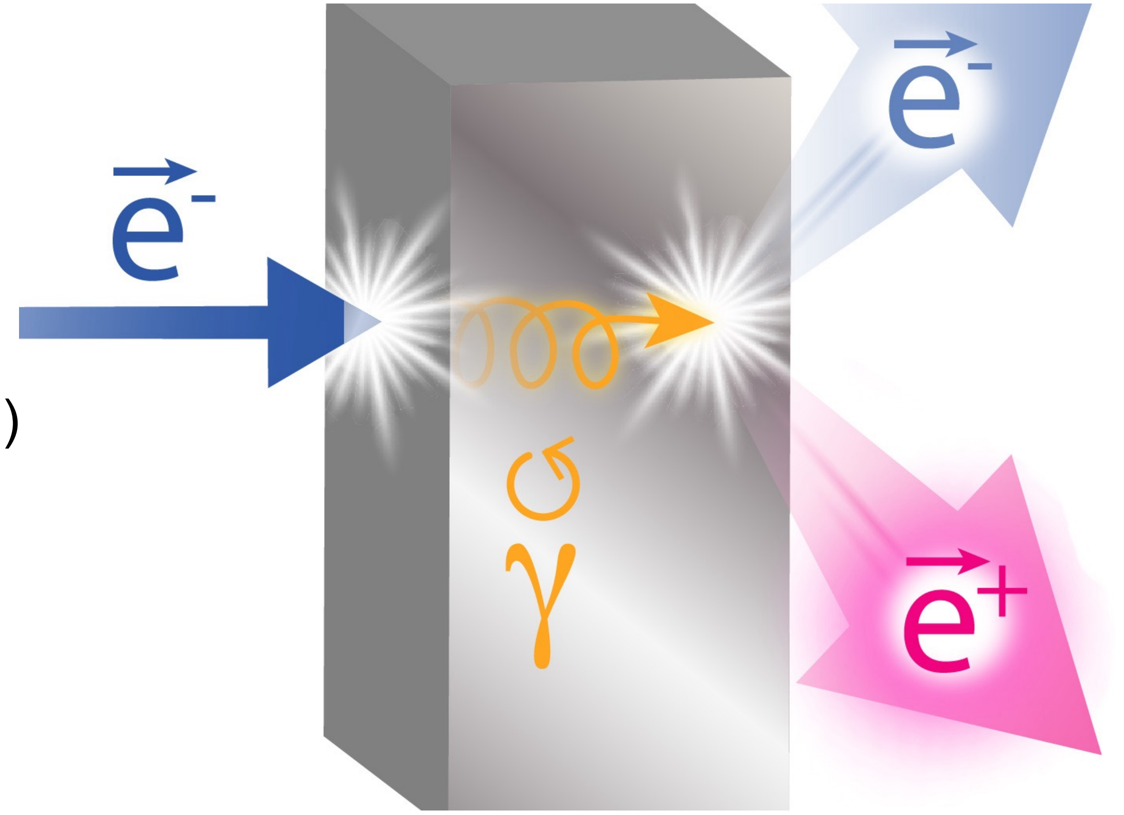
CFD Simulations of High-Power Positron Targets

- Design with CFD
- High-power e^+ target designs with CFD
- Summary



Silviu Covrig Dusa (on behalf of the Ce^+BAF Group)

Jefferson Lab, USA

International Workshop on Future Linear Colliders

LCWS2024

The University of Tokyo, Japan

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CFD Target Design at Jefferson Lab

- Computational Fluid Dynamics (CFD) software has been in use to design low noise, high power targets for an e^- beam at Jefferson Lab since 2005
- Qweak was the first target designed with CFD at Jefferson Lab, 2005-2009: 2.5 kW of beam power on 35 cm long liquid hydrogen (LH2) cell. Physics results published in Nature **557**.207 (2018), target design and performance published in NIM-A **1053**.168316 (2023)
- The outstanding performance of the Qweak target established CFD as a baseline design tool for low noise targets at Jefferson Lab (we predicted with CFD 0.8% LH2 density loss in nominal operating conditions and we measured 0.8% LH2 density loss in these conditions)
- With a DOE Early Career Award (2012-2017) we stood up a dedicated CFD computational farm at Jefferson Lab with the goal to design targets for the physics program at the Lab and beyond
- Targets designed/assessed with CFD: LH2/LD2/4He/3H up to 4.5 kW, 3He (high p,T), solid targets up to 1 kW (208Pb, 48Ca, W etc.)

- 2021 took charge of the target design for the future positron source at Jefferson Lab, started collaborating with SKEK-B, SLAC and Xelera, Inc on e^+ target design

CFD Target Design Process

- Fixed-target high precision physics measurements require low noise targets
- An e^- beam interaction with a target involves heat deposited in the target, up to tens of kW
- LH2/LD2 targets at Jefferson Lab without CFD design had 20% luminosity loss with a beam power in the target about 500 W. Targets designed with CFD have a luminosity loss less than 1% at 4.5 kW beam power

- The CFD target design process:
  - Define the performance parameters for the target
  - Define a geometry, simulate with CFD and post-process results
  - Refine the geometry to improve performance, find an optimal geometry
  - If needed, determine the target parameters phase-space that would maintain target performance

- Current CFD software in use at Jefferson Lab: ANSYS-CFD (Fluent and CFX), current CFD computational farm capacity: 512 CPUs

High-power Positron Target Designs

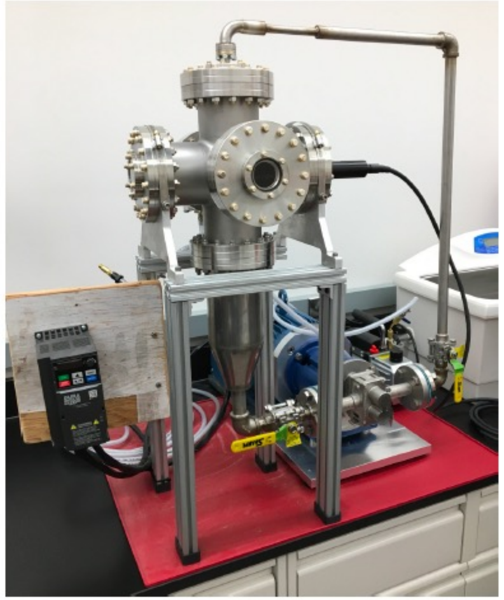
- Target concepts we are evaluating:
  - Xelera Research LLC (Ithaca,NY), pursuing a liquid metal jet target (originally for isotope production) that could produce e+
  - SLAC group, pursuing liquid xenon (LXe) recirculating target concept (NIM-A, **1053**.168329 (2023), Spencer G. et al)
  - SKEKB group has developed a high power rotating solid target for a pulsed source (Yoshinori E. et al)
  - Designing a target that could be part of Jefferson Lab's positron source

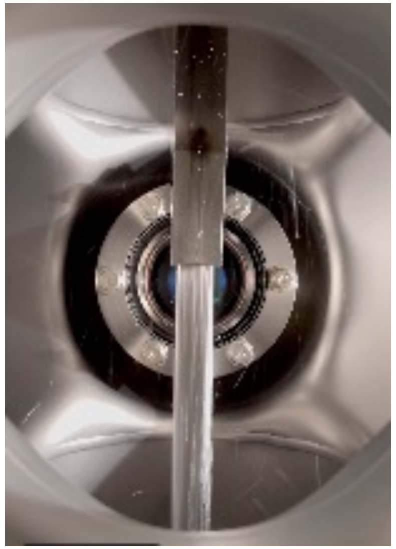
- JLAB-Xelera are collaborating under the DOE SBIR program

- JLAB-SLAC-SKEKB are collaborating under a DOE-SC-HEP grant funding opportunity that supports the development of advanced accelerator technologies

Xelera Target Design

- DOE-SBIR phase I completed, phase II funding approved
- SBIR phase I: successfully constructed and tested a 3 mm x 10 mm GaInSn metal jet target prototype (shown in upper right picture, lower right picture shows the nozzle and liquid jet)
- SBIR phase II (2024-2026) aims to test a recirculating liquid metal target at LERF with 10 MeV and 1 mA beam (the e+ production liquid metal would be PbBi)
  - Assess (with CFD) and study the thermal properties of the target
  - Vacuum compatibility with SRF
  - If possible, characterize the e+ distribution
  - Assess the risks/issues associated with operating such a target
    - Integration with the jlab source
    - Radiation (shielding, contamination etc.)
    - Lifetime/decommissioning/changing the target, target parts, servicing

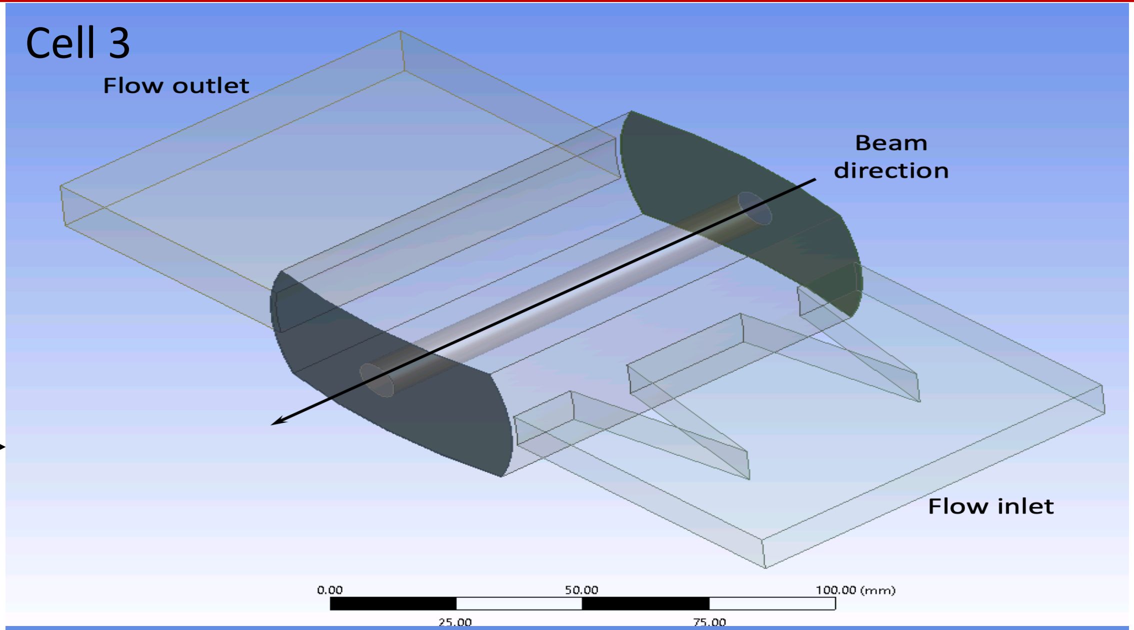


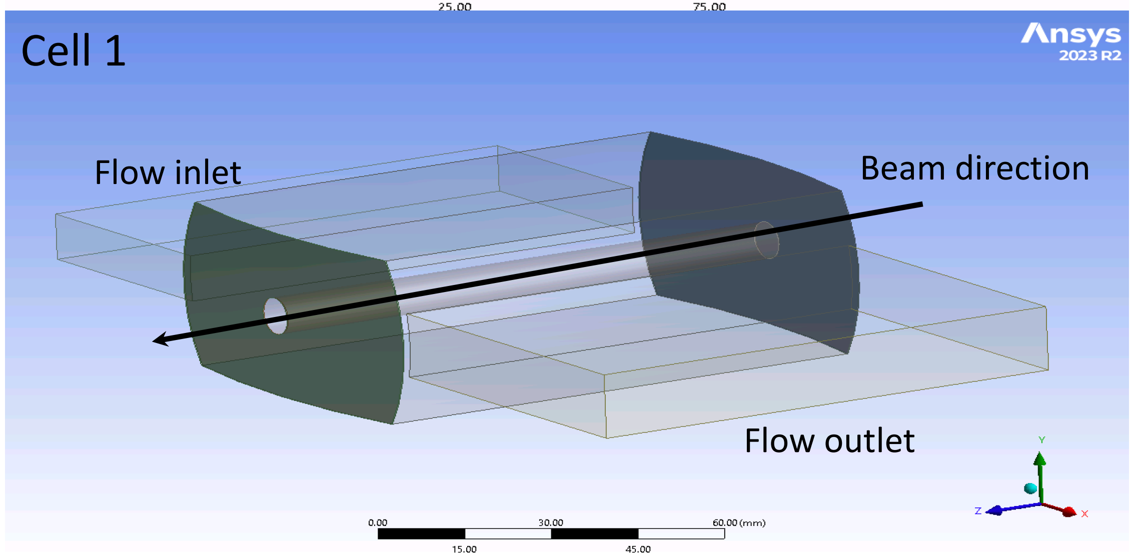


Pictures are courtesy of K. Smolenski and V. Kostroun

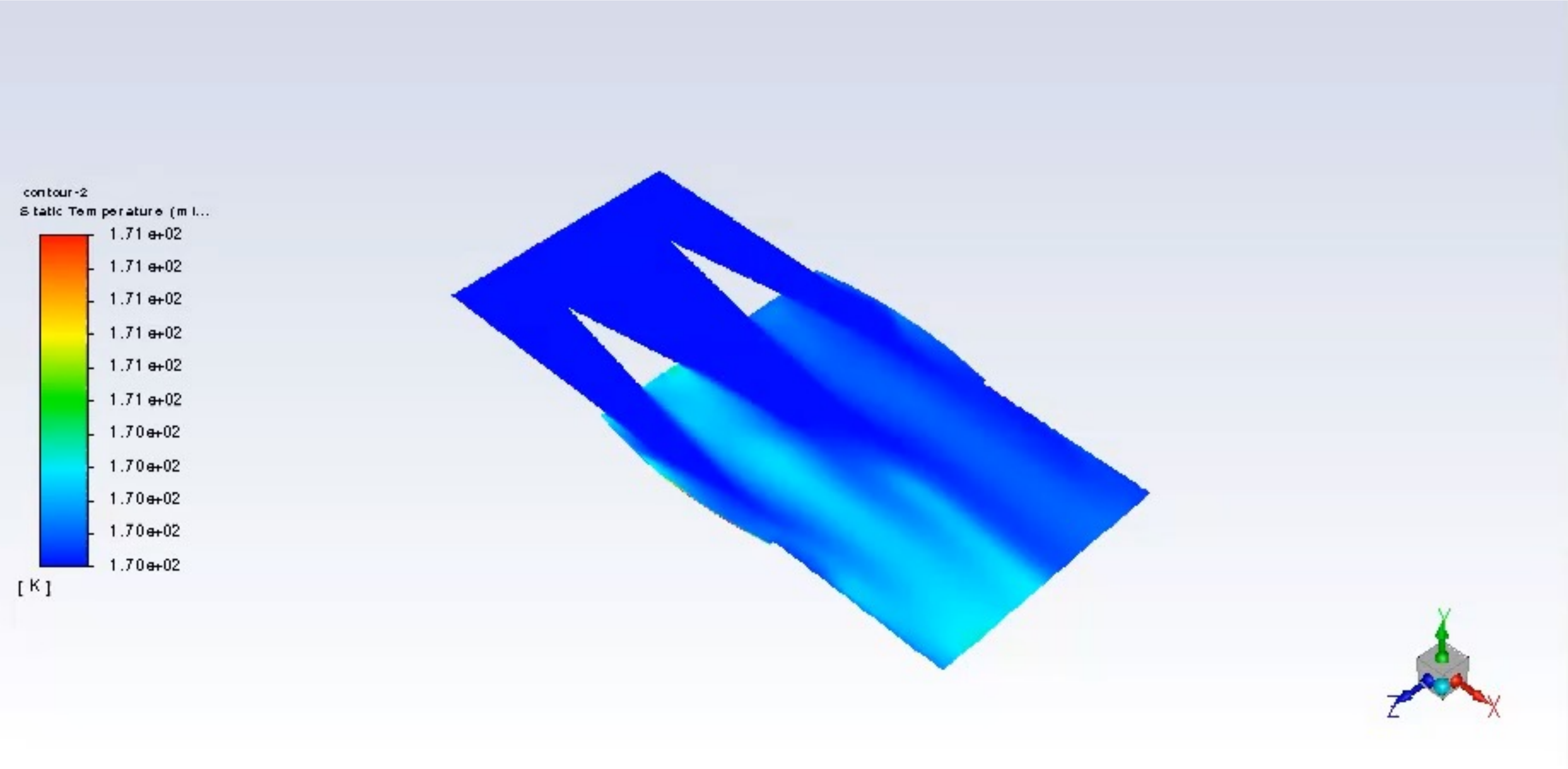
LXe Target Concept

- SLAC-RIKEN group: LXe positron target concept for future Linear Colliders
  - 10 cm long for 3, 6 and 10 GeV e- beams
- As part of our 3-party collaboration (jlab-slac-skekb), funded under a DOE-HEP grant:
  - developed a cell geometry at and simulated it with CFD
  - After 3 geometry iterations found a model that might satisfy the ILC requirements
- CFD simulation parameters:
  - 2-phase flow considered, LXe at cell inlet at 170 K, 35 psia, 2.5 m/s (saturates at 181.8 K and freezes at 160.4 K), properties corrected for T-dependence
  - Beam power considered from a Fluka fit for energy deposition (SLAC)
  - Time-dependent simulations: beam is ON for 1 ms then OFF for 199 ms, and so on, beam frequency 5 Hz
  - Beam pulse sampled with 4 time steps (time resolution 0.25 ms)



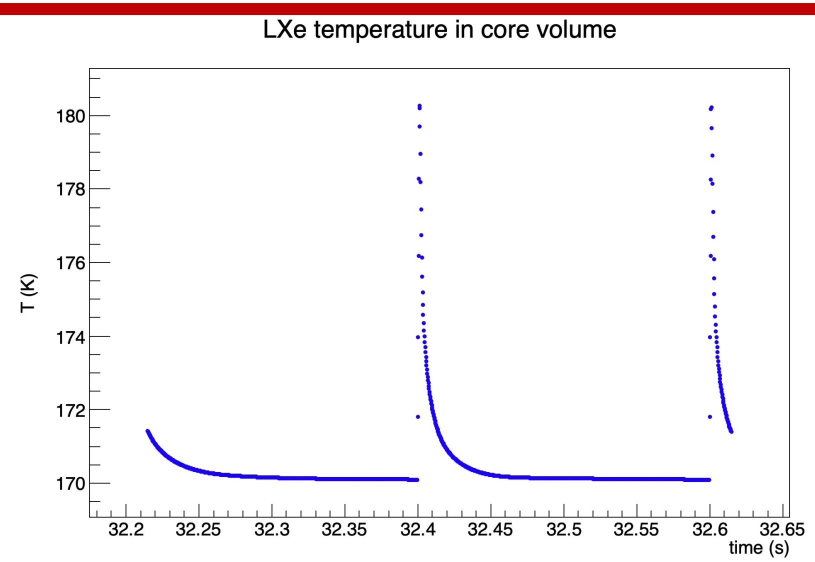


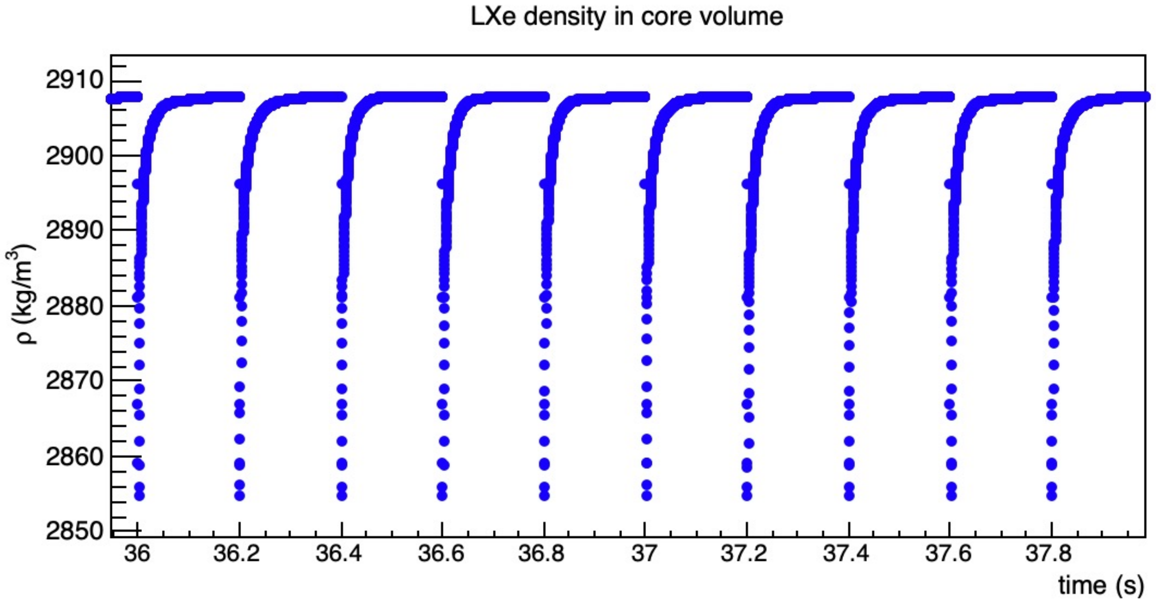
SLAC LXe Cell Temperature Profile v. Time

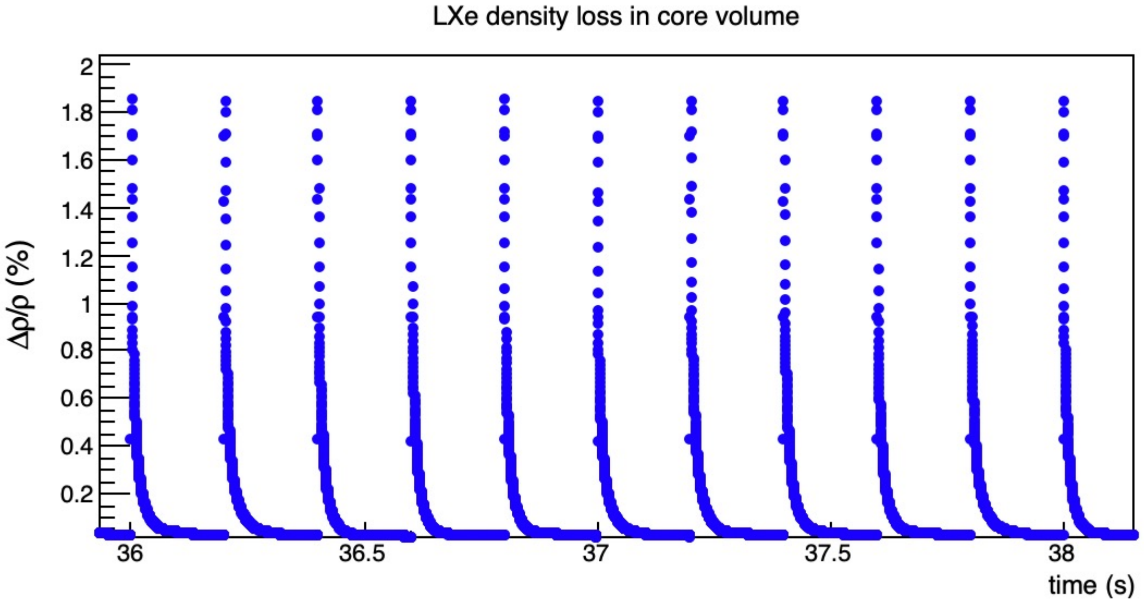


LXe Target CFD Results

- LXe max density loss during the beam pulse 4%, average density loss less than 1% (2% LXe density loss means reaching saturation)
- Max ΔT in cell windows during beam pulse < 7 K
- Pressure spikes when the beam turns ON, this should be investigated with a finer time resolution to check for shock waves
- CFD simulations are on-going





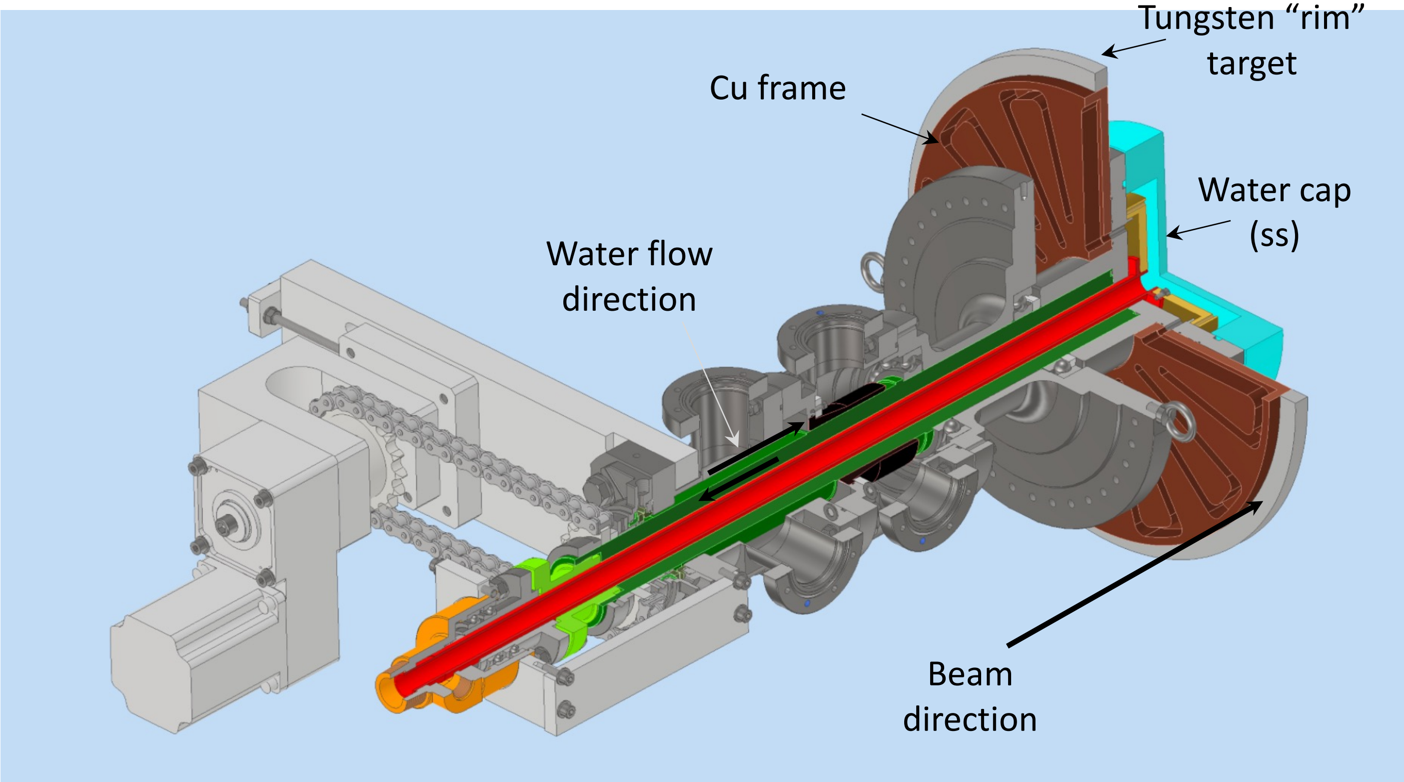


SKEKB Rotating Target Design

- As part of the 3-party collaboration (jlab-slac-skekb):
  - Assessing with CFD the SKEKB rotating target at full beam power with the time structure of the ILC beam and the space structure of the beam power deposition in target from Fluka (from SKEKB)

- CFD parameters:
  - target material W 16 mm thick, 25 cm radius, W "welded" to Cu frame, rotates at 3.75 Hz
  - Simulated CW and ILC beam, 20 kW, σ = 2.2 mm, beam spot diameter 6 mm
  - Water coolant in at 293 K, 1.167 kg/s, 2 atm
  - Only conductive heat-transfer considered (to be conservative in predictions)

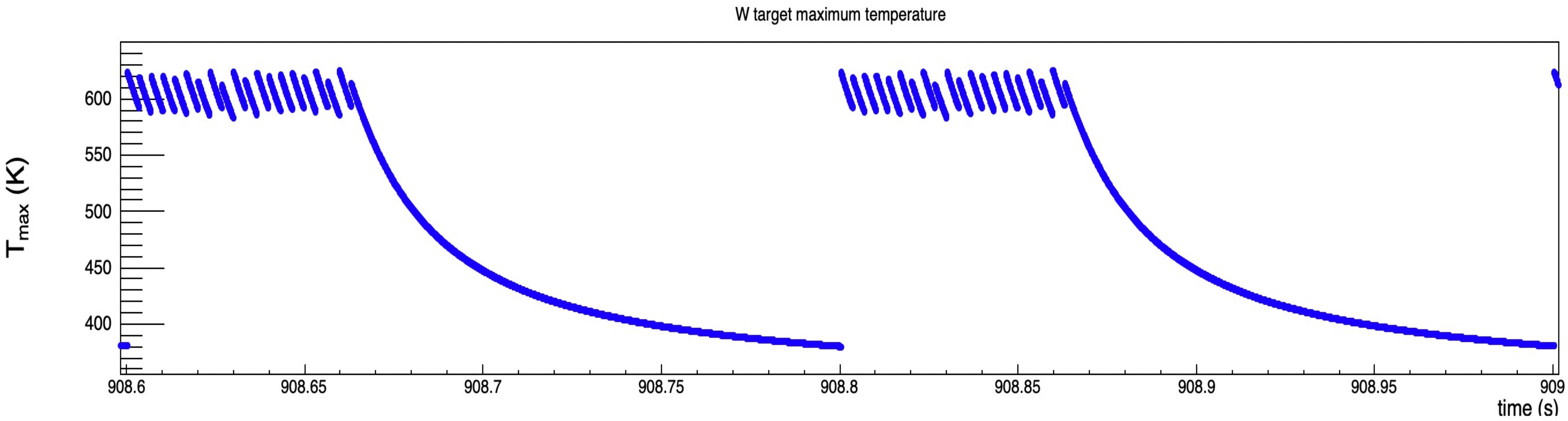
- CFD simulations: temperature maps, optimizing water flow, assessing the contact copper-tungsten



SKEKB Target CFD Predictions with ILC Beam (I)

- ILC beam time structure: 20 pulses for 66 ms, no beam for 134 ms, repeat
- The beam is actually ON for 0.474 μs of the 3.3 ms ”pulse”
- CFD time resolution 50 μs for these simulations
- Space-time distribution of beam power deposition in the target follows the SKEKB provided fits

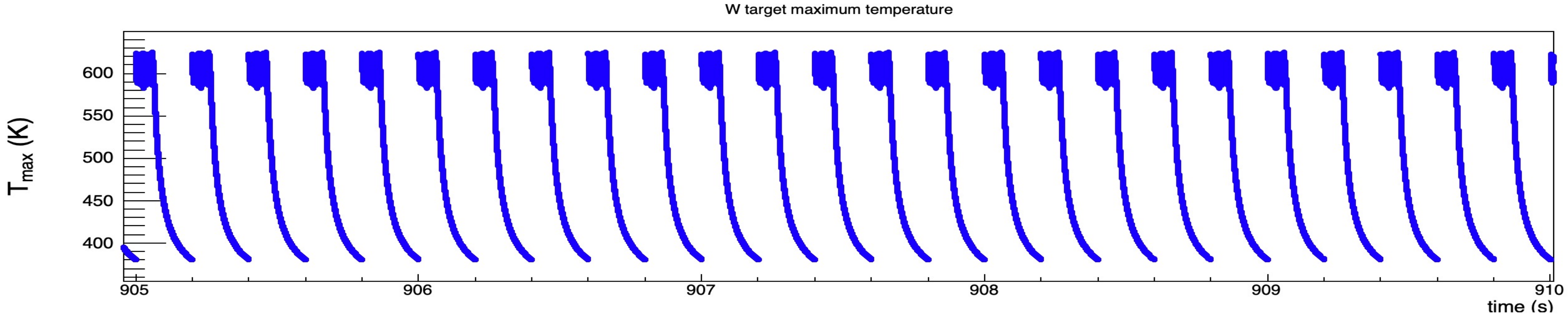
- Tmax in W: 626 K, during a beam pulse (3.3 ms) varies 580– 626 K, during beam off, Tmax = 380 – 580 K



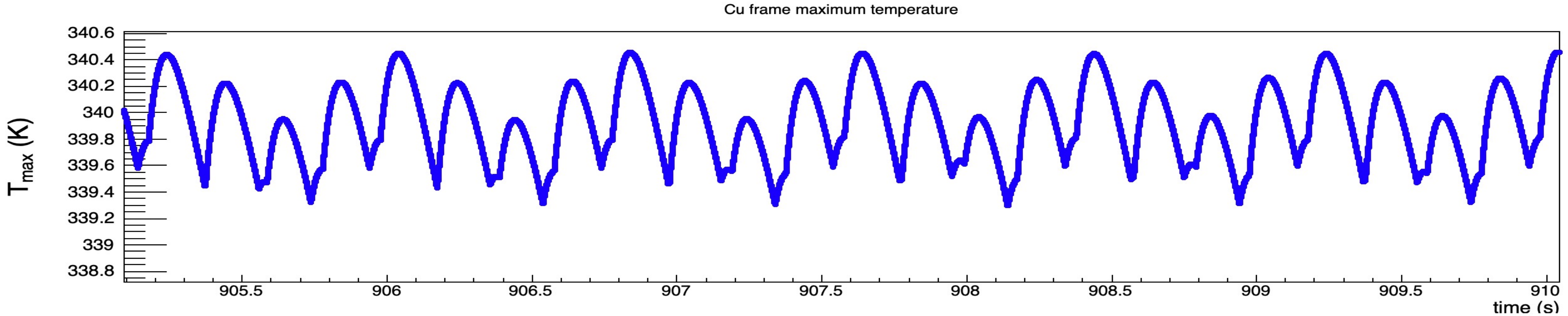
SKEKB Target CFD Predictions with ILC Beam (II)

5 sec of ILC beam time

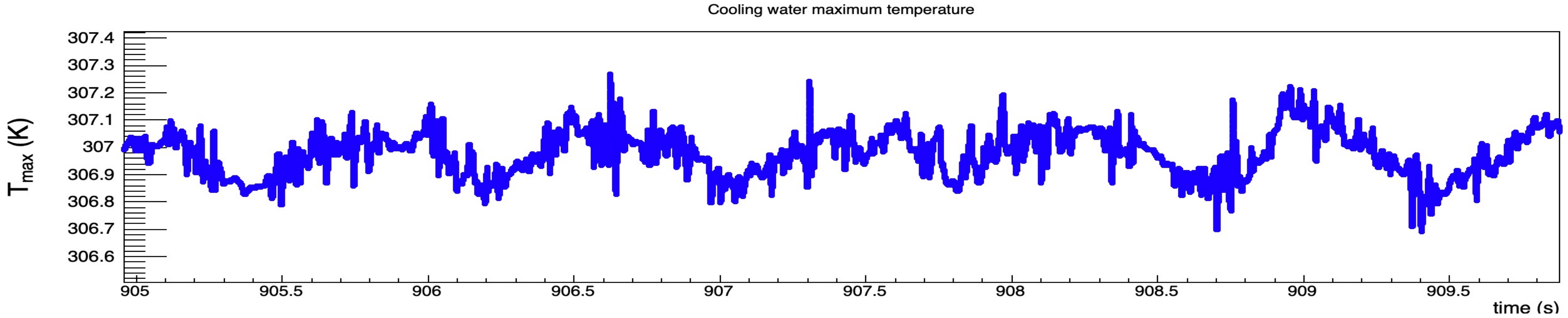
Evolution of Tmax in W target



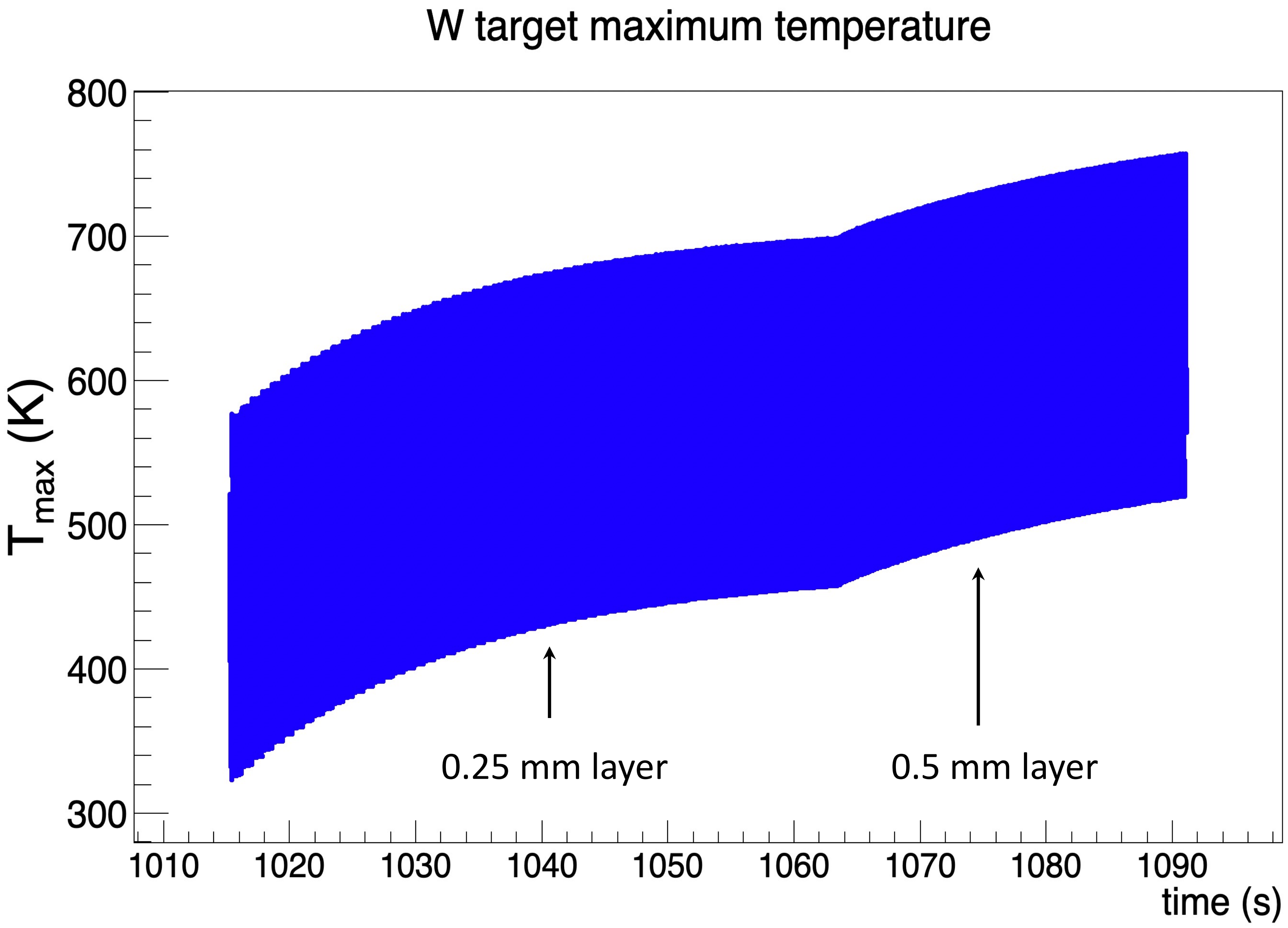
Evolution of Tmax in Cu: <341 K, range 1.2 K



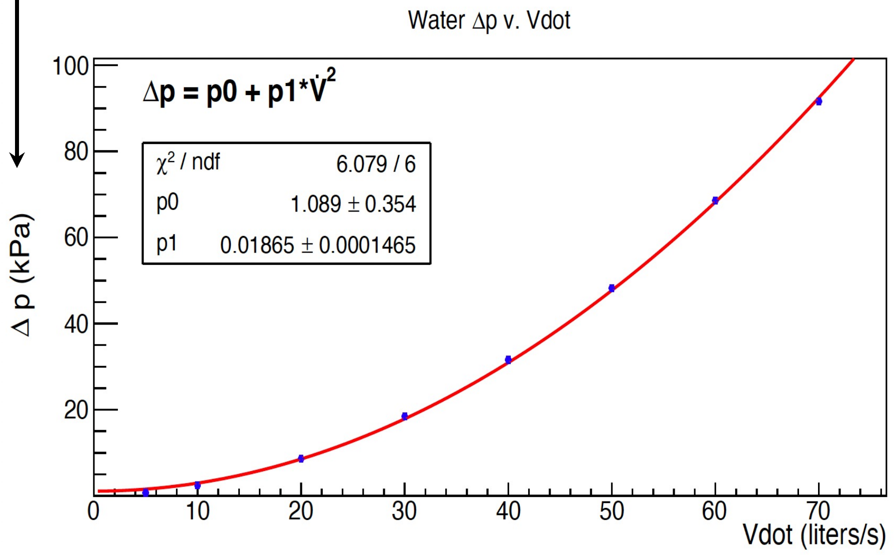
Evolution of Tmax in H2O: <308 K, range 0.5 K



SKEKB Target CFD Predictions with ILC Beam (III)



- Influence of thermal resistance layer (WO3) between W target and Cu frame on max T in W (work in progress)
- Cooling water circuit pressure loss between inlet and outlet v. volume rate



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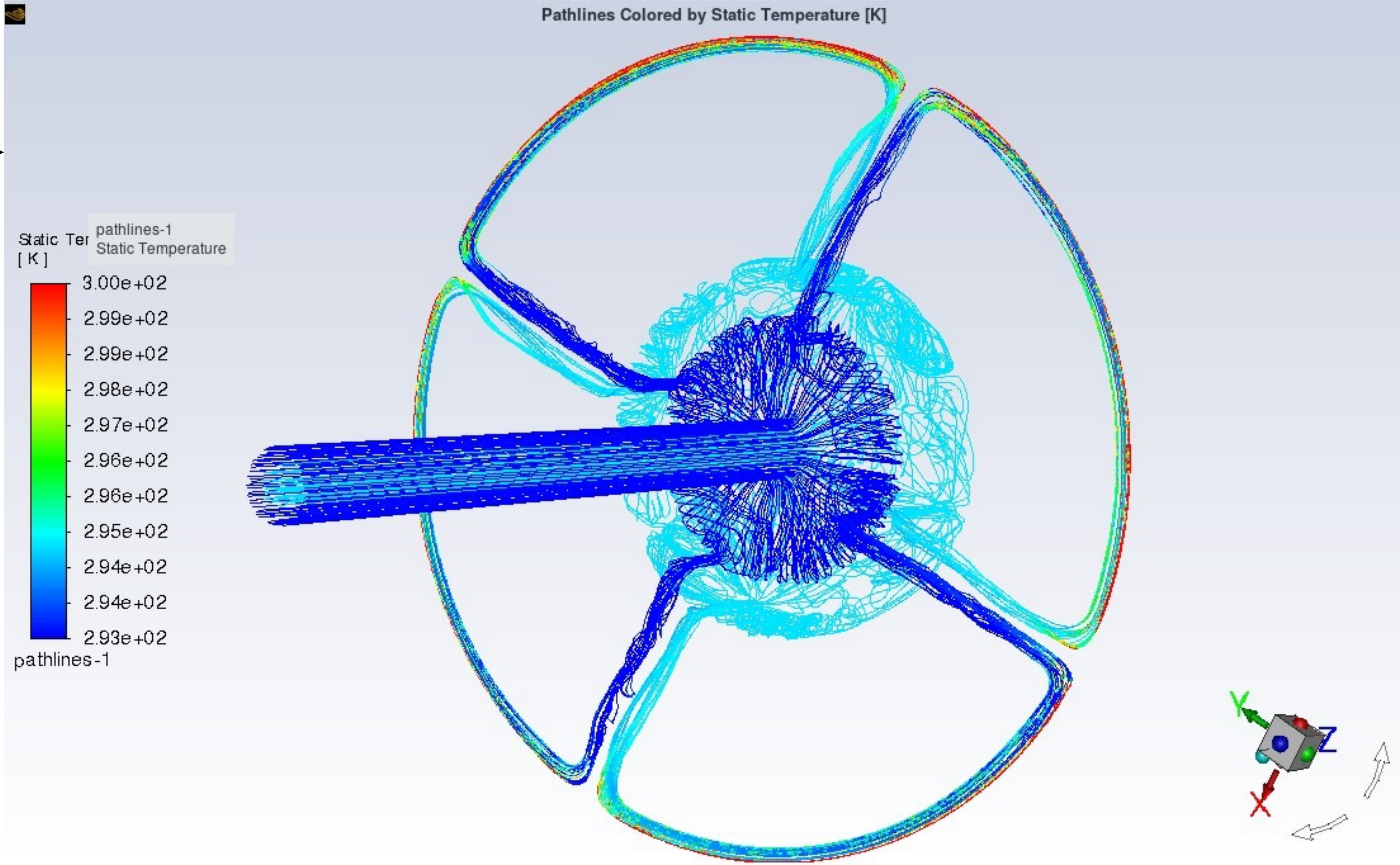
SKEKB Target CFD Predictions with ILC Beam (IV)

- Cooling water flow pathlines colored by temperature →

- Can "visualize" any parameter of the cooling circuit that the CFD simulation tracks (velocity, temperature, pressure etc.)

- Can fine-tune the design of the cooling circuit to optimize target cooling and address engineering issues



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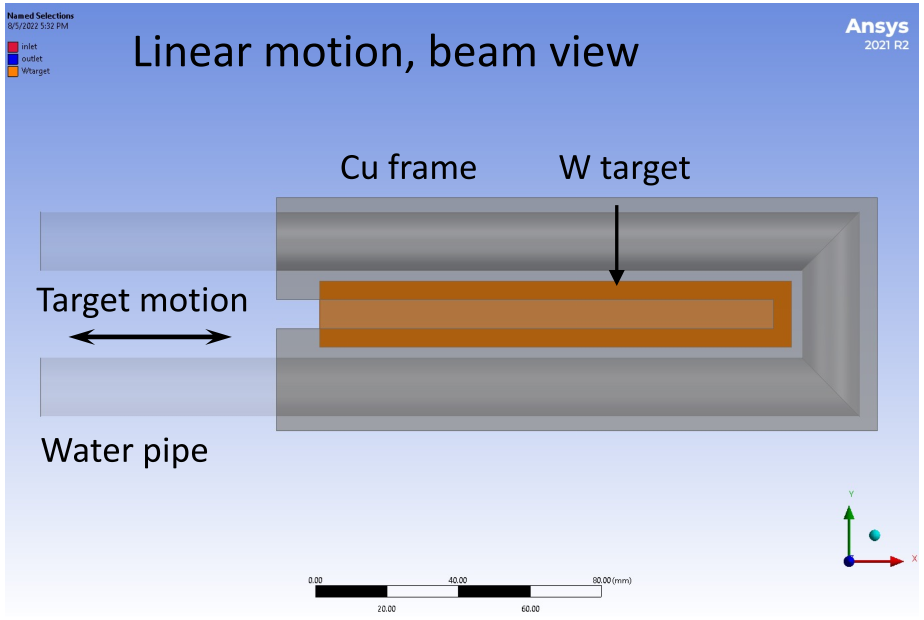
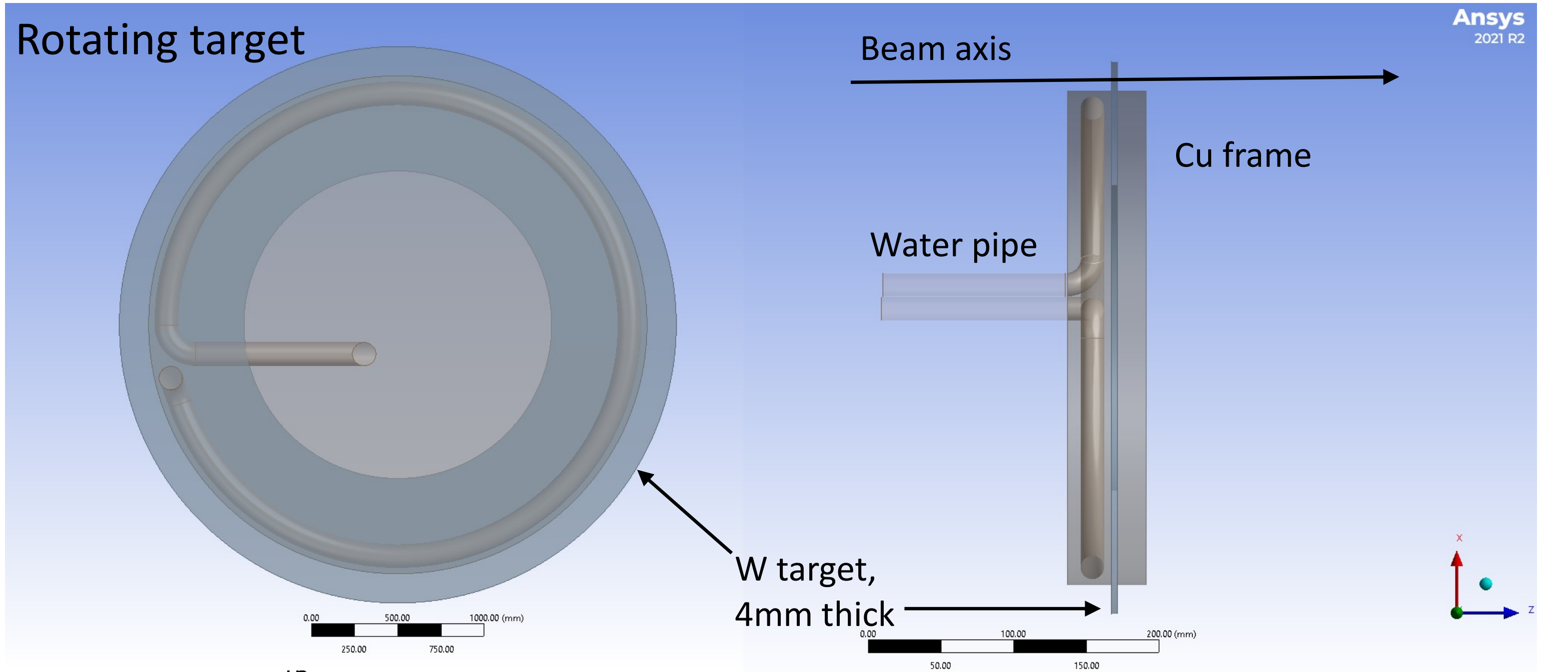
Ce^+BAF General e^+ Target Design Parameters

- Design goal: the target should be able to take a 1 mA, 123 MeV CW e^- beam current and have a lifetime of 6 months to 1 year (or longer)
- Tungsten is preferable as a target material: high Z (high e^+ yield) and high melting temperature (thermal resilience to high power beam deposition)
- Optimal W target thickness for e^+ production from an incoming e- beam, would be 4 mm
- Fluka estimates for heating power deposition in such a target are in the range of 17 kW, designing the target for 20 kW
- CFD simulations seem to indicate that the W target will have to be rotated with a mild frequency (less than 10 Hz) to extend its lifetime (the W disk radius depends somewhat on the rotation frequency)

High Power e⁺ Solid Converter Target Designs

- Focused on assessing with CFD high-Z targets, mostly W, for e^+ production:
  - A static target could take ~ 1 kW beam power before it melts
  - A linearly moving target could take ~ 4 kW beam power before it melts
  - A rotating target (<10 Hz, >30 cm diameter) could take 20 kW beam power with T_{max} < 1000 K

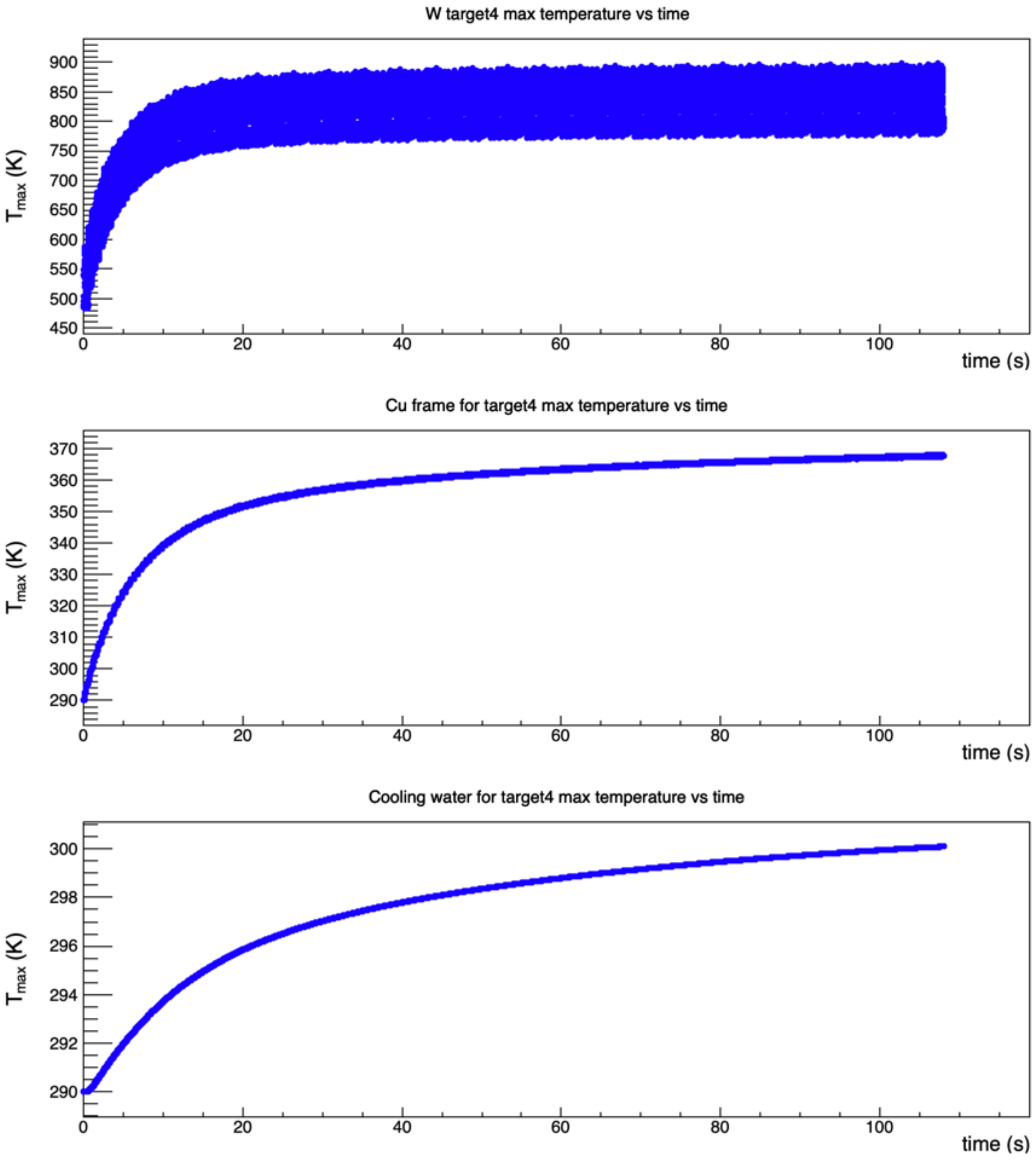




$Ce^{+}BAF$ Rotating W Target with CFD

- Beam area on W target 4x4 mm^2 or Gaussian profile with σ ~ 1-3 mm
- The beam hits the W target on a circle with radius 18 cm
- The W target rotates at 2 Hz and the water flow is 0.6 kg/s, water pressure loss is 1.5 psi
- Full time-dependent CFD simulations implemented

- Started scratching the surface on target design at Jefferson Lab



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Summary

- CFD-driven design and engineering is an essential stage in the development of high power targets for positron sources
- Collaborating with Xelera Inc, SLAC and SKEKB on target design
- Working on developing a feasible design for the e+ source at Jefferson Lab within 3-5 years accounting for radiological issues, shielding etc.

- There is a Positron Working Group (PWG) at Jefferson Lab, made of staff and users, to develop and promote a positron physics program at the Lab. We have monthly meetings and an annual workshop

Acknowledgments

We would like to acknowledge members of the **Ce$^+$BAF Working Group**, the **Jefferson Lab Positron Working Group**, the **DOE industry partner Xelera**, members of the **DOE US-Japan HEP Collaboration,** and collaborators at **Universities and National Labs** which contribute to the positron R&D effort.

T. Abe, J. Benesch, A. Bogacz, L. Cardman, J. Conway, S. Covrig, P. Degtiarenko, Y. Enomoto, S. Gessner, P. Ghoshal, S. Gopinath, J. Grames, J. Gubeli, S. Habet, C. Hernandez-Garcia, D. Higinbotham, A. Hofler, R. Kazimi, M. Kostin, F. Lin, V. Kostroun, V. Lizarraga-Rubio, K. Mahler, Y. Morikawa, S. Nagaitsev, E. Nanni, M. Poelker, N. Raut, B. Rimmer, Y. Roblin, A. Seryi, K. Smolenski, M. Spata, R. Suleiman, A. Sy, D. Turner, C. Valerio-Lizarraga, E. Voutier, M. Yamamoto, S. Zhang

Back-up slides

What is Target Noise (an example from Parity-Violation measurements)

Target density reduction = luminosity loss

$$\frac{\Delta Y}{Y} = \frac{Y_{low\ beam} - Y_{high\ beam}}{Y_{low\ beam}}$$

10% Y loss → 10% longer running

Target density fluctuations = asymmetry width enlargement

$$A_{exp} = \frac{Y_+ - Y_-}{Y_+ + Y_-} = \frac{\Delta Y}{Y}$$

$Y_{+/-} \sim N/I$

+/- are electron beam helicity states

$$(\Delta A_{exp})^2 = \sigma_{exp}^2 = \sigma_0^2 + \sigma_{noise}^2$$

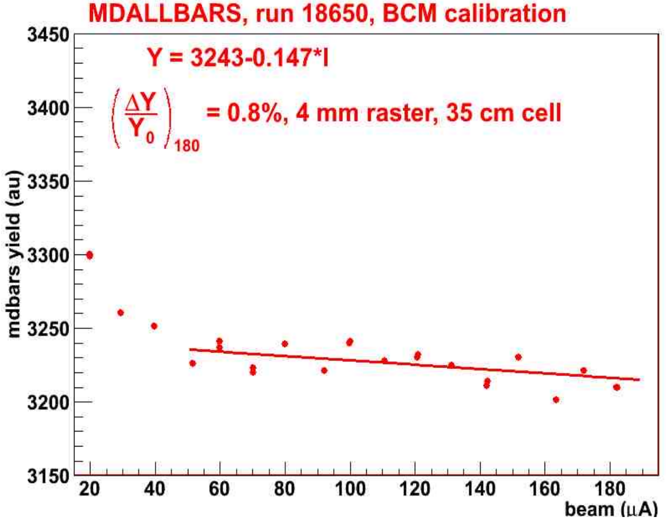
10% noise increase → 20% longer running

$$\sigma_0^2 = \frac{1}{N_0} = \frac{f_h}{2R}$$

σ_0 = counting statistics
R = scattered particle rate
f_h = helicity frequency

CFD is the most efficient tool for low noise target design

Yield loss, Qweak LH2 target



G0 asymmetry width enlargement