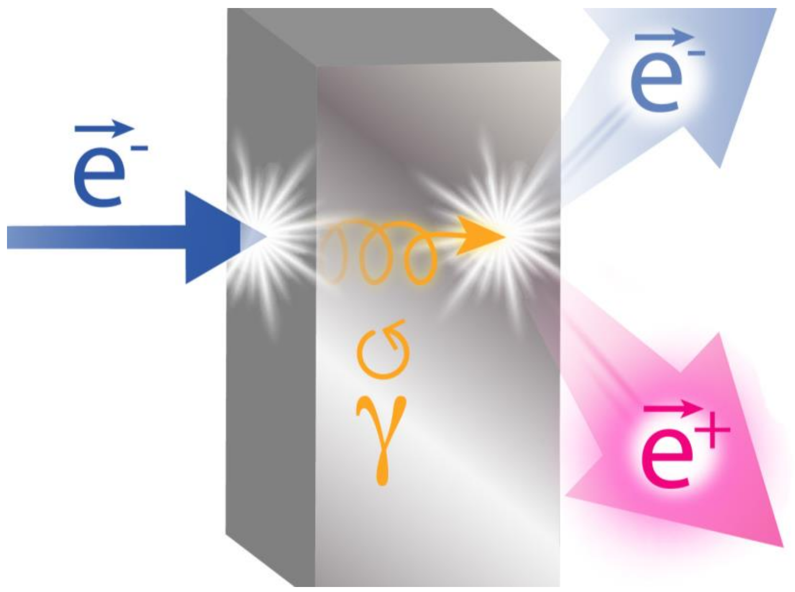
The Solid Positron Converter Target at Jefferson Lab

- CFD target design at Jefferson Lab
- Prototype target project
- Summary



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Computational Fluid Dynamics (CFD)

- High precision physics measurements at fixed-target facilities require low noise targets
- An e^- beam's interaction with a target involves heat deposited in the target, up to tens of kW
- Liquid hydrogen/deuterium targets at Jefferson Lab (Jlab) without CFD design had up to 20% luminosity loss with a beam deposited power in the target around 500 W. Targets designed with CFD have a luminosity loss less than 1% at 4.5 kW beam power

- The general CFD target design process:
  - Define the required 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 Jlab: ANSYS-CFD (Fluent and CFX), on a dedicated (corner) of the local scientific computing farm

CFD Target Design at Jefferson Lab

- CFD has been used to design low noise, high power targets for an e^- beam at Jlab since 2005
- Qweak was the first target designed with CFD at Jlab, 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 we established a dedicated CFD computational farm at Jlab with the goal to design targets for the physics program at the Lab and beyond
- Targets designed/assessed with CFD: LH2/LD2/GT2/4He up to 4.5 kW, 3He (high p,T), solid targets up to 1 kW (208Pb, 48Ca, W etc.)

- Since 2021 driving the positron target design at Jlab

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JLab High-Power Positron Target Collaborations

- JLAB-Xelera are collaborating under the DOE-SBIR program (check K. Smolenski's presentation)

- JLAB-SLAC-SKEKB are collaborating under a DOE-HEP grant funding opportunity that supports the development of advanced accelerator technologies (check Y. Morikawa's presentation)

- Target concepts we are assessing:
  - Xelera Research LLC (Ithaca,NY): liquid metal jet target that could produce e+
  - SLAC group: 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 Jlab's positron source

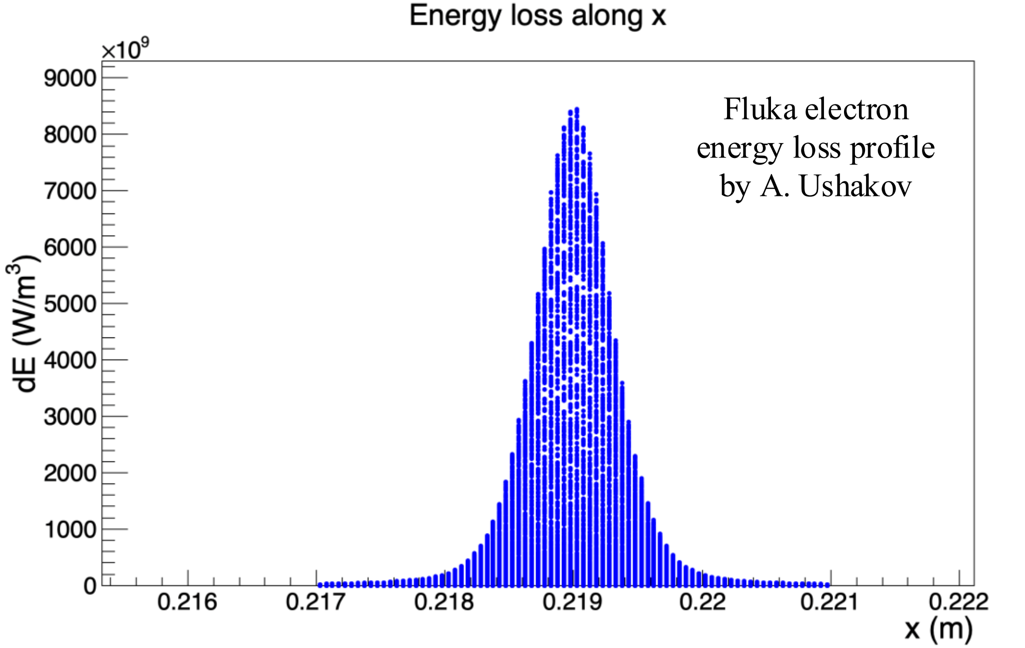
Solid Converter Target Design Criteria

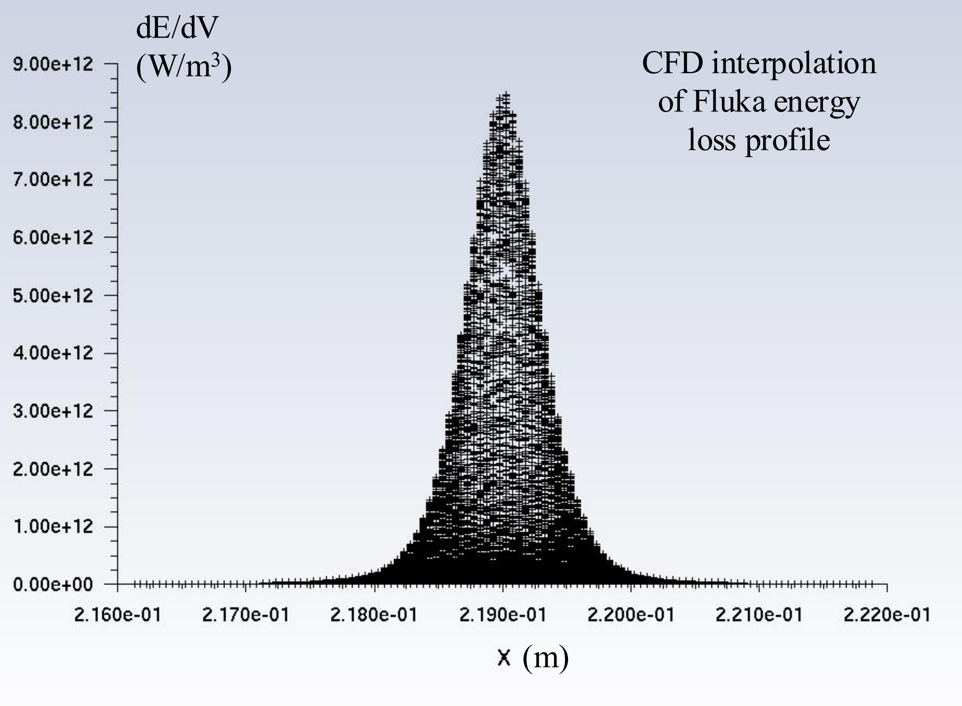
- Electron beam:
  - Energy, current -> cumulative energy deposited (10-20 kW)
  - Spot size/shape -> local energy deposition
  - Frequency -> CW or pulsed (CW at Jlab)

- Target:
  - Material -> positron yield, typically 10^{-3} positrons/primary electrons (high-Z materials needed with satisfactory thermo-mechanical properties)
  - Shape -> thickness, diameter, framing, contacts
  - Cooling -> effective system
  - Rotation -> mitigate maximum temperature on target
  - Operated in high vacuum (<1e-6 Pa) -> make it compatible with the vacuum of the source
  - Stresses -> how do thermo-mechanical properties change over time
  - Radiation damage -> how do thermo-mechanical properties change over time
  - Magnetic field operation -> may increase target heating, influence rotation

Converter Target Design Process at Jlab

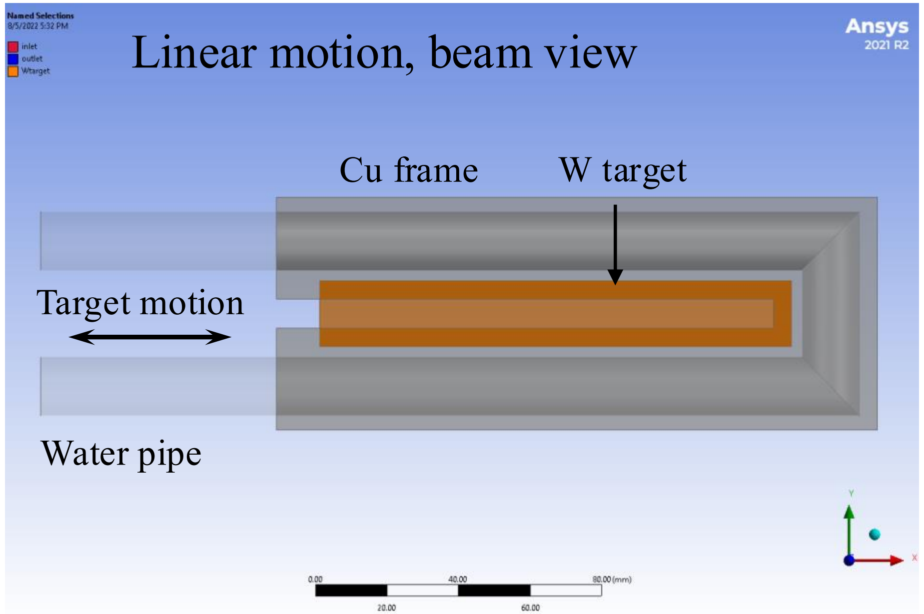
- This will be the first Jlab target designed and operated at more than 10 kW
- Roughly two design stages towards a production converter target:
  - First, find an optimal geometry for target material, shape, efficient cooling, rotation and vacuum compatibility
  - Second, optimize the first stage design for thermo-mechanical stresses, radiation damage and magnetic field operations
- CFD will be used to assess models at every stage of the design process. The accuracy of the CFD predictions will depend on:
  - Mesh size effects, boundary conditions, material properties
  - Implementation of energy loss (either as a fit or directly as a csv datafile of energy loss predictions from a program like Fluka, implementing profiles files in ANSYS-Fluent is tricky!)
  - Time-dependent simulations will be needed to account for target rotation and assess the dynamic equilibrium with beam on target (stability etc.). Using proper time steps is essential.
  - Thermal conduction is the primary mechanism to dissipate the heat deposited in the target material
- The CFD should be benchmarked to validate the simulations

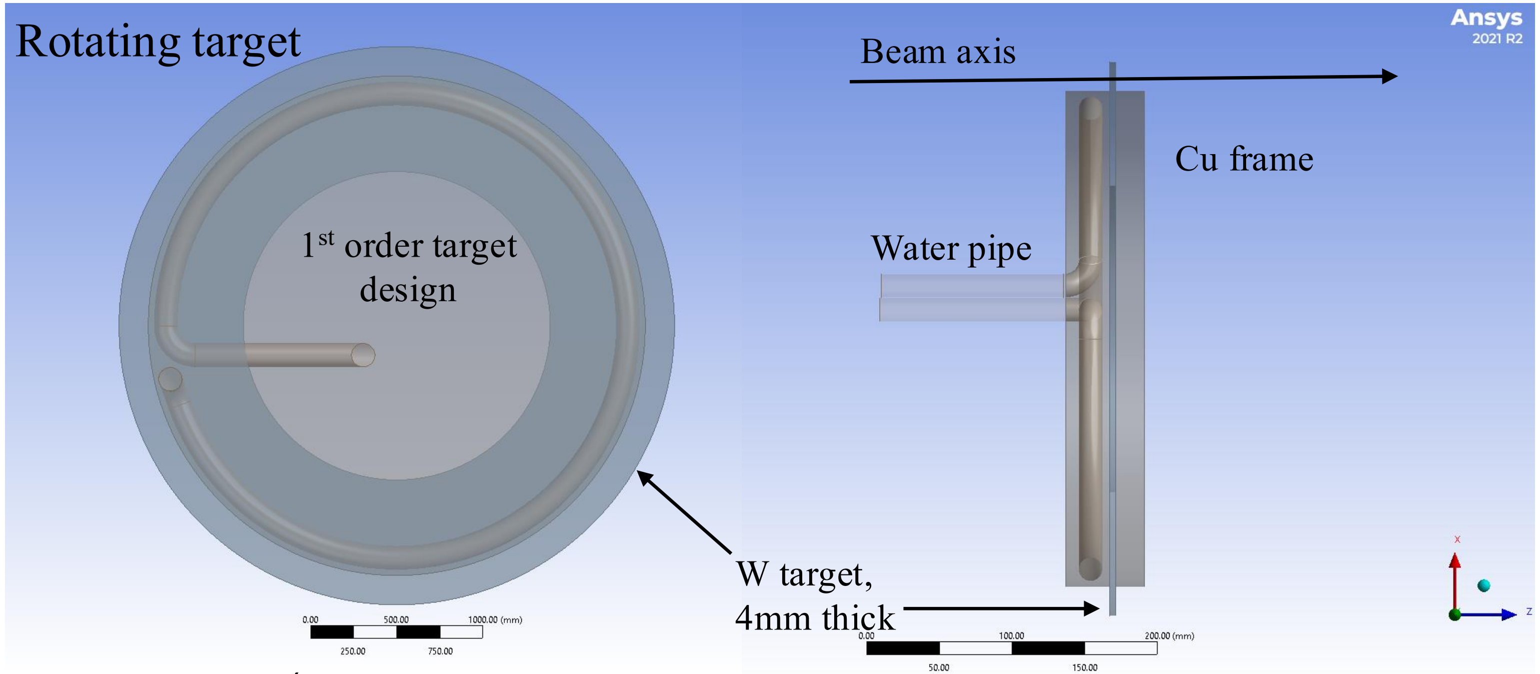




From Static to Rotating Solid Targets

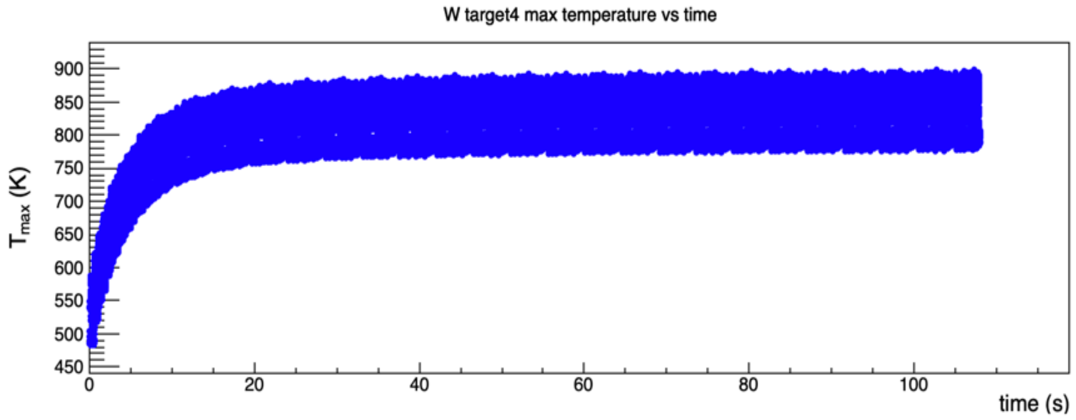
- Why do we need a rotating target for positron production (for the W family of materials)?
  - A static target could take ~ 1 kW beam power before it melts
  - A linearly moving target could take ~ 4 kW beam power before it melts
  - A rotating target (<10 Hz, >30 cm diameter) could take 20 kW beam power with T_{max} < 1000 K

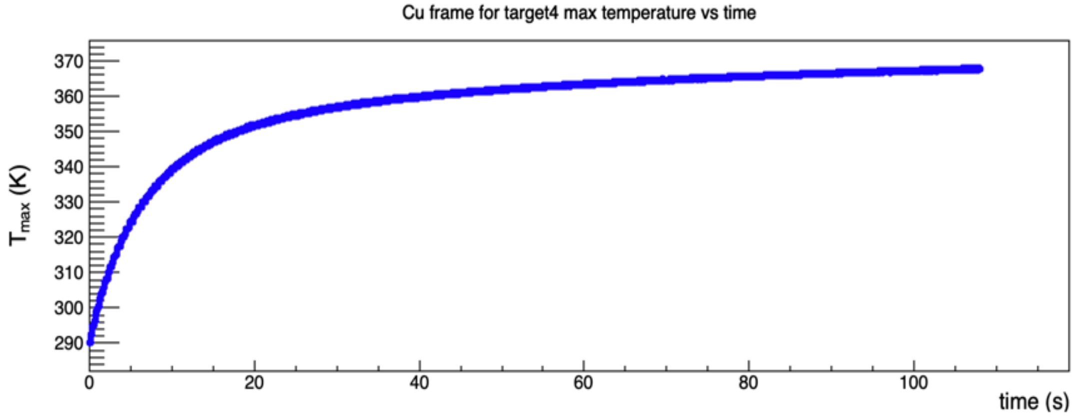


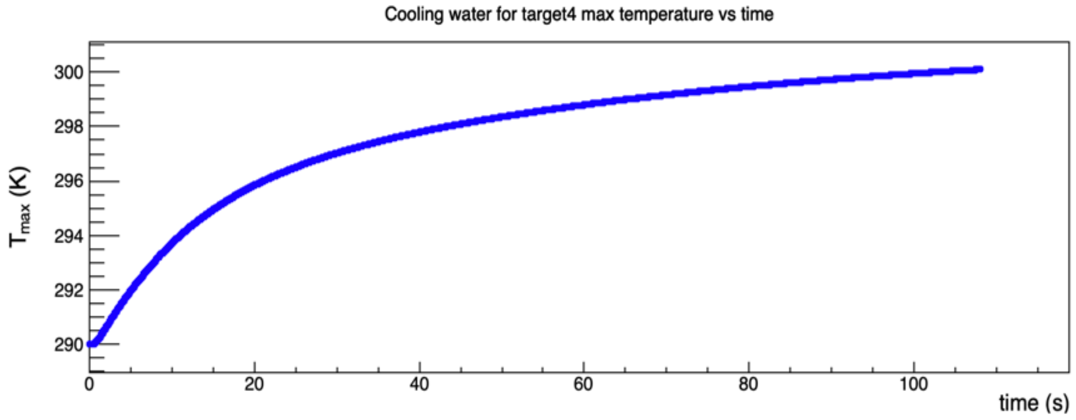


1st Order Rotating Target Design

- Beam area on W target with Gaussian profile with σ 1 mm
- The beam hits the W target on a circle with radius 18 cm, wheel radius 19 cm
- Two ways to implement the target rotation in CFD:
  - The target is fixed and the beam spot rotates (speeds up the simulation, does not account for the rotations' effect on the coolant flow!)
  - The beam spot is fixed and the target rotates (closer to reality, slows the simulations, careful considerations in implementation)
- 1st order target design simulated with the fixed target, rotating beam spot approach
- Preliminary results are promising, the second approach to rotation is required to validate an optimized design







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Target Design Approach beyond 1st Order

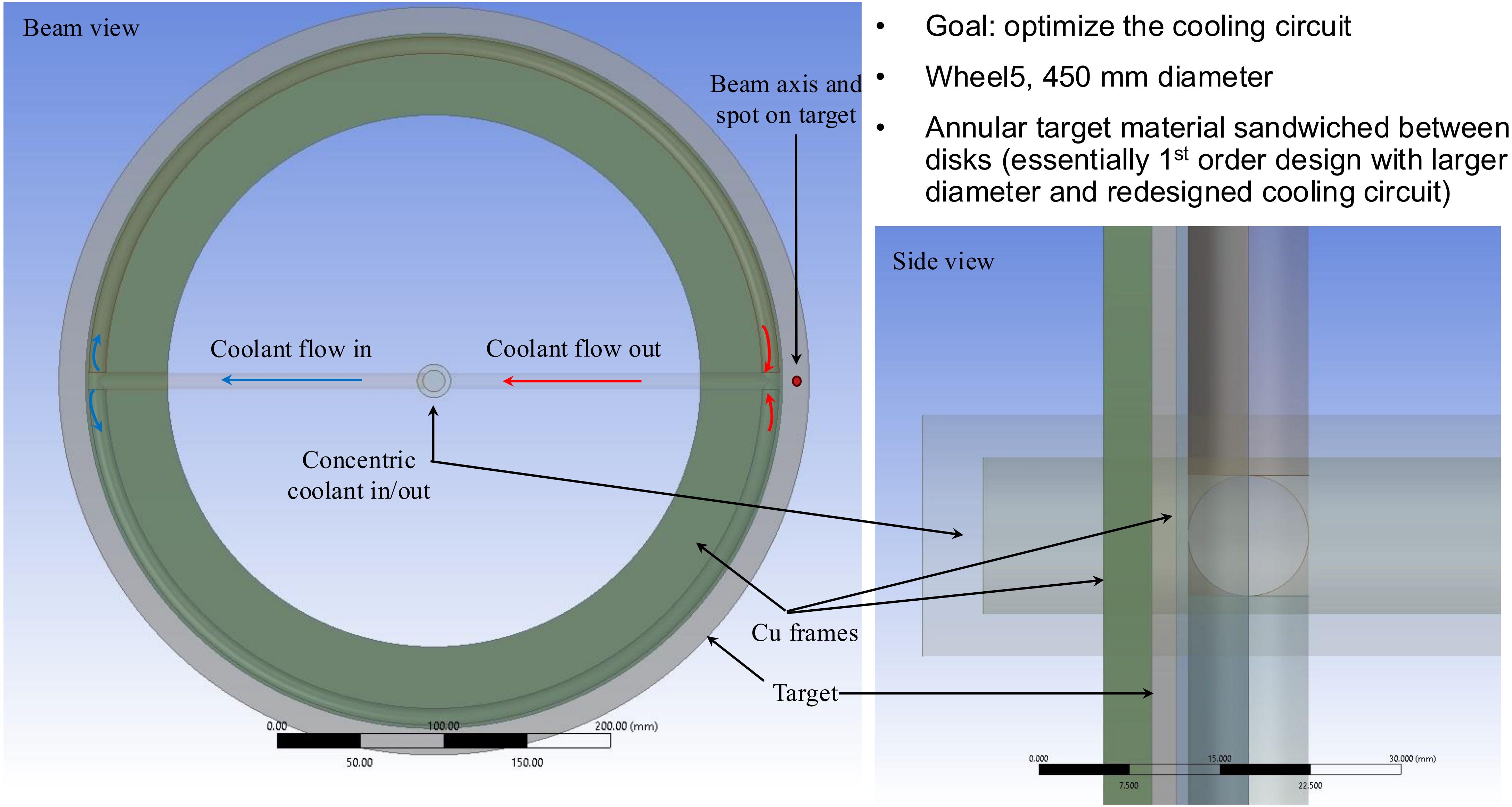
- Fluka estimates for heating power deposition in such a target are in the range of 10-20 kW
- CFD simulations indicate that the target will have to be rotated with a mild frequency (less than 10 Hz) and have a diameter 400-500 mm
- CFD for Ce^{+}BAF design process parameters:
  - 3 target materials: W, Au, W85Cu15
  - 3 electron beam energies: 130 MeV, 250 MeV and 370 MeV
  - 3 electron intrinsic beam spot σ: 0.25 mm, 0.5 mm and 0.75 mm

material	W (Z = 74)	W85Cu15	Au (Z = 79)
ρ (g/cm^3)	19.3	16.4	19.28
k (W/m*K)	170	196	318
T_l (K)	3695	>1356	1337
X_0 (mm)	3.5	4.44	3.35

- Goal: determine the maximum primary beam current, in each case, in order to maintain less than 1000 K maximum temperature in the target for W family and less than 700 K for Au

2nd Order Target Design (I)

- Goal: optimize the cooling circuit
- Wheel5, 450 mm diameter
- Annular target material sandwiched between two copper disks (essentially 1st order design with larger wheel diameter and redesigned cooling circuit)



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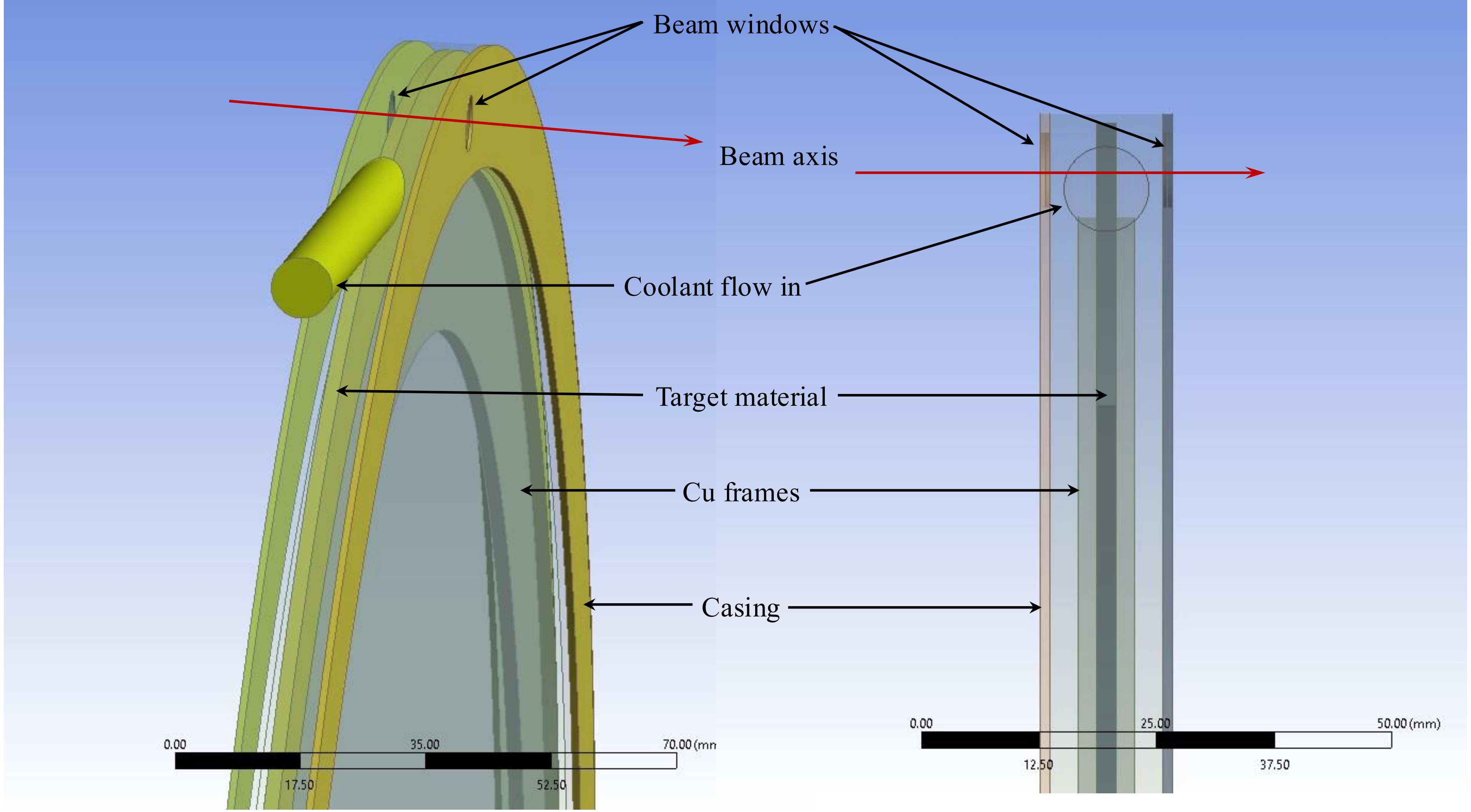
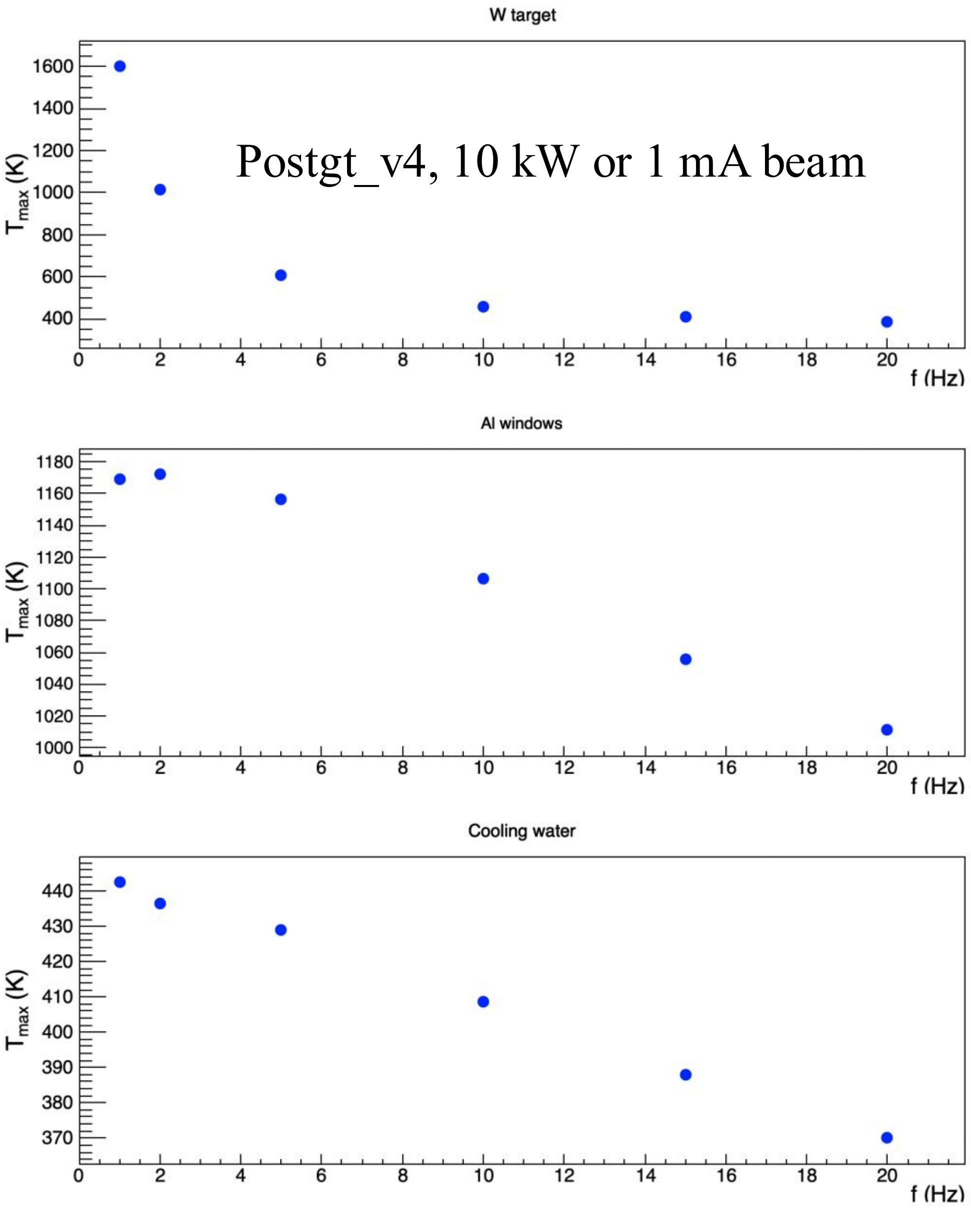
2nd Order Target Design (II)

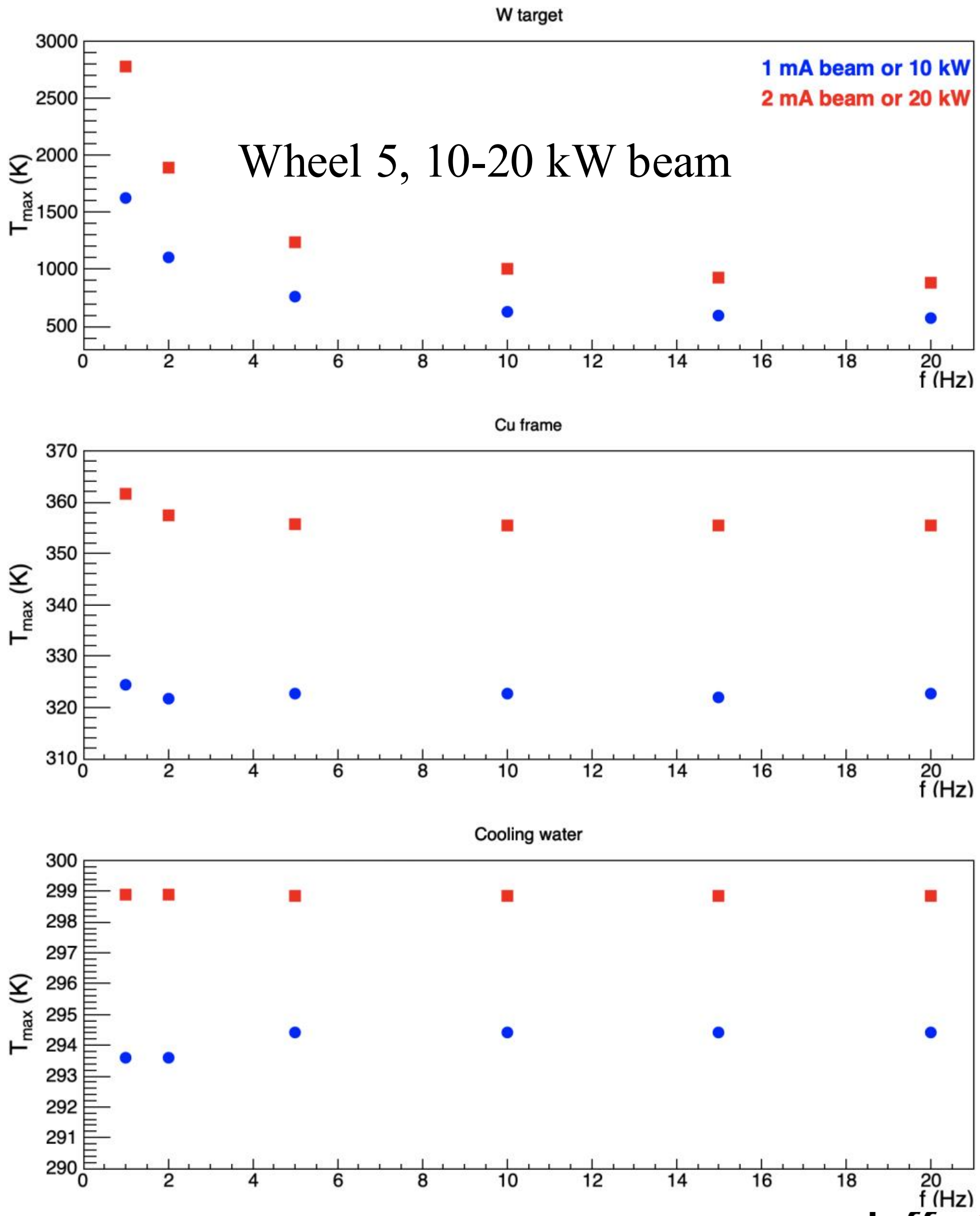
- Postgt.v4, 450 mm diameter



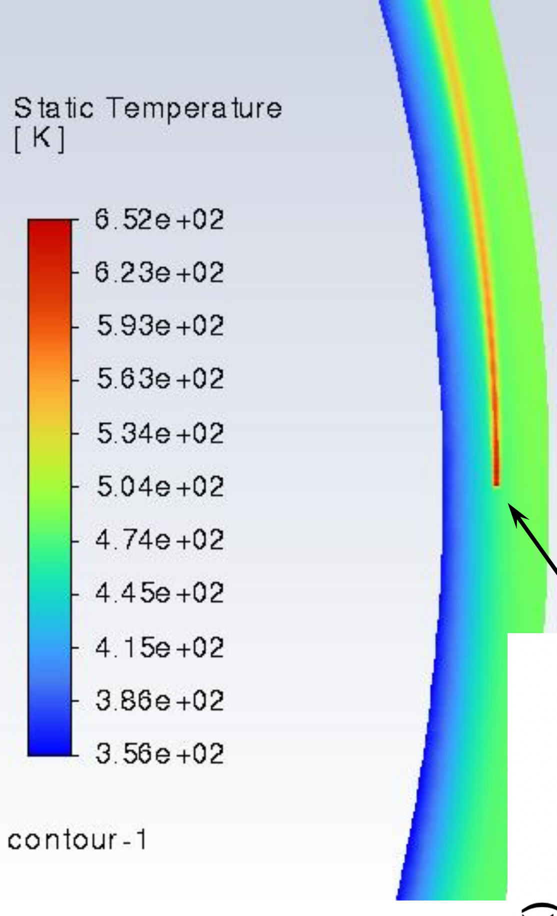
- The target wheel rotates inside a fixed casing. The coolant lines in/out connect to the casing and are fixed, do not rotate
- The target material is sandwiched between two copper disks
- The casing has thin windows for beam (considered to be made of Al for these simulations). The Al windows are fixed
- The primary beam traverses the coolant, the casing's windows and the target material
- This design simplifies the engineering of the coolant circuit

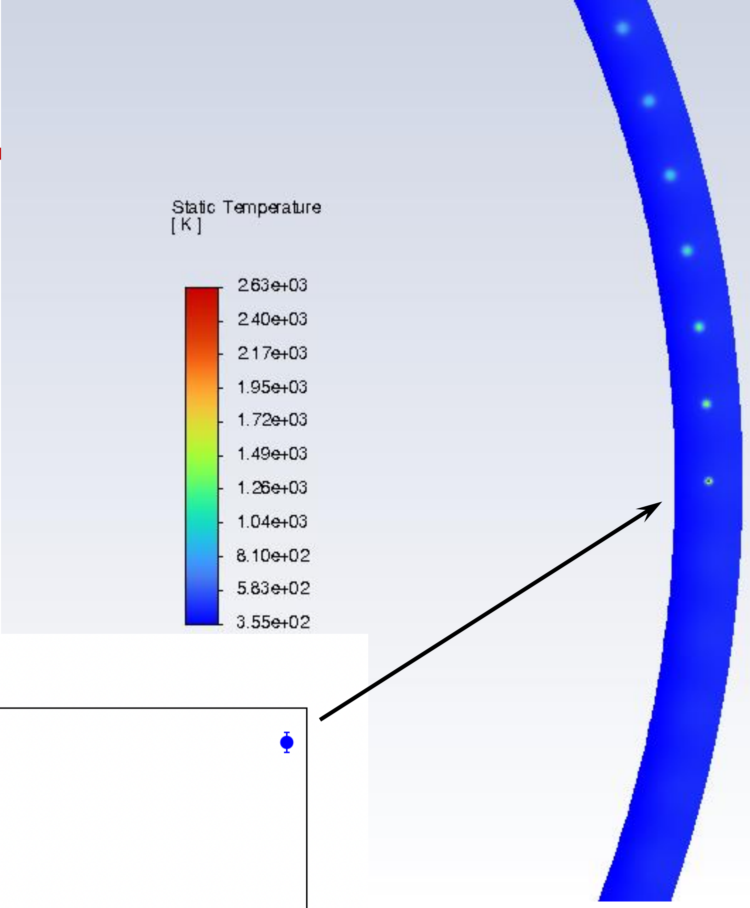
2nd Order Target Designs Compared

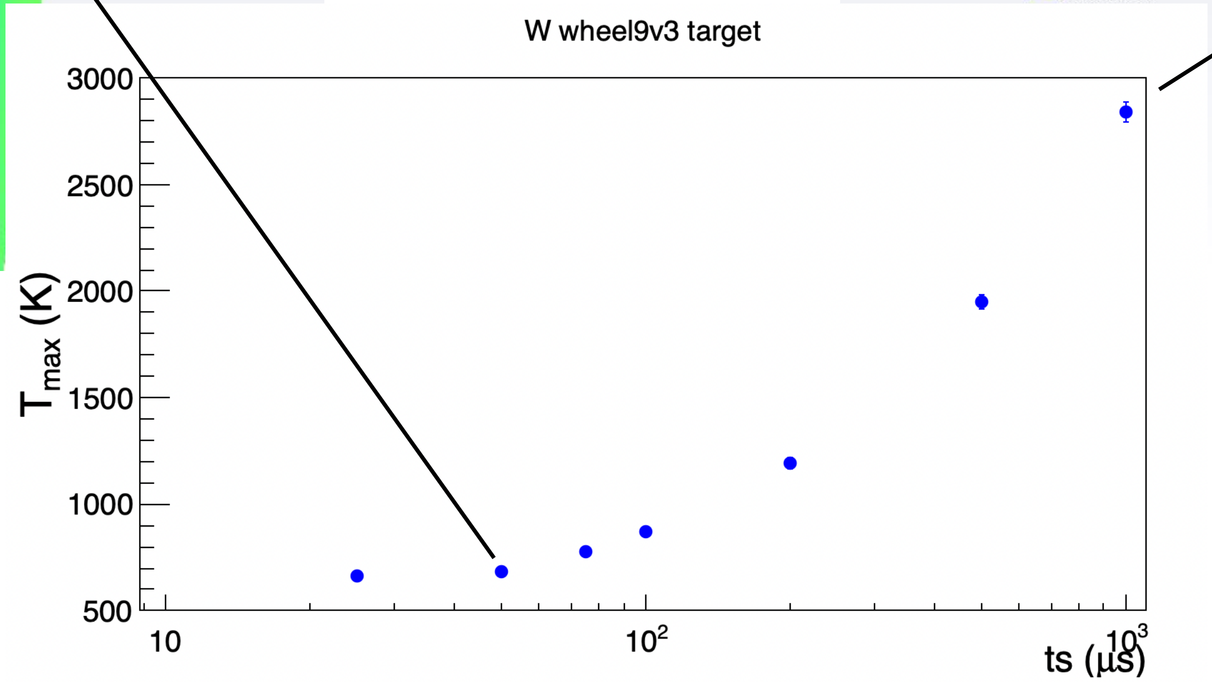




Maximum target temperature variation vs CFD time step, target rotates at 10 Hz, the energy loss in target is 11.7 kW, the beam spot has $\sigma = 250\ \mu m$



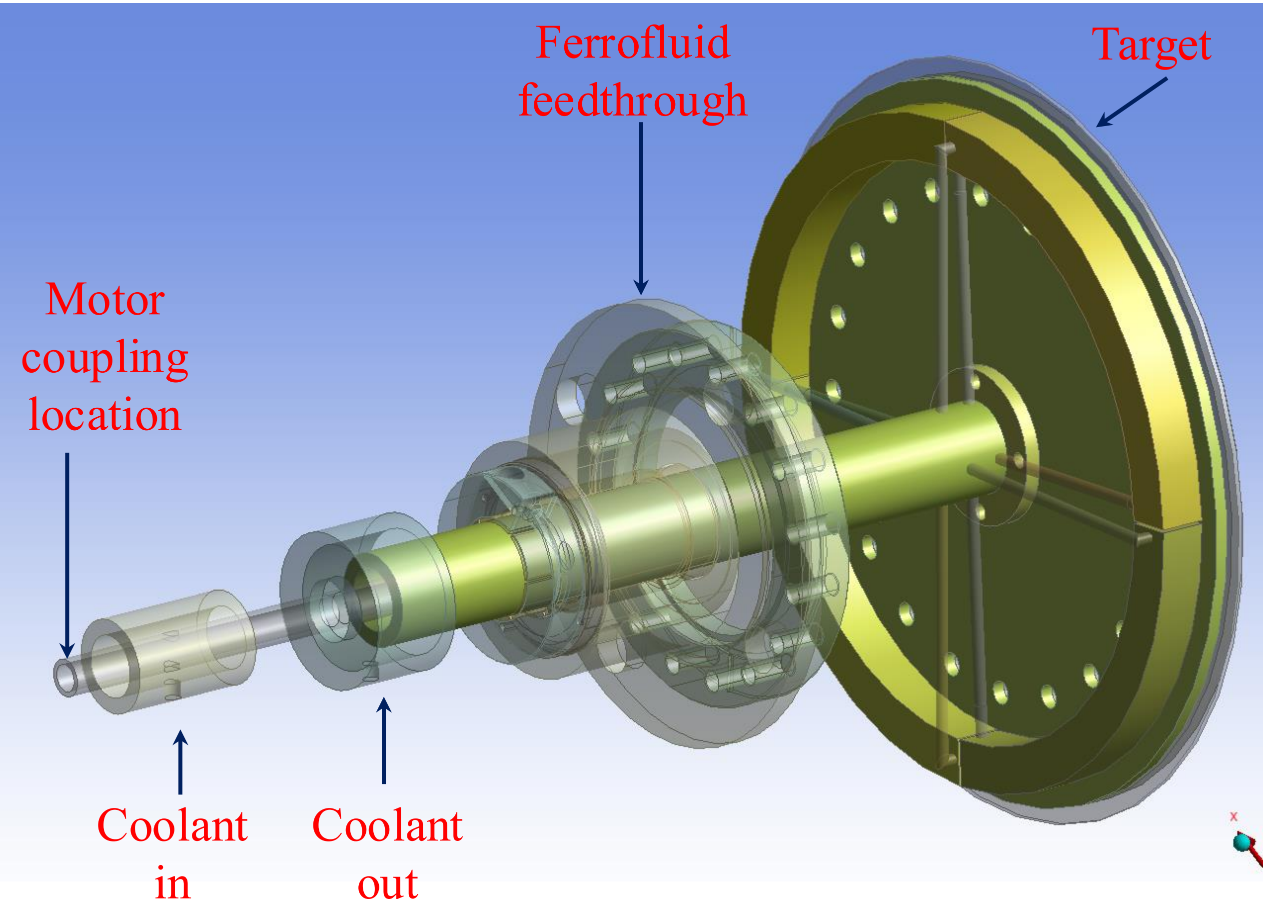


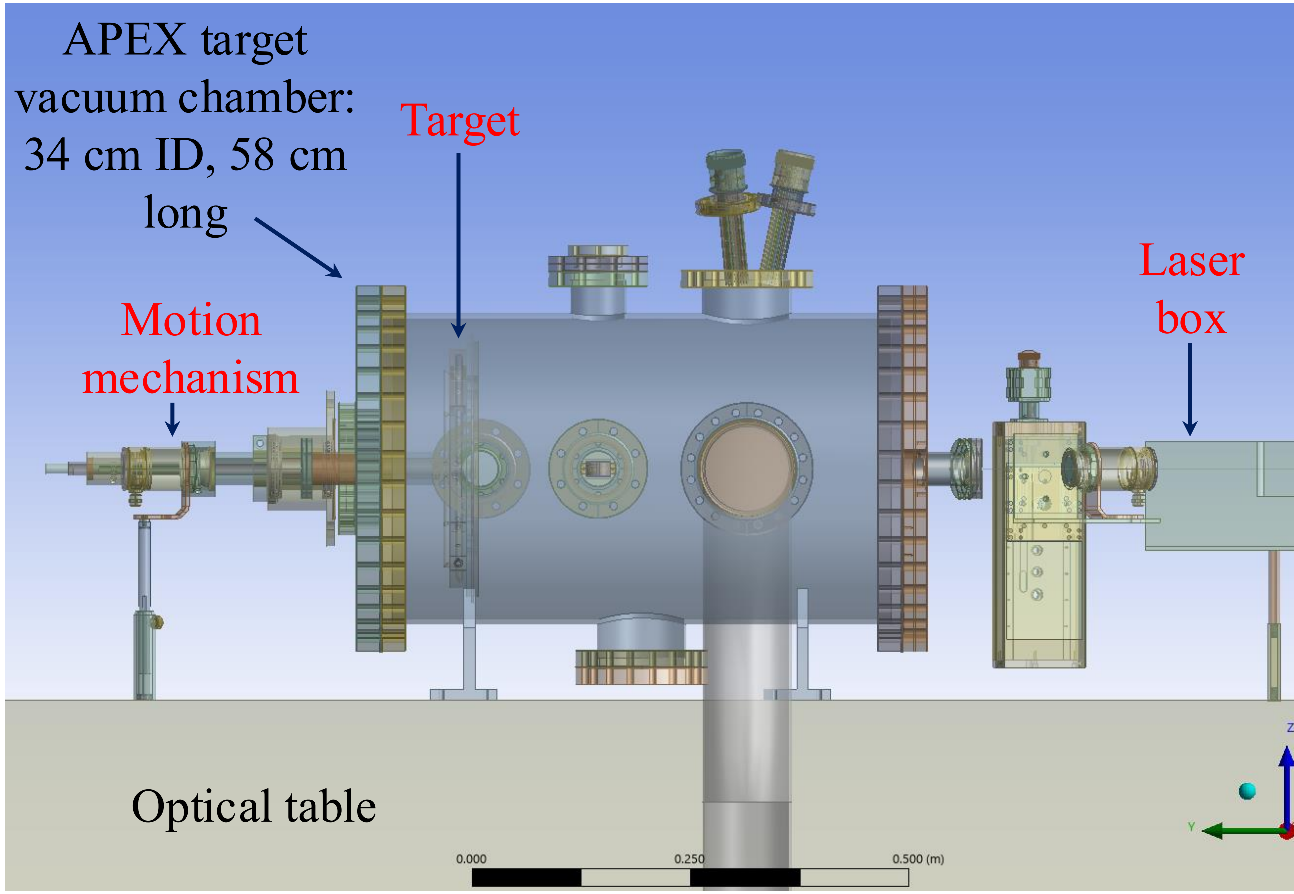


Prototype Target Project

- DOE-NP is funding a 2-year project to develop a prototype for the solid rotating target, as a stepping stone to a positron production target at Jefferson Lab
- Project goals:
  - CFD benchmarking
  - Vacuum integrity at 1e-6 Pa
  - Target rotation up to 5 Hz
  - Target cooling with water
- To accomplish the project goals we will design, build and test a rotating solid target. The target will rotate in a vacuum chamber, with water cooling provided under a vacuum of 1e-6 Pa
- CFD benchmarking will be done by heating the rotating target with a high-power laser and comparing measurements with CFD predictions to improve the CFD modeling of the production target
- Laser heating means no activation of the target: no radiological mitigation or constraints issues!

Prototype Target Assembly





- The motion mechanism will afford stable rotation in vacuum up to 10 Hz through a ferrofluid feedthrough rated for 10^{-6} Pa
- The target disk is sandwiched between two copper disks/frames, which a bolted together

Black = existing
Red = new

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Prototype Target Status

- CFD calculations are completed at the level of 80%, to reach 90% by the end of Mar-2026
- Instrumentation integration: spring 2026
- Engineering the target rotation and cooling circuit to be completed by the end of Apr 2026
    - Assess the current vacuum chamber, if any modifications needed, to be completed by the end of spring 2026
    - Assembly of vacuum chamber to start Mar - Apr 2026
    - Laser needed for first heating tests May-Jun 2026
    - Laser tests of graphite wheel, pure-tungsten wheel and a tungsten-copper (85-15) wheel, Jun-Aug-2026
    - Laser endurance tests Aug-Sep-2026
    - Any miscellaneous measurements Sep-Nov 2026

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Summary

- CFD-driven design is an essential tool in the development of high power targets for positron sources
- Collaborating with Xelera Inc, SLAC and SKEKB on target design
- Prototype solid rotating target project underway

- Jlab's approach to target from design to operations:
  - 1st stage : materials, shape, rotation, cooling, vacuum and CFD benchmarking
  - 2nd stage: thermo-mechanical stresses, radiation damage and magnetic field compatibility
  - 3rd stage: build and operate a production target

- There is a Positron Working Group (PWG) at Jefferson Lab, made of staff and users, to develop and promote a positron physics program at Jlab