Designing Targets with CFD

- Design with CFD
- High/low-power target designs with CFD
- Summary

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Polarized Sources, Targets and Polarimetry

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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: first target designed with CFD at Jefferson Lab: 2.5 kW of beam power on 35 cm long liquid hydrogen (LH2) cell.
- The outstanding performance of the Qweak target established CFD as a baseline design tool for low noise targets at Jefferson Lab
- 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
- Current CFD software in use at Jefferson Lab: ANSYS-CFD (Fluent and CFX), current CFD computational farm capacity: 512 CPUs

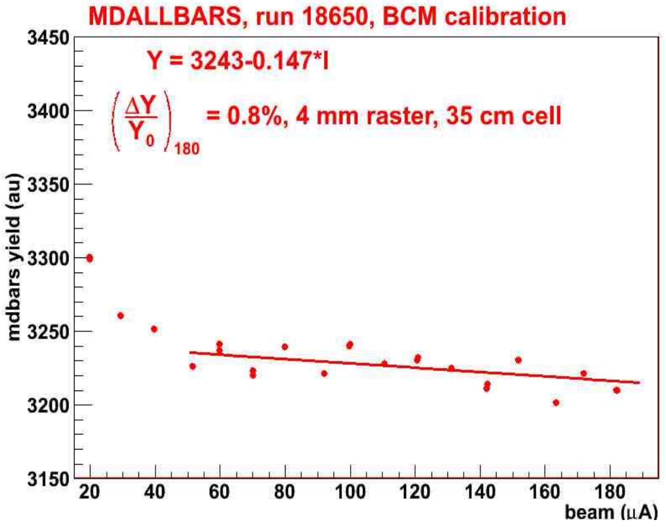
What is Target Noise (an example from Parity-Violation measurements)

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

Yield loss, Qweak LH2 target



Target density fluctuations = asymmetry width enlargement

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

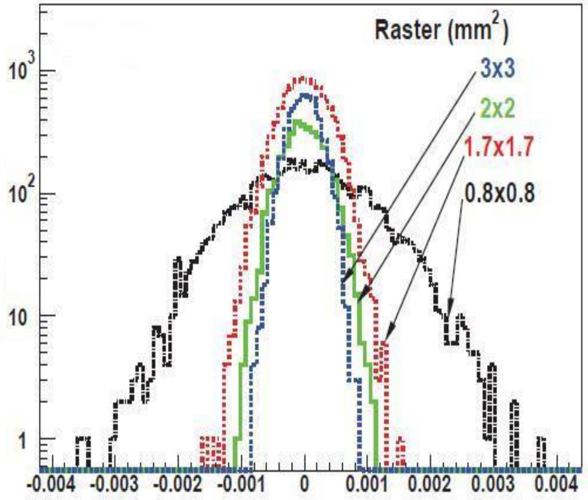
$Y_{+/-} \sim N/I$

+/- are electron beam helicity states

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

10% noise increase → 20% longer running

G0 asymmetry width enlargement



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

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

CFD is the most efficient tool for low noise target design

LH2 Targets for Parity Violation

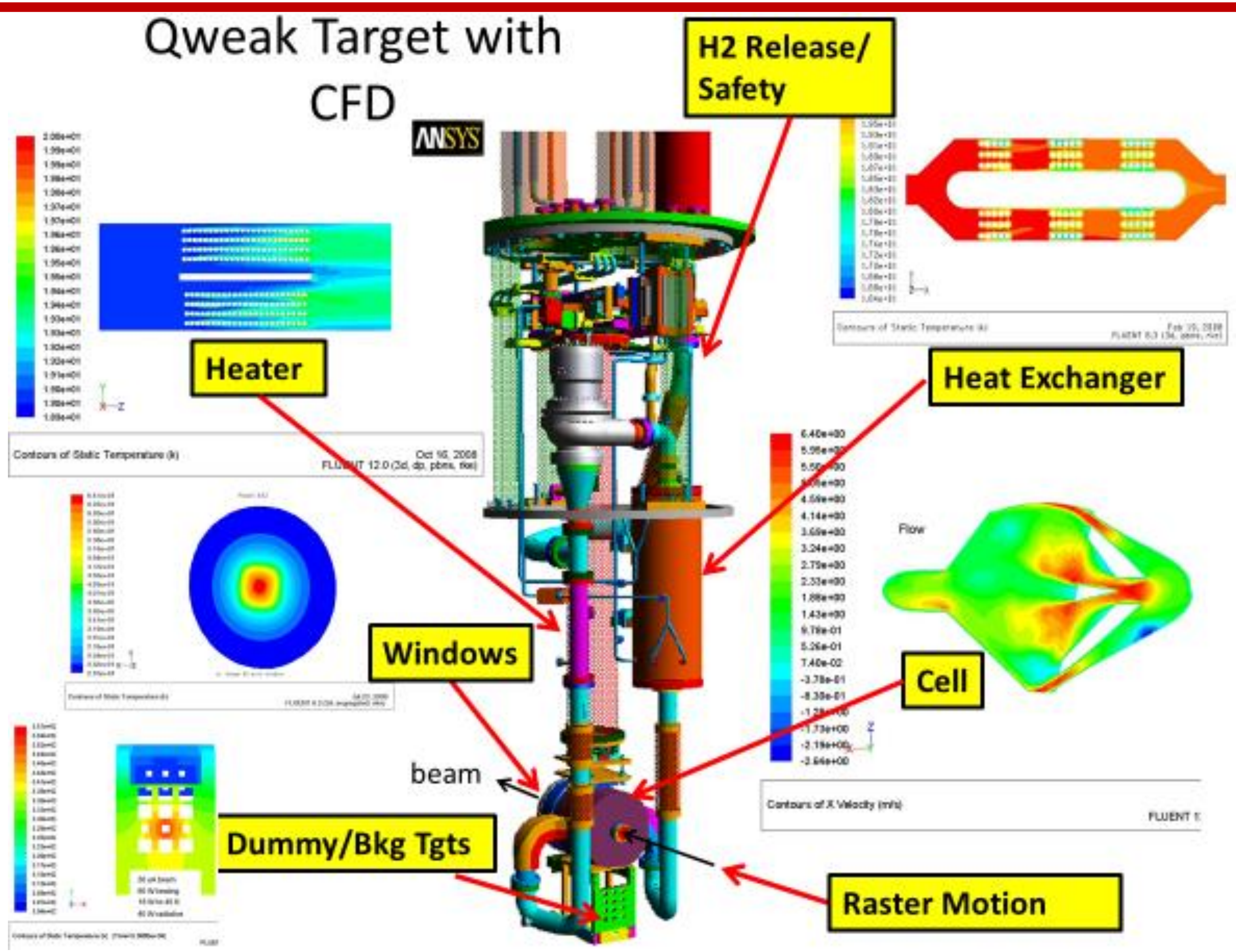
	p / T / $\dot{m}$ psia / K / kg/s	L cm	P / I W / μA	beam spot mm	Δρ/ρ %	δρ/ρ ppm	E GeV
Sample	25 / 20 / 0.6	40	700 / 40	2	1	1000@60 Hz	0.2
Happex I	26 / 19 / 0.1	20	500 / 35-55	4.8 x 4.8 6 x 3		100@30 Hz	3
PV-A4	25 / 17 / 0.13	10	250 / 20	0.1	0.1	392@50 Hz	0.854
E158	21 / 20 / 1.8	150	1000 / 11-12	1	<1.5	65@120 Hz	45/48
G0	25 / 19 / 0.3	20	500 / 40-60	2 x 2	1.5	238@15 Hz	3
Q_{weak}	35 / 20 / 1	35	2500 / 180	4 x 4	0.8	46@480 Hz	1
MØLLER	**35 / 20 / 1.8**	**125**	**4500 / 75**	**5 x 5**	**<2%**	**<25@1000 Hz**	**11**
P2	**35 / 20 / 2**	**60**	**4000 / 150**	**5 x 5**	**<2%**	**<11@1000 Hz**	**0.2**

CFD@JLAB: selection of targets

Target	material	L mm	P / I W / μA	beam spot mm	Work done	E GeV
PREX-2	C-208Pb-C	0.55	100 / 70-85	4x5	Design/assessment	1.1
CREX-1	40Ca/48Ca	5	340 / 150	2x2	Design/assessment	2.2
Marathon	3H/H	250	4 / 22	2x2	assessment	several
APEX	W	0.1	80/ 100	1x5	Design/assessment	several
A1n/d2n	3He	400	5 / 30	4.5	Assessment/some design	several
Standard	LH2/LD2	<300	500 / 100	2x2	Design/assessment	several
Gen-2	**3He**	**600**	**8 / 60**	**6**	**Assessment/some design**	**several**
MØLLER	**LH2**	**1250**	**4300 / 70**	**5x5**	**Design/assessment**	**11**
Ce^+BAF	**W(?)**	**4**	**20000 / 1000**	**4**	**Design**	**0.123**

CFD for the Qweak Target

- CFD driven design was used for all Qweak target loop components except the pump
- H_2 release into Hall C was analyzed with CFD to establish keep-out zones around the target chamber
- Steady-state and time-dependent CFD simulations have been developed
- The CFD design process extended over 3 years starting in 2006
- In the absence of CFD the Qweak would have employed an extended G0 target cell
- The Qweak target cell design started with the extended G0-type cell and morphed into a fully transverse flow to the beam line cell used successfully in 3 run periods (2010-2012)



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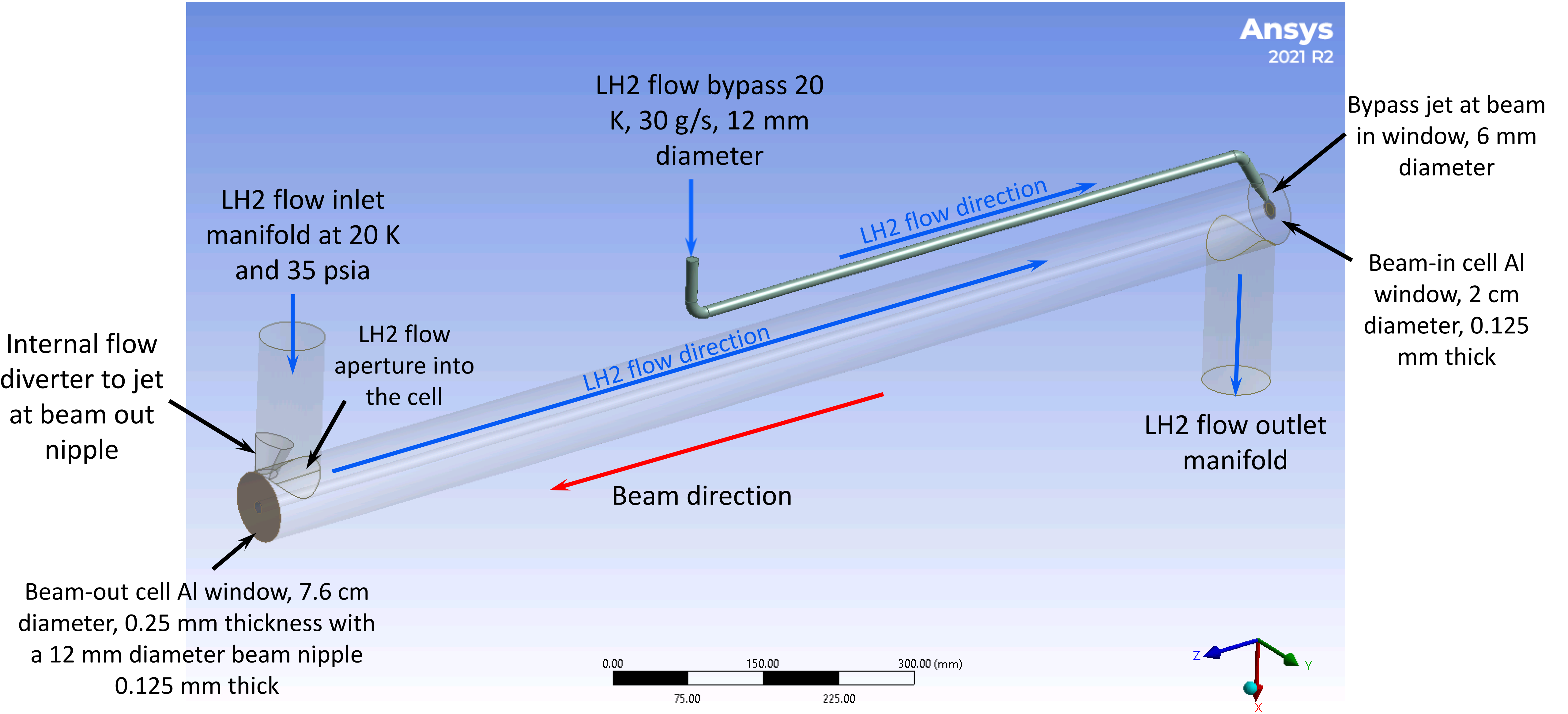
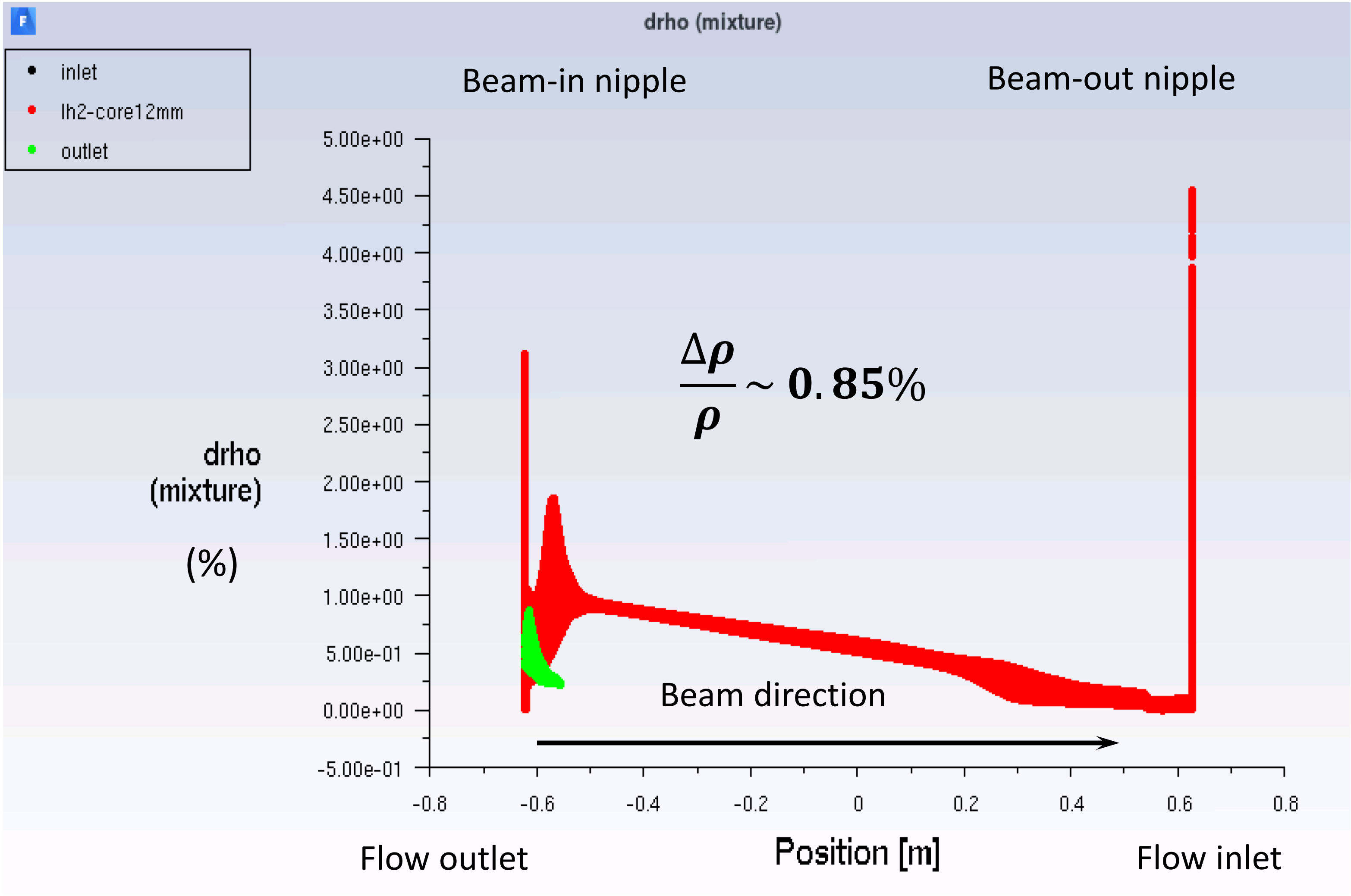
MOLLER Cell Model 21 Flow Space

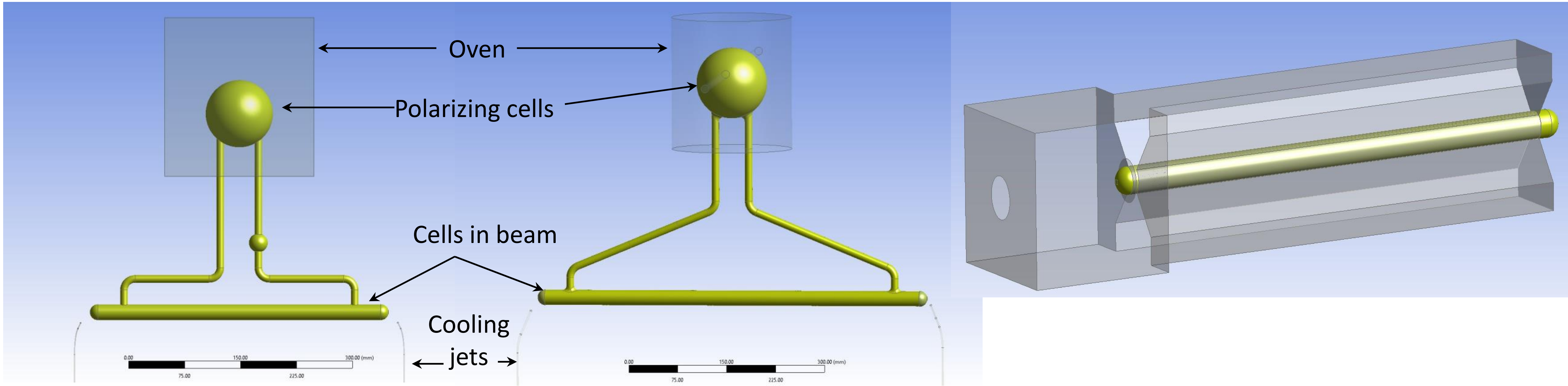


CFD predictions for the MOLLER Cell

- Beam raster 4x4 mm^2 (nominal is 5x5 mm^2)
- Beam current 75 μA (max expected 70 μA)
- Mass flow 1.5 kg/s (max expected 1.8 kg/s)
- T = 20 K (saturates at 23.7 K) , p = 35 psia
- 2-phase model with nucleate boiling accounted for
- Estimated max luminosity loss 0.9%
- Estimated LH2 noise at 960 Hz less than 15 ppm for pairs PV asymmetry



Natural Convection Cells (low power)

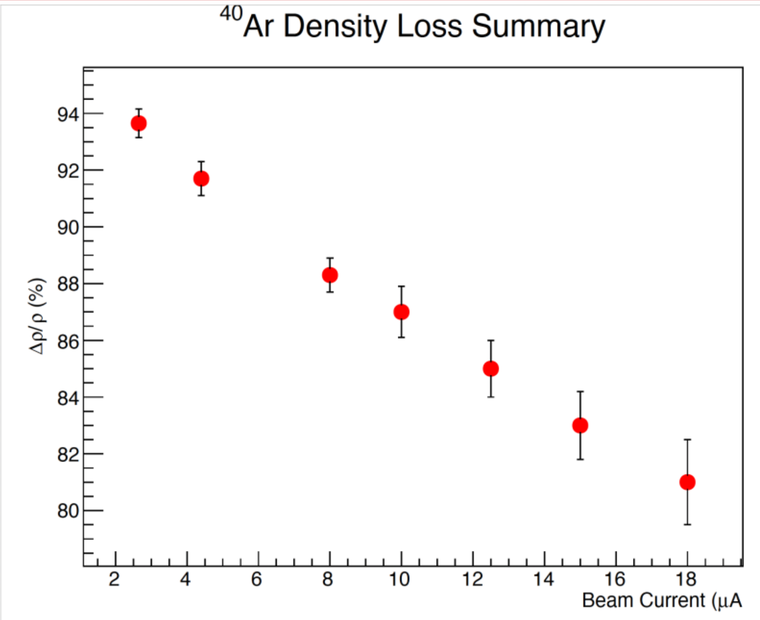


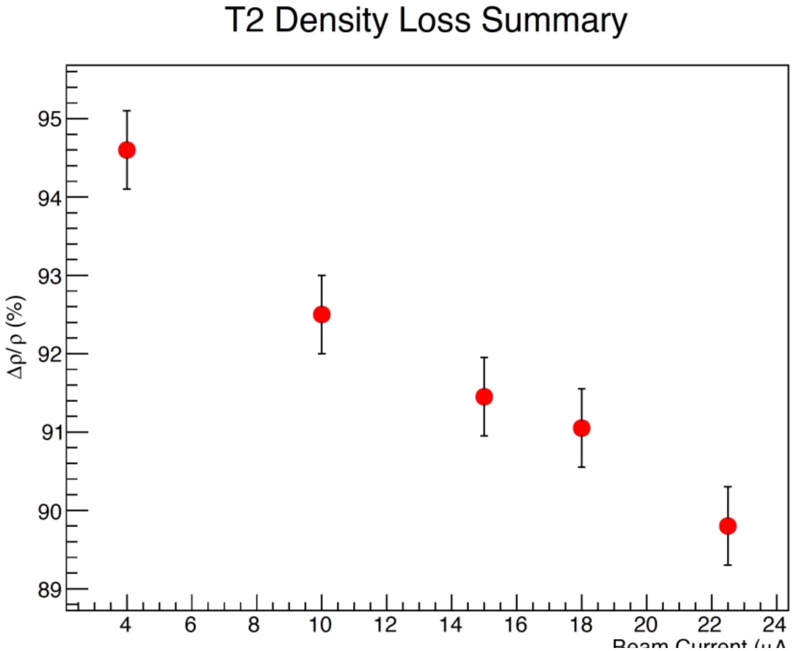
- A1n/d2 40 cm glass cell, UVA/W&M/JLAB design
- CFD assessments: cooling jets for the beam line windows, beam raster frequencies, beam ramp rate, gas internal convection, density loss in beam volume etc.
- Assessed for 30 μA beam current

- GEn2 60 cm glass cell, UVA/W&M design, high T, high p
- CFD assessments: cooling jets for the beam line windows, beam raster frequencies, beam ramp rate, gas internal convection, density loss in beam volume etc.
- Assessed for 60 μA beam current

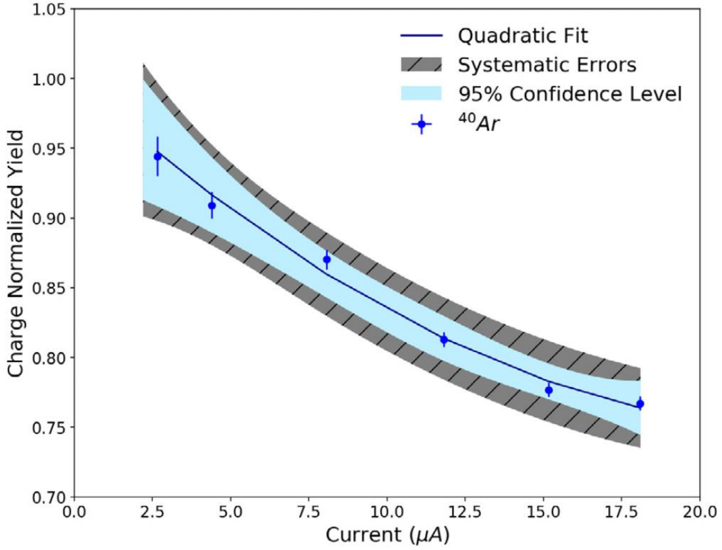
- T2/40Ar 25 cm Al cell, JLAB design (Dave Meekins)
- CFD assessments: cryogenic cell, density loss v. beam current, beam raster effect, beam line windows heating
- Assessed for 25 μA beam current

Density Loss for 40Ar/T2 Cell

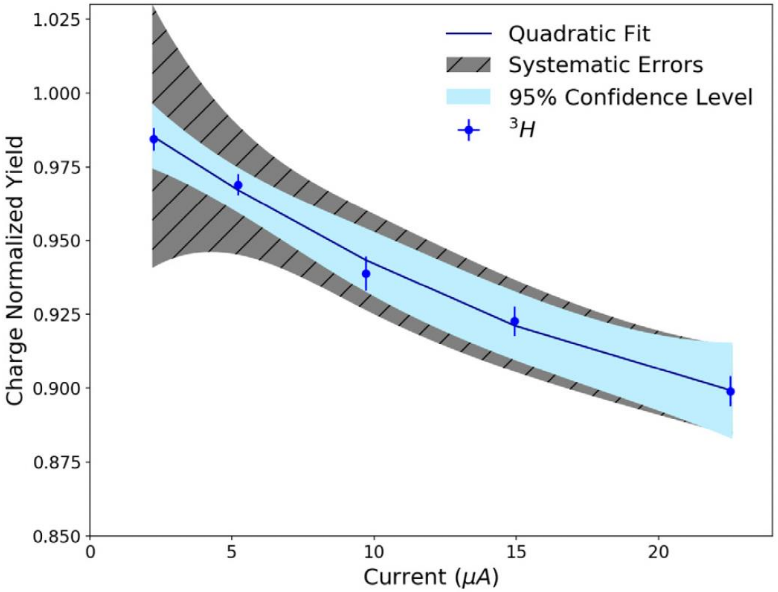




CFD predictions



Data from: “Density changes in low pressure gas targets for electron scattering experiments”, S. N. Santiesteban et al., NIM A 940, 351-358, 2019

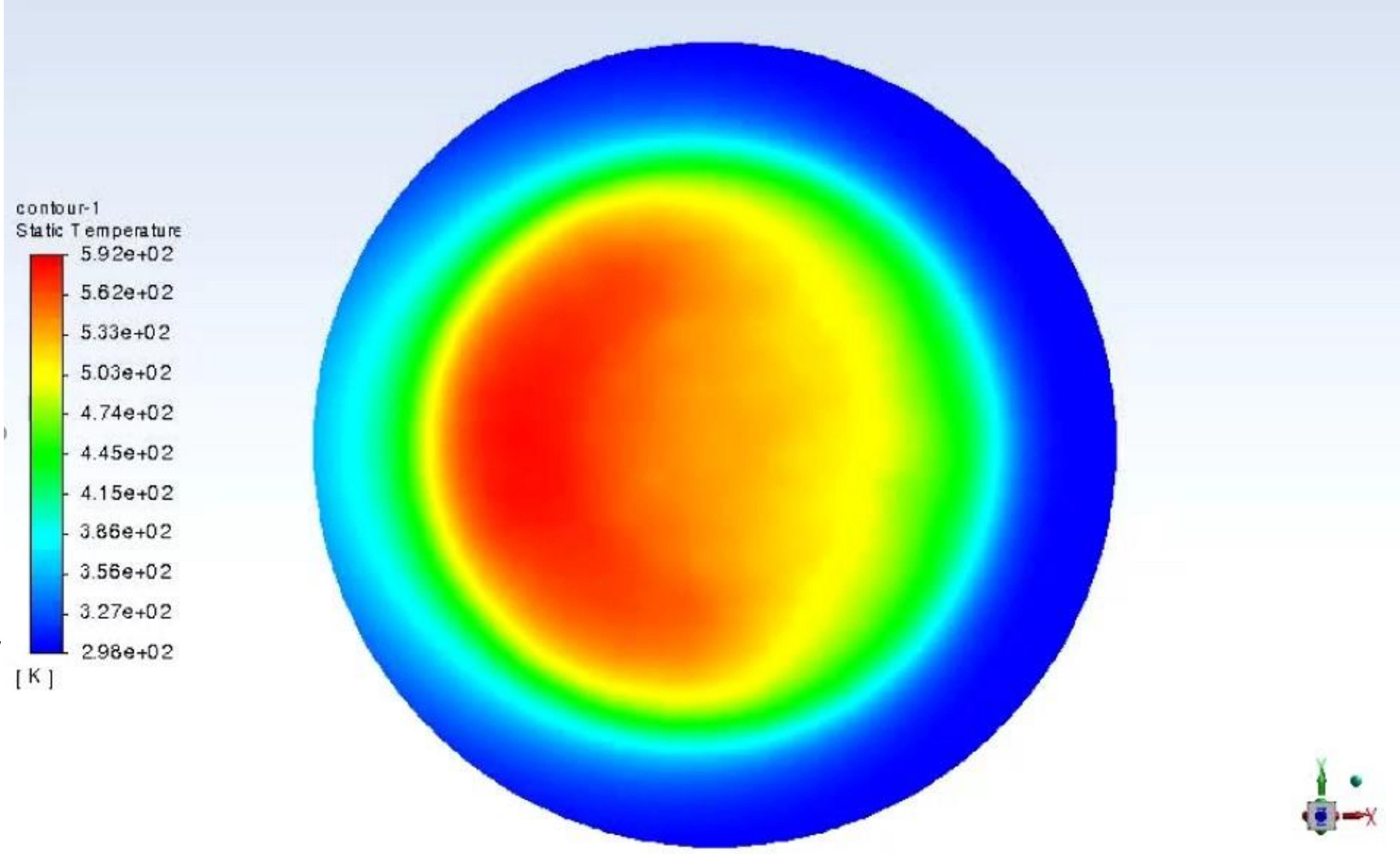


GEn2: beam raster and cooling jets effects

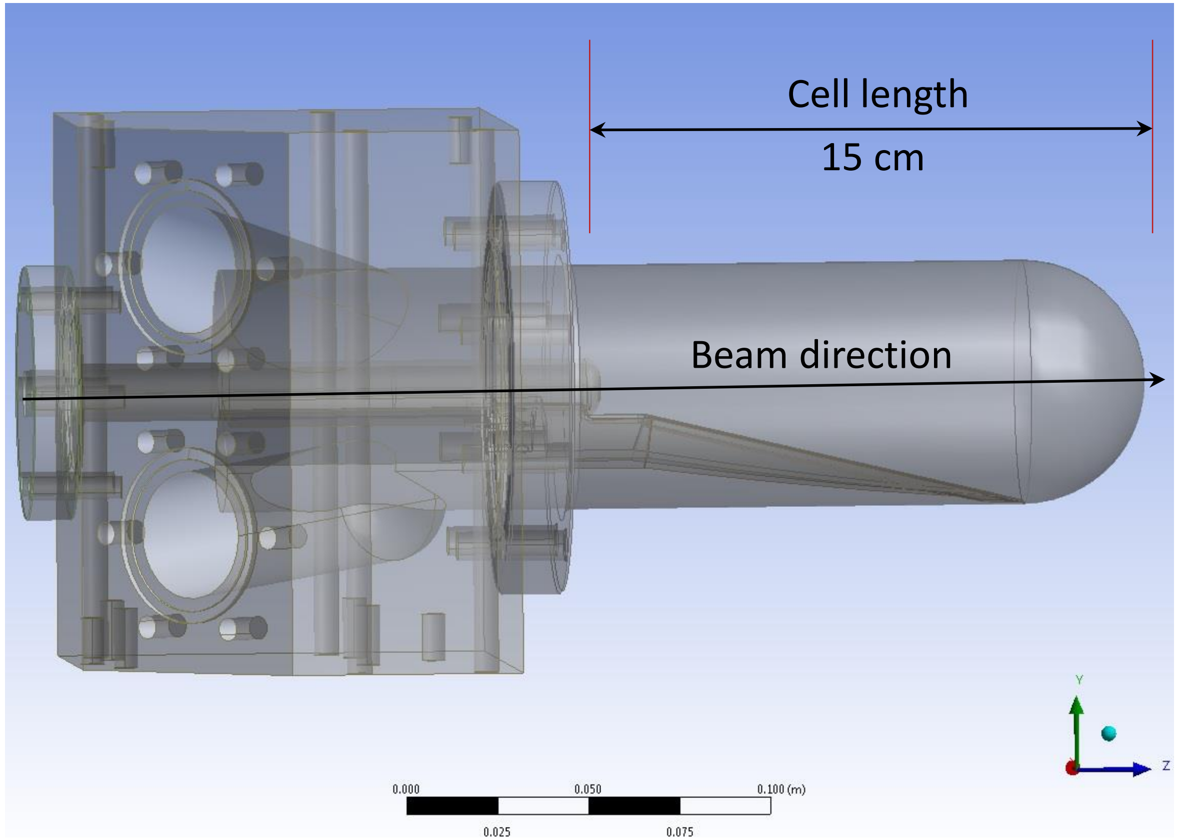
- Circular beam raster 5 mm diameter, 320 μm intrinsic beam spot diameter

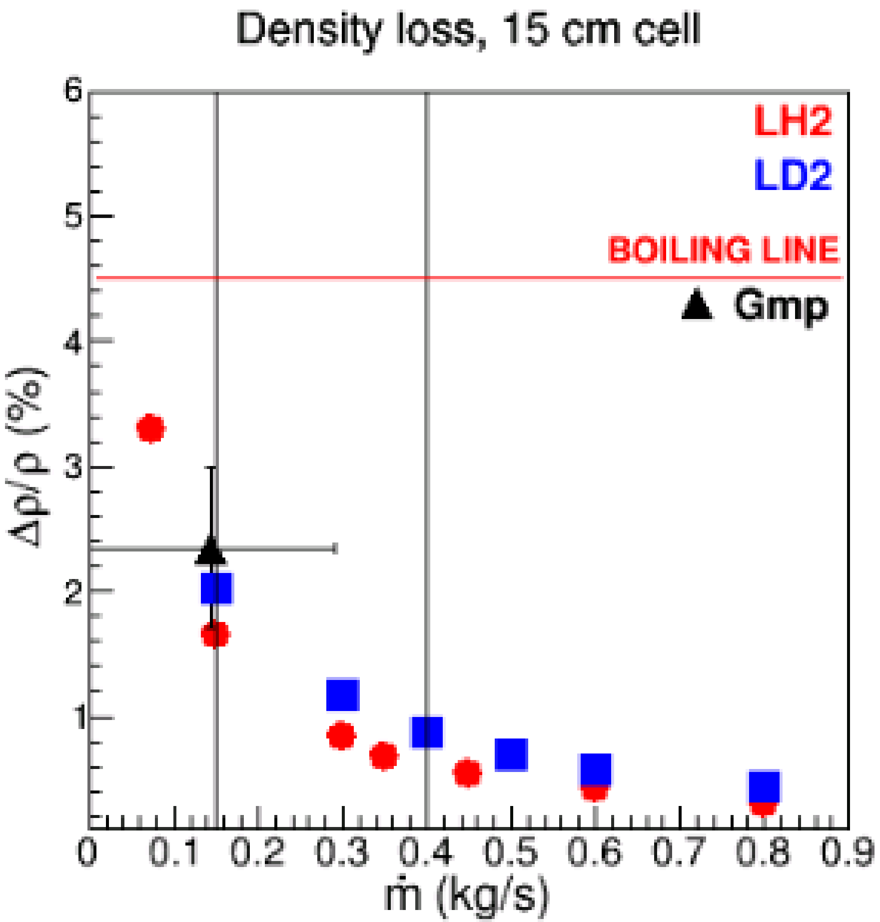
$$x(t) = R_0\sqrt{tf_r - [tf_r]} \cdot \cos(2\pi f_c t)$$
$$y(t) = R_0\sqrt{tf_r - [tf_r]} \cdot \sin(2\pi f_c t)$$

- f_r = 50 Hz, f_c = 7551 Hz (fixed)
- Cooling jet: air, 100 lpm for 2 windows
- Beam current 60 μA, beam power in one glass window 5 W
- Time-dependent simulations



Standard Target Cell with CFD





- 5-600 W, 15 cm cell for the standard targets in Halls A/C for the 12 GeV program
- Predicted LH2 density loss with CFD at 100 μA beam current, 2x2 mm^2 beam raster and standard LH2 pump at 60 Hz: 1.8%, measured 2.3% (at 50 Hz on the LH2 pump)

(Very) High-power Positron Target Designs

- We are in the process of evaluating with CFD several target concepts, based on our collaborations:
  - Xelera Research LLC (Ithaca,NY) in collaboration with Jlab is pursuing a liquid metal jet target that could produce e+
  - SLAC group has a liquid xenon 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 that we are assessing (Yoshinori E. et al)
  - We are also assessing a rotating target design different from the SKEKB design
- 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 (1 year funding in progress, submitted in Dec 2023 for a 3 year grant 2024-2027, approved for 2 years)
- Our goal is to pool resources with our collaborators to help their positron target designs/assessments and along the way design a positron target for the Jefferson Lab physics program too

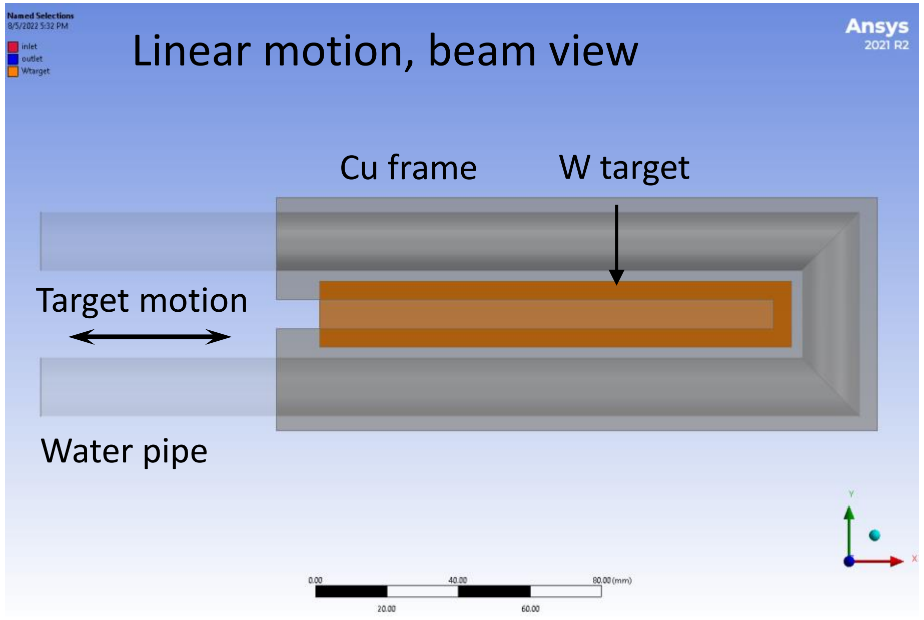
Ce+BAF General Target Design Parameters

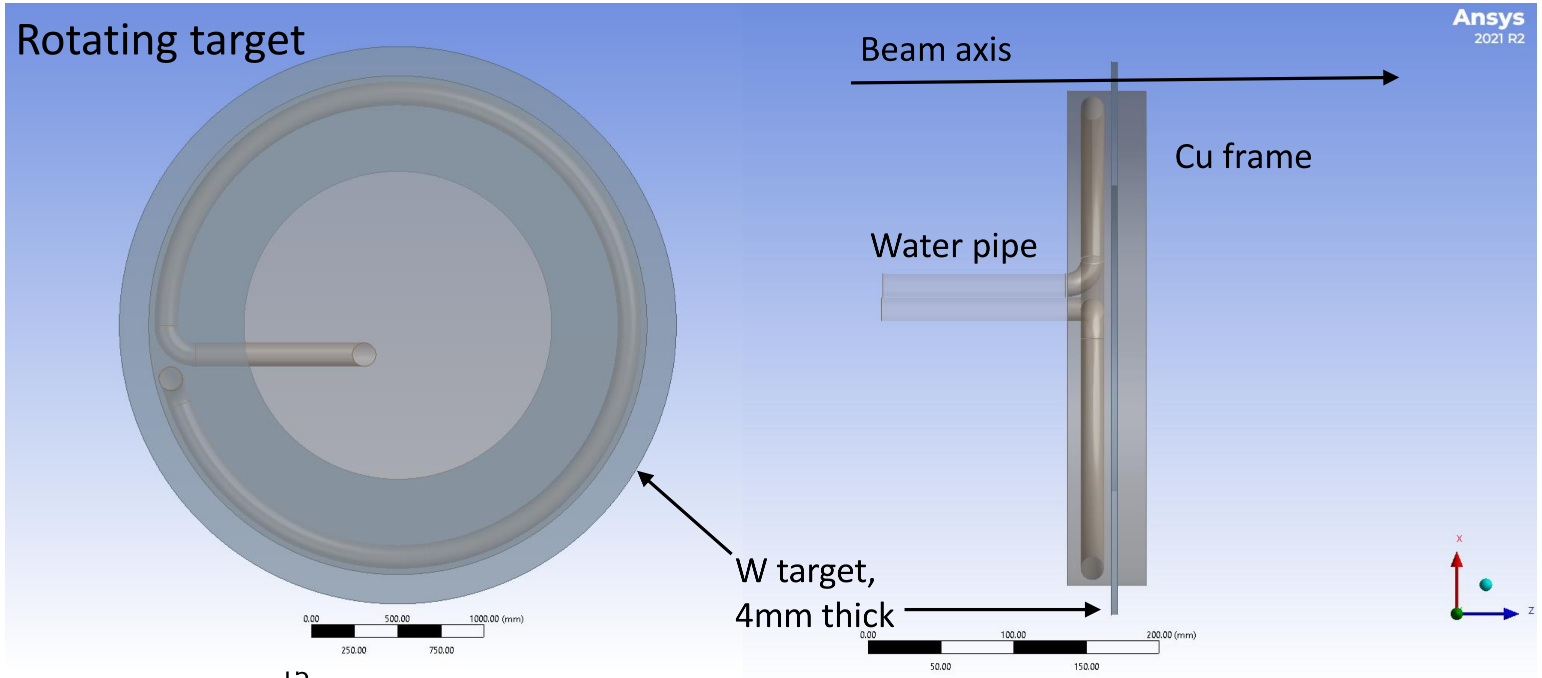
- Design goal: the target should be able to take a 1 mA CW e^- beam current and have a lifetime of 6 months to 1 year (or longer)
- Tungsten is preferable as a target material: high Z (high e^+ yield) and high melting temperature (thermal resilience to high power beam deposition)
- Optimal W target thickness for e^+ production from an incoming 120 MeV, 1 mA e- beam, would be 4 mm
- Fluka estimates for heating power deposition in such a target are in the range of 17 kW
- Water seems to be the best option for cooling such a target

- 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)

Positron Solid 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

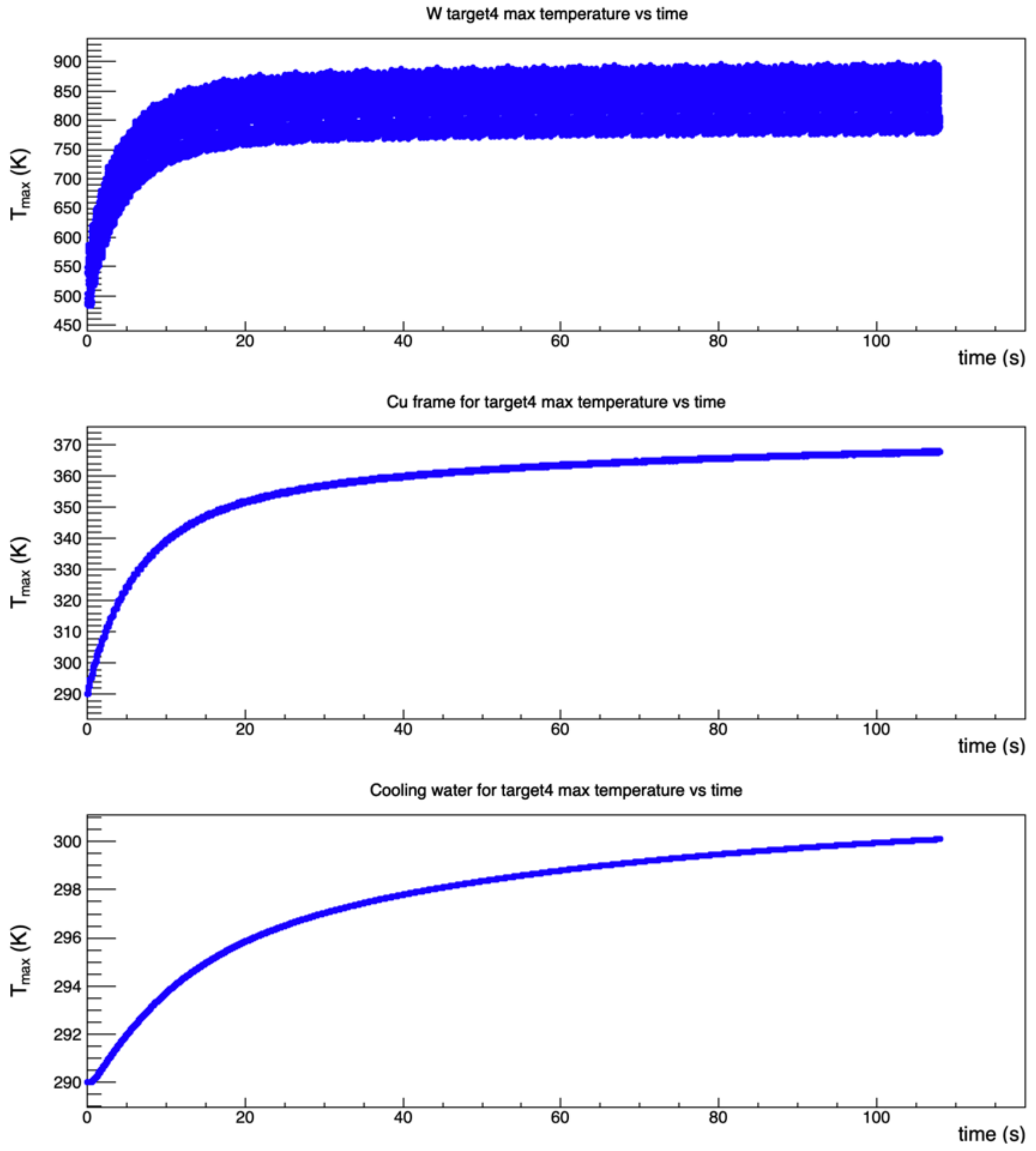




Ce+BAF Rotating W Target with CFD

- 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

- No studies on target material lifetime
- Started looking at the target engineering, radiological issues, shielding



Summary

- 20 years of experience in target design with CFD at Jefferson Lab

- Covered all aspects of a fixed target (polarized and unpolarized) design process

- Collaborating with Xelera Inc, SLAC and SKEKB on positron target design and prototyping

- Working on developing a feasible design for the e+ source at LERF@JLab within 3-5 years