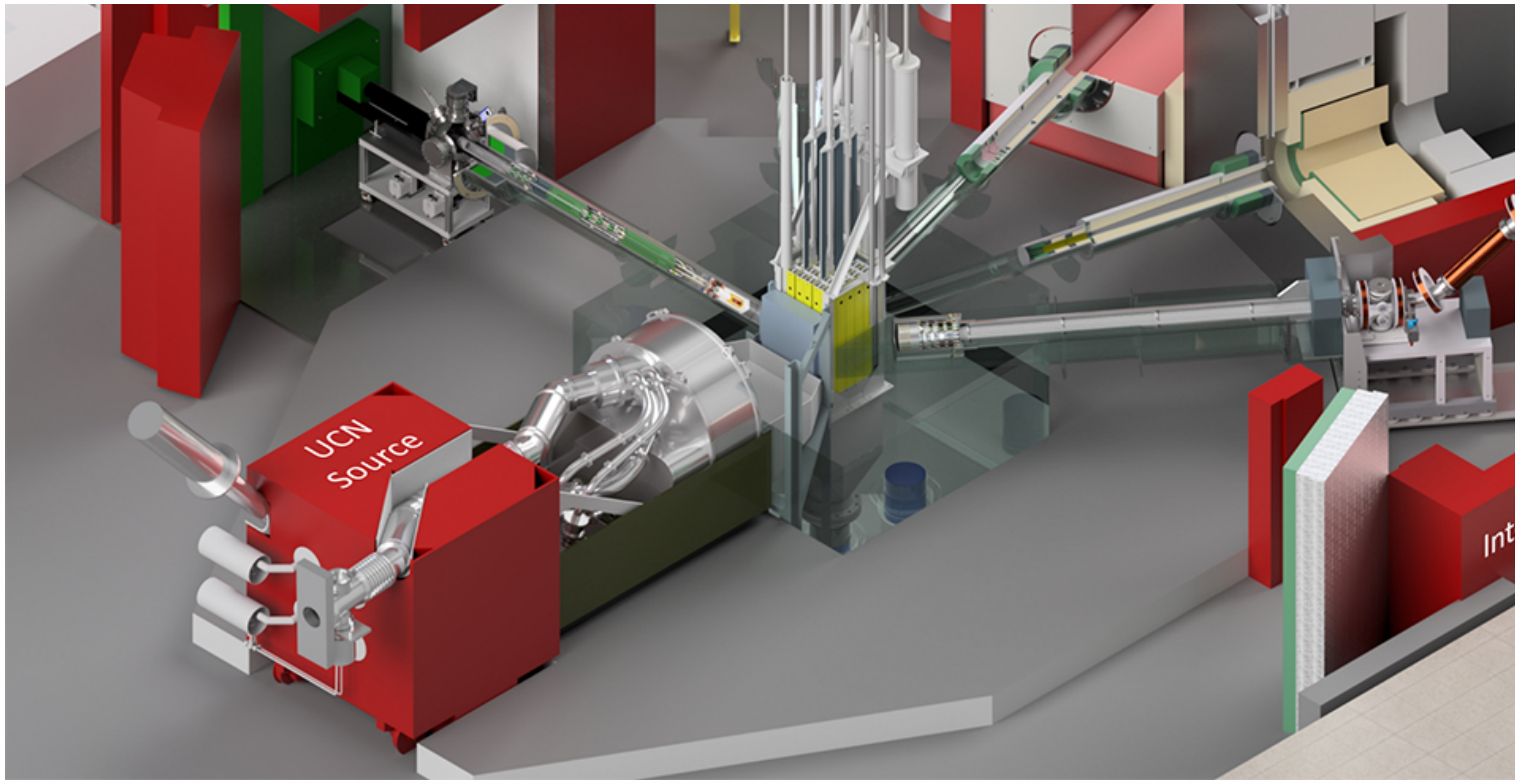
# UCN source at PULSTAR reactor

***E. Korobkina***

*B. Wehring, G. Medlin, A. Hawari, A. Young, P. Huffman, R. Golub, C. Teander, K. Kaake, T. Rao, I. Berkutov, M. Morano, C. Hickman, K. Leung, G. Palmquist*

***NC State University, USA***



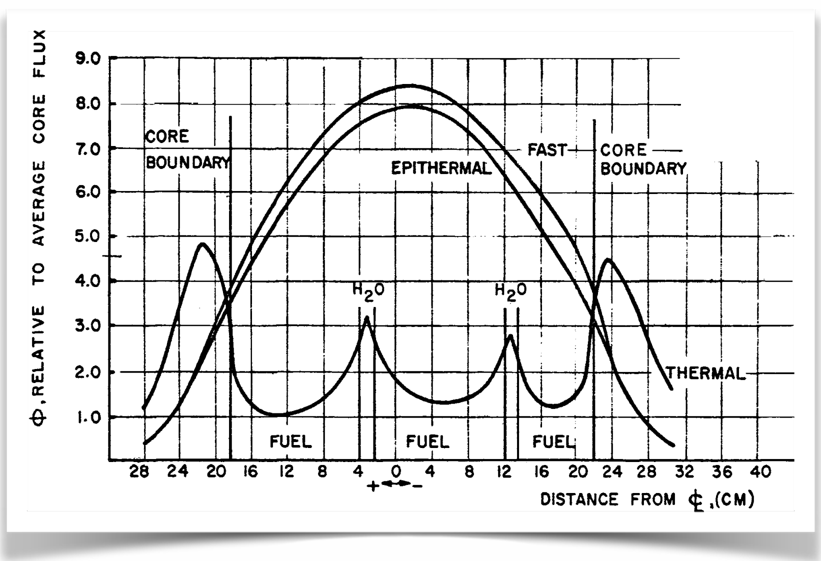
# PULSTAR 1 MW reactor at NCSU campus

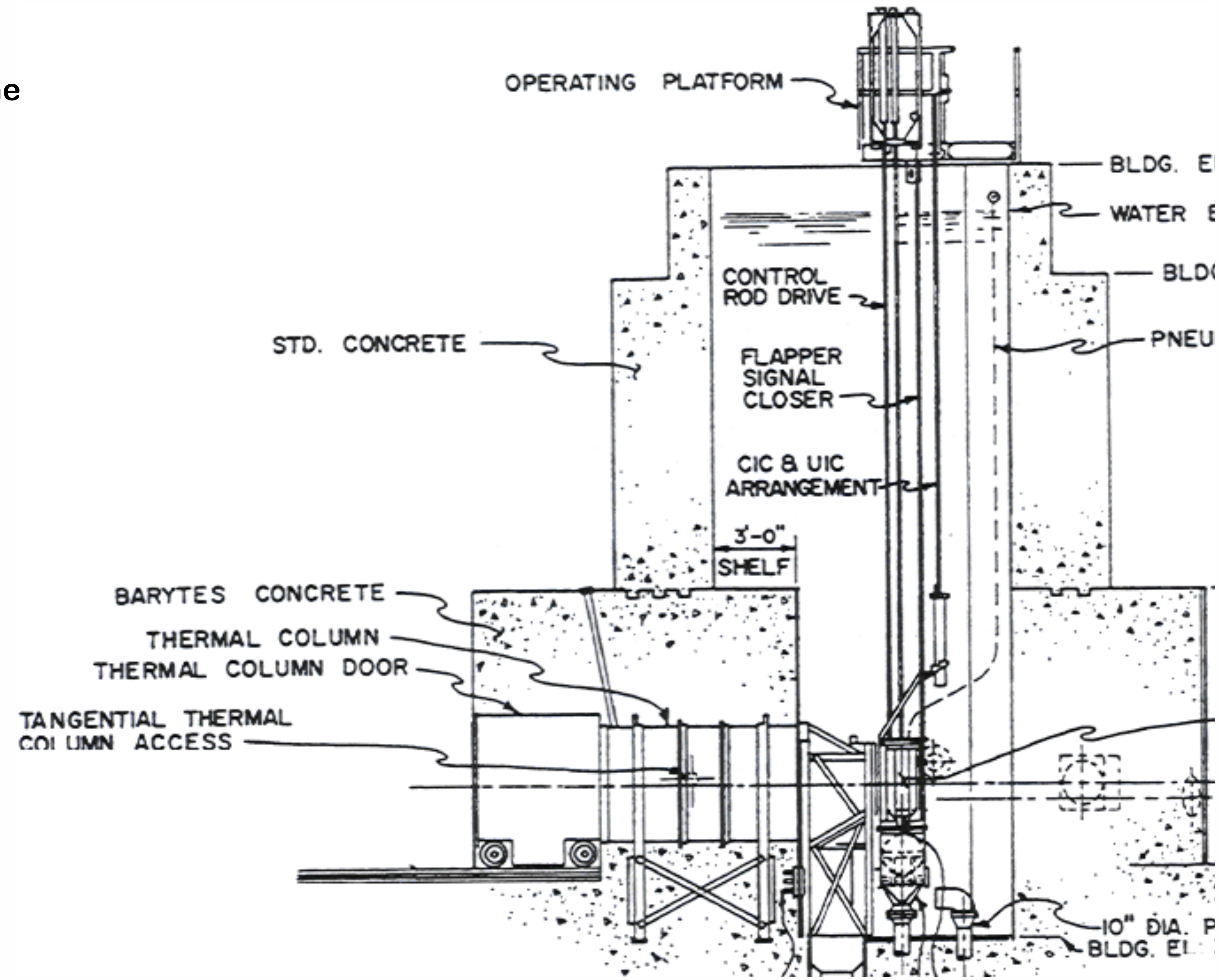
**Properties**

- **Heavy loading of U-235 -- 12.5 kg**
- **Low ratio of H to U-235 atoms**
- **High ratio of fast to thermal flux in the core**

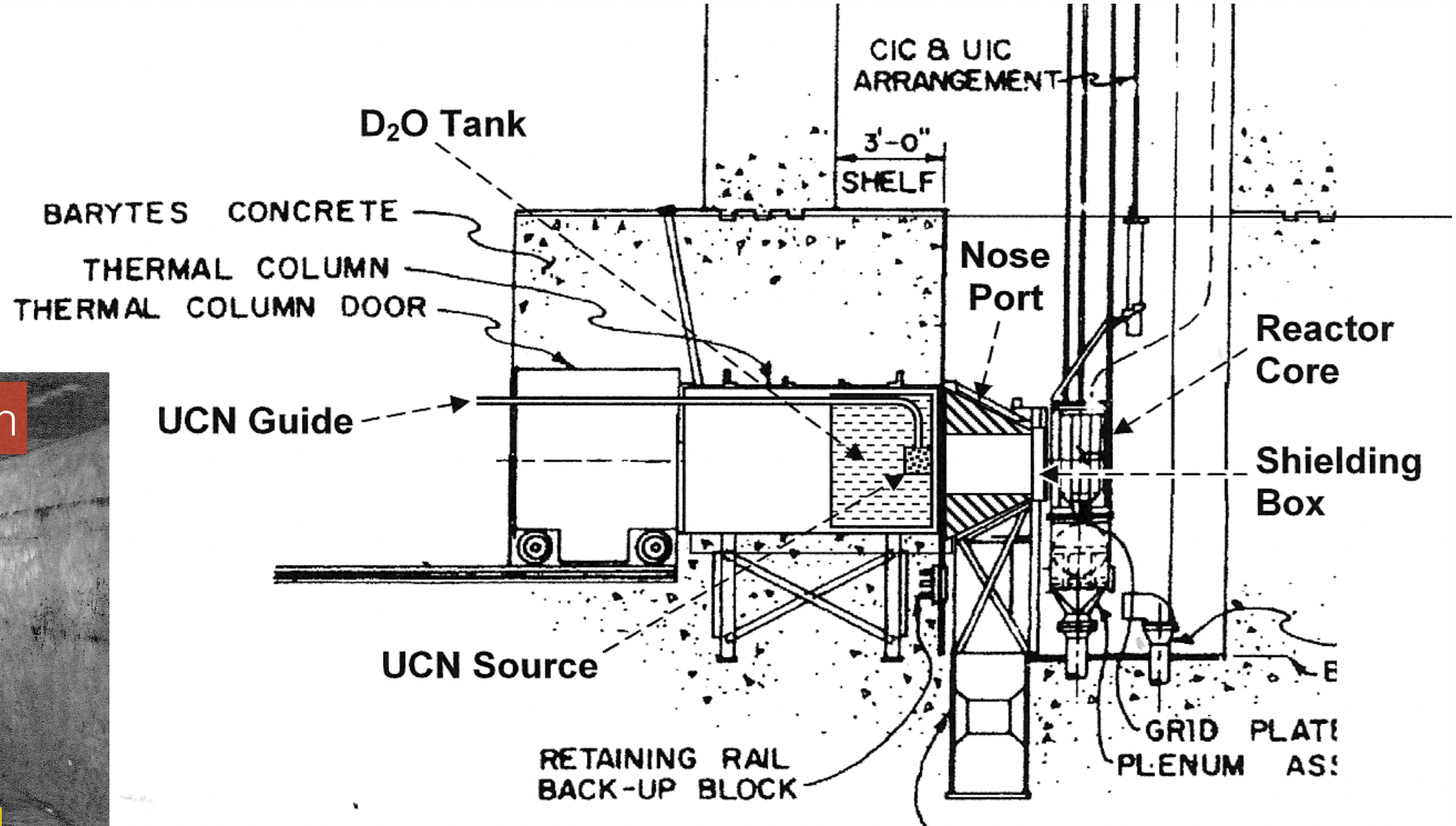
**Benefits**

- **Long core lifetime**
- **High sensitivity to reflector material**
- **High fast-flux leakage**



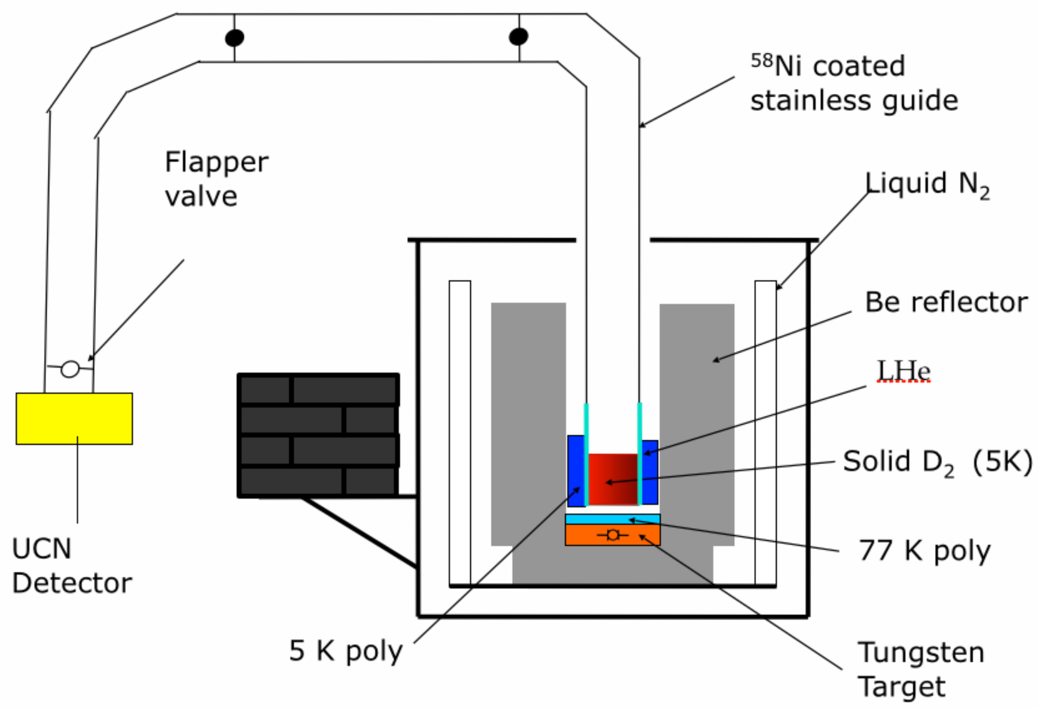
# Conceptual design

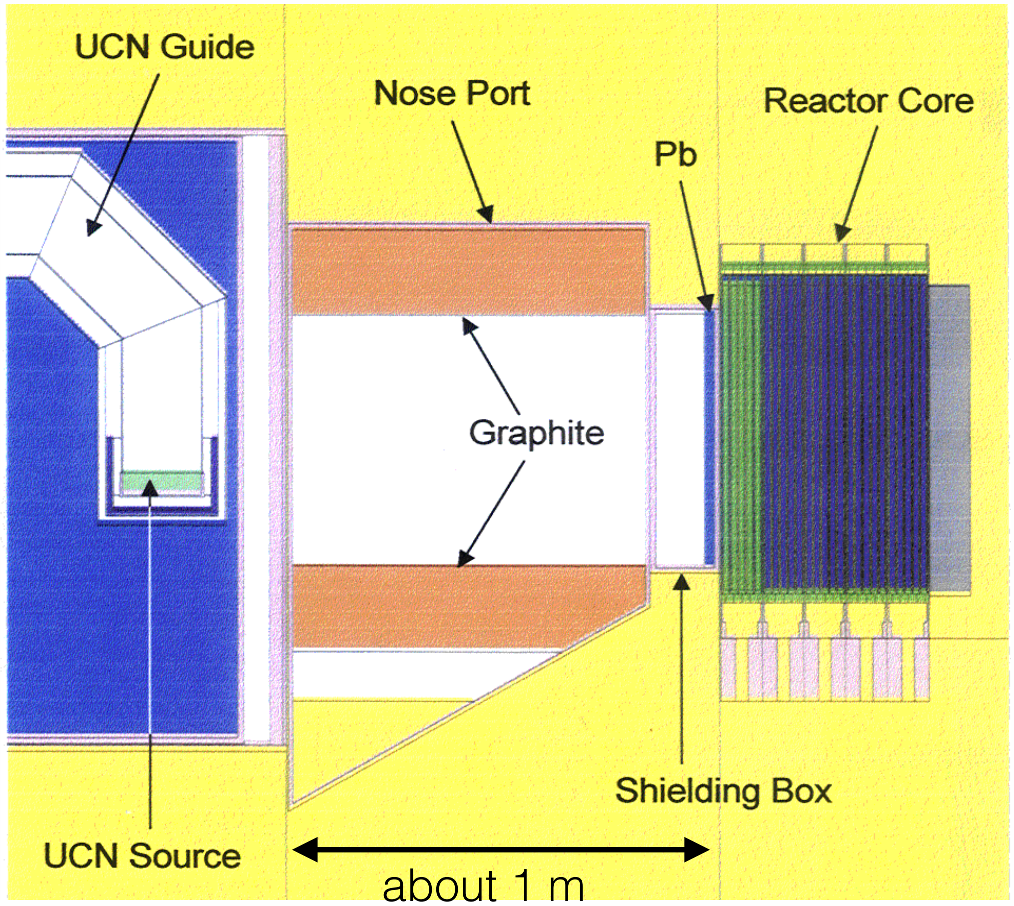

The end wall consists of 2-in. x 3/8-in. webbing, 1-in. thick sheet, and 1/4-in. thick pool liner, all 6061 aluminum.

# Conceptual neutronic design

LANL pulsed prototype source:
- proton+tungsten as a neutron source
- Be reflector
- 5K & 77K Poly as pre-moderators
- D2 crystal grown from vapor
- 120 UCN/cc in horizontal guide measured
- Ni-58 coated Stainless steel
- LHe dewar

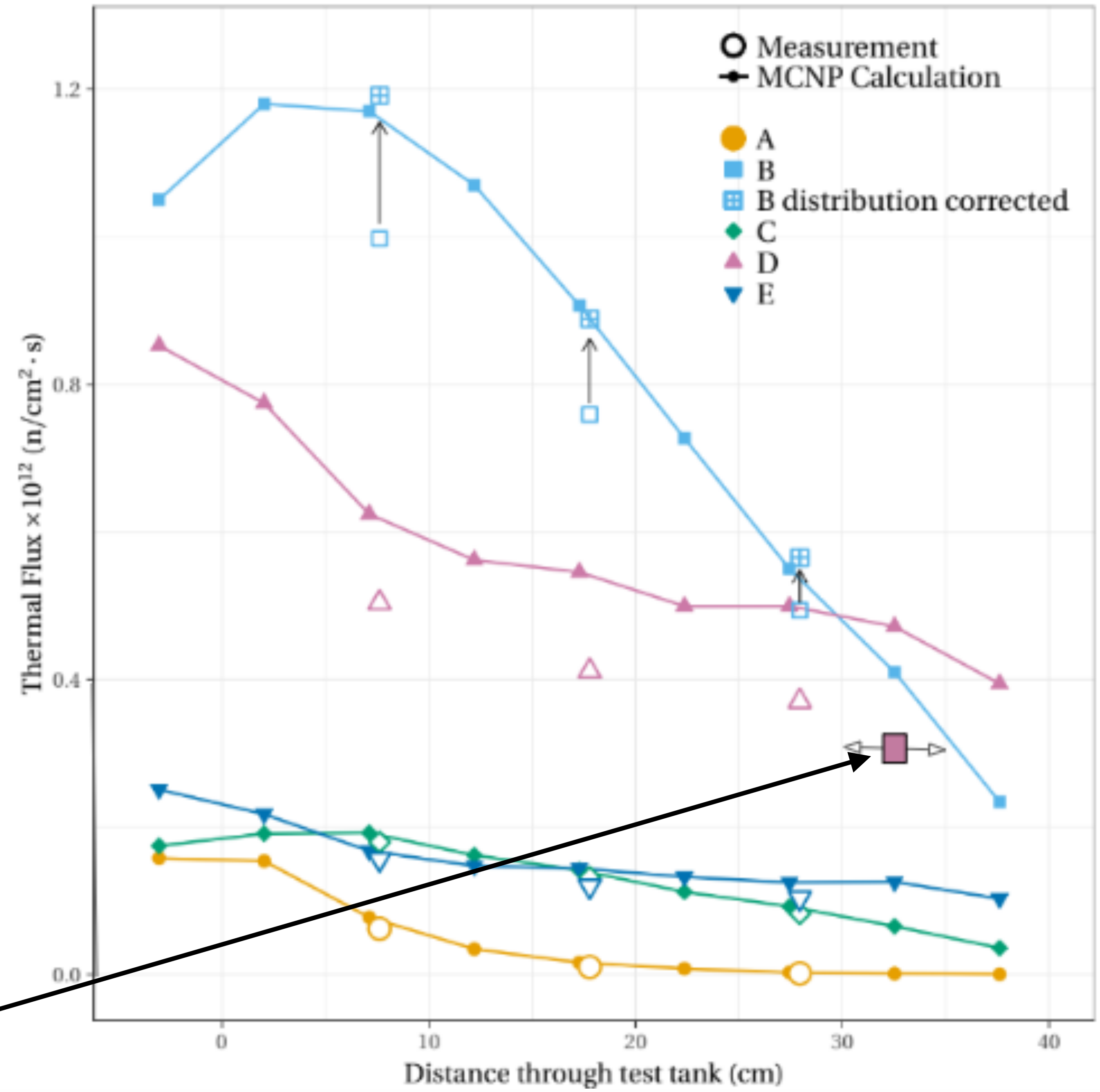



PULSTAR conceptual design (2005)
- reactor as a neutron source
- Graphite reflector
- D2O (300K) and solid methane (~40K) as pre-moderators
- D2 crystal can be grown from vapor
- ~ 30 UCN/cc at the exit port predicted
- Ni-58 coated Aluminum and Quartz
- flow of LHe



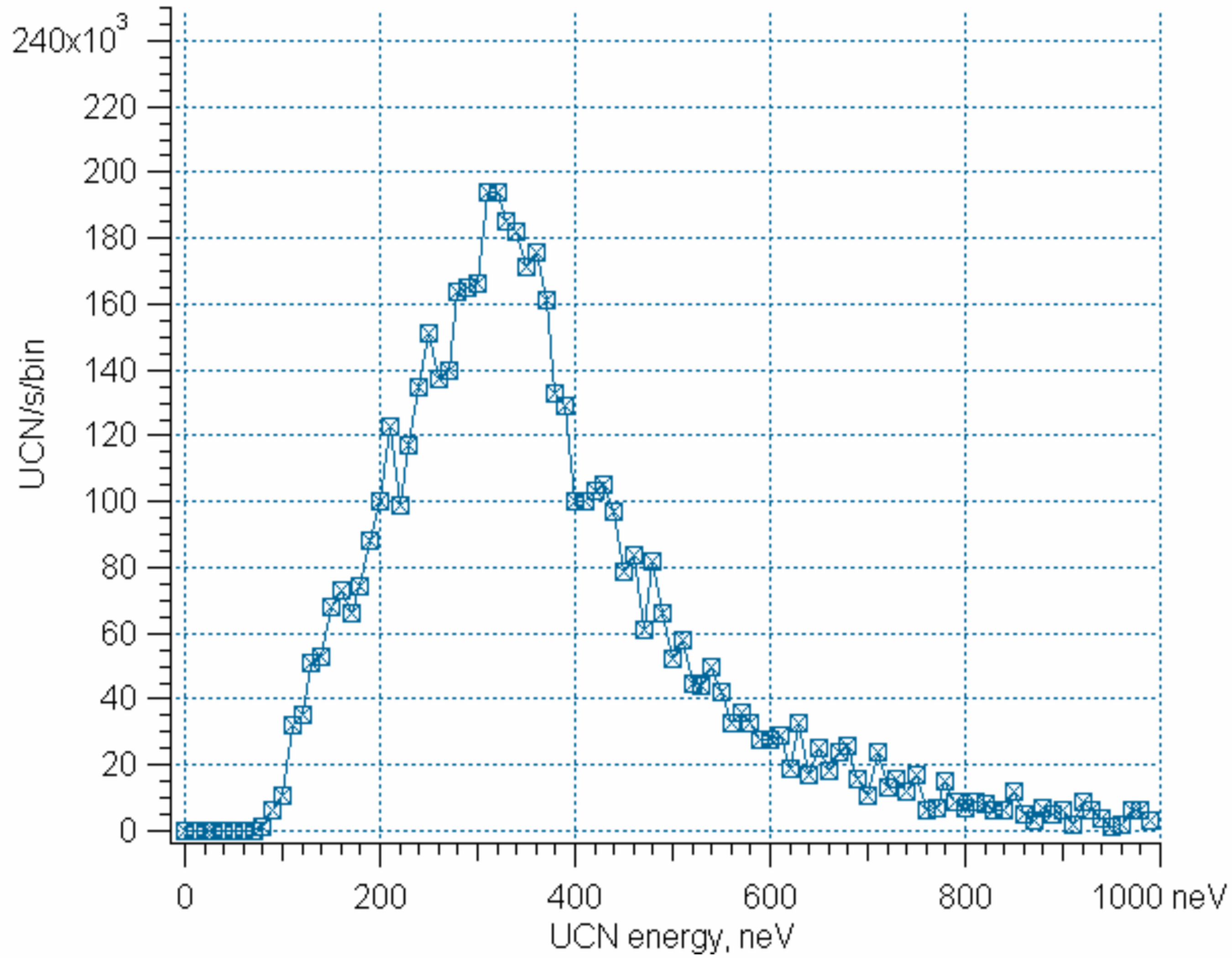
# Thermal flux

- Moderated Thermal flux was simulated using MCNP
- In 2010 the MCNP results were benchmarked using gold foils located in the test tank filled with D2O
- In Dec 2023 we verified the thermal flux with gold foils in the real UCN source

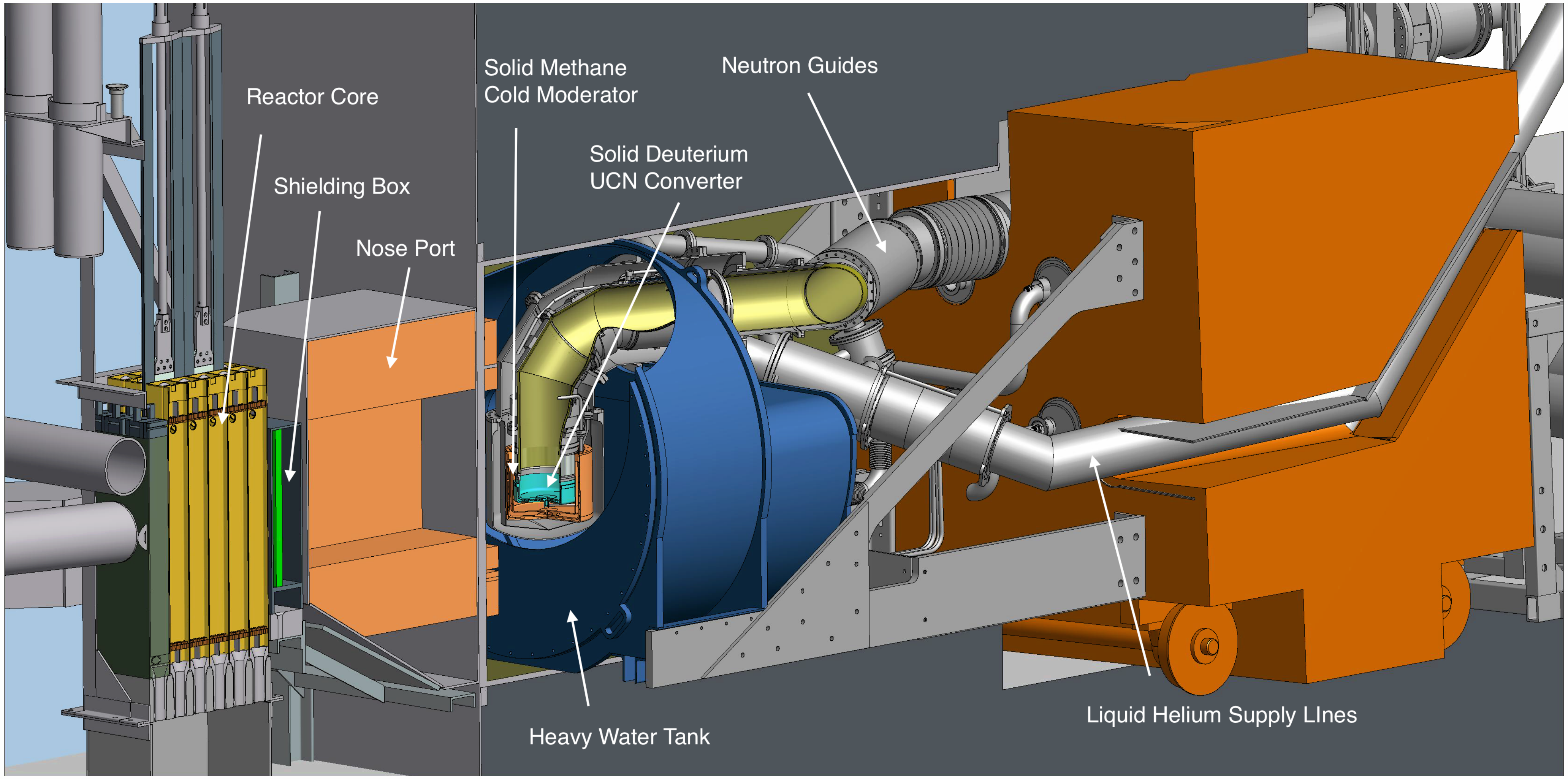


# Neutronic design results

- ~ $2.5x10^{11}$ n/cm2/s CN Flux in Deuterium
- ~$0.8x10^4$ $n/cm^3/s$ UCN Production rate
- ~250 $UCN/cm^3$ Limiting Density inside SD2, $N=P\tau$
- ~ 30 UCN/cm3 Density at the exit port

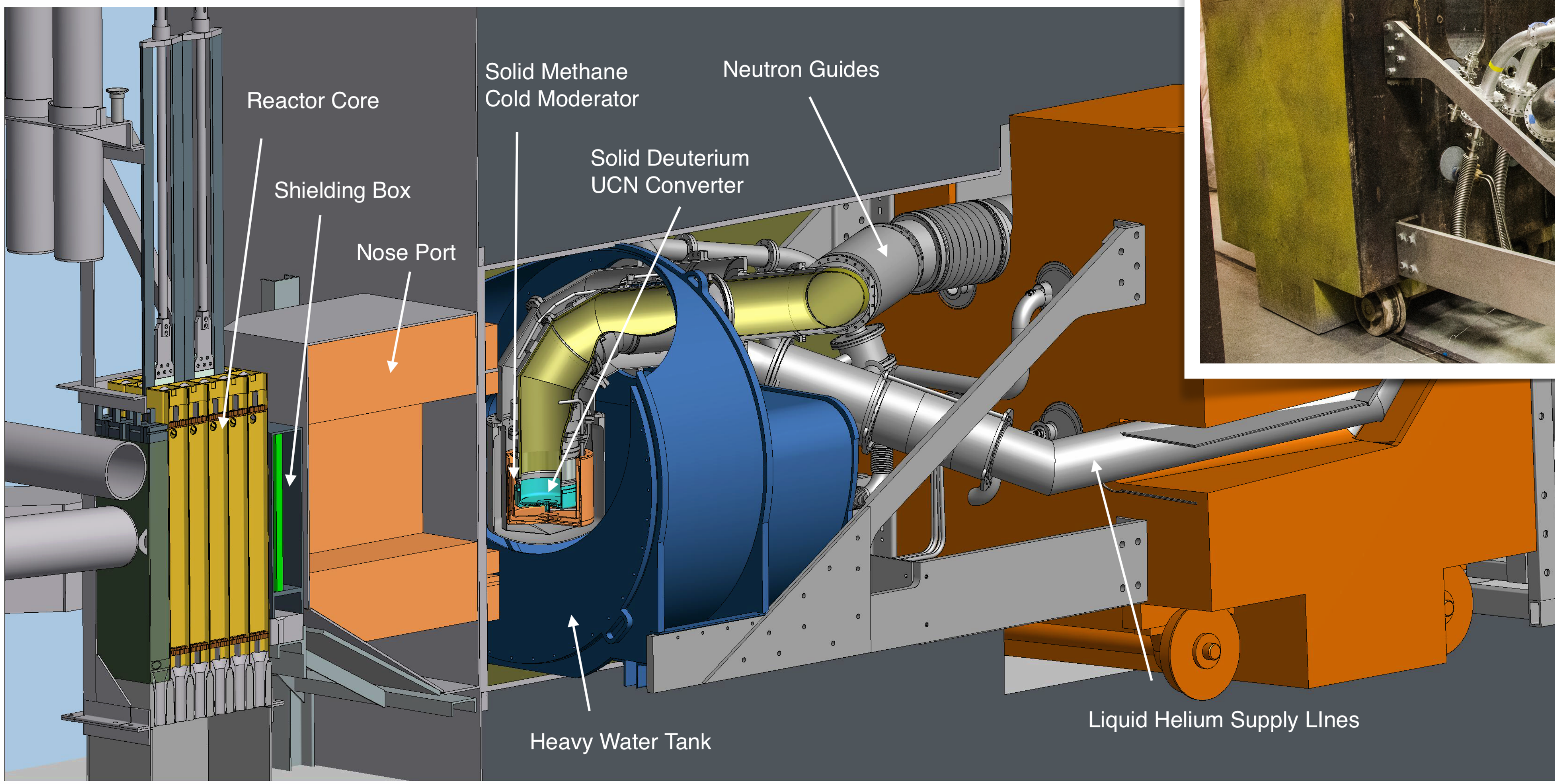


# Engineering design




- Nose post/shielding box with He gas handling system
- Heavy water tanks and circulation system
- Methane gas handling system
- Deuterium gas handling system
- LHe plant and cooling loops
- UCN source cryostat and UCN guides

# Engineering design

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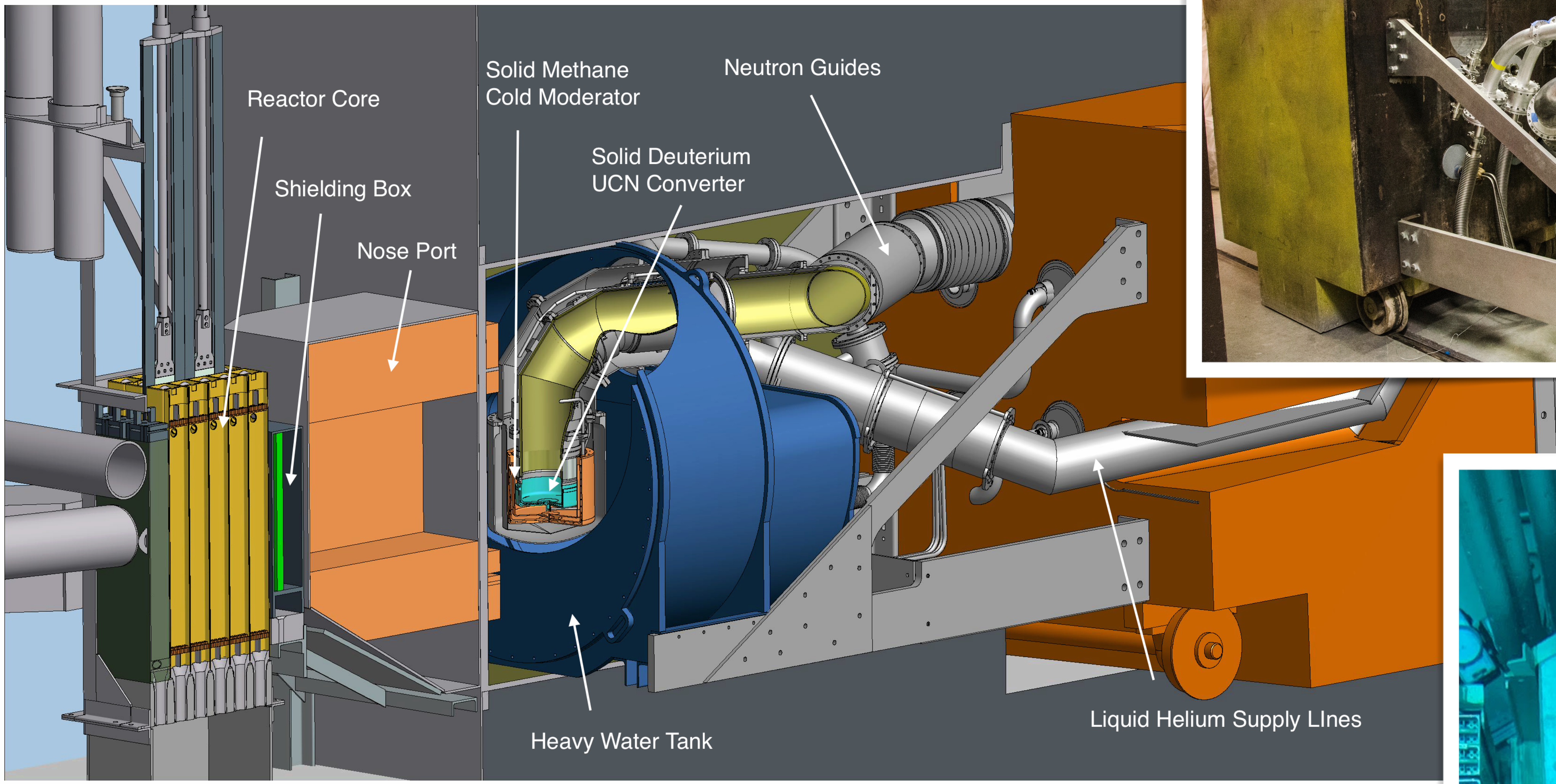


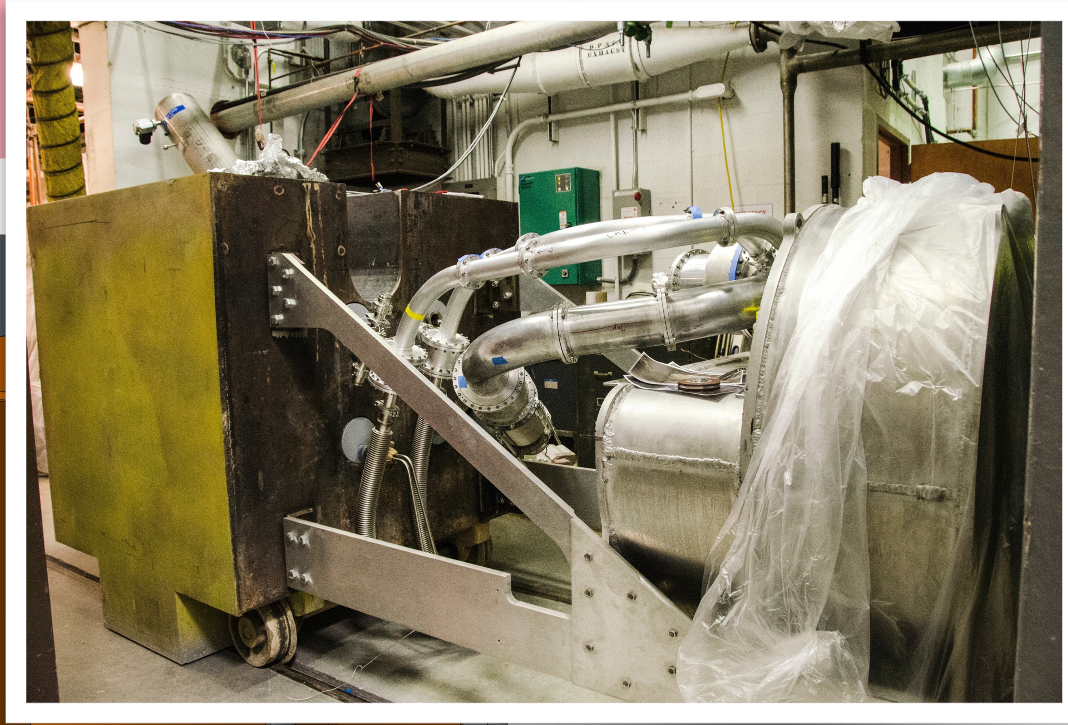

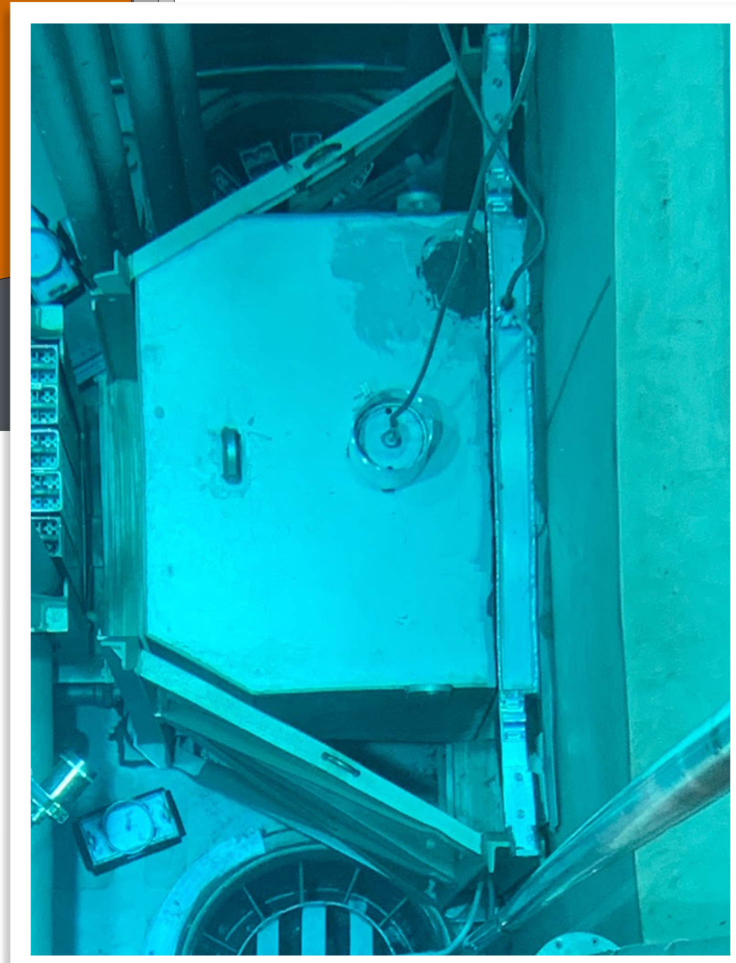

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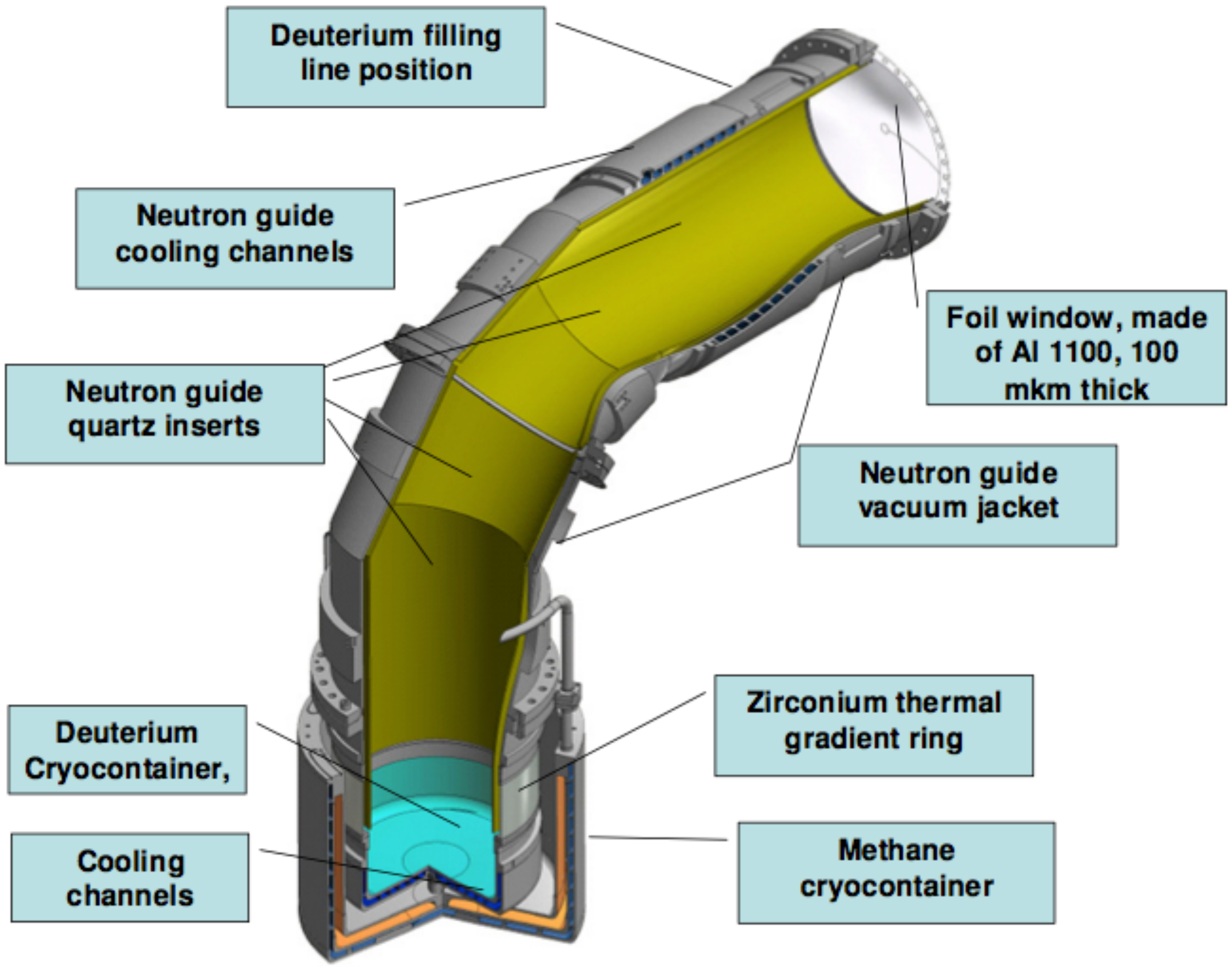
# UCN source cryostat design

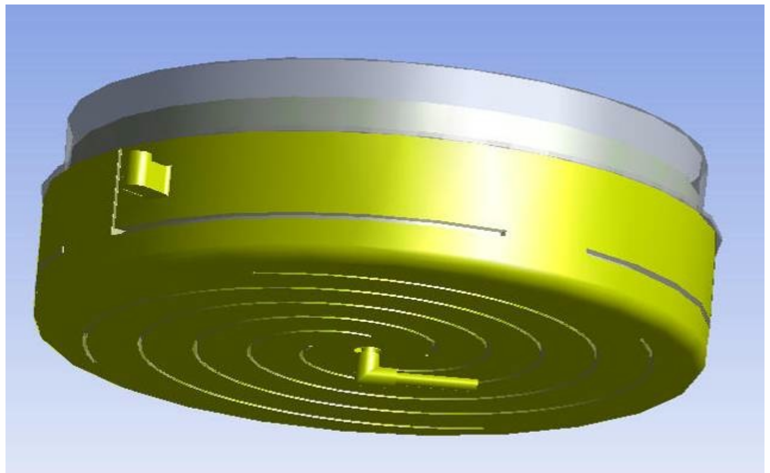


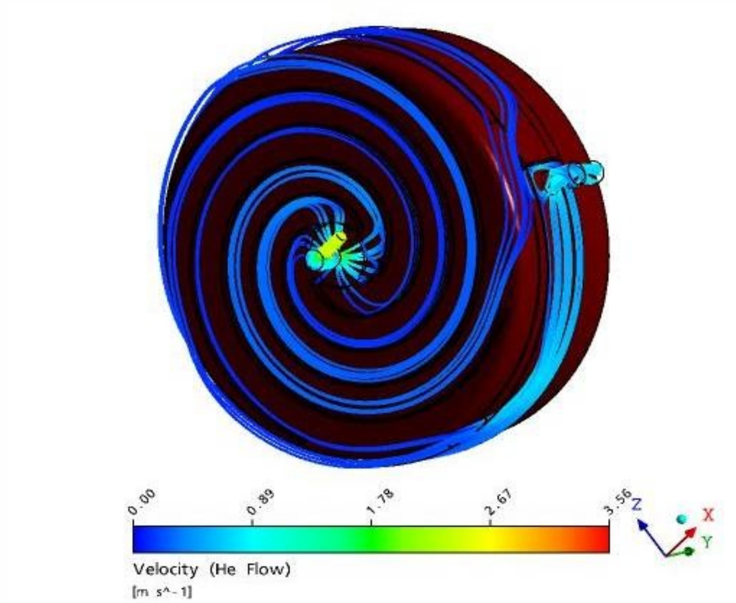

- All materials has to be neutron friendly
  - Low capture cross section
  - Negligible long life time activation
  - Radiation resistant – no plastics, no elastomer seals
- We need cryogenic materials with good and very poor thermal conductivity
- Choice of materials:
  - Aluminium – Al6061 as structural and 1100 as a good conductor
  - Titanium – Ti6Al4V as thermal isolator
  - Zirconium – Zircaloy IV as thermal isolator
- Al window is a pressure relief device, tested to rupture at 2.9 bar

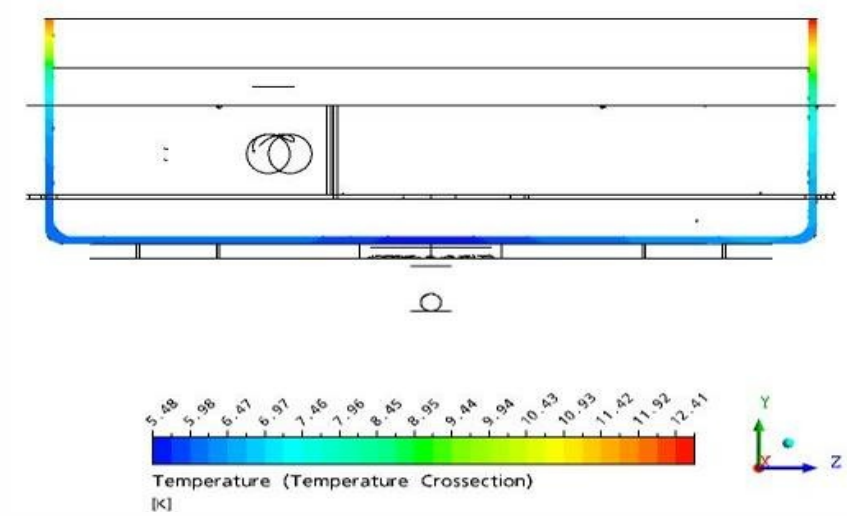
# Design heat loads at 1 MW reactor power

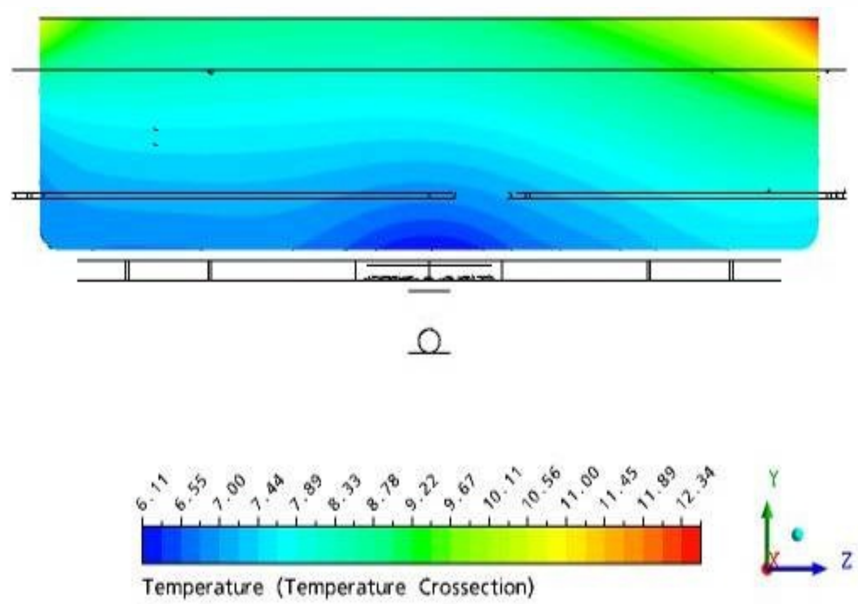
| | Heat load, W | flow, g/s | Operational T, K |
|---|---|---|---|
| **D2 container** | 10 | 0.3 | 5 |
| **CH4 container** | 10 | 0.05 | 45-60 |
| **CH4 container Black Body** | 35 | 0.05 | 100 |
| **Neutron guide** | 26 | 0.1 | 50 |

# Deuterium container design



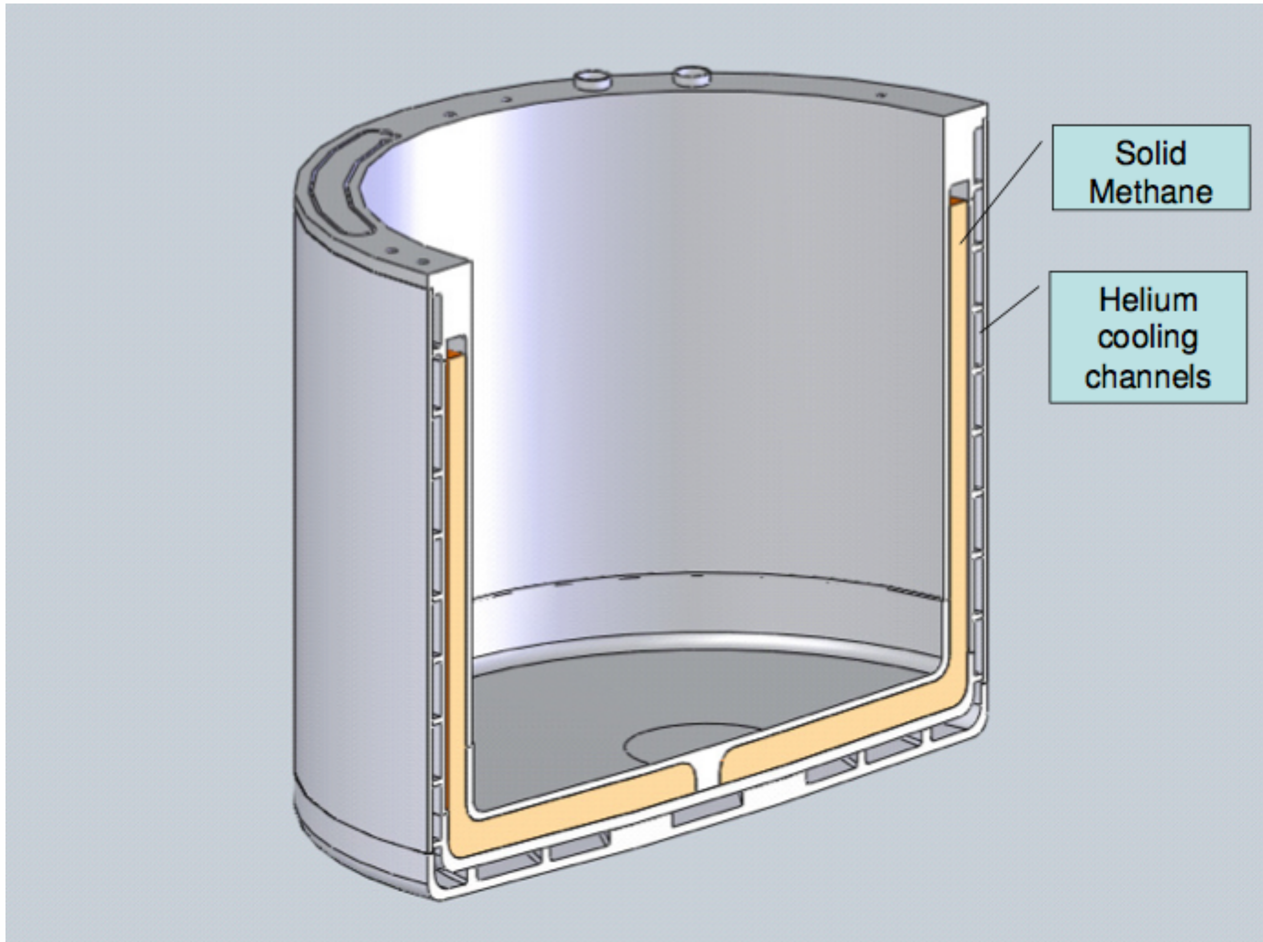


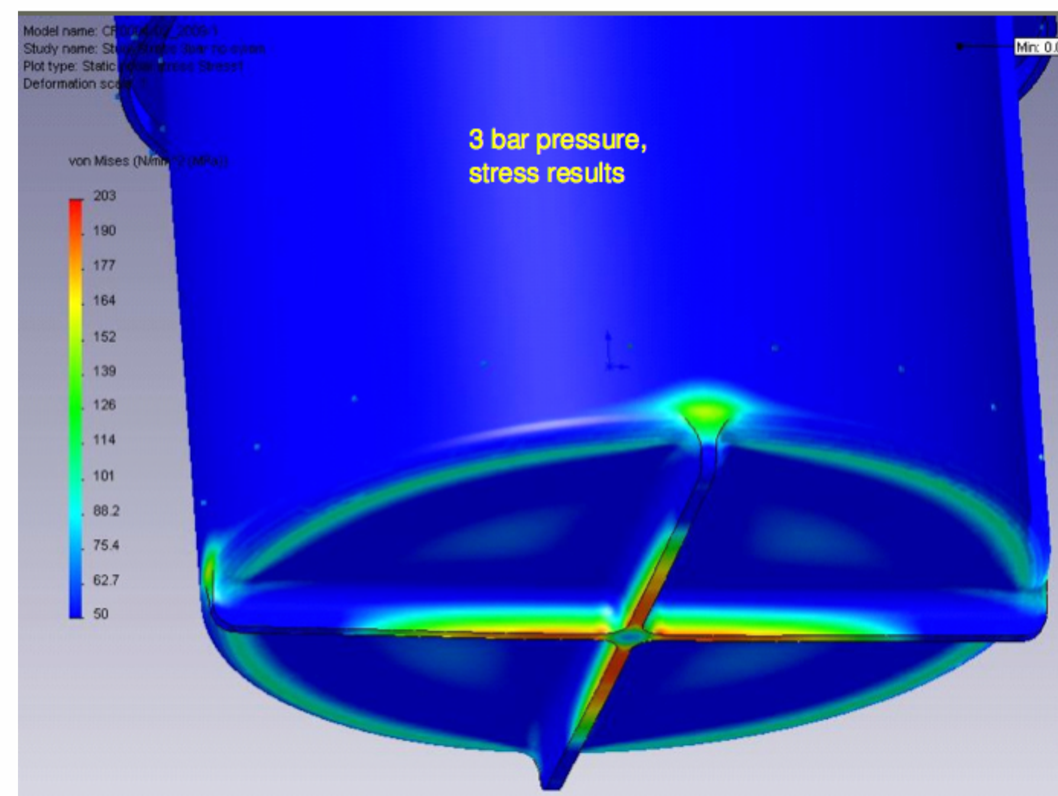




200g of SD2; 1.35kg of Al,   total nuclear heat  1+2.5 W

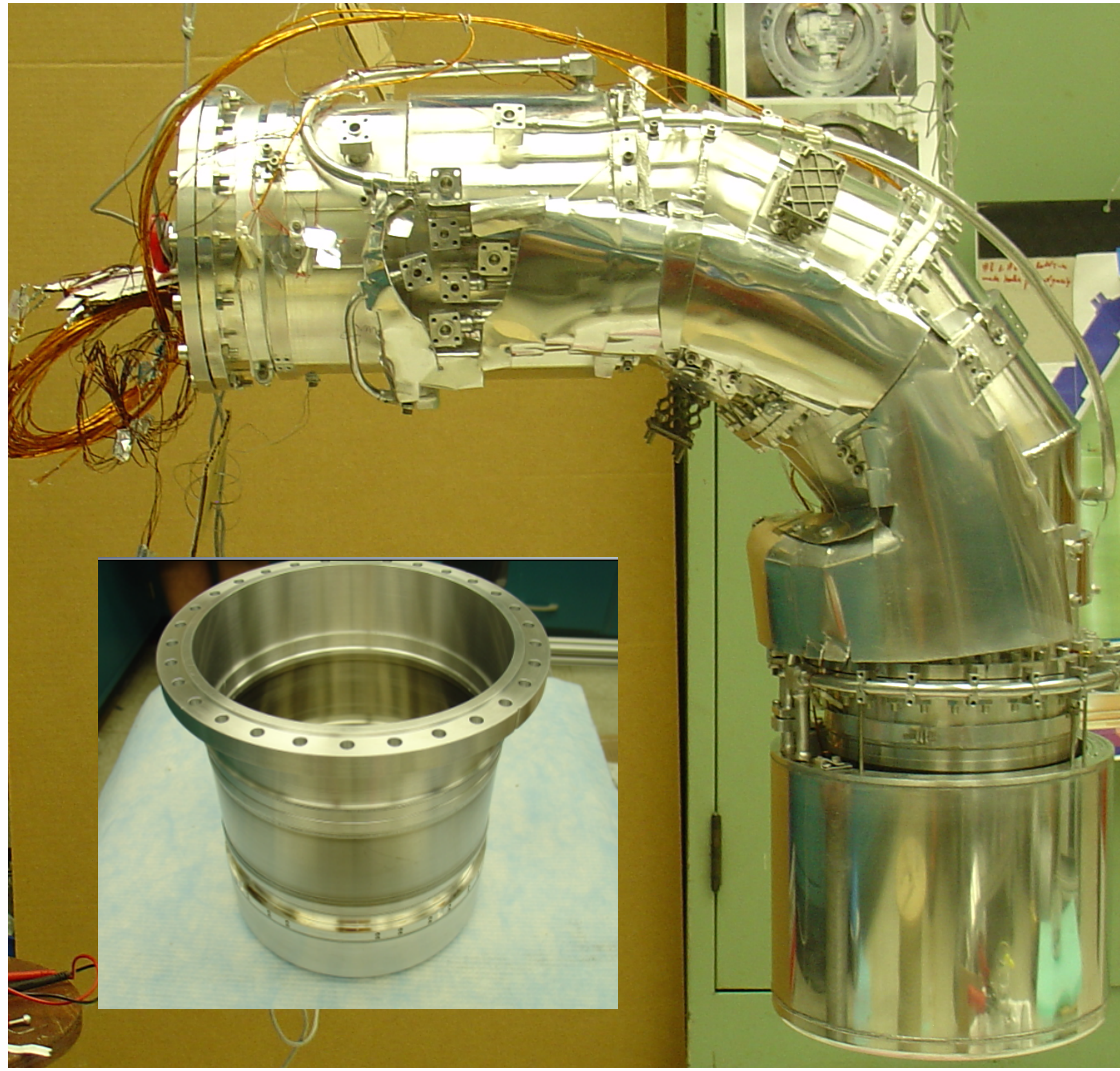
# Methane container design




- methane volume 1.4 liters
- mass 680 g
- container mass 2.35 kg of AL
- total nuclear heat 4.3 +2.8=8.1 W
- Can withstand 3 bar internal pressure



# Engineering challengies: Cryostat design



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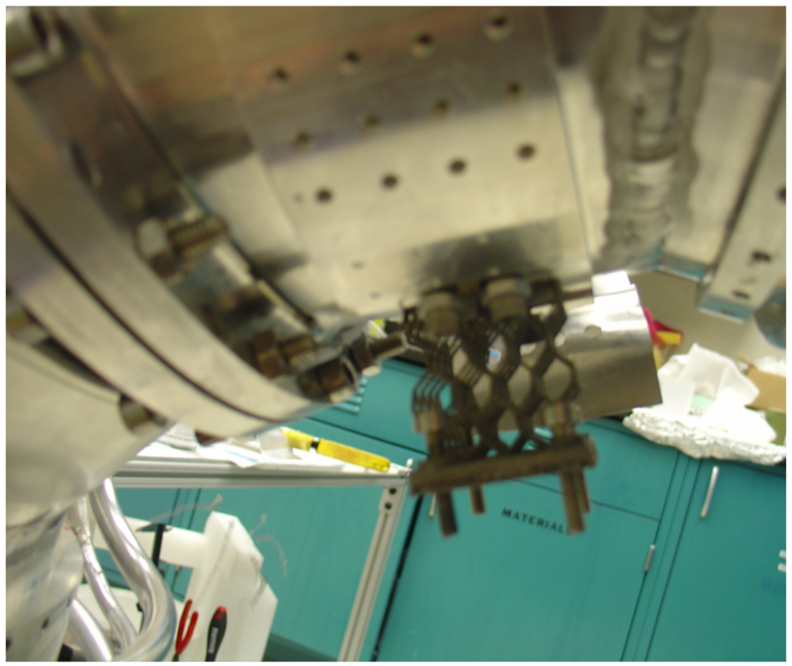
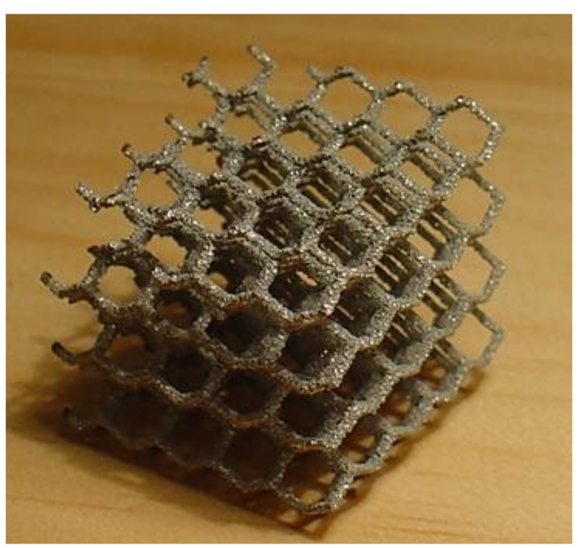
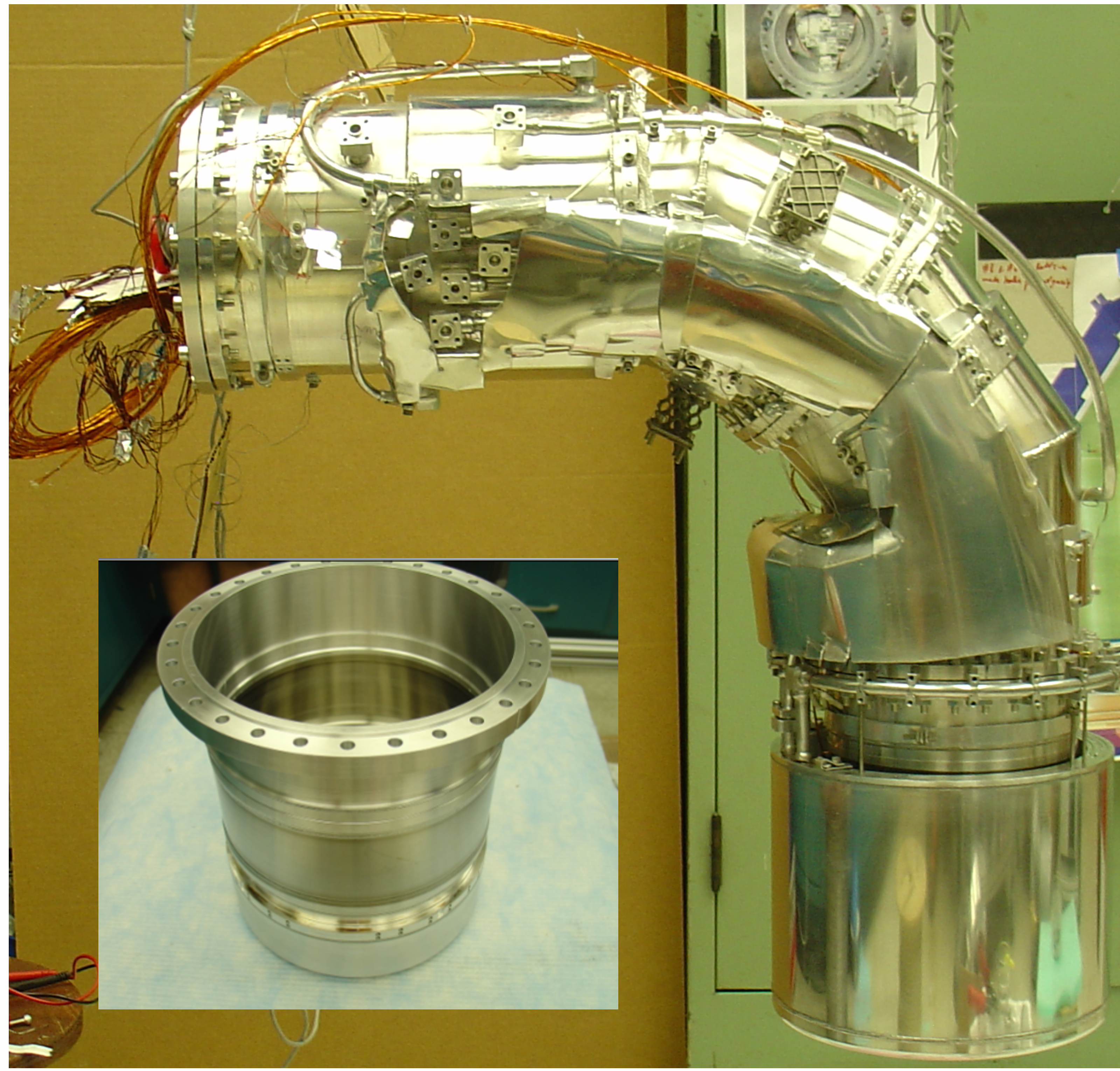






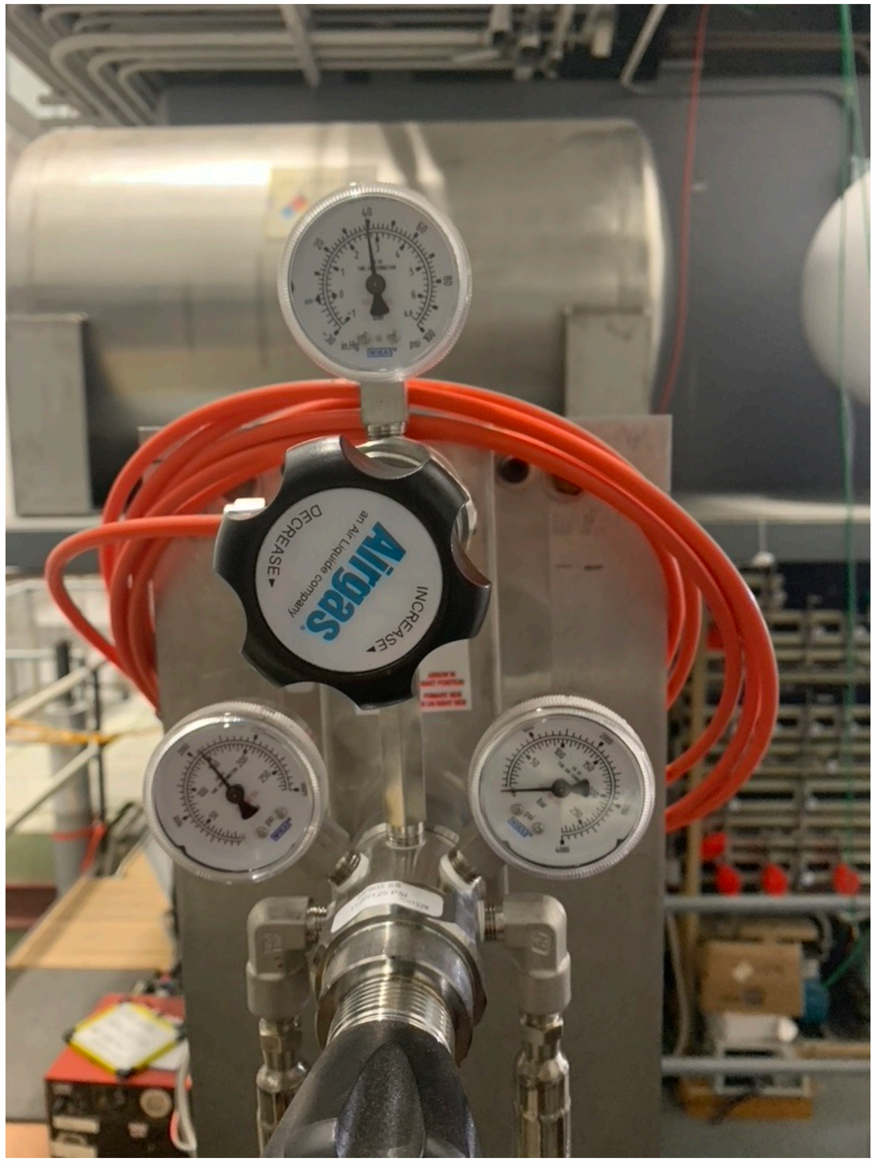
# Safety analyses for PULSTAR UCN source

# Possible Hazards affecting Reactor safety

- **Beam port flooding/draining** affects reactor reactivity during normal operation
- **Cryogenic hazard** of 500l LHe dewar: Oxygen deficiency affects personnel during normal operation
- **Gamma/neutron radiation** from grooves in Thermal Column (TC) Door affects personnel and visitors during normal operation
- **Reactor pool liner:** sudden pressure rise in cryostat may result in accidental mechanical damage of the reactor pool liner
  - Air leak into the Flammable gases system may result in accidental deflagration
  - Methane burp - (our mitigation is operate methane at T>45K)
  - Thermal runaway - (mitigated by relieve devices and passive design of connecting tubing to avoid freeze out)

# Beam port flooding/draining

- Beam port boxes are drained using helium gas.
- To avoid accidental flooding we installed a manifold, which automatically switch between 2 He bottles
- The fastest flooding measured in Dec 2024 took at least 10 ,im, which is slow enough to allow control rods response.

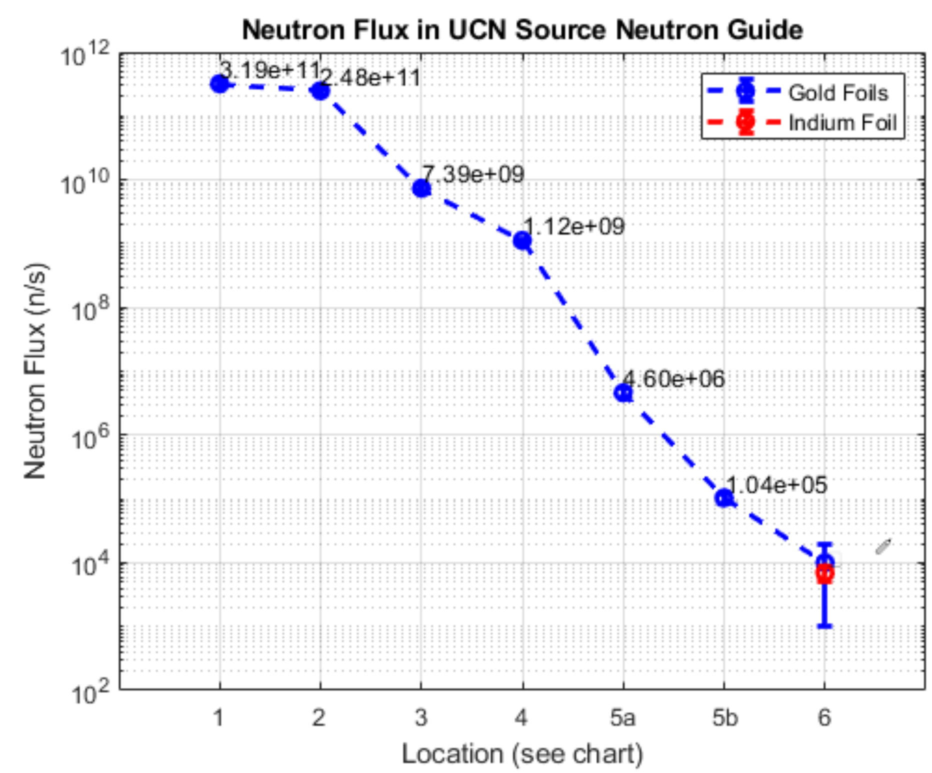


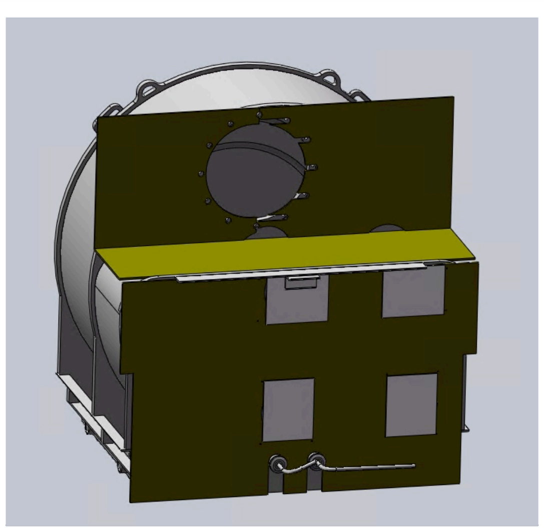
# Cryogenic hazard of 500l LHe dewar:

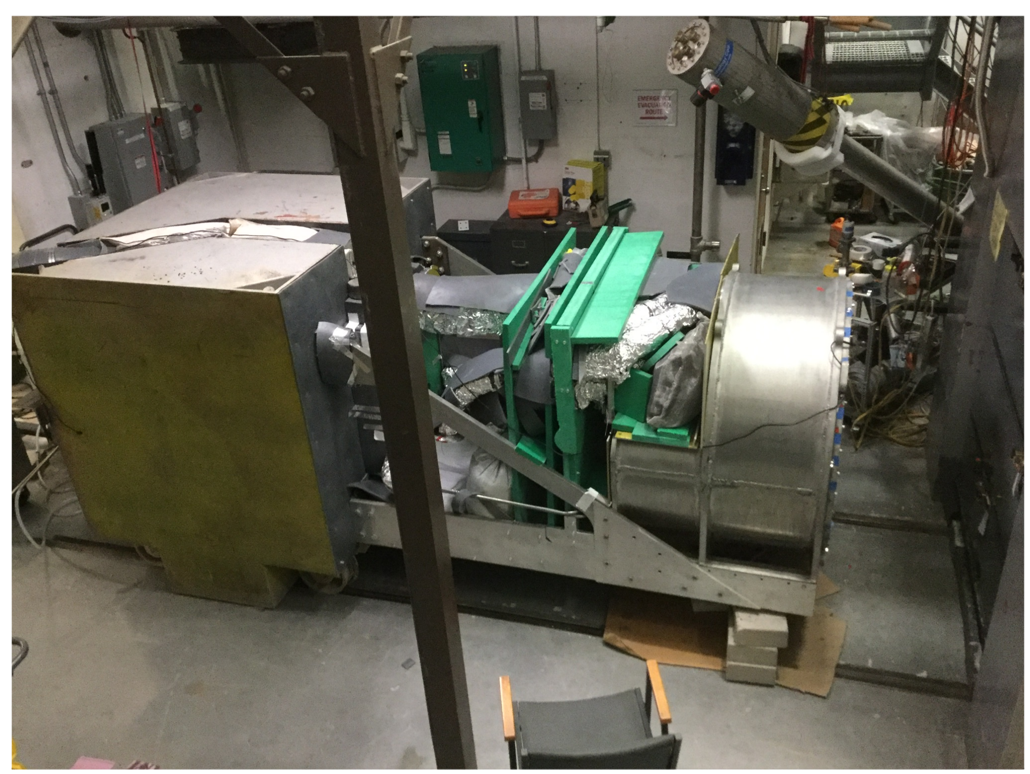
- Oxygen deficiency monitor with a light and sound alarm is installed near the dewar
- Individual portable O2 monitor is available in control room

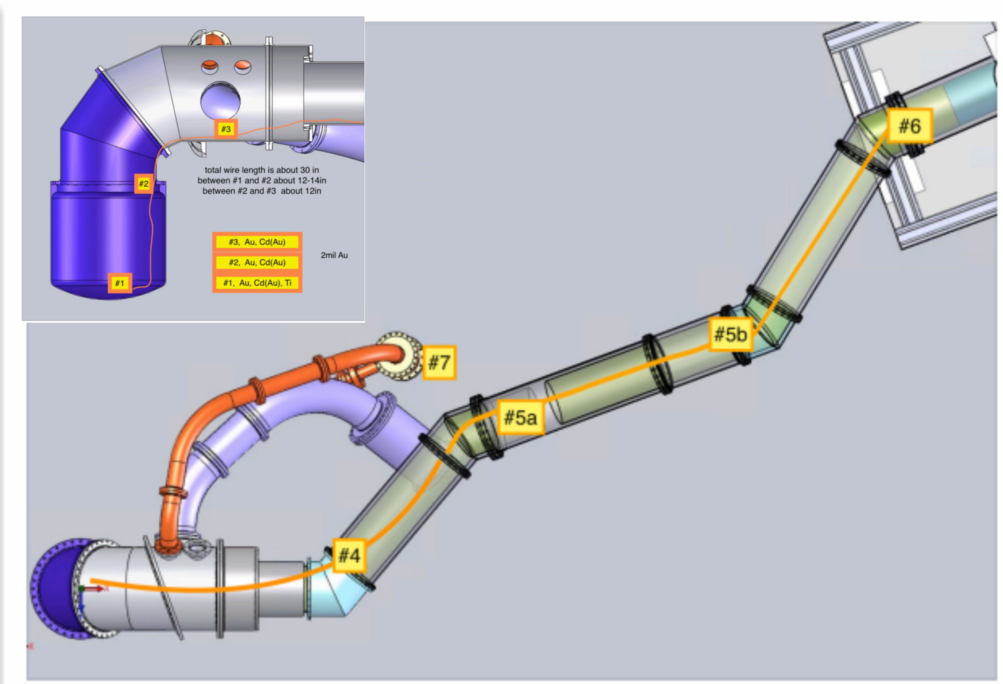
# Neutron radiation

- Neutron flux was probed along the neutron guide
- At the exit from TC door the flux is about 6E+3 n/cm/s, which is easily shielded by plastic sheets containing Boron or Li
- All guides were wrapped in Boron containing plastic
- The tank was shielded with Boral and Borated HDPE plates



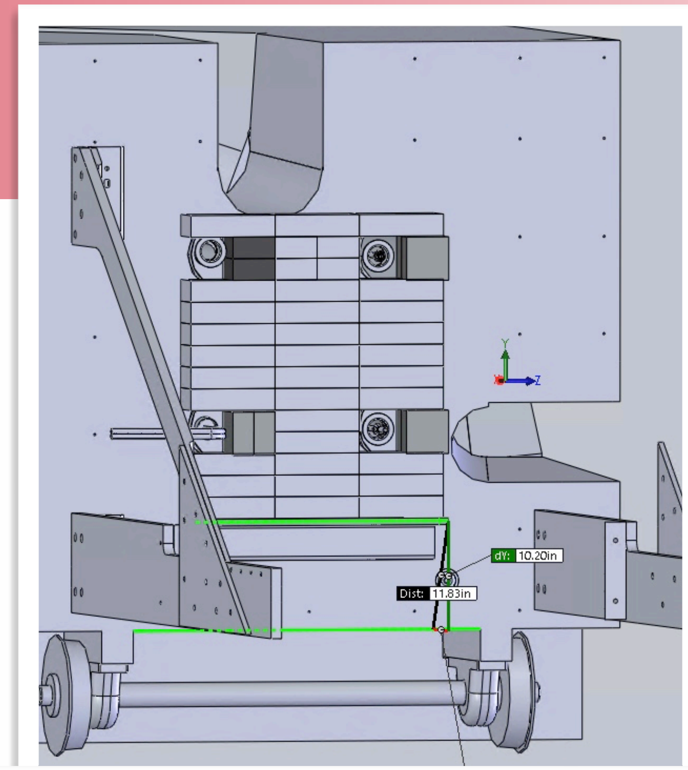



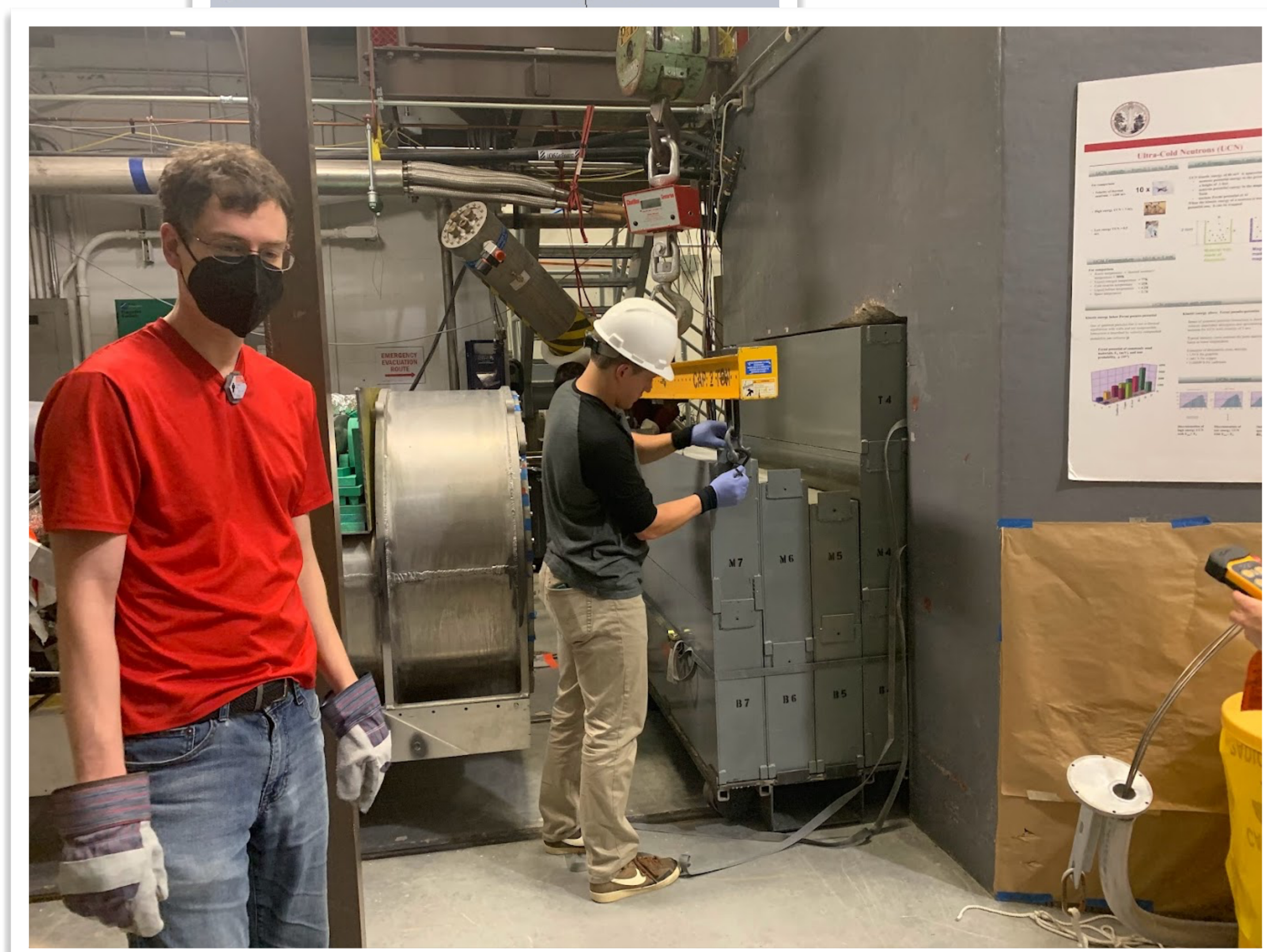




# Gamma shield

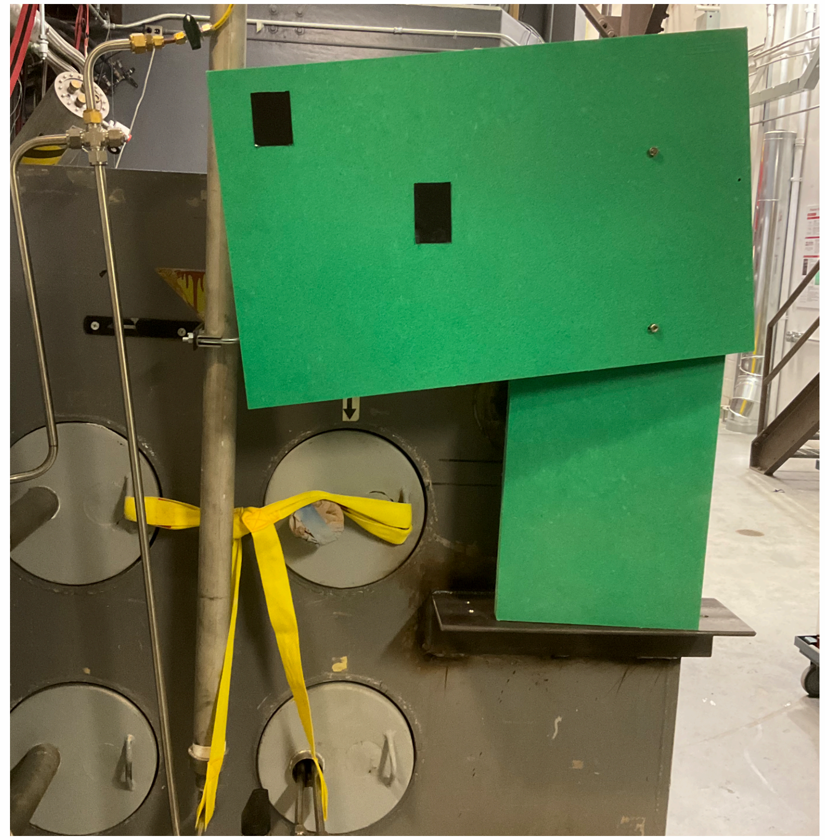
- Lead bricks to shield from direct reactor core gamma's
- We fill TC cave with concrete blocks and use additionally a temporary shield when TC is outside for source assembling

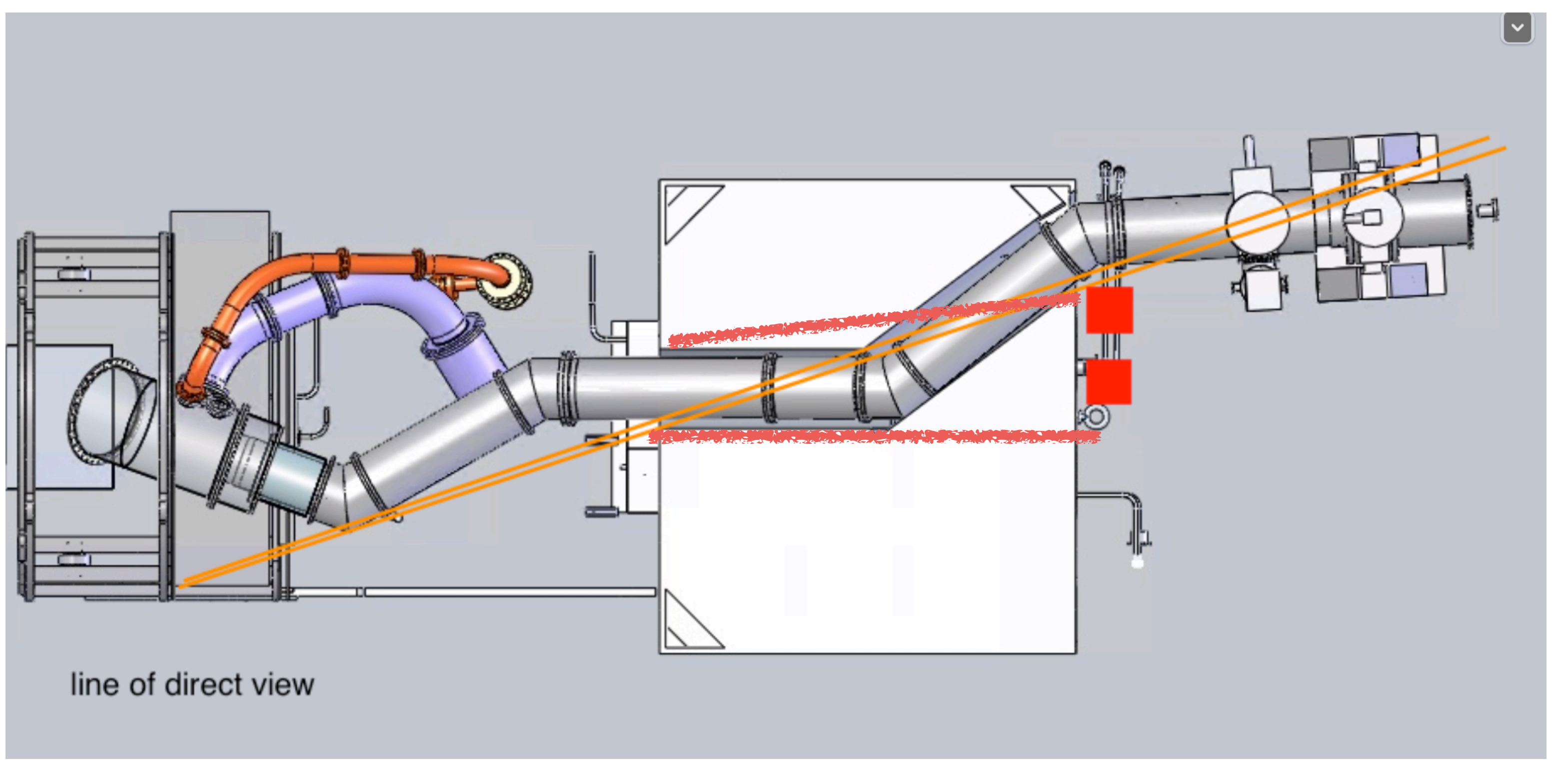


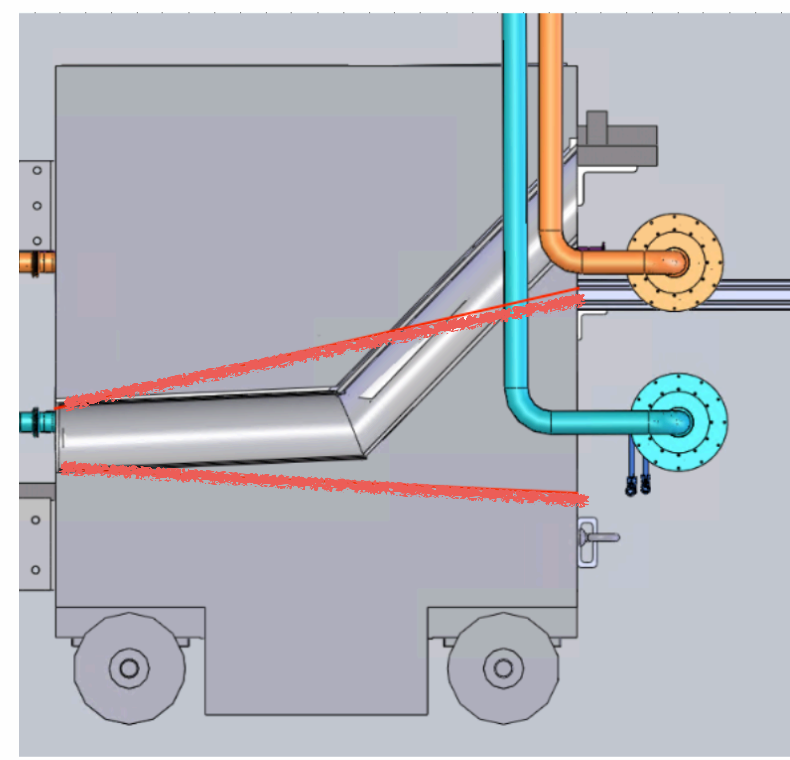



# Gamma shield

- Gamma doses were measured in Dec 2023 and interpolated to 1 MW power
- The maximum gamma dose is below 5 rem/h and will be shielded by lead and concrete blocks of the temporary shield





# Explosive pressure rise mitigation

- Flammable gases hazard is present when such a gas might be mixed with certain amount of air (Oxygen)
- The main result is a fast rise of the high pressure
- **Therefore, UCN source design must have passive features to prevent air leakage and mitigate pressure rise**
- To prevent air leaks:
  - we use only all metal seals in the gas handling system. In addition, we leak check after each opening of the system.
  - all piping between cryostat and storage tank are designed to be either vacuum or He jacketed.
  - all lines outside TC are protected from mechanical damage by thick wall steel jacket
- To mitigate pressure rise we use rupture foils, relief and check valves.
- When flammable gas is pumped out of the system, we use a dedicated exhaust line to the reactor exhaust tower, which is vented with nitrogen and equipped with a check valve

# Explosive analys: detonation vs deflagration

- Our conclusion is that a global detonation is highly improbable.
- A main reason for this is that such an event requires an initiating energy, which is improbable because of the design of the source.
- Second reason is that both, deuterium and methane cryocontainers and tanks diameters are smaller then detonation cell values in the Table III.
- Only for deuterium stoichiometric mixture the cell size is smaller than the tank, but the detonation initiation energy is not available.
- Therefore, for safety analysis we considered only most severe case of deflagration

Table III. Detonation Properties at NTP for Flammable Gasses Used in the UCN Source

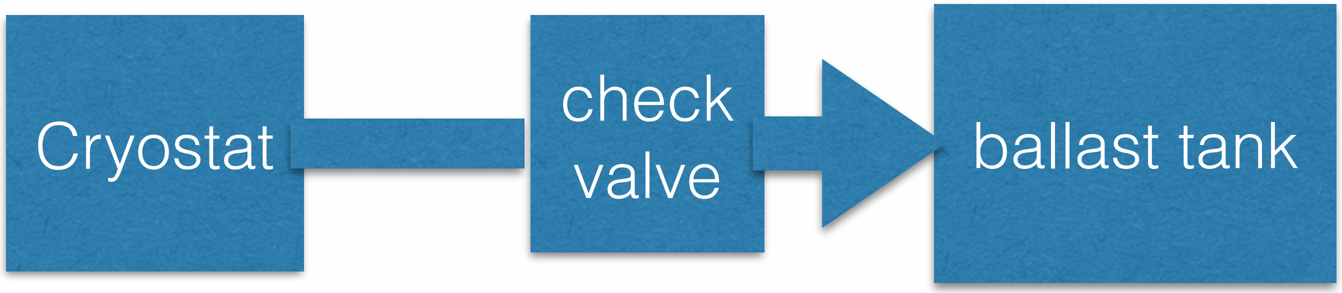
| Flammable Mixture | %Vol Flammable Gas | Deflagration Initiation Energy (mJ) | Detonation Initiation Energy (kJ) | Detonation Cell Size λ (cm) | Detonation Critical Tube Dia. (cm) |
|---|---|---|---|---|---|
| $D_2$ + Air | 15 | | 200 * | 40 ** | 550 |
| | 29.5 | 0.02 * | 4 * | 2 ** | 30 |
| | 58 | | 750 * | 30 ** | 350 |
| $CH_4$ + Air | 9.5 | 0.3 | 100,000 | 30 | 550 |

* Values for hydrogen

** Scaled to hydrogen as (Mol Wt)$^{1/2}$ G.W. Koroll, R.K. Kumur "Isotope Effects on the Combustion Properties of Deuterium and Hydrogen," Combustion and Flame 84, 154 (1991)

# Deflagration

- In our system during normal operation gasses are frozen, while the deflagration is possible only in the gas phase
- only possibility for deflagration arises during cryostat warming up
- deflagration requires an air leak, sufficient for formation of a stoichiometric mixture
- To be conservative, estimations are made for the *most severe case*, which occurs at highest pressure when all of the condensed cryogen vaporizes, check valve is open and gas is relieved to the tank



# $P_{AICC}$ Pressure of Deuterium deflagration

- The following assumptions are made:
  - Pressures of the gas mixtures in the cryocontainers are $\mathbf{P_0}$ =1340 mbar for deuterium and 1580 mbar for methane
  - Gasses in a cryocontainer are well mixed
  - Gas mixtures in a cryocontainer is stoichiometric
  - Temperature of the gas mixture is 100 K
  - piping size allows pressure relief with zero $\Delta p$
  - *no pressure relieve device on the tank*

$\mathbf{P_{AICC}}$ is adiabatic isochoric complete combustion (AICC) pressure

| Cryocontainer | $P_{AICC}/P_0$ | $P_{AICC}$ (bar) | $\Delta p_B$ (mbar) |
|---|---|---|---|
| Deuterium | 27.8 | 37.2 | $< 470$ |
| Methane | 21.9 | 34.2 | $< 64$ |

# Air leaks and possible deflagration pressures

- Air leaking into cryostat can happen only from the room temperature piping
- All piping between cryostat and storage tank are designed to be either vacuum or He jacketed.
- All lines outside TC are protected from mechanical damage by thick wall steel jacket
- Therefore, realistic frozen air amount is highly restricted by the acceptable leak levels, which is below $1 \times 10^{-8}$ mbar l/s
- Nevertheless, we have estimated possibility of deflagration for different amounts of frozen air up to 640g
- **Conclusions:**
  - no deflagration for methane is possible
  - deuterium deflagration is possible for *credible deuterium* amounts but only for *non credible air* amount

# Air leaks and D2 deflagration pressures

**Deuterium Air Mixture Deflagration in Ballast Tank at 293 K**

Deuterium pressure above deuterium triple point pressure

| D2 pressure (mbar) | tank pressure (mbar) | deuteriu % vol | Paicc/Po | deflagra pressure (bar) | D2 pressure (mbar) | tank pressure (mbar) | deuteriu % vol | Paicc/Po | deflagra pressure (bar) |
|---|---|---|---|---|---|---|---|---|---|
| *160-g air* | | | | | *320-g air* | | | | |
| 170 | 245 | 69 | 6.8 | 1.7 | 170 | 320 | 53 | 8.3 | 2.7 |
| 240 | 315 | 76 | no deflagration | | 240 | 390 | 62 | 7.4 | 2.9 |
| 370 | 445 | 83 | no deflagration | | 370 | 520 | 71 | 6.5 | 3.4 |
| 505 | 580 | 87 | no deflagration | | 505 | 655 | 77 | no deflagration | |
| 640 | 715 | 90 | no deflagration | | 640 | 790 | 81 | no deflagration | |
| 775 | 850 | 91 | no deflagration | | 775 | 925 | 84 | no deflagration | |
| 911 | 986 | 92 | no deflagration | | 911 | 1061 | 86 | no deflagration | |
| *480-g air* | | | | | *640-g air* | | | | |
| 170 | 395 | 43 | 9.2 | 3.6 | 170 | 470 | 36 | 9.6 | 4.5 |
| 240 | 465 | 52 | 8.4 | 3.9 | 240 | 540 | 44 | 9.2 | 5.0 |
| 370 | 595 | 62 | 7.5 | 4.5 | 370 | 670 | 55 | 8.1 | 5.4 |
| 505 | 730 | 69 | 6.8 | 5.0 | 505 | 805 | 63 | 7.4 | 6.0 |
| 640 | 865 | 74 | 6.1 | 5.3 | 640 | 940 | 68 | 6.9 | 6.5 |
| 775 | 1000 | 77 | no deflagration | | 775 | 1075 | 72 | 6.4 | 6.9 |
| 911 | 1136 | 80 | no deflagration | | 911 | 1211 | 75 | 6.1 | 7.4 |

# Failure of Thermal Column End Wall

- Two different situations are examined:

- a constant uniform pressure on the analysis plate due to deflagration in some portion of the UCN source system,

- a concentrated impulse force at the center of the analysis plate due to a deflagration that causes a projectile to strike the analysis plate.

- Al plate strength was taken to be for material adjacent to a weld ( 165 MPa/24000 PSI)


The end wall consists of 2-in. x 3/8-in. webbing, 1-in. thick sheet, and 1/4-in. thick pool liner, all 6061 aluminum.

| |
|---|
| width and length of analysis plate, $a$ = 57.7 cm |
| thickness of analysis plate, $t$ = 2.54 cm |
| uniform pressure on analysis plate, $p$ = 6.9 atm = 96.6 psi = 0.00966 ksi |
| width and length of projectile area, $b$ = 10 cm |
| impulse pressure on analysis plate, $q$ = 100 atm = 1470 psi = 1.47 ksi |

Analysis parameters

# Failure of Thermal Column End Wall

## Results

| | Maximum Stress | Maximum Deflection |
|---|---|---|
| Uniform Pressure | $\sigma_m$ = 16 ksi (mid edges) | $y_m$ = 0.9 mm (center) |
| Impulse Force | $\sigma_m$ = 12.4 ksi (mid edges) | $y_m$ = 1.3 mm (center) |

- The value assumed for the constant uniform pressure (6.9 bar) gives a maximum middle-of-edge stress (16 ksi) , which is about 70% edge yield strength (24 ksi, weld heat-affected-zone).
- The value assumed for the concentrated impulse force (qb2 = 16,560 lbs) gives a maximum middle-of-edge stress 12.4 ksi, which is about 50% of the edge yield strength (24 ksi, weld heat-affected-zone).
- **Conclusion:** The end wall has load capacity sufficient to protect the end wall from irreversible deformation under both, constant uniform pressure and the concentrated impulse force, calculated using the maximum deflagration pressure in the Deuterium tank
- Note: the air leak required for such pressure is not credible

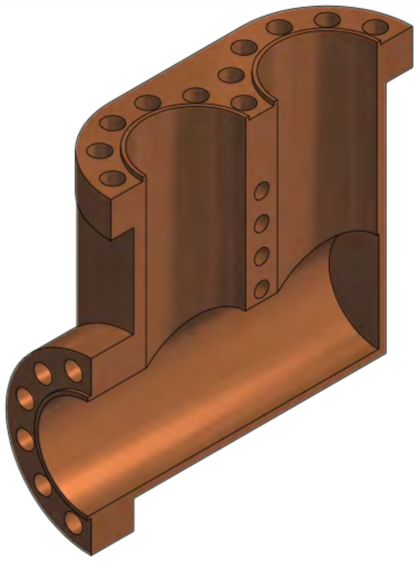
# Safety analyses conclusions

- Reactivity change due to flooding of the beam port is slow enough to be mitigated by control rods
- Detonation is highly improbable
- Deflagration in cryostat is not credible
- Damage of reactor pool liner wall is not credible

- Backup

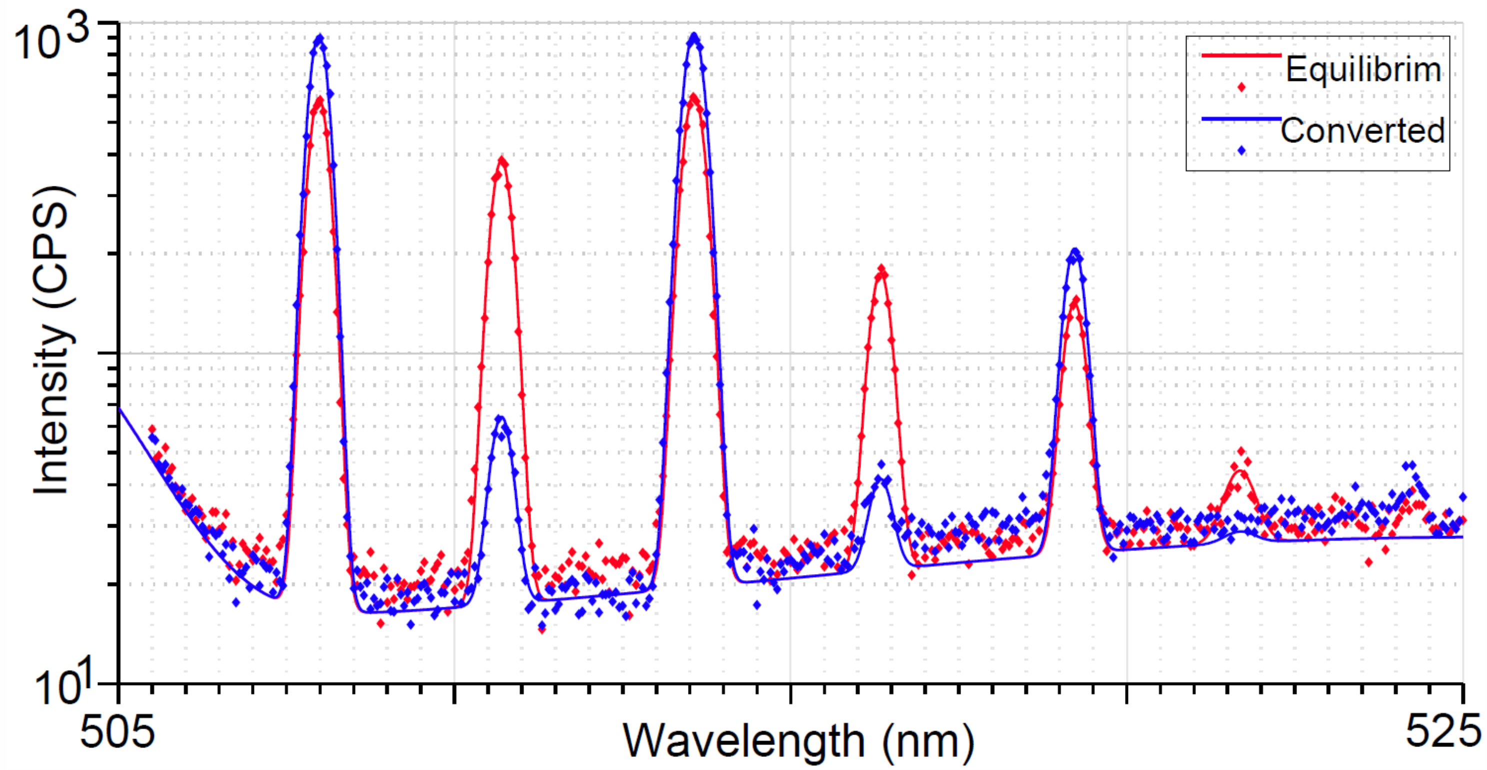
# Para-to-Ortho converter & Raman spectroscopy

- Equilibrium deuterium in 2-to-1 ratio of ortho- to para- spin states, coupled to even and odd rotational angular momentum
- Converter prepares few percent ortho- state utilizing Chromium(II) Oxide (Oxysorb) or Iron(III) Hydroxide at triple point
- We have developed  a procedure to make crystal Iron(III) Hydroxide
- The converter was tested with both materials

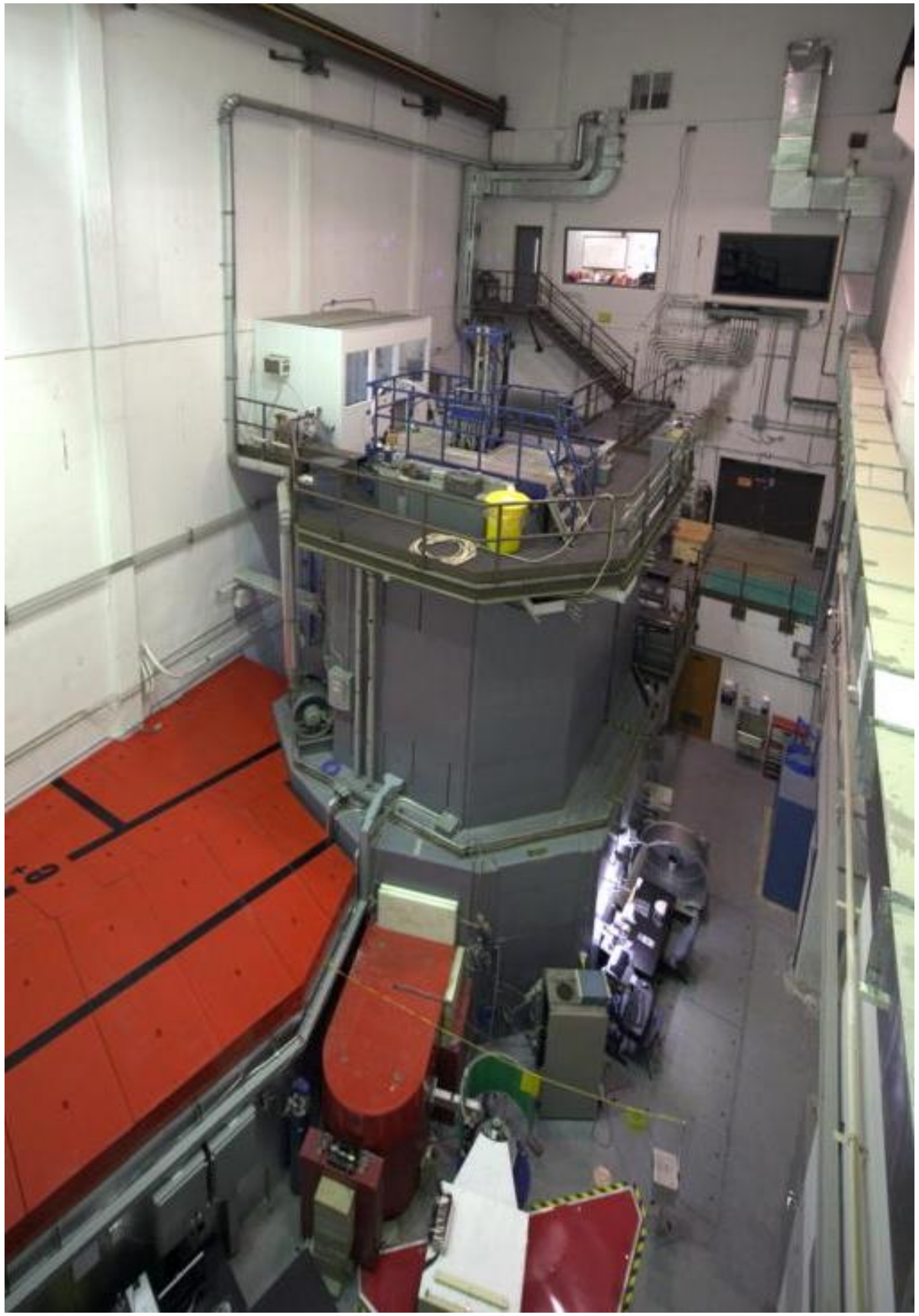


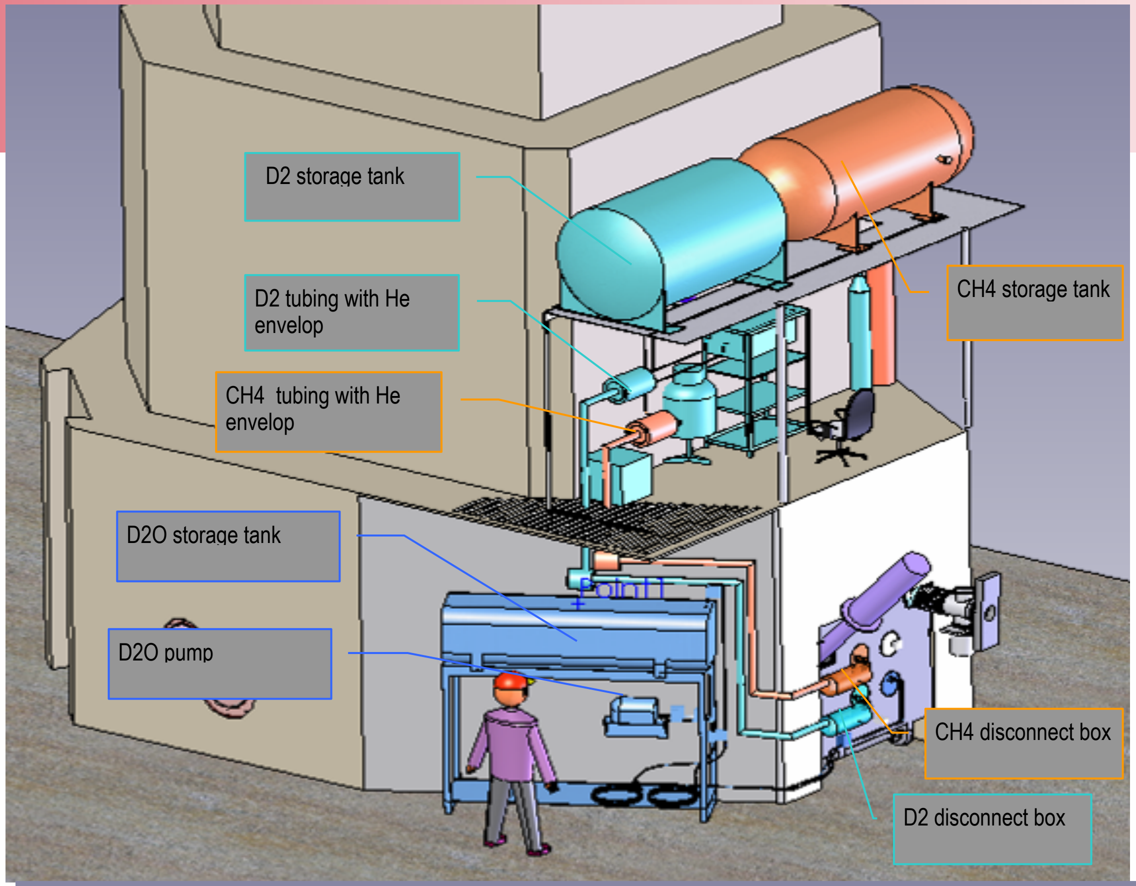
**Raman Spectroscopy**

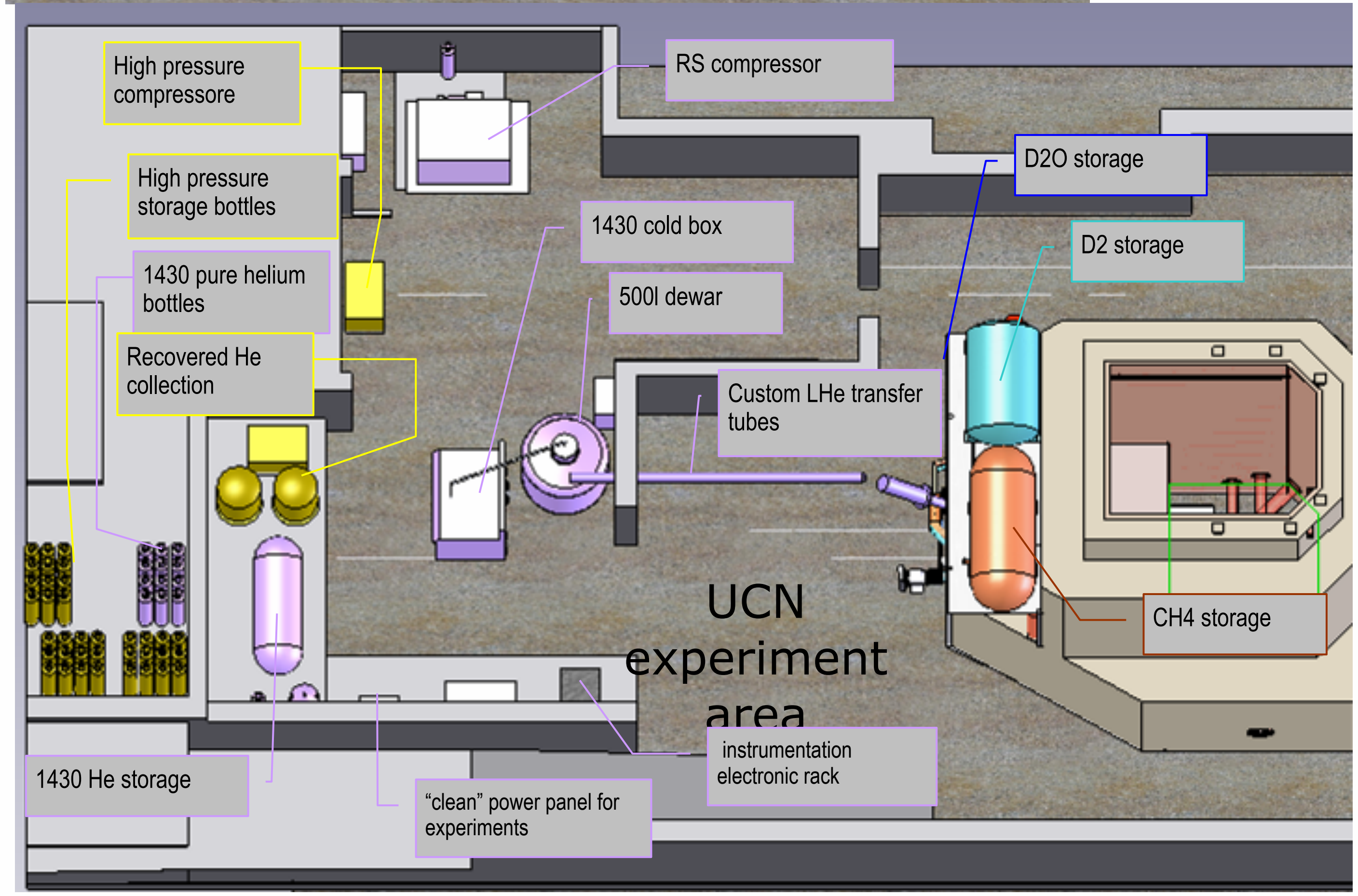
- Spectrometer precisely determines para- to ortho- ratio of sample
- Allows for strict limits on the hydrogen, HD contamination, a source of up-scattering
- Pictured left are Stokes lines of deuterium



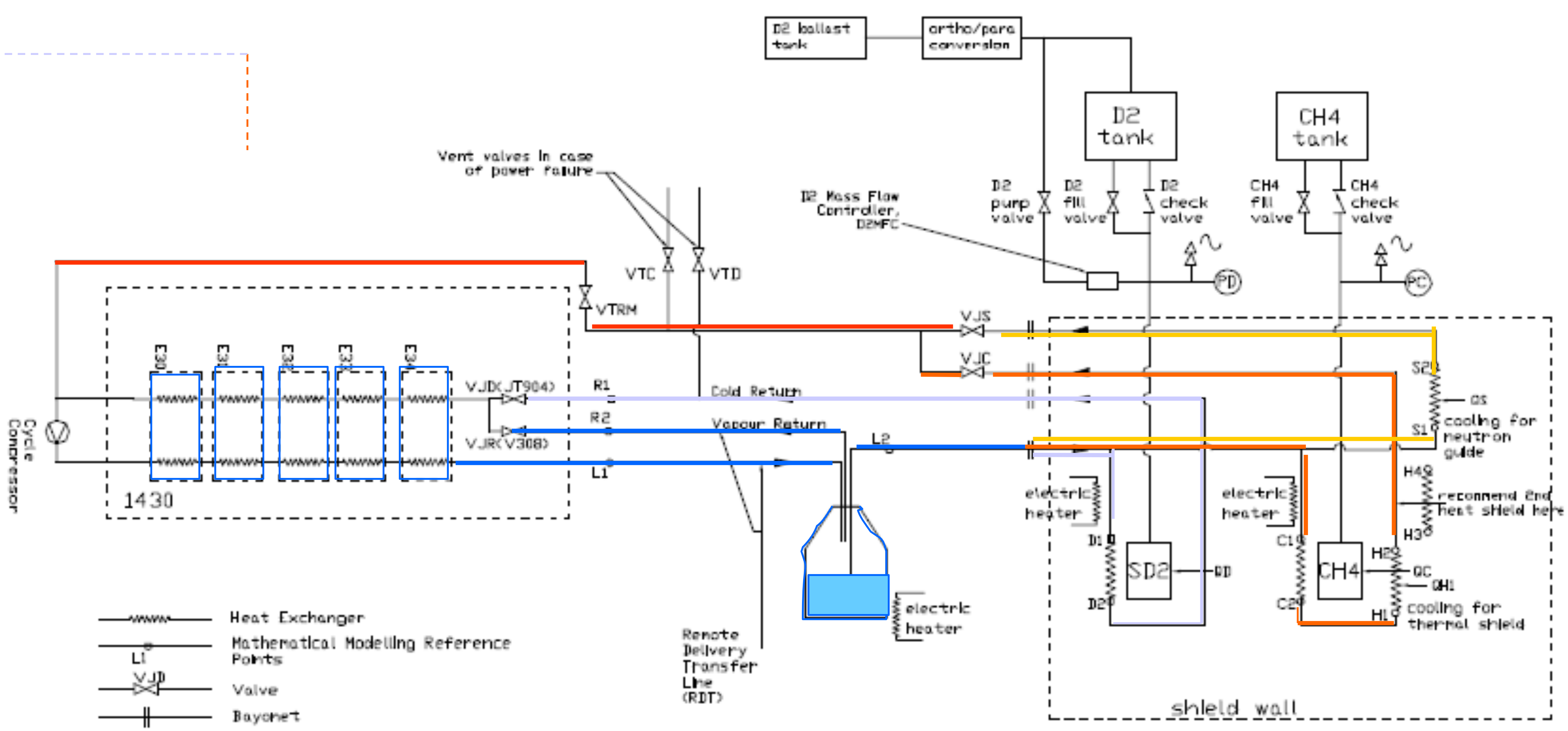

# Facility overview





# Cryogenic cooling loops design



# Cryogenic cooling loops design