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# A new solution to plasma chamber cooling for high power ECR ion source operation


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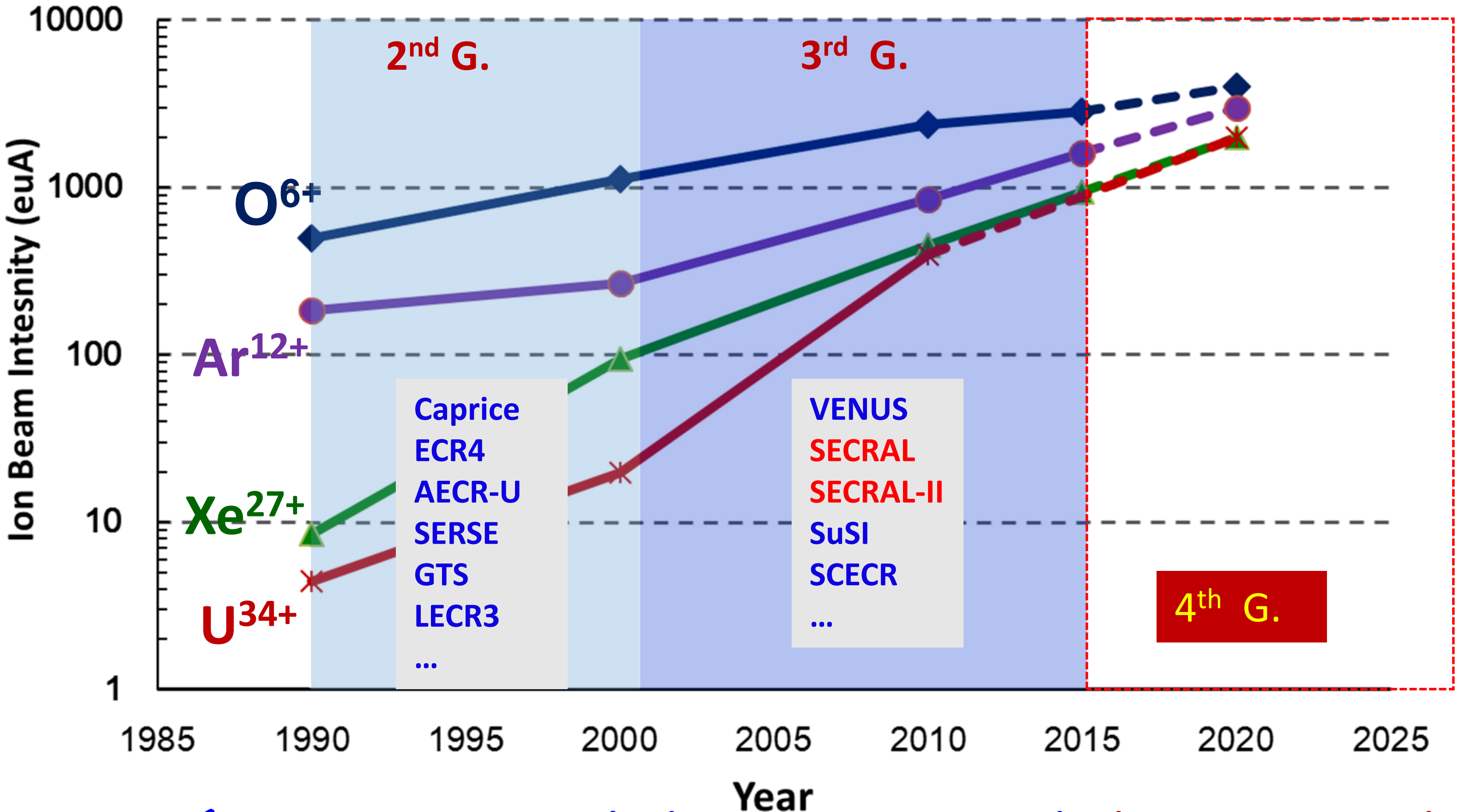
# Outline

- **Introduction**
- **Analysis of microchannel cooling for plasma chamber**
- **On-line high power test**
- **Summary**

# Evolution of ECRIS Generations

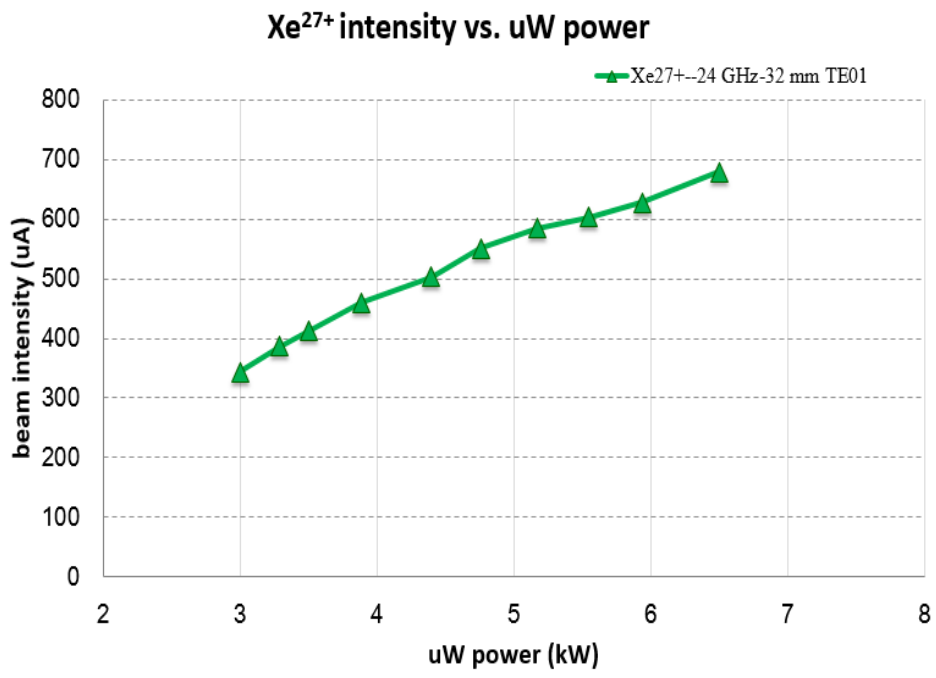


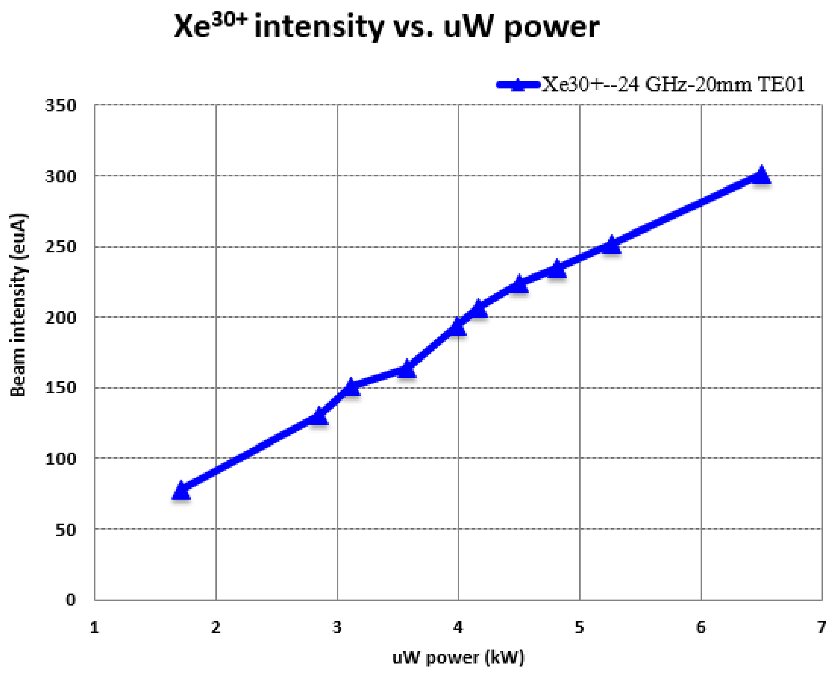

**Frequency** 6.4~18 GHz | 24~28 GHz | 40~60 GHz

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

# Power Scaling Laws

## SECRAL $Xe^{27+}$ and $Xe^{30+}$ scale linearly with power




**$TE_{01}$ , ∅ waveguide 32mm**

**$TE_{01}$ , ∅ waveguide 20 mm**

# SECRAL-II
# 28 GHz Superconducting ECR Ion Source

## High power operation

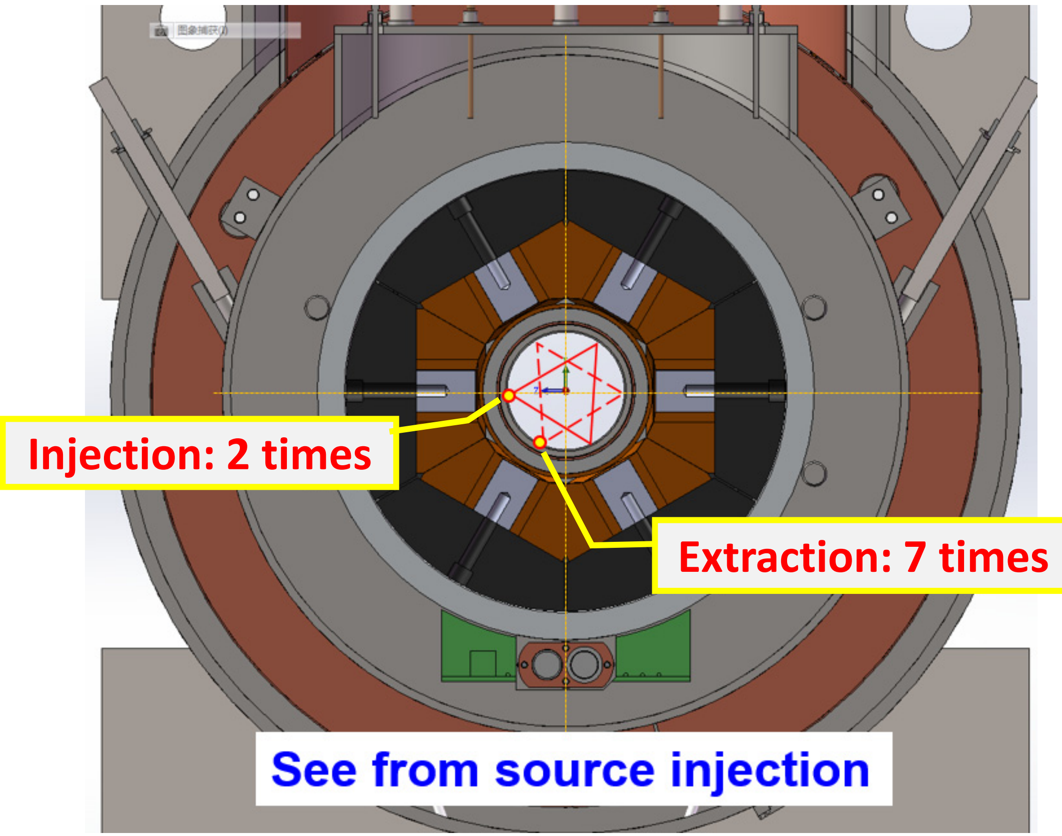
**Frequency： 28 + 18 GHz**
**Max. Power： 10 + 2 kW**

| | SECRAL-II（eμA） |
|---|---|
| $Ar^{16+}$ | 620 |
| $Ar^{17+}$ | 130 |
| $Xe^{30+}$ | 365 |
| $Xe^{34+}$ | 110 |


| Parameters | SECRAL-II |
|---|---|
| $\omega_{rf}$ (GHz) | 18-28 |
| Axial Field Peaks (T) | 3.7 (Inj.), 2.2 (Ext.) |
| Mirror Length (mm) | 420 |
| $B_r$ at r=63 mm (T) | 2.06 |
| Magnet Cooling | LHe bathing |
| Dynamic cooling power (W) | ~6 |
| Warm bore ID (mm) | 142 .0 |
| Chamber ID (mm) | **125.0（$B_r$=1.96T）** |

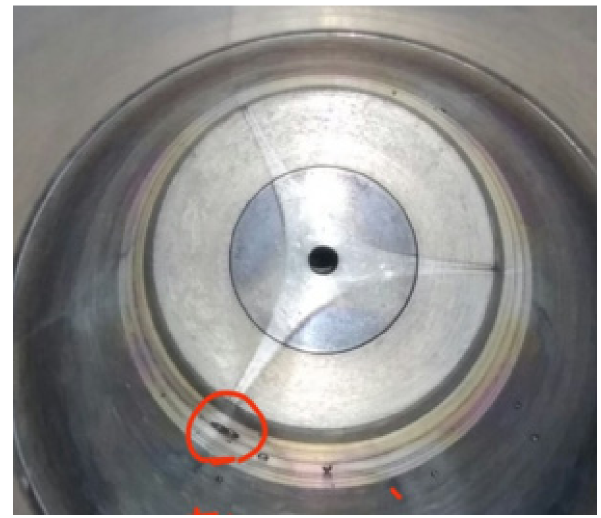
# Plasma chamber burnout

- **The plasma chamber cooling has become a serious obstacle for high power operation**



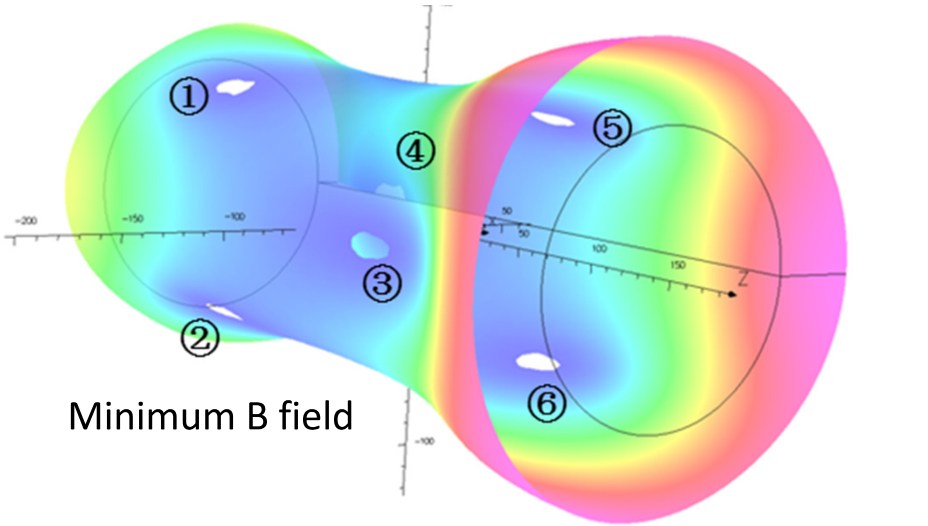

*VENUS chamber was burned out twice*
*（D. Z. Xie, ECRIS2016）*

*SECRAL-II (2019) 6.5kW (24GHz)+1.7kW (18GHz)*

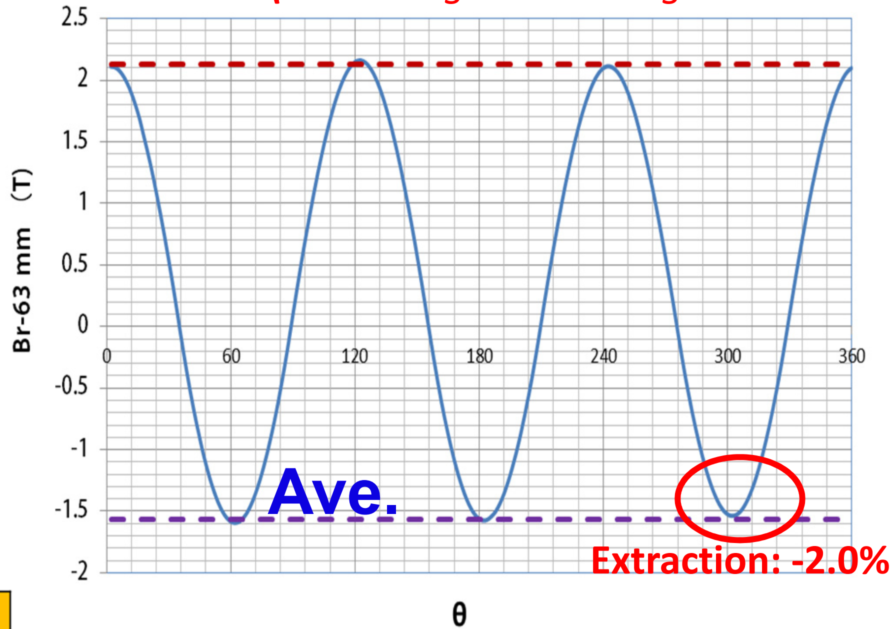


# Origin of plasma chamber burnout

**6 points where the magnetic field is weakest**

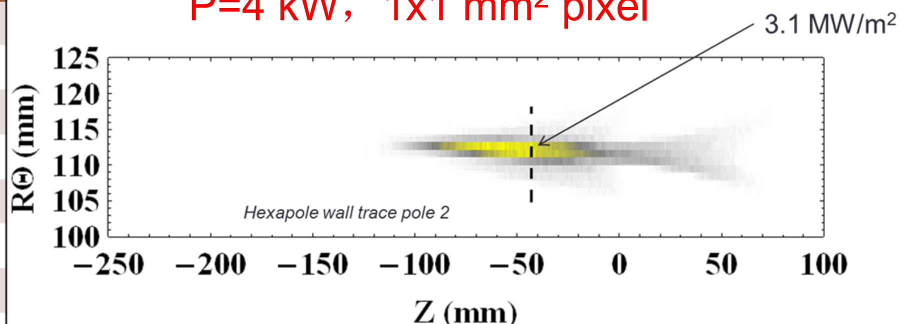



***SECRAL-II*** *(machining error during wire winding)*




| | 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



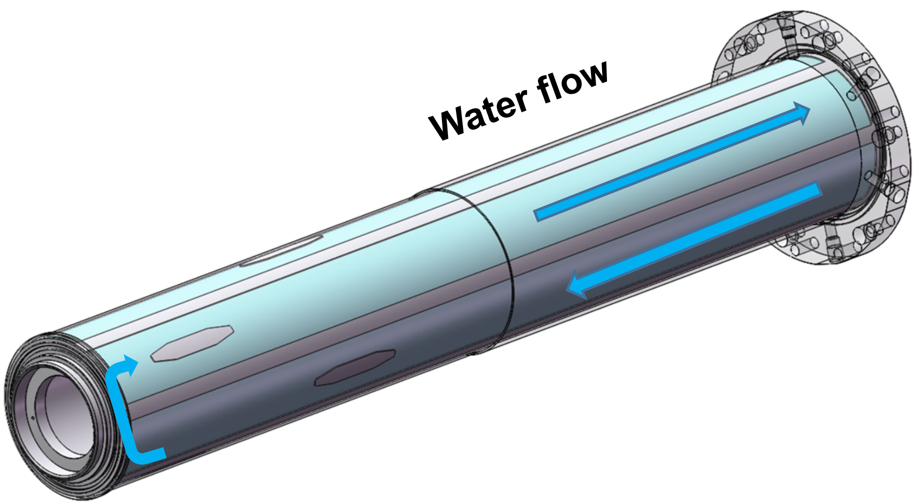

*T. Thuillier, et al., Rev. Sci. Instrum. 87, 02A736 (2016)*

# Main reason of plasma chamber burnout

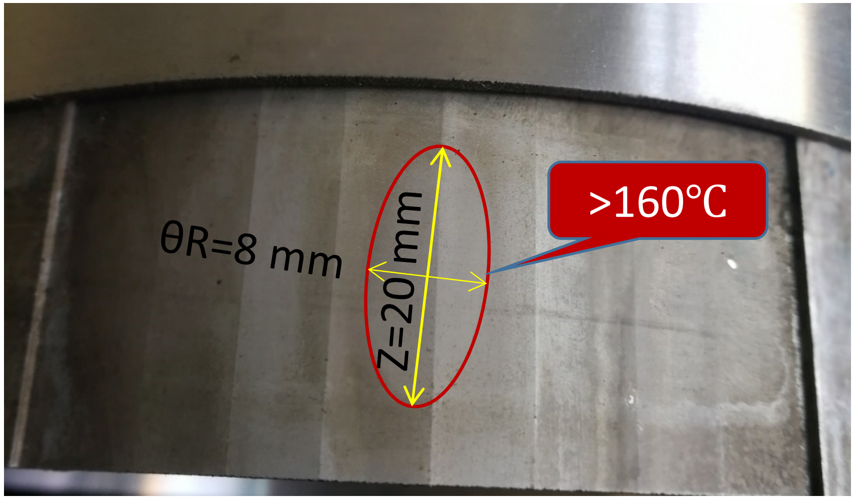
## Very high heat flux

- **Power density: ≈ 1 kW/cm$^2$ Very high heat flux !!!**

**Power: 12 kW** **The overall cooling capacity is sufficient to remove much more than 12 kW power. (Total flow rate:15 L/m, $\Delta T$=11.4 °C)**




Water pressure: 6 bar
Boiling point: ≈150 °C

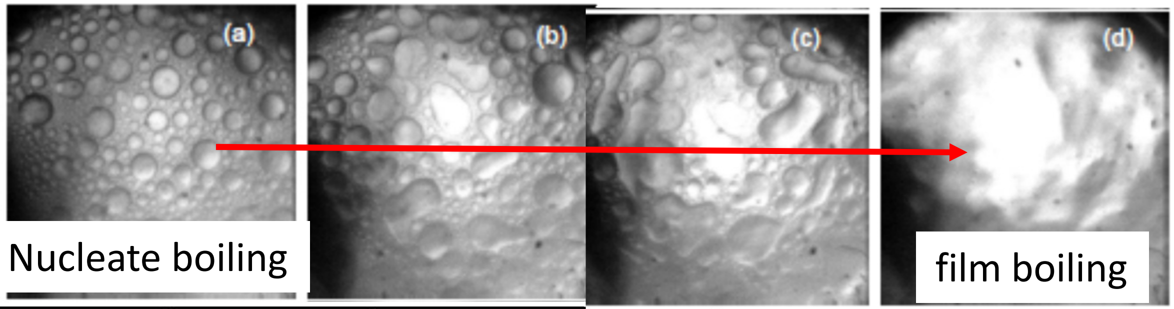


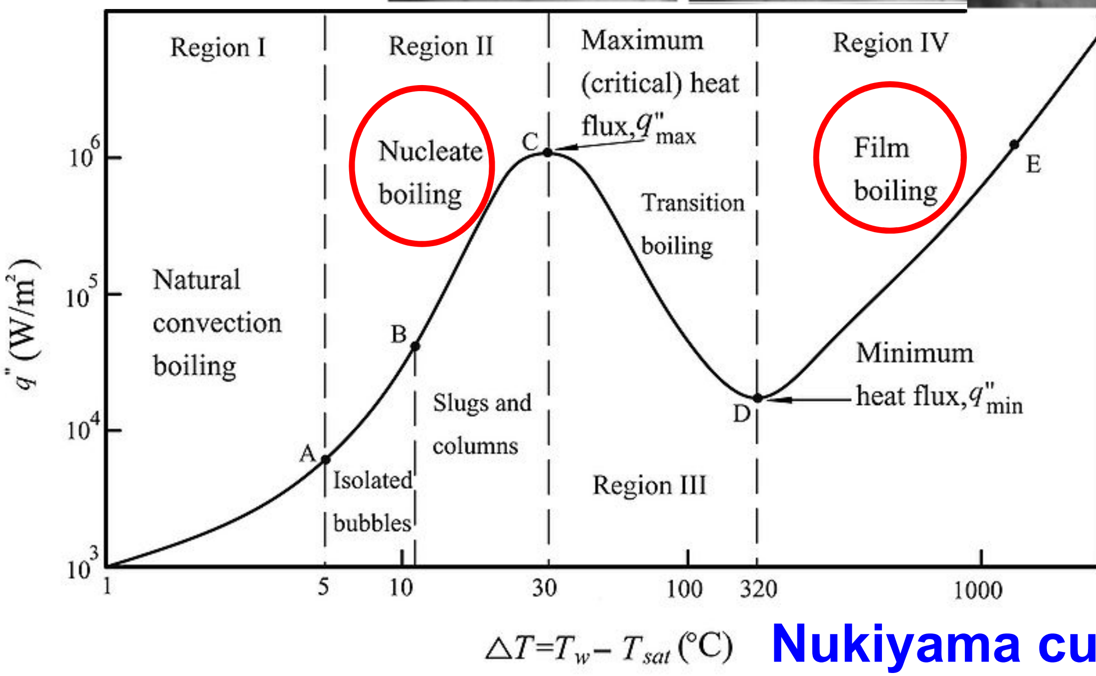

Obvious over heating mark in at the surface of cooling water channel.

**Size of overheating area < 8 * 20 mm**

# Origin of wall destruction

## Transition from nucleate boiling to film boiling



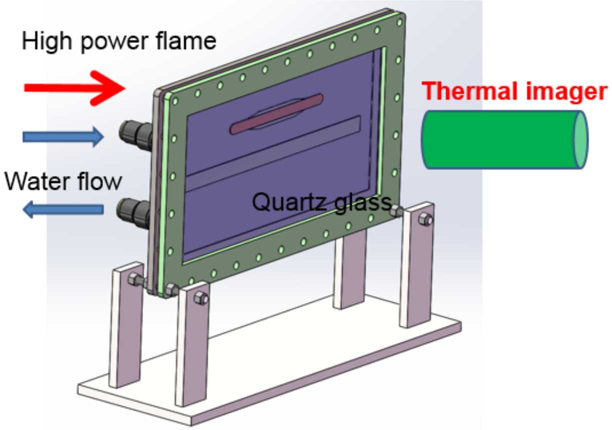



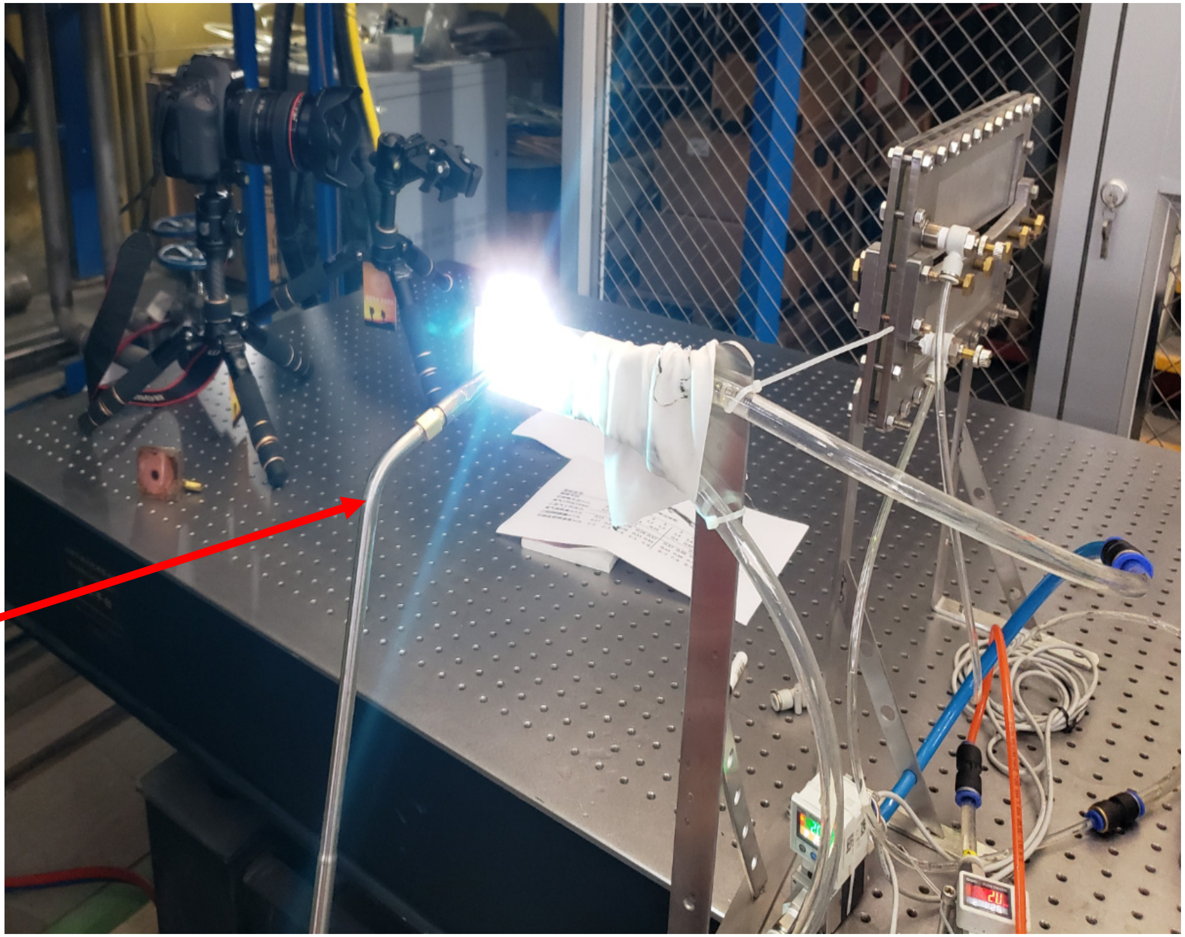

Bubbles coalescence→ surface dryout →
Rapid surface temperature increase

**Nukiyama curve for Pool boiling**

**CHF (Critical heat flux) point at Twall ≈ 30 + 150 = 180 ℃**

# Thermal testing platform



oxy-acetylene flame

# The burnout process of plasma chamber

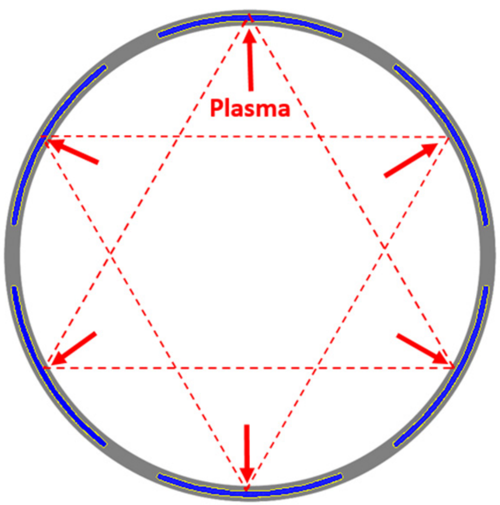
## Transition from nucleate boiling to film boiling

- As the heat flux is too high, the local water boils completely.
- The heat exchange decreases and the aluminum temperature rises rapidly, then burnout.

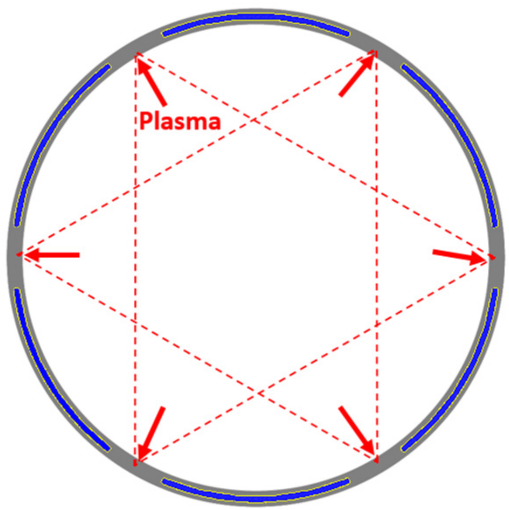
# Cooling & Structure Optimization

## Goal : to enhance heat transfer

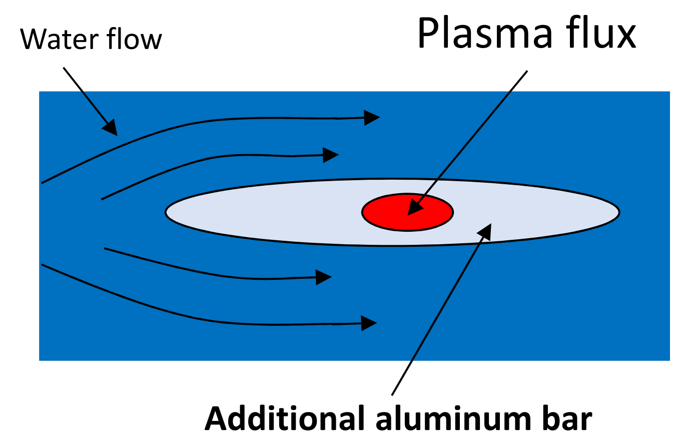
a) Plasma flux to the water channel
b) Plasma flux to the solid aluminum (rotating 30° of the chamber)
c) Plasma flux to the Additional bar




a



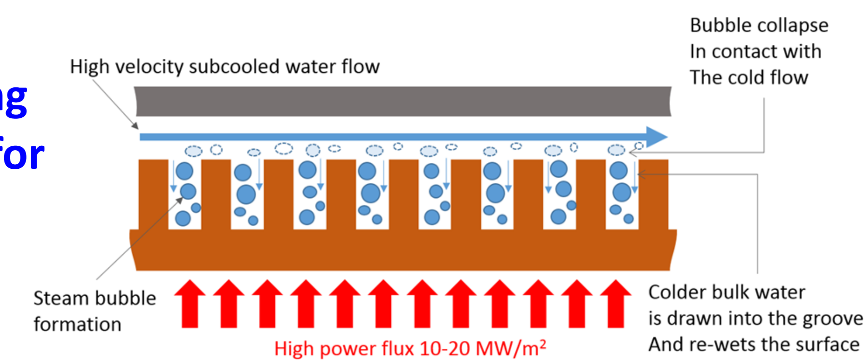

b




c

- Thuillier Proposed an hyper-vapotron cooling schemes， but it requires a total thickness for the plasma chamber of ~20 mm.

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



# Microchannel cooling

Technically it means using a **micro-fluidics** device as **heat exchanger** for the thermal management of a heat source

*Power*

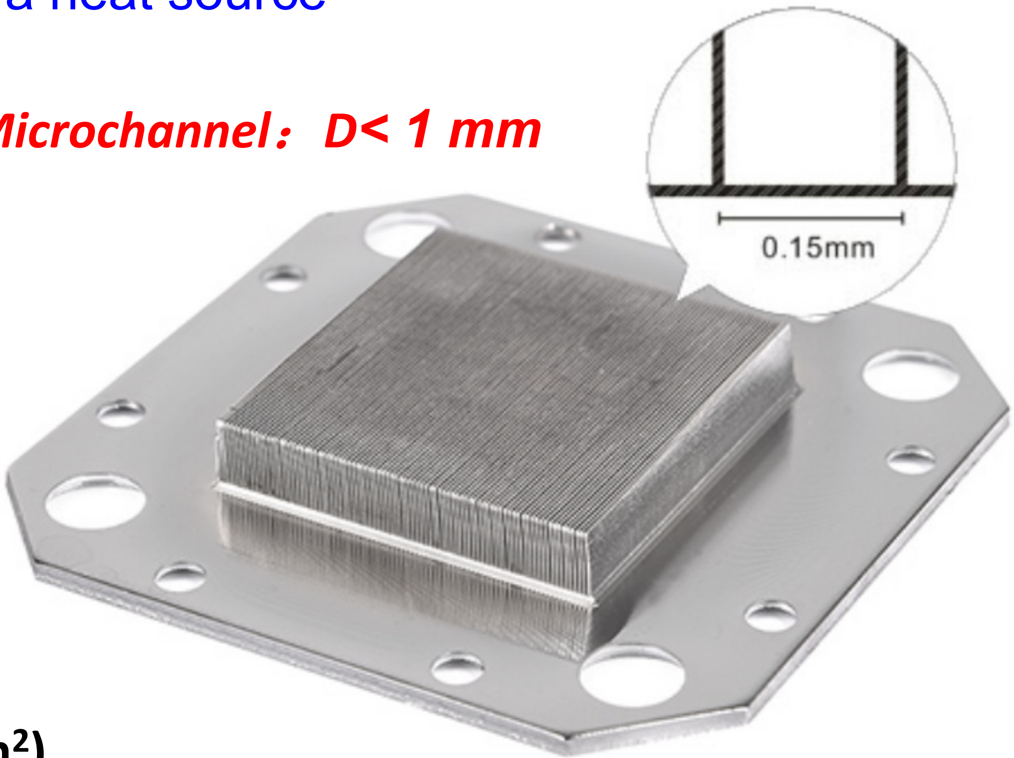
*Surface ↑*

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

*Heat exchange coefficient ↑*

*Temperature difference Between water and metal*

***Microchannel：D< 1 mm***




*D.B. Tuckerman, R.F.W. Pease, High performance heat sink for VLSI,IEEE Electron Dev.Lett.EDL-2(5)(1981)126-129.*

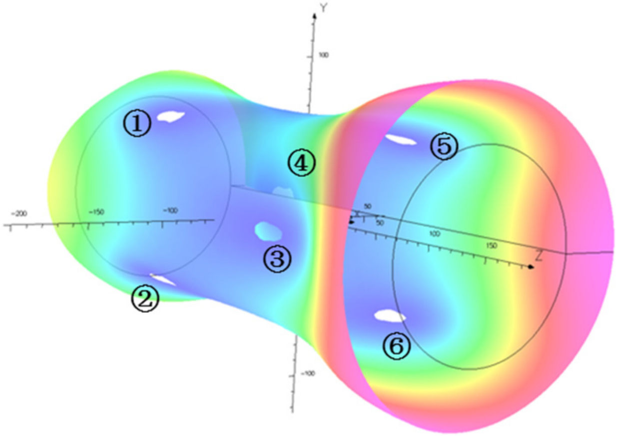
## Features:

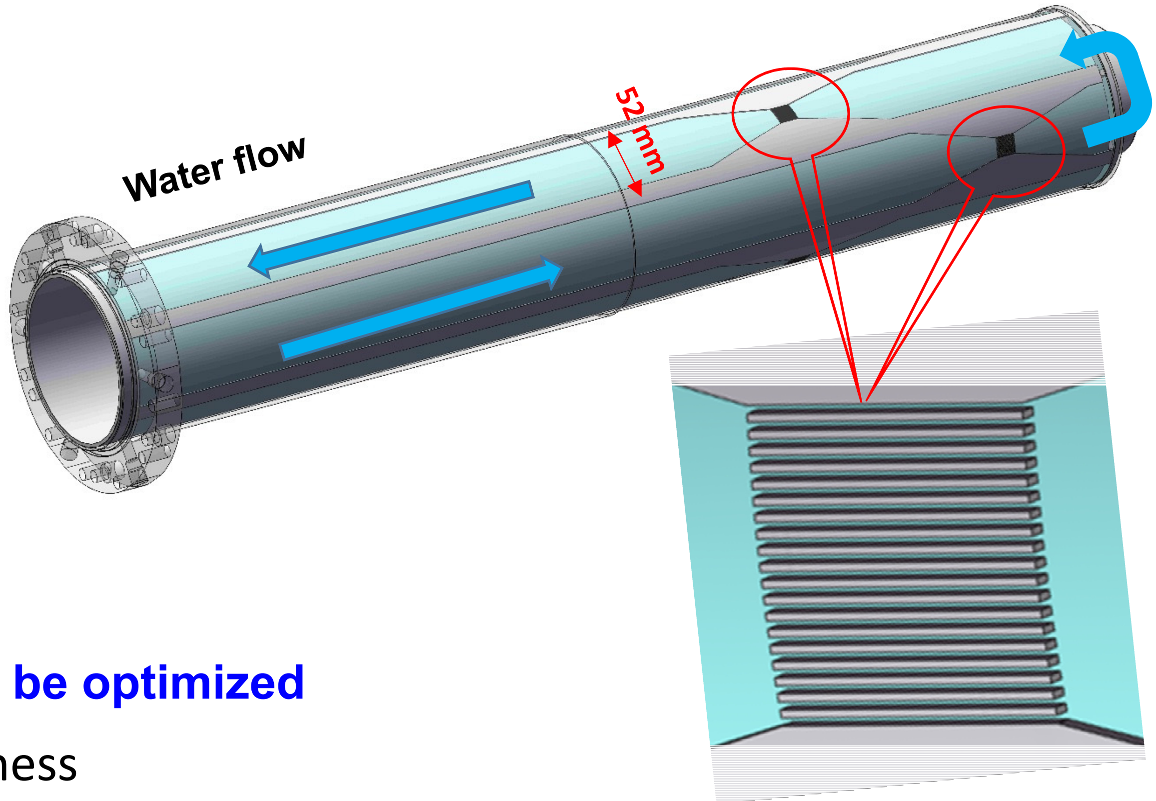
- **Very thin thickness**
- **High power flux (0.5-2 kW/cm$^2$)**
- **Acceptable pressure drop**

**Micro Channel Cooling seems to be an excellent solution**

# Plasma chamber with microchannel cooling

**The microchannel structure is set up in the 6 high heat flux poles**




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

**Parameters that need to be optimized**

- Water channel thickness
- Chamber wall thickness
- Pressure loss and flow velocity
- Water flow rate

# Simulation conditions

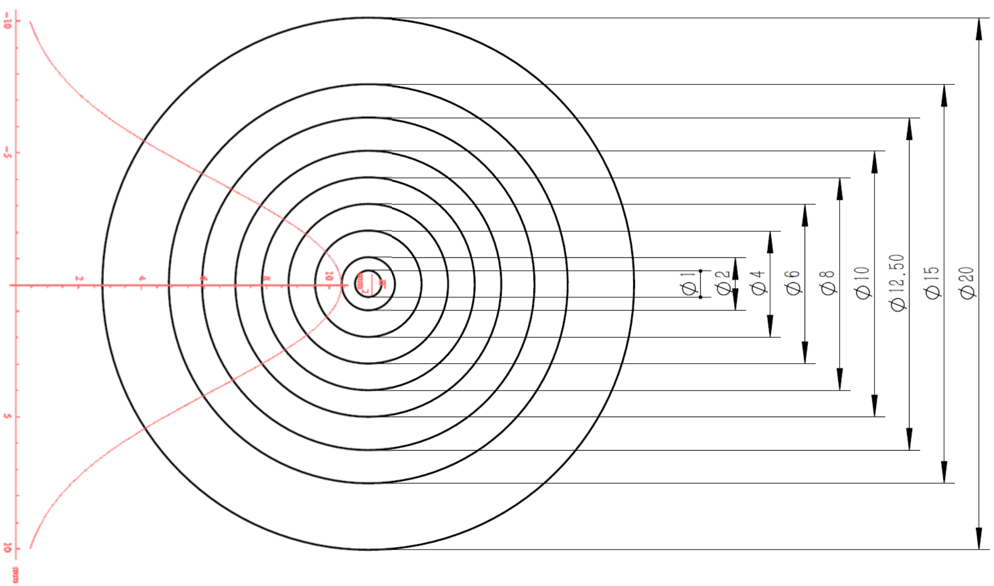
**Total power at each pole:≈ 1 kW** **Max. power density: ≈ 1 kW/cm$^2$**

- **Uniform power density distribution**

  Power density : 1 kW/cm$^2$, Surface: 100 mm$^2$ (ϕ11.28 mm) , Power : 1 KW

- **Gaussian power density distribution**

  Max. power density : 1 kW/cm$^2$ , Surface: 314 mm$^2$ (ϕ20 mm) , Power : 1 KW

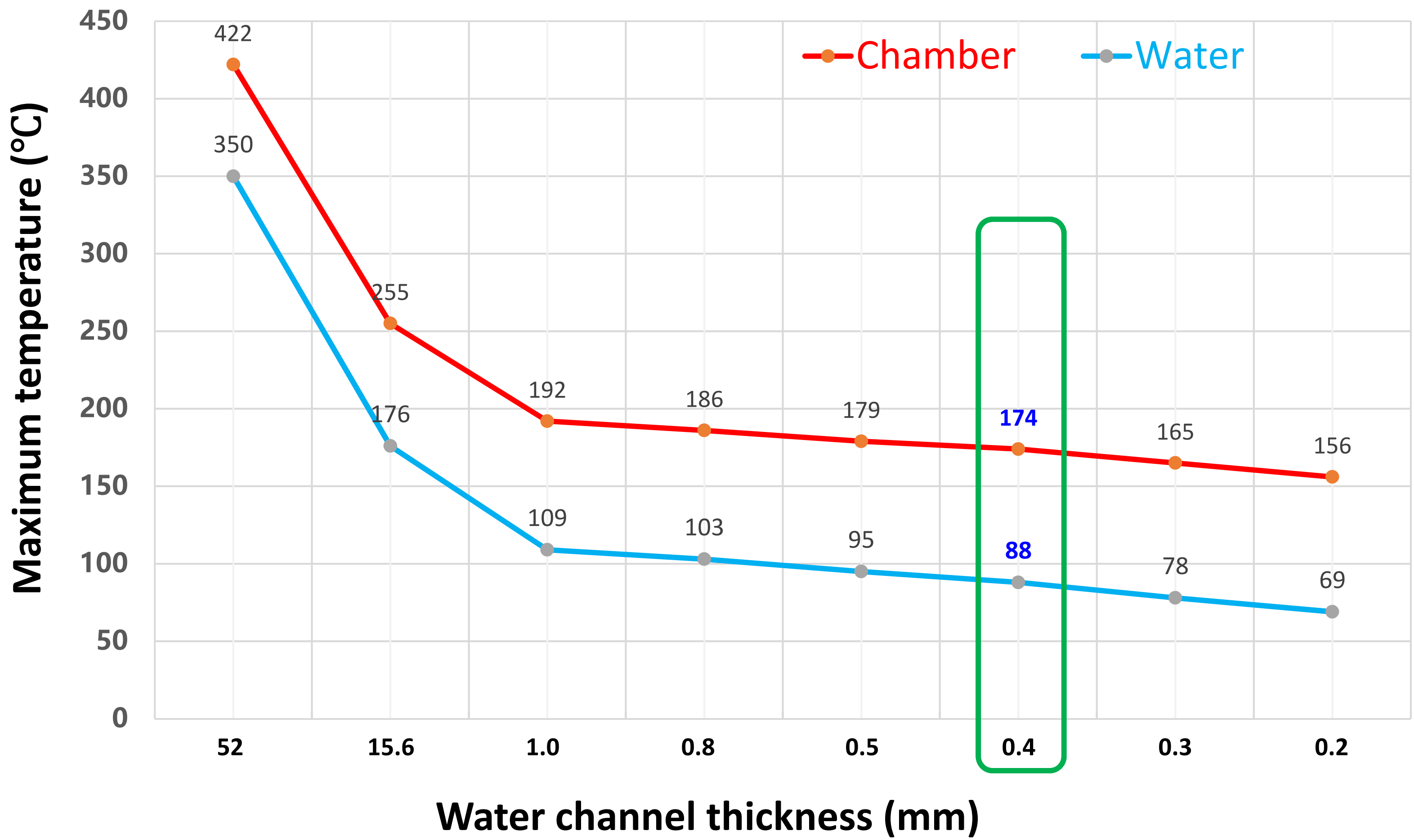



| | Surface (cm2) | Power (W) | Power density (MW/m$^2$) |
|---|---|---|---|
| ϕ1 | 0.79 | 8.14 | **10.3038** |
| Φ2-ϕ1 | 2.36 | 24.04 | 10.1864 |
| Φ4-ϕ2 | 9.42 | 90.72 | 9.63057 |
| Φ6-ϕ4 | 15.71 | 133.52 | 8.49905 |
| Φ8-ϕ6 | 21.99 | 155.12 | 7.05412 |
| Φ10-ϕ8 | 28.27 | 155.53 | 5.50159 |
| Φ12.5-ϕ10 | 44.18 | 170.29 | 3.85446 |
| Φ15-ϕ12.5 | 54 | 128.24 | 2.37481 |
| Φ20-ϕ15 | 137.45 | 134.39 | 0.97774 |
| **total** | **314** | **1000** | |

# Water channel thickness

## Uniform power density distribution

Al 6061-T6, Flow rate: 7 L/min, Chamber wall thickness: 1.5 mm, Channel height： 1 mm

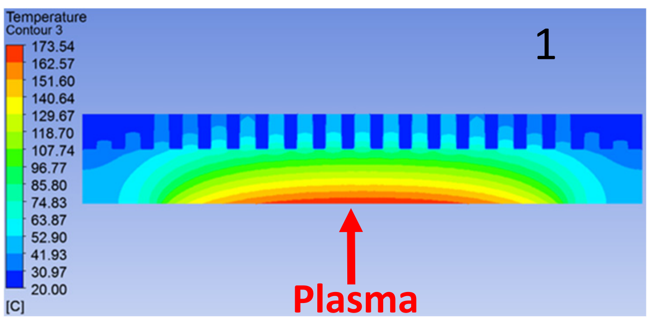


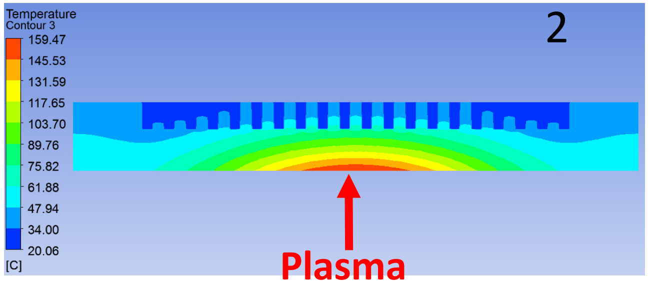
# Temperature distribution

Al 6061-T6, Flow rate: 7 L/min, Chamber wall thickness: 1.5mm

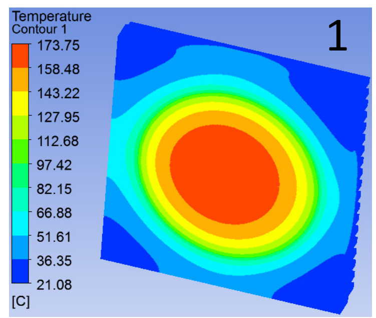
Microchannel: 0.4 mm *20, Channel height： 1 mm

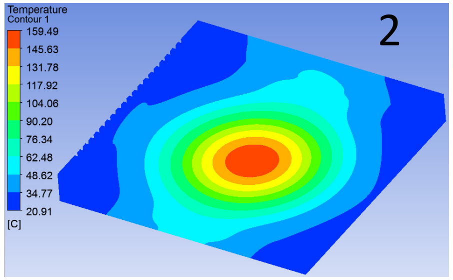
| | Power density distribution | $T_{max}$ chamber | $T_{max}$ water |
|---|---|---|---|
| 1 | Uniform (ϕ11.28 mm) - 1 kW/cm2 | 174℃ | 88℃ |
| 2 | Gaussian (ϕ20mm)- 1 kW/cm2 | 159℃ | 78℃ |



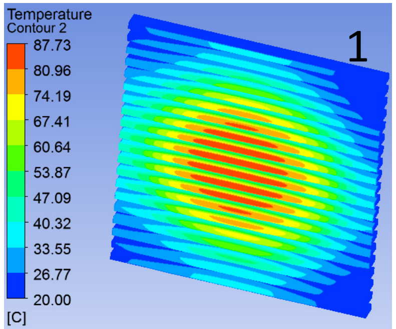



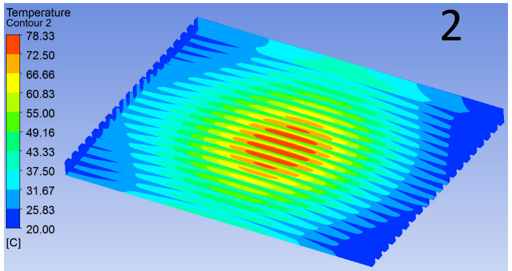

Cross section




Inside-wall



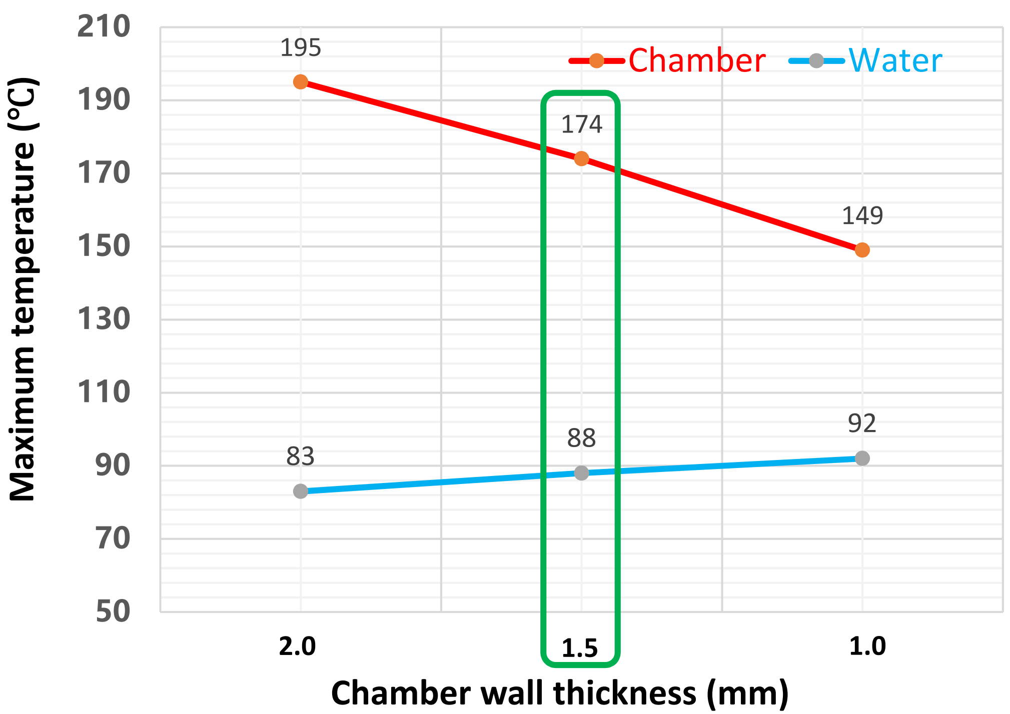



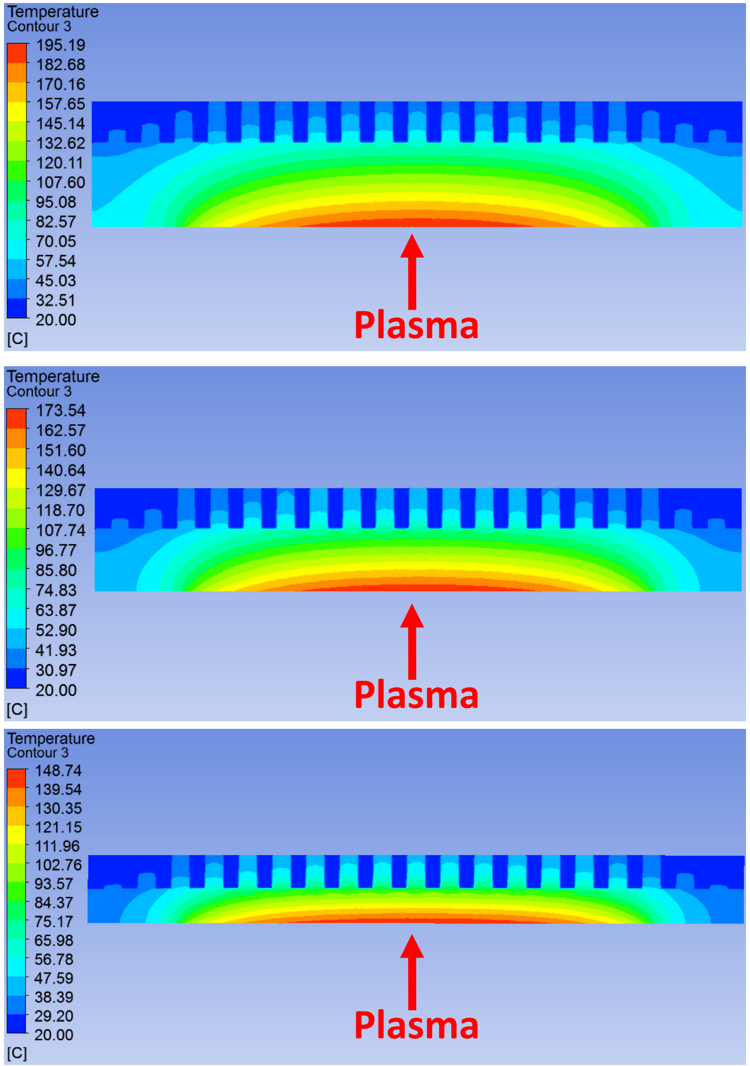

Water

# Chamber wall thickness

## Uniform power density distribution

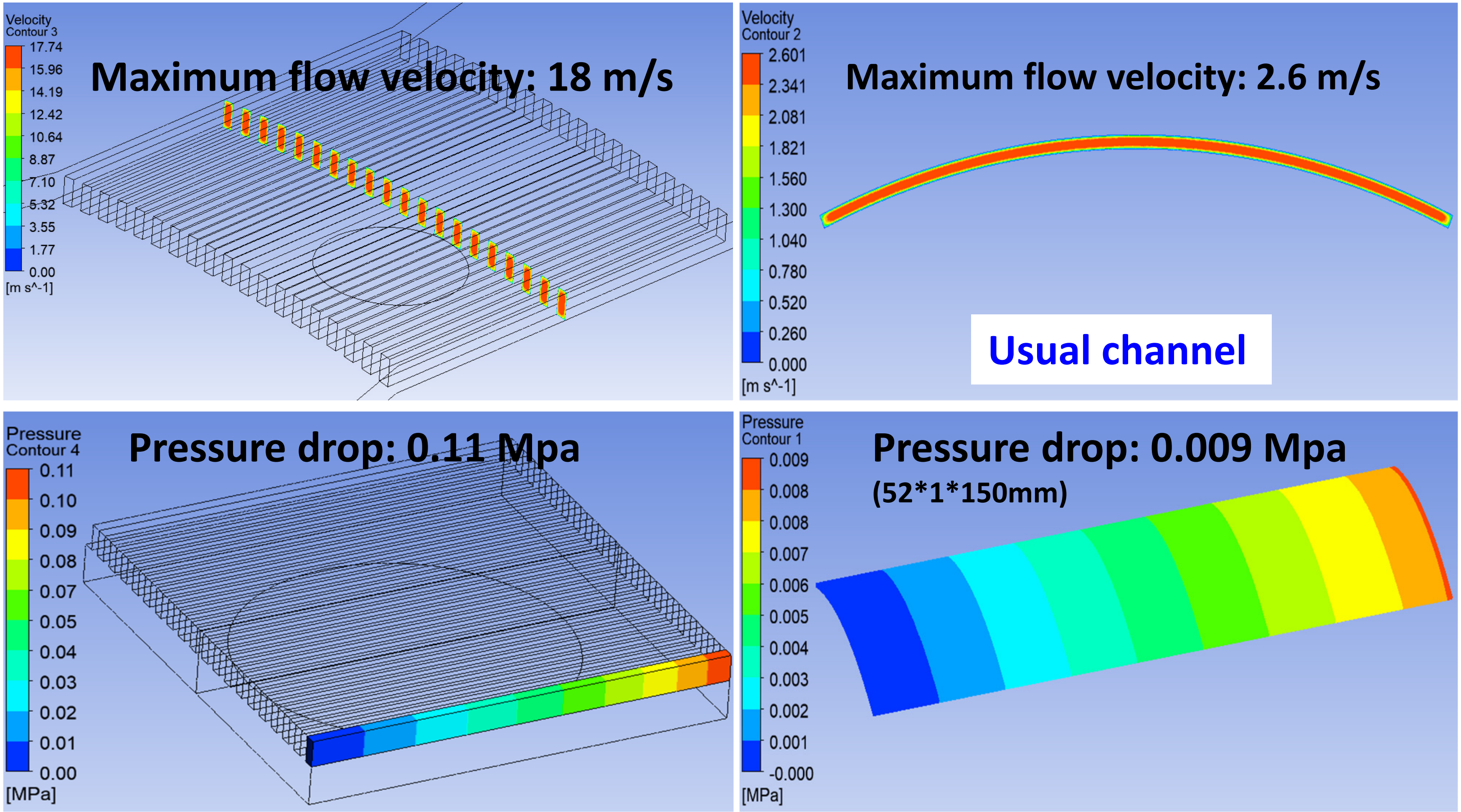
Al 6061-T6, Flow rate: 7 L/min,
Microchannel: 0.4 mm *20, Channel height： 1 mm



# Water pressure drop & flow velocity

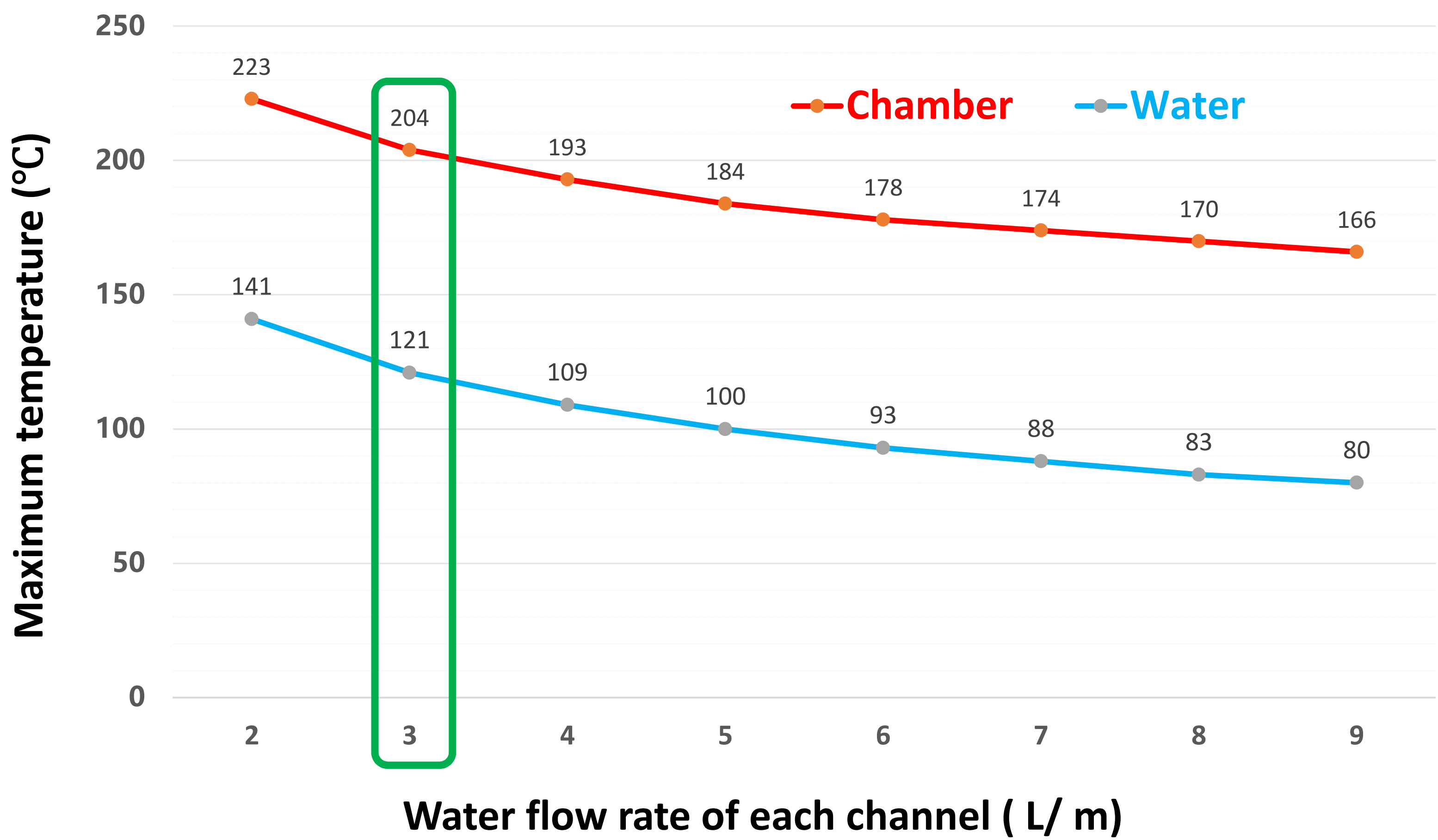
Microchannel: 0.4 mm *20, Channel height： 1 mm, Flow rate: 7 L/min



# Water flow rate

- **Uniform power density distribution**

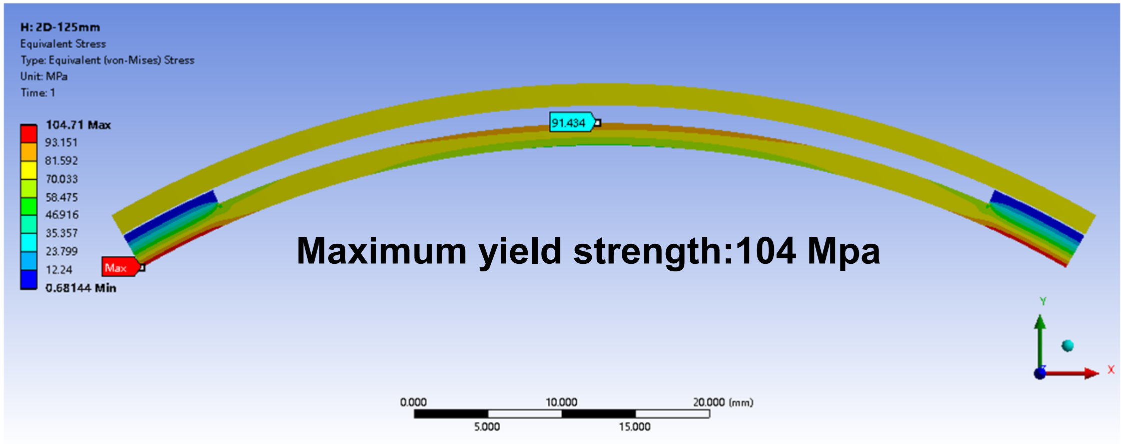
Microchannel: 0.4 mm *20, Channel height： 1 mm, Chamber wall thickness: 1.5 mm

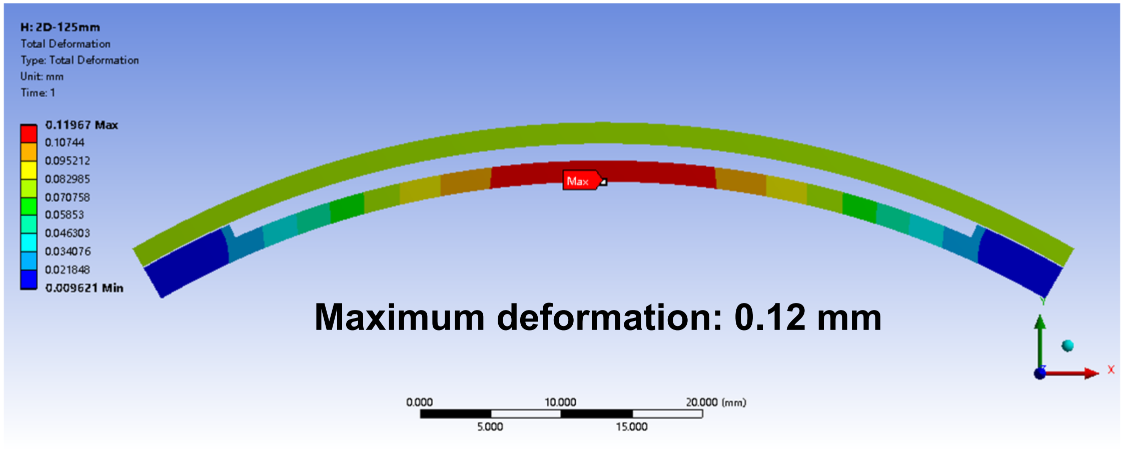


# Strength analysis

Maximum pressure：2.0 MPa

Al 6061-T6 Yield strength: 100 MPa (@200 ℃);



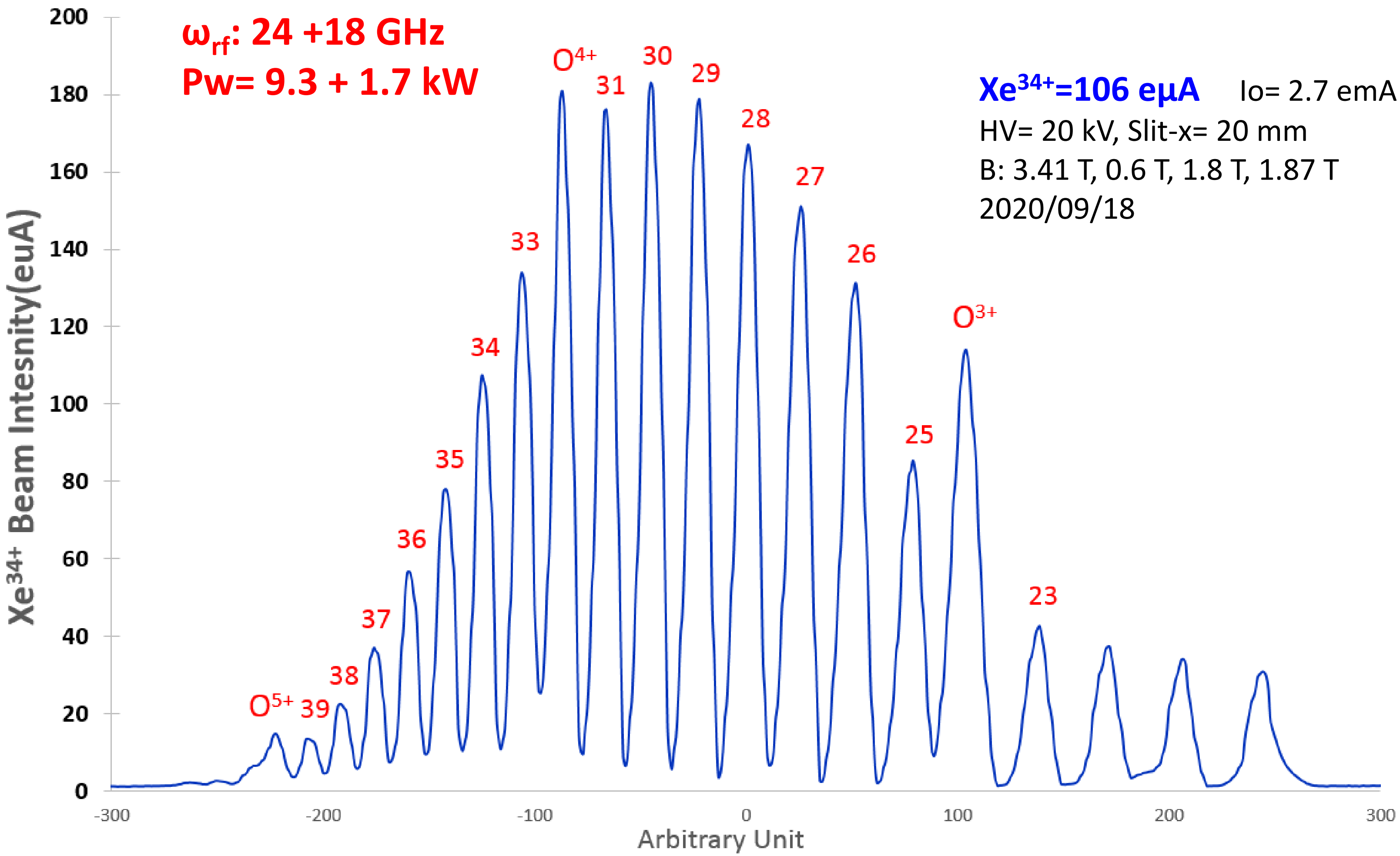




# Plasma chamber with microchannel cooling

| Water pressure (Bar) | Flow rate Channel A (L/m) | Flow rate Channel B (L/m) | Flow rate Channel C (L/m) |
|---|---|---|---|
| 8.9 | 4.3 | 4.2 | 4.6 |

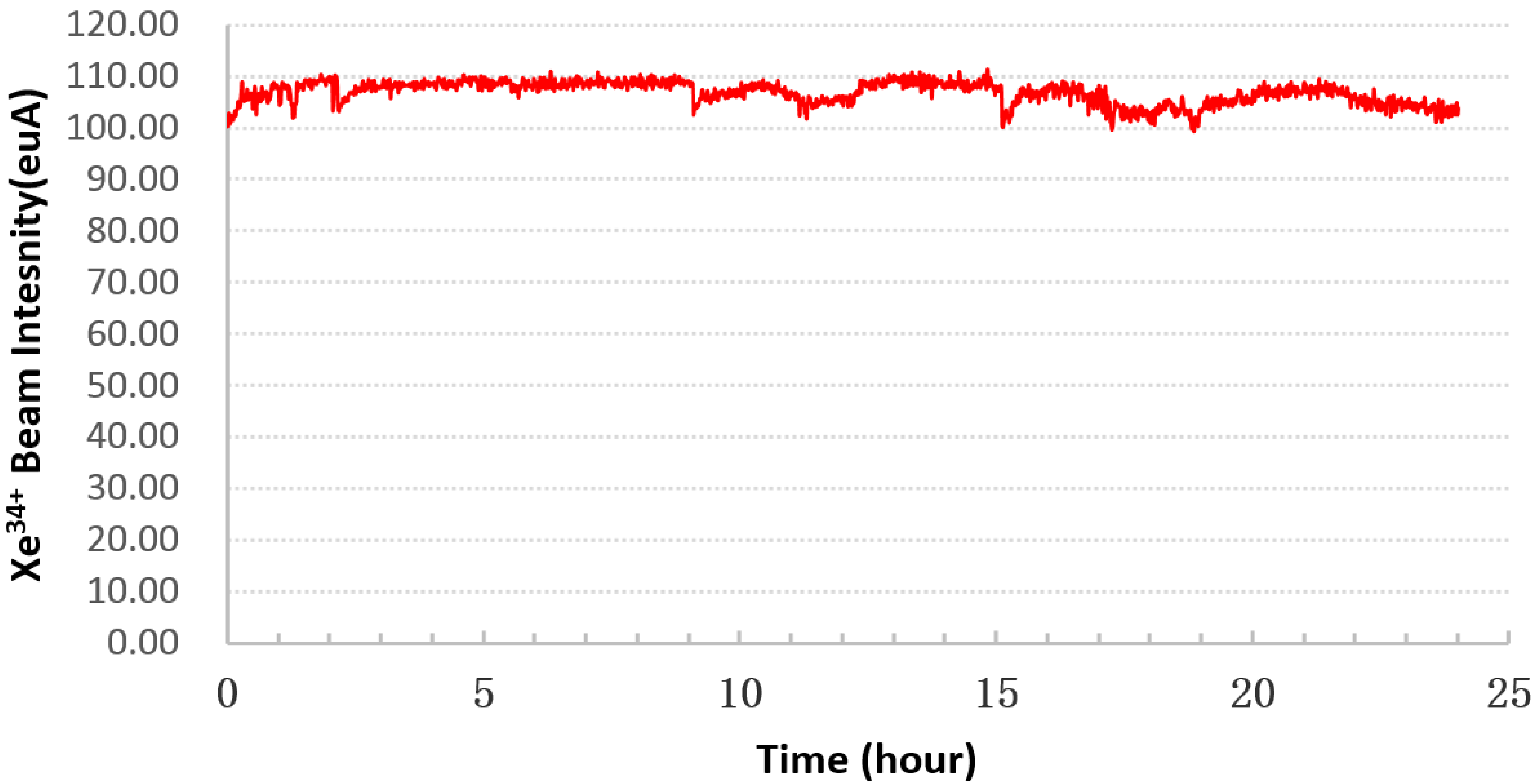
# High power operation

## SECRAL-II operate at the maximum power of the microwave system



# High power operation

**Reliable operation at total power 11 kW for more than 48 hours, including 24 hours for $Xe^{34+}$**



# Summary

- ***The efficiency of microchannel cooling embedded in plasma chamber of ECRIS at high power operation is demonstrated at IMP***

- ***The breakthrough of plasma chamber cooling can make high power (>10 kW) operation reliable***

- ***Microchannel cooling technology is the promising solution for chamber cooling of the fourth-generation ECR ion source with power of 20 kW***

***Thanks for your attention!***