The development of a BNCT facility at Birmingham University using a solid lithium target

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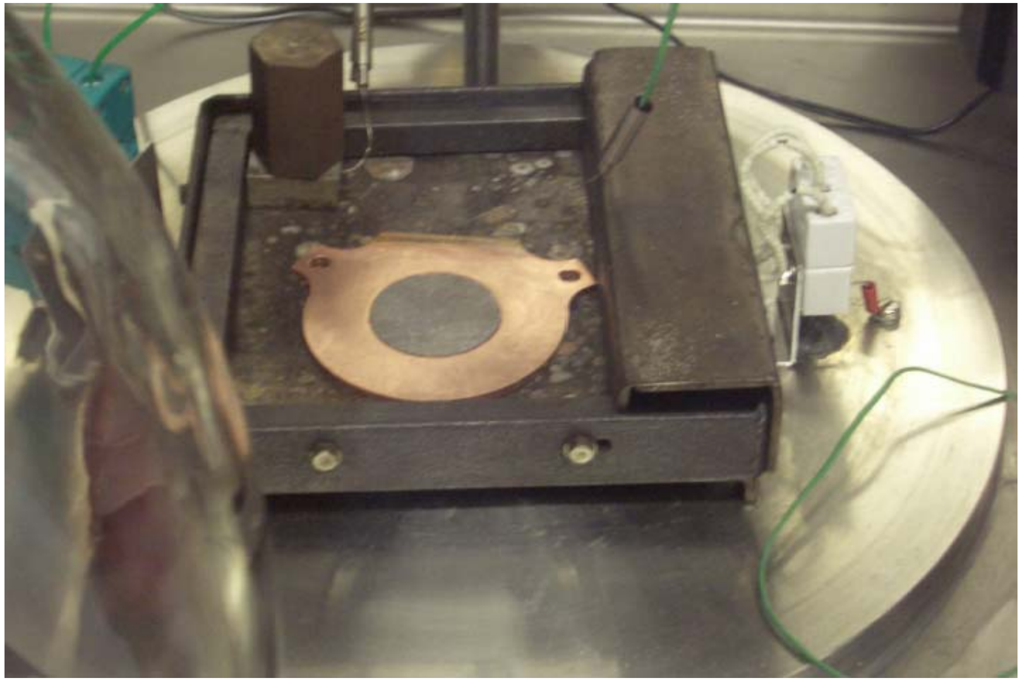
Current target

- Natural lithium bonded to an oxygen free copper backing.
- The lithium is thick in comparison to the proton range; 0.7mm lithium thickness vs ~0.3mm range at 2.8MeV.

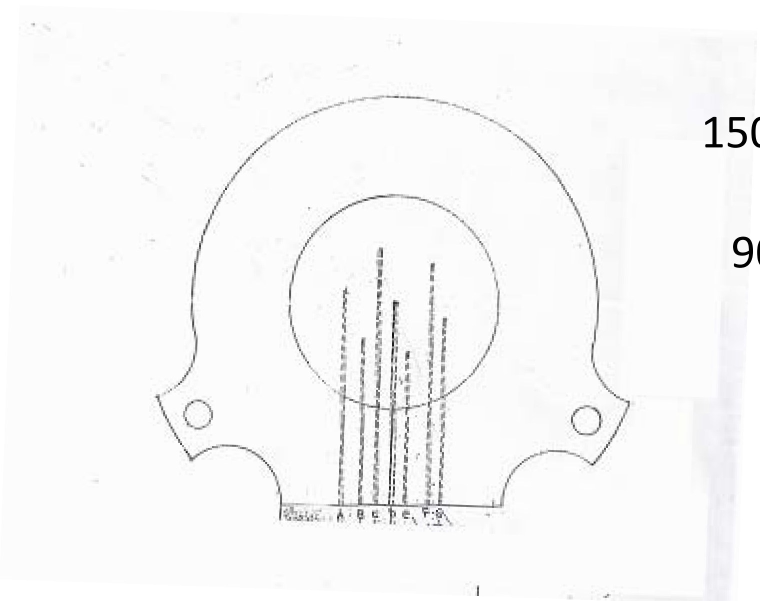
This avoids potential blistering of the copper at the expense of more demanding cooling requirements and slightly increased gamma dose.

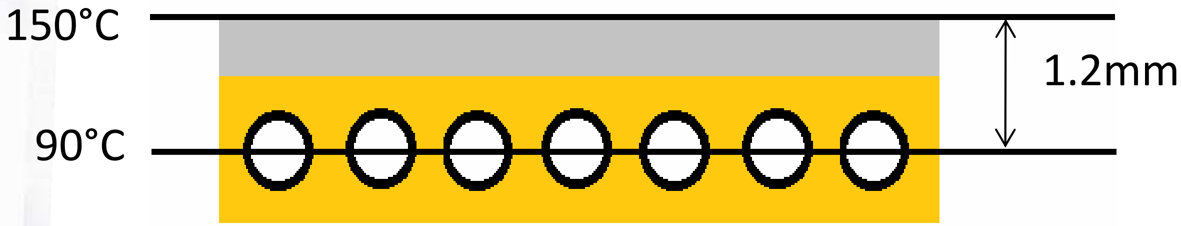


Target monitoring

The temperature of the target is monitored by 7 thermocouples positioned in a radial pattern within the copper backing.

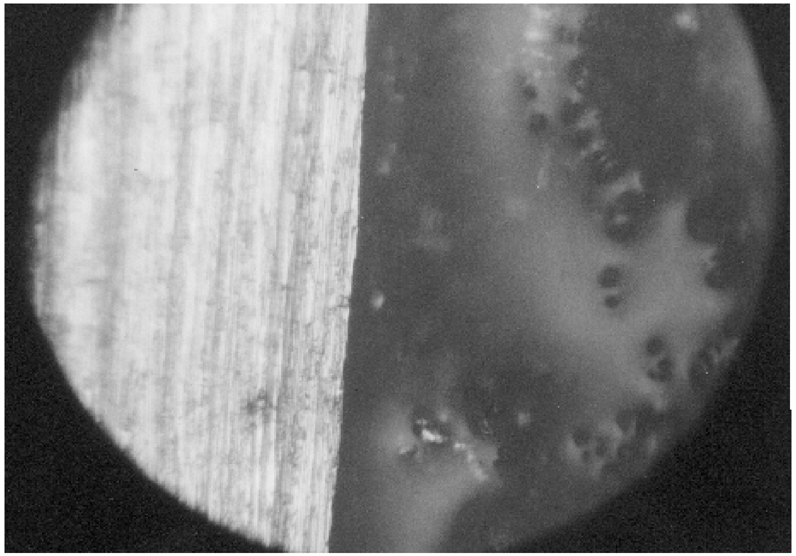
These are an integral part of our safety system and result in the beam being cut off in the event of overheating.

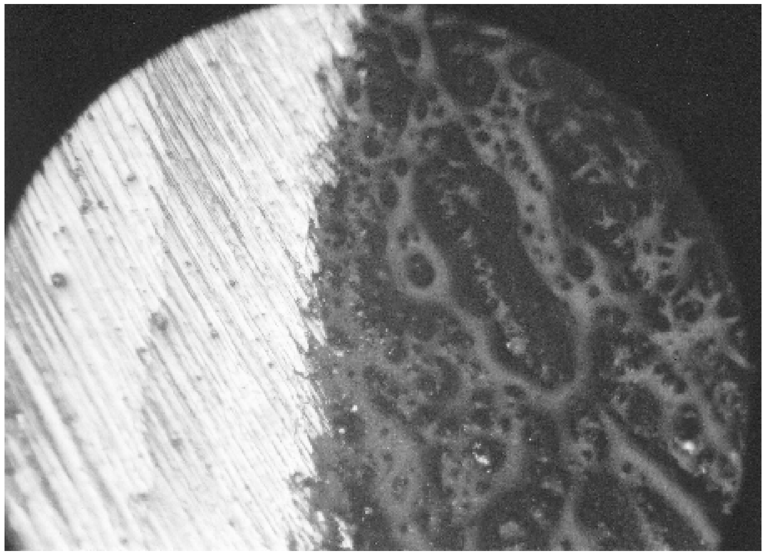




Lithium bond

- Simply pressing lithium into the target proved inadequate.
- A combined mechanical and thermal bonding process was developed experimentally.
- An intermetallic layer is formed at the interface with very low thermal impedance and excellent mechanical properties.



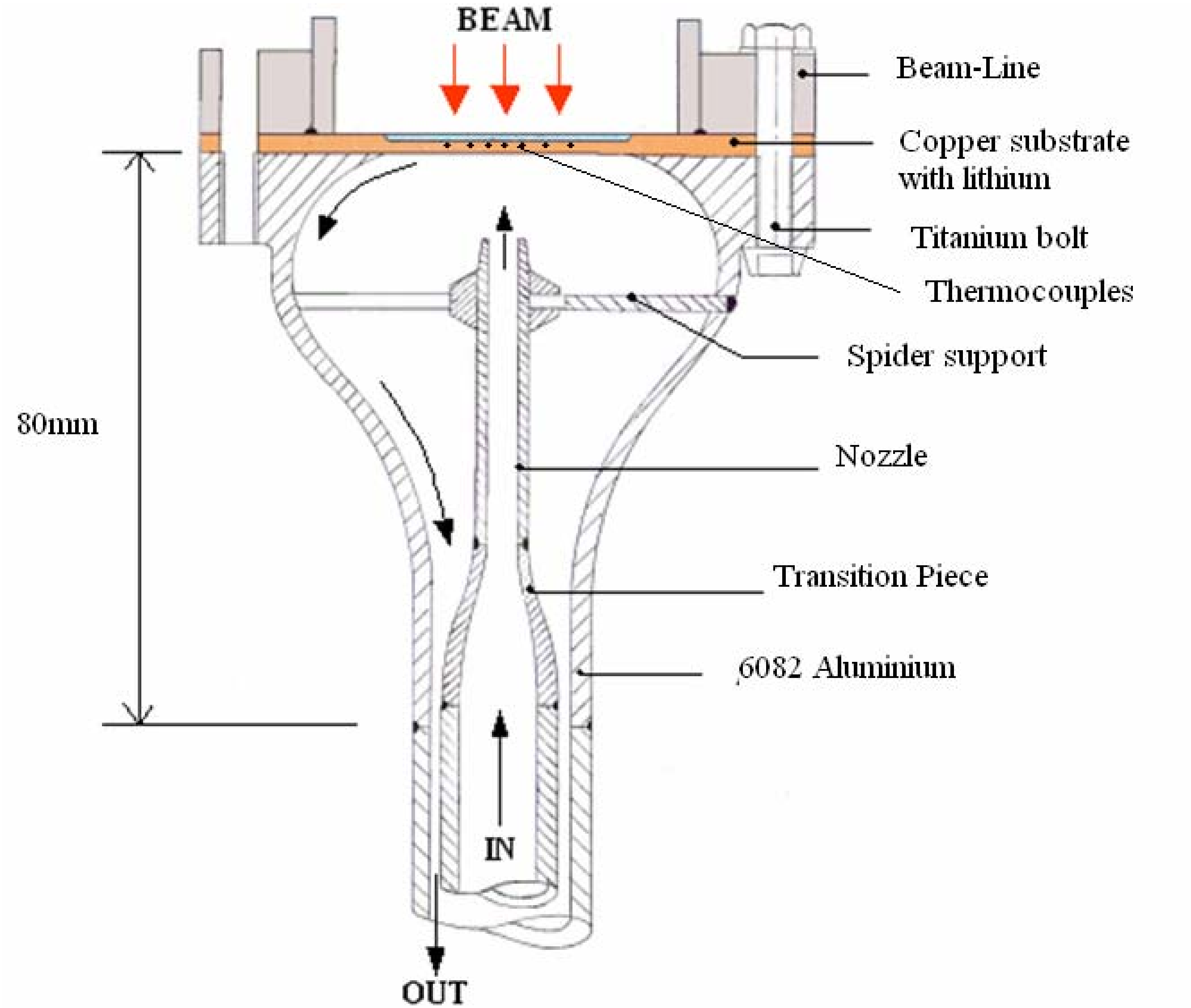


Unheated vs 200 degrees C for 4 hours, 240x magnification

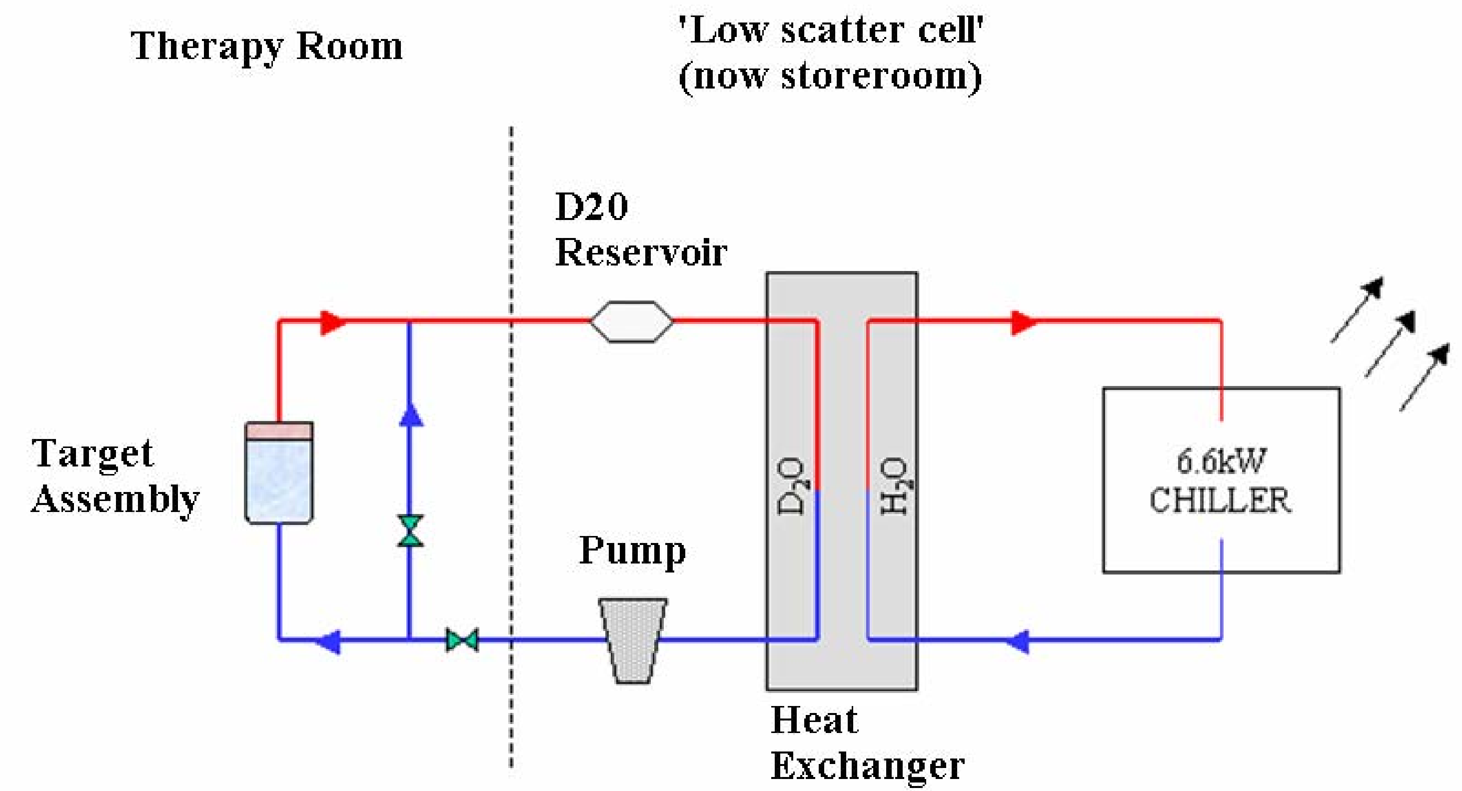
Original cooling system design requirements

- Keep the lithium below it’s melting point at all times.
- Handle beam currents of 2mA at 2.5MeV on a 40mm diameter target.
- Neutron losses as low as practically possible.
- Enable quick target changes to minimise operator radiation doses.

Original cooling design



Cooling loop layout



- Current pumping rates are ~40L/min, with an inlet pressure at the target assembly of around 10 bar.
- This setup handles the maximum output of the accelerator with peak target temperatures of ~110 degrees.

Possible modifications to cope with higher beam powers

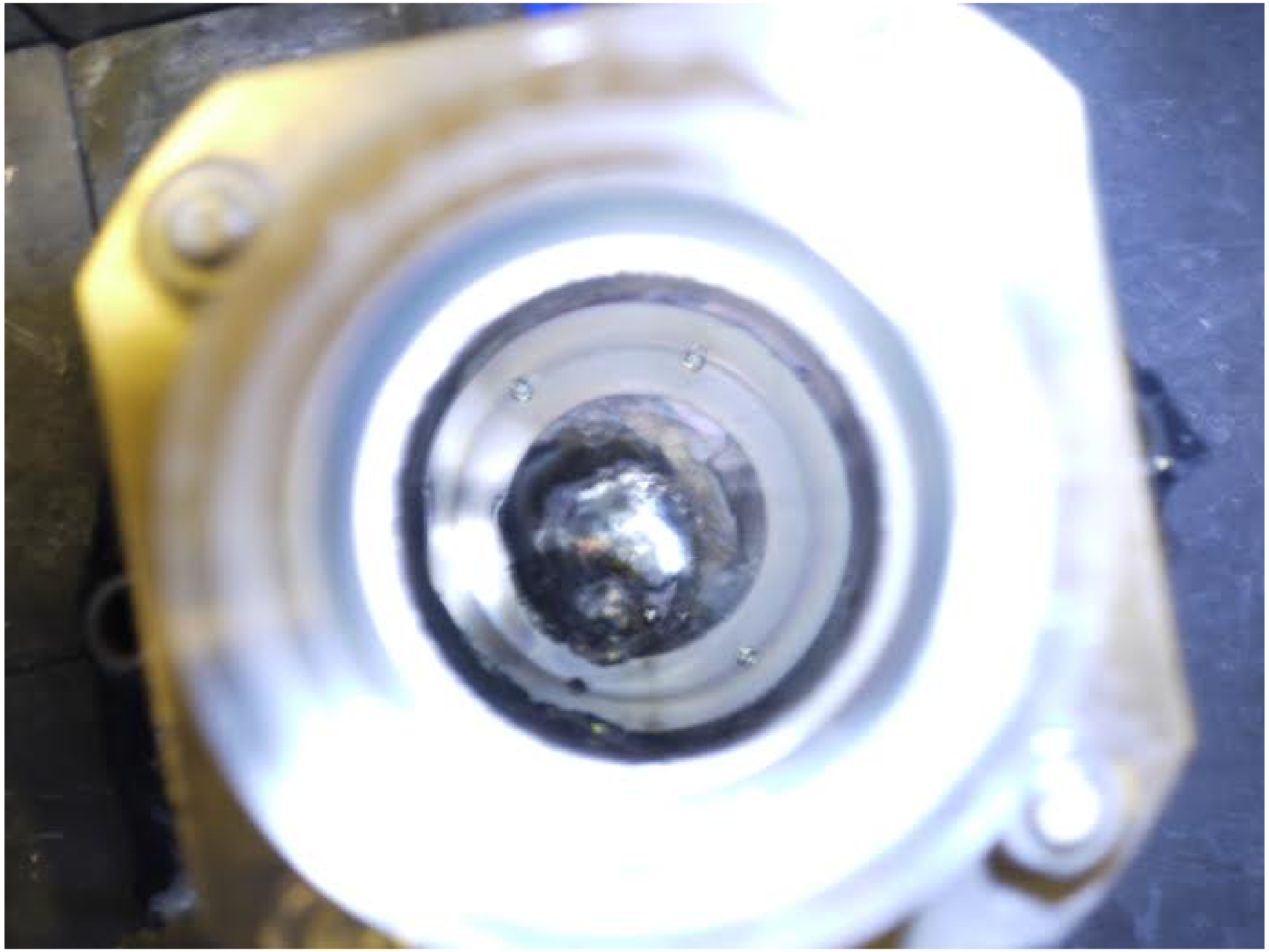
It is proposed that a replacement ion source and supporting modifications will increase the maximum output current by a factor of three or more.

- Increase pumping power
- Lower coolant temperatures (along with a change of coolant?)
- Increase target size and beam scanning
- Allow higher lithium temperatures
- Change the coolant jet geometry

Molten lithium

- Original restriction of no lithium melting was driven by safety case concerns, not fundamental physics. The vapour pressure of lithium is actually very low, near the melting point.
- Other groups are testing circulating molten lithium loops.
- Recent experience suggests that the lithium could be molten for >50 hours in our system with no significant evaporation.

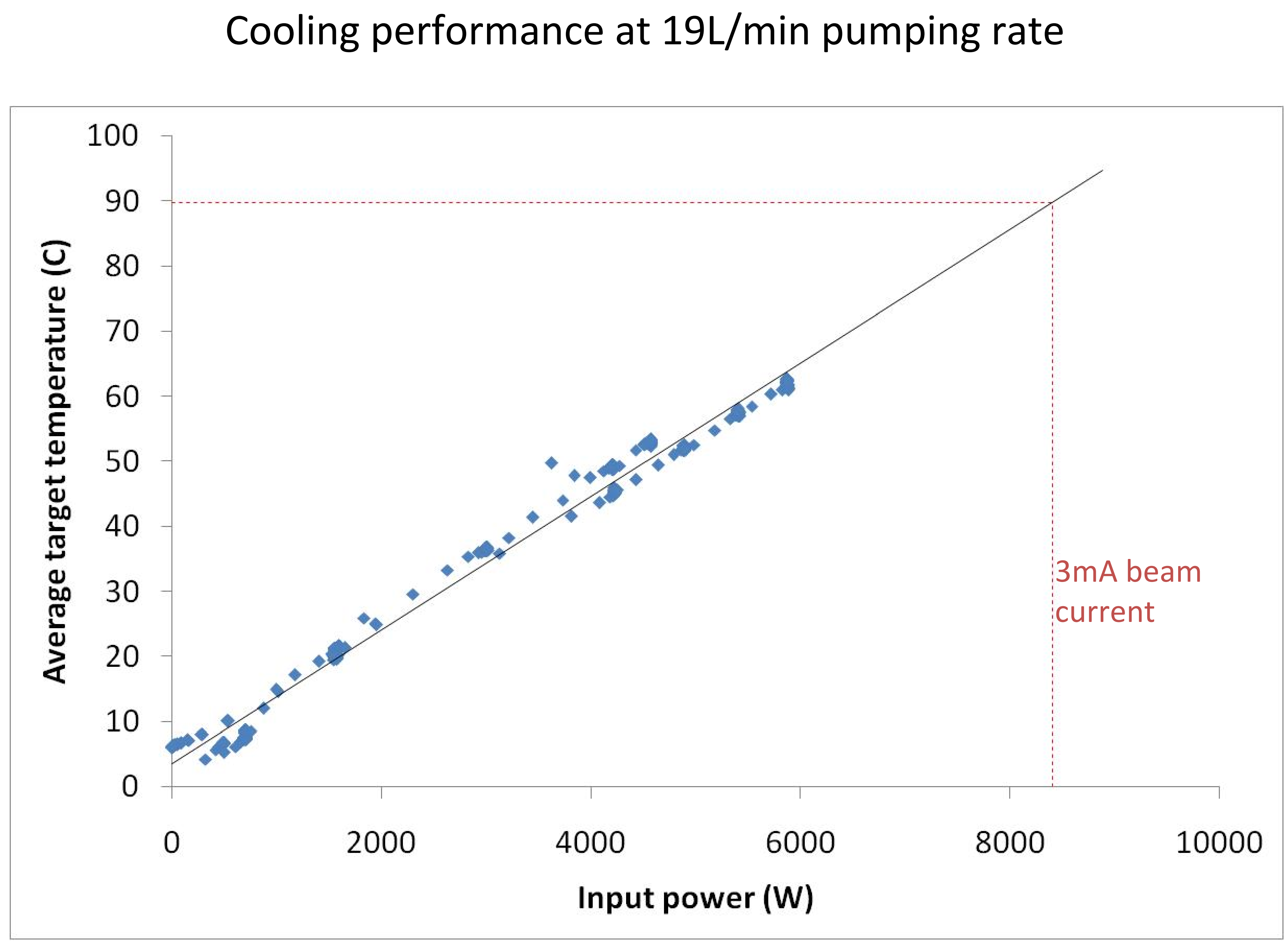
Further tests with molten lithium on copper are required. These will establish the stability of the lithium-copper interface layer over long time periods.



Thick lithium target after extended 2.5MV, 0.5mA irradiation

Coolant temperatures

- The current water inlet temperature is ~12°C. Reducing this will give a gain in cooling performance. This is currently limited by the existing chiller specification.
- Reducing temperatures to the point where anti-freeze is required is a trade off; the heat transfer coefficient is reduced from that of pure water. Novel fluorocarbon coolants allowing extremely low temperatures are available.
- Experiments with an induction heated target blank suggest that uniform beam scanning over a full 40mm circle and coolant temperatures of ~6°C would allow 3mA of beam current with acceptable target temperatures.


Cooling performance at 19L/min pumping rate
Average target temperature (C)
100
90
80
70
60
50
40
30
20
10
0
0
2000
4000
6000
8000
10000
Input power (W)
3mA beam current

Phase change coolants

Coolants which exploit the latent heat of melting of microscopic solid particles suspended in a water/anti-freeze mixture.

We tested "binary ice" in our system; a mixture with tens of micron scale ice crystals as the phase change material.

- It has similar pumping characteristics to water.
- It is widely used in submersion cooling of food – particularly fish. Some use in large refrigeration/air conditioning plants with variable cooling demands.

Binary ice tests in our submerged jet system

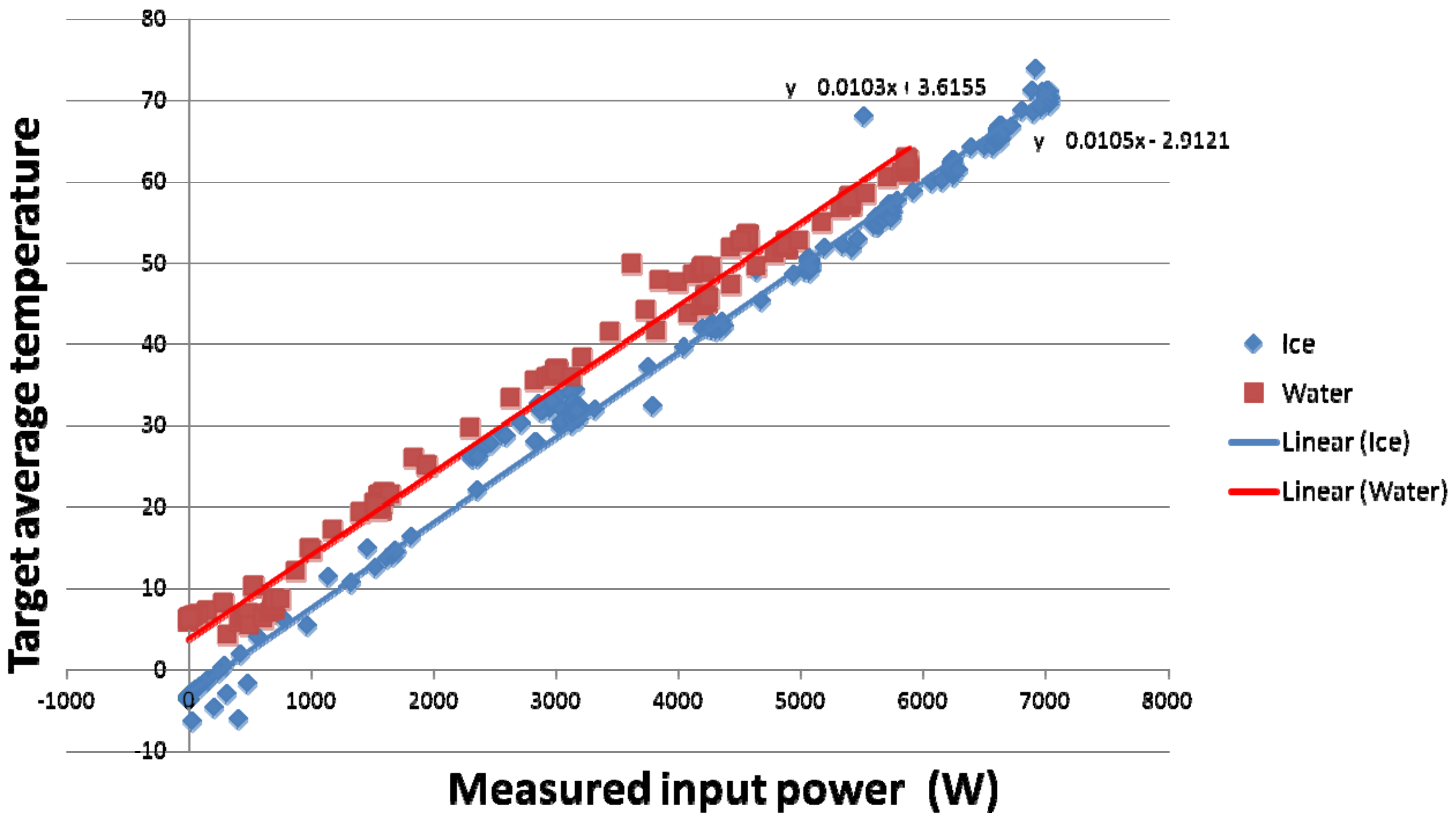
Tests were carried out at Cooltech GmbH in Germany; manufacturers of the binary ice production equipment.

We used a commercially available induction heating unit (EFD Minac) to provide the heat input, with a nominal 25kW continuous output. Difficulties with coupling the power directly into copper meant that we were limited to approximately 7kW maximum input.

Mains water at 6°C was directly compared to a 20% ice fraction mixture at -3 degrees Celsius at various flow rates

Target blank with copper boss and steel plate.

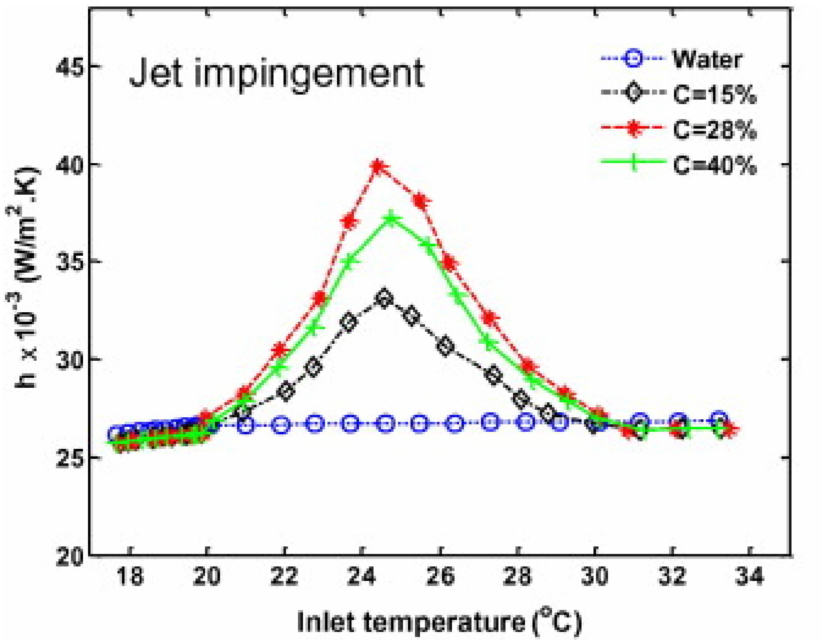
Comparison of the cooling performance of binary ice and water



No clear advantage, in our system, of binary ice over chilled water. The temperature distance is approximately constant and equal to the difference in coolant input temperatures.

Why no improvement?

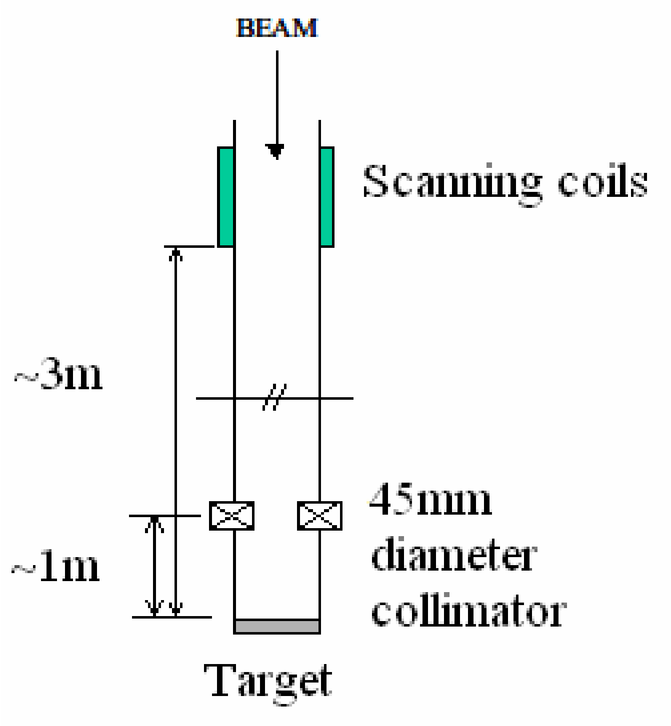
The flow velocity in our jet system is high (~20 ms^{-1}) so the residence time where a given ice crystal is in contact with the backing plate is very short. This may mean that there is not enough time for significant melting of the ice crystals close to the plate.



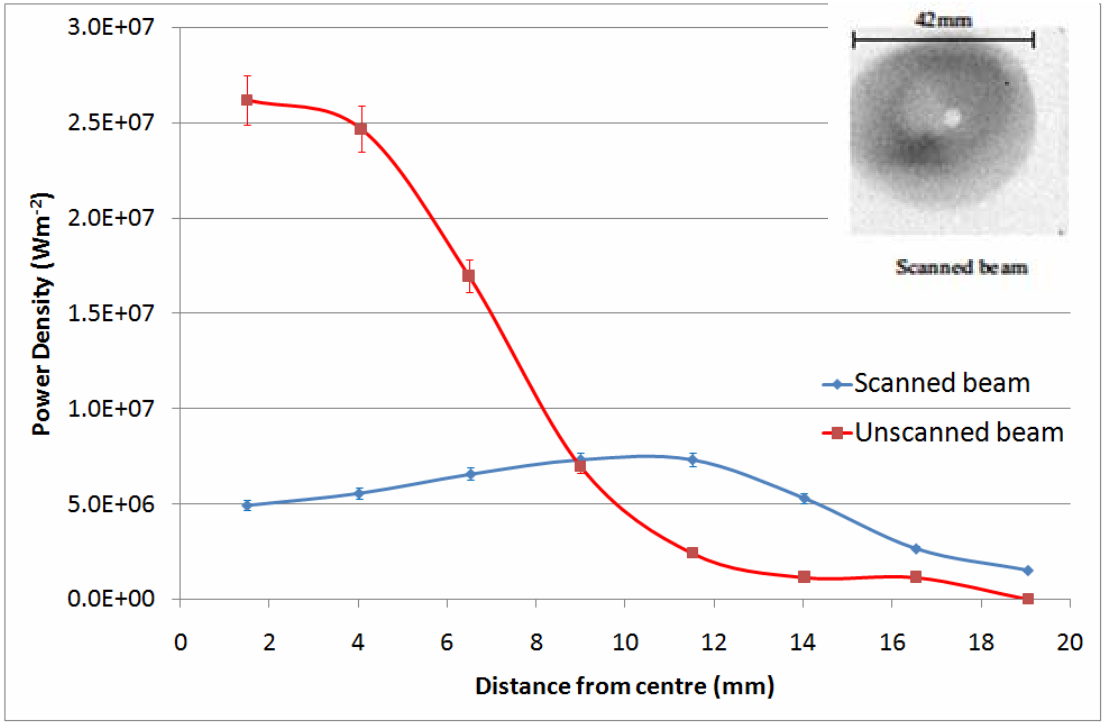
From; Wu, W., et al. "Jet impingement and spray cooling using slurry of nanoencapsulated phase change materials." *International Journal of Heat and Mass Transfer* 54.13 (2011): 2715-2723.

Nozzle geometry and beam scanning

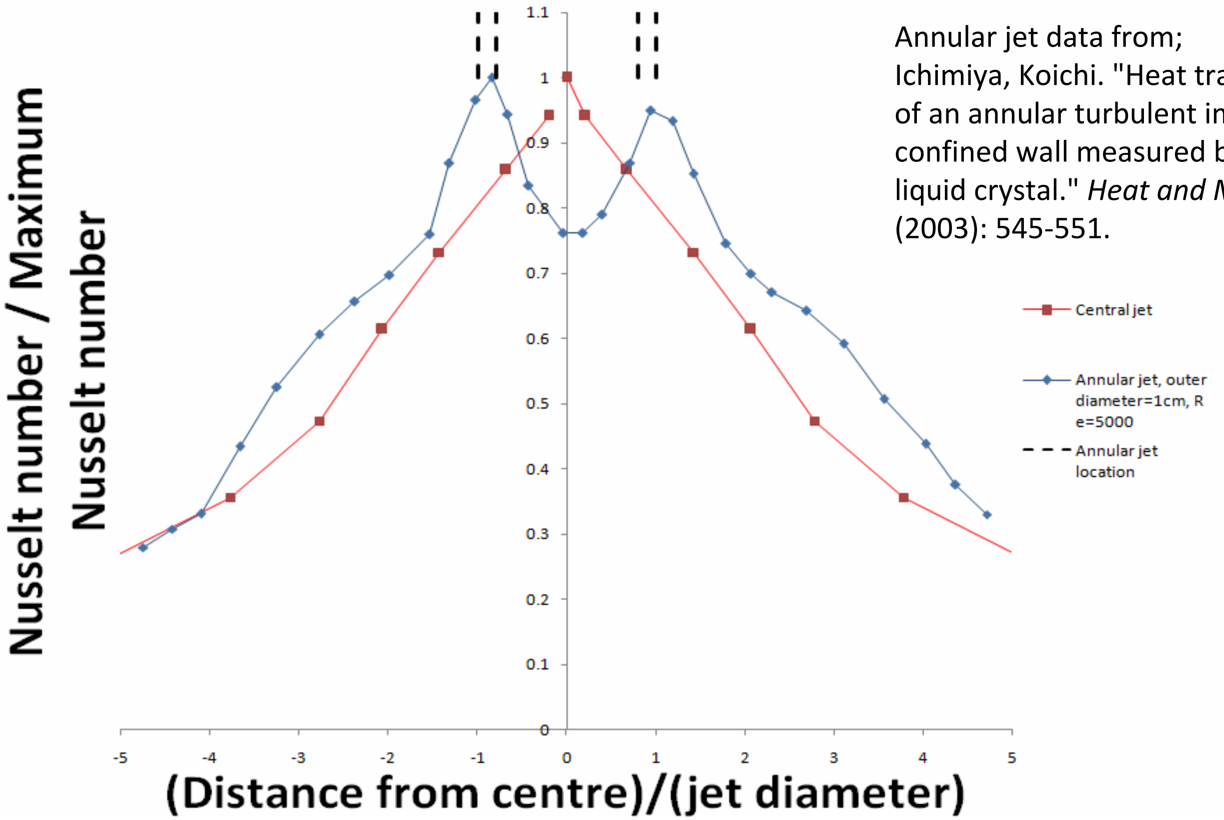
Scanning system



Power density profile



Annular jet heat transfer profile

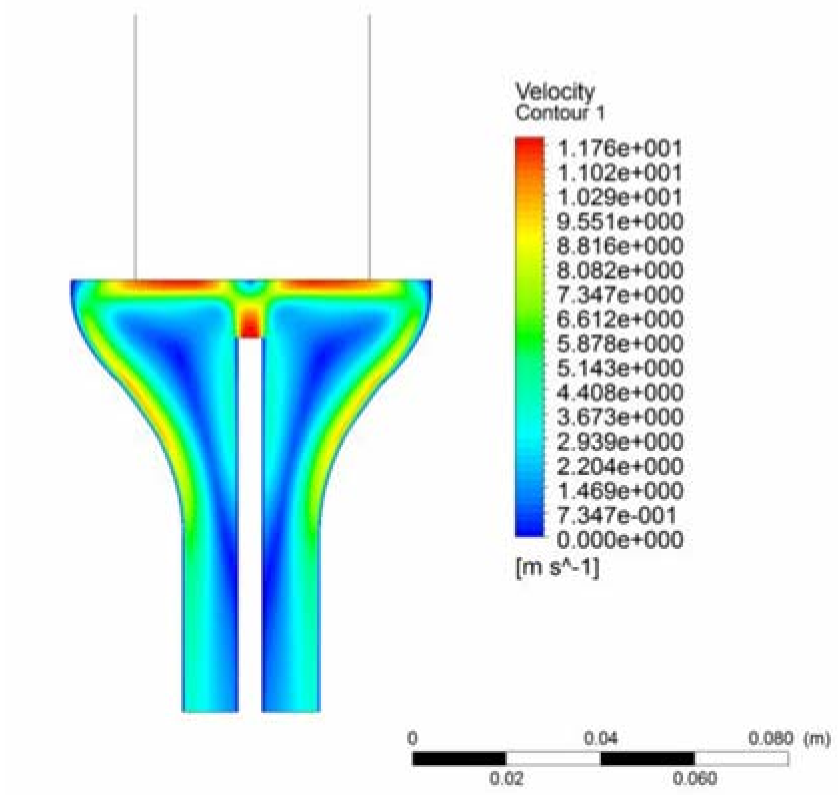


Annular jet data from;
Ichimiya, Koichi. "Heat transfer characteristics of an annular turbulent impinging jet with a confined wall measured by thermosensitive liquid crystal." *Heat and Mass Transfer* 39.7 (2003): 545-551.

A central submerged jet's centrally peaked heat transfer profile is a poor match to our 'doughnut' shaped beam scanning. An annular jet may be more suitable.

Current and future work

- Experimental and FEA analysis of cooling jet performance.



- Dynamitron beam alignment and upgrades.
- Long term molten lithium stability tests.