High Density Targets for External Beams

Silviu Covrig Dusa
Jefferson Lab

Intense Electron Beams Workshop
Cornell
18 June, 2015

- Liquid hydrogen (LH2) targets
- Designing the Qweak target with Computational Fluid Dynamics (CFD)
- Designing the next generation of targets with CFDFAC(ility)@JLAB
- Summary

Liquid Hydrogen Targets

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

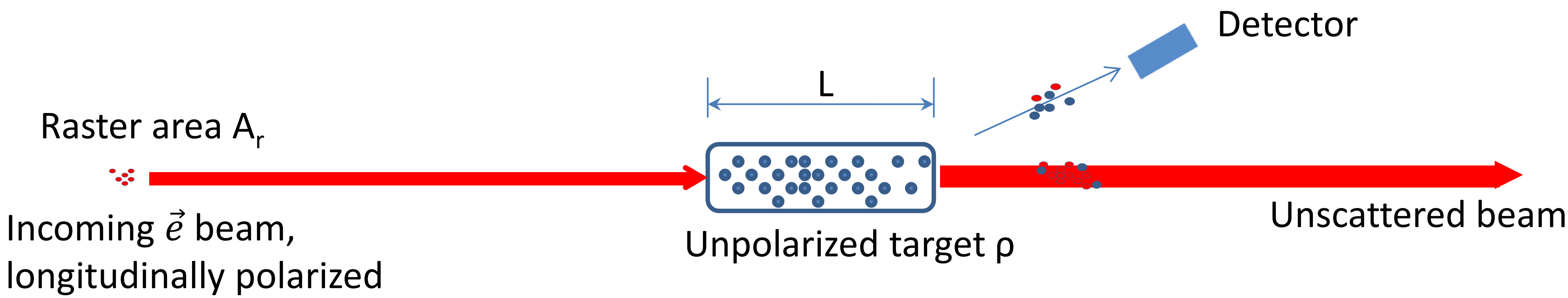
- Typical conditions: 20 cm LH2, 100 μA beam, 71 kg/m^3 density (25 psia, 20 K), expect P ~ 700 W heat and luminosity $\mathscr{L}$ ~ 5e38 cm^{-2}s^{-1}

- High power targets P < **1 kW**, early developments at SLAC (1990s), continued at Caltech (SAMPLE, G0, E158 targets 1994-2002) and JLAB (1994-present)

- Very high power targets P > **1 kW**, Qweak@JLAB (2.5 kW, 2010), MØLLER@JLAB (5 kW, ~2020), P2@MESA (4 kW, ~2018)

- IEB-like target: 20 cm LH2, 1 mA, beam heating power **6500** W, cooling power needed >7000 W (rule of thumb for costing a He cryogenic plants $1M/1kW)

A Liquid Hydrogen Target in PVES @JLAB



Typical parity violating electron scattering or PVES experiment:

- Electron beam helicity flipped periodically with frequency $f_h = 1/T_h$
- Beam rastered on area A_r on target, impinges on a Al-made cell of length L, heating the fluid in the bulk and at the Al windows
- LH2 recirculates in a closed loop, beam heating removed by a heat exchanger
- Measure a particle yield (N) for each helicity state, normalized to beam current and a PV asymmetry is formed between opposite helicity state yields
- Typical PV asymmetry ~ 1 ppm (parts per million)

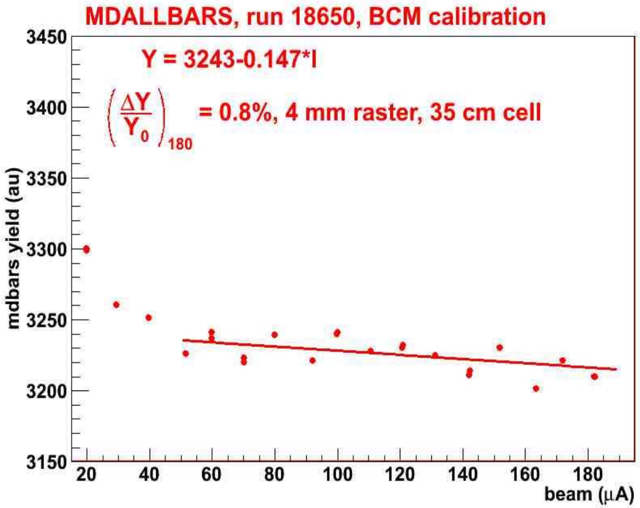
The heated fluid produces luminosity loss (density reduction) and PV asymmetry width enlargement (density fluctuations on the beam helicity time scale)

Systematic Effects of Fluid Targets for PVES

Target density reduction = luminosity loss

$$\frac{\Delta N}{N} = \frac{N_{low\ beam} - N_{high\ beam}}{N_{low\ beam}} \ (\%)$$

Yield loss, Qweak LH2 target



Target density fluctuations = asymmetry width enlargement

Helicity patterns for PV asymmetry: pairs + - , quartets +--+

$$A_{exp} = \frac{\sum N_+ - \sum N_-}{\sum N_+ + \sum N_-} = \frac{\Delta N}{N}$$

$N_{+/-} \sim R/f_h$

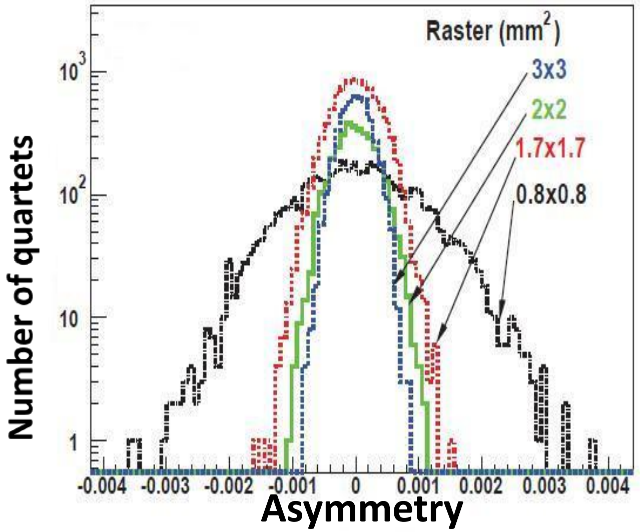
$$(\Delta A_{exp})^2 = \sigma^2_{A_{exp}} = \sigma_0^2 + \sigma^2_{noise}$$ per helicity pattern

$$\sigma_0^2 = \frac{1}{N} = \frac{f_h}{xR}$$

x = 2 for pairs
x = 4 for quartets

Counting statistics

G0 asymmetry width enlargement



Target design focuses on minimizing the target noise

Asymmetry Width

Qweak case

f_h = 960 Hz

	$\sigma_{A_{exp}}\ (ppm)$
σ_0	200
α = 0.1	210
dt = 0.11	221
60 ppm	229
50 ppm	234

Counting statistics $\sigma^2_{A_{exp}} = \sigma_0^2$

Excess noise sources

- Detector resolution (α) $\sigma^2_{A_{exp}} = \sigma_0^2(1+\alpha)$
- Deadtime (dt) $\sigma^2_{A_{exp}} = \sigma_0^2(1+\alpha)(1+dt)$
- BCM resolution (σ_{BCM}) $\sigma^2_{A_{exp}} = \sigma_0^2(1+\alpha)(1+dt) + \sigma^2_{BCM}$
- Target boiling (σ_b) $\sigma^2_{A_{exp}} = \sigma_0^2(1+\alpha)(1+dt) + \sigma^2_{BCM} + \sigma_b^2$

Asymmetry width: counting statistics + excess noise

Qweak asymmetry excess noise 17%

Qweak target excess noise ~3%; target design requirement was < 5%, achieved design goal

Expected Qweak PV asymmetry ~ 200 ppb (parts per billion!)

MØLLER@2kHz: σ_0 = 80 ppm, which makes everything that much harder

IEB@1kHz, 20 cm LH2 target at 1 mA, 20 GHz rate, σ_0 ~ 100 ppm, no worse than MØLLER

LH2 Targets for Parity Violation

Experiments	p / T / $\dot{m}$ psia / K / kg/s	L cm	P / I W / μA	beam spot mm	Δρ/ρ %	δρ/ρ ppm	E GeV
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		**150**	**5000 / 85**		**<2%**	**<25@960 Hz**	**11**
P2		**60**	**4000 / 150**				**0.2**
IEB		**20**	**7000+ / 1000**		**<4%**	**<30@480 Hz**	**<0.5**

No actual designs for the MØLLER and P2 target cells exist yet that are predicted to achieve the target noise requirements for these experiments

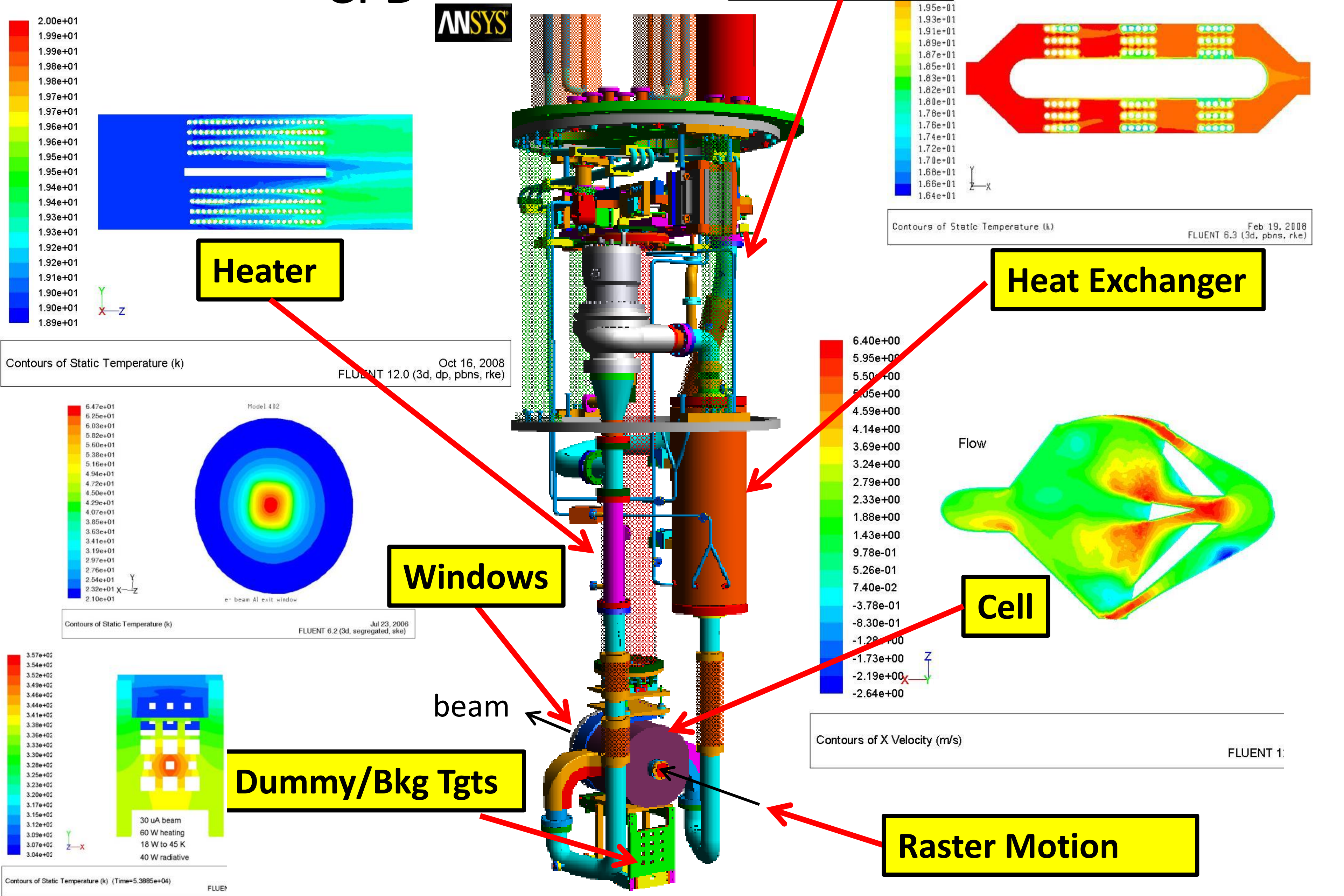
CFD-Driven Target Design

- CFD is a finite volume analysis software that solves the equations of fluid dynamics numerically with boundary conditions, modeled multi-phases, heating, beam raster motion etc.
- CFD can run either steady-state (predicts density reduction) or transient (could predict density fluctuations, but never done before) and it benefits from high performance computing (HPC, another name for parallel computing)

- The Qweak target was the 1st target at JLAB designed with CFD and it achieved its goals: CFD predicted 0.8% LH2 density reduction and we measured 0.8% yield reduction
- Transient CFD simulations are being developed to predict the Qweak target LH2 density fluctuations; this technology could be used to design the MØLLER and P2 LH2 targets (it would also benefit an IEB LH2 target)

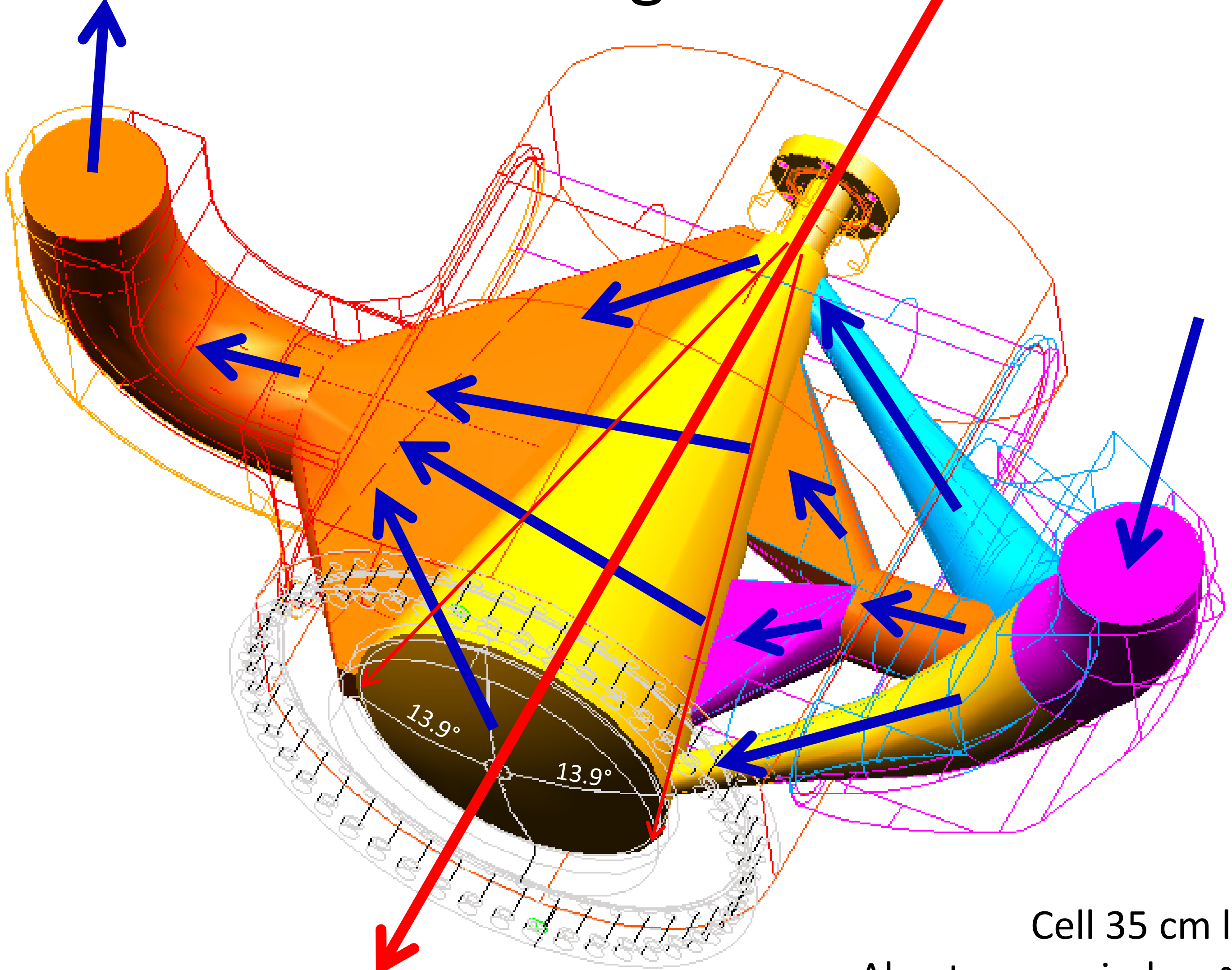
- CFD software used ANSYS-CFD (which includes Fluent & CFX)

Qweak Target with CFD



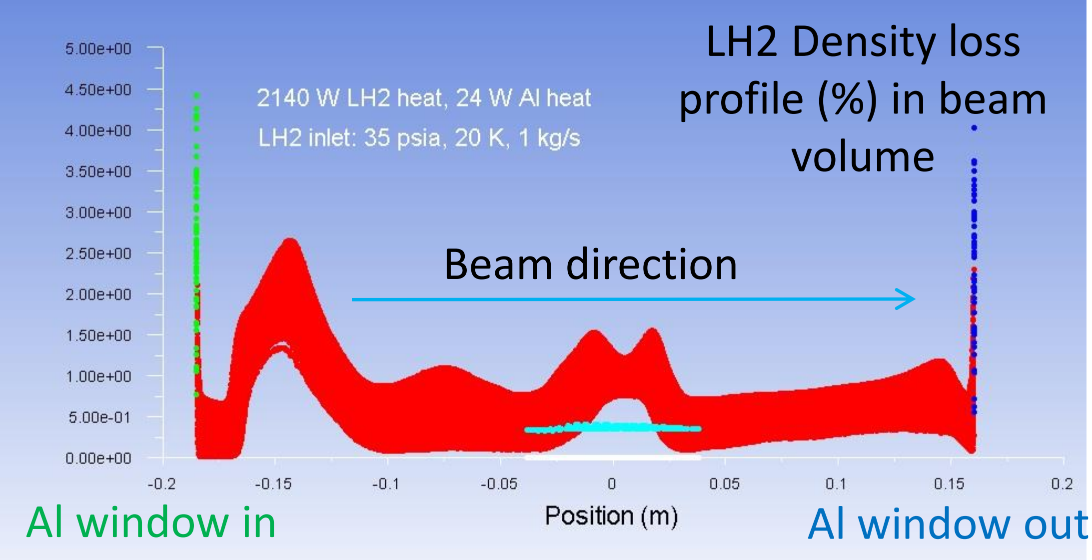
The Qweak Target Cell

LH2 Transverse Flow:
1.1 kg/s, 15 L/s
35 psia, 20 K
3.7 K subcooled
0.23 psid
7.8 liters cell
55 liters target loop



Electron Beam
180 μA, 4x4 mm²

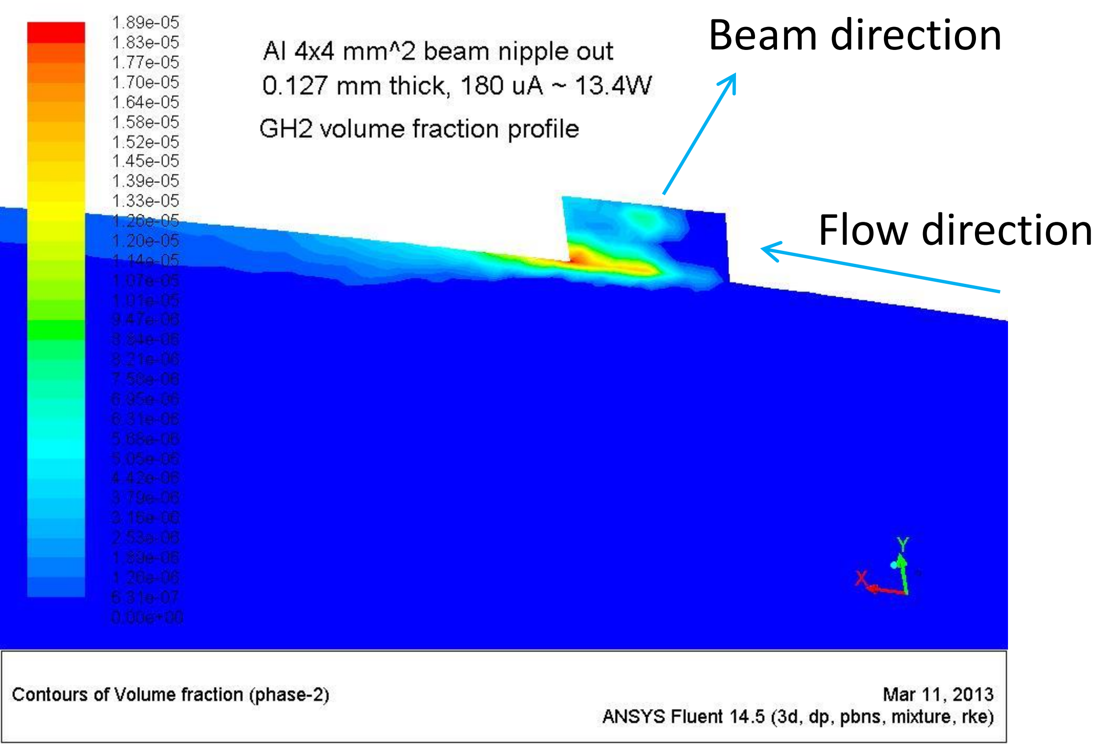
Cell 35 cm long
Al entrance window ~0.1 mm thick
Al exit window ~0.125 mm thick nipple,
the rest 0.635 mm thick
Scattered electron acceptance ±13.9°



The Qweak target cell with Fluent at 180 μA beam, rastered 4x4 mm^2, LH2 in at 1 kg/s

CFD predicted average relative density change in beam volume

Δρ/ρ ~ 0.8%



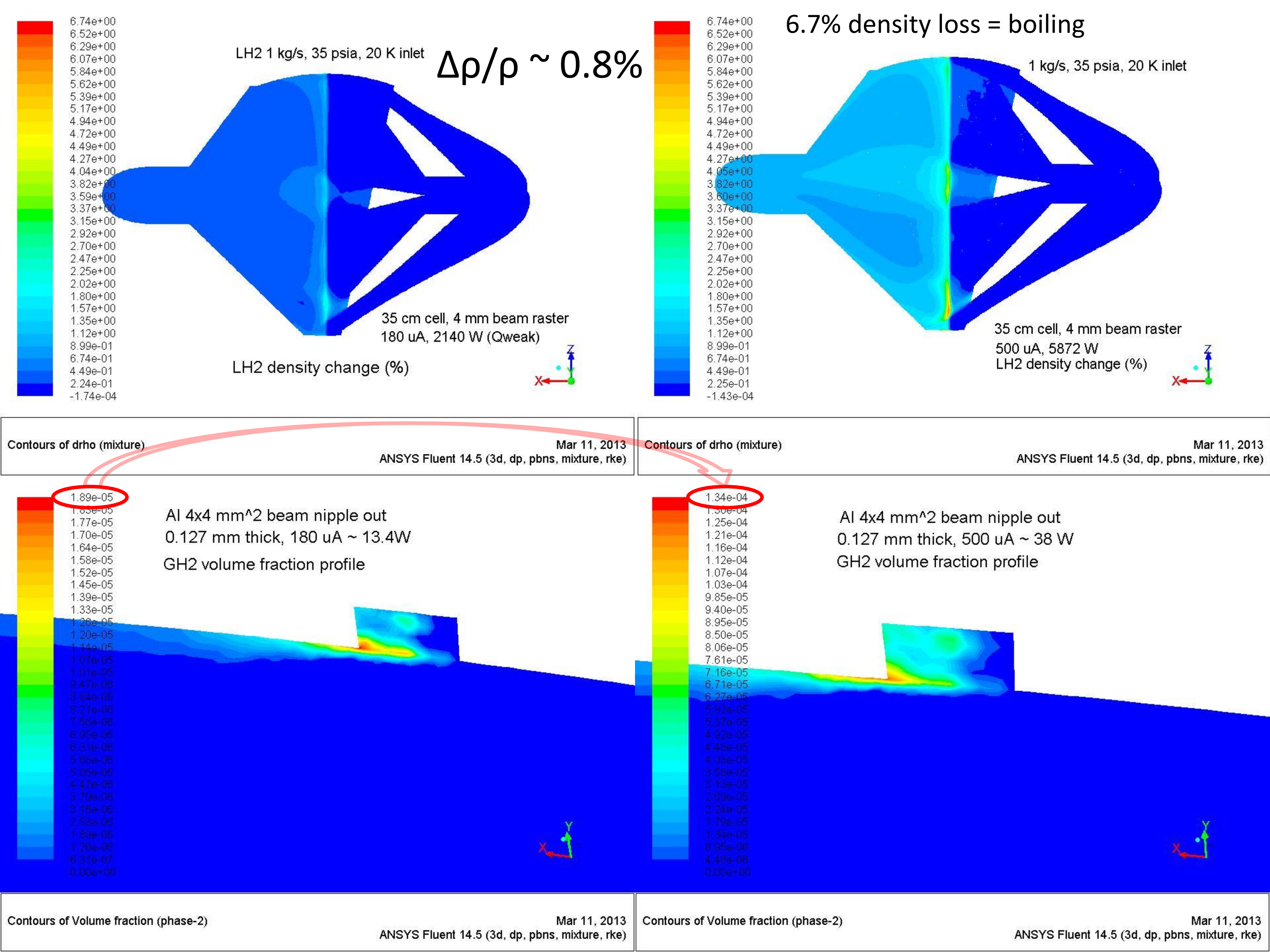
Electron beam heating at the Al windows

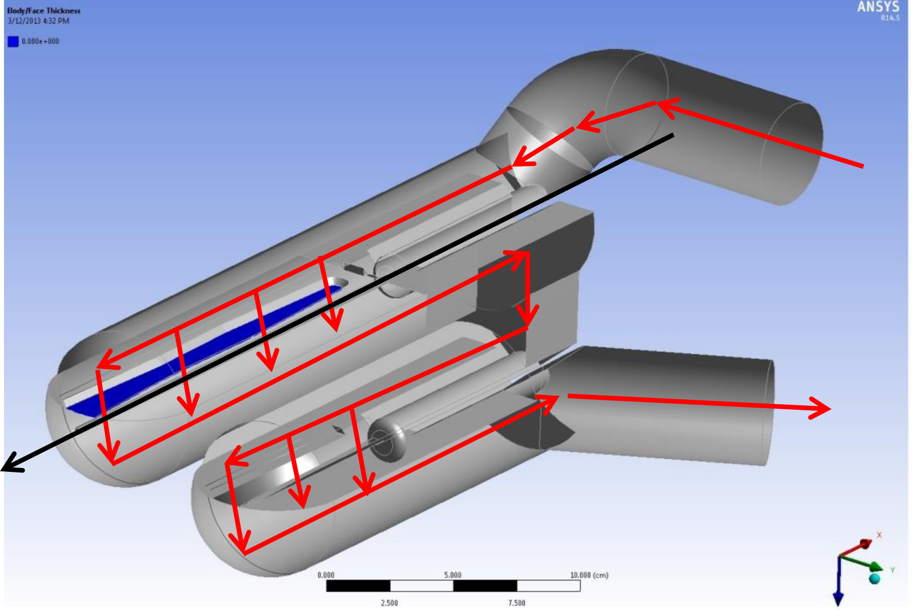
LH2 boiling observed with a 2-phase mixture model in Fluent

Possible IEB LH2 Targets at 500 μA with CFD

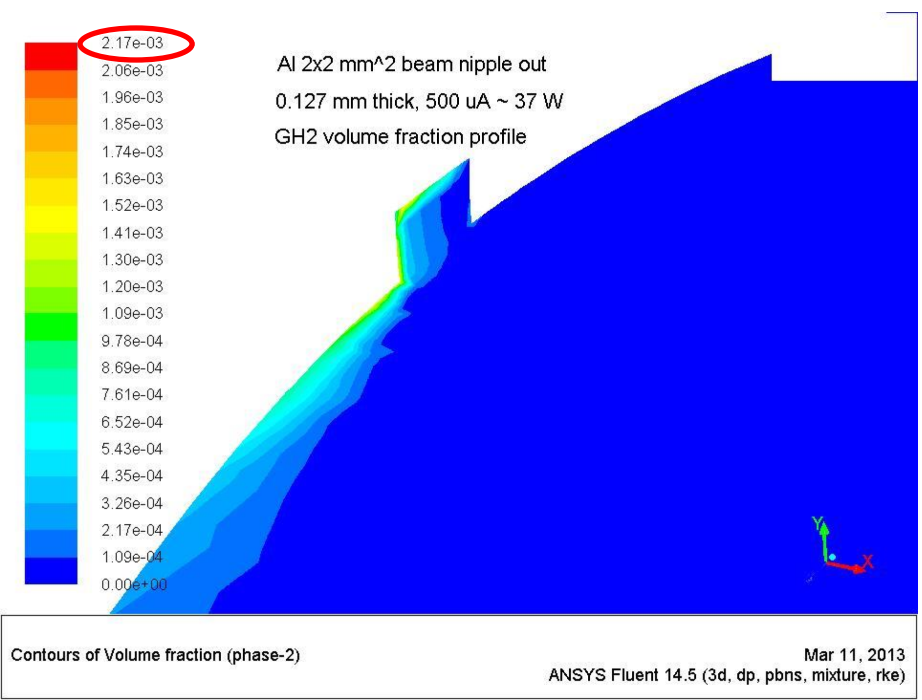
- 35 cm Qweak-like target
  - 500 μA, 4x4 mm^2 beam raster
  - Δp = 0.25 psid @ 1 kg/s and 0.56 psid @ 1.5 kg/s, 7.5 liter cell
  - Al windows, 0.1 mm beam-in, 0.127 mm beam-out (same for both)
  - Beam power LH2 5870 W, Al windows 68 W, total power: **6500 W@20 K**

- 20 cm cylindrical cell target
  - 500 μA, 2x2 mm^2 beam raster
  - Δp = 0.61 psid @ 0.3 kg/s, 1.6 liter cell
  - Beam power LH2 3570 W, Al windows 68 W, total power: **4000 W@20 K**

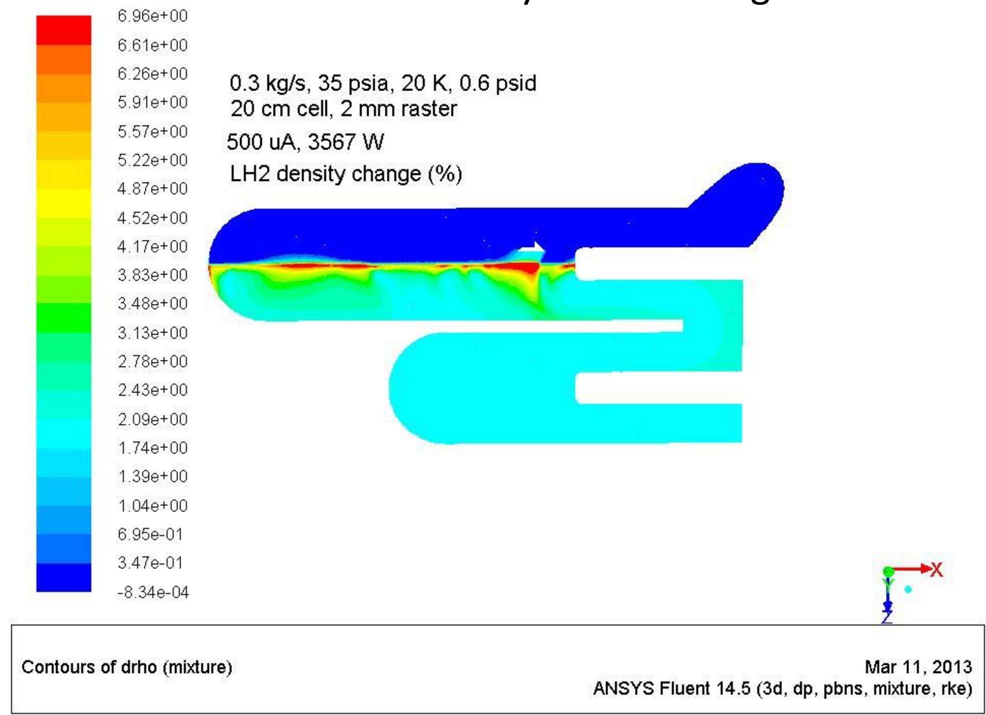

6.7% density loss = boiling
Δρ/ρ ~ 0.8%
LH2 1 kg/s, 35 psia, 20 K inlet
35 cm cell, 4 mm beam raster
180 uA, 2140 W (Qweak)
LH2 density change (%)
1 kg/s, 35 psia, 20 K inlet
35 cm cell, 4 mm beam raster
500 uA, 5872 W
LH2 density change (%)
6.74e+00
-1.74e-04
-1.43e-04
Contours of drho (mixture)
Mar 11, 2013
ANSYS Fluent 14.5 (3d, dp, pbns, mixture, rke)
Contours of drho (mixture)
Mar 11, 2013
ANSYS Fluent 14.5 (3d, dp, pbns, mixture, rke)
1.89e-05
Al 4x4 mm^2 beam nipple out
0.127 mm thick, 180 uA ~ 13.4W
GH2 volume fraction profile
1.34e-04
Al 4x4 mm^2 beam nipple out
0.127 mm thick, 500 uA ~ 38 W
GH2 volume fraction profile
Contours of Volume fraction (phase-2)
Mar 11, 2013
ANSYS Fluent 14.5 (3d, dp, pbns, mixture, rke)
Contours of Volume fraction (phase-2)
Mar 11, 2013
ANSYS Fluent 14.5 (3d, dp, pbns, mixture, rke)



- 20 cm cylindrical cell – top, sharing fluid space with a smaller length cylindrical cell, bottom, fluid space shown
- The cells have internal flow diverters that make the flow transverse to the beam direction
- Red arrows = fluid flow direction
- Black arrow = beam direction



6.7% density loss = boiling



Summary of 500 μA Cells from Fluent

	Qweak Cell 35 cm	**Cylindrical Cell 20 cm**
Pressure drop (psid) @ Mass flow (kg/s)	0.25 @ 1	0.61 @ 0.3
Beam volume cross flow (m/s)	2.8	2.85
$\Delta\rho/\rho$ (%)	2.1	4.4
T in/out (K) Al windows	**93/97**	**199/232**
Power beam/total (W)	5940/6500	3630/4000

- Boiling spots in the bulk, **film boiling** at the windows!
- Design needed for both geometries to make them non-boiling in the bulk and mitigate the film boiling at the Al-windows

Conclusions

- The Qweak target has been a great success due to CFD design
- CFD has become a critical tool in designing high power, high density targets
- A CFD facility (CFDFAC) has been setup at JLAB to address targets design, CFDFAC has two HPC farms: one on 32 CPUs and one on 128 CPUs
- State of the art transient CFD simulations are being developed to capture target density fluctuations on any time scale

- The success of future PV experiments requires less than half the Qweak target noise while doubling the beam power

LH2 Target Design Considerations

Goals:

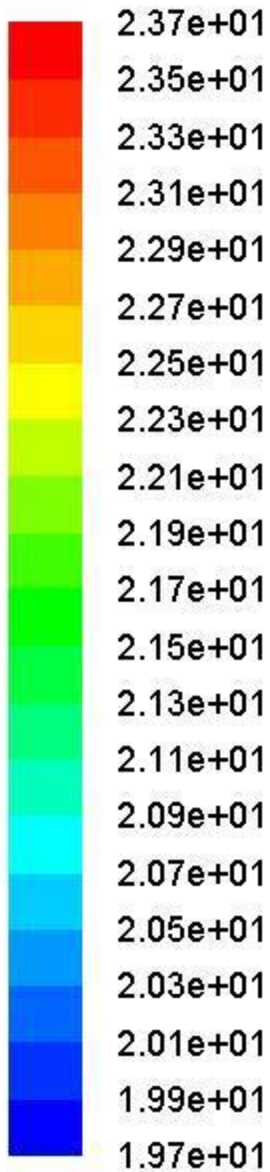
1. minimize LH2 density reduction (at 25 psia and 20 K LH2 density is 4.5% from boiling!)
2. minimize LH2 density fluctuations $\delta\rho/\rho$ (ppm) (for PV)

$\delta\rho/\rho \rightarrow \sigma_b < 5\%$ of σ_A

Knobs (left) to turn (once the design is frozen):

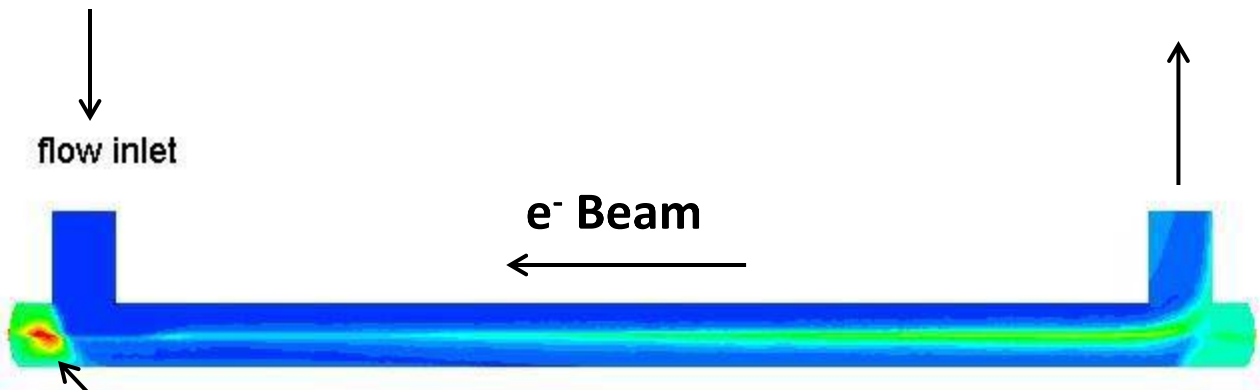
1. LH2 pump speed, penalty: viscous heating (if immersed motor, add motor cooling to it)
2. Beam raster size, penalty: background, …
3. Beam current, penalty: statistics
4. Sub-cooling LH2, penalty: available cooling power
5. Beam raster frequencies – unknown effect (no studies yet)
6. Helicity frequency (for PV)
7. ….

MOLLER Target Prototype



Beam: 85 μA, 11 GeV, 5x5 mm^2

Heating: 4.5 kW (LH2) + 12.5 W (Al)

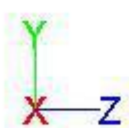


Prototype: E158-type Target Cell

Need $\delta\rho/\rho$< 25 ppm@ 2000 Hz

RED = boiling present in the bulk (bad)

CFD: Internal E158 cell meshes do not seem to help!



Contours of Static Temperature (k)

Nov 14, 2008

FLUENT 12.0 (3d, dp, pbns, rke)