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# A Novel Packaging with Direct Dielectric Liquid Cooling for High Voltage Power Electronics

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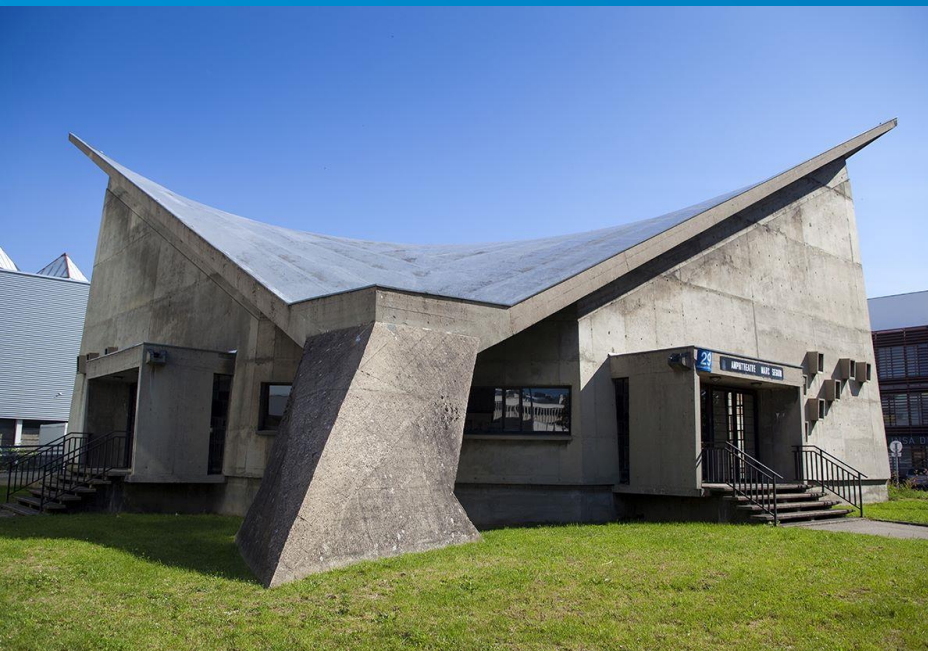
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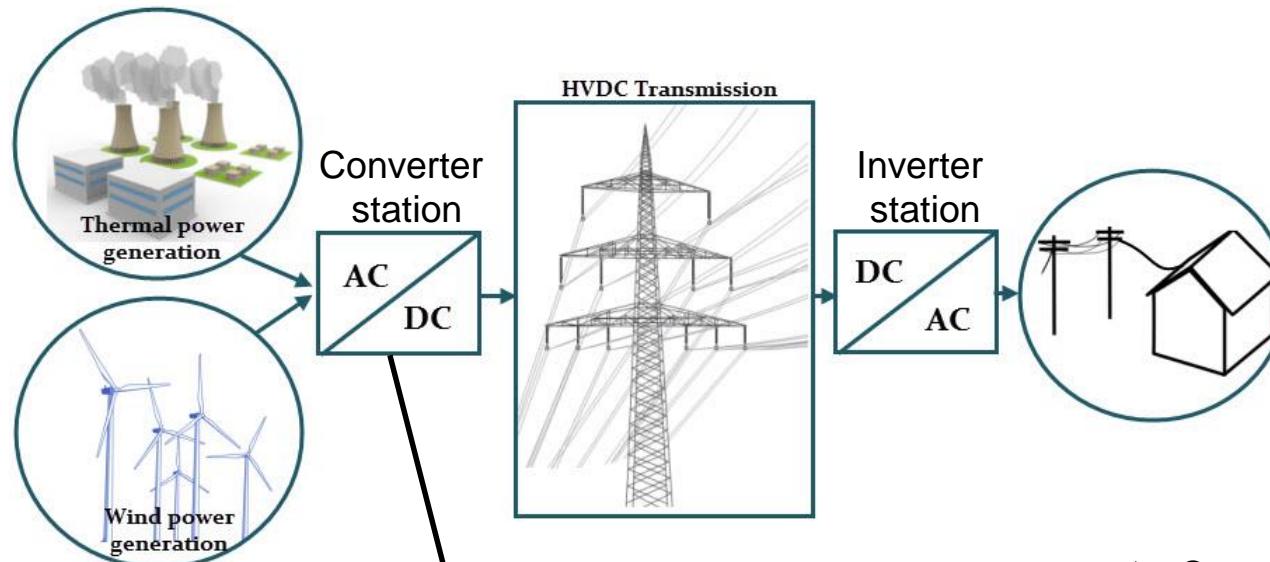
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26.08.2022



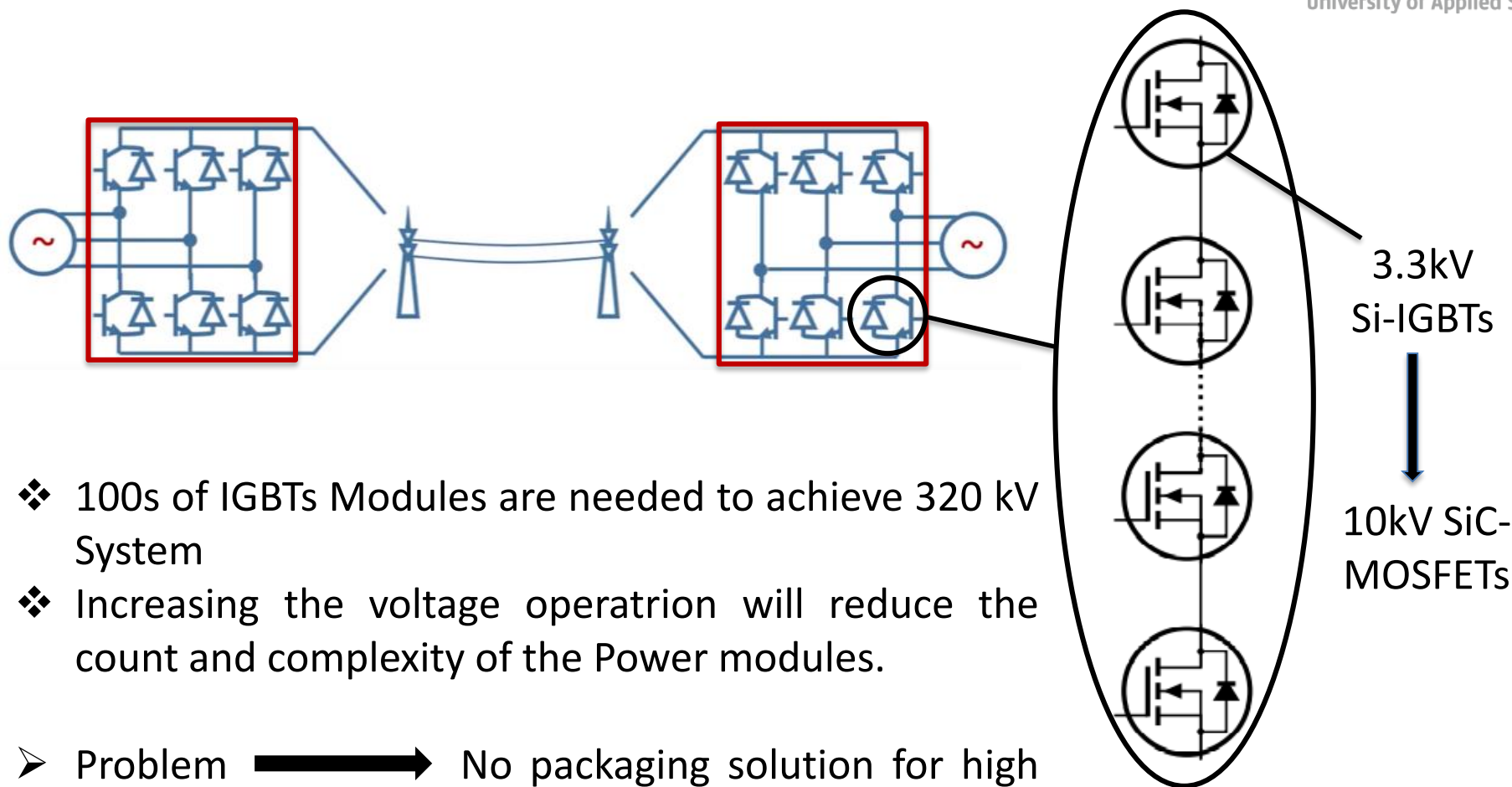
# Motivation: HVDC Converter

- ❖ HVDC converters for high-voltage direct current transmission over long distances
- ❖ Transmission losses significantly reduced by high-voltage direct current transmission



- ❖ Connect fewer modules in series:
  - Lower operating costs
  - Fewer materials
  - Less complexity

# Motivation: HVDC Converter



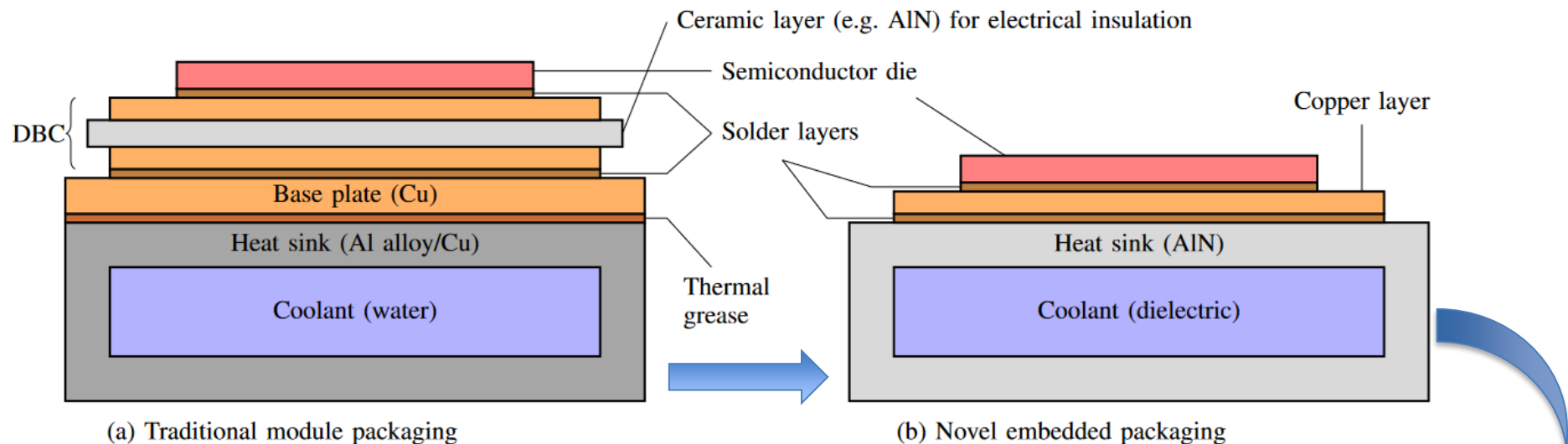
- ❖ 100s of IGBTs Modules are needed to achieve 320 kV System
- ❖ Increasing the voltage operation will reduce the count and complexity of the Power modules.
- Problem **—————>** No packaging solution for high voltage modules (>10kV) yet.
- **This presentation** introduces a novel cooling packaging solution for high voltage power modules



# Outline

- **Motivation**
- **Power module packaging**
- **Selection of dielectric coolant**
- **CFD procedure and packaging design**
- **CFD results**
- **Experimental results**
- **Conclusion and future work**

# power module packaging



(a) Traditional module packaging

(b) Novel embedded packaging

## Advantage:

- Reducing the layers and materials.
- Reducing the complexity of packaging.
- Reducing in the thermal path.

A dielectric fluid is needed for the insulation and cooling

## Challenges:

- Finding a di-electric fluid with good thermal properties.
- Finding a cooling design for efficient cooling.

# Goal of the work

- **Demonstrate a novel approach with simplified single-chip.**
  
- **Select a dielectric coolant:**
  - Thermal performance
  - Good insulation
  - Environmental properties
  
- **Optimize thermal performance**
  - Using CFD calculations
  - Changing the design parameters
  - Trade-off between pumping power and thermal resistance
  
- ❖ **This presentation focuses on thermal performance.**

# Thermal and electrical requirement

- Electrical properties
  - Electrical resistivity:  $9.0 \times 10^5 \Omega\text{m}$
  - Relative Permittivity: matching that of AlN  $\epsilon \approx 8 - 9$ )
- Thermophysical properties
  - Operating junction temperature  $T_o$ :  $-55^\circ\text{C}$  to  $175^\circ\text{C}$
  - Generated heat:  $\dot{Q} = 125 \text{ W}$
  - Die size:  $9.1 \text{ mm} \times 9.1 \text{ mm}$
  - Thermal resistance junction to case:  $R_{th} < 0.48 \text{ K/W}$
  - Target junction temperature:  $T_j \leq 100^\circ\text{C}$
  - Maximum fluid inlet temperature:  $T_{in} = 40^\circ\text{C}$
- Pumping capacity
  - Pumping capacity per die:  $W_{pump} \leq 1.25 \text{ W}$  (1% of dissipated power, arbitrary)
- Environmental requirements
  - Global Warming Potential:  $GWP \leq 200$ , Non-toxic, Non-flammable

# Coolants

Fluid	Sp. heat $c_p$ [W/(kgK)]	dyn. Viscosity $\eta$ [mPas]	Conductivity $\lambda$ [W/(mK)]	Boiling/Flash $T_b$ [°C]	Permittivity $\epsilon$ [-]	Diel. Strength [kV]	Resistivity [MΩm]	GWP [-]
Novec 7100	1213	0.47	0.0659	61	7.4	28	33	297
Novec 7200	1241	0.3625	0.0661	76	7.3	32	4	59
Novec 7300	1166	0.92	0.0625	98	6.1	26.7	10 <sup>3</sup>	210
Novec 7500	1151	0.98	0.0625	128	5.8	35	2	100
Novec 7600	1319	2.4	0.071	131	6.4	≈ 40	10	700
Novec 7700	1045.8	2.83	0.0624	167	6.7	35	5 × 10 <sup>3</sup>	420
MIVOLT DF7	1907	15	0.129	> 194	3.2	> 75	> 9 × 10 <sup>4</sup>	< 1
MIVOLT DFK	1902	72.6	0.147	> 250	3.2	> 75	> 9 × 10 <sup>4</sup>	< 1
Alpha-6	2203	25.265	0.1561	246	2.11	58	?	< 1
Alpha-4	2206	15.38	0.1470	220	2.10	58	?	< 1
Alpha-2	2205	4	0.1358	160	≈ 2	58	?	< 1
OptiCool-H	2206	3	0.1346	> 135	2.12	53	10 <sup>6</sup>	< 1
OptiCool PH5	2203	4.9	0.1363	> 151	2.12	53	10 <sup>6</sup>	< 1
EC-120	2212	4	0.1359	157	2.1	60	> 10 <sup>6</sup>	< 1
BIO ELECTRA	1970	36	0.1691	> 250	3.1	65	74	< 1
BitCool	2054	6.64	0.1396	> 130	-	-	-	-
Silicon Transormer	1510	48	0.151	> 300	2.7	50	10 <sup>6</sup>	< 1
Panolin Trafosynth	2040	11.7	0.13	< 240	-	-	-	-
Water/Glycol	3420	2.45	0.404	110	-	-	-	-
Water	4135	0.65	0.63	100	-	-	-	-

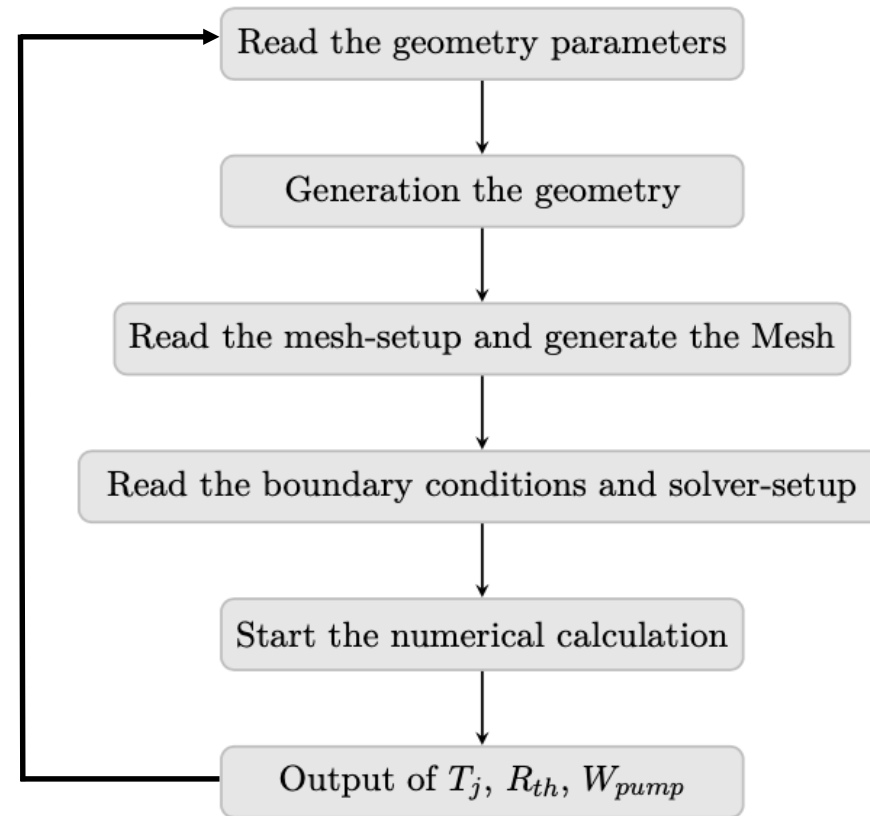
Selected fluid:  
- Novec 7500

- Meets the Requirements
- Near to the Requirements
- Very far from the Requirements



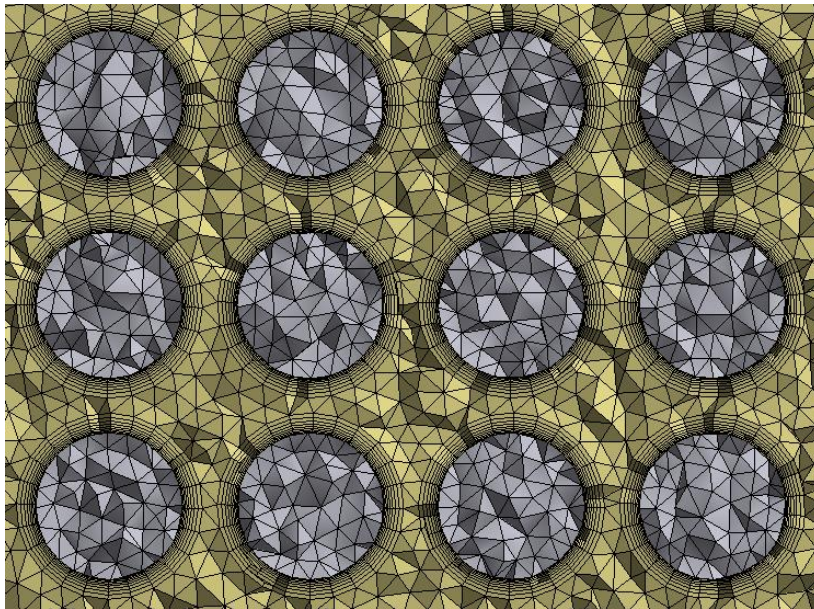
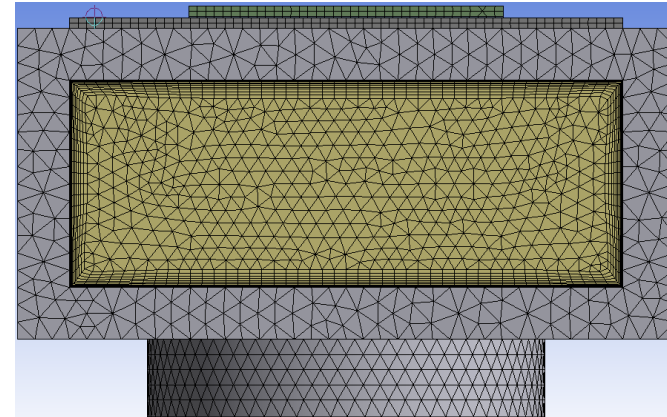
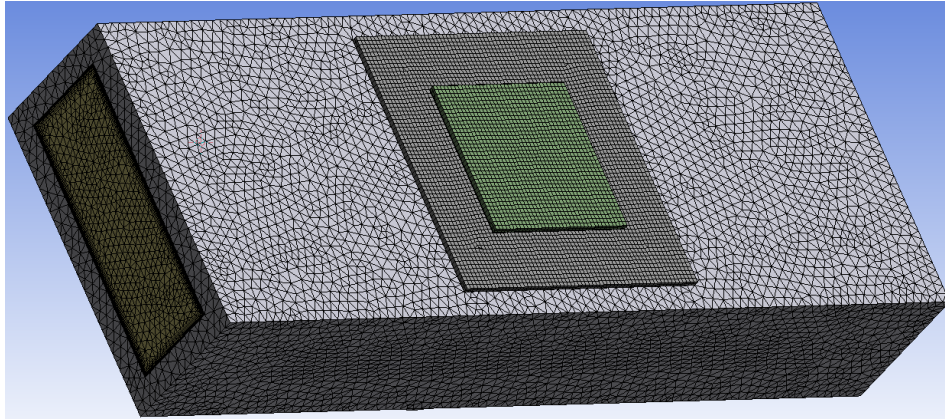


# Procedure for the CFD simulation



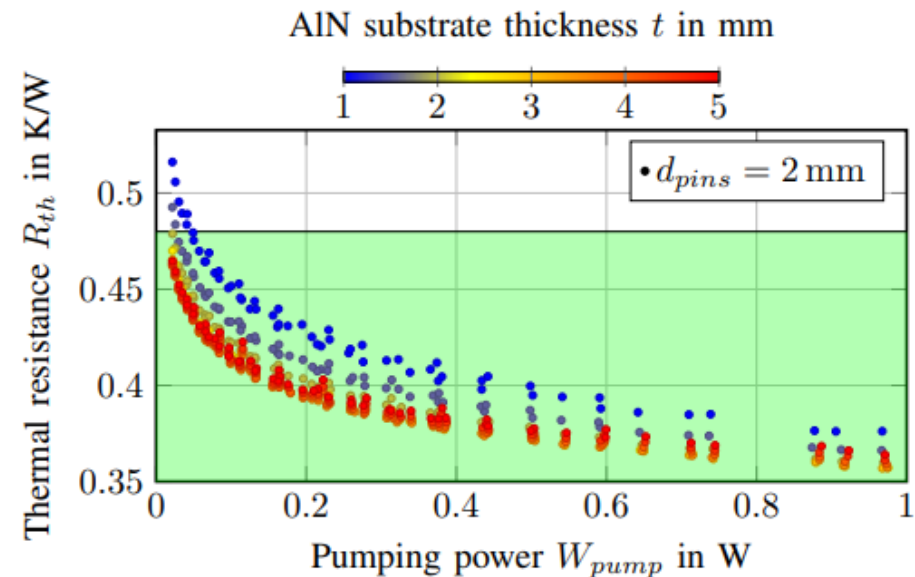
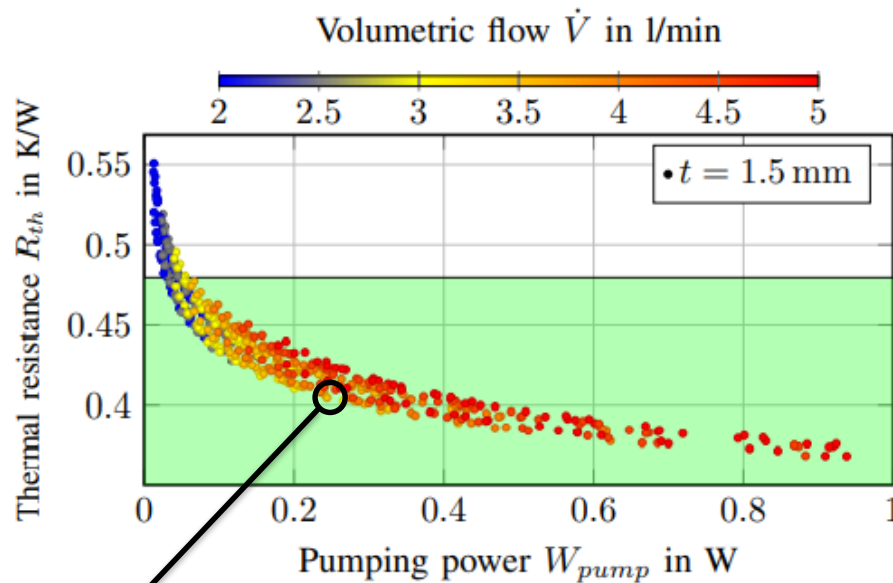
- The simulation were carried out using the “ANSYS CFD”.
- Every simulation takes between 10 and 30 minutes depending on the parameter.
- Hundreds of simulations are done.

# Numerical Mesh



- Finer mesh at the fluid-solid interface because of higher temperature and velocity gradient there.
- The mesh layers (inflations) deliver a better resolution of the velocity and the temperature gradient at the boundary.

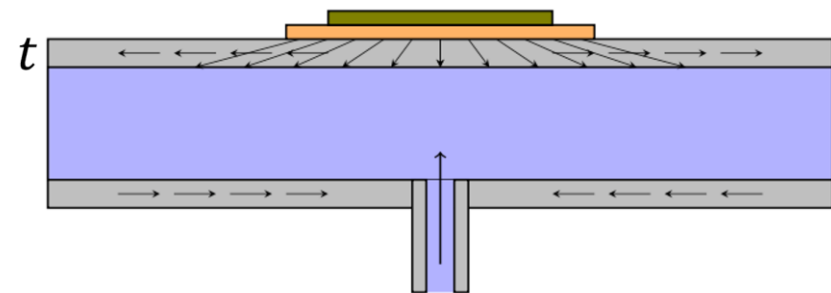
# CFD Results (Novec 7500)



## Parameter set:

- $d_{pins} = 2$  mm
- $d_{jet} = 7.5$  mm
- $h_{pins} = 6$  mm
- $t = 1.5$  mm & 3 mm

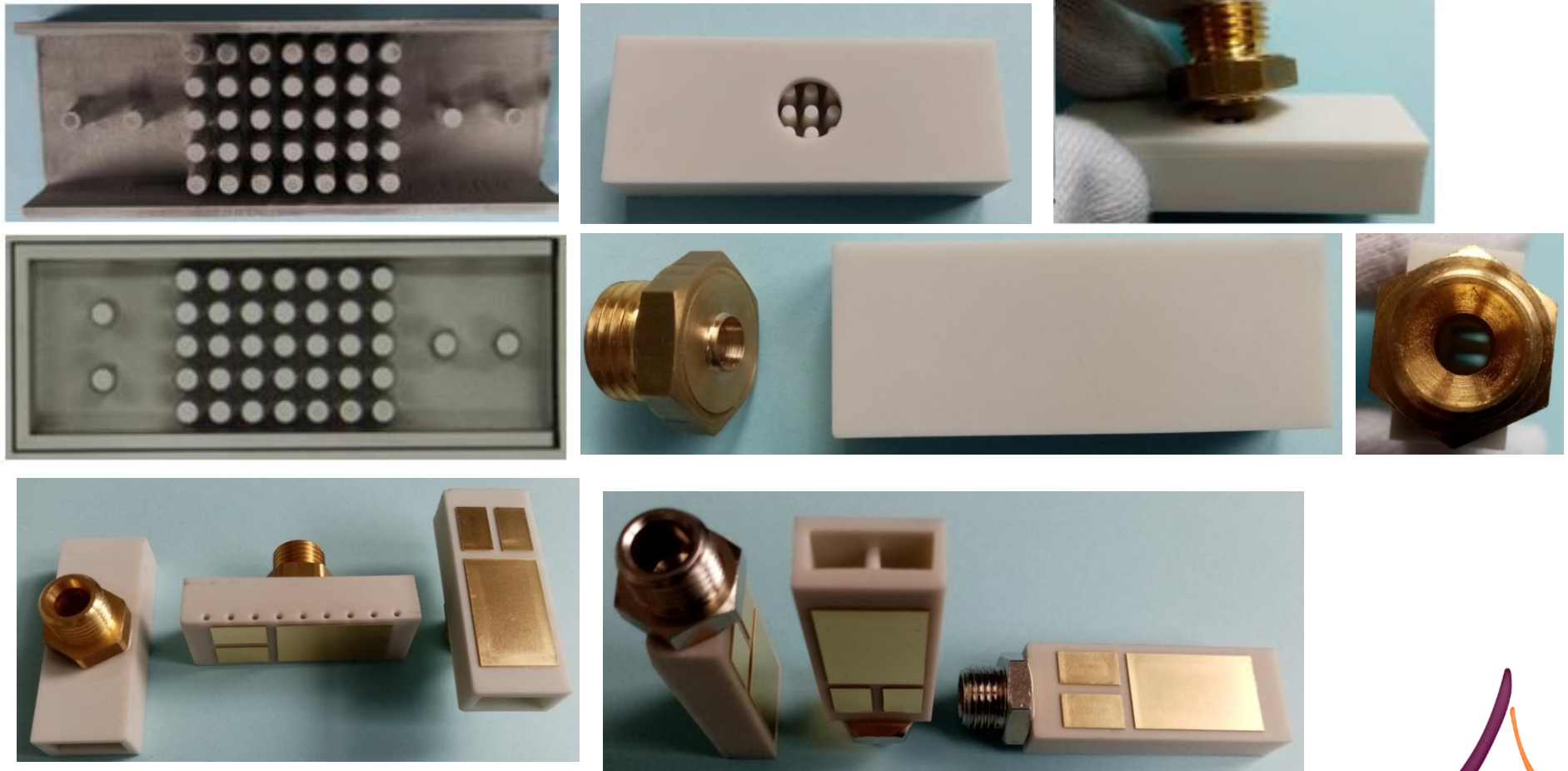
- ❖ Higher flow rate  $\rightarrow$  lower  $R_{th}$
- ❖ Longer pins  $\rightarrow$  lower  $R_{th}$
- ❖ Thicker AlN shows a better cooling
- ❖ Above 3 mm AlN no further improvement to see





# Fabrication of the coolers

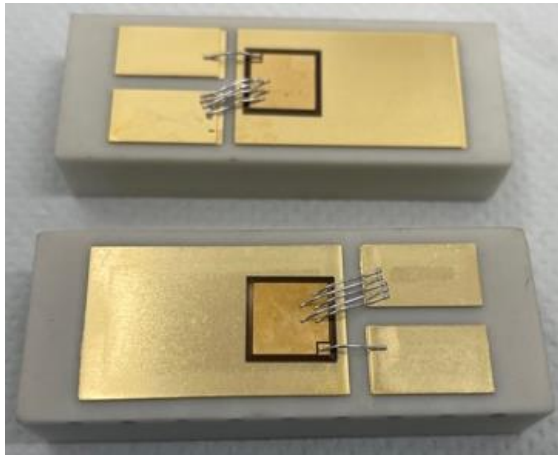
- 1) Two ceramic parts (a flat bottom and a top) are joined together to form a single unit cooler
- 2) Copper metallizations (for the chip interconnects) and a brass fitting (forming the inlet) are then attached to the ceramic cooler





# Fabrication of the coolers

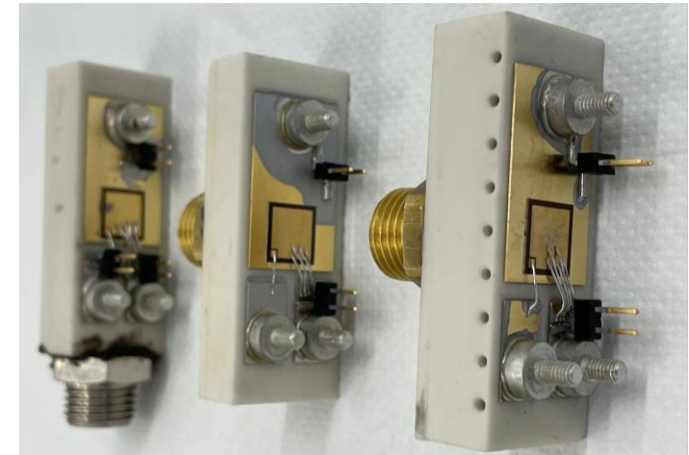
- 3) 9.1 x 9.1 mm<sup>2</sup> IGBTs (heat source) are sintered on the copper pad
- 4) Thick Al wire-bonding between the copper pads and chip
- 5) connectors are soldered on the metal pads for the electrical connection to the outside world



IGBTs sintering and  
Al wire-bonding



connector soldering

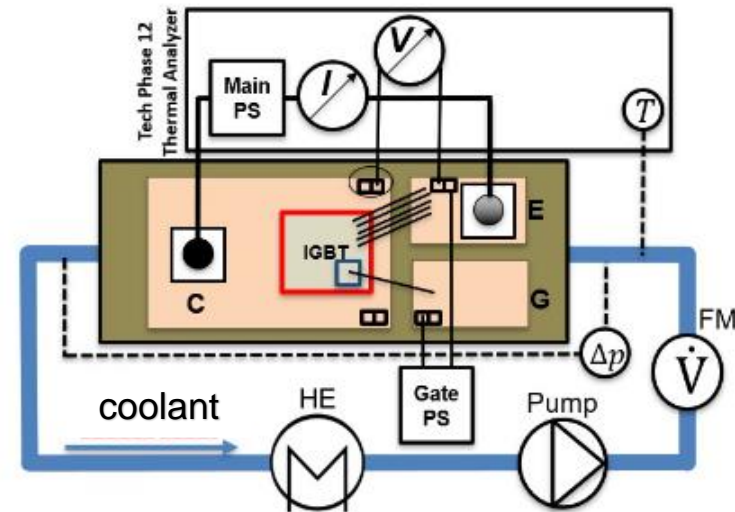


final prototypes

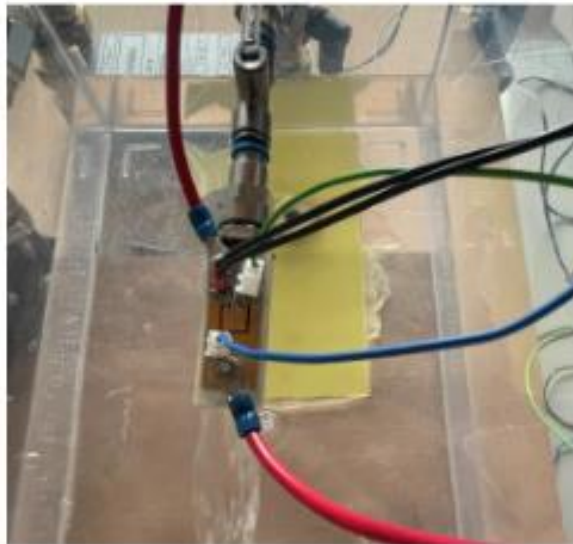
# Test setup



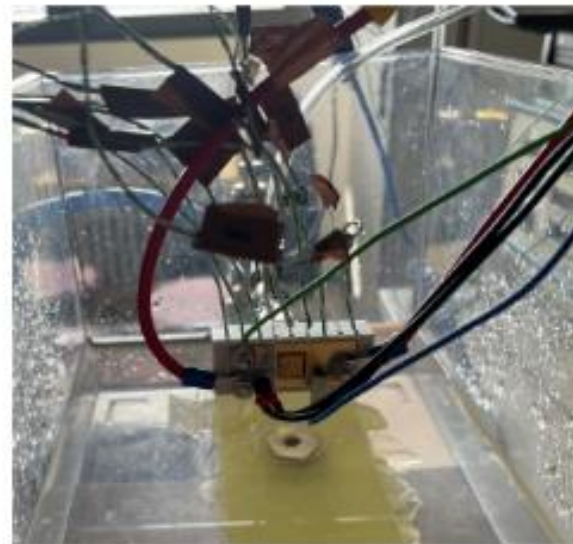
A photograph of the test setup  
(Phase 12B, Analysis Tech)



Schematic test setup

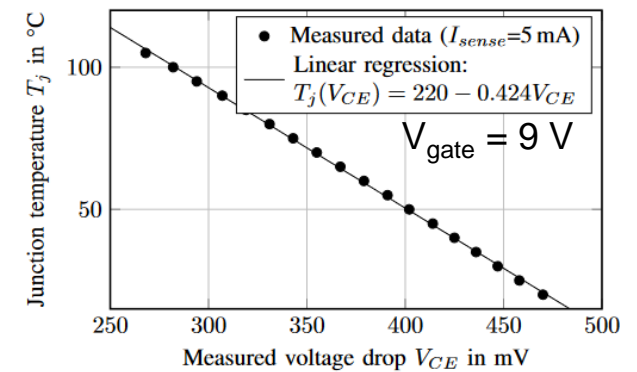


Channel flow



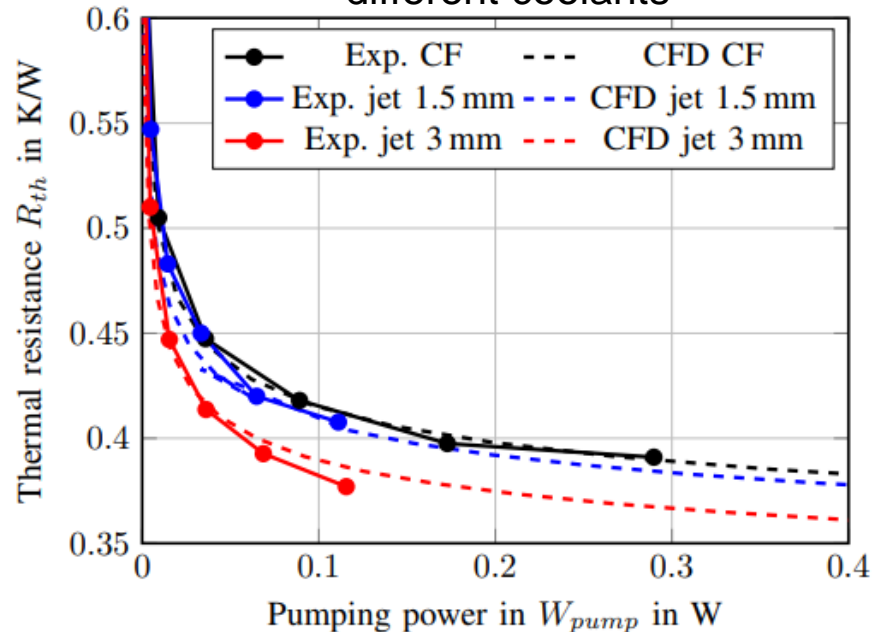
Jet impingement

Calibration the temperature-sensitive electrical parameter used for junction temperature monitoring

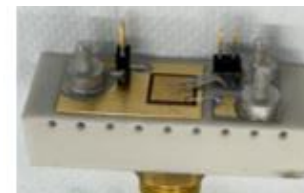
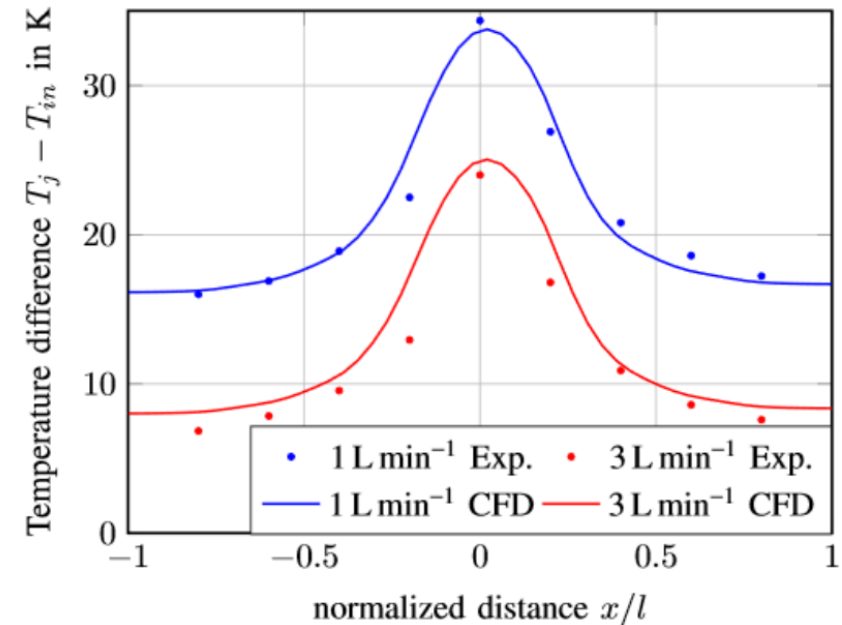


# CFD vs Experiment

CFD vs experimental for different coolants

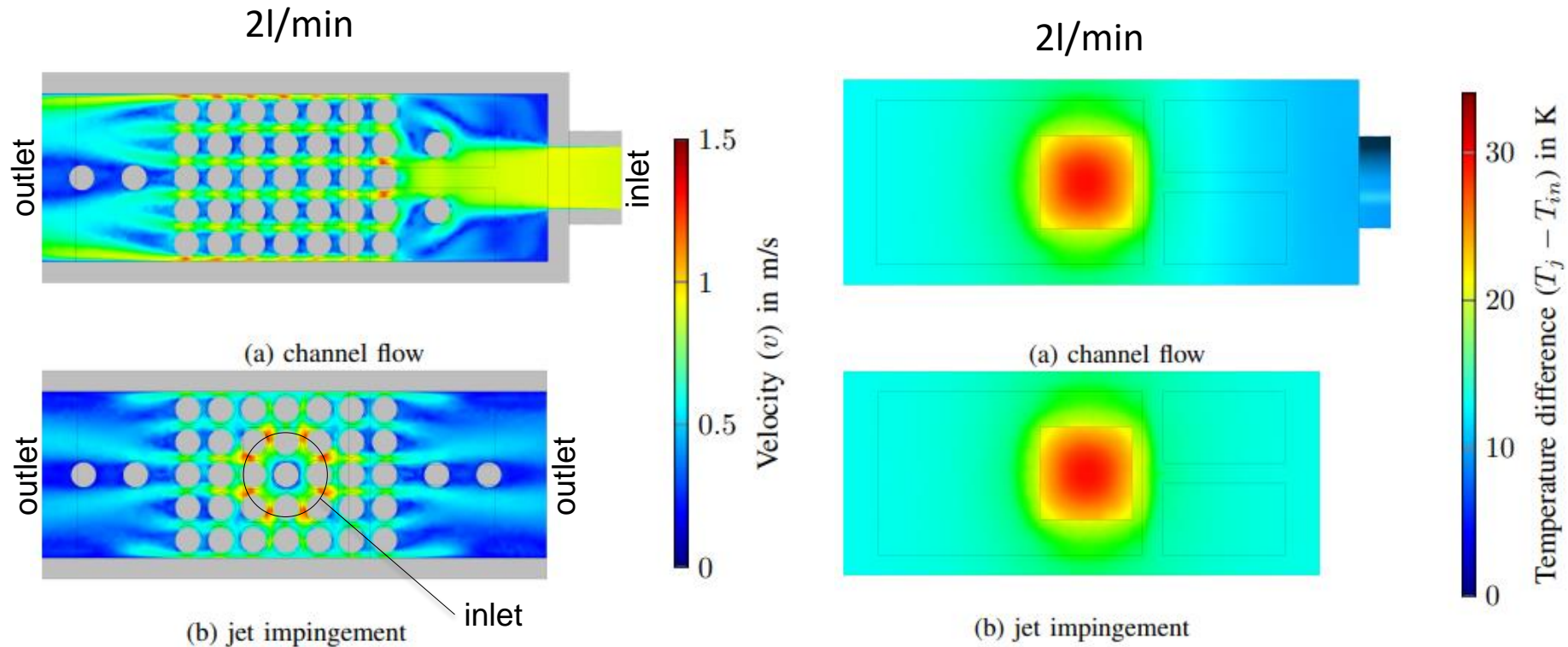


Temperature distribution in the AIN for the jet cooler ( $t = 3\text{mm}$ )



- ❖ In general, a good agreement between the CFD und experimental results.
- ❖ The thermal requirement was achieved by reaching a junction temperature of less than 100 C.

# Channel flow vs jet impingement



- By the jet impingement concept a higher velocity could be achieved
- A similar temperature distribution by both concepts. However jet impingement has much lower pumping power



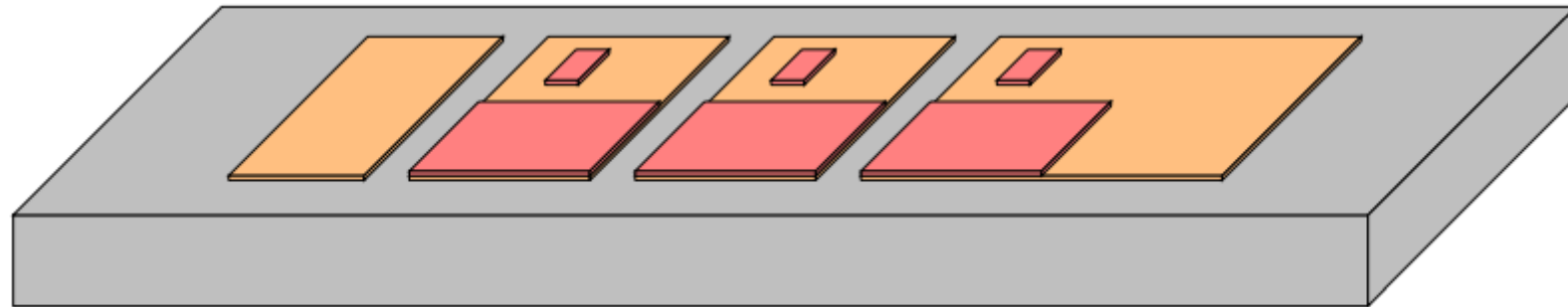
# Conclusion

- A single-chip cooling novel structure is optimized using CFD simulation
- Simulation and experimental results are in good agreement, and show that the demanding requirements ( $R_{th} < 0.48 \text{ K/W}$  for a 125 W power dissipation over a  $9.1 \times 9.1 \text{ mm}^2$  chip area) can be met.
- Because of its lower pressure drop and higher fluid velocity the jet impingement structure is found to be more efficient than the channel flow structure.
- A thick ceramic layer (up to 3 mm) is found to be beneficial because of the increased heat spreading effect it offers.

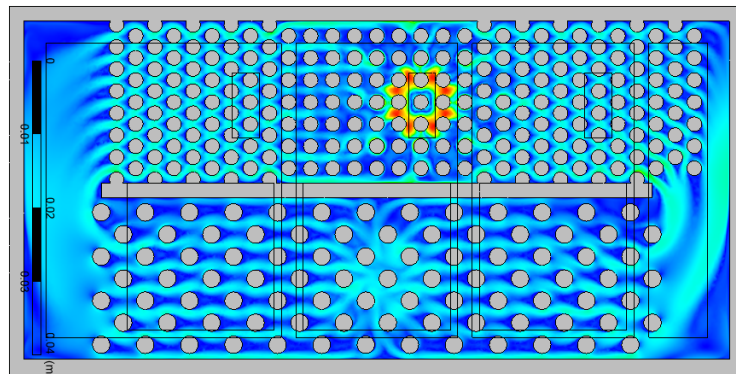
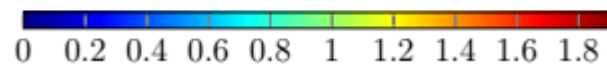


# Future work

- Build a multi-dies „20kV“ module

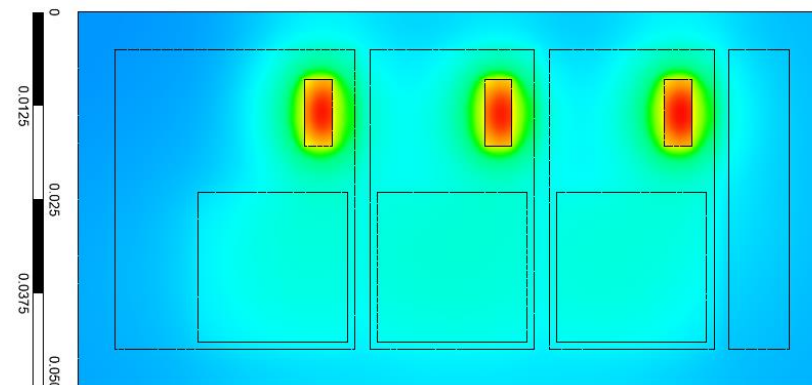


Velocity ( $v$ ) in m/s



Velocity in the middle of the system (3l/min)

Temperature ( $T$ ) in °C



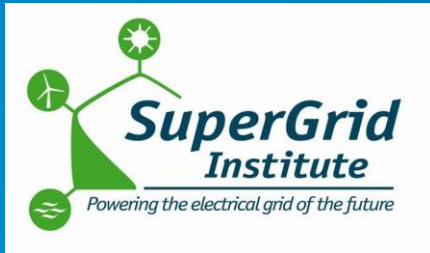
Temperature distribution in the system (3l/min)

- ❖ Mixture of in-line and staggered pins
- Better temperature distribution ( $dT < 3^\circ \text{C}$ )



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**Thank you for your attention**

