PICO 250-liter Bubble Chamber Dark Matter Experiment

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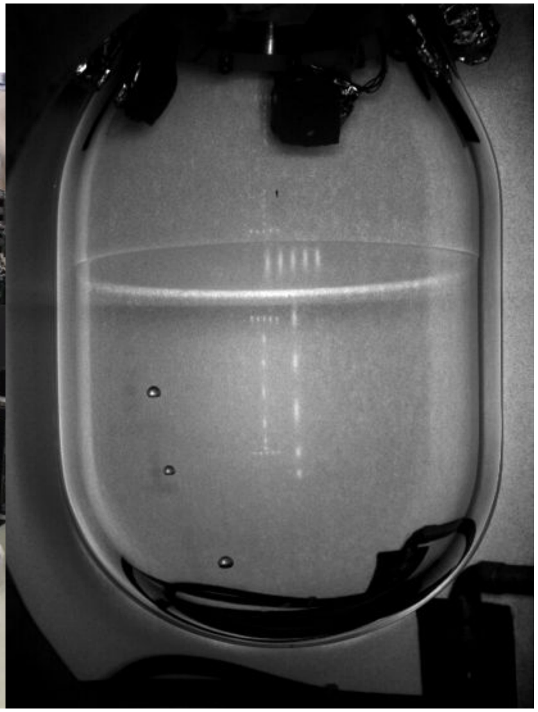

PICO
Collaboration

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PICASSO + COUPP = PICO

- New collaboration is PICO
- PICASSO
  - Ongoing efforts with Superheated Droplet Detectors
  - Committed to Geyser Chamber R&D through FY13
- COUPP
  - Ongoing efforts with COUPP-60 bubble chamber
  - Committed to Fast-Compression Bubble Chamber R&D through FY13

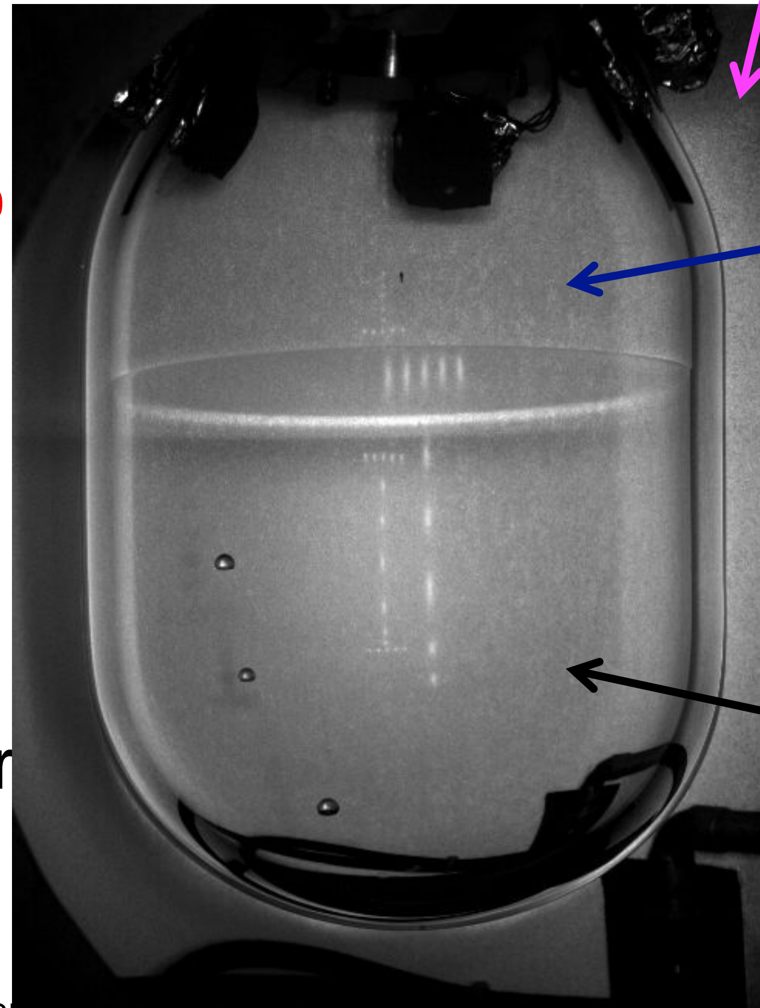
PICASSO + COUPP = PICO

- PICASSO
  - focus on spin-dependent couplings
  - Fluorine based fluids – C_4F_{10}
- COUPP
  - focus on simultaneous SI & SD couplings
  - Fluorine and iodine - CF_3I
- First Collaborative PICO Effort = PICO-2L:
  - 2-liter C_3F_8 chamber at former COUPP-2L site
  - Spin-dependent couplings + low mass SI

The Bubble Chamber

fast compression

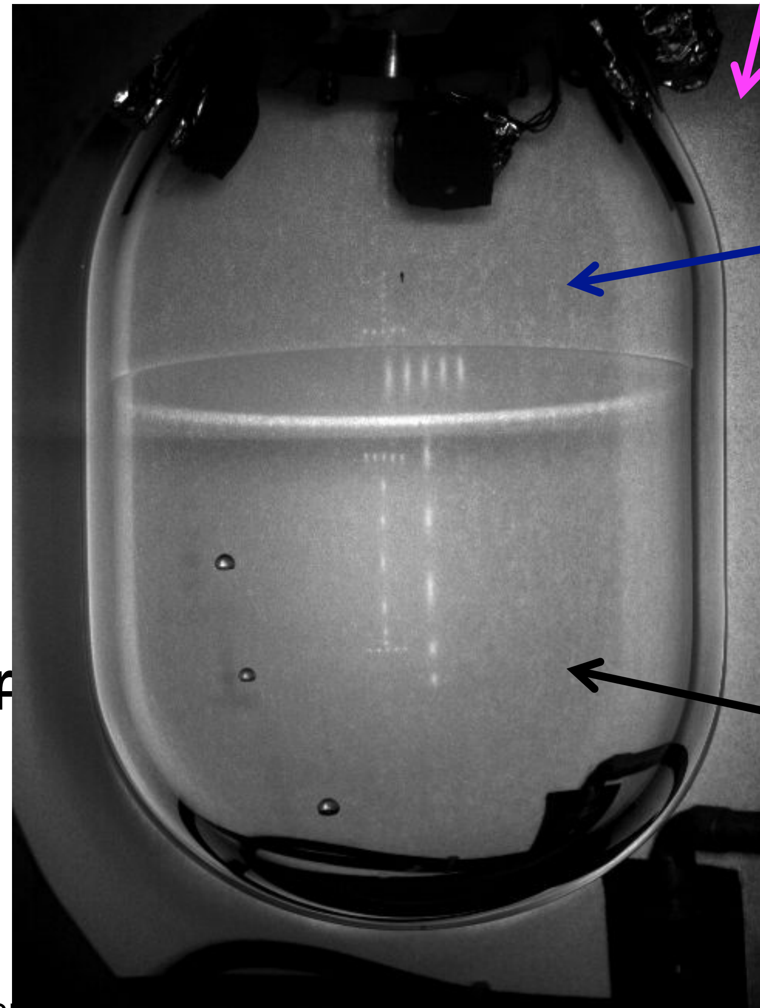
- Superheated CF_3I target
  Spin-indep
  ~~Spin-dep~~*
  Spin-dep → C_3F_8–C_4F_{10}
- Particle interactions nucleate bubbles
- Cameras capture bubbles
- Data Logged, Chamber compressed after each event



* This doesn't work so well…

The Geyser Chamber

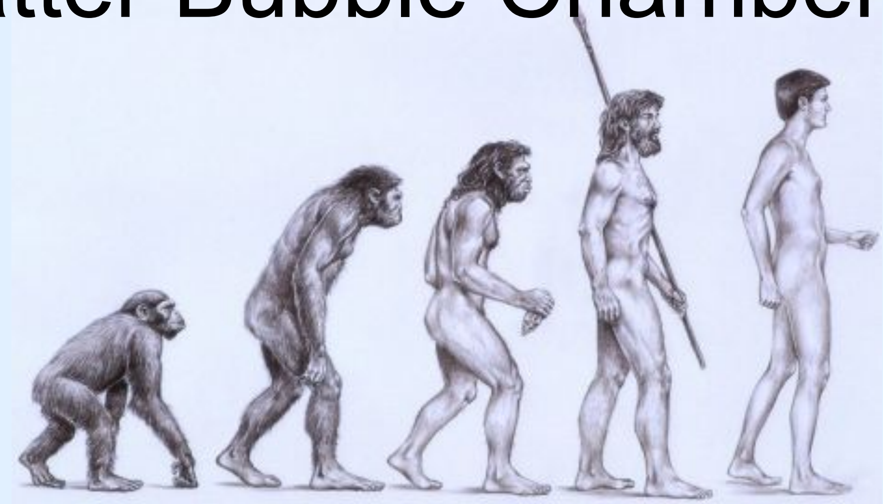
- Superheated target
  Spin-dep $\rightarrow$ C_3F_8–C_4F_{10}
- Particle interactions nucleate bubbles
- Cameras capture bubbles
- Data Logged, ~~Chamber compressed~~ after each event

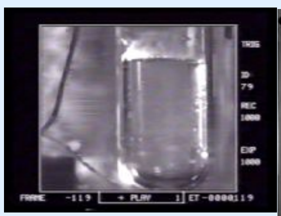


The Geyser Chamber Idea:

- Add a cold condenser space at the top of the chamber volume
- Establish thermodynamic conditions so that bubbles rise to the top, condense, and the liquid falls back into the active volume
- Continuous operation without dead-time
- Eliminates the need for fast compression

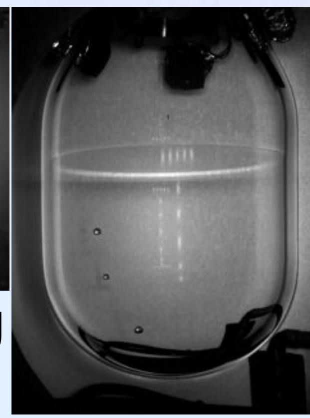
Dark Matter Bubble Chamber Evolution





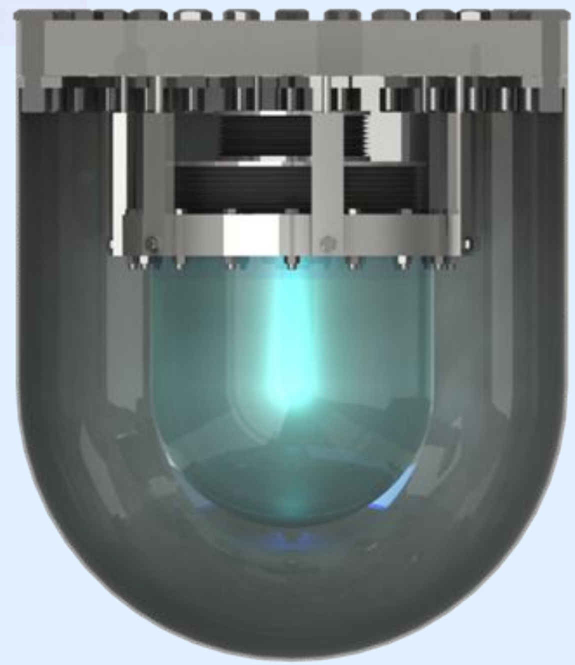
Test tube

COUPP 2kg



COUPP 4kg

COUPP 60kg



PICO 250 liter

PICO 0.01

PICO 0.1

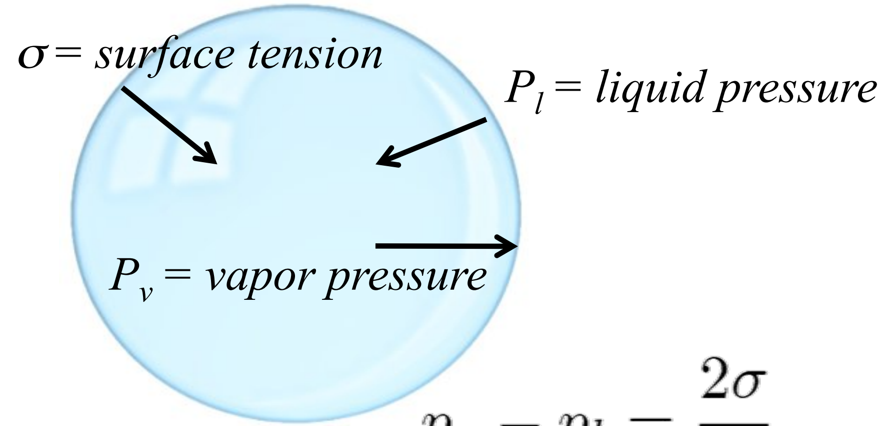
PICO 1liter

PICO 2liter

PICO' 2liter

The Physics of Bubble Nucleation

- Energy from particle interactions produces "proto-bubbles"
- Macroscopic bubbles arise from proto-bubbles with radius $r > r_c$
- The energy threshold E_{th} is the energy required to produce a critical radius bubble
- Bubble nucleation requires $E_R > E_{th}$ *and* recoil path length $< R_c$



$$p_v - p_l = \frac{2\sigma}{r_c}$$

$$E_{th} = \boxed{4\pi r_c^2 \left(\sigma - T\frac{\partial \sigma}{\partial T}\right)} + \frac{4}{3}\pi r_c^3 \rho_v h$$

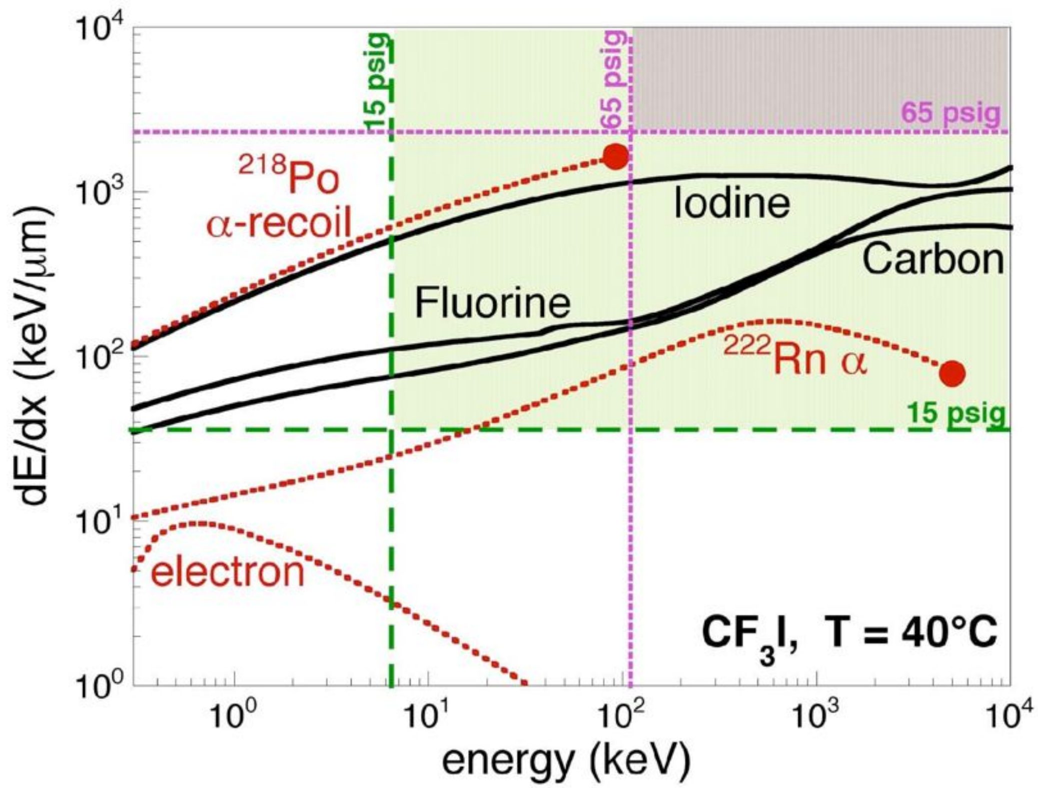
Surface energy

Latent heat

Seitz "Hot Spike" Model
Phys. Fluids 1, 2 (1958)

The Physics of Bubble Nucleation

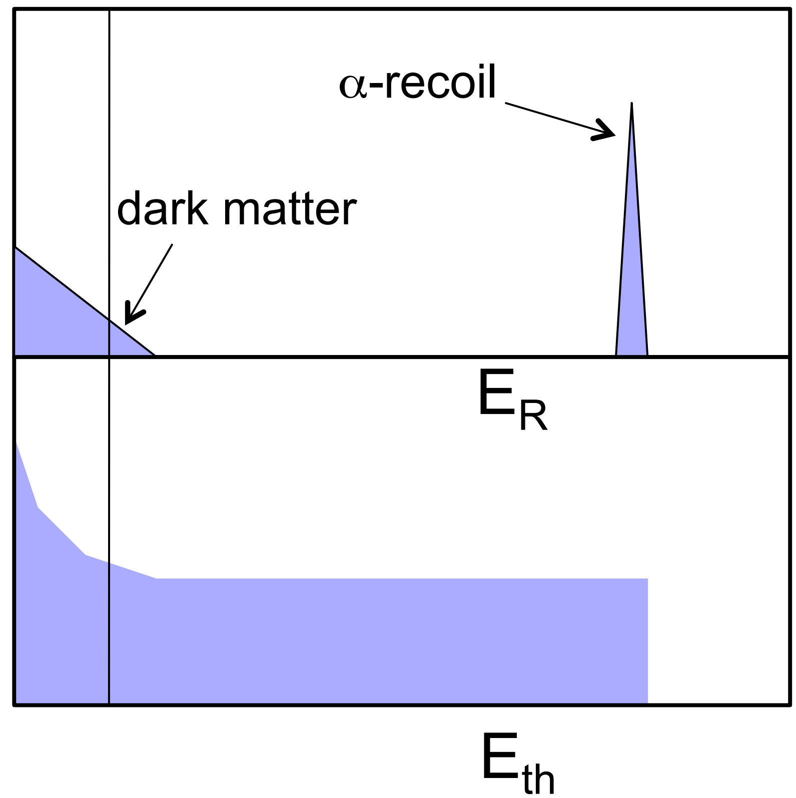
- Tune Temperature T and Pressure P for set nuclear recoil threshold.
- No sensitivity to electron recoils



The Bubble Chamber is a Threshold Device

We do not measure E_R…

…we measure $\displaystyle\int_{E_{th}}^{\infty} \frac{dN}{dE_R}\, dE_R$

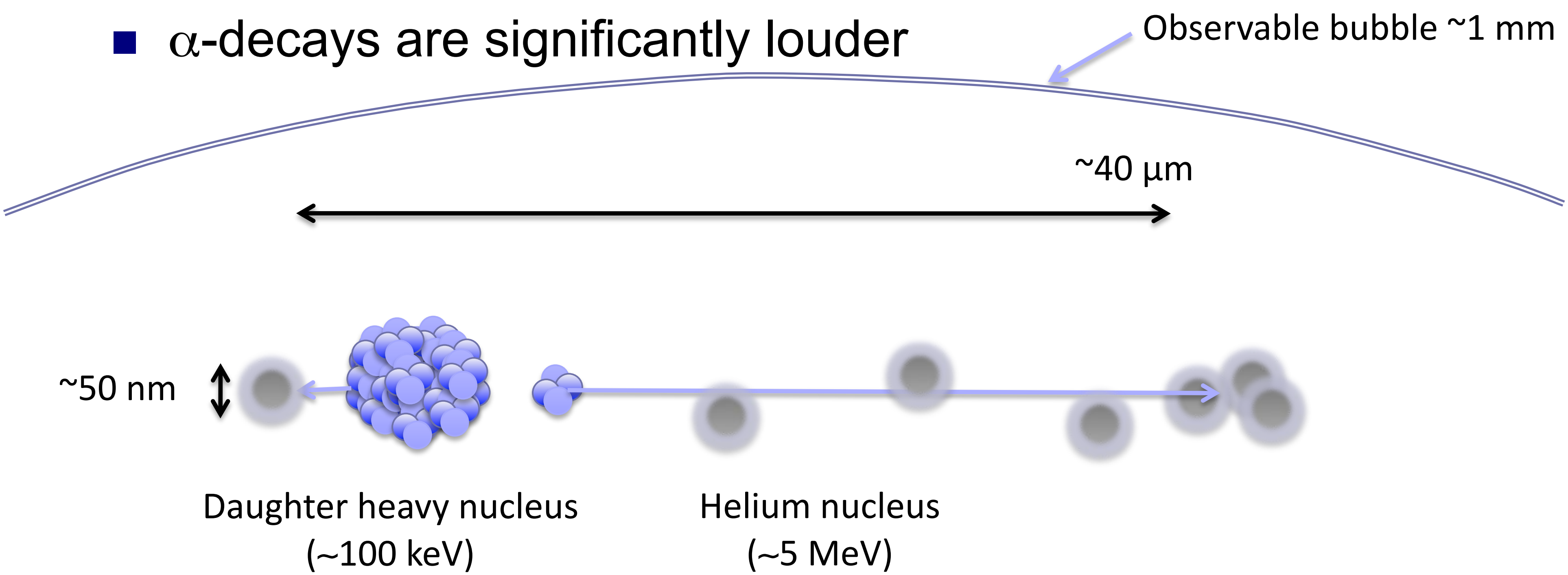


…so bubbles initiated by recoiling α-decay daughters are counted along with dark matter candidate events.

The Physics of Bubble Growth

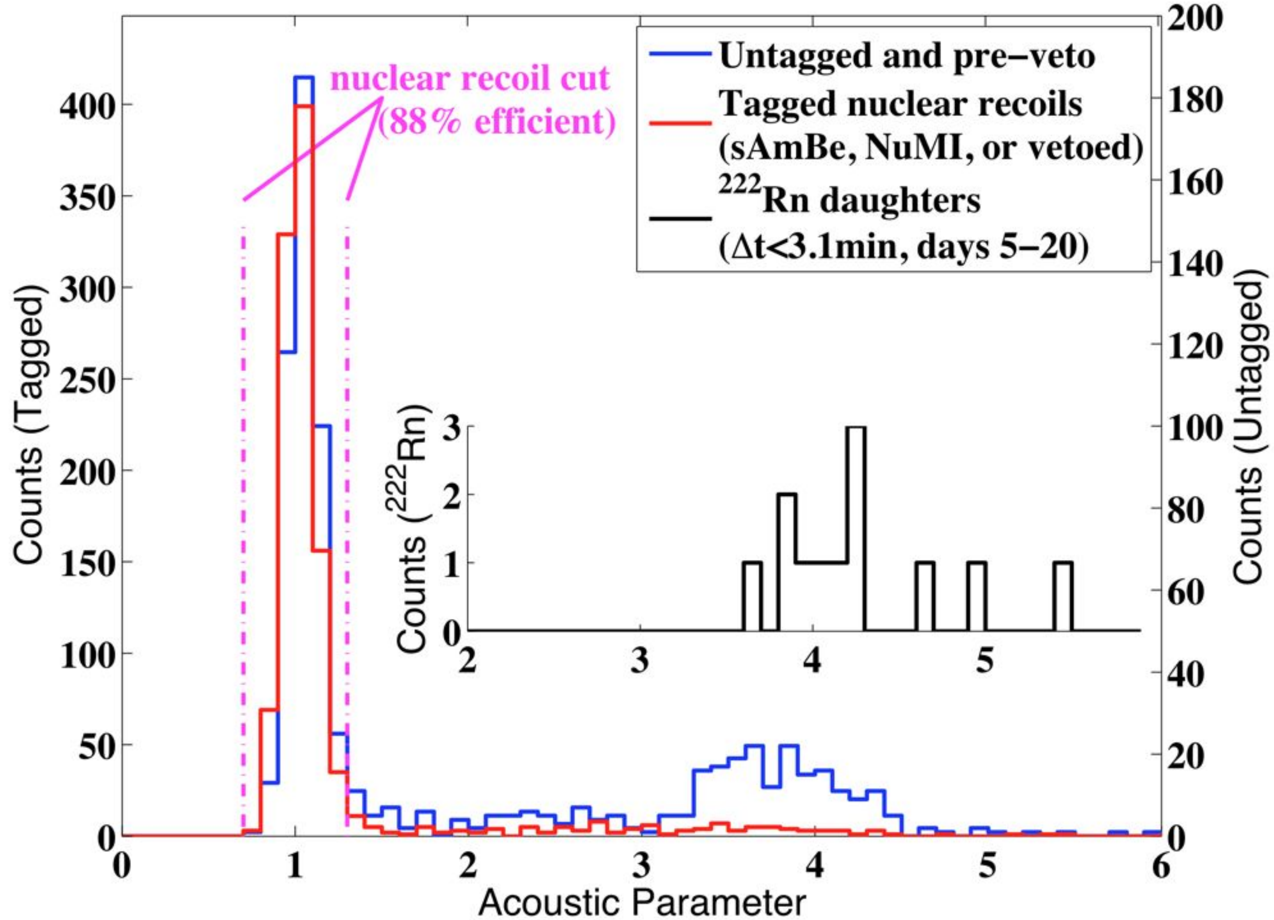
PICASSO (Aubin et al., arXiv:0807.1536)

- Sound emission from a bubble peaks at r_{bubble} ~ 10 um
- Clear acoustic signature for a *single* nuclear recoil
- α-decay results in separate nucleation sites ~ 40 μm
- α-decays are significantly louder



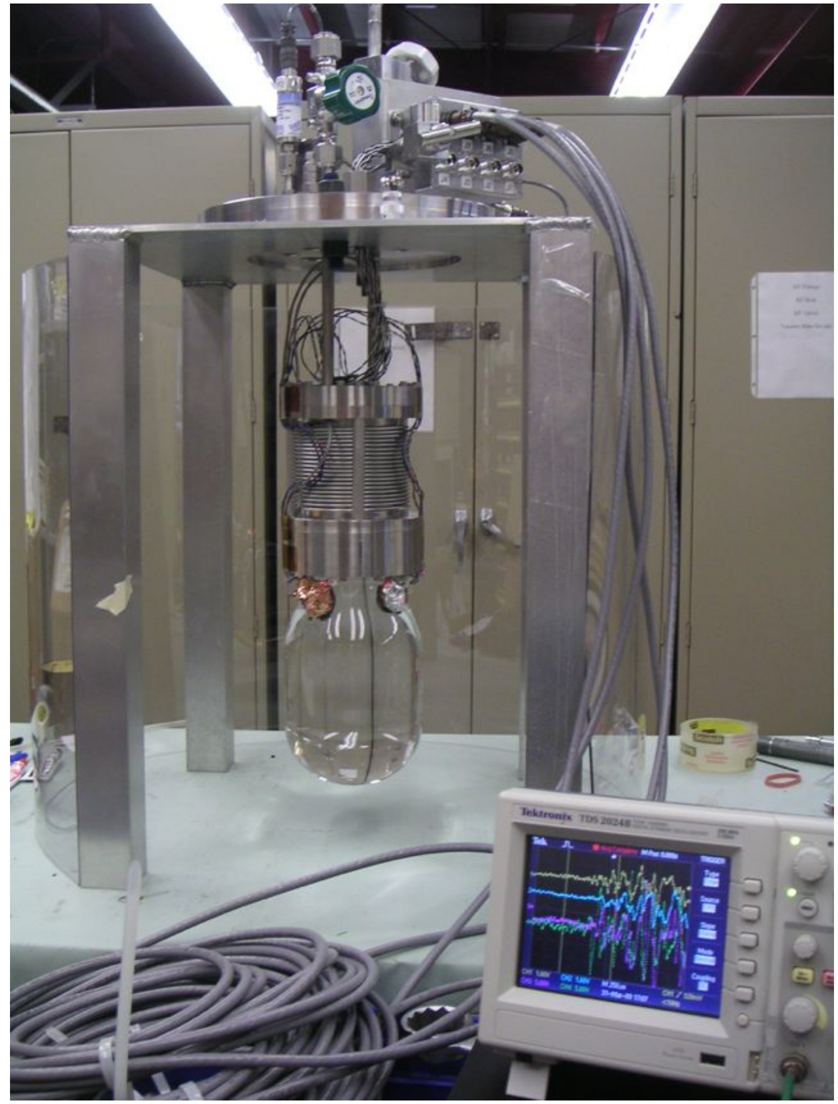
Acoustic Parameter

- $(\text{Amp} \bullet \omega)^2$
  (Normalized and position-corrected for each freq-bin)
- Measure of acoustic energy deposited in chamber
- Alphas are louder than neutrons

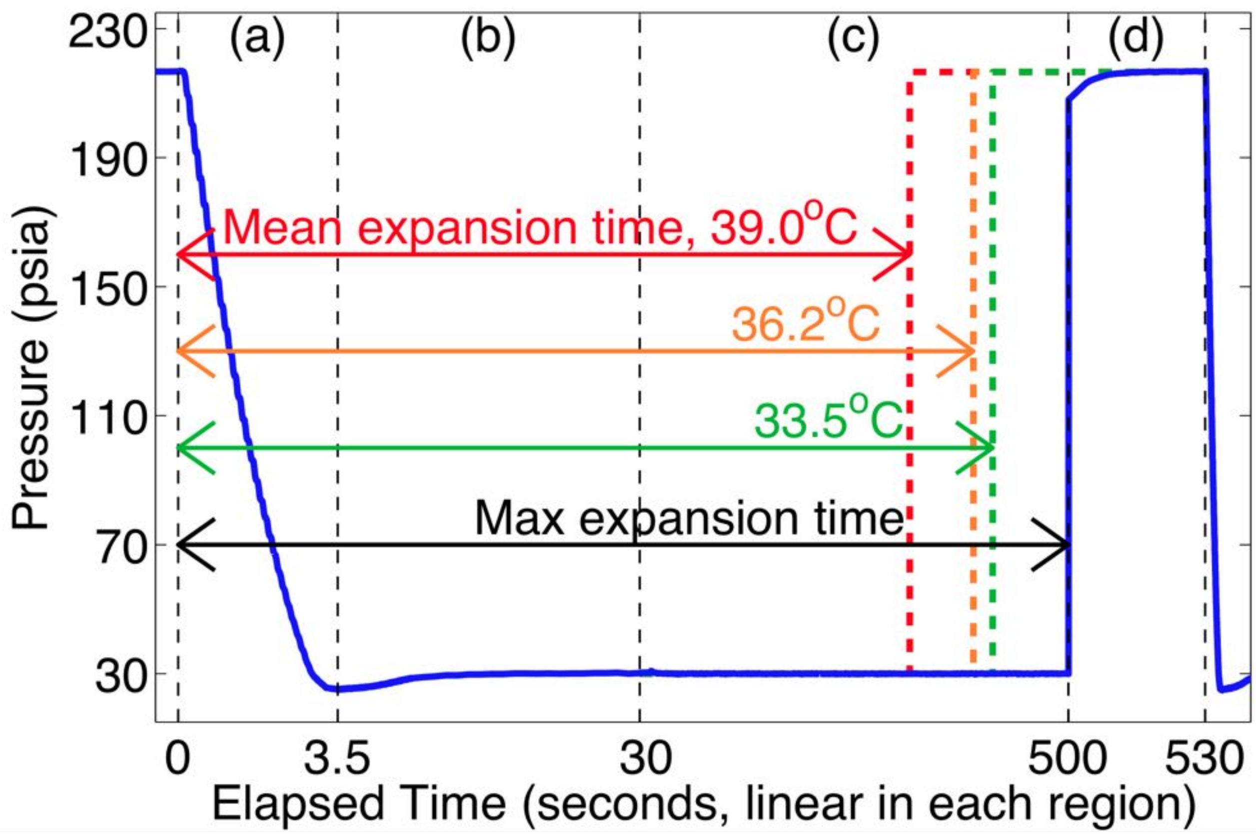


The Bubble Chamber

- fused silica inner vessel
- Flexible pressure balancing bellows
- Instrumented with
  - Temperature, Pressure Transducers
  - Fast Transient Pressure Transducer
  - Piezo Electric Acoustic Transducers
- Immersed in hydraulic fluid within a stainless steel pressure vessel
- Hydraulic pressure controls the superheated fluid pressure
- Viewed by machine vision cameras



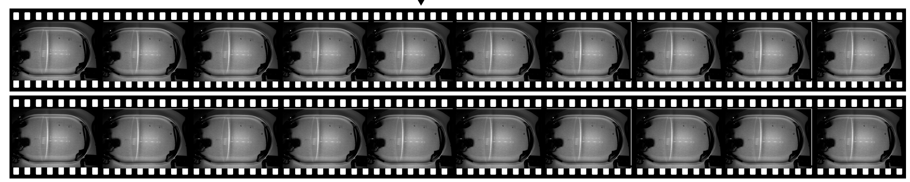
Bubble Chamber Operation Cycle



The Data

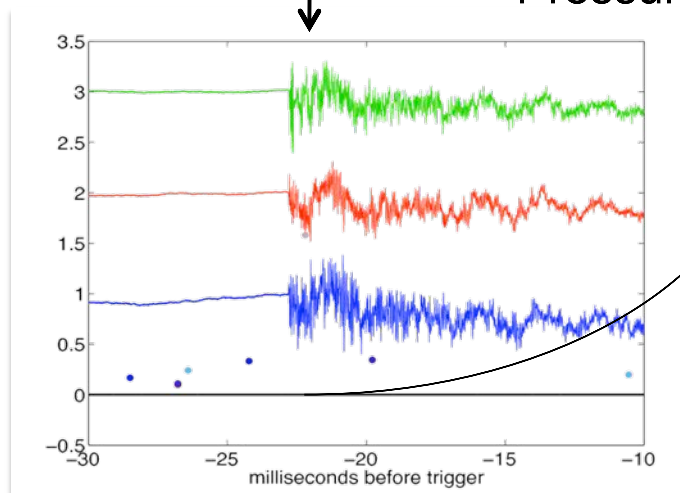
- 10 frames of Stereo Camera Images
- Synchronized measurements of P, T, and control parameters
- 2.5 Mhz waveform digitizer for acoustics and fast pressure transducer.

Trigger frame



Acoustic Traces

Pressure Growth



Dark Matter Bubble Chambers

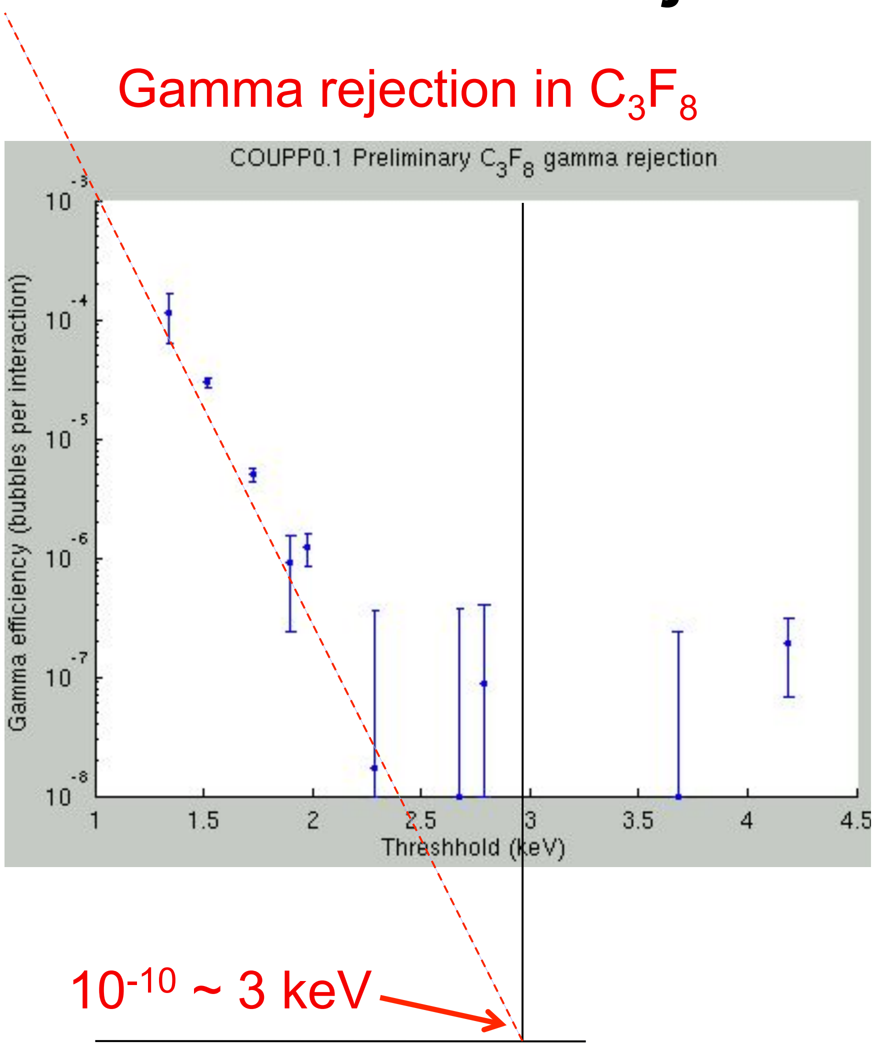
- Insensitive* to γ and β backgrounds
- Threshold device, integral distribution
- Event-by-event tagging of α-recoils
- Only background should be neutrons

Dark Matter Bubble Chambers

- Insensitive* to γ and β backgrounds
  - * There is a *catch* here…
    - Our γ and β rejection is not perfect,
    - and the onset of gamma sensitivity <u>limits the lowest viable operating threshold</u>

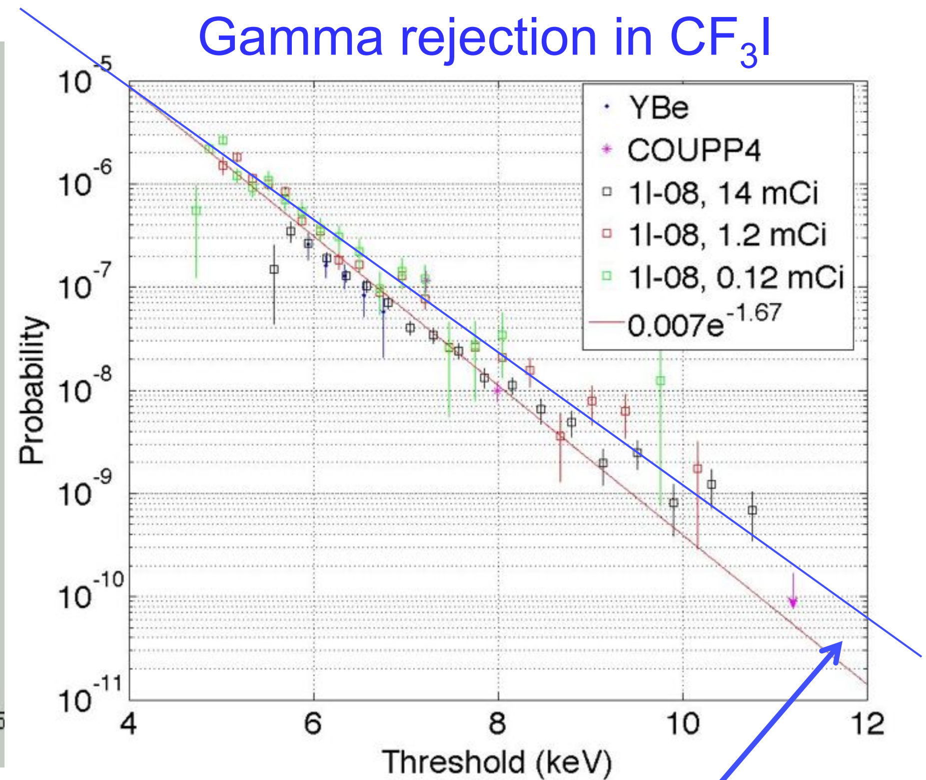
Gamma Rejection Measurements

Gamma rejection in C_3F_8



10^{-10} ~ 3 keV

Gamma rejection in CF_3I

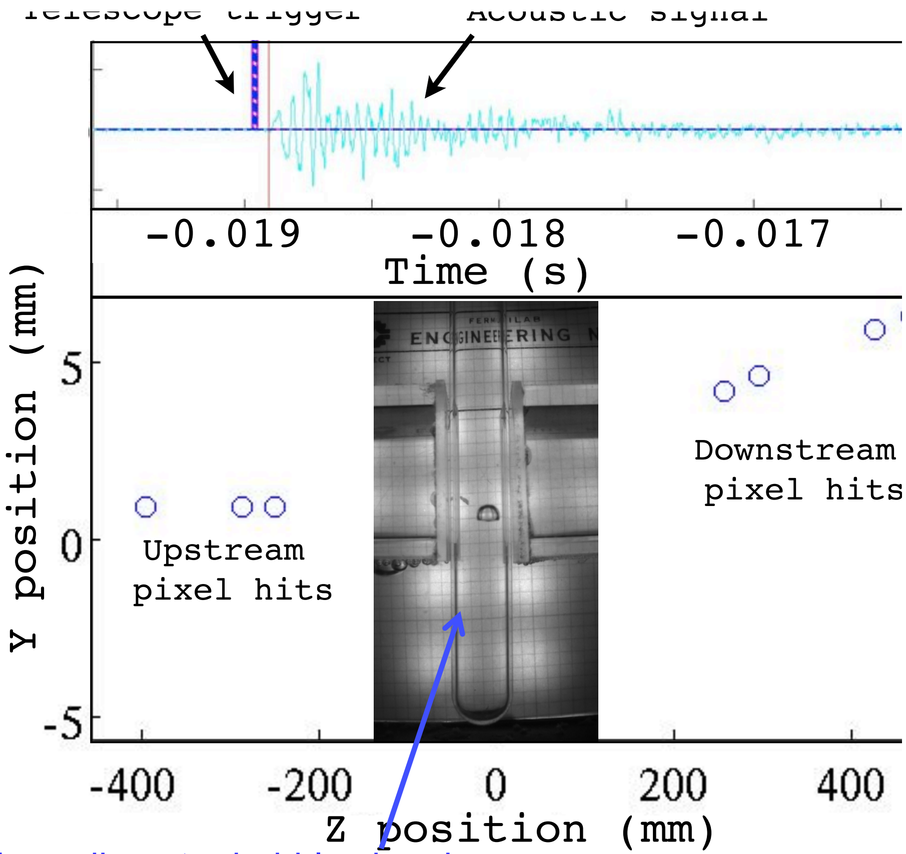


10^{-10} ~ 12 keV

Dark Matter Bubble Chambers

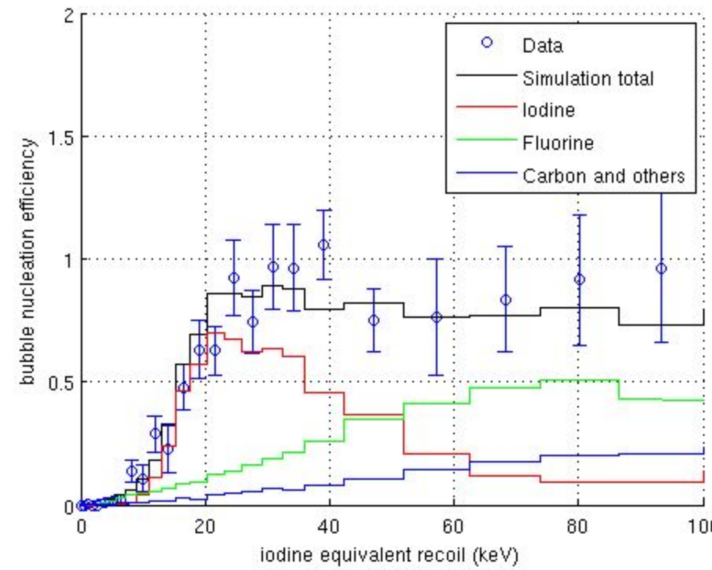
- E_{min} determines dark matter sensitivity
  - For a velocity of 300 *km/sec*
    - E_{iodine} = 63 *keV* so E_{min} = 12 *keV* is OK
    - $E_{fluorine}$ = 9.5 *keV* so E_{min} = 12 *keV* is *not* OK
    - Good sensitivity to fluorine recoils from dark matter requires a 2-3 *keV* threshold attainable only with C_3F_8 or C_4F_{10}

NEW Explicit Confirmation of a *sharp* Bubble Nucleation Threshold for Iodine Recoils in CF_3I



1 cm diameter bubble chamber

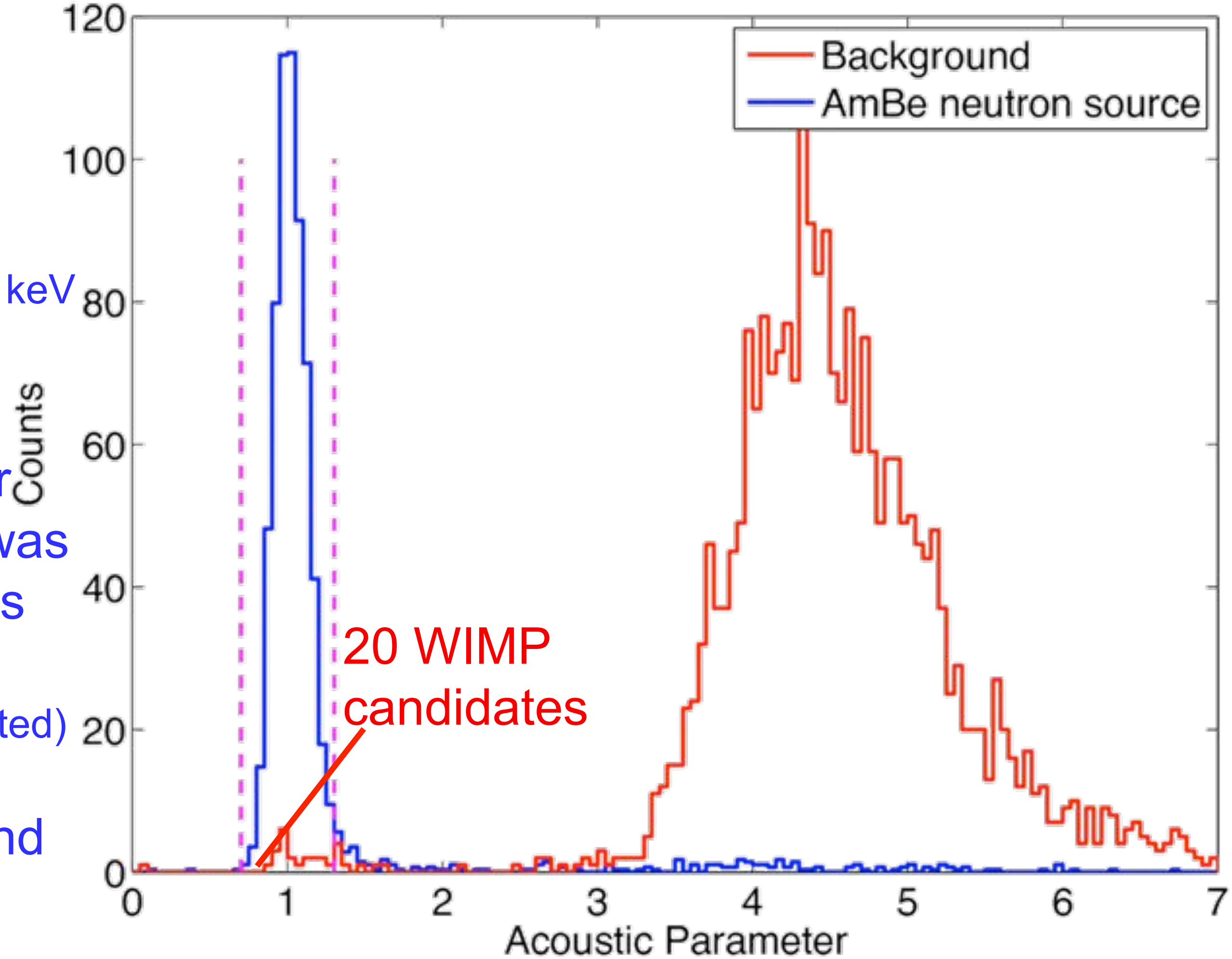
12 GeV/c π^- test beam



The Seitz Model works *very well* for iodine in CF_3I

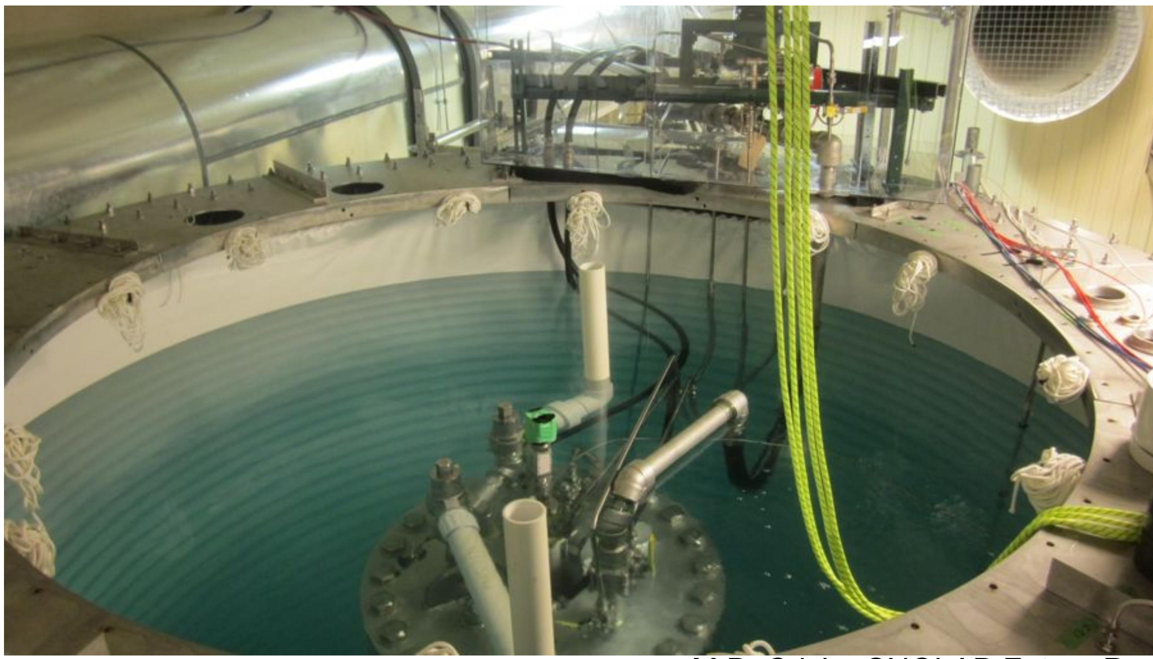
COUPP 4kg @ SNOLAB

- Excellent Rejection of Alpha Backgrounds in CF_3I
  - α rejection >98.9%
  - α rejection > 99.3% 15 keV data
- COUPP-4 Dark Matter Sensitivity from CF_3I was limited by backgrounds
  - Neutrons
  - Anomalous* (CF3I related)
    - Not random in time
- Anomalous Background not yet understood



COUPP-60 at SNOLAB

- CF_3I effort continues with COUPP-60
- Operating since June 2013
- >1000 kg-days
- Competitive for Spin-Independent



Problems with ^{19}F response in CF_3I

COUPP
Carbon and Fluorine Recoil Thresholds

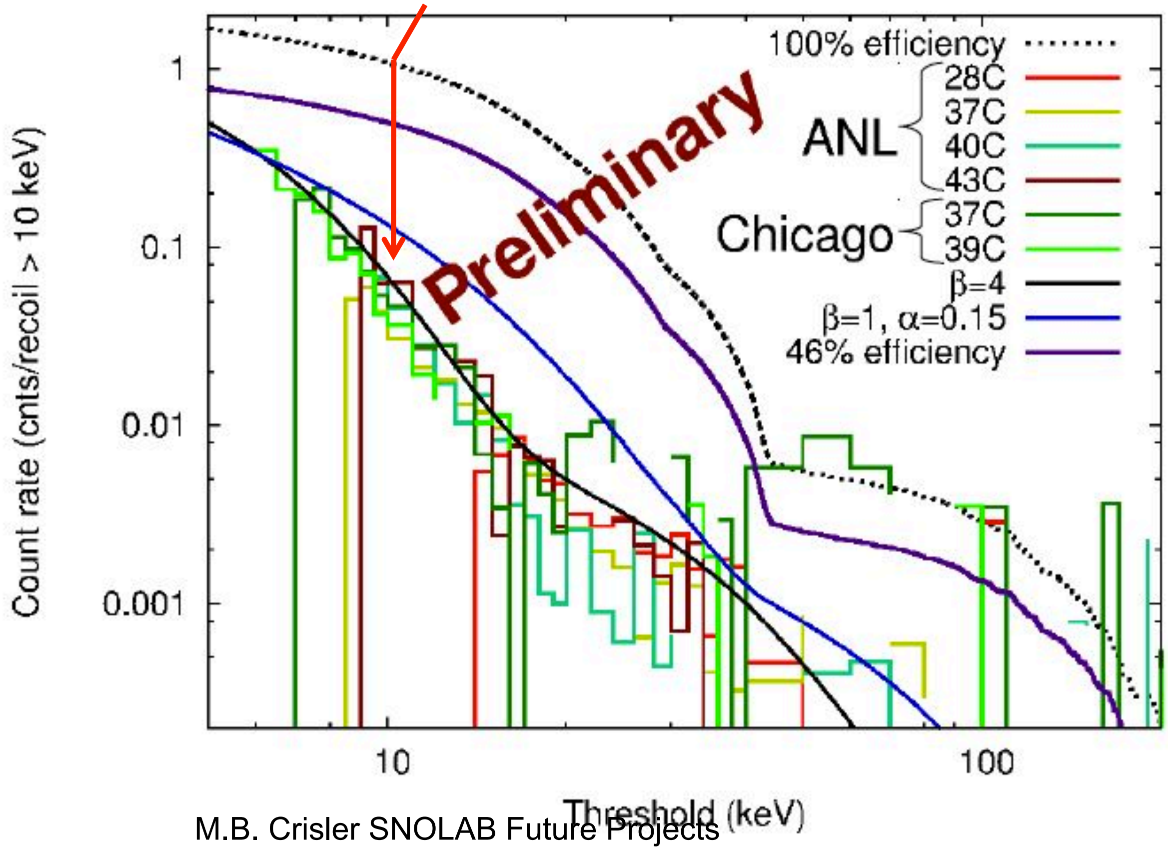
Count rates

- Method
- Previous calibrations
- This calibration
- Prospects

NEW

Normalized and background subtracted count rate for Y/Be neutrons on CF3I bubble chambers

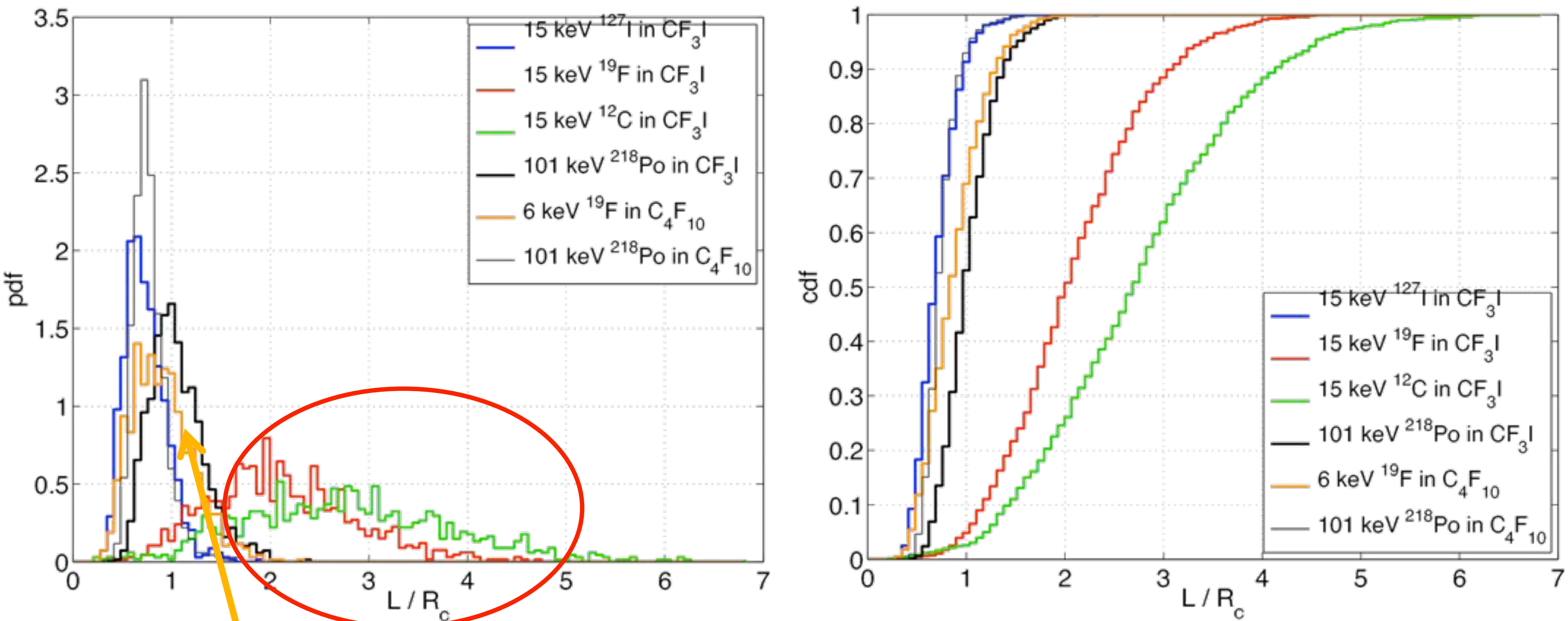
…poor fluorine recoil nucleation efficiently



Slide 12/16
IDM 2012

Threshold and Efficiency: SRIM simulation*

15 keV ^{19}F and ^{12}C recoils in CF_3I have tracks significantly longer than the critical radius for bubble formation



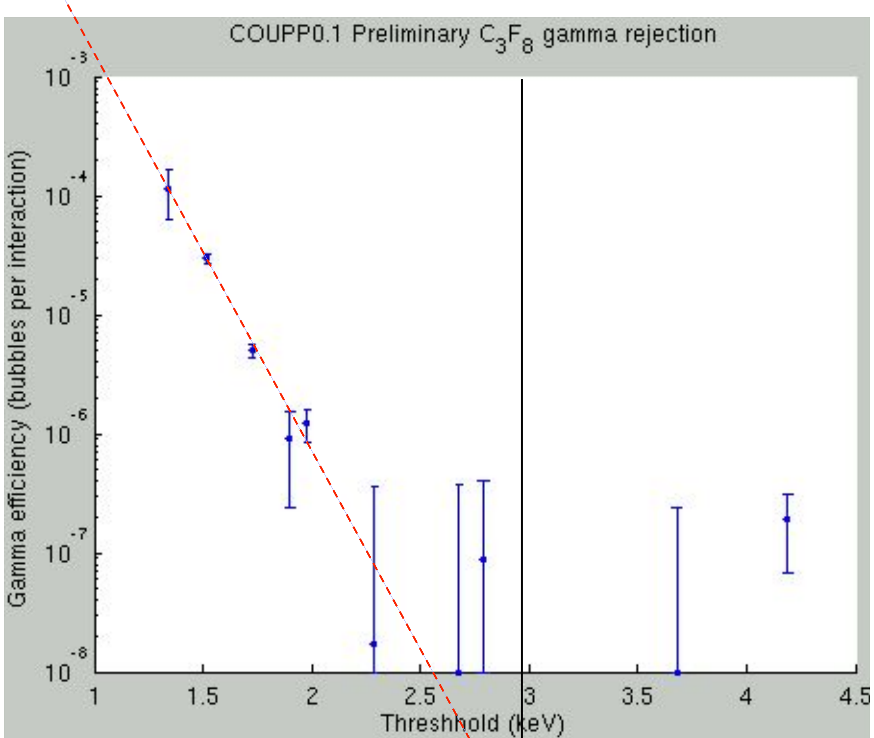
…so fluorine recoils do not nucleate efficiently in CF_3I

fluorine recoils do nucleate efficiently in C_3F_8

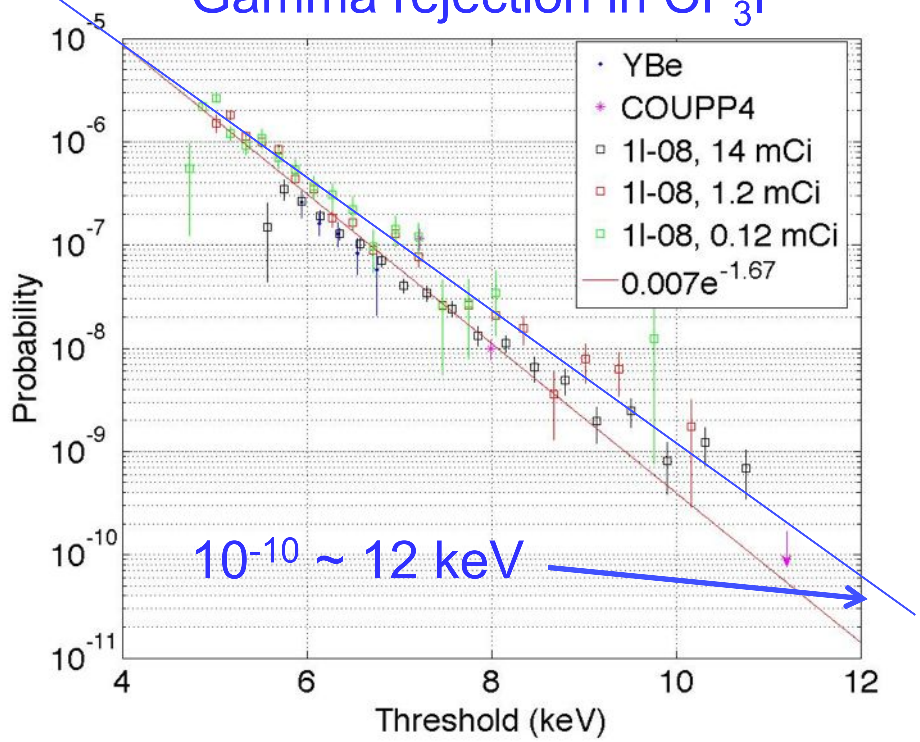
C_3F_8 for SD, low mass

Gamma rejection sets the threshold.
The 10-15 keV Threshold necessary for CF_3I is kinematically unfavorable for ^{19}F recoils

Gamma rejection in C_3F_8



Gamma rejection in CF_3I

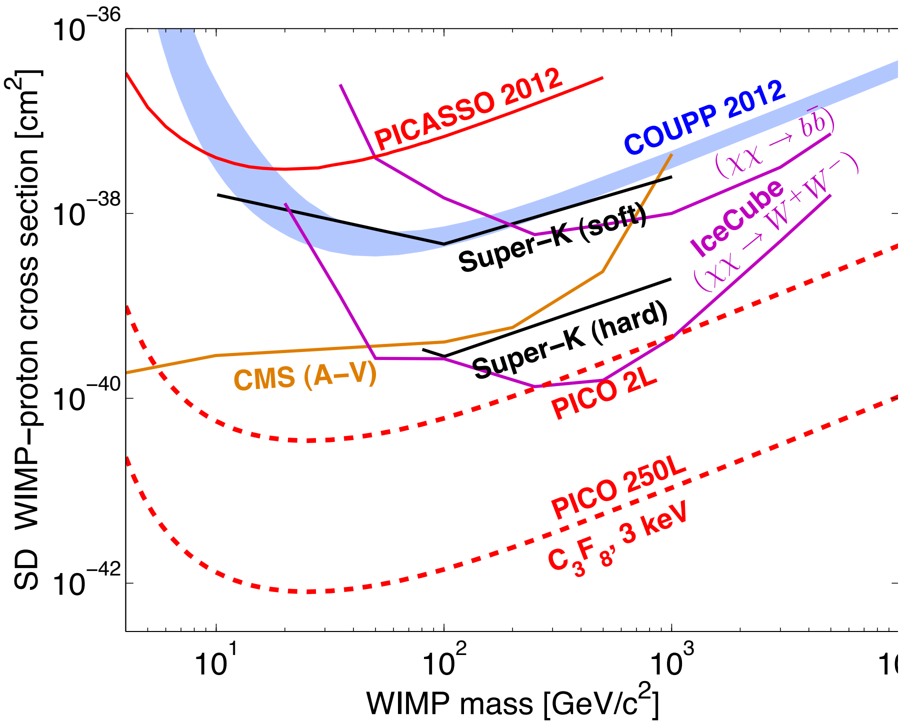


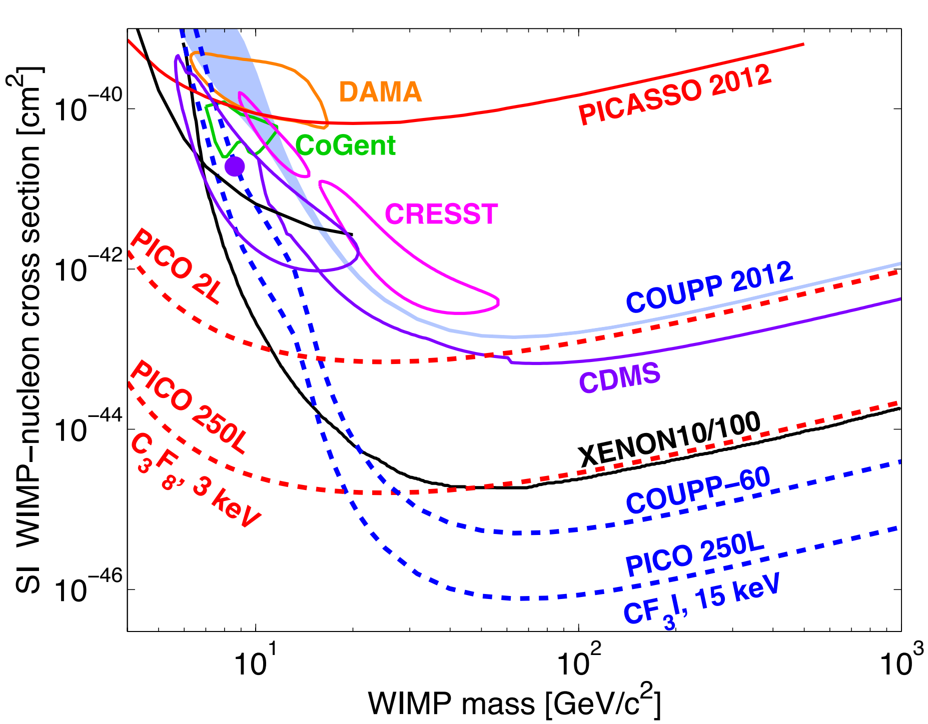
10^{-10} ~ 12 keV

10^{-10} ~ 3 keV

3 keV threshold provides excellent sensitivity for ^{19}F recoils → Excellent Spin-dependent Plus Spin-Independent Low Mass

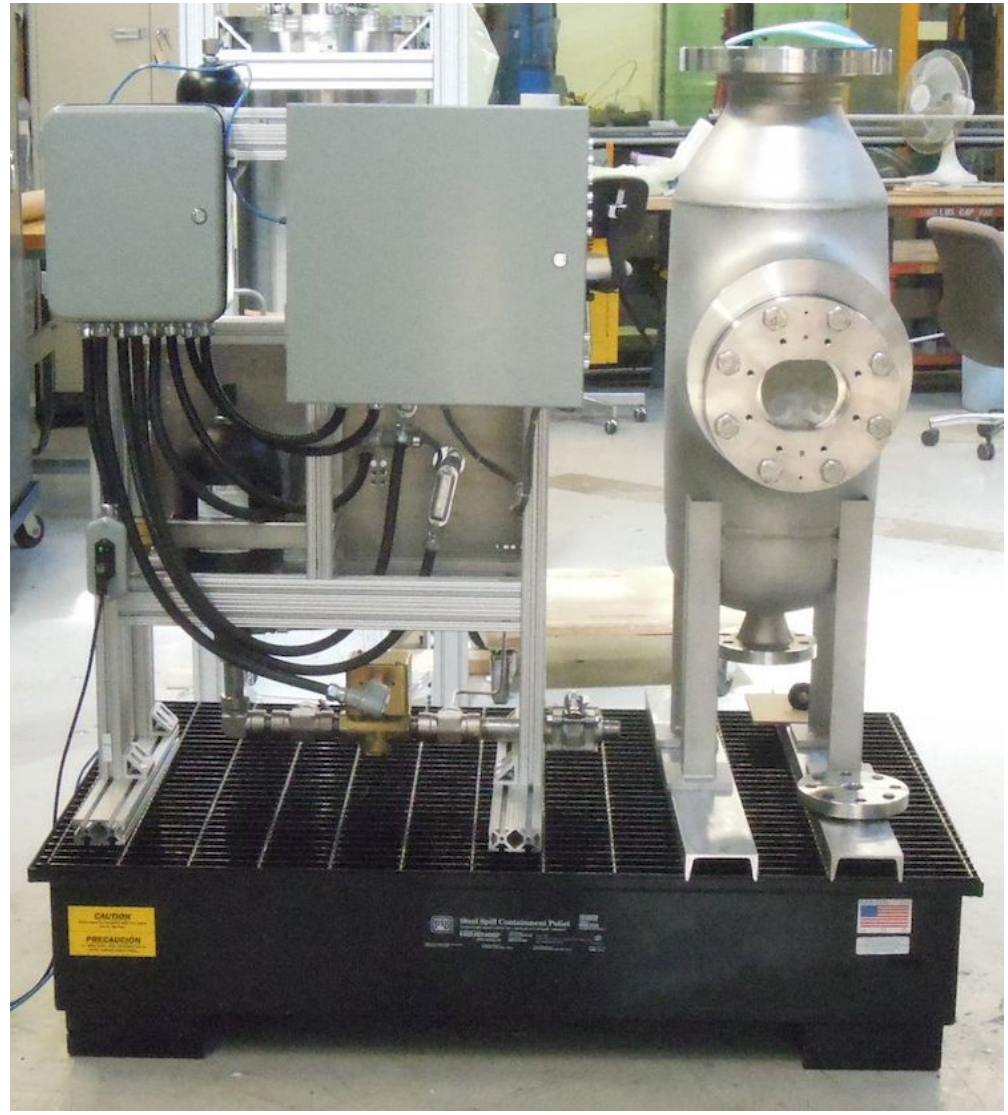
Dark Matter Sensitivity with C_3F_8 / CF_3I



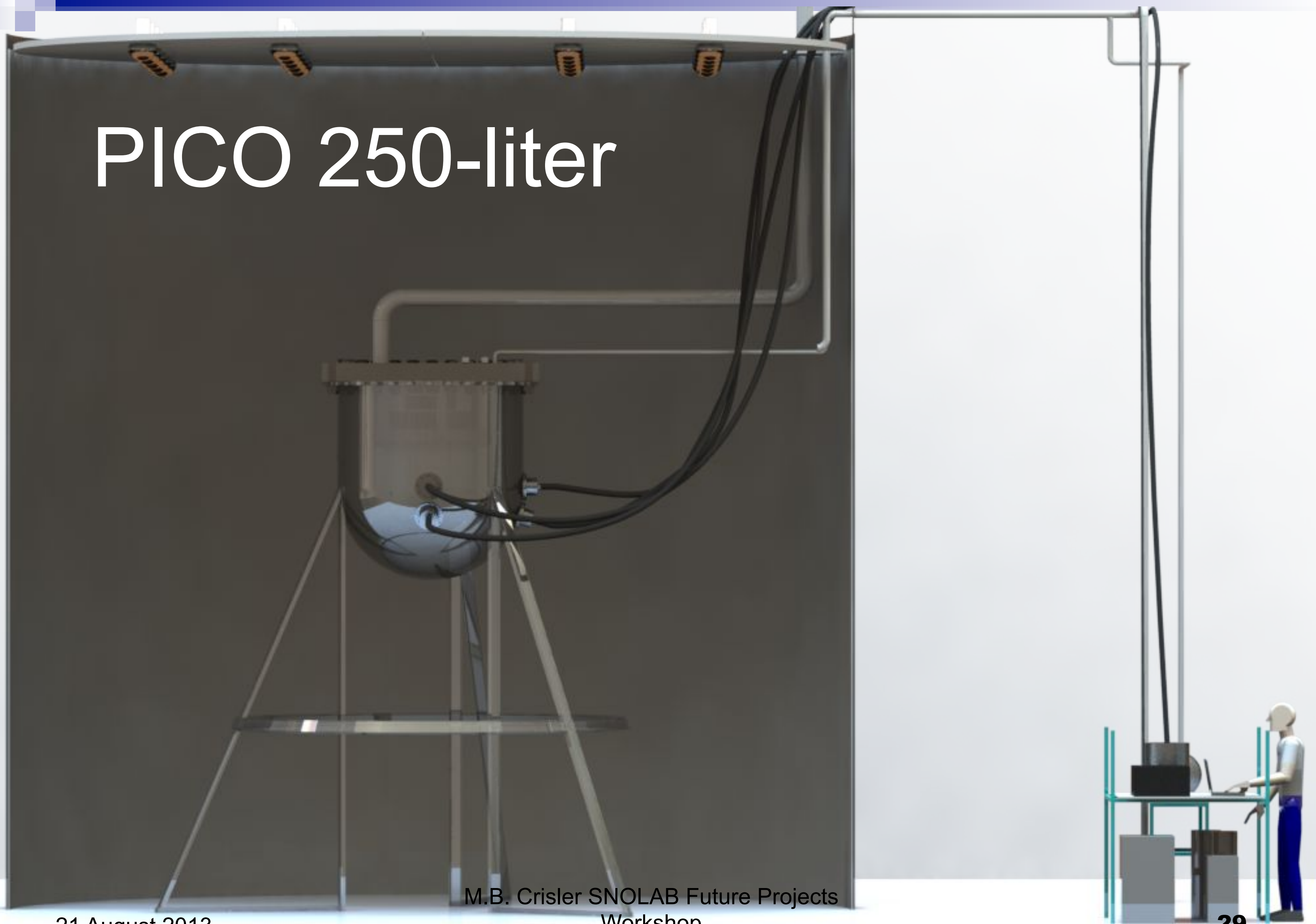


PICO-2L

- Focus on
  - SD couplings
  - low mass SI
- 2-liter C_3F_8 target
- Expect 3 keV threshold
- Installation in progress
- Physics this year



PICO 250-liter



250-L Bubble Chamber Design (1)

- Instrumentation, DAQ, Controls
- Synthetic Silica Inner vessel
- Bellows Assembly
- Optics, Photography
- Outer Pressure Vessel
- Hydraulic and Thermal Components

250-L Bubble Chamber Design (1)

- Instrumentation, DAQ, Controls
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- Optics, Photography
- Outer Pressure Vessel
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250-L Bubble Chamber Design (2)

- Shielding and Experiment Infrastructure
- Cleaning Infrastructure
- Assembly and Handling Fixtures
- Fluid purification
- Fluid handling
- Site Specific Engineering

Inner Vessel

- Synthetic Silica is the only proven option
  - 250 liters is manufacturing limit
  - 600 mm (24”) diameter
  - 1.3 meter overall length

- Acrylic might be an option for C3F8/C4F10
  - Not yet demonstrated – surface nucleation?

Synthetic Silica Inner Vessel

A 30” (762 mm) diameter vessel would yield a roughly spherical active volume, minimize the surface area to volume ratio, and optimize the camera coverage.

But…
requires 10 mm wall thickness

Three different vendors agreed, (for different reasons) that the 30” (609.6 mm) diameter vessel and the 10 mm wall thickness were beyond their technical capabilities.

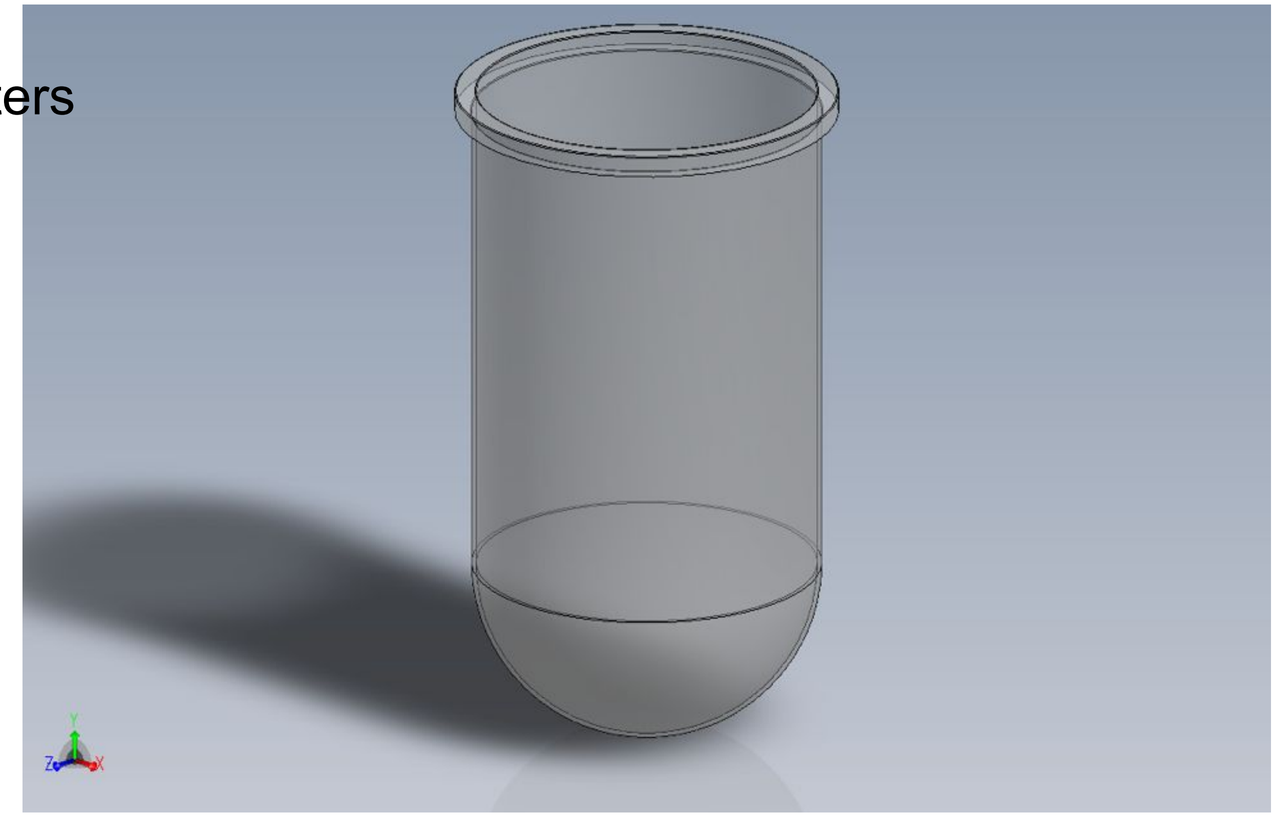
…but this vessel could be fabricated with acrylic or other plastic

Synthetic Silica Inner Vessel

The largest vessel that the vendors can deliver is 250 liters
But with a taller aspect ratio:

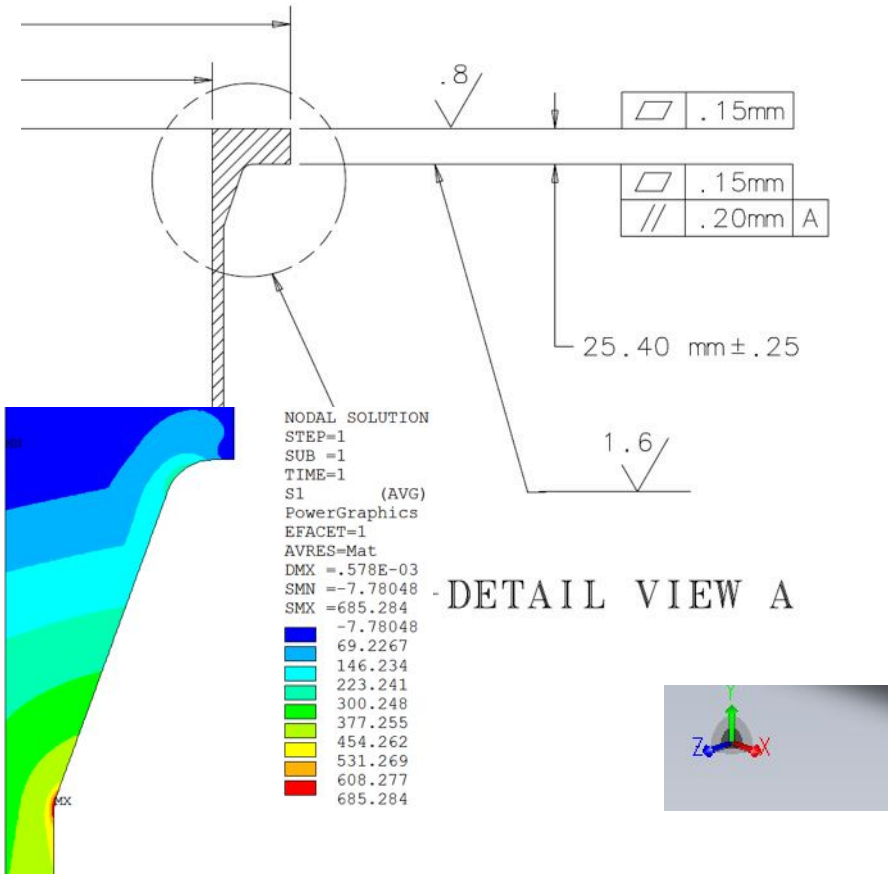
The vessel would be
24” (609.6 mm) diameter
with 8 mm wall thickness

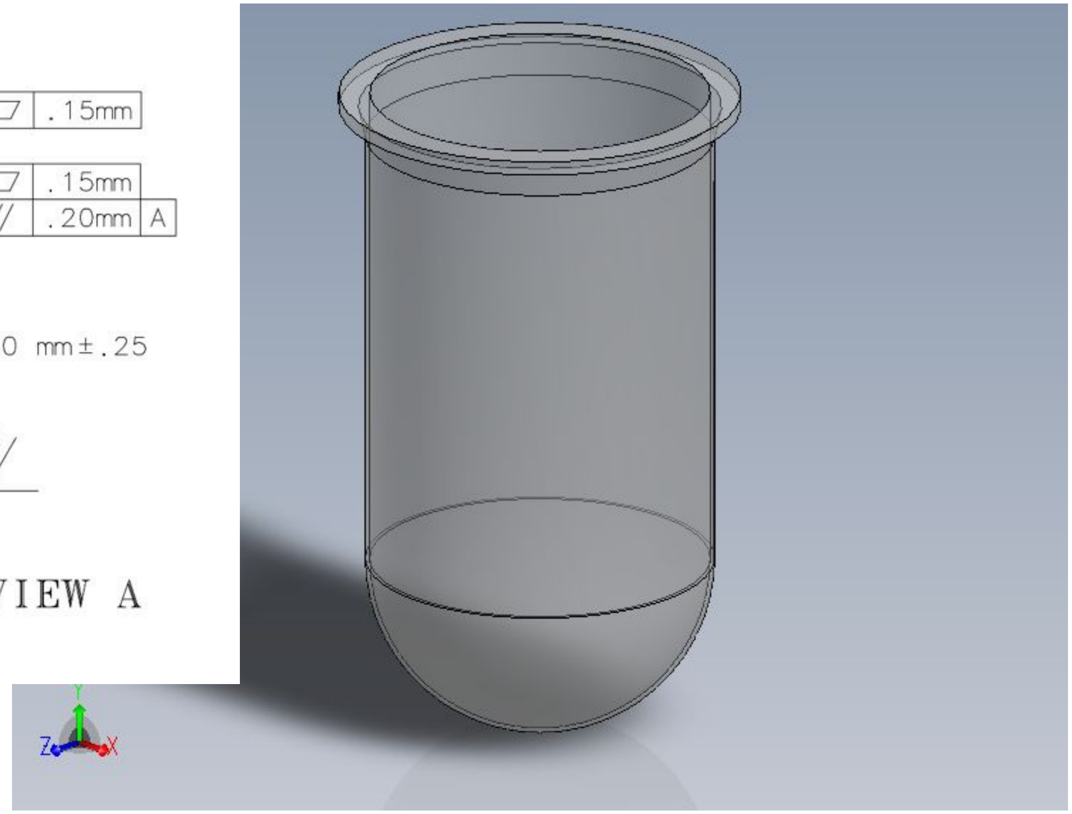
The optics are more challenging but it works.
Requires 4 cameras



Synthetic Silica Inner Vessel

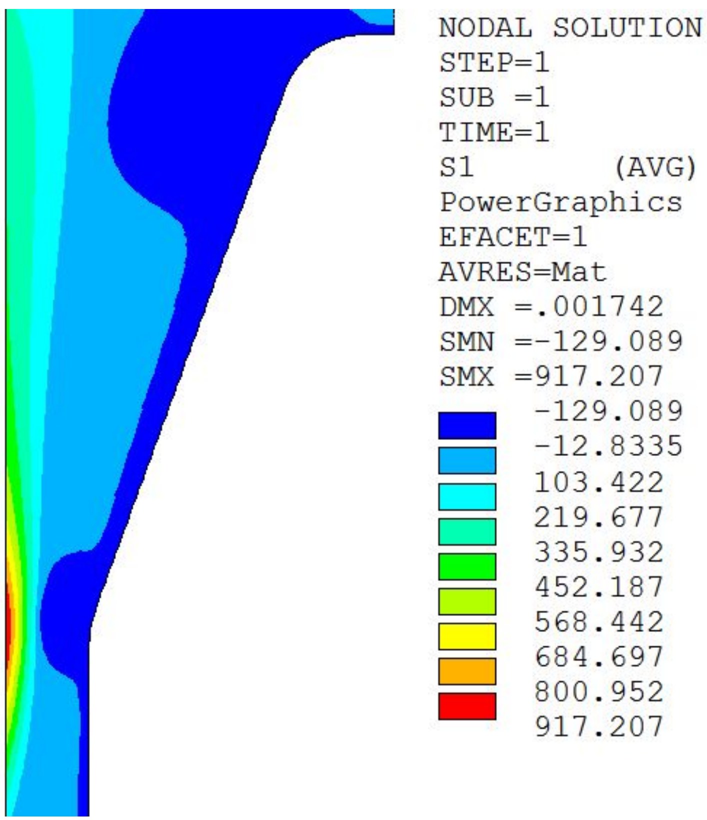
FEA tells us that we need a very robust flange



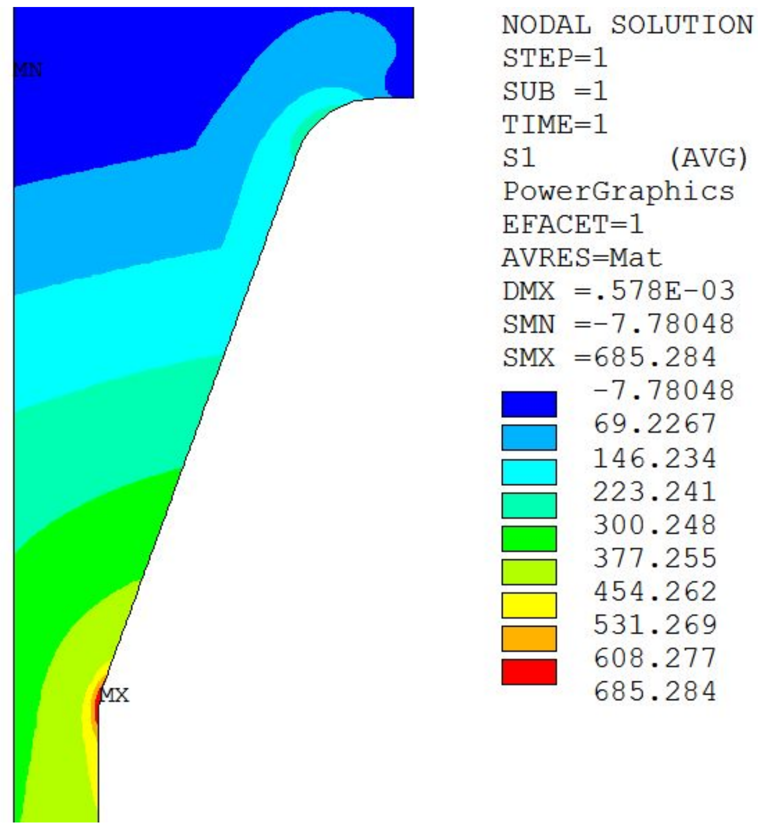


Maximum Tensile Principal Stress

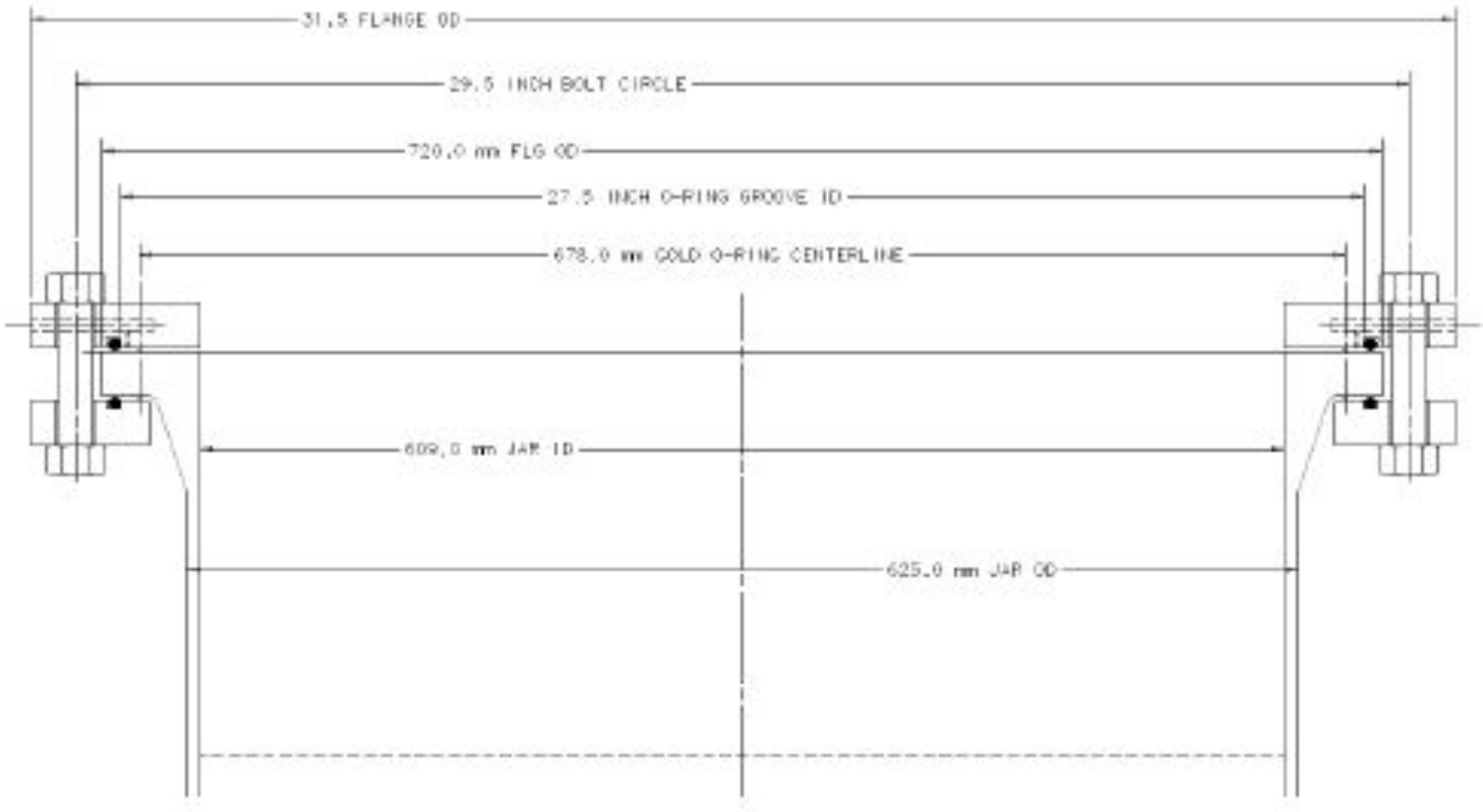
Vacuum (18 psi) Loading



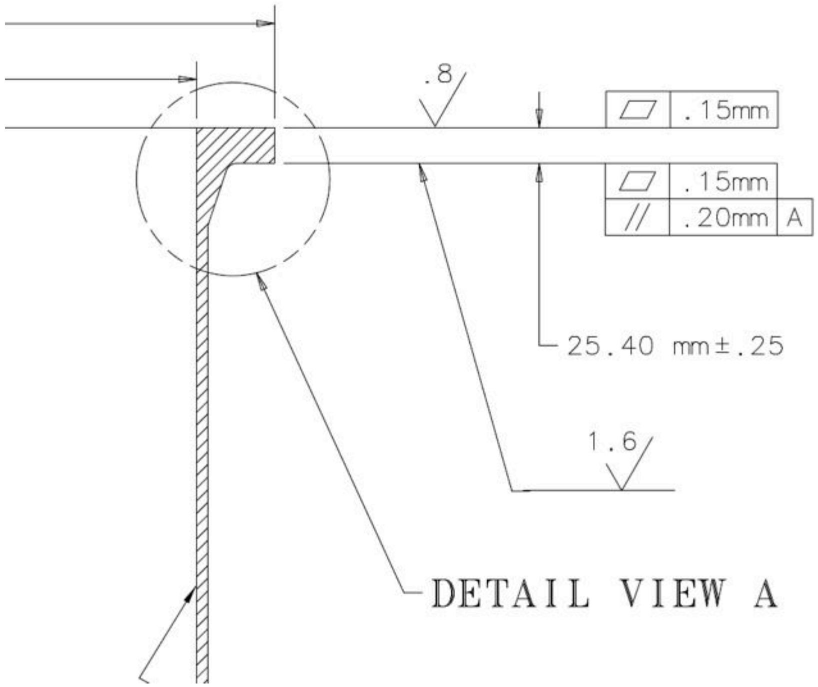
Hydrostatic + 6 psi overpressure

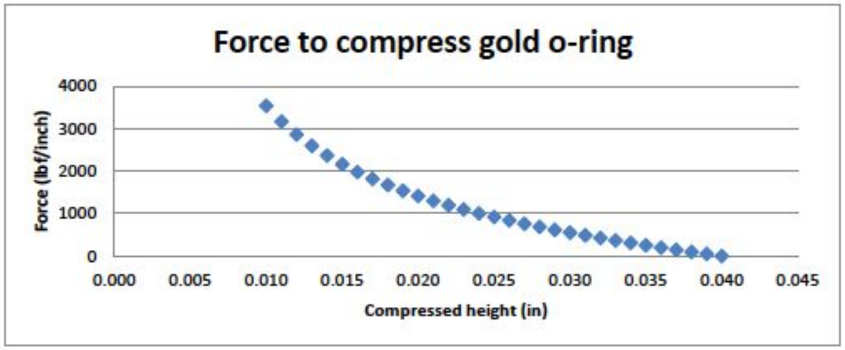


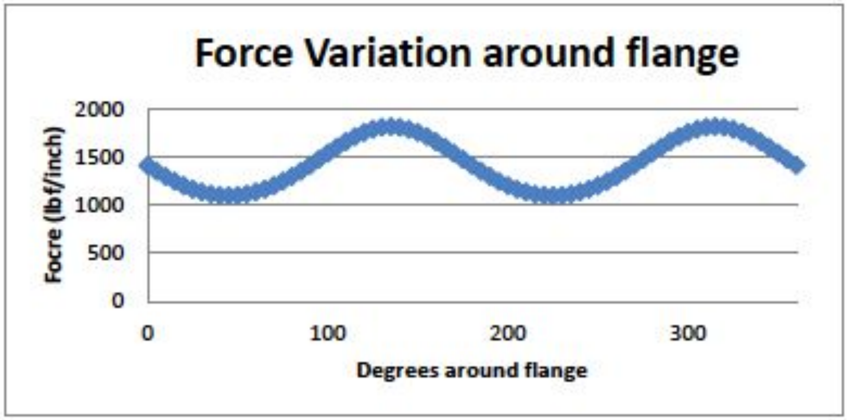
Inner Vessel - gold wire seal design



Inner Vessel – flange flatness specification

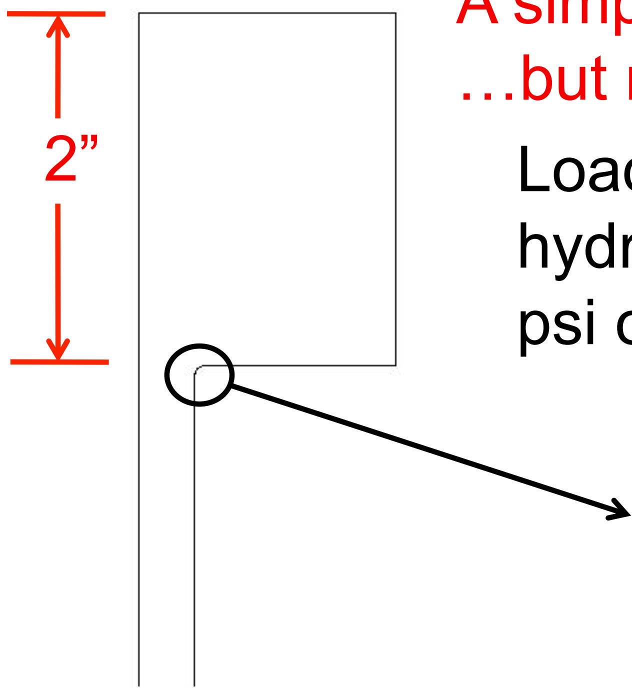




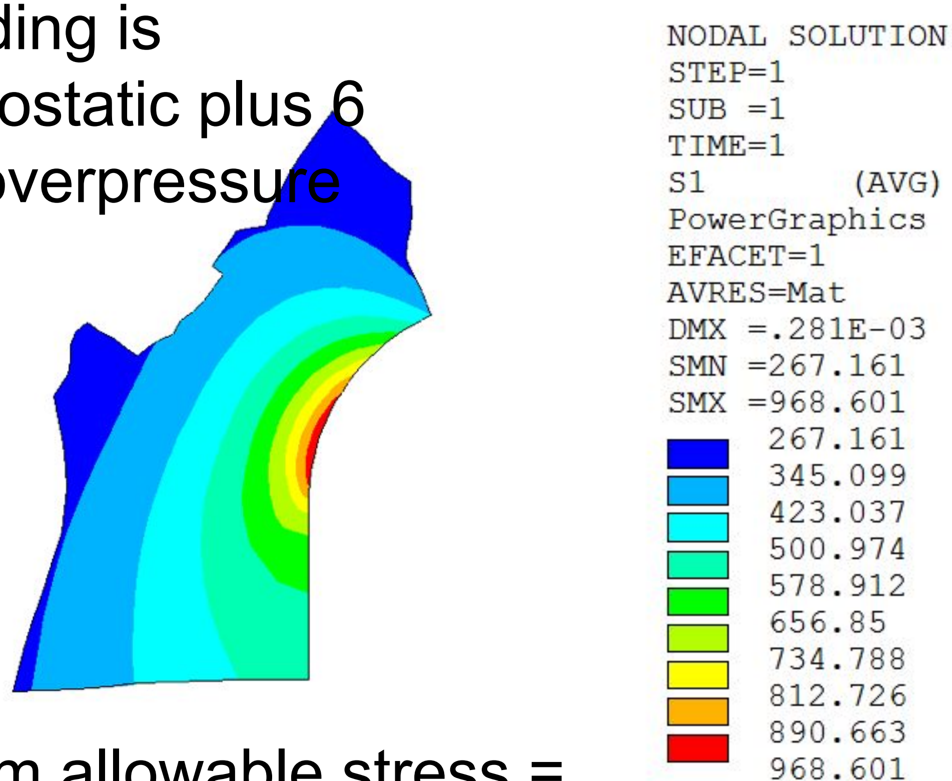


Maximum Principal Stresses in Flange-to-Shell Transition

A simpler flange works,
…but requires 51 mm flange thickness



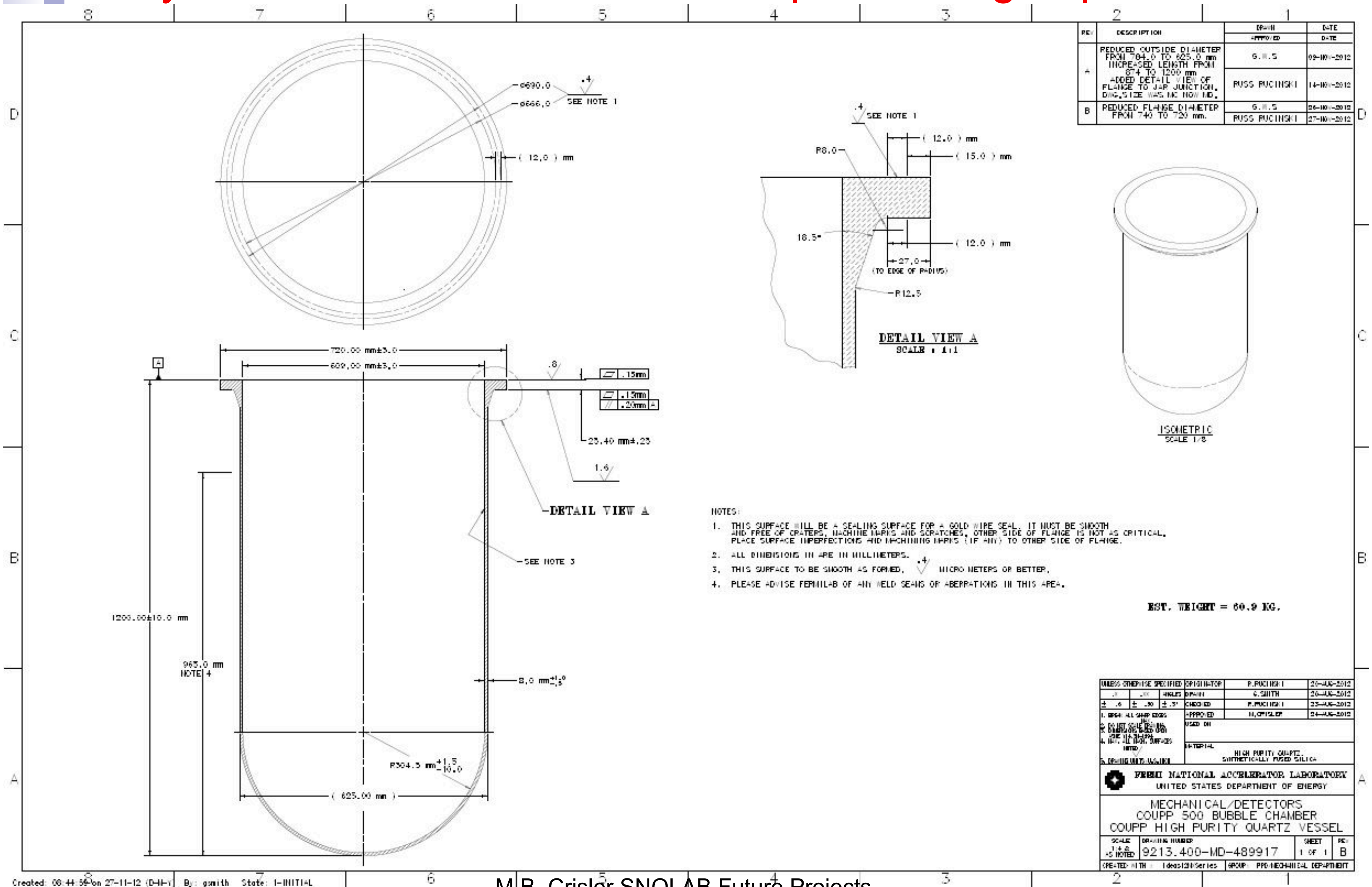
Loading is hydrostatic plus 6 psi overpressure



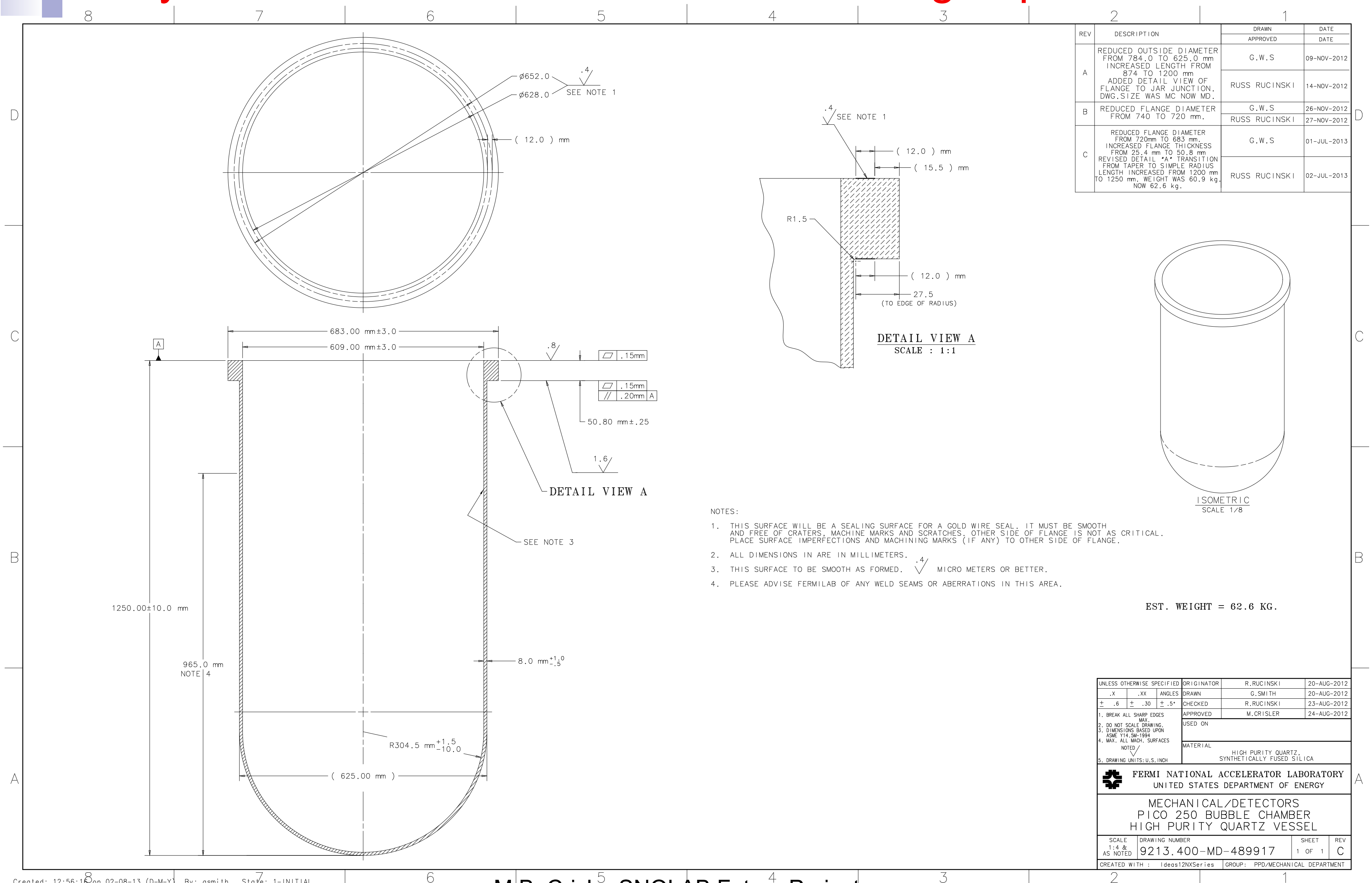
psi

Maximum allowable stress = 1000 psi

Synthetic Silica Inner Vessel – tapered flange option



Synthetic Silica Inner Vessel – thick flange option

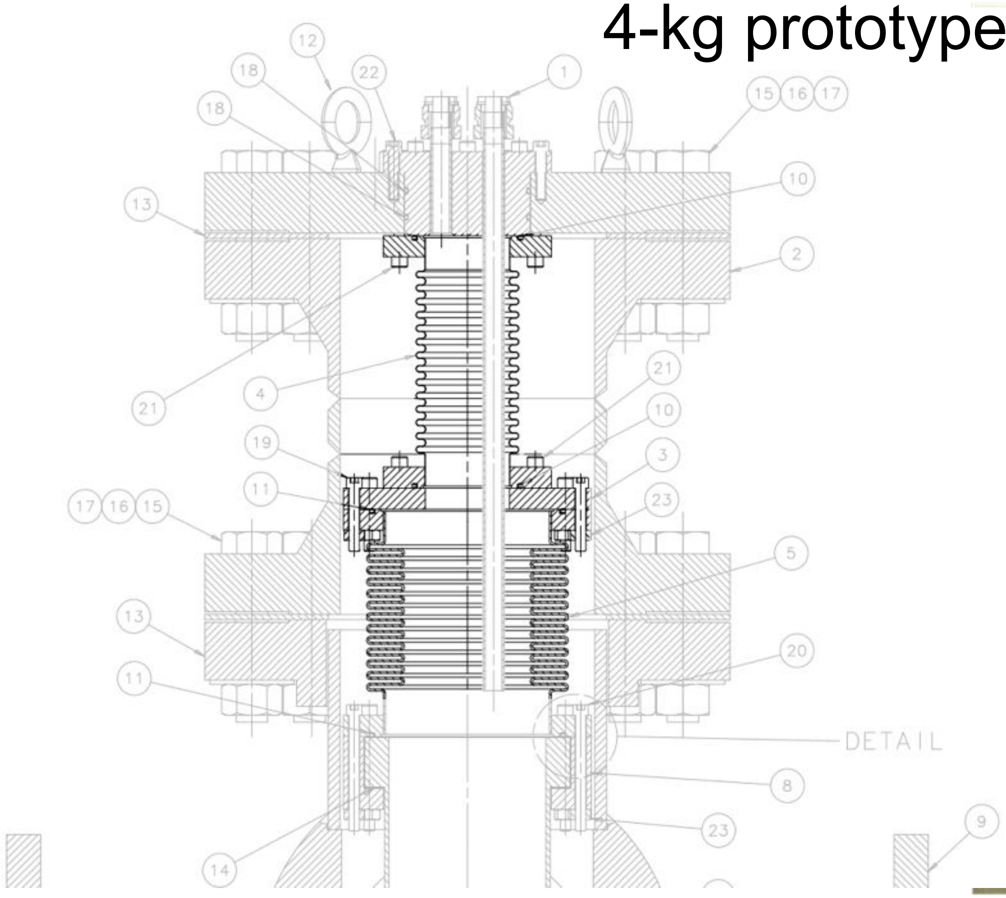


Inner Vessel – status

- Design complete
  - Drawings
  - FEA
  - Seal design
  - Engineering note
  - Procurement specifications
- Vendor Preliminary Quotations
  - Range from $150K to $270K

Inline pressure balancer

4-kg prototype

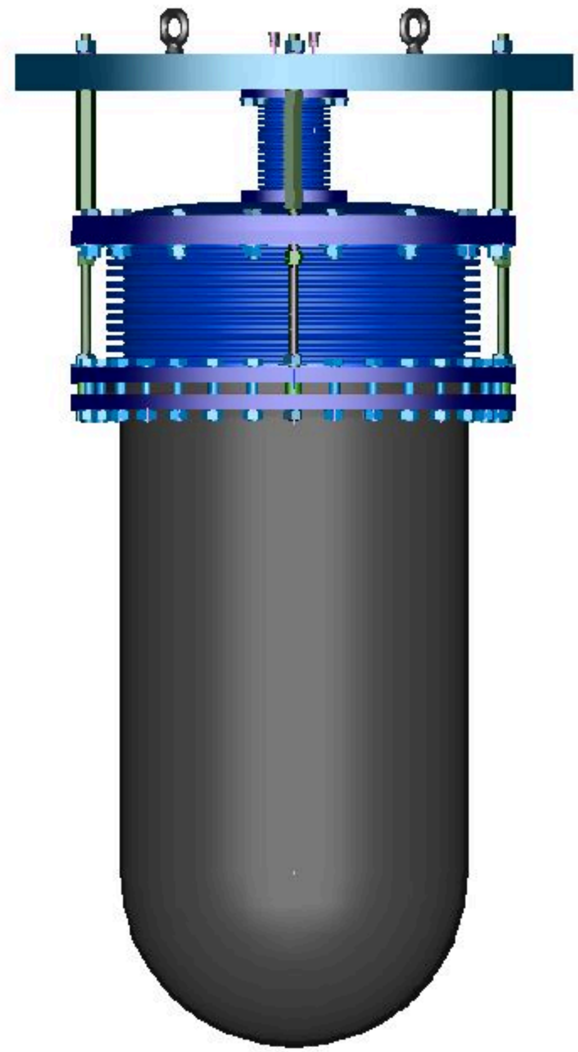


21 August 2013

M.B. Crisler SNOLAB Future Projects Workshop

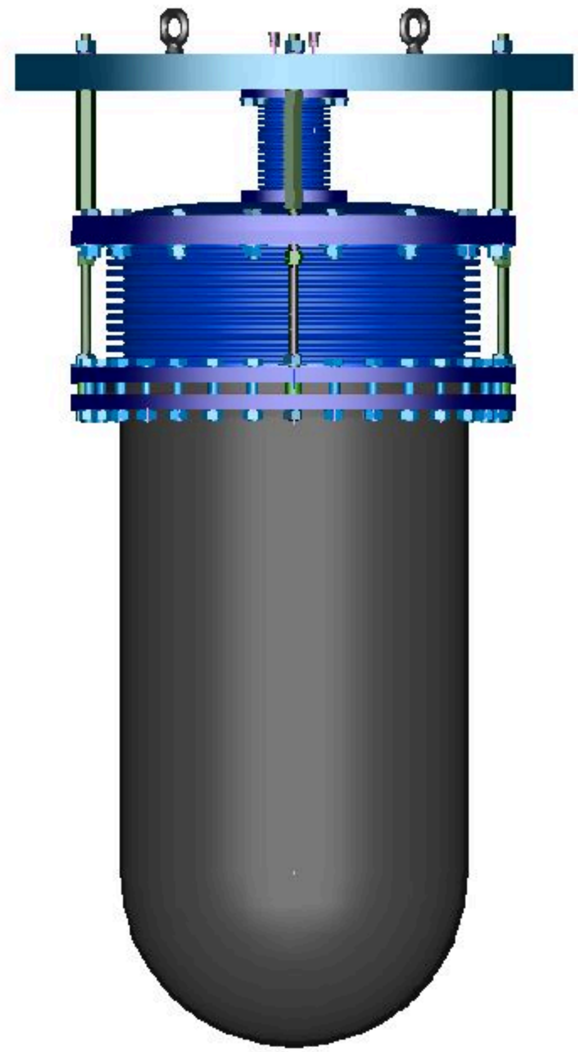
Inline pressure balancer

- COUPP-500 design:
  - Simple scale-up
- Easier design at larger diameters
- Very small pressure differential ~1/2 psi



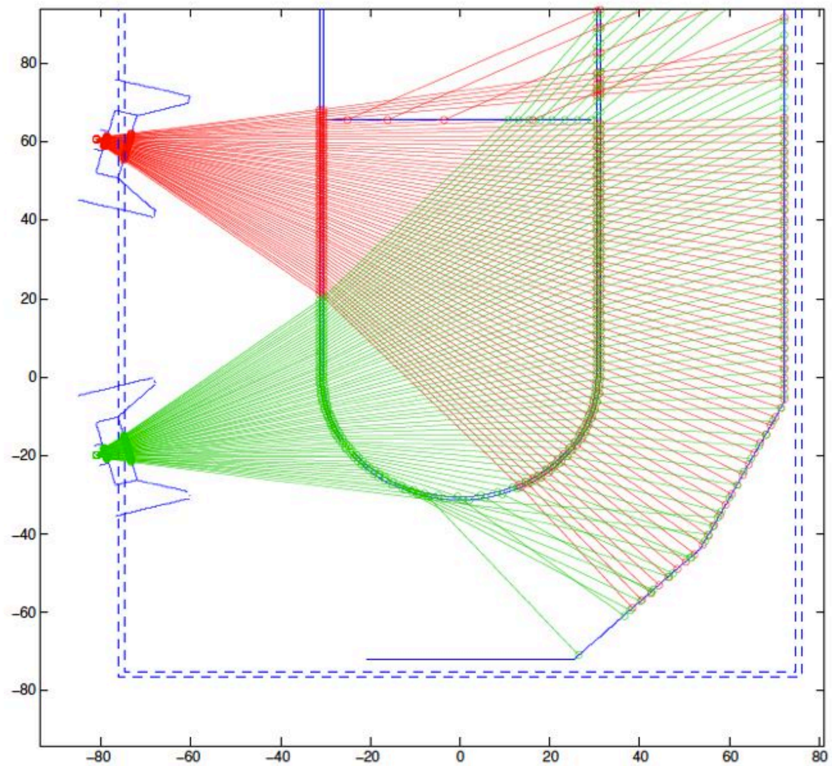
Inline pressure balancer -status

- 90% solid model
- Needs work on details of mounting and alignment



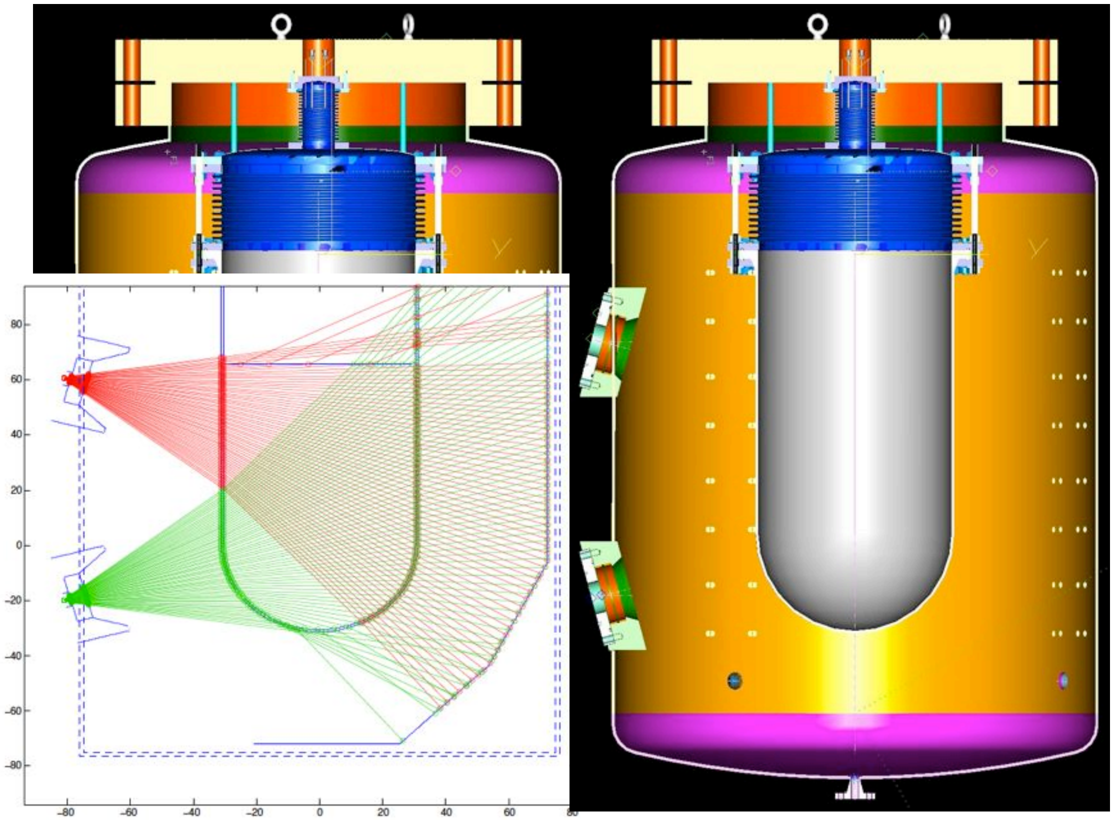
Camera Mount /Chamber Optics

- Hexapod camera mount
- Reproducible alignment

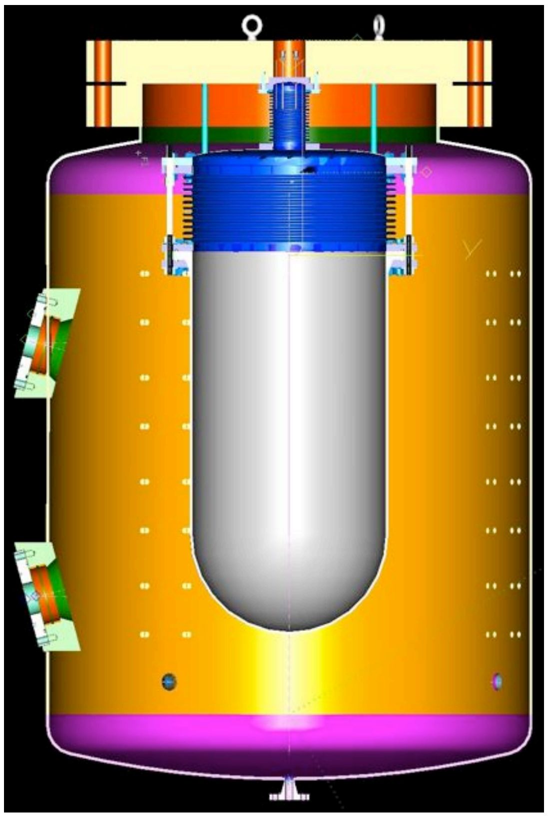


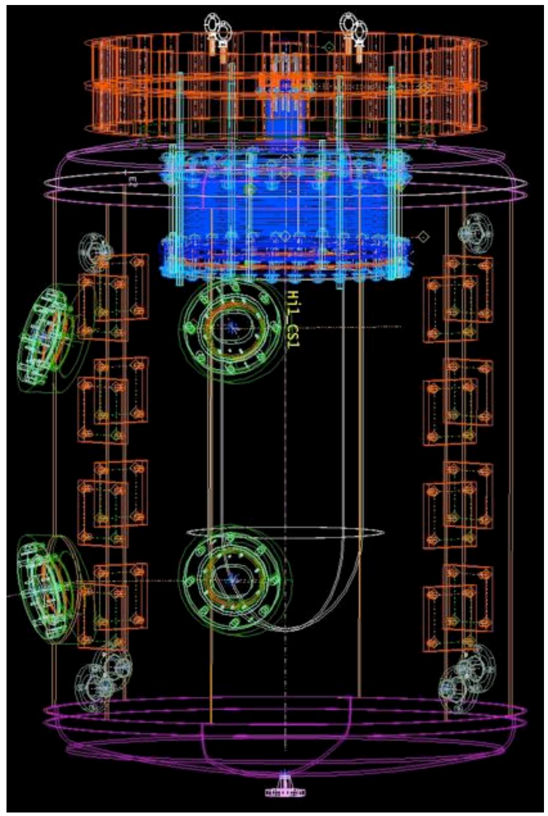
Optical Model for the Chamber

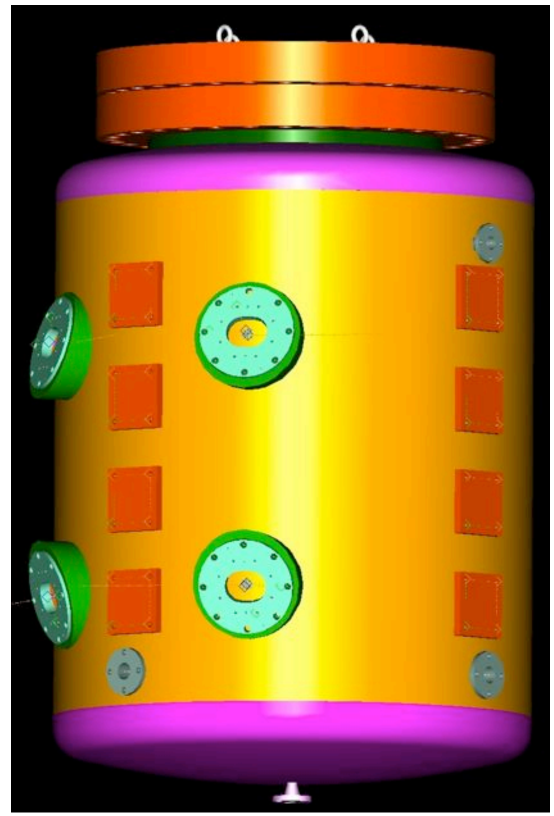
- Optics model determines viewport placement and orientation
- Determines space requirements for retro-reflective screen

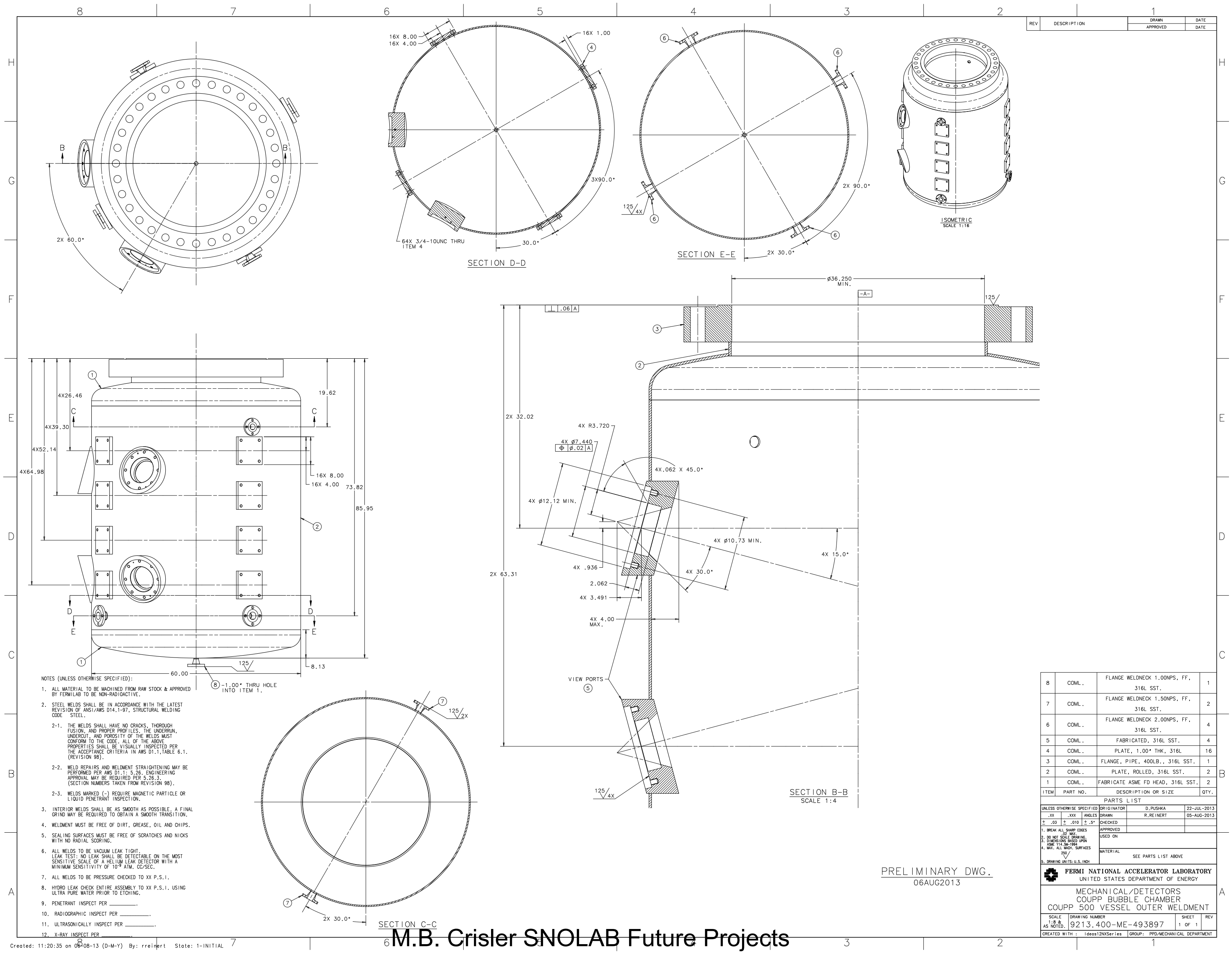


Solid model of the Chamber







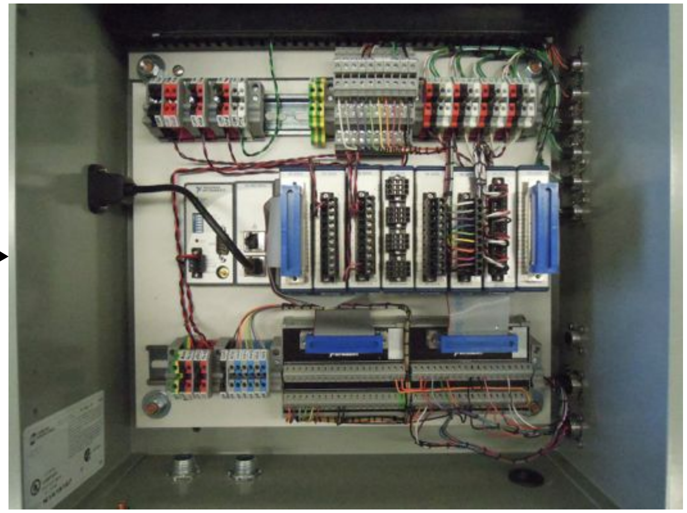


SECTION D-D
SECTION E-E
ISOMETRIC
SCALE 1:16
SECTION B-B
SCALE 1:4
SECTION C-C
VIEW PORTS
PRELIMINARY DWG.
06AUG2013
NOTES (UNLESS OTHERWISE SPECIFIED):
1. ALL MATERIAL TO BE MACHINED FROM RAW STOCK & APPROVED BY FERMILAB TO BE NON-RADIOACTIVE.
2. STEEL WELDS SHALL BE IN ACCORDANCE WITH THE LATEST REVISION OF ANSI/AWS D14.1-97, STRUCTURAL WELDING CODE STEEL.
2-1. THE WELDS SHALL HAVE NO CRACKS, THOROUGH FUSION, AND PROPER PROFILES. THE UNDERRUN, UNDERCUT, AND POROSITY OF THE WELDS MUST CONFORM TO THE CODE. ALL OF THE ABOVE PROPERTIES SHALL BE VISUALLY INSPECTED PER THE ACCEPTANCE CRITERIA IN AWS D1.1,TABLE 6.1. (REVISION 98).
2-2. WELD REPAIRS AND WELDMENT STRAIGHTENING MAY BE PERFORMED PER AWS D1.1: 5.26. ENGINEERING APPROVAL MAY BE REQUIRED PER 5.26.3. (SECTION NUMBERS TAKEN FROM REVISION 98).
2-3. WELDS MARKED (-) REQUIRE MAGNETIC PARTICLE OR LIQUID PENETRANT INSPECTION.
3. INTERIOR WELDS SHALL BE AS SMOOTH AS POSSIBLE. A FINAL GRIND MAY BE REQUIRED TO OBTAIN A SMOOTH TRANSITION.
4. WELDMENT MUST BE FREE OF DIRT, GREASE, OIL AND CHIPS.
5. SEALING SURFACES MUST BE FREE OF SCRATCHES AND NICKS WITH NO RADIAL SCORING.
6. ALL WELDS TO BE VACUUM LEAK TIGHT. LEAK TEST: NO LEAK SHALL BE DETECTABLE ON THE MOST SENSITIVE SCALE OF A HELIUM LEAK DETECTOR WITH A MINIMUM SENSITIVITY OF 10-9 ATM. CC/SEC.
7. ALL WELDS TO BE PRESSURE CHECKED TO XX P.S.I.
8. HYDRO LEAK CHECK ENTIRE ASSEMBLY TO XX P.S.I. USING ULTRA PURE WATER PRIOR TO ETCHING.
9. PENETRANT INSPECT PER ________.
10. RADIOGRAPHIC INSPECT PER ________.
11. ULTRASONICALLY INSPECT PER ________.
12. X-RAY INSPECT PER ________.
8 COML. FLANGE WELDNECK 1.00NPS, FF, 316L SST. 1
7 COML. FLANGE WELDNECK 1.50NPS, FF, 316L SST. 2
6 COML. FLANGE WELDNECK 2.00NPS, FF, 316L SST. 4
5 COML. FABRICATED, 316L SST. 4
4 COML. PLATE, 1.00" THK, 316L 16
3 COML. FLANGE, PIPE, 400LB., 316L SST. 1
2 COML. PLATE, ROLLED, 316L SST. 2
1 COML. FABRICATE ASME FD HEAD, 316L SST. 2
ITEM PART NO. DESCRIPTION OR SIZE QTY.
PARTS LIST
ORIGINATOR D.PUSHKA 22-JUL-2013
DRAWN R.REINERT 05-AUG-2013
MATERIAL SEE PARTS LIST ABOVE
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY
MECHANICAL/DETECTORS
COUPP BUBBLE CHAMBER
COUPP 500 VESSEL OUTER WELDMENT
DRAWING NUMBER 9213.400-ME-493897
SHEET 1 OF 1
Created: 11:20:35 on 06-08-13 (D-M-Y) By: rreinert State: 1-INITIAL

Hydraulic Cart Architecture

AC Chassis

Instrumentation Chassis

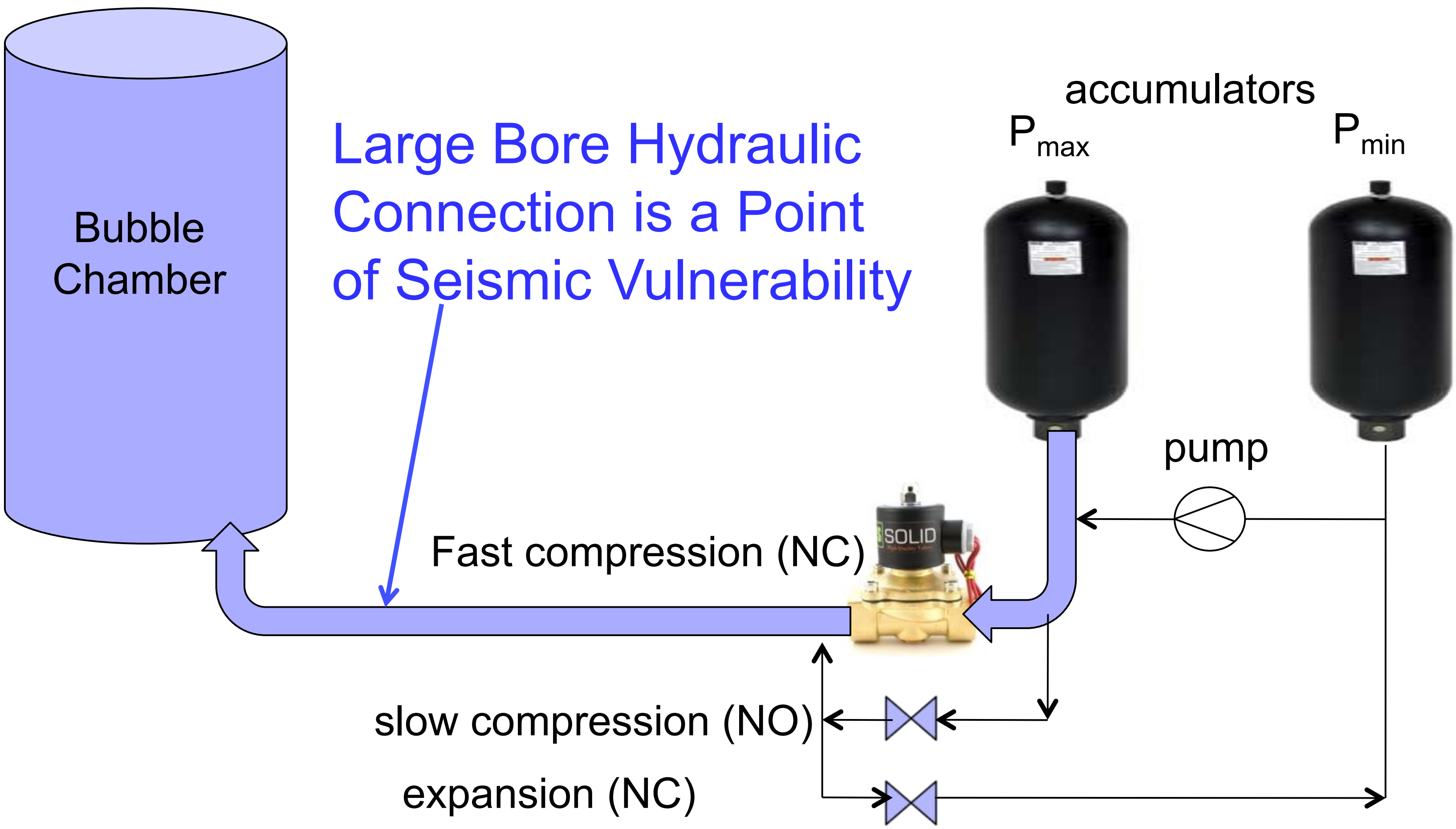


AC Power Entry

- Isolated AC Power Entry
- AC Chassis
  - DC supplies
  - Switching Relays
- Instrumentation Chassis
  - DC only +12 VDC, +24 VDC

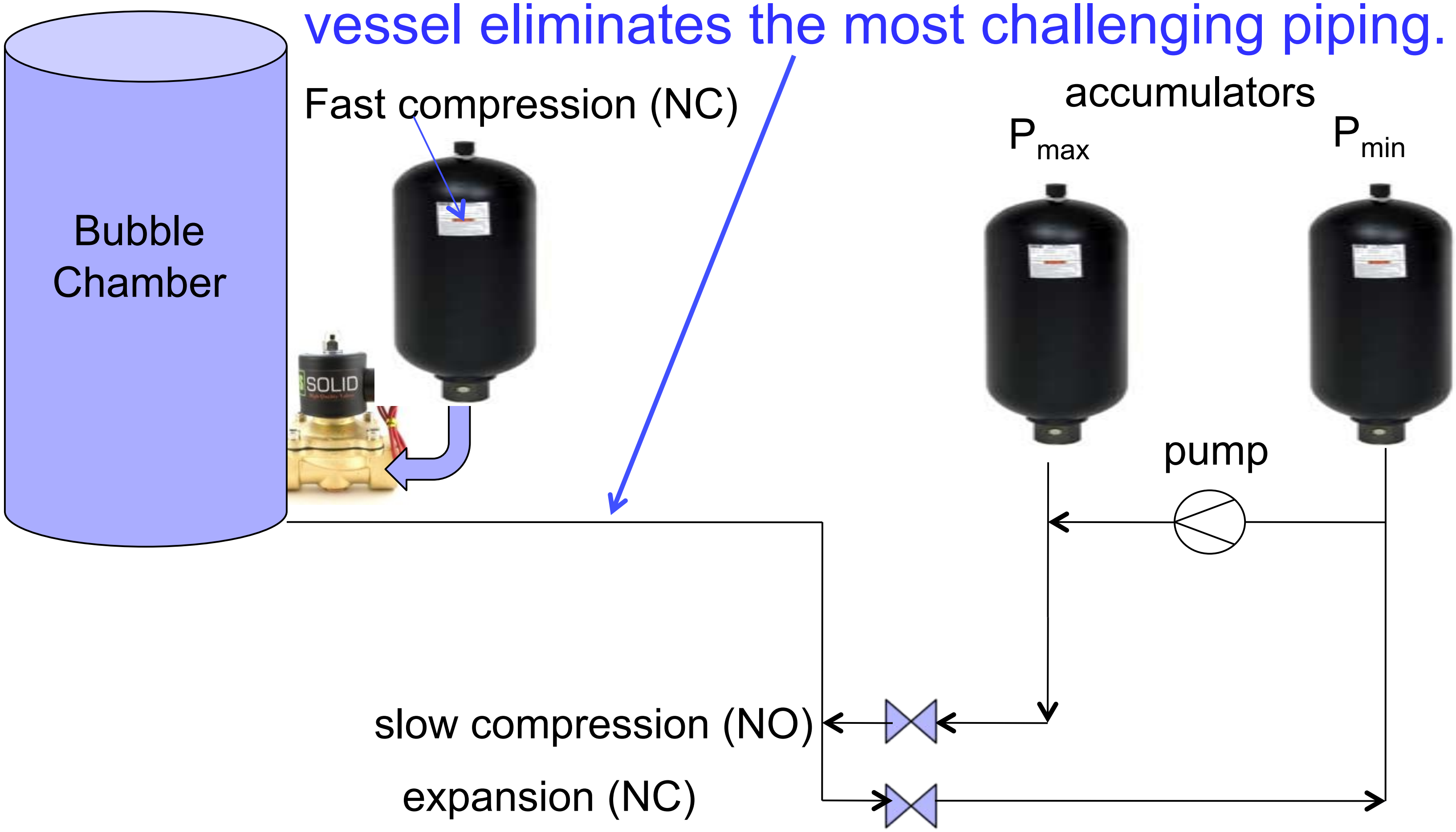
2-liter Hydraulic Cart

Hydraulic Cart Functional Diagram (simplified)



Hydraulic Cart Functional Diagram

Moving the fast compression to the pressure vessel eliminates the most challenging piping.

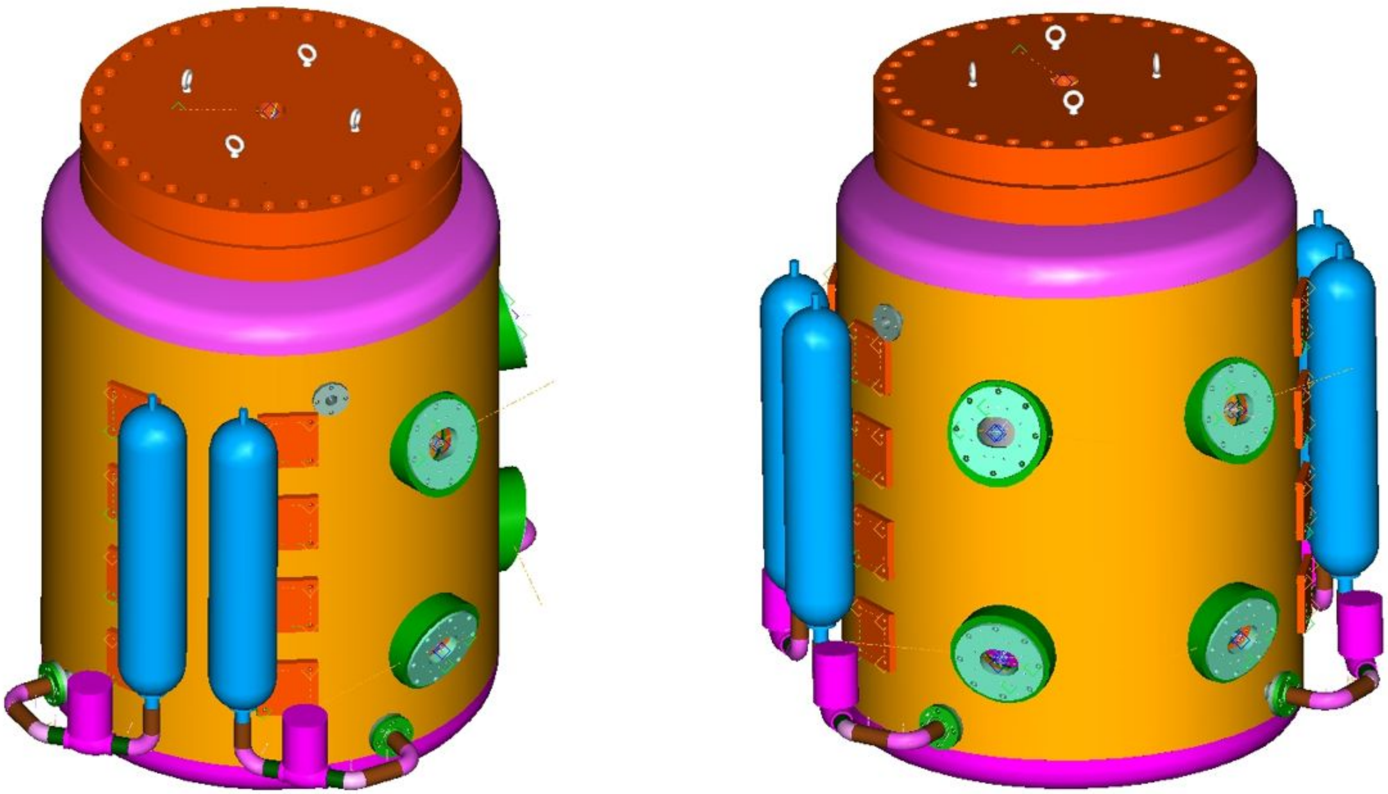


Choice of hydraulic fluid

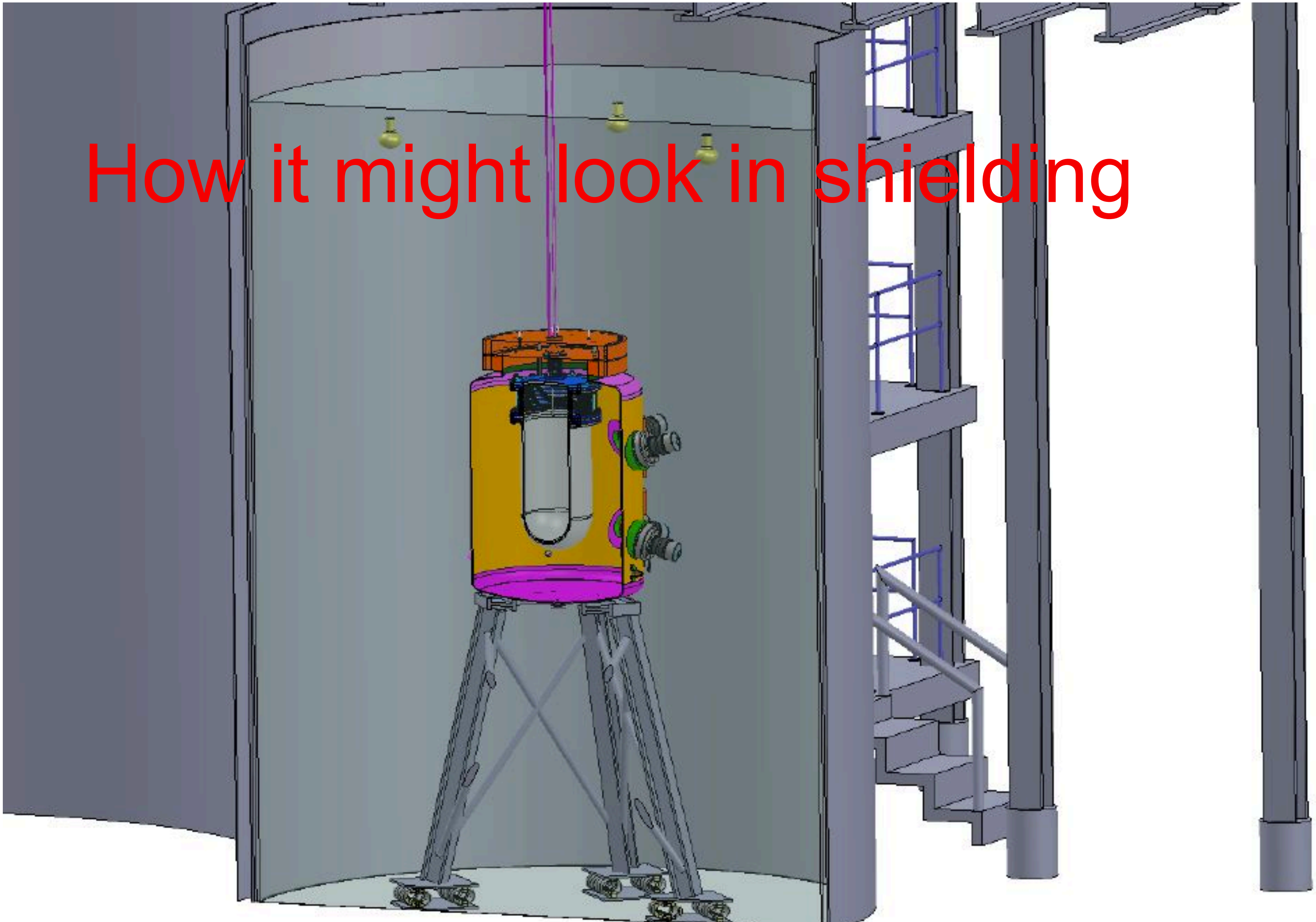
- Hydraulic Fluid serves as
  - Hydraulic fluid for compression
  - Optical medium for photography
- Low compressibility is desirable
- Index of refraction is a trade-off
  - High index matches silica & reduces reflections
  - Low index matches target fluid and reduces demagnification
- Should be environmentally acceptable

Choices:
mineral oil
propylene glycol
Water
glycerol

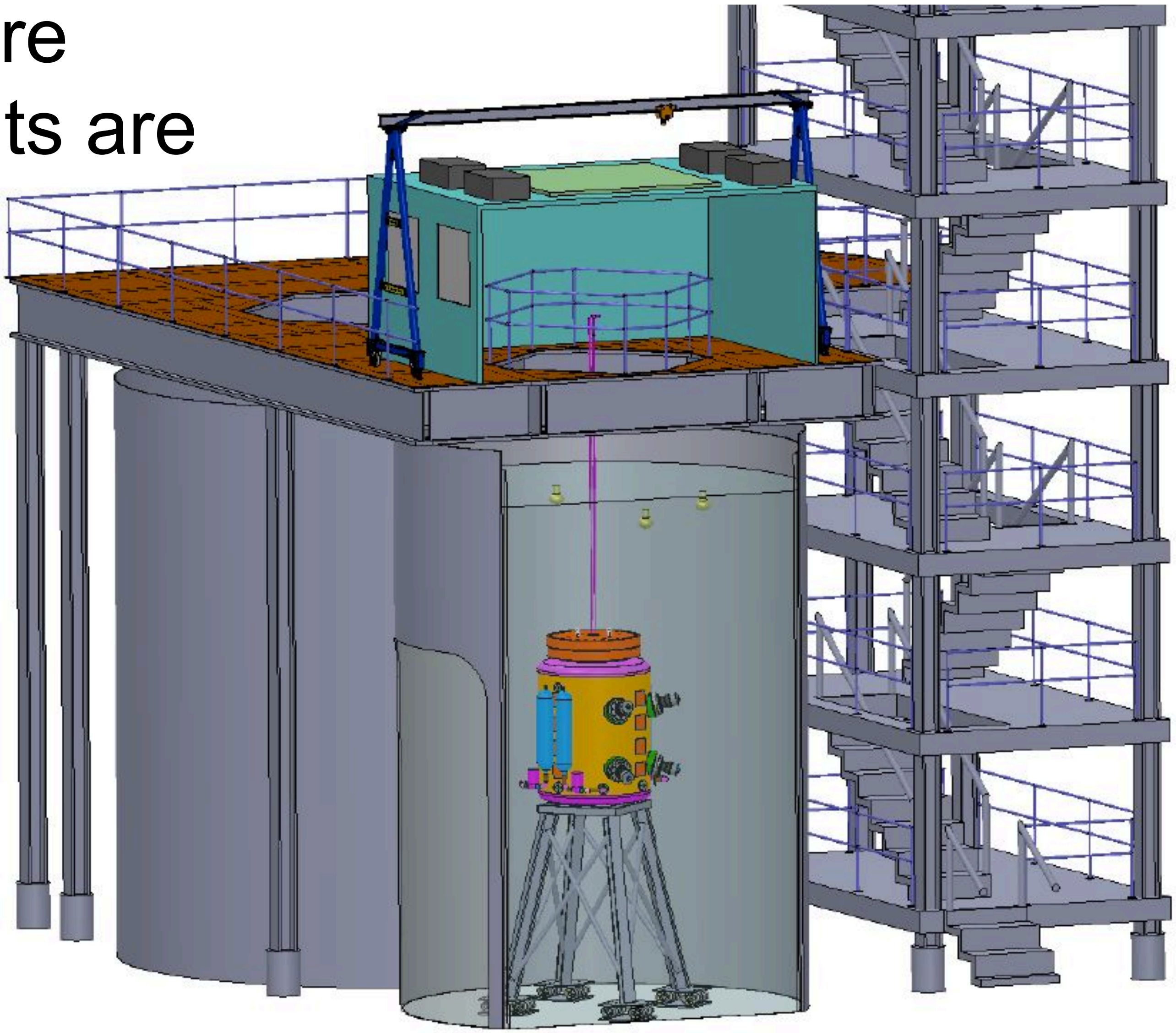
Pressure Vessel with integral fast compression



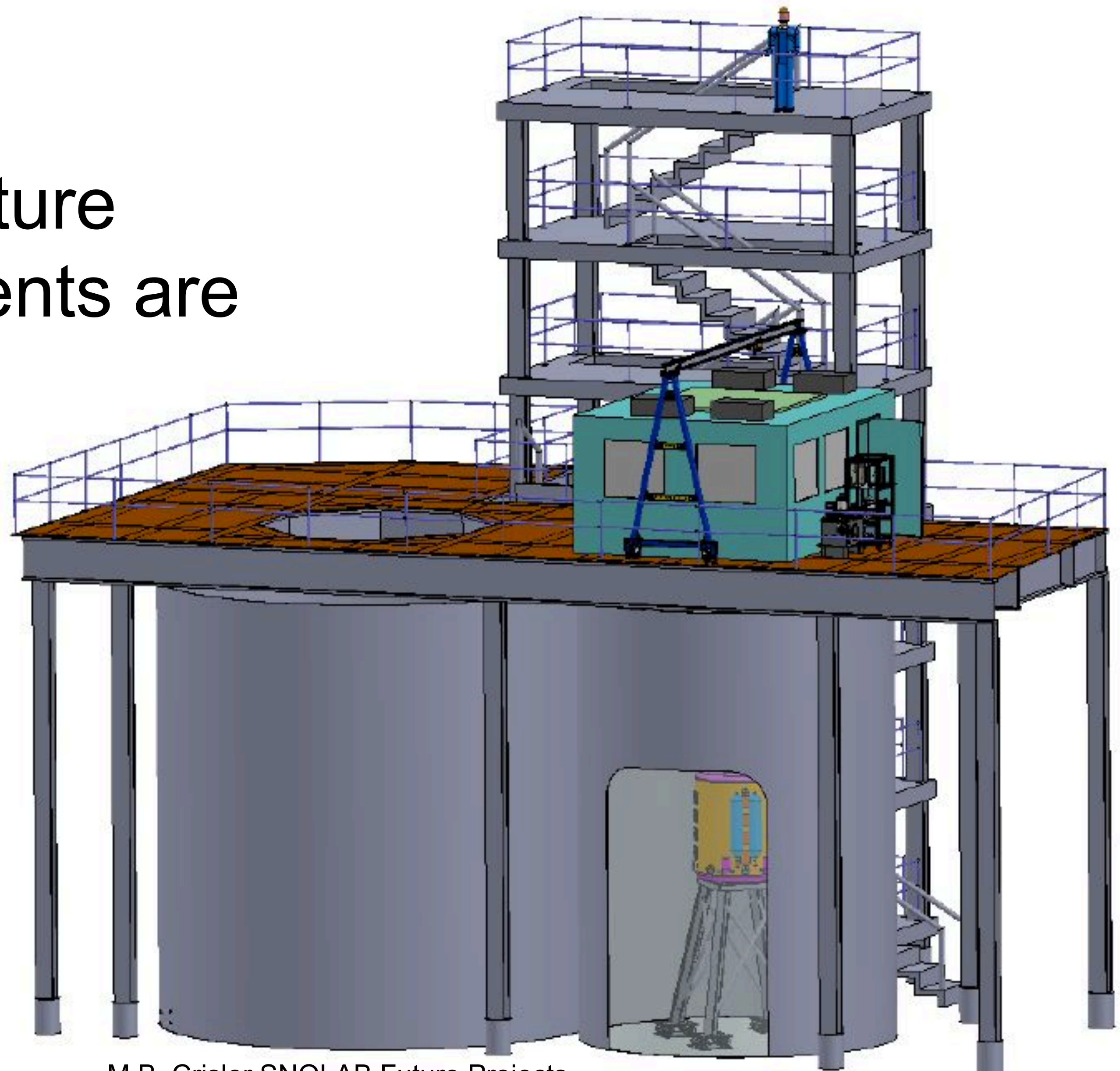
How it might look in shielding



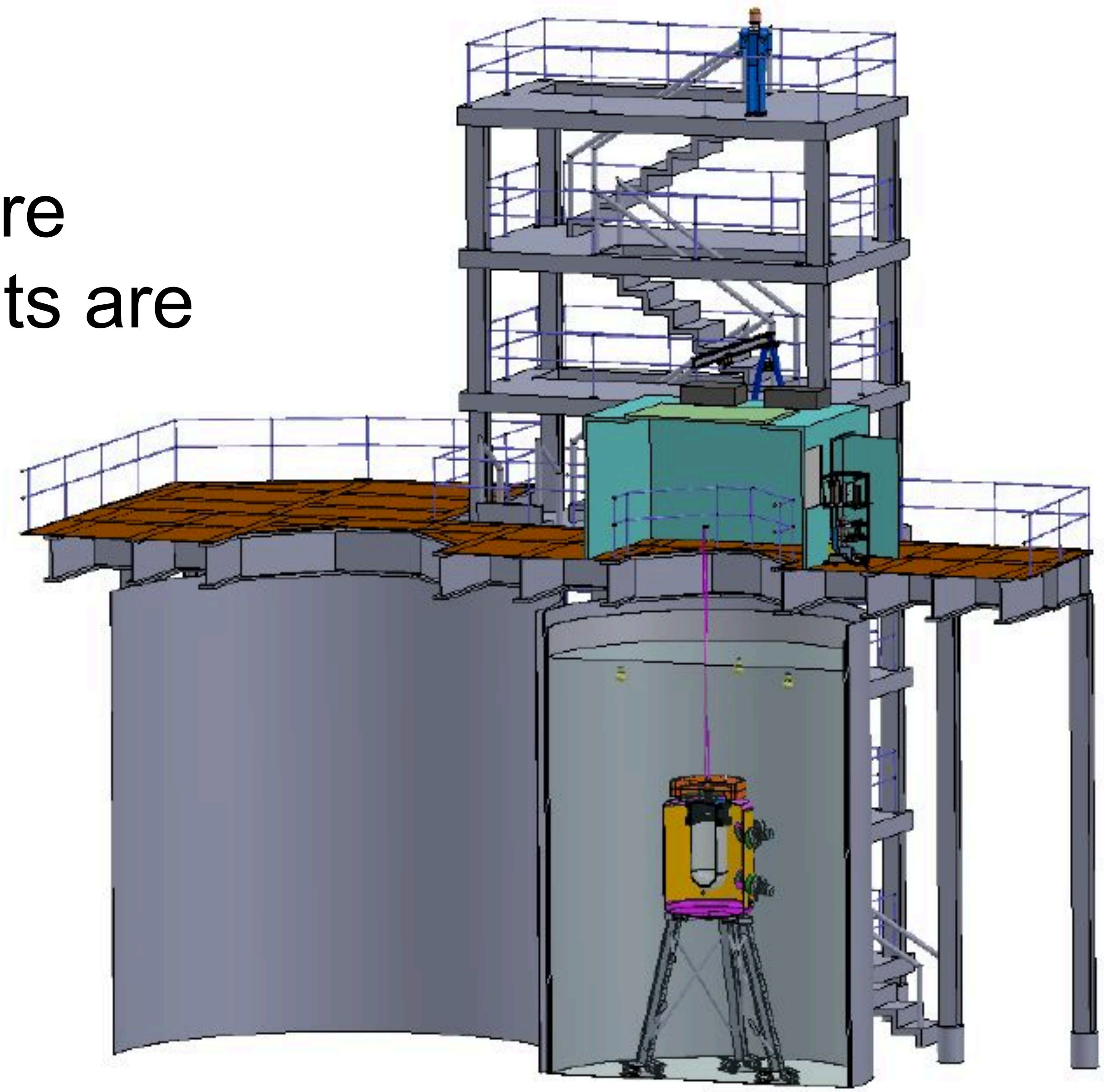
- Infrastructure requirements are modest:



- Infrastructure requirements are modest:



- Infrastructure requirements are modest:



COUPP-500 engineering to do:

- Thermal Control of large pressure vessel
  - Baseline model is to:
    - insulate the pressure vessel
    - Circulate the hydraulic fluid
    - Heat Exchanger and Pump integral to Pressure Vessel Body
- Mechanical handling fixtures
  - Fixtures for cleaning, handling, and assy of IV.
- Site Specific Engineering

Expectations for FY13

- First Results from COUPP-60 (CF_3I)
- First Results from PICO-2L (C_3F_8)
- Complete Baseline Engineering Design of PICO-250L (the bubble chamber and its auxiliary equipment, not necessarily the site-specific infrastructure at SNOLAB.)
- Complete R&D on C_3F_8 characterization

Nominal FY14-FY15 construction

	FY 12	FY13	FY14	FY15	**Total**
DOE					
Design, eng. & tech. supp.		1297	575	575	**2447**
Equipment			425	425	**850**
Fabrication			850	850	**1700**
NSF					
Research	143	937	920	946	**2946**
R&D	600	250			**850**
Construction		378	623	501	**1502**