Target Design with CFD

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Hall A - SBS meeting

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LH2 Target Design with CFD (I)

- Generate a geometry with a CAD program, mesh it
- Define boundary conditions (35 psia, 20 K, 300 g/s, beam heating in LH2 and Al nipples etc.
- Define isobaric fluid properties vs. temperature (20 K – 300 K)
- Solve a fluid mixture model (primary phase = liquid, secondary phase = gas) with evaporation-condensation at phase transition with latent heat in steady-state or transient mode
- If convergent: post-process (LH2 density profile in beam volume, velocity, turbulence etc.), fine-tune, re-run
- If not-convergent: change geometry, remesh, change fluid model etc.

LH2 Target Design with CFD (II)

- Before CFD became available target cell design was an educated guessing game, based on experience
- The Qweak target was the first designed with CFD at JLab
- The Qweak target performance validates CFD as a powerful design tool for LH2 targets
- Other parts of the target system can be addressed with CFD: high power heater, heat exchanger, pump, safety etc.

- Setting-up a CFD-Facility @ JLab to address target design
- CFD-Facility uses ANSYS-CFD (includes both Fluent and CFX) to design LH2 targets for the 12 GeV program at JLab

Liquid Hydrogen Targets

- 1974 FNAL had 12 operational LH2 targets + 12 in design + construction
- 1964-2003 SLAC developed more than 30 LH2 targets
- 1994-present JLab operated 4(+) LH2 targets, "standard" (Halls A and C) and 2 custom (G0, Qweak)

- Electron energy loss in a target: $P = IL\rho \frac{dE}{dx}$ [W], x = target "thickness" [g/cm^2]

- Typical conditions: 20 cm cell, 100 μA beam, 71 kg/m^3 density, P ~ 700 W heat
- For a beam raster of 2x2 mm^2, power densities are

  p_{LH2} ~ 9e8 W/m^3 in LH2 and p_{Al} ~ 1.5e10 W/m^3 in Al windows

- High power targets P < **1000 W**, early developments at SLAC, continued at Caltech (SAMPLE, G0, E158 targets) and JLab
- Very high power targets P > **1000 W**, Qweak@JLab

High Power LH2 Targets @ JLab

• both Halls A and C used "standard" high power LH2 targets, up to 1000 W

• Qweak-Hall C was the highest power LH2 target in the world at 2500 W

• LH2 poses two systematic effects to experiments:

- **global density reduction (10% density loss = 10% statistics loss!)**
- **density fluctuations at the e^- helicity frequency (10% density effect ~ 20% statistics loss)**

• 6 GeV LH2 standard target performance all over the place, as bad as 20% density loss over 20 cm at 100 μA, 2 mm raster (GepIII-2007)

• there is a need to standardize the performance of LH2 targets for a successful 12 GeV program at JLab in both Halls A and C (to start 2014)

LH2 Targets for Parity Violation

	p / T / $\dot{m}$ psia / K / kg/s	L cm	P / I W / μA	beam spot mm	$\Delta\rho/\rho$ %	$\delta\rho/\rho$ 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@7.5 Hz	3
Q_{weak}	35 / 20 / 1	35	2500 / 180	4 x 4	0.8	46@240 Hz	1
MØLLER	**? / ? / ?**	**150**	**5000 / 85**	**? x ?**	**?????**	**<25@500 Hz**	**11**

LH2 Density Loss @ JLab[1]

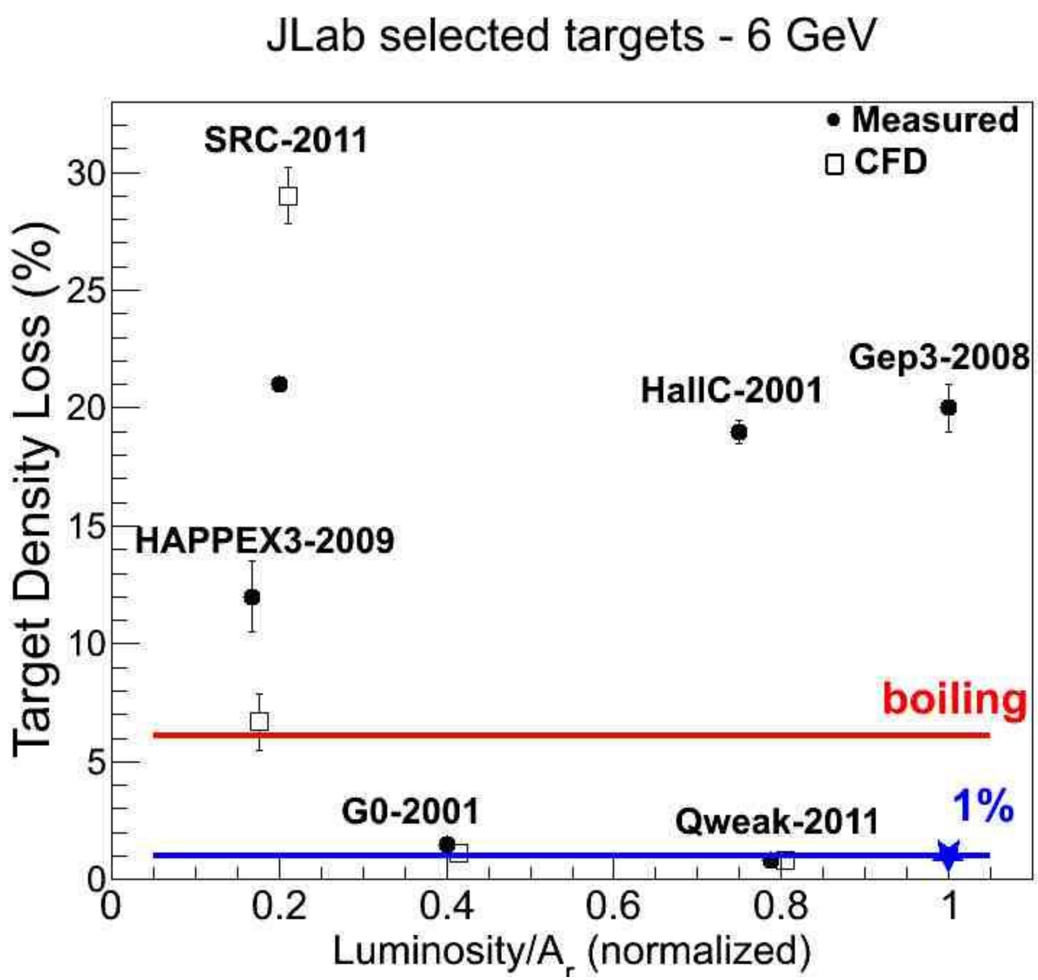
Target	Raster (mm × mm)	Fan Speed (Hz)	Slope $(100\mu A)^{-1}$	Reference
lH_2, 4 cm 'beer can'	1.1 × 1.1	60	−7 %	Hall C, 1996 [7]
lD_2, 4 cm 'beer can'	2.0 × 2.0	60	−4 %	Hall C, 1996 [7]
lD_2, 4 cm 'beer can'	2.4 × 2.4	60	−3 %	Hall C, 1996 [7]
lD_2, 4 cm 'beer can'	2.0 × 2.0	67	−2.4%	Hall C, 1997 [7]
lD_2, 12 cm 'beer can'	2.0 × 2.0	67	−2.3%	Hall C, 1997 [7]
lH_2, 4 cm 'beer can'	2.0 × 2.0	67	−1.1%	Hall C, 1997 [7]
lH_2, 4 cm 'beer can'	2.0 × 2.0	40	−3.2%	Hall C, 1997 [7]
lH_2, 15 cm 'beer can'	3.4 × 2.8	?	−5 %	Hall A, 1997 [8]
lD_2, 15 cm 'beer can'	3.4 × 2.8	?	−3 %	Hall A, 1997 [8]
lD_2, 4 cm 'tuna can'	2.0 × 2.0	60	−2.4 %	Hall C, 1999 [9]
lH_2, 15 cm 'cigar tube'	2.0 × 2.0	60	−19 %	Hall C, 2001 [10]
lD_2, 15 cm 'cigar tube'	2.0 × 2.0	50	−10 %	Hall C, 2001 [10]
lD_2, 4 cm 'cigar tube'	2.0 × 4.0	60	−7.2 %	Hall C, 2000 [10]
lD_2, 4 cm 'cigar tube'	2.0 × 4.0	60	−7.4 %	Hall C, 2000 [10]
lD_2, 15 cm 'cigar tube'	2.0 × 4.0	60	−12 %	Hall A, 2002 [11]

Table 2: Bulk effect slopes: % change in apparent luminosity for a beam current change from 0 to 100 μA, from other JLab cryotarget studies.

[1] D. Armstrong, B. Moffit, R. Suleiman, "Target Density Fluctuations and Bulk Boiling in the Hall A Cryotarget", JLAB-TN-03-017, 2003

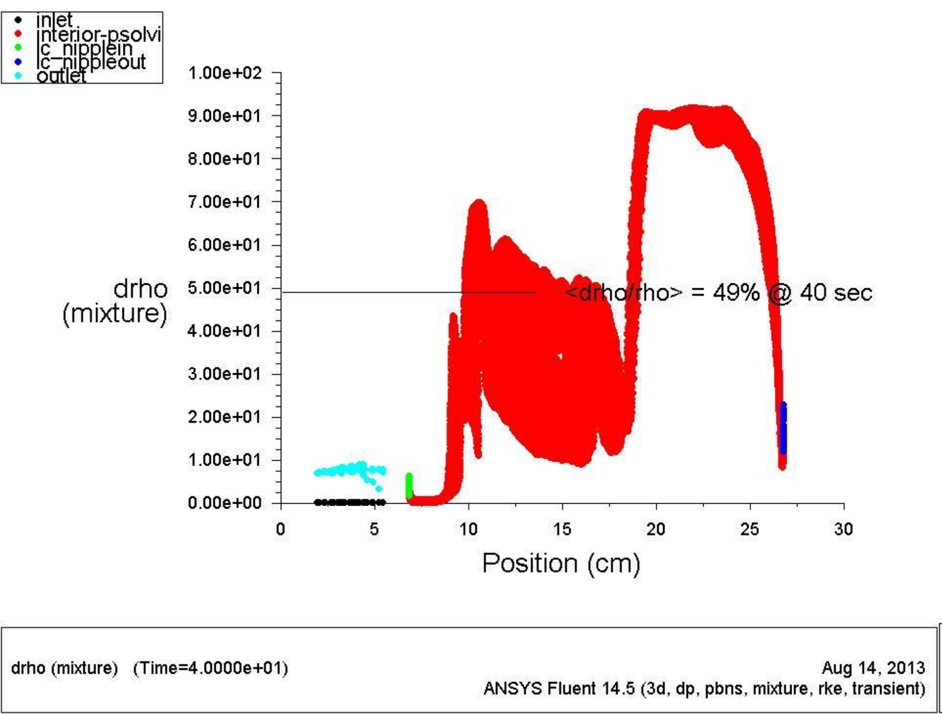
6 GeV Targets Performance

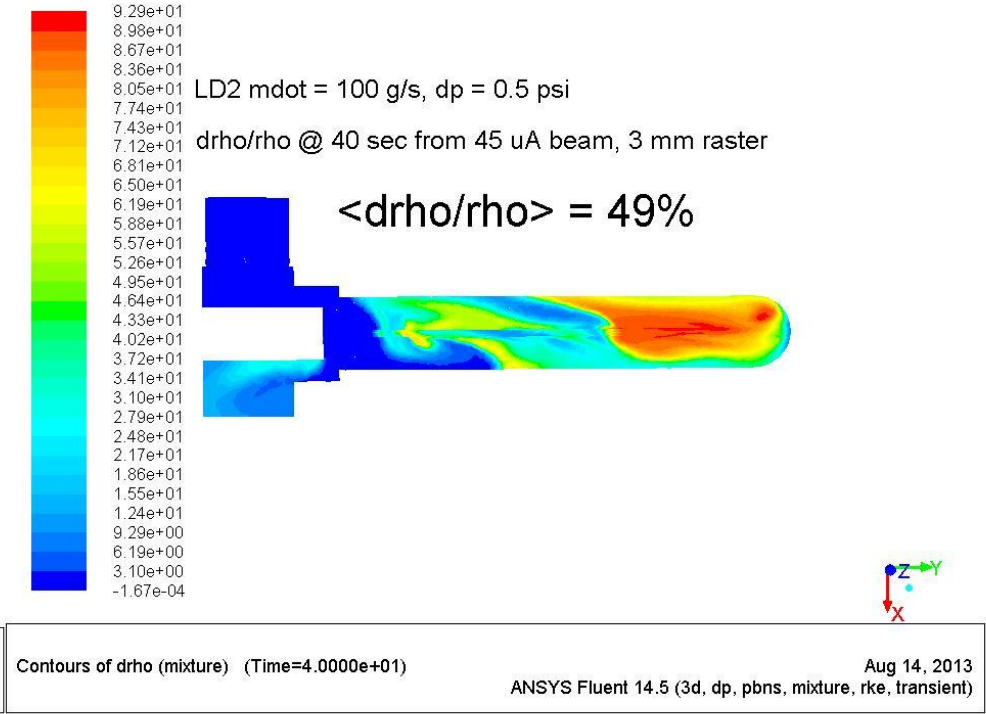
- HAPPEX3 cell was 25 cm long, racetrack design
- All the other cells, except qweak cell, were cylindrical cells
- The only high performance target cells at jlab with lengths > 15 cm were G0 and Qweak! (G0 designed at Caltech, Qweak designed with CFD)
- The goal is to standardize target performance for the 12 GeV program at 1 % density loss over 20 cm with beam of 100 μA, 2 mm raster



The Hall A SRC-2011 Target

- Target Group installs: 20 cm machined Al cell
- LD2 up to 45 µA, 4He/3He up to 120 µA (202 psia!)
- CFD predictions for running LD2 at 30.5 psia, 100 g/s, 0.5 psid over the cell-block only, 45 µA beam, 3 mm raster
- Dangerous vapor-lock bubble over 8 cm in length and 90 % of LD2 density lost



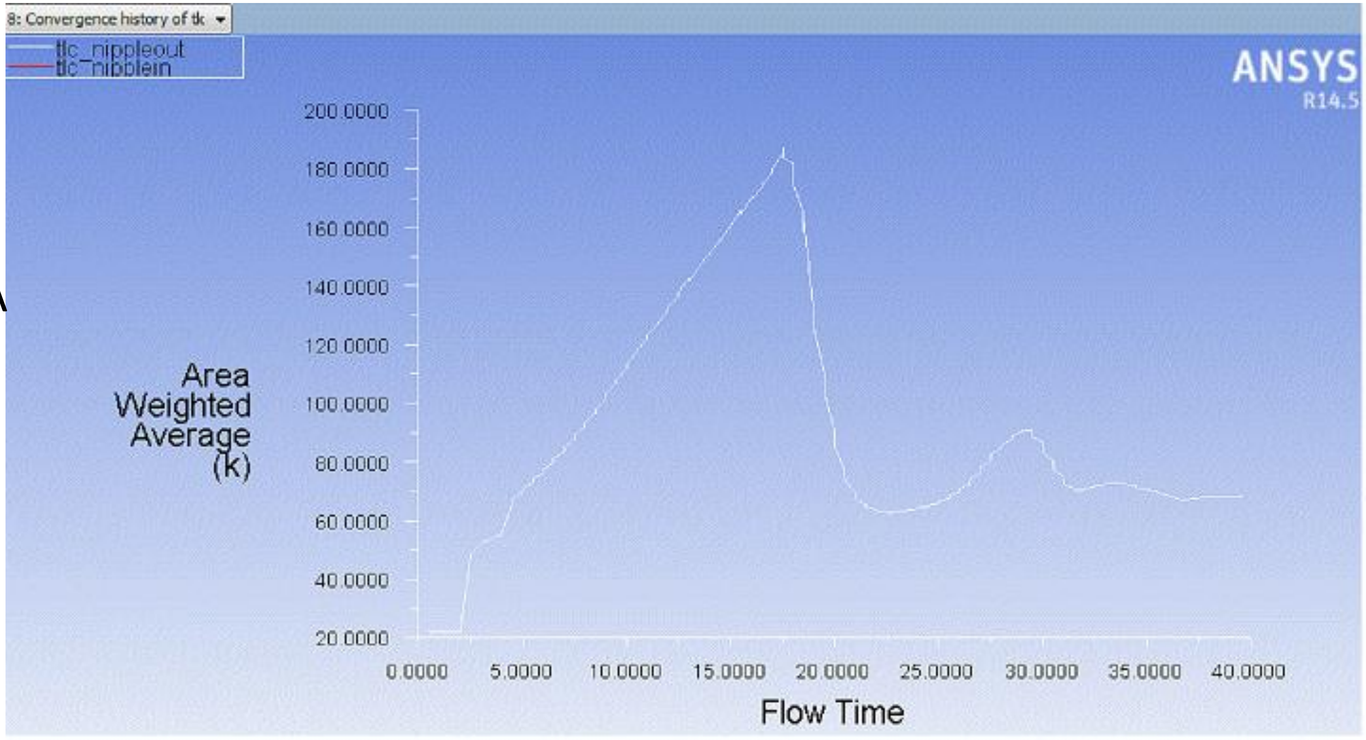


SRC-2011 Al Windows Heating

- Target cells made of Al, cell diameter 3.114 cm, 20 cm long, it ran 210 psia with 3He/4He and 30.5 psia with LD2
- Beam nipples assumed 0.1016 mm beam-in and 0.127 mm (0.005") beam-out
- Plot shows the average temperature of the beam-out Al nipple (3x3 mm^2) versus time, beam being ramped from 0 to 45 µA in ~ 20 sec

CFD predictions for this cell design:

- <T> reaches **200 K** at 45 µA, T_{max} ~ **250 K!!!**
- Runaway T for Al7075 ~ **433 K**
- Beam-out nipple likely to fail at I>70 µA with this ramp rate or lower I for faster ramps
- There is also a pressure spike associated with beam ramping

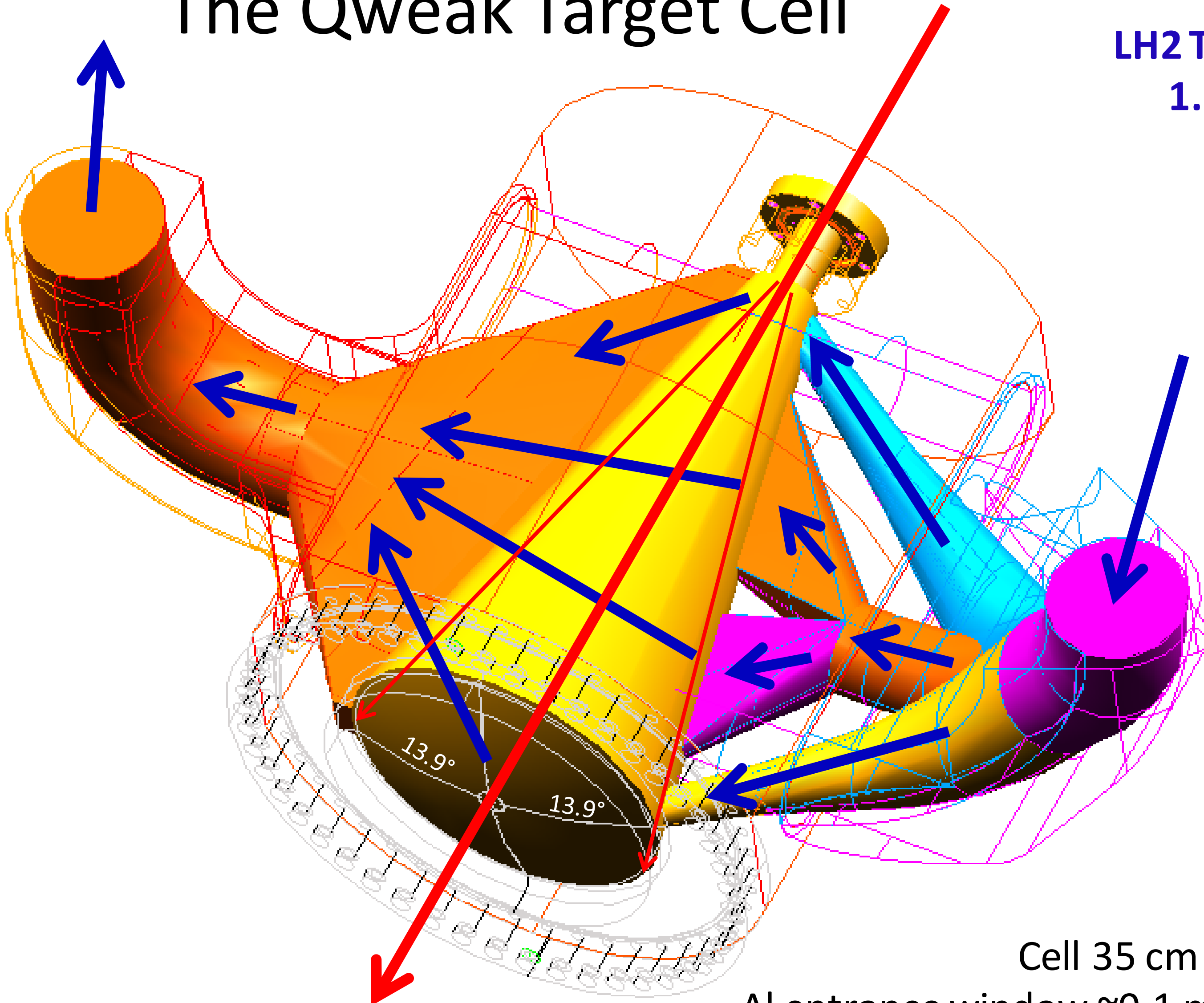


Qweak Target Design

- 2003: the original plan was to use an extended 35 cm G0-type cell, longitudinal flow
- 2005 started using CFD (Fluent)
- 4 years of cell design looking at 3 major geometries: G0-type, hybrid G0 – transverse flow, transverse flow, and tens of tweaks for each geometry
- By 2009 the cell design morphed into a transverse to beam axis LH2 flow in a conical shaped cell
- Spring 2009: cell engineered in 2-3 months
- Manufactured 3 cells (1st one had a leak from manufacturing and was aborted)
- Qweak ran successfully 2010-2012

The Qweak Target Cell

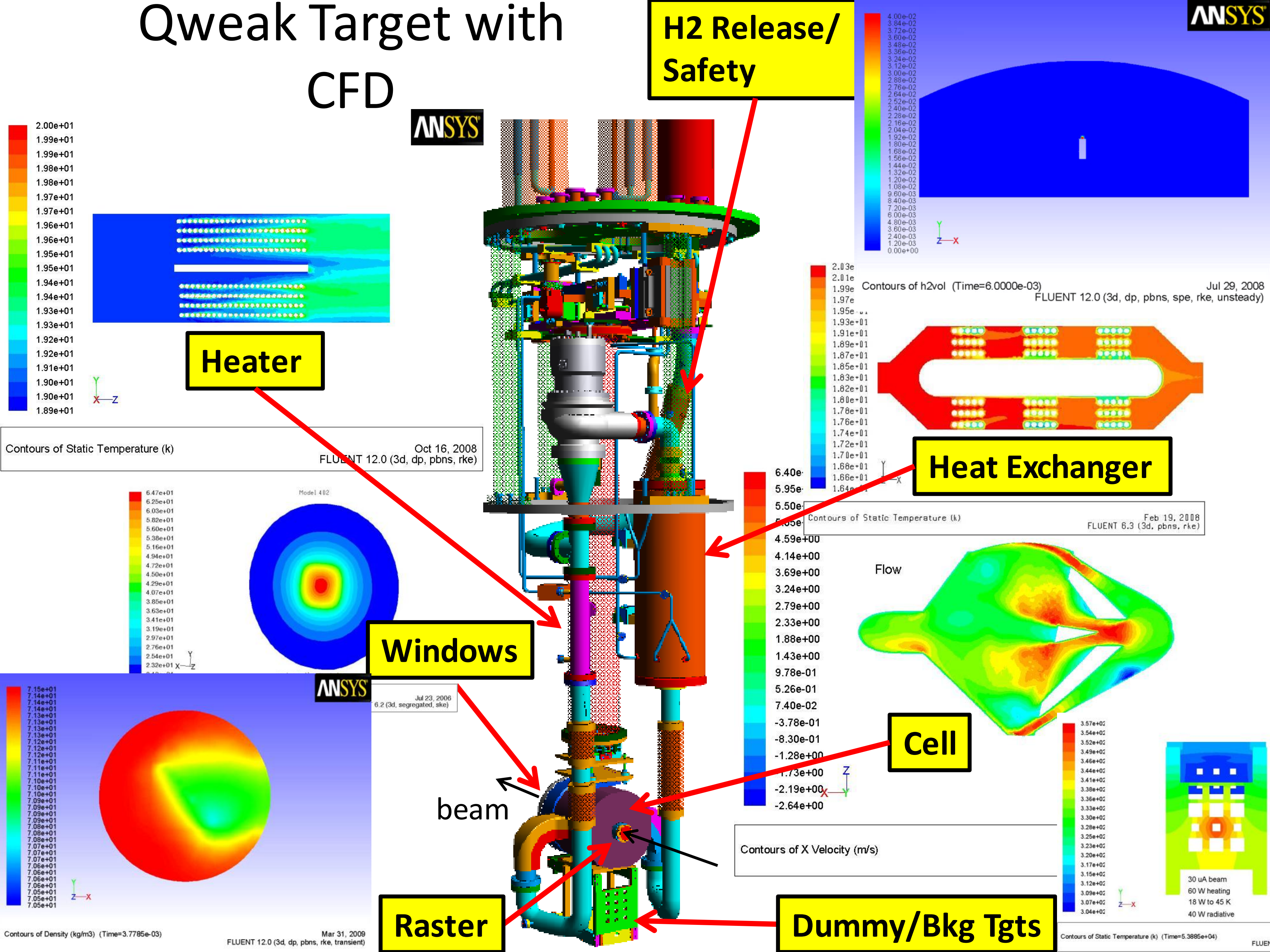
LH2 Transverse Flow:
1.1 kg/s, 15 L/s
0.23 psid
7.8 liters



Electron Beam
180 μA, 4x4 mm^2

Cell 35 cm long
Al entrance window ~0.1 mm thick, 22.2 mm Φ
Al exit window ~0.125 mm thick over 15 mm Φ,
0.635 mm thick over 173.5 mm
Scattered electron acceptance ±13.9°

Qweak Target with CFD

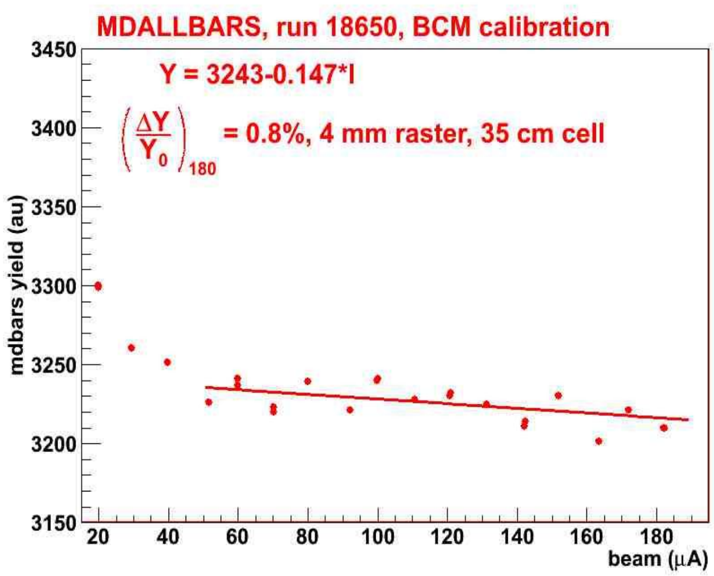


The Qweak Target Performance

LH2 density fluctuations studied versus beam current (I), LH2 pump frequency (or flow velocity), beam raster size and helicity frequency (vary one parameter, keep all others constant)

δρ/ρ of 50 ppm means a 2% increase on pv asymmetry width (the goal was <5%)

- Run I:
  - Δρ/ρ(150 μA) < 1% density reduction
  - from beam current scan δρ/ρ = **46 ppm** @ 170 μA, 4x4 mm^2, 28.5 Hz
  - from LH2 pump scan δρ/ρ = **42 ppm** @ 170 μA, 4x4 mm^2, 28.5 Hz
  - from beam raster scan δρ/ρ = **46 ppm** @ 182 μA, 4x4 mm^2, 28.5 Hz
  - helicity frequency from 480 Hz to 960 Hz, δρ/ρ dropped from **68 ppm** to **46 ppm** @ 170 μA



- Run II:
  - unclean data (C100 tests done at the same time, trippy, noisy beam), δρ/ρ = **51±5** ppm @ 180 μA, 4x4 mm^2, 30 Hz
  - sub-cooling @19 K, **δρ/ρ = 36 ppm** @ 180 μA, 4x4 mm^2, 30 Hz

Run successfully 2010-2012

LH2 Pumps @JLab

	STD 1.0	G0	Qweak	STD 2.0
V_s (l)	0.13132	0.198	0.5	0.266
f_{run} (Hz)	60	30	30	30(-60)
$\dot{V}_{th}$ / $\dot{V}_m$ (l/s)	7.88/2	5.49/4	?/15.4	8(?)
ε	0.25	0.73	?	?
$\dot{m}_{run}$ (g/s)	150	290	1100	600
Δp_{max} (psid)	0.5	1	1.3	1.2
τ_{max} (oz.in)	2.6	25	101	50
P (W)	7	14	135	67
Size (L/ϕ) (in)	6.8/3.22	6/6.75	18/10	?

12 GeV Target Design Principles

6 GeV lessons on the standard JLab LH2 target performance

- Cells geometries were not optimized for performance
- LH2 pump flow drastically limits performance

12 GeV Design principles: performance and safety

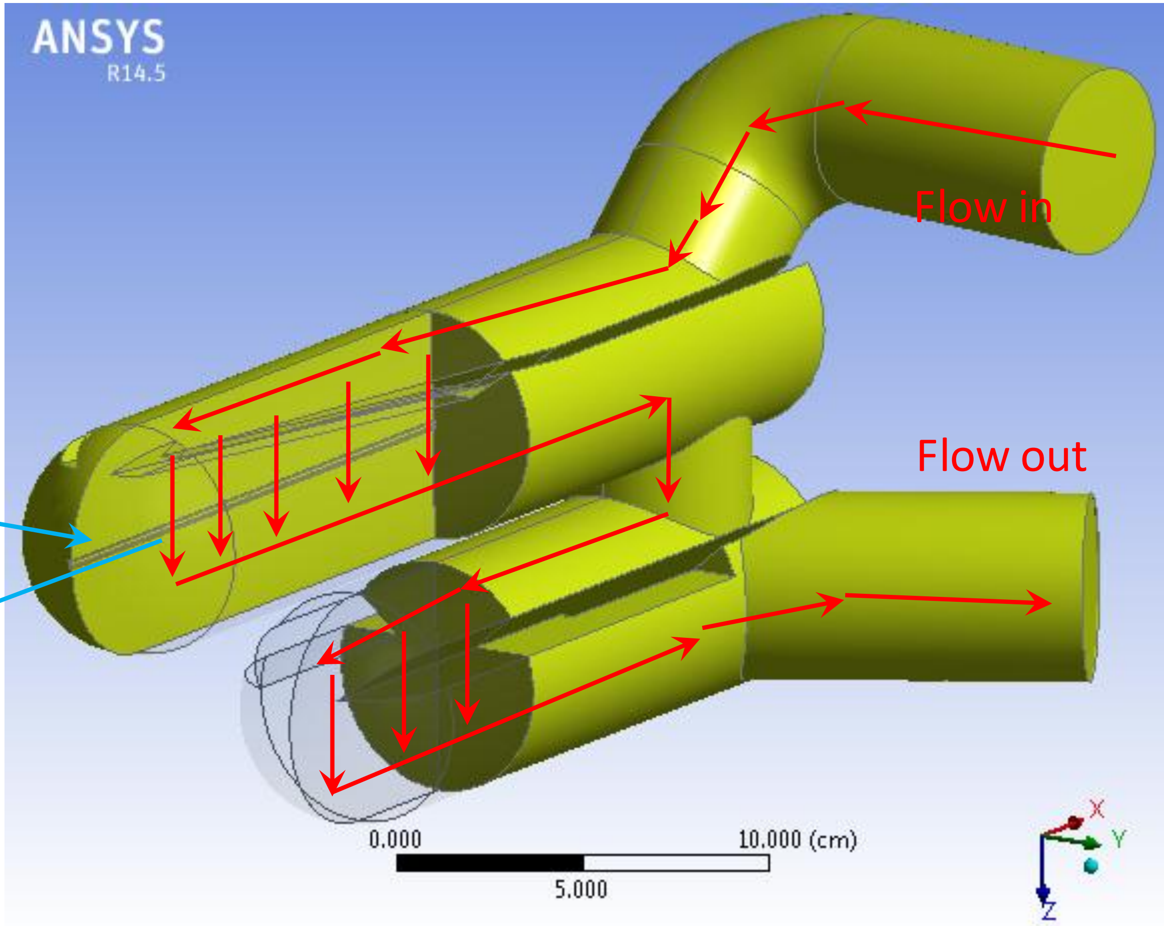
- Performance: limit density reduction **$\Delta\rho/\rho < 1\%$** for cells of 20 cm long, beam currents up to 100 μA, rastered on a square of side 2 mm on the target cell
- Safety (principle: avoid H2 release in the Hall)
- The new target could have 2 high performance loops, each with 2 cells
- A 3rd loop could be installed on demand, single cell, low performance
- **How**: using computational fluid dynamics (CFD)

Flow Space in the 2 Cell-Block

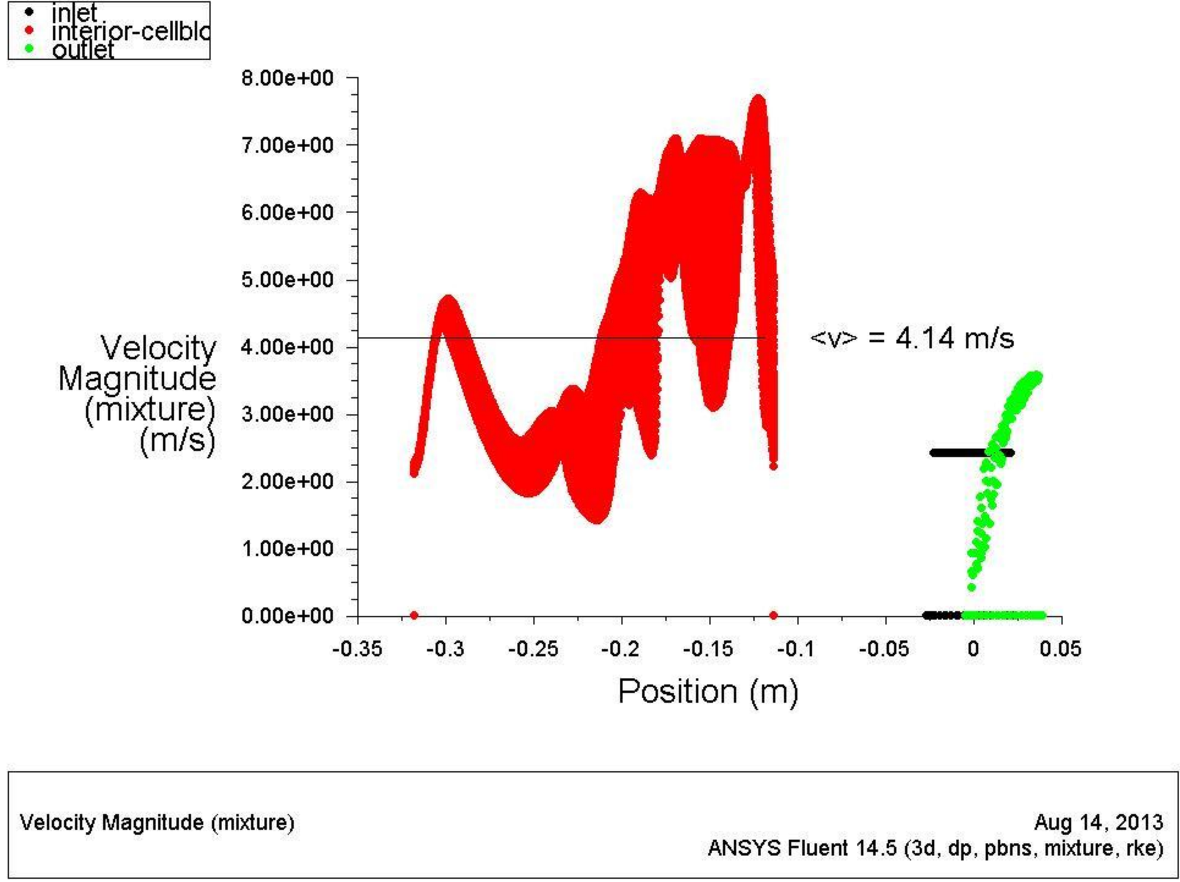
- Cell-block volume 1.9 liters with 2 cells, one 20 cm and one 10 cm long
- Cell diameter 6.28 cm, beam-in cell diameter 1.6 cm

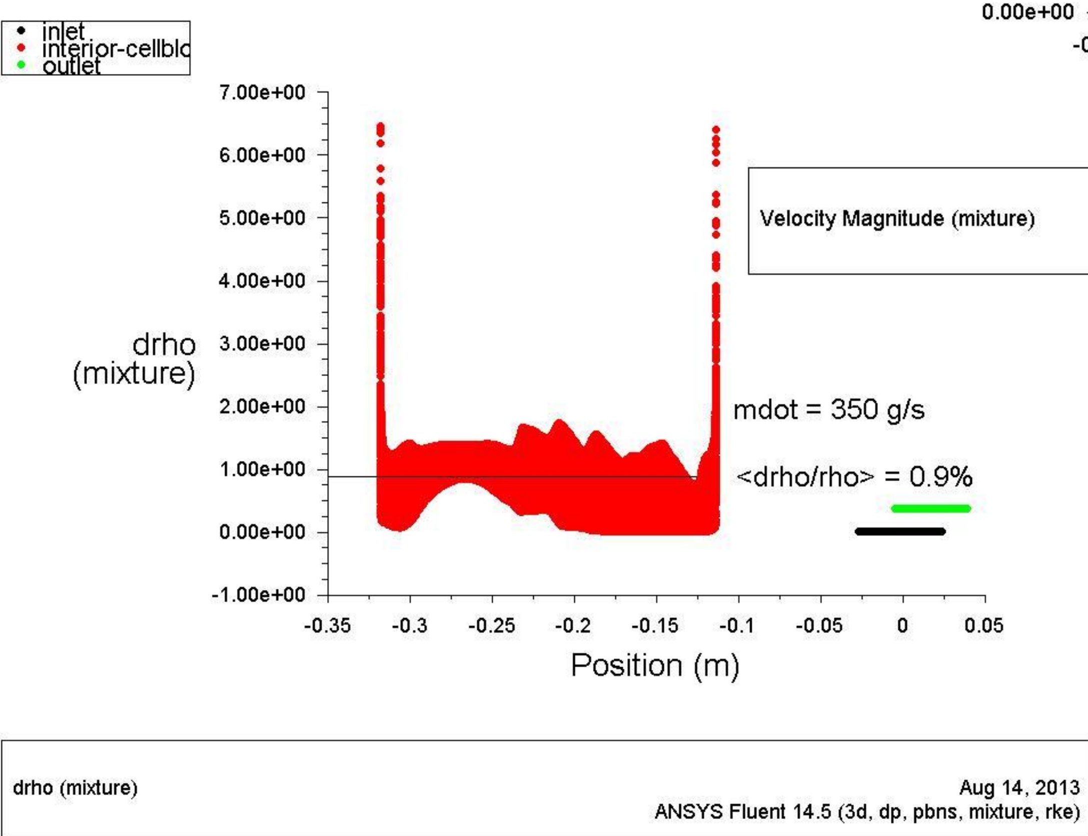
- For a beam envelope of 4 mm the in-beam plane acceptance/clearance is 100 mrad
- Nominal running point would be 20 K, 35 psia
- Beam volume 2x2x200 mm^3

Beam direction



- LH2 density loss (%) along the beam axis for 100 µA beam rastered at 2 mm
- Vertical spread is the density loss distribution in the raster area at that location
- End-points are generated by heating at the Al windows



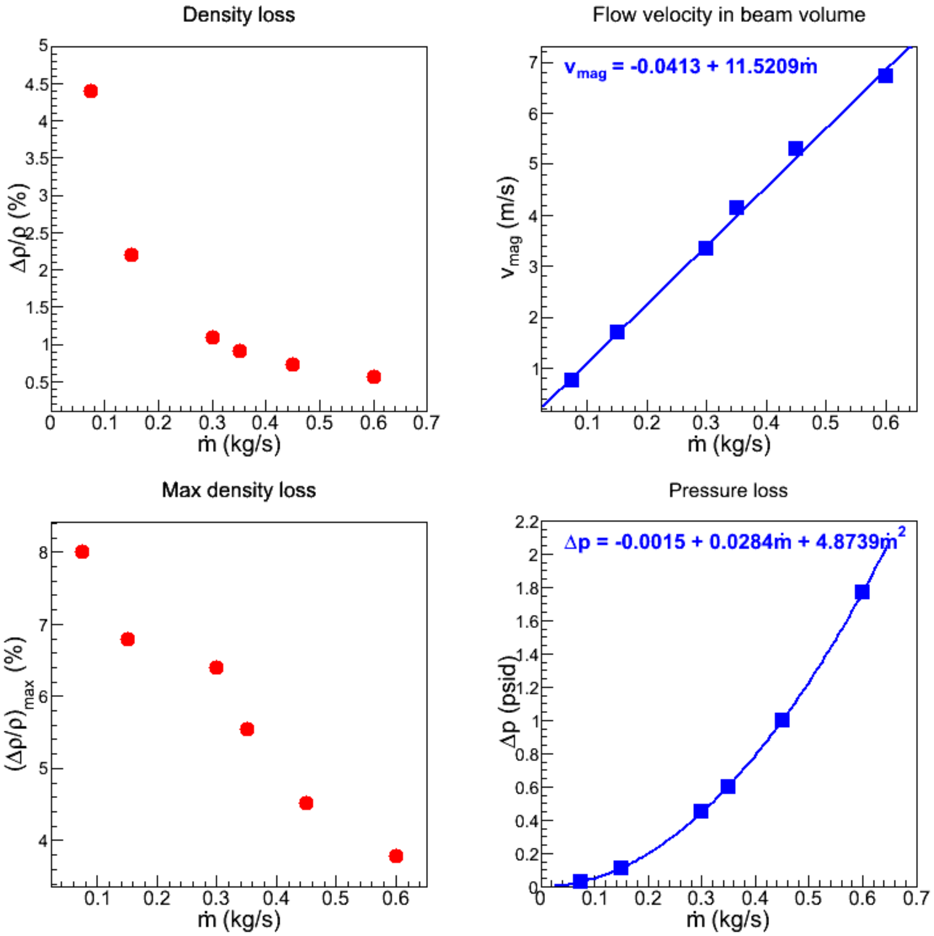


- Fluid velocity distribution along the beam axis in the beam volume (same conditions as above)

CFD Predictions for the New Cell

- Cell-block volume 1.9 liters with 2 cells, one 20 cm and one 10 cm long
- Cell diameter 6.28 cm, beam-in cell diameter 1.6 cm

- $\Delta\rho/\rho$ ~ 1% reached for mass flows greater than 300-350 g/s
- Dramatic improvement in performance between 100 g/s and 300 g/s, not much more gain above 400 g/s
- Pressure drop expected over the cells-block: 0.45 psi@300 g/s and 0.6 psi@350 g/s
- A new LH2 pump is needed to achieve this performance! (the old pump could give some 3-5% density loss)



Possible Cell Designs for Gep-5

- 40 cm long qweak cell
- 40 cm long G0 cell or similar