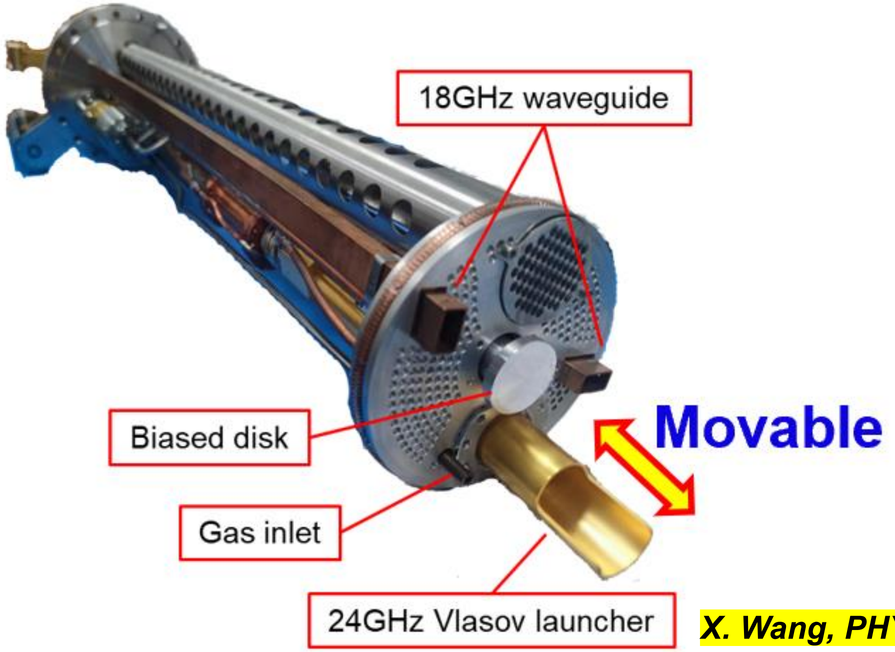




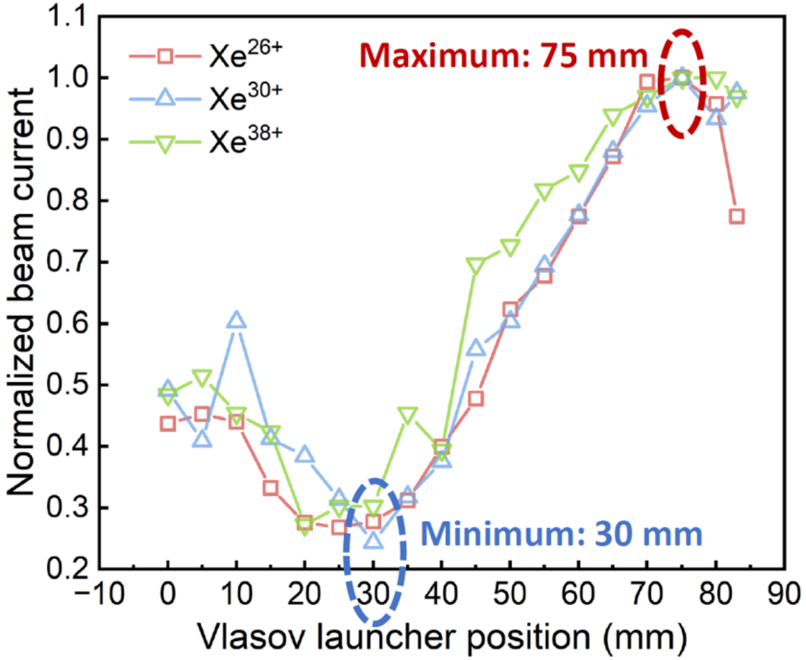
J. Guo@ICIS'19

Movable Vlasov launcher for Online Manipulation of Microwave Power Distribution

- Fine tuning to microwave ECR heating
- Recorded beam intensities production：
  - **18 eμA Xe^{42+}、47 eμA Xe^{38+}、**
  - **146 eμA Xe^{34+}、374 eμA Xe^{30+}**



4.5 (24 GHz) + 0.5 (18 GHz) kW, beam intensity Vs. Vlasov Position



- Beam intensity with different charge state shows the same variation trend.
- Max beam intensity / Min beam intensity is up to 4~5.

X. Wang, PHYS. REV. ACCEL. BEAMS 27, 083401 (2024)

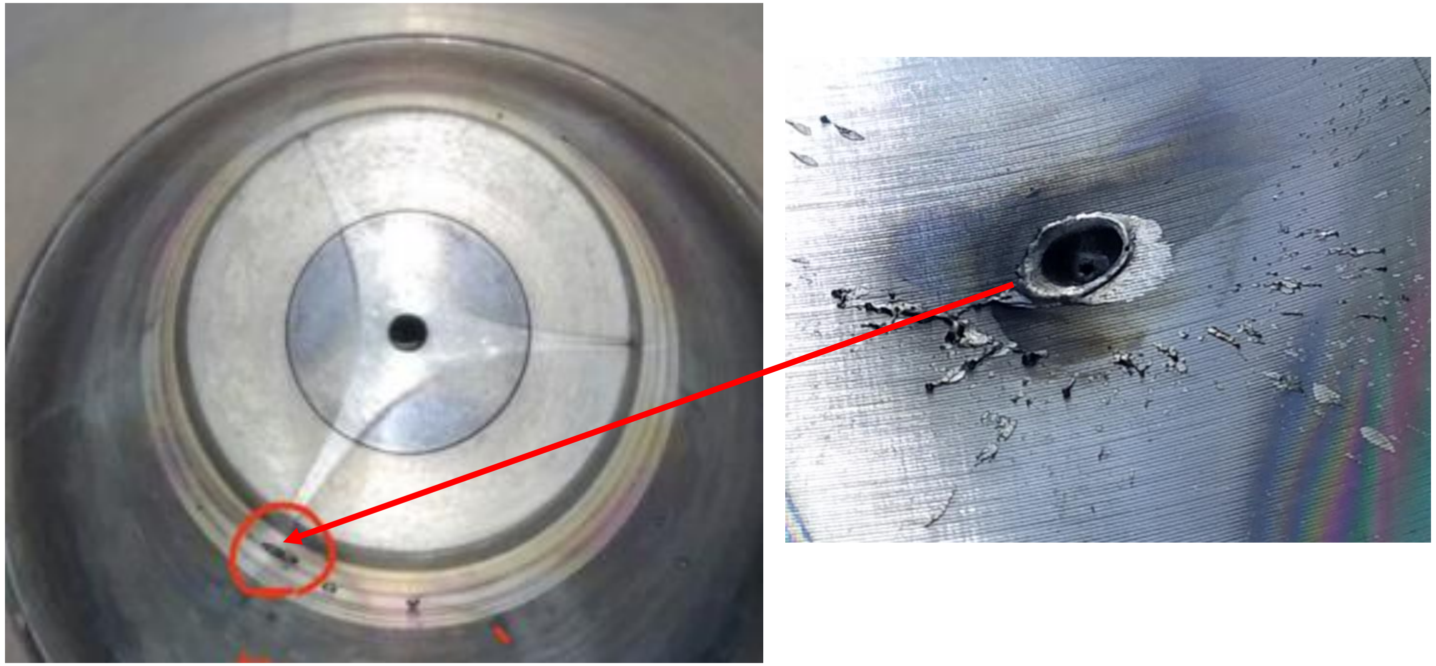
See J.B. Li's talk **on Thursday**

SECRAL Source Performance Improvement

	SECRAL 24 +18 GHz TE_{01}-32 mm (eμA)	SECRAL 24 +18 GHz TE_{01} -ø 20 mm (2015~2019) (eμA)	Improvement	SECRAL 24 +18 GHz Vlasov launcher (2023) (eμA)
Ar^{11+}		1620		
Ar^{12+}	1030	1420	**1.38**	
Ar^{14+}	506	846	**1.67**	
Ar^{16+}	182	350	**1.91**	
Ar^{17+}		50		
Xe^{26+}		1100		
Xe^{27+}	700	920	**1.31**	
Xe^{30+}	235	322	**1.37**	**374**
Xe^{34+}		120		**146**
Xe^{35+}	45	90	**2**	

Plasma Chamber Burnout at High Power Operation

- Plasma chamber cooling has become a serious bottleneck for high power operation (> 5 kW)



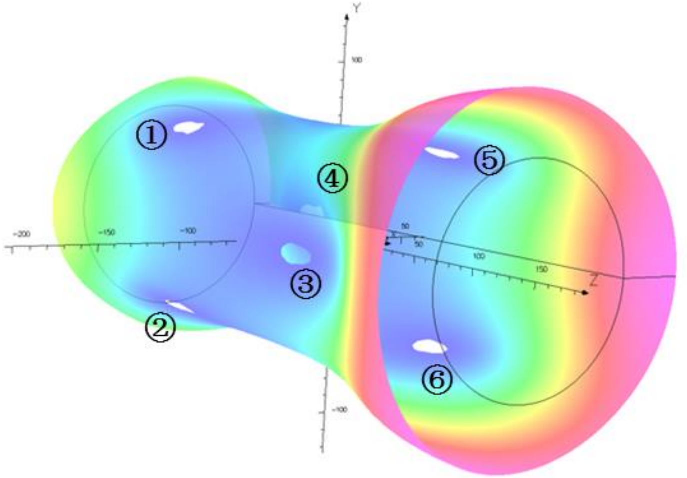
Chamber burnt with SECRAL-II at 7 kW

Chamber burnt with VENUS

（D. Z. Xie @ECRIS2016）

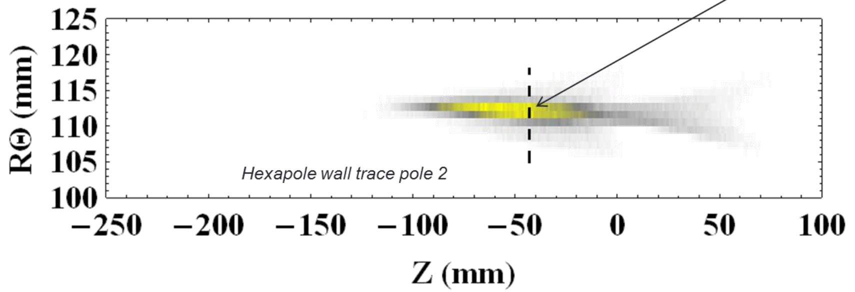
Origin of Plasma Chamber Burnout in ECRIS
Mini-B Structure Cause Six Hot Spots at Magnetic Field Weak Points

- Very high heat flux on the six hot spots- 1 kW μW~1.25 MW/m^2 heat flux



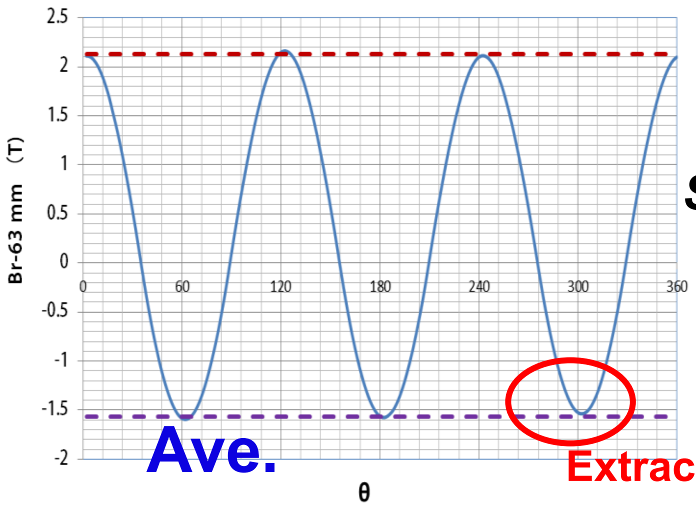
	Surface (cm^2)	Power deposited (W)	Peak Power density (MW/m^2)
Injection	1.3	73	3.4±0.1
Extraction	18.2	425	4.6 ±0.1
Pole 1	23.2	546	1.6±0.1
Pole 2	22.0	754	3.0±0.1
Pole 3	23.9	604	2.0±0.1
Pole 4	19.7	591	3.1±0.1
Pole 5	21.6	449	1.3±0.1
Pole 6	19.3	558	2.6±0.1
total	149.2	4000	

P=4 kW, 1x1 mm^2 pixel



T. Thuillier, et al., Rev. Sci. Instrum. 87, 02A736 (2016)

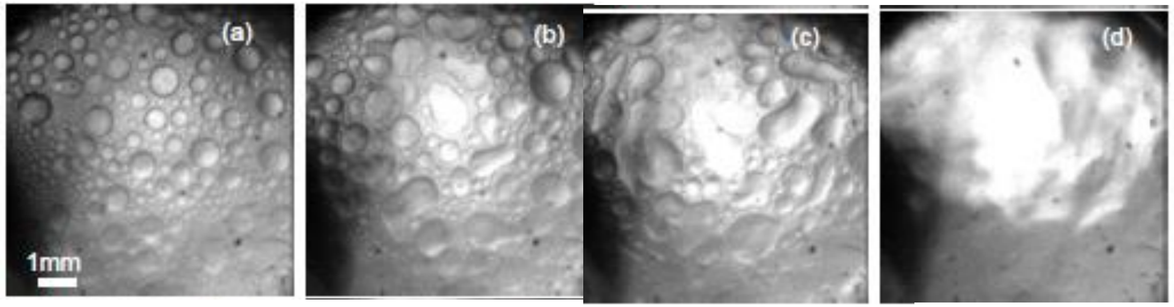
- Magnetic field deviation can cause deterioration at a certain point
  - Differences in sextupole fields
  - Misalignment of sextupole poles

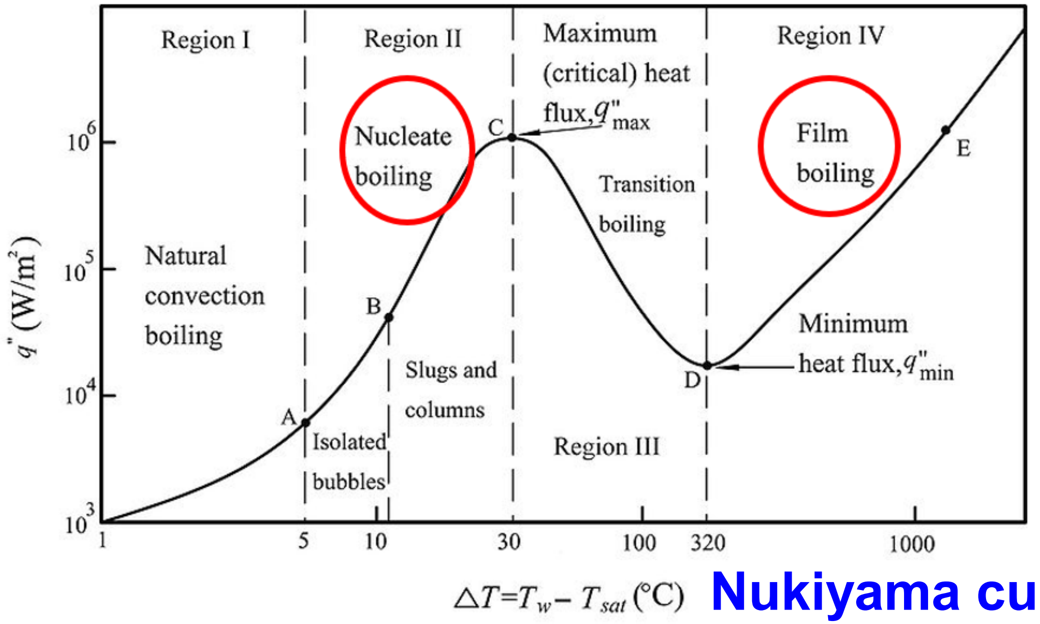


SECRAL-II

Plasma Chamber Burnout
Transition from Nucleate Boiling to Film Boiling

- Plasma chamber burnout process
  a. Bubble accumulation along with rising heat flux
  b. Localized drying on the surface
  c. Rapid surface Temp. increase
  d. Material yield strength decreases at high temperatures
  e. High-pressure water bursts through the inner chamber wall.



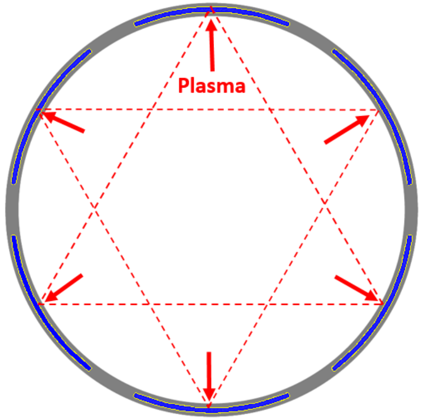


Nukiyama curve for Pool boiling

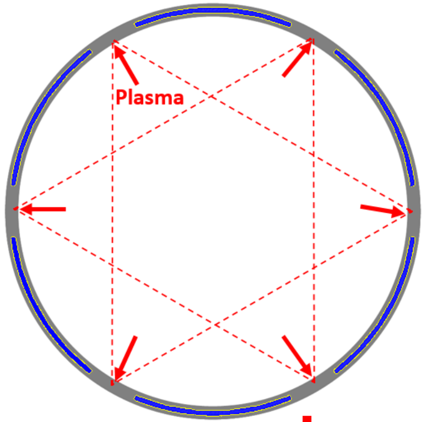
Early Exploration of Cooling Structures to Enhance Heat Transfer (2015~2019), Chamber Burned Out at 5~8 kW

a. Plasma flux to the water channel b. the solid aluminum (rotating 30° of the chamber)

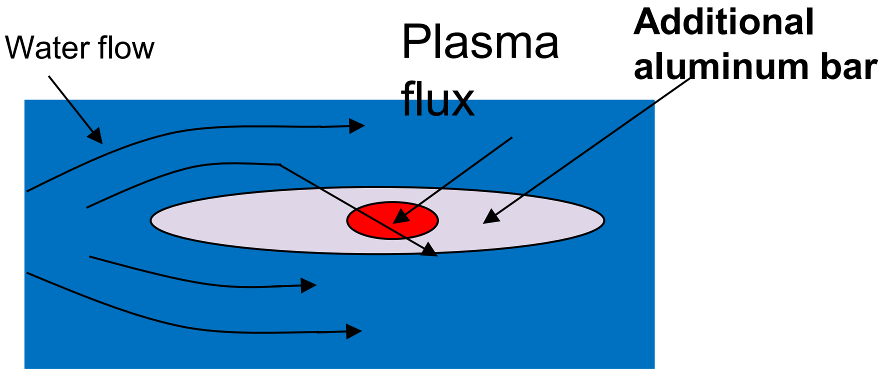
c. Plasma flux to the additional solid bar



a



b



c

Micro-channel Cooling Structure

- Using micro-sized flow channels to enhance heat transfer.
- It has been widely applied in high-power semiconductor electronic devices.

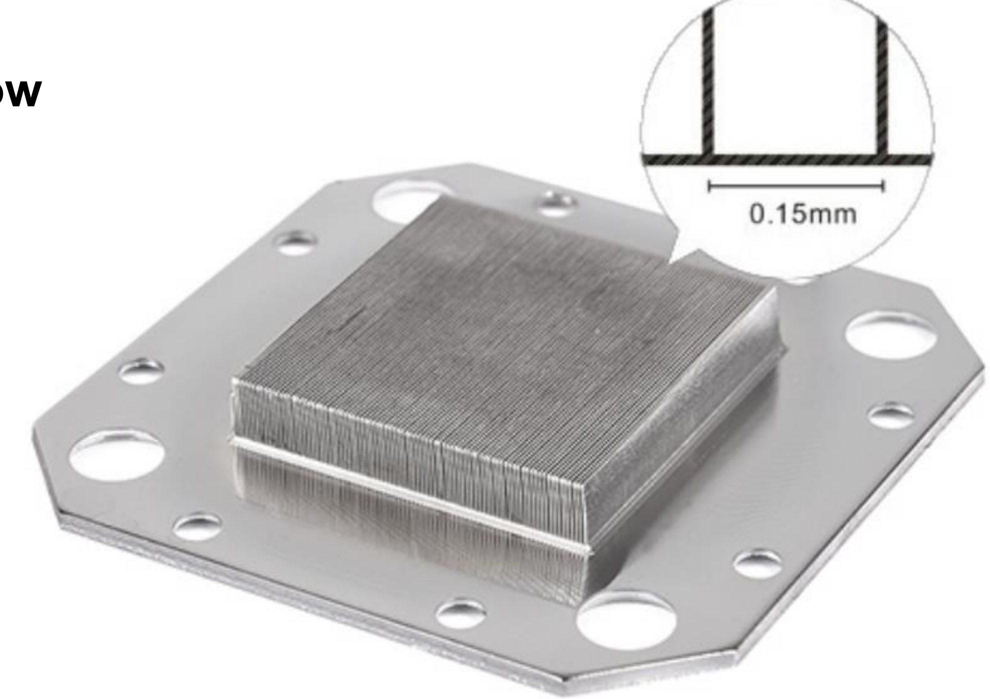
Advantages:

- **High heat exchange efficiency (~ kW/cm^2)**
  - **High flow velocity achieves violent tumultuous flow**
  - **Large specific surface area**
- **Small size and acceptable pressure drop**

$$P = h(T) \times S \times \Delta T$$

Power (P); *Surface* ↑ (S); *Heat exchange coefficient* ↑ ($h(T)$); *Temperature difference Between water and metal* (ΔT)

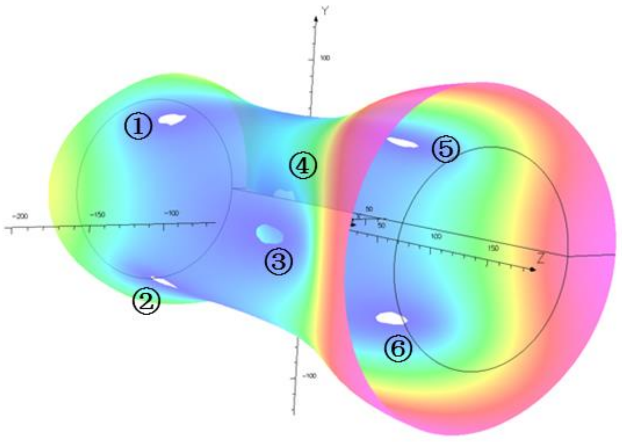
Microchannel：D< 1 mm

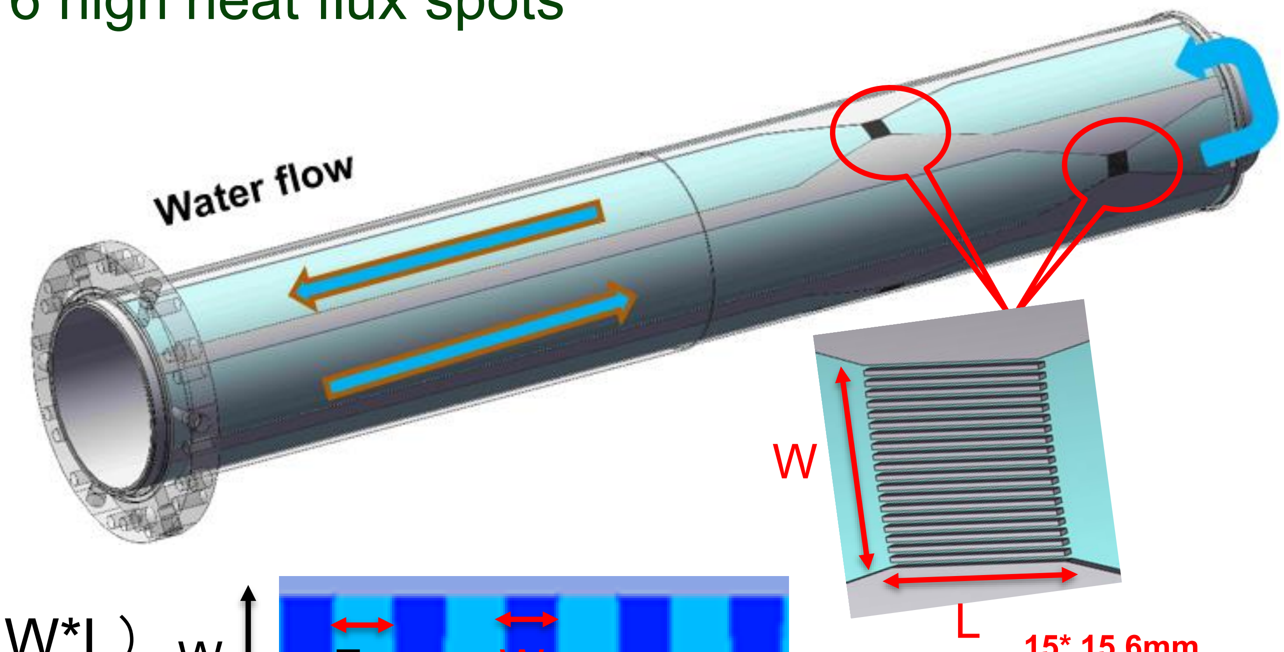


D.B. Tuckerman, IEEE Electron Dev.Lett.EDL-2(5)(1981)126-129.

Micro-channel Cooling Plasma Chamber Design

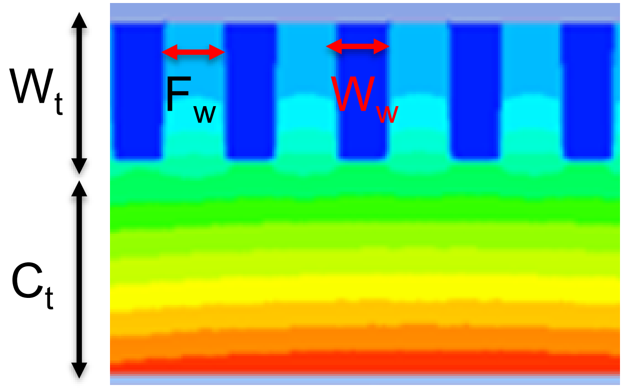
- The microchannel structure is set up in the 6 high heat flux spots





15* 15.6mm
Fins: 0.4 mm*19
Channel: 0.4 mm *20

- Parameters that need to be optimized
  - Overall size of the microchannel region（W*L）
  - Fin width: F_w
  - Water channel width: W_w
  - Water channel thickness: W_t
  - Chamber wall thickness: C_t

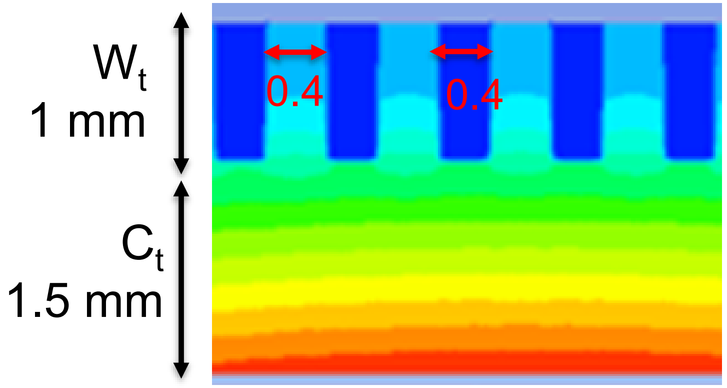


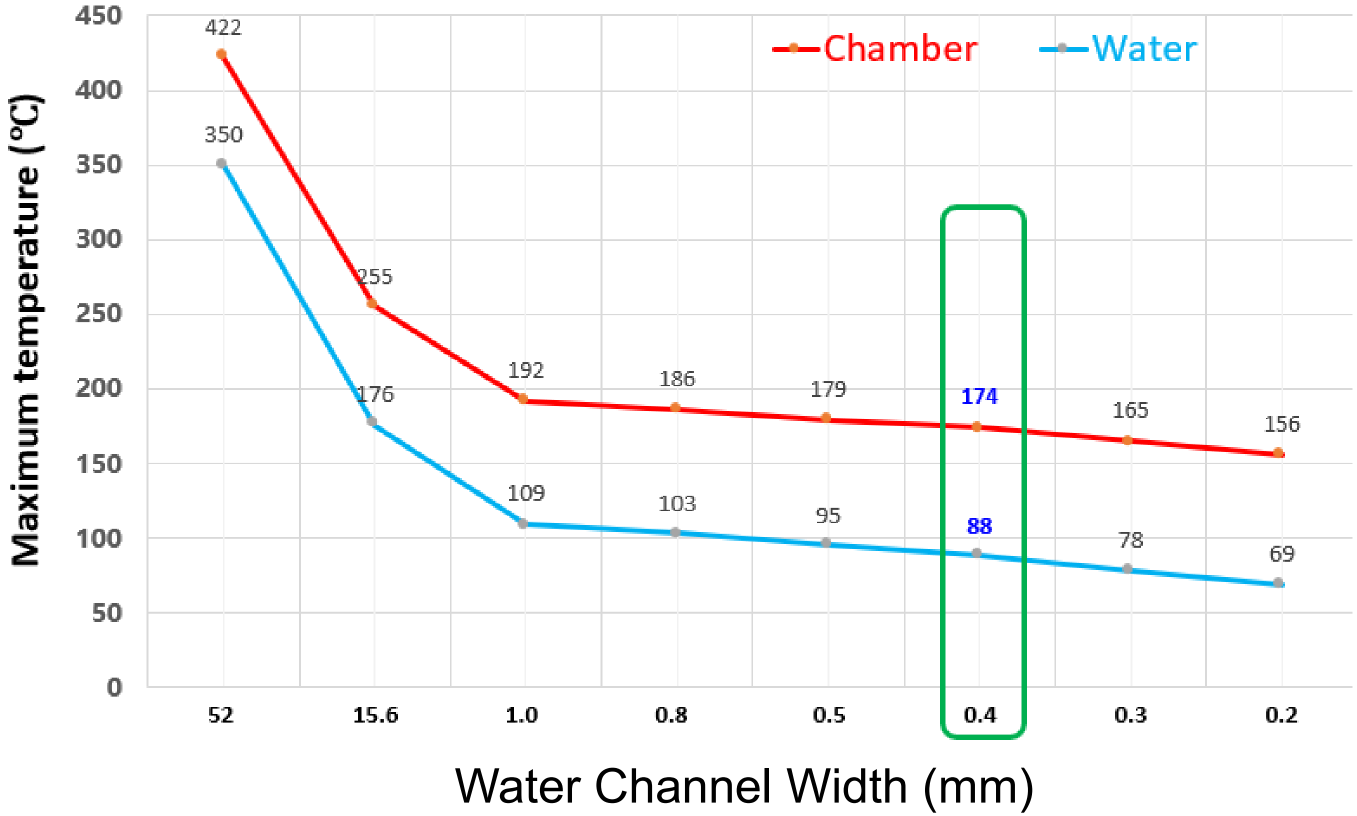
J. W. Guo's talk @ECRIS 2020

Analysis: Water Channel Width of the Micro-channel

- Analysis condition
  - Uniform power density distribution 1 kW/cm^2, Surface: 100 mm² （⌀ 11.28 mm), Total power : 1 KW
  - Al 6061-T6, Flow rate: 7 L/min, Chamber wall thickness: 1.5 mm, Channel thickness：1 mm

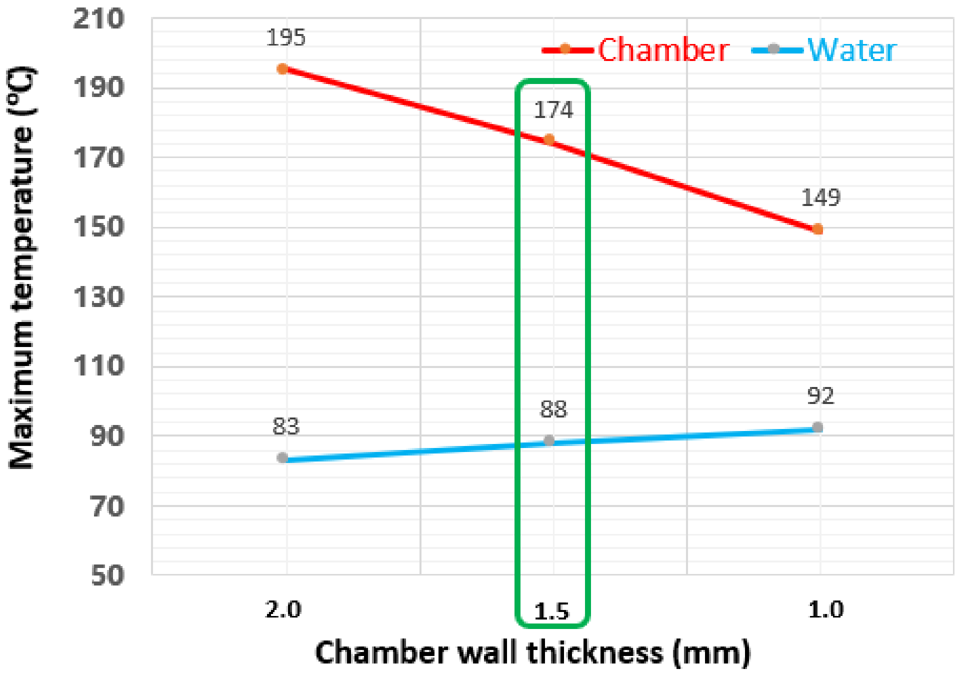
- Considering performance and machining costs, a 0.4 mm micro channel was selected.

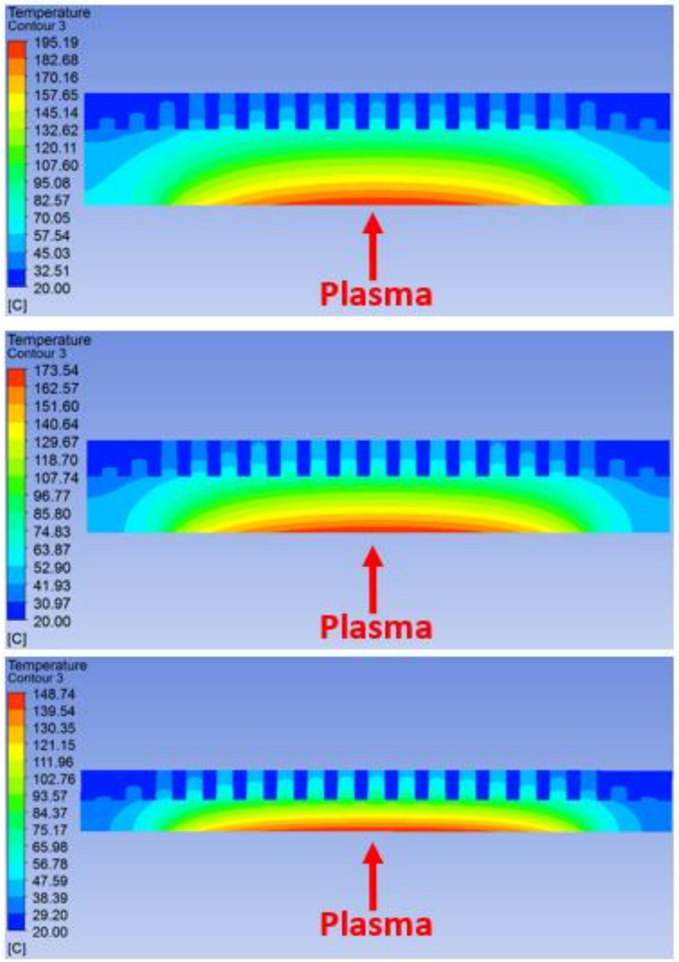




Analysis: Chamber Wall Thickness

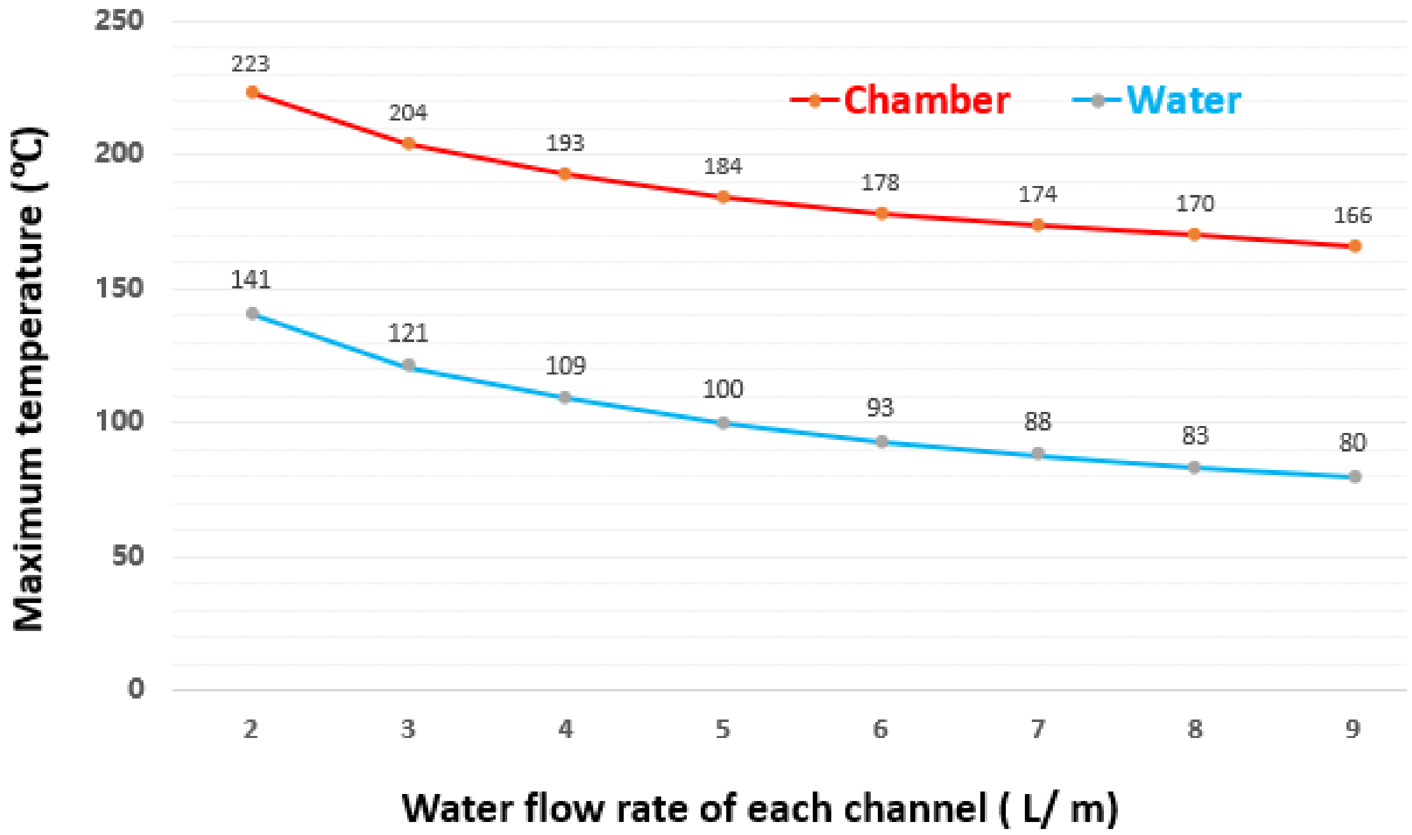
- Analysis condition
  - Uniform power density distribution 1 kW/cm^2, Surface: 100 mm^2 （⌀ 11.28 mm), Total power : 1 KW
  - Al 6061-T6, Flow rate: 7 L/min, Channel thickness：1 mm
  - Microchannel: 0.4 mm *20





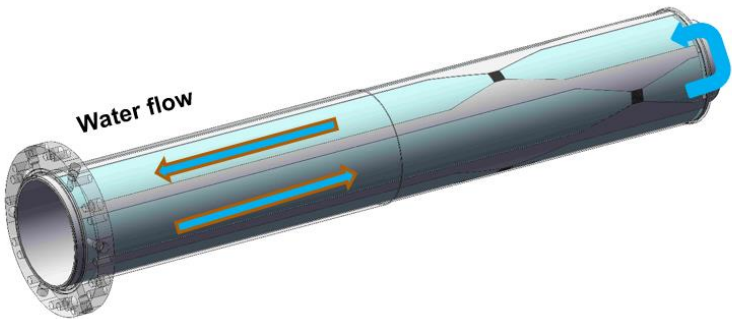
Analysis: Water Flow Rate

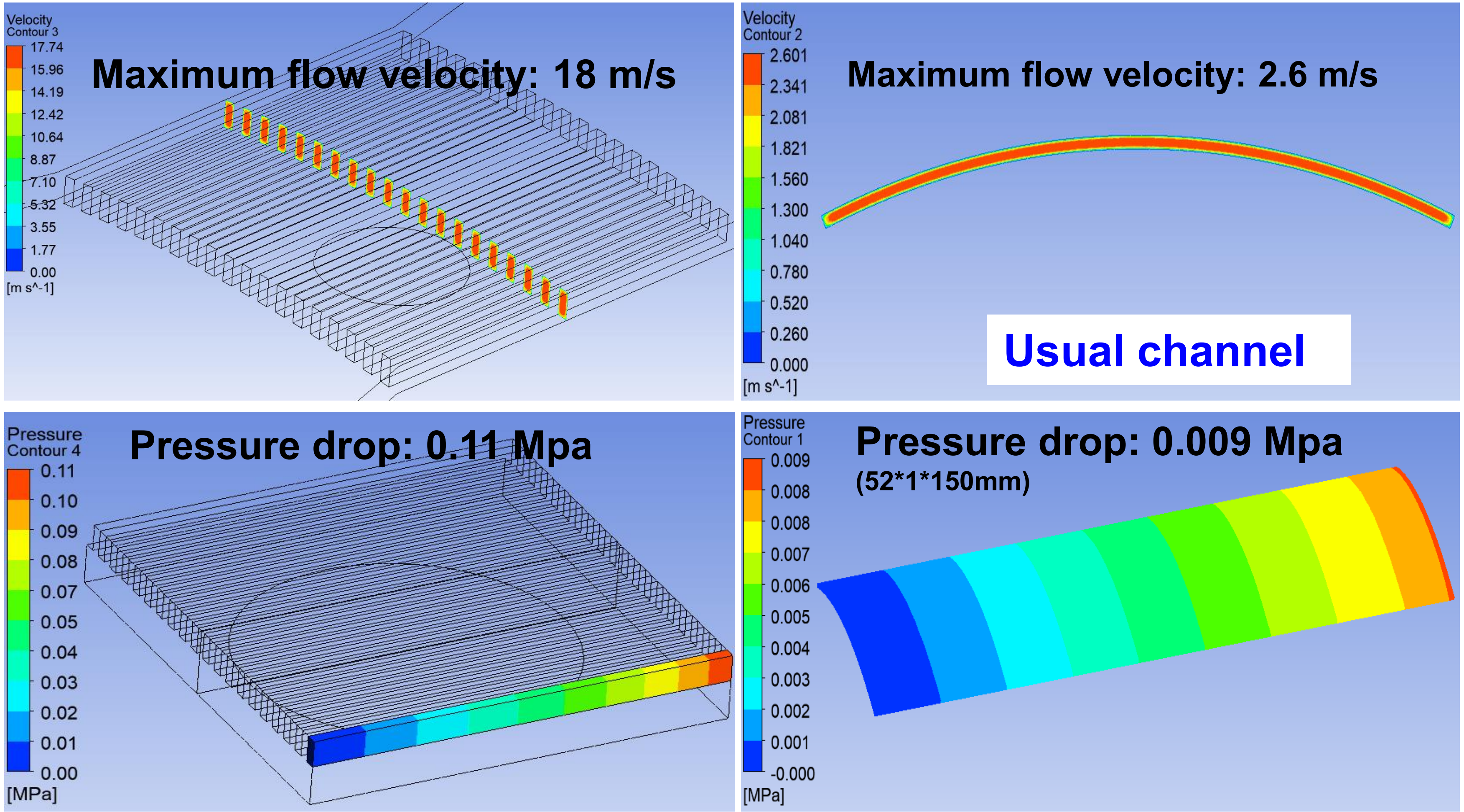
- Analysis condition
  - Uniform power density distribution 1 kW/cm^2, Surface: 100 mm^2 (⌀ 11.28 mm), Total power : 1 KW
  - Al 6061-T6, Chamber wall thickness: 1.5 mm, Channel thickness：1 mm
  - Microchannel: 0.4 mm *20



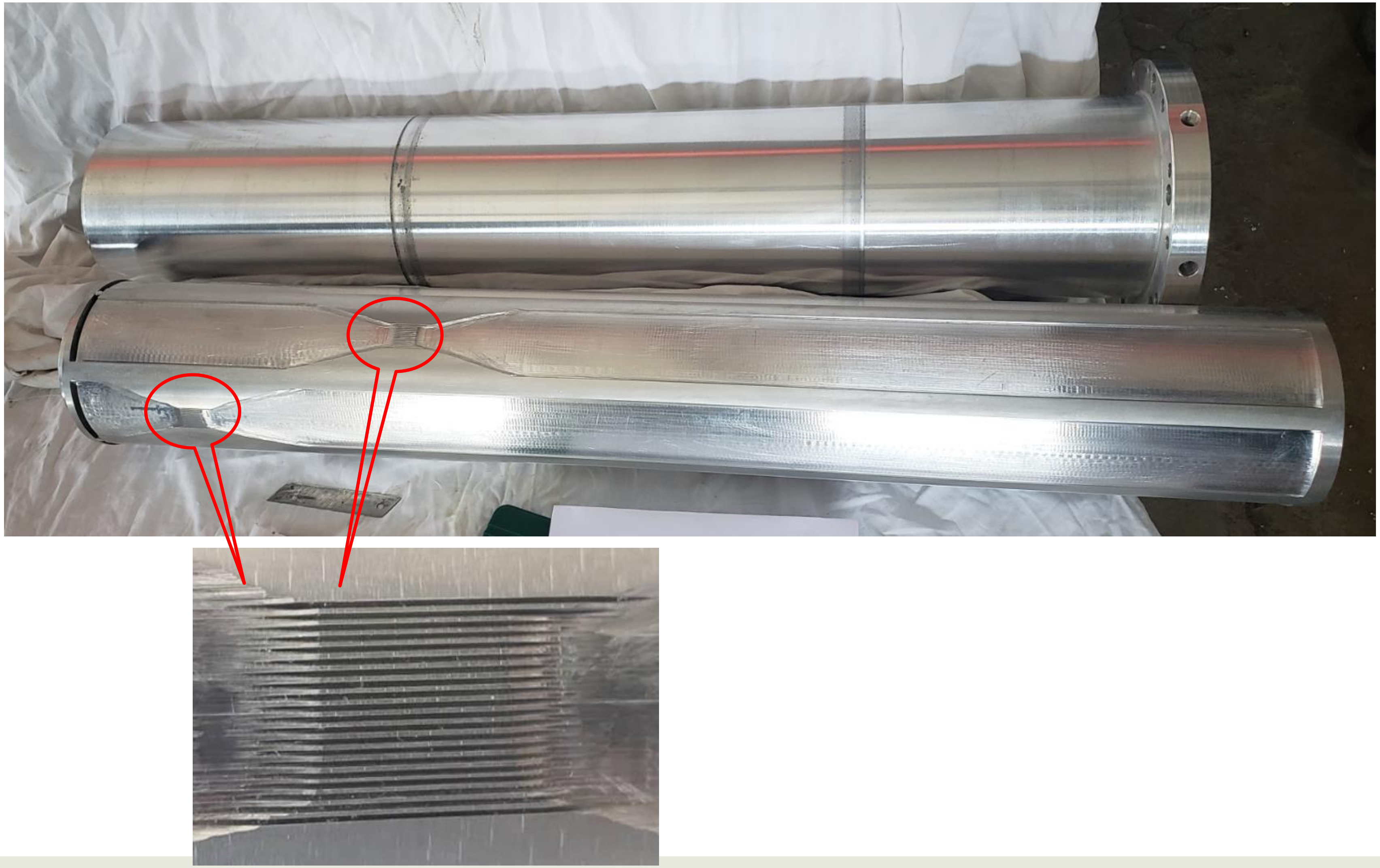
Analysis: Water Pressure Drop & Flow Velocity

- Microchannel: 0.4 mm *20, Channel thickness：1 mm
- Flow rate: 7 L/min





Plasma Chamber with Microchannel Cooling



Plasma Chamber Fabrication

Shrink Fit of the Inner Tube and Outer Sleeve to Prevent local Short Loops

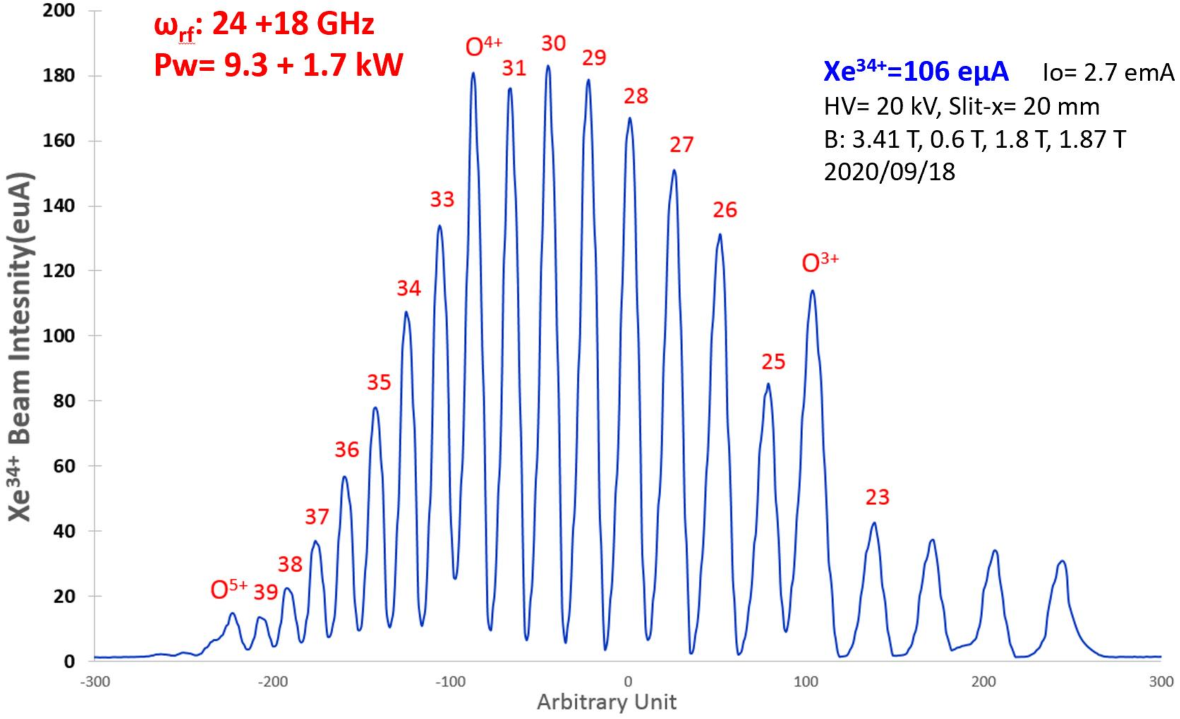
- The shrink-fit assembly of the inner tube and outer sleeve ensures the independence of each water channel, preventing local short loops.
- Immerse the inner tube in liquid nitrogen and heat the outer sleeve to ~ 200 ℃.

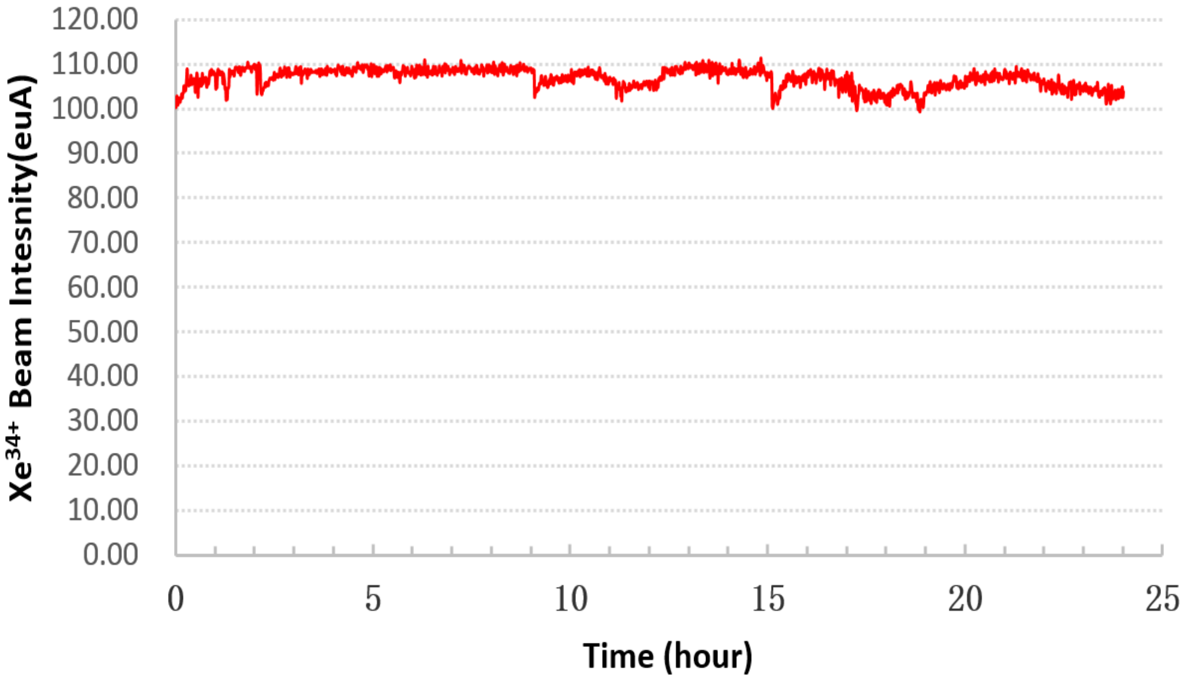
Comparison of Flow Rate Tests for Two Chambers

	Water pressure (bar)	Flow Rate (L/m) Only open channel A			Flow Rate (L/m) Only open channel B			Flow Rate (L/m) Only open channel C			All three channels are open		
		A	B	C	A	B	C	A	B	C	A	B	C
Chamber- #1 (No Shrink Fit)	9	5.4	6	3.8	3.2	5.3	5	6	3.5	4.2	8	6.7	6.8
Chamber- #2 (Shrink Fit)	9	17.6	< 1	< 1	< 1	11	< 1	< 1	< 1	12.4	5.5	4.5	4.5

Test in 2020 Demonstrated its Reliability at High Power

- Reliable operation at total power 11 kW for more than 48 hours



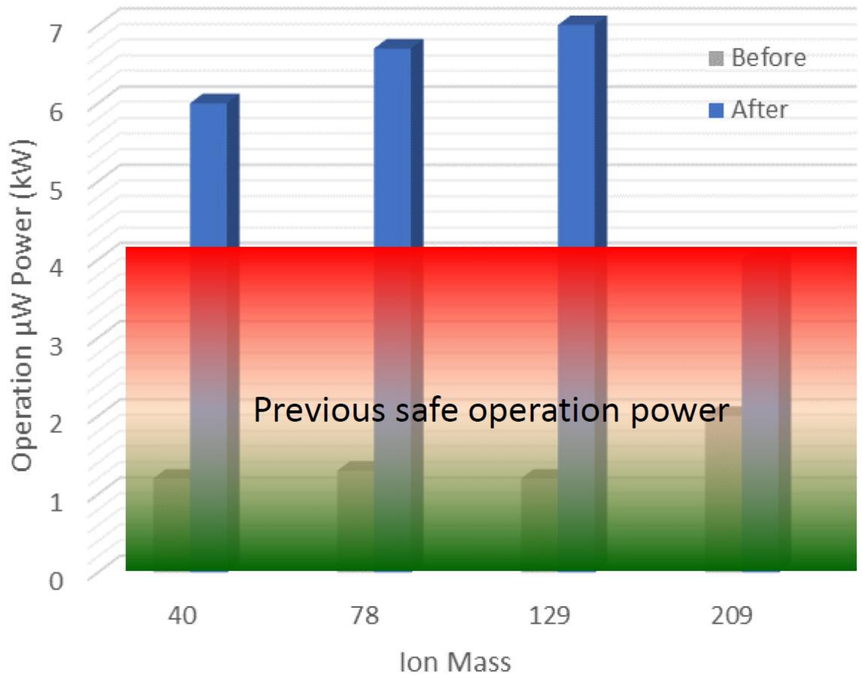


Micro-channel Plasma Chambers for SECRAL and FECR

- The water flow rate of the FECR plasma chamber has been improved to 50 L/min through optimized flow channel design, expected to operate reliably up to 25 kW

Key Parameters	FECR Chamber	SECRAL-II Chamber
Max. Microwave Power	25 kW	12 kW
Max. Localized Power Density	20 MW/m^2	10 MW/m^2
Chamber ID	Ø140 mm	Ø125 mm
Chamber OD	Ø156 mm	Ø136 mm
Length	1225 mm	887 mm
Microchannel region	$15\times15.6\times1.5$ mm^3	$15\times15.6\times1.0$ mm^3
Fins	0.4 mm×19	0.4 mm×19
Channel	0.4 mm×20	0.4 mm×20
Inside-wall thickness	1.5 mm	1.5 mm
Outside-wall thickness	1.5 mm	1.5 mm
Water pressure	10 bar	8.9 bar
Water flow per channel	> 15 L/m	> 4.0 L/m
Total water flow	> 50 L/m	> 13 L/m

SECRAL-II Ion Source Achieved Stable High-power Operations
IMP HIRFL Performance Enhancement Since 2021



$^{36}Ar^{15+}$

SECRAL-II: ~350 eμA （~4 times historical operation current）

- **High current：SFC--8.5 AMeV/15 eμA**
- **CSR_m Beam Current Increase by a factor of 5**

$^{78}Kr^{26+}$

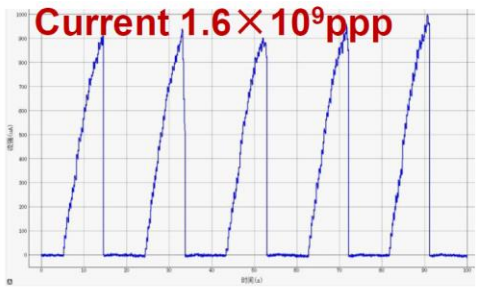
SECRAL-II: ~280 eμA (not available before)

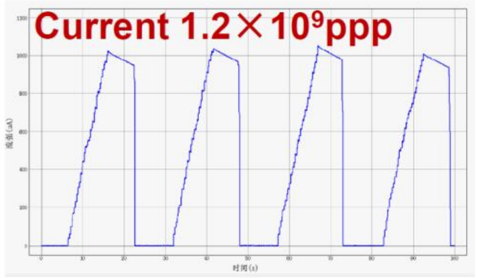
- **High current：SFC--6 AMeV/12 eμA**
- **CSR_m Beam Current Increase by a factor of 10**

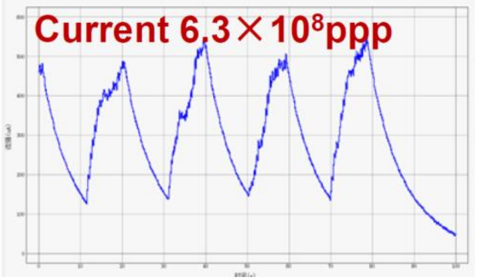
$^{129}Xe^{32+}$

SECRAL-II: ~200 eμA (not available before)

- **High current：SFC—3.9 AMeV/8 eμA**
- **CSR_m Beam Current Increase by a factor of 5**





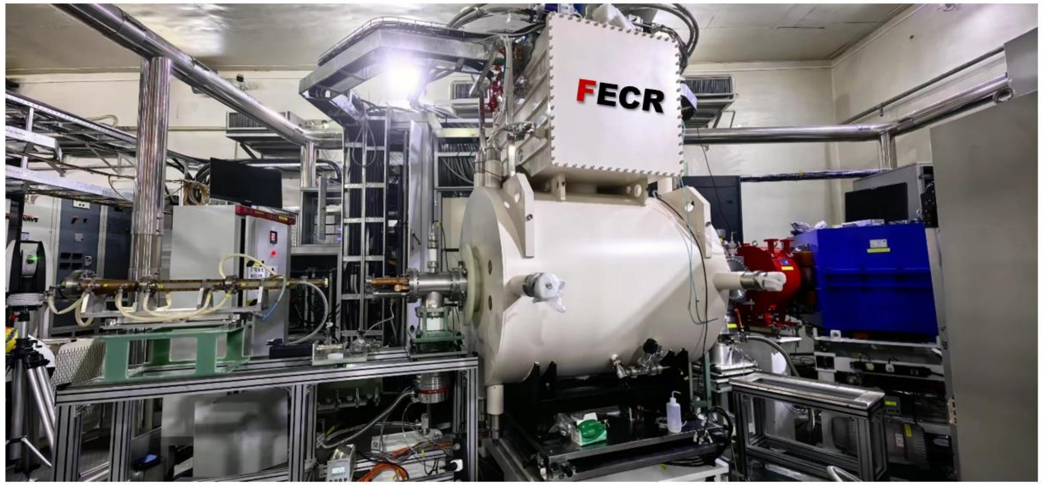


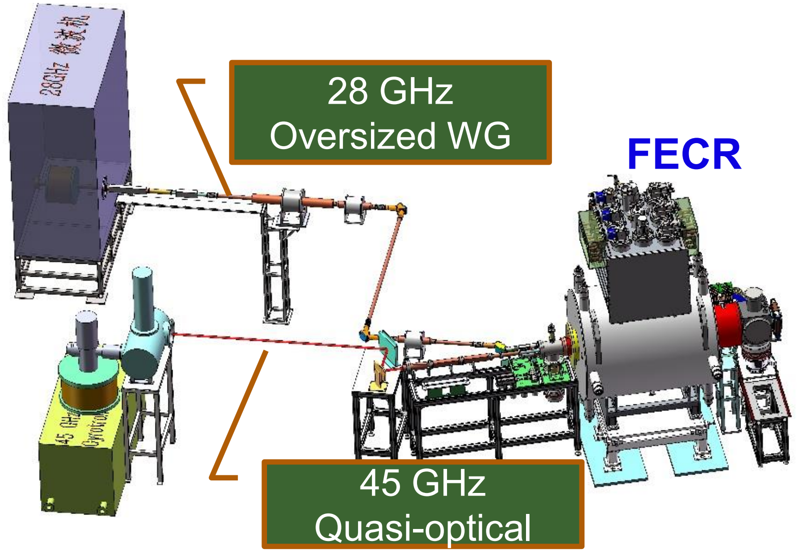
H. W. Zhao's talk @ECRIS 2024

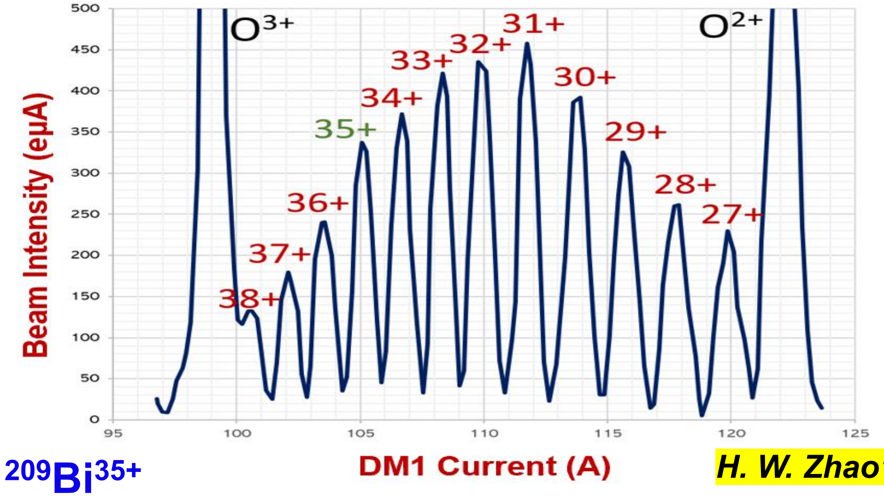
FECR Results with Micro-channel Plasma Chamber in 2024

Stable Operation Has Been Demonstrated at 12 kW

Parameters	Value
Microwave	**45 GHz + 28 GHz**
45 GHz Power	**5-8 kW**
28 GHz Power	**5-6 kW**
Typical operation fields	**Mirror peaks: 3.9 T/2.1 T** **B_r= 2.3 T**
Commissioned ions	**O, Xe, Bi**
Operation voltage	**25 kV**







$^{209}Bi^{35+}$

H. W. Zhao's talk @ECRIS 2024

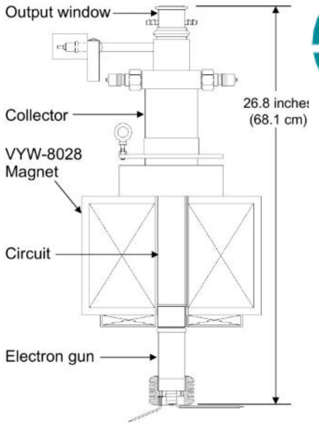
6.5 kW, 45GHz+5.5 kW 28GHz

Innovative Cooling Chamber
Makes the 3rd Gen Source Capable of Operation at 20 kW

- 28 GHz 10 kW gyrotron (VGA-8028) operates in a 0.5 T magnetic field, with the cathode held 30 kV below the grounded gyrotron body. The output mode is the second harmonic TE_{02}
- 28 GHz 20 kW gyrotron (VGA-8028B) is available (32 kV/1.9A)

Continuous Wave (CW) Gyrotron

Product Description	Frequency (GHz)	Continuous Wave Power Output (kW)	Beam Voltage (kV)	Beam Current (A)	Model Number
10 kW Gyrotron CW Oscillator VGA-8028	28	10	30	1.1	VGA-8028
20 kW Gyrotron CW Oscillator VGA-8028B	28	20	32	1.9	VGA-8028B



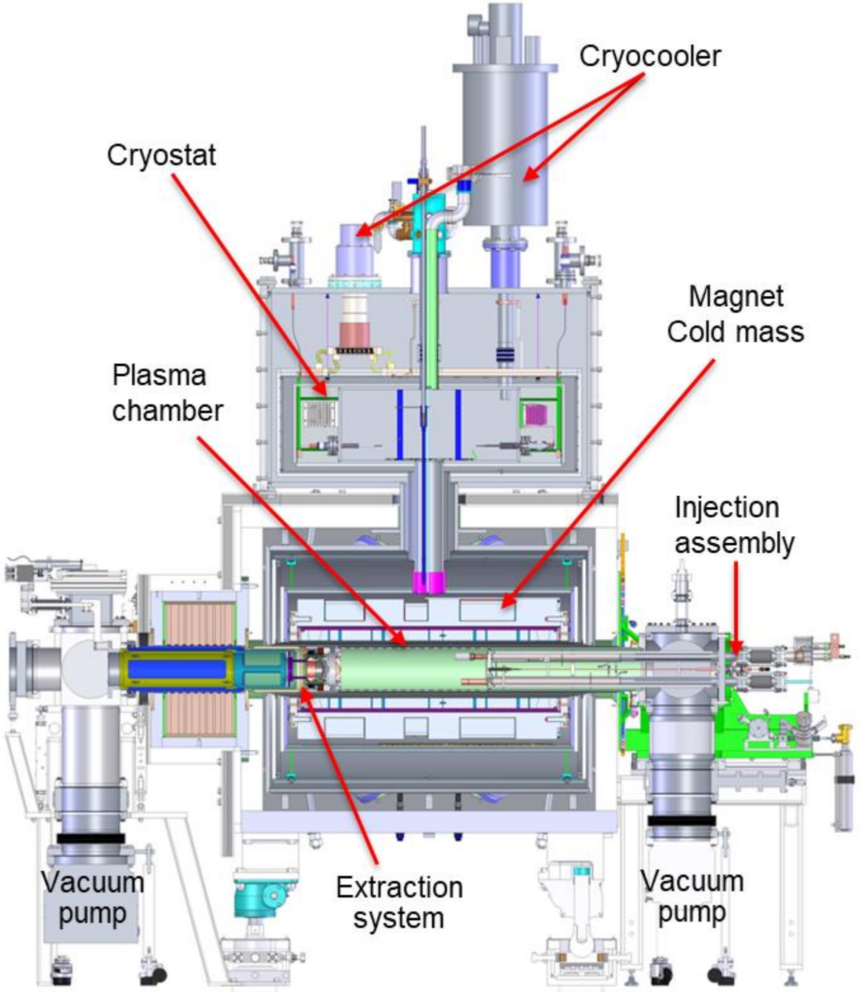
https://www.mppinc.com/product/gyrotrons-18/continuous-wave-cw-oscillators-30

FRIB 28 GHz High Power (HP) ECR Ion Source Overview

- 28 GHz HPECR source is a VENUS-like design
  - Magnet - LBNL
  - Cryostat and conventional components - FRIB

Parameters	HP ECR
RF Frequency (GHz)	28 + 18
RF Frequency (kW)	10 + 2
Axial Field Peaks (T)	4.0 (Inj.), 3.0 (Ext.)
Mirror Length (mm)	500
Resonance zone Length (mm)	170
B_{min} (T)	0.4~0.8
B_r at Plasma Chamber Wall (T)	2.0
SC-material	NbTi
Chamber ID (mm)	143.5
Max. Cooling Capacity@4.2 K (W)	10
Max. extraction voltage (kV)	30

Milestones	Date
Start of LBNL CDR for SC-ECR	Mar 2013
Delivery of SC-ECR cold mass to FRIB	Dec 2017
Magnet cool down to 4 K	Dec 2020
Magnet ramping to full field (J. Guo joined FRIB in Sep 2021)	Jan 2022
First plasma at 18 GHz	Jan 2022
First beam from SC-ECR	Oct 2022
Start of operations at 18 GHz	Jan 2023
Start of supporting FRIB 10 kW operations	Oct 2023
Start of supporting FRIB 20 kW operations	Mar 2025
Demonstrated 300 euA of U^{35+} at 28 GHz	Jul 2025
Start of operations at 28 GHz	Oct 2025



28 GHz ECR Ion Source Supporting FRIB Operating with 20 kW Beams on Target including ^{238}U since March 2025

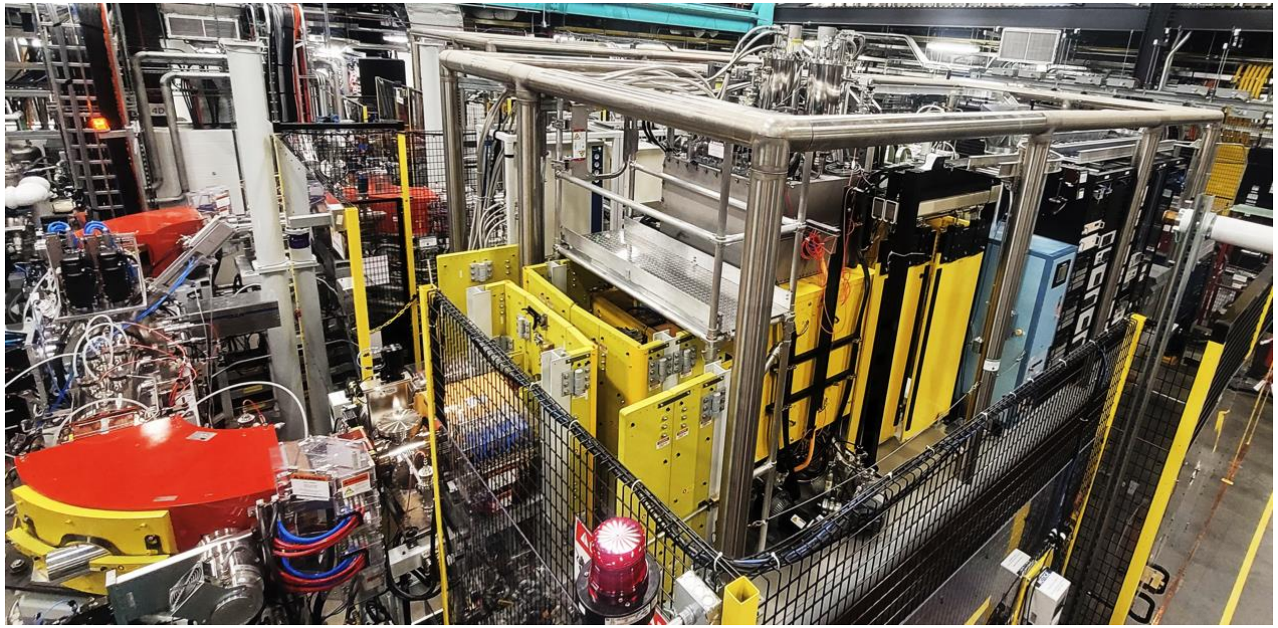
- During the past year, FRIB 28 GHz ECR source operated more than 3200 beam hours with ~99% availability serving scientific users.

HP-ECR operation stats from Oct. 2024 to Jul. 2025

Beam	A	Q	Hours	Vapor Production
Calcium	48	10	1117	Cartridge Oven (520 C)
Nickel	58	17	458	High Temp. Oven (1450 C)
Zinc	64	19	158	Cartridge Oven (300 C)
Xenon	124	26	231	Gas
Platinum	198	31	120	High Temp. Oven (2000 C)
Uranium	238	35	1168	High Temp. Oven (2000 C)
Overall			3252	

Breakdown for FY23 - FY25

HP-ECR Source	Total Downtime(Hrs.)	# Occurrence	# Occurence > 1hr	Mean duration
FY23	39.37	5	3	7.87
FY24	1.78	3	0	0.59
FY25	36.21	1	1	36.21

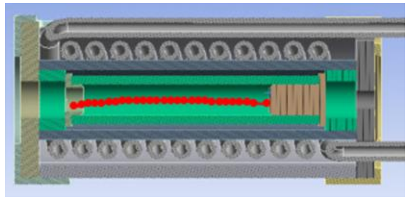


28 GHz HPECR ion source on HV platform at the FRIB front end

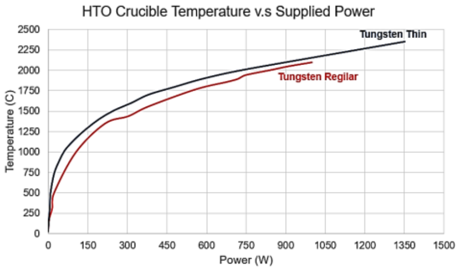
See Guillaume's poster this afternoon

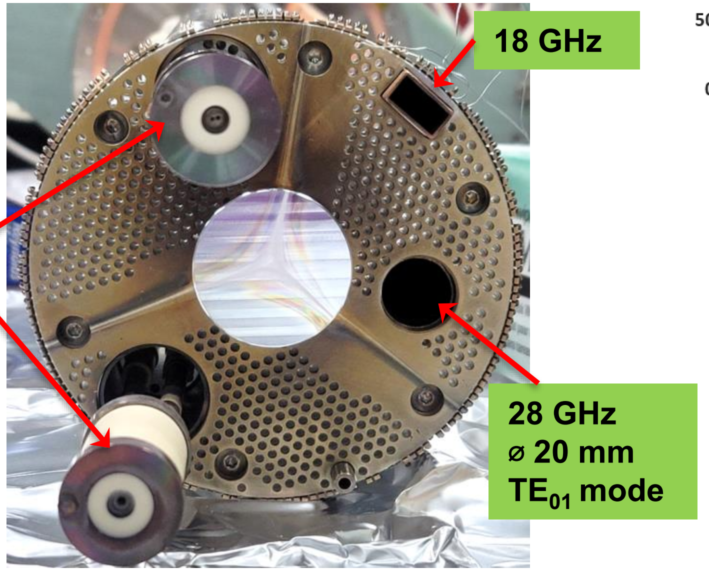
Demonstrated 300 euA of U^{35+} Meet FRIB 400 kW Operations

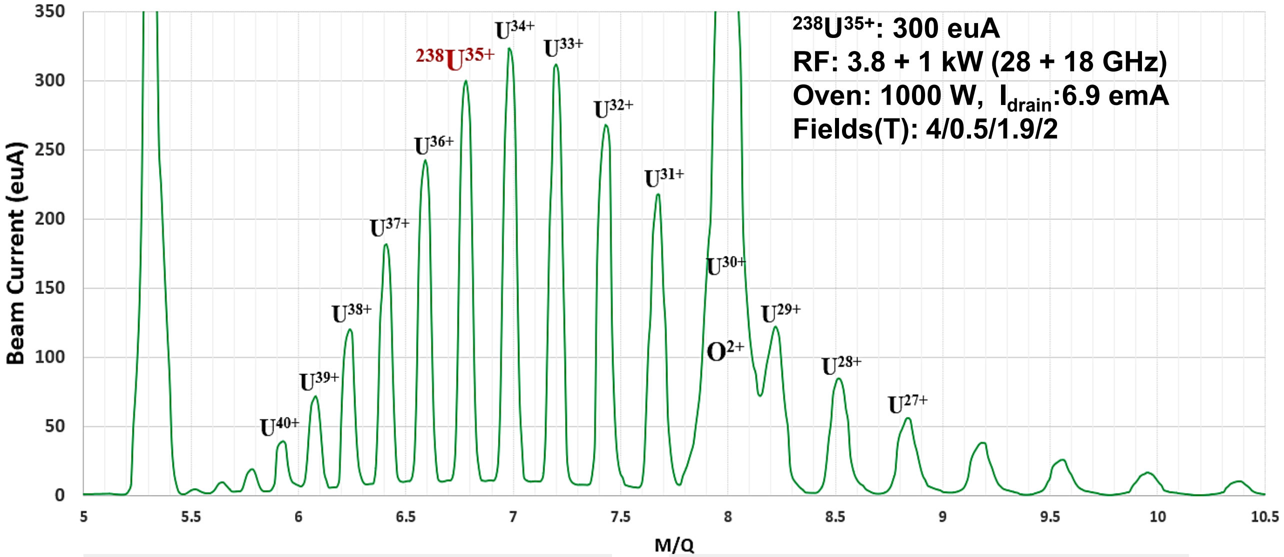
- Advanced technologies
  - Microwave heating- 20 mm TE_{01}
  - Mini induction heating oven: Improved design mitigates nozzle clogging
  - New plasma chamber with micro channel design is underway

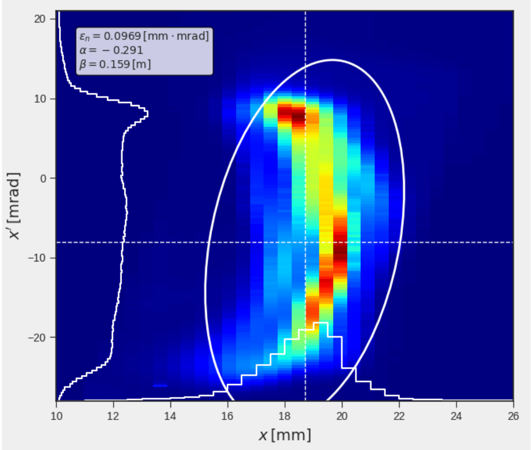


Temperature profile measured (Red dots)

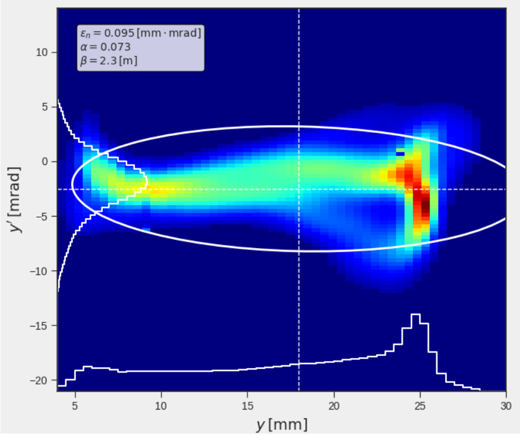








X: 0.097 π mm- mrad



Y: 0.095 π mm-mrad

Summary

- The performance of the 3rd generation ECRISs have been significantly improved, achieving stable high-power routine operations.
  - ✓High-efficiency microwave heating
  - ✓Micro-channel cooling plasma chamber

(28 GHz/10 kW)

(28 GHz/20 kW)

- These technologies are also promising solutions for the 4th generation ECRIS. (45 GHz/25 kW)
- FRIB 28 GHz ECR ion source demonstrated 300 euA of U^{35+}, meet FRIB 400 kW operations

- Open questions:

  High frequency high power microwave heating needs to be better understood and has the potential to further improve ECRIS performance.

Thank you!

FRIB
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