SAND2011-7027C

20th Target Fabrication Meeting
Honolulu, Hawaii
October 2-7, 2011

Cryogenic Targets for Dynamic Material Properties and Fusion Studies at Sandia National Laboratories

D. L. Hanson, A. J. Lopez, M. D. Knudson, S. Root,
M. E. Cuneo, J. R. Asay, K. P. Shelton, J. M. Villalva
Sandia National Laboratories, Albuquerque, NM 87185

D. G. Schroen
General Atomics, San Diego, CA 92121

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

We have developed cryogenic target systems for dynamic material properties and fusion studies on the Sandia Z accelerator

Z is a pulsed power accelerator capable of producing currents > 20 MA and magnetic fields > 10 MG; the resulting large current and field densities can generate magnetic field pressures up to ~ 650 GPa and can accelerate flyer plates up to 40 km/s and efficiently compress cylindrical metal liners

We have developed cryogenic systems to condense a wide range of liquid cryogenic samples for:

- shock compression experiments on Z to study dynamic material properties for comparison with density functional theory simulations and for improved understanding of gas giant planetary structure
- support of target development for future MagLIF (Magnetized Liner Inertial Fusion) concept experiments on Z

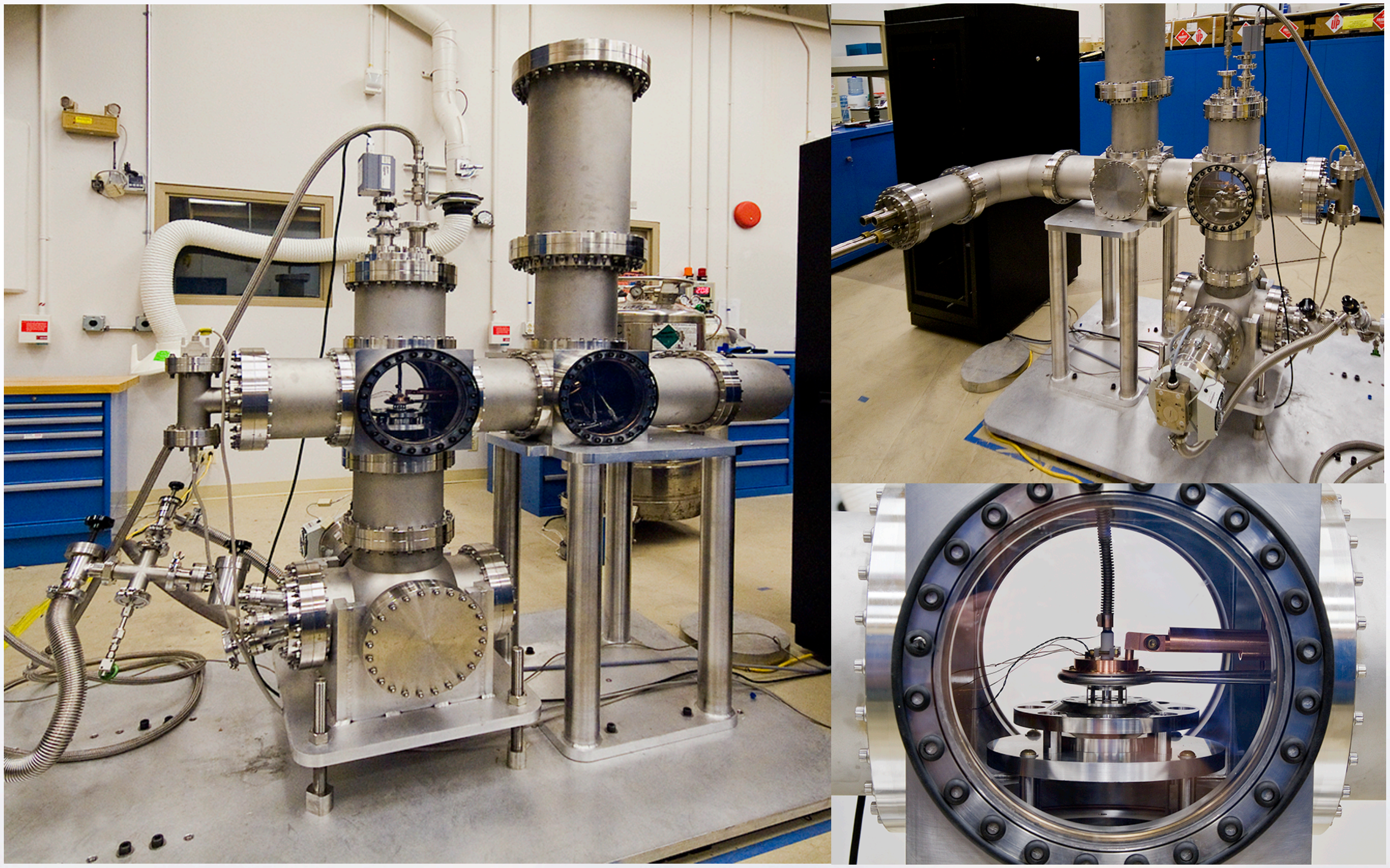
This talk will present an overview of the various cryogenic target systems in use or under development to produce low temperature liquid samples for these experiments

The liquid, fluid, and solid cryogenic samples required for Z experiments cover a wide range of temperatures and pressures

Sample	Application	Phase	Triple pt.	Normal b.p.	T window	Typical Fill P
Normal H_2	DMP	liquid	13.95 K	20.23 K	15-22 K	18 psi
D_2	DMP, MagLIF	liquid	18.71 K	23.26 K	20-22.5 K	18 psi
N_2	DMP	liquid	63.15 K	77.24 K	65-75 K	18 psi
Ar	DMP	liquid	83.80 K	87.17 K	84.5-86 K	18 psi
Kr	DMP	liquid	115.77 K	119.62 K	117-118.5 K	18 psi
Xe	DMP	liquid	161.36 K	164.78 K	162.5-164 K	18 psi
Ethane	DMP	liquid	90.35 K	184.31 K	160-180 K	18 psi
^{4}He	DMP	liquid	λ-pt 2.177 K	4.216 K	1.5-1.8 K	18 psi

The wide range of cooling conditions needed to generate these samples requires a variety of cryogenic target system configurations

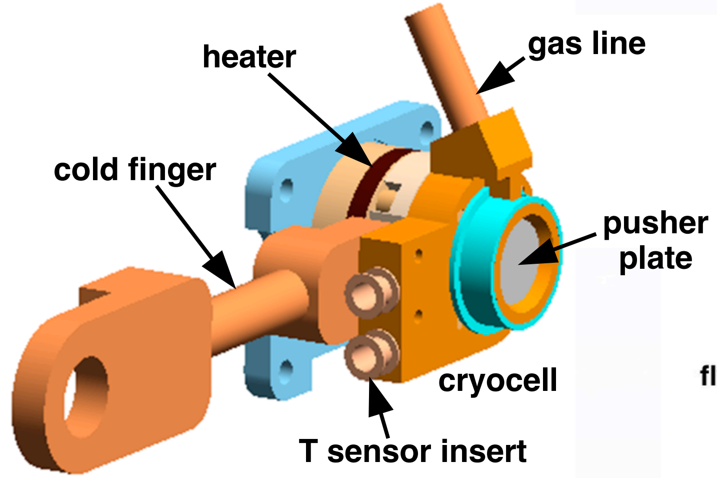
Performance of cryogenic system designs is characterized in our Cryogenics Development Laboratory before use on Z

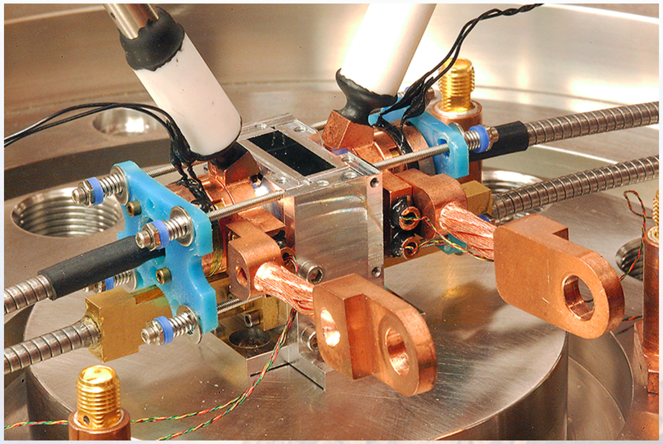


We have developed a toolkit of modular cryogenic components and Z load hardware modifications together with a flexible LabVIEW-based cryogenic data acquisition and control system to allow rapid planning and execution of cryogenic experiments on Z

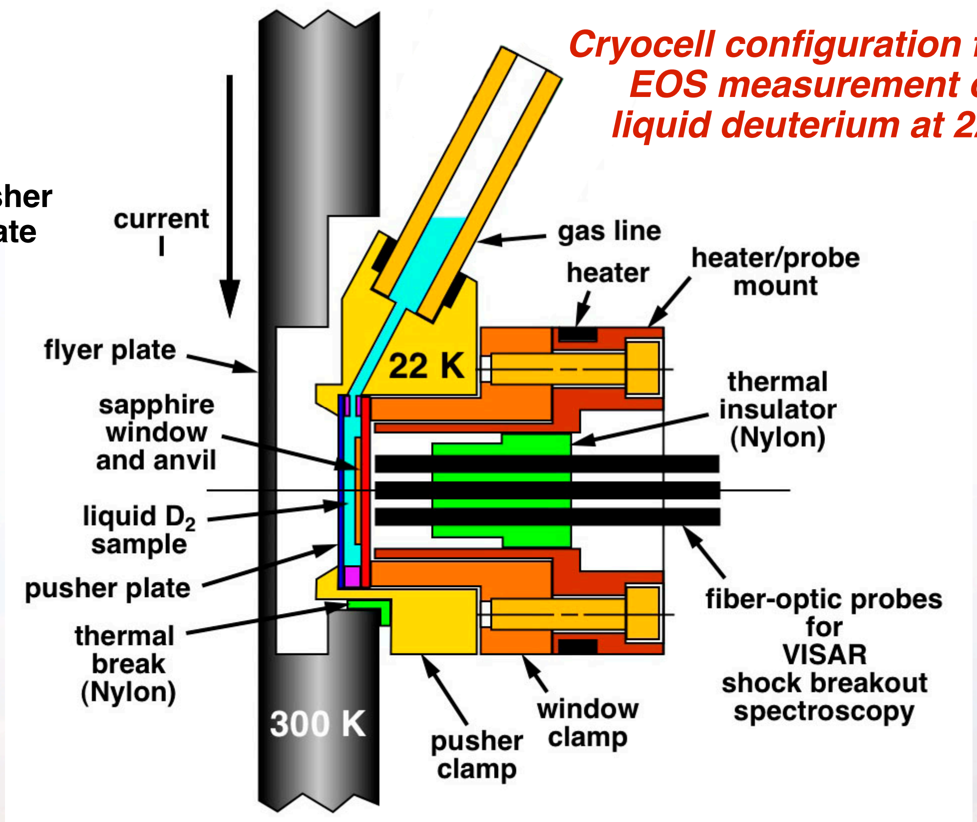
Hugoniot measurements are performed on cryogenic liquid samples condensed in large area unshielded cryocells

The largest number of cryocell targets have been used in liquid deuterium EOS measurements with magnetically-driven flyer plates





Twin cryocells on anode current panels

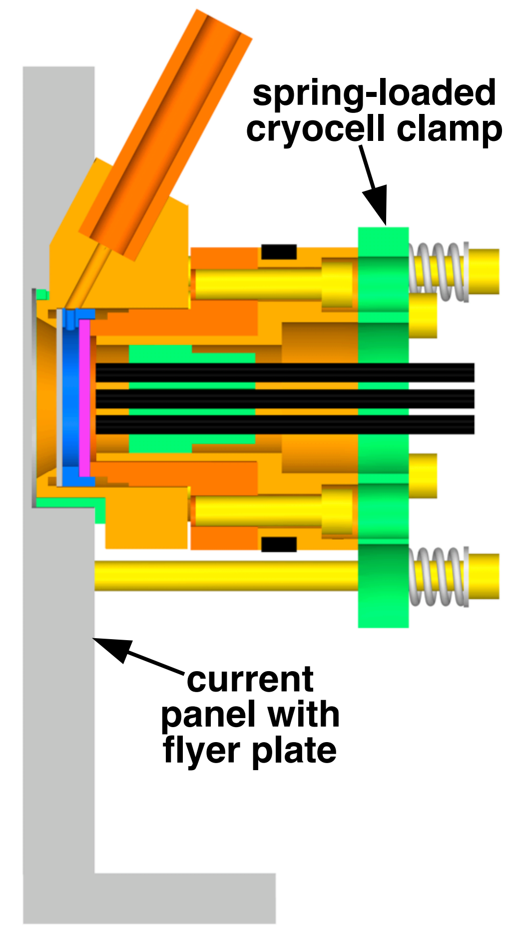


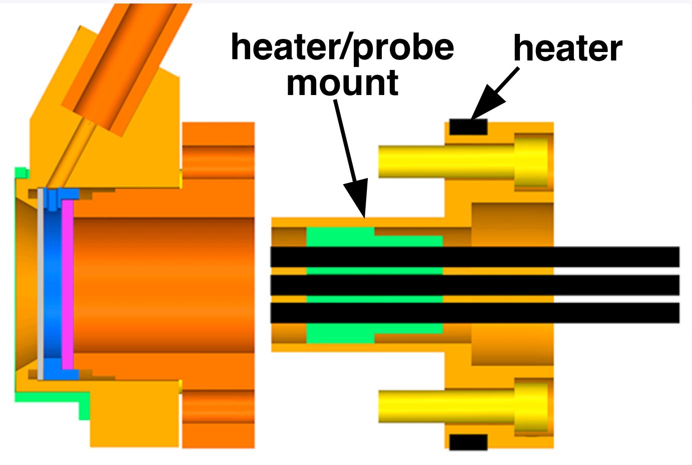
Cryocell configuration for an EOS measurement on liquid deuterium at 22 K

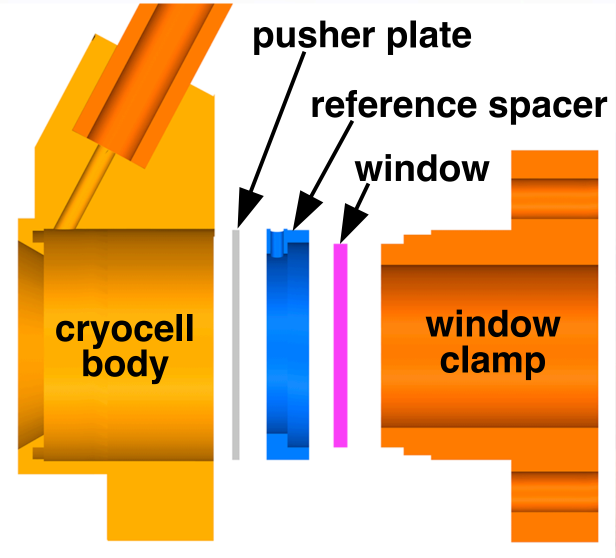
M. D. Knudson *et al*., Phys. Rev. Lett. 87, 225501 (2001)
M. D. Knudson *et al*., Phys. Rev. Lett. 90, 035505 (2003)
M. D. Knudson *et al*., Phys. Rev. B69, 144209 (2004)

The basic cryocell for condensing cryogenic liquid samples is assembled as a sandwich of components

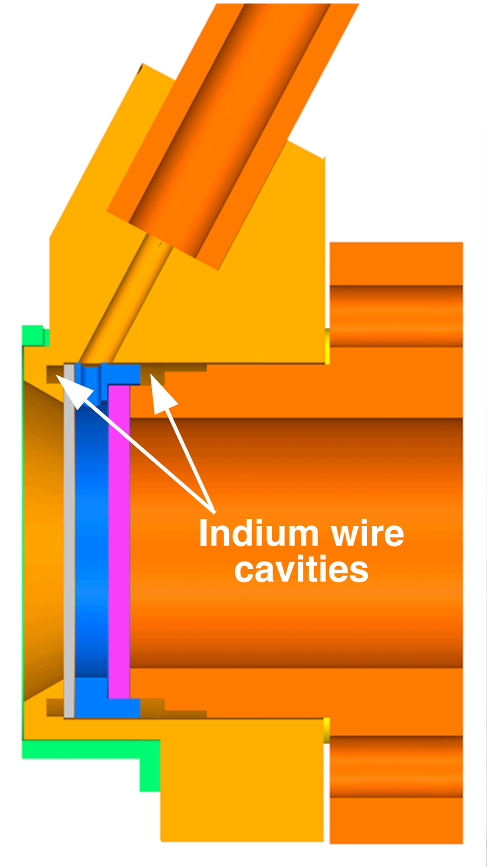
Cryocell assembly





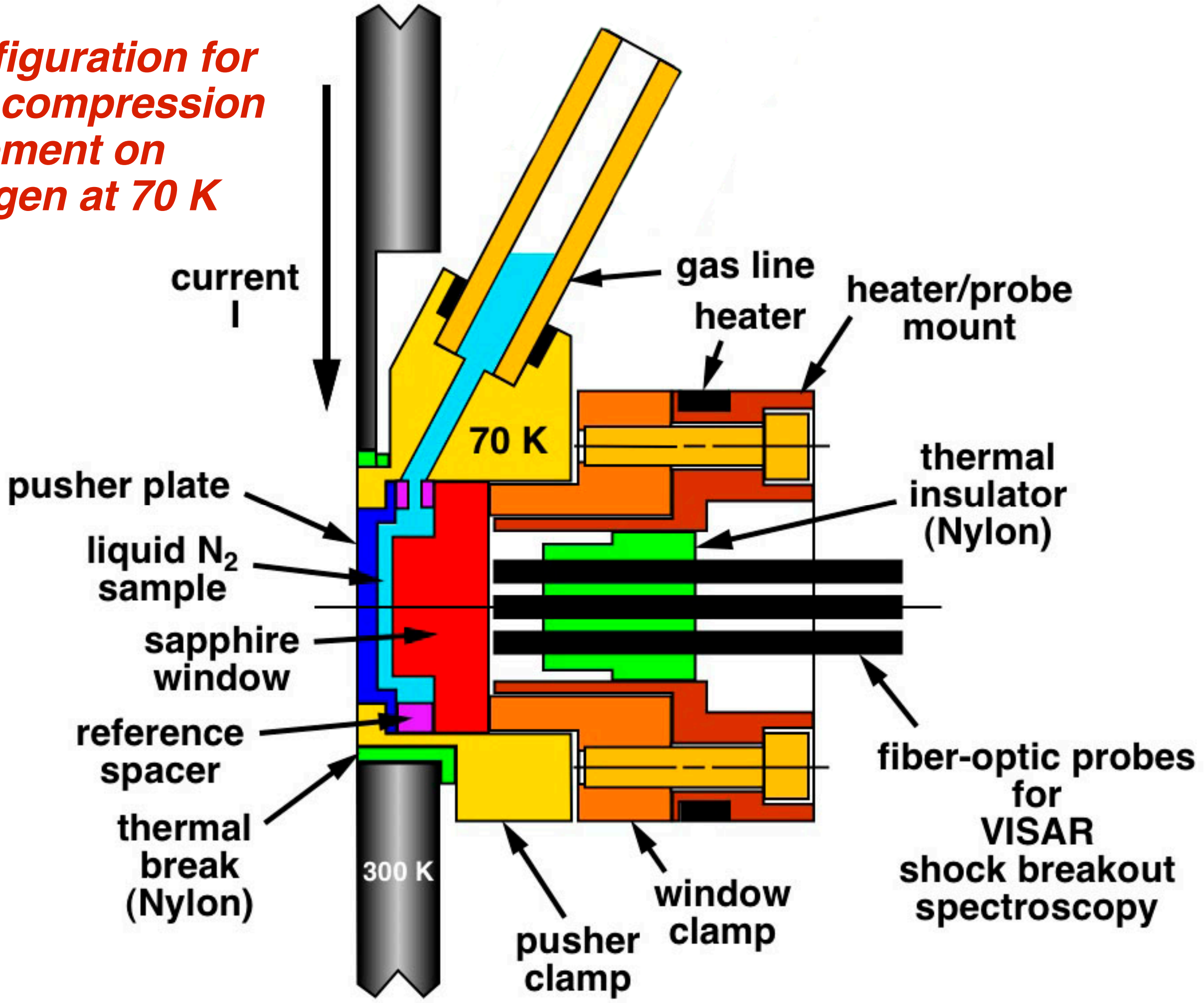


Cryogenic vacuum seals are formed by extruding indium wires
- assembly is done with mini torque wrenches



A slightly different configuration is required for isentropic compression measurements with shaped current pulses

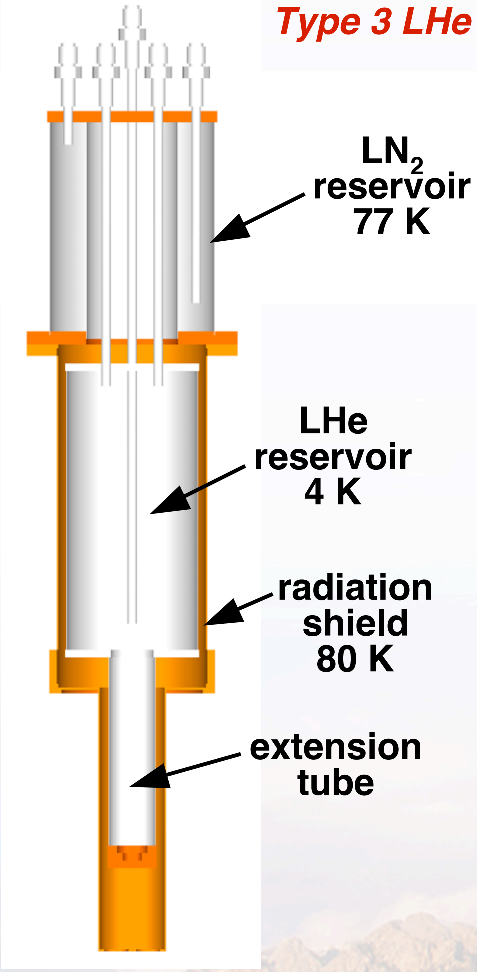
Cryocell configuration for an isentropic compression measurement on liquid nitrogen at 70 K

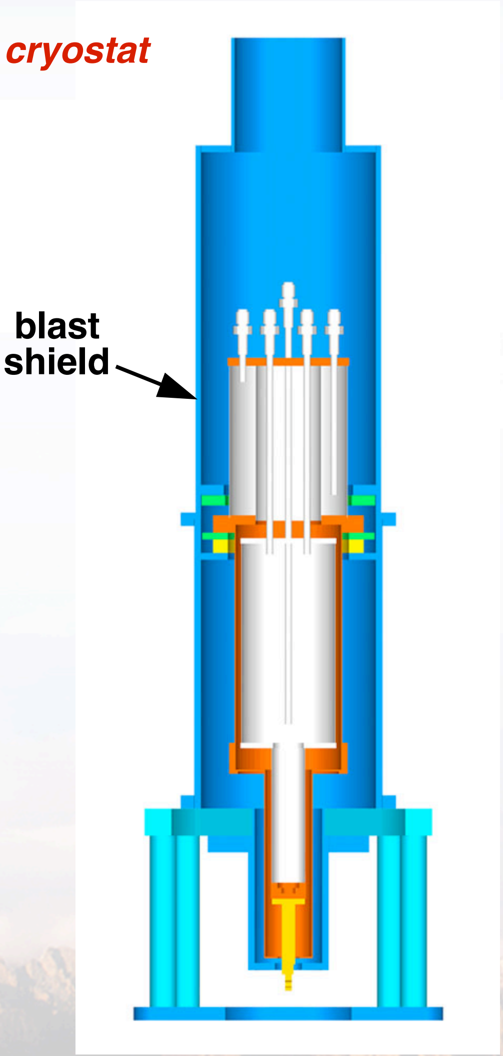


The front of the thermally-insulated cryocell now forms an integral part of the electrode panel for ramp-loading of the sample

A key element for cooling the LD_2 cryocells and other cryocell configurations is a “Type 3” liquid helium cryostat

Type 3 LHe cryostat





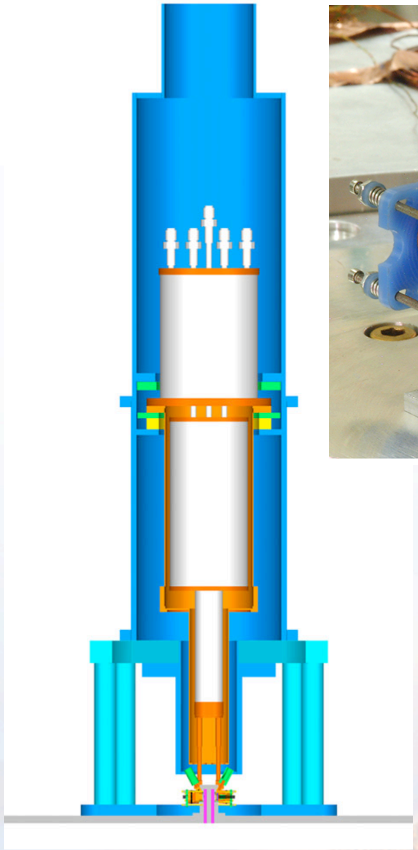
Use of LHe allows rapid cooling (25 - 70 min) of cryogenic liquid targets after chamber pumpdown

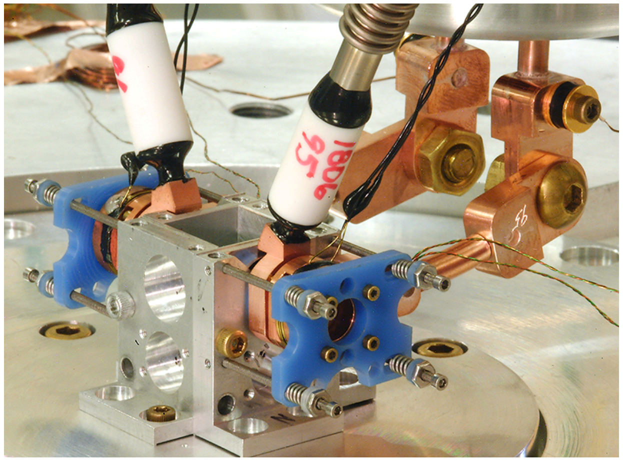
Continuous flow of LN_2 and LHe at a controlled rate allows continuous operation for up to 4 hours

On a Z shot, up to 1.5 MJ of energy is released close to the cryogenic system, vaporizing the cryocell and load hardware at small radius; survivability of the essential cryostat components requires the use of blast shields and/or standoff

The Type 3 cryostat must be in close proximity to the *unshielded* cryocell to cool LD_2 samples to 22 K

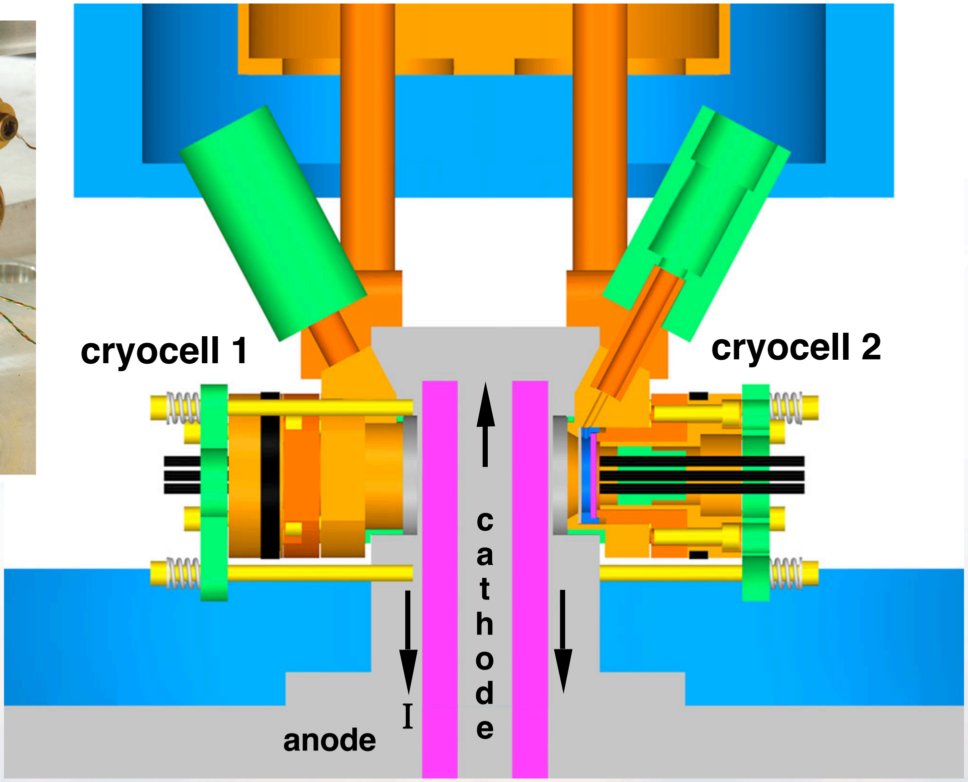
Type 3 LHe cryostat with blast shield and double cold finger to cool two cryocells





The cryostat, radiation shield, and upper blast shield survive the impulse and axial jet of hot metal and vapor released on a Z shot

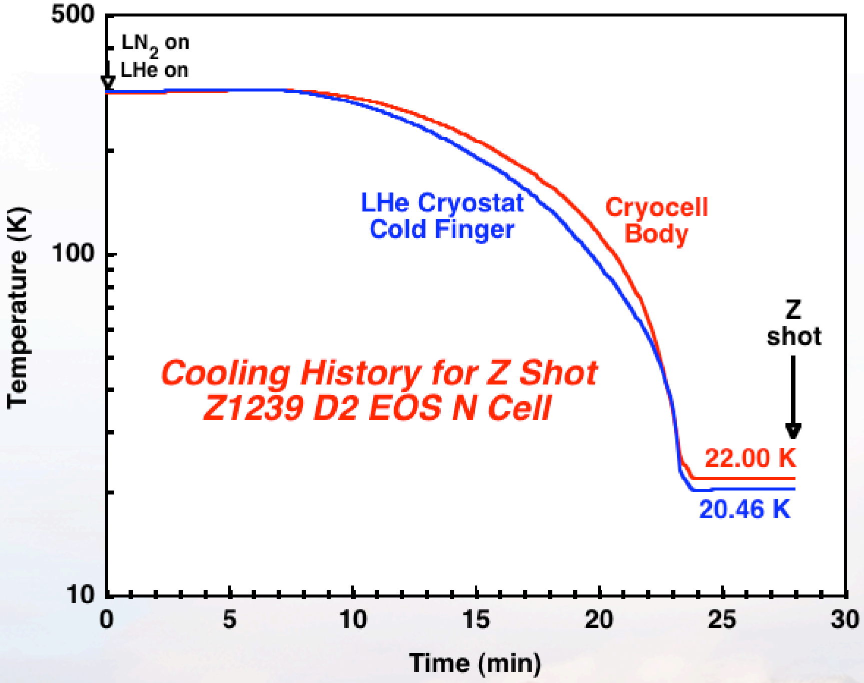
Detail of flyer-plate panel load with two cryocells



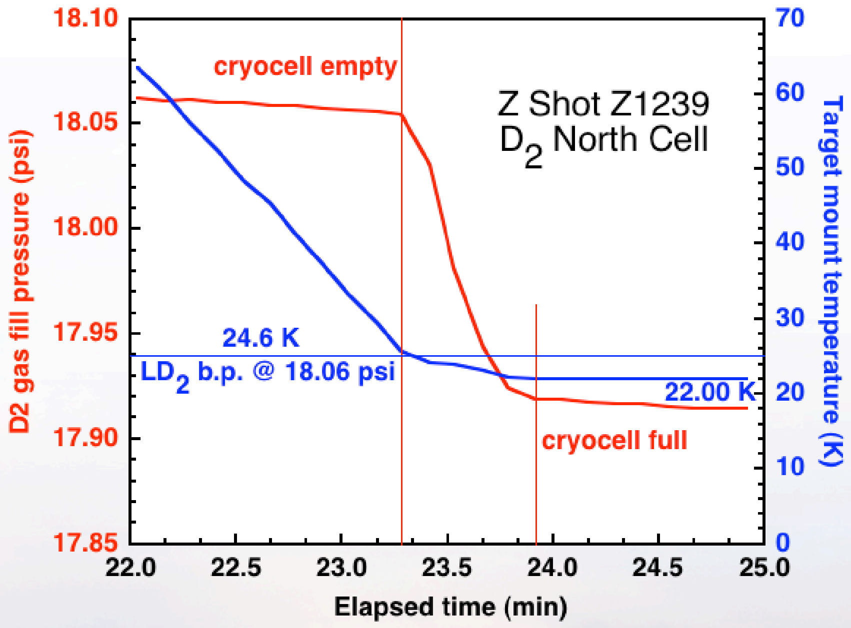
All components in this detail are destroyed on a Z shot

Mounting the Type 3 cryostat inside a blast shield close to the Z machine axis allows rapid cryocell cooldown to 22 K

On this shot, only 24 min was required to cool and fill the cryocells with LD_2 after the start of cryogen flow to the cryostat



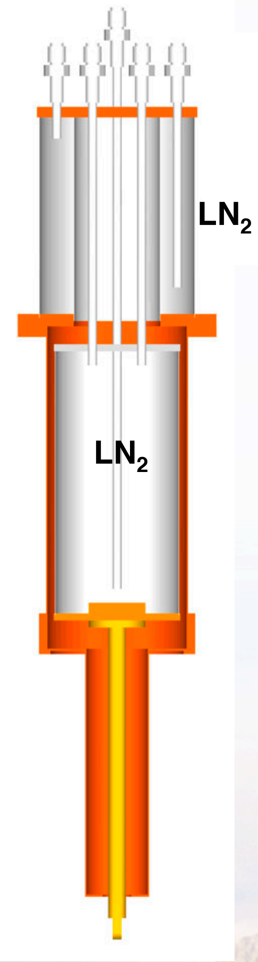
After cooling to the D_2 boiling point at fill pressure, only 45 sec was required to condense a quiescent (bubble-free) sample of supercooled LD_2 at 22 K

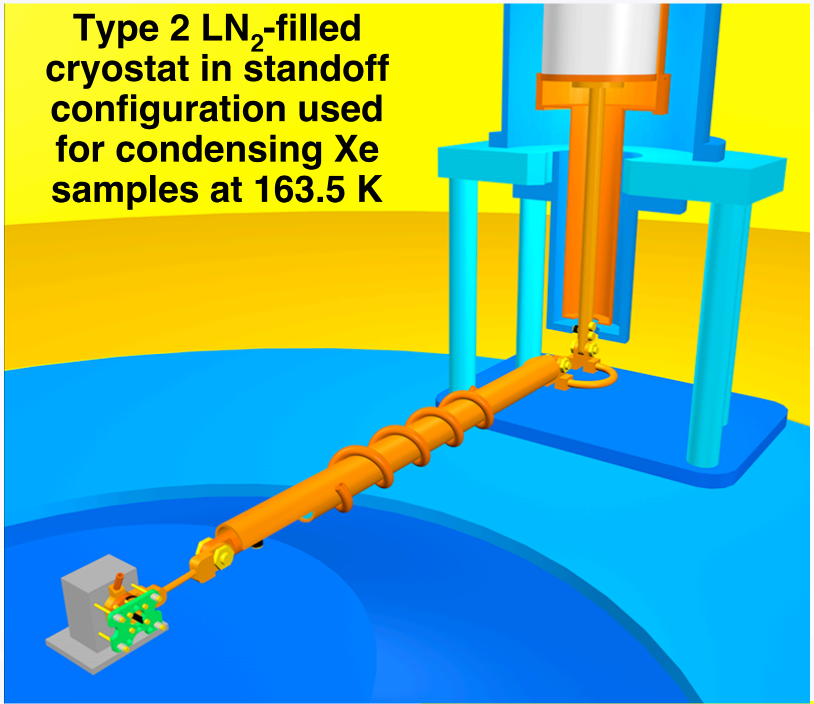


This rapid preparation of the LD_2 sample does not interfere with or delay the Z machine shot sequence

We use a variety of different system configurations to condense other cryogenic liquid samples (Ar, Kr, Xe, N_2, Ethane) at higher temperatures

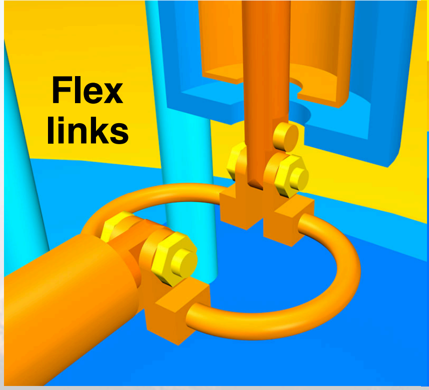
Type 2 cryostat

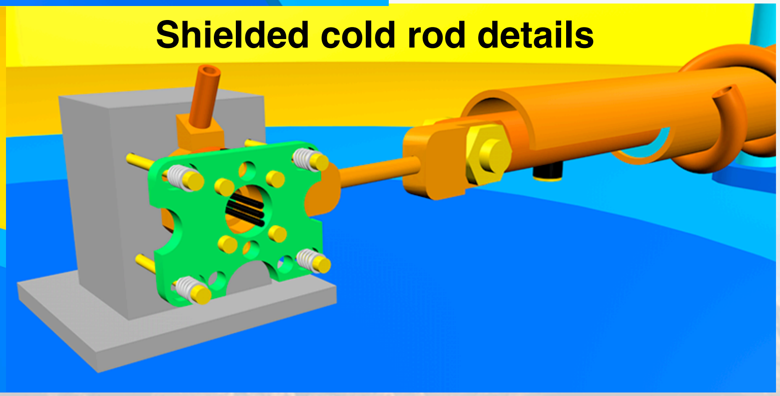



Type 2 LN_2-filled cryostat in standoff configuration used for condensing Xe samples at 163.5 K

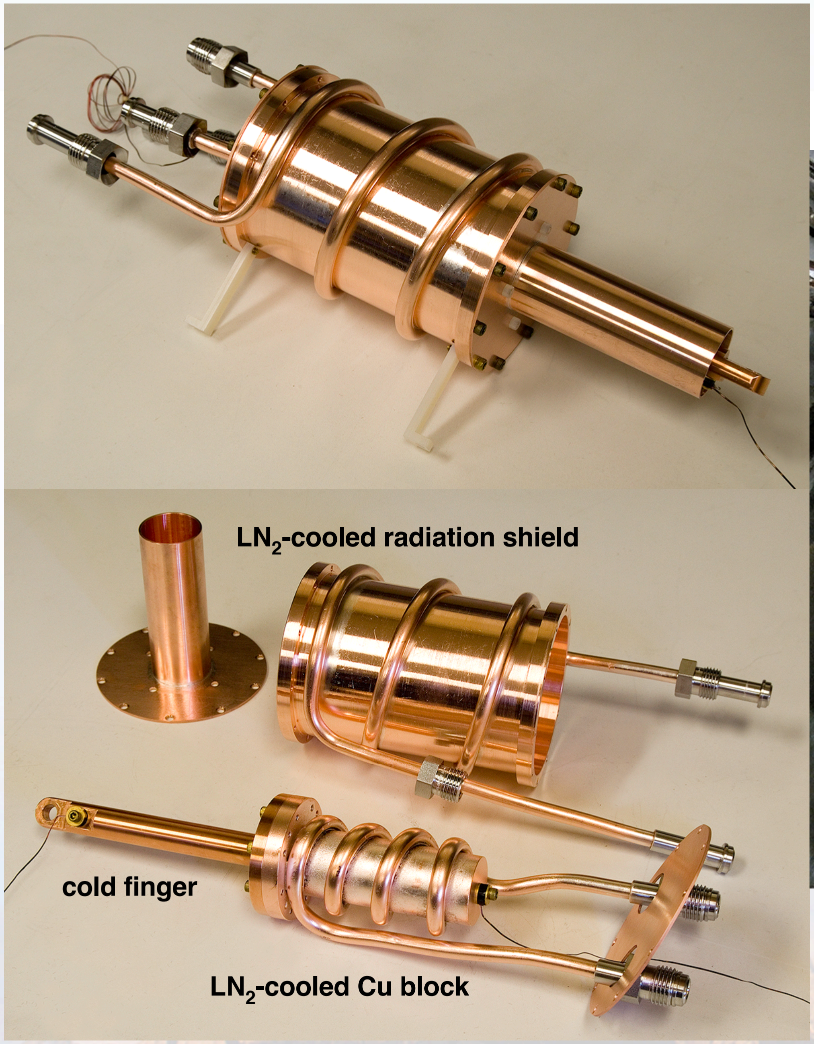
The material and dimensions of conducting elements and heater locations, as well as the cryostat design and cryogens used for cooling can be varied to achieve the required temperature range

We have developed a *modular toolkit* of cryogenic components including cryostats, conducting elements, radiation shields, and heaters to permit cooling over a temperature range of 10-200 K

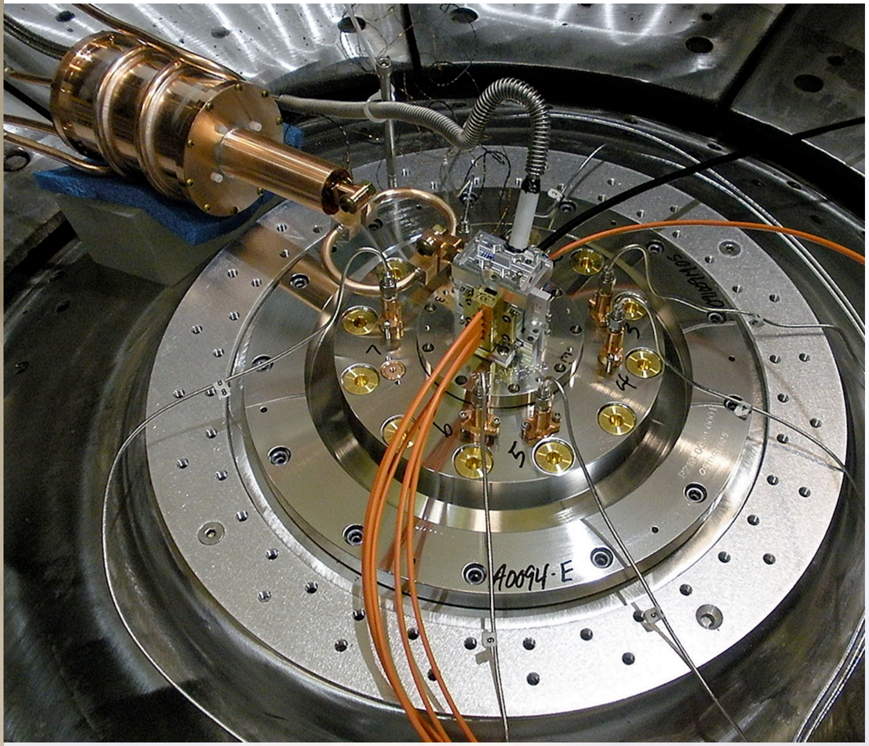

Flex links


Shielded cold rod details

We use a variety of different system configurations to condense other cryogenic liquid samples (Ar, Kr, Xe, N2, Ethane) at higher temperatures

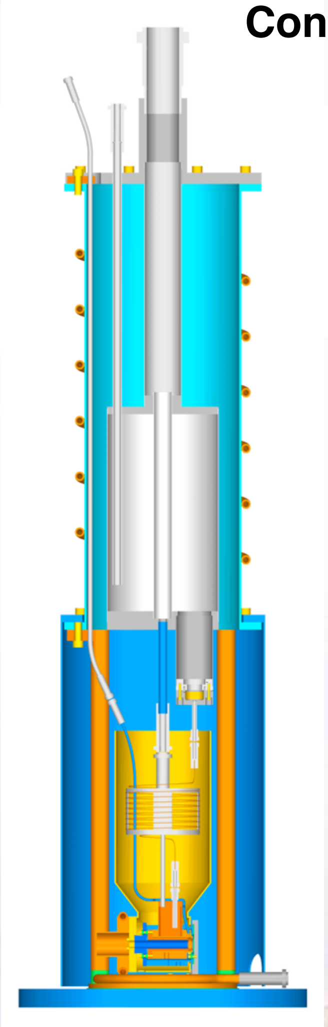


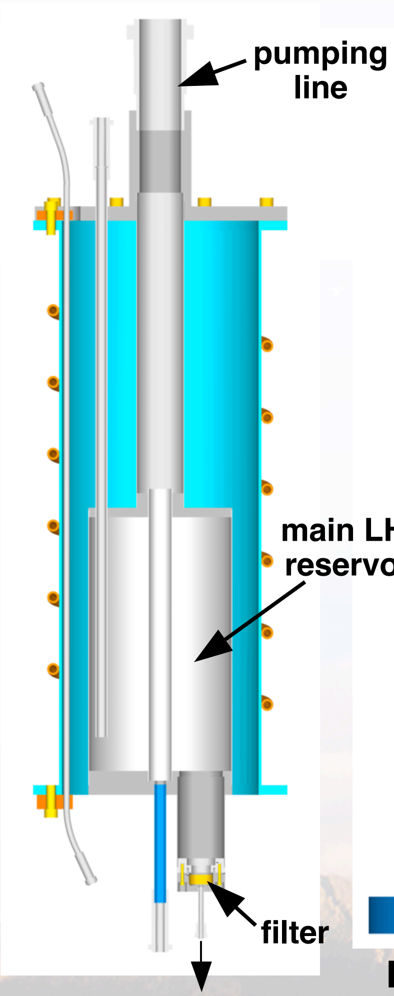
Simple LN$_2$ cooling coil cryostat with flex links for condensing Kr samples at 117.5 K



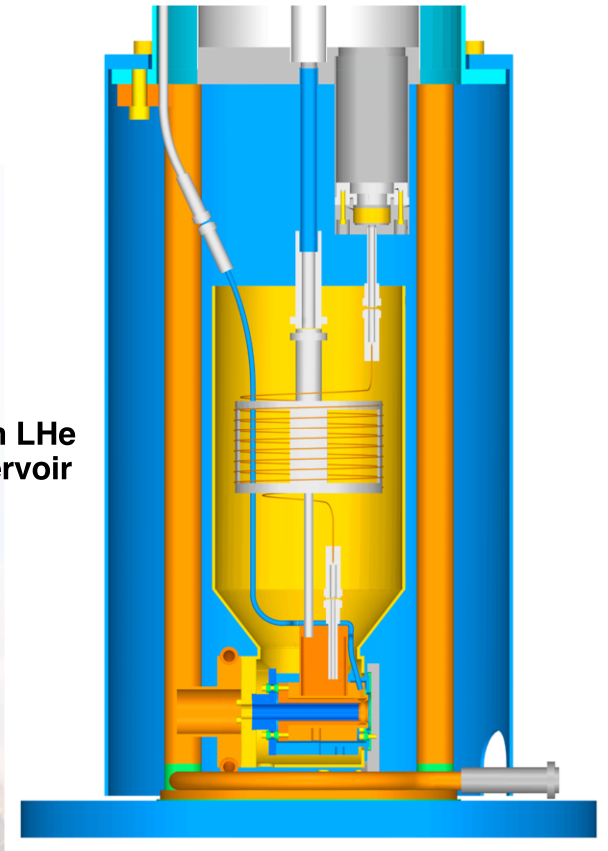
We are developing the capability to condense superfluid liquid helium samples at 1.6 K for shock compression experiments

Continuous-flow evaporation refrigerator with capillary flow impedance





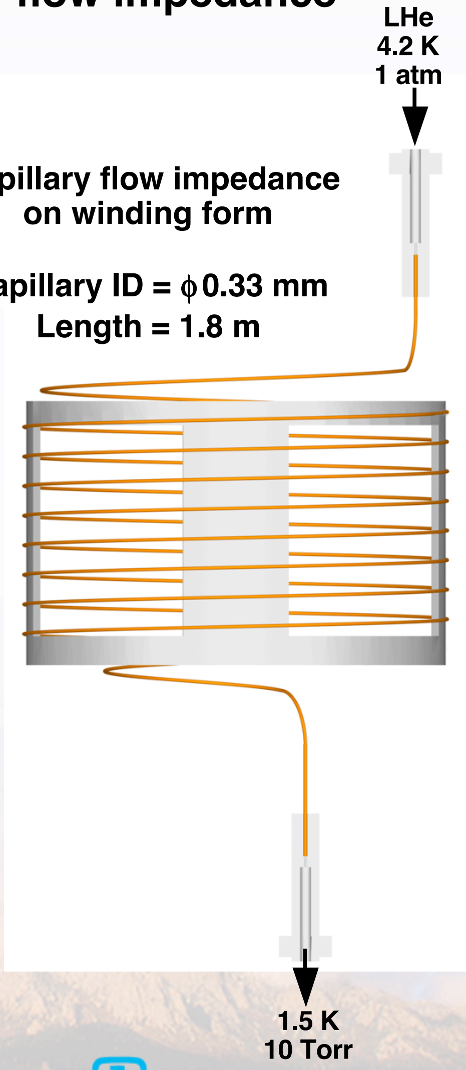
LHe Cryostat



Evaporation refrigerator target assembly below LHe cryostat

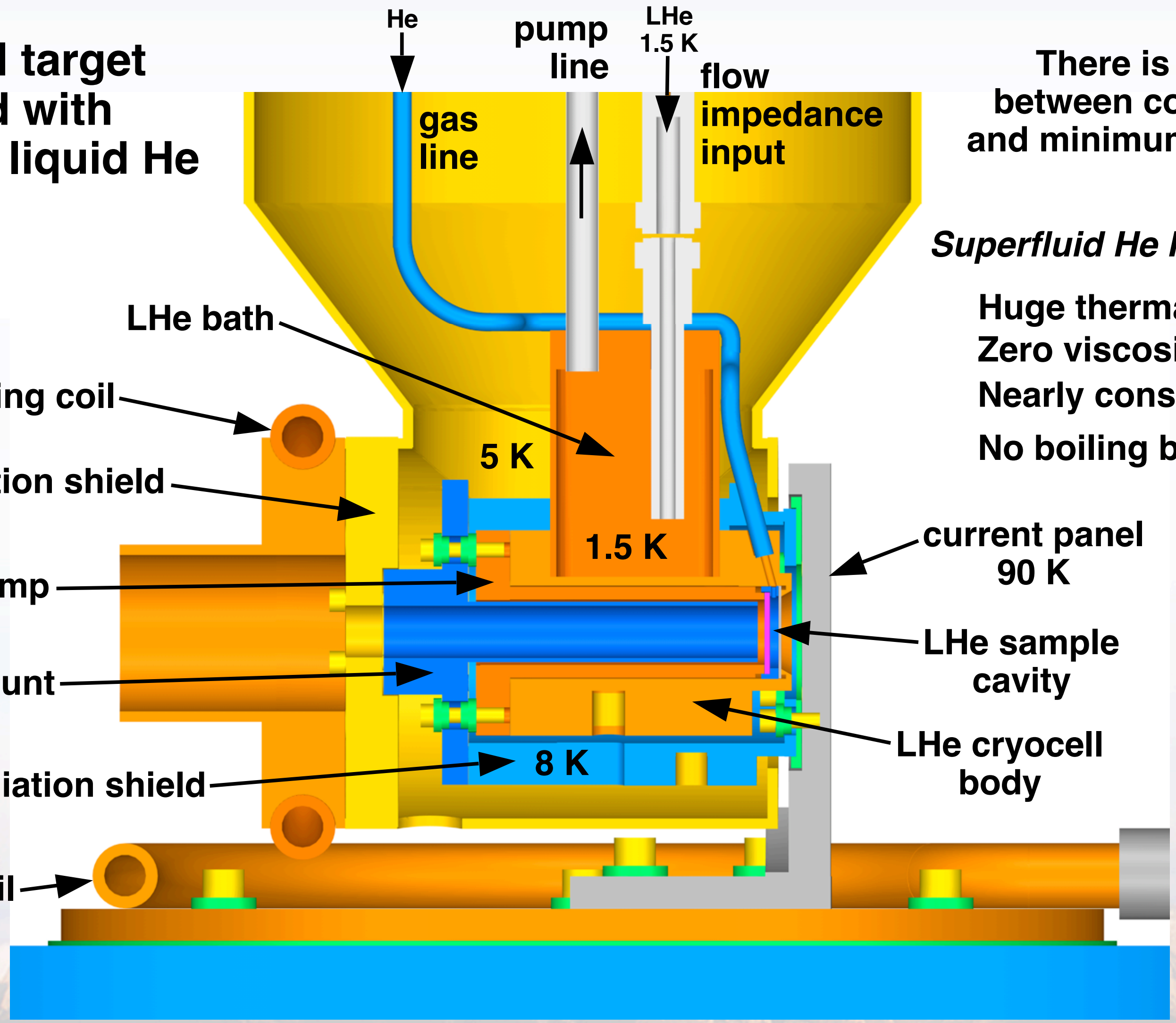
Capillary flow impedance on winding form

Capillary ID = ϕ0.33 mm
Length = 1.8 m



Additional layers of radiation shielding are required to reduce the heat loading on the cryocell target to the few mW level

Cryocell target cooled with superfluid liquid He



He

gas line

pump line

LHe 1.5 K

flow impedance input

LHe bath

LHe cooling coil

outer radiation shield

window clamp

probe mount

inner radiation shield

LN_2 cooling coil

5 K

1.5 K

8 K

current panel 90 K

LHe sample cavity

LHe cryocell body

There is a tradeoff between cooling power and minimum temperature

Superfluid He II properties:

Huge thermal conductivity
Zero viscosity
Nearly constant ρ for $T < T_\lambda$
No boiling below λ point

Prototype hardware has been fabricated for proof-of-principle testing

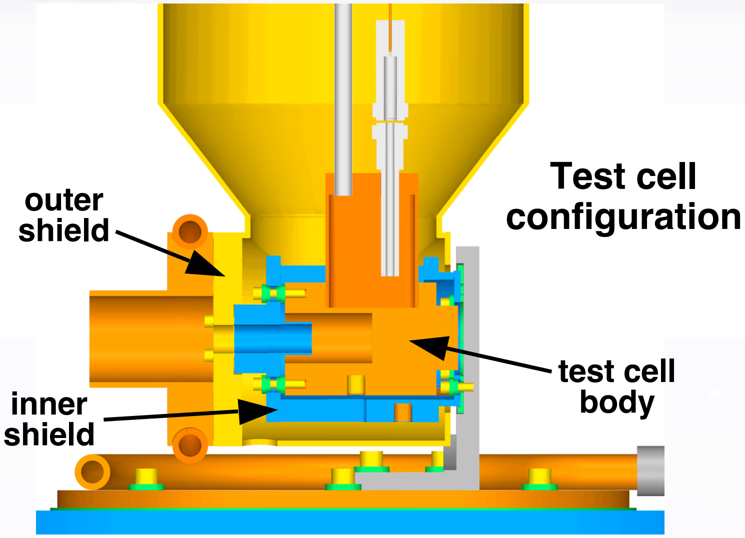
Evaporation refrigerator with cryocell target

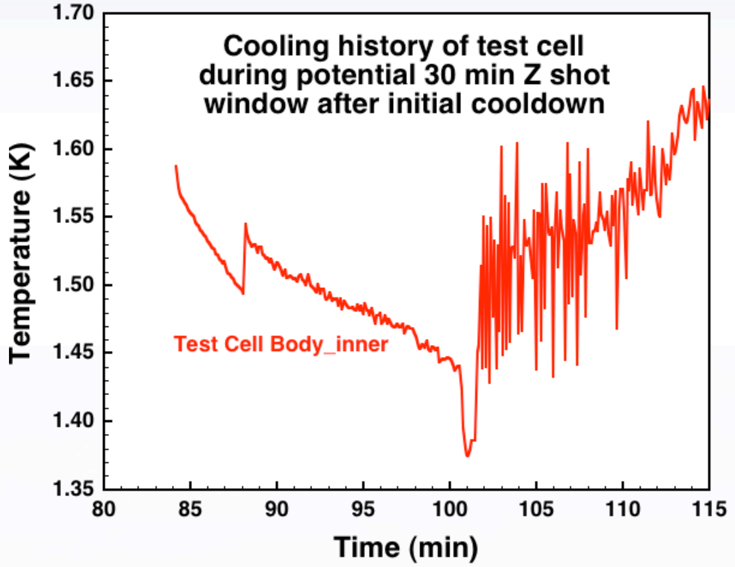
Complete system with LN_2-cooled radiation shield

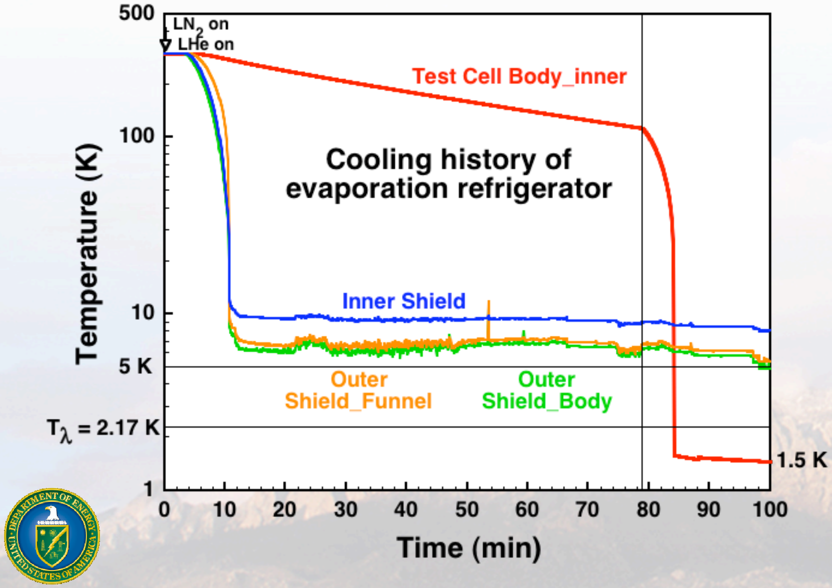
Outer target radiation shield assembly with LHe cooling coil

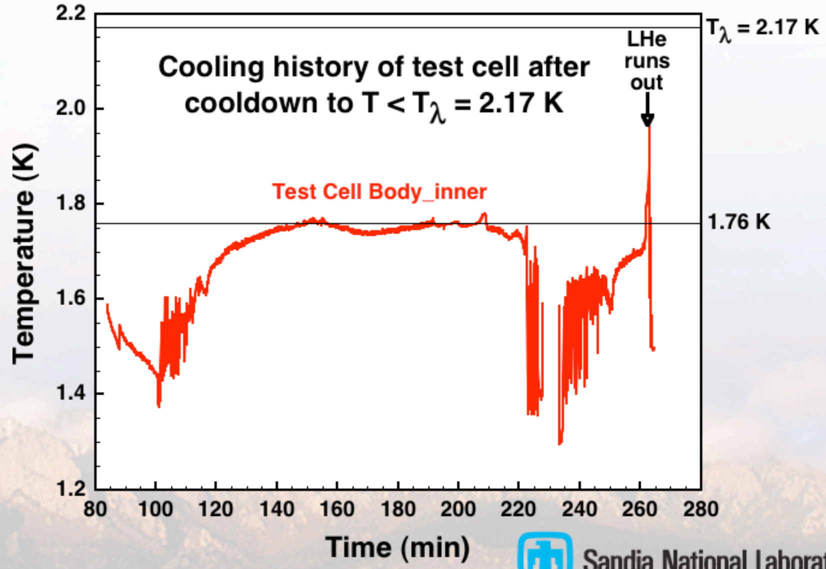
Capillary flow impedance and pumping line connections

We have performed cooling tests to demonstrate operation of evaporation refrigerator with flow impedance at $T < T_\lambda = 2.177$ K

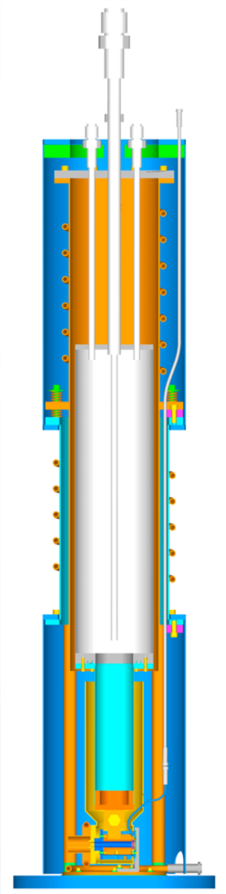




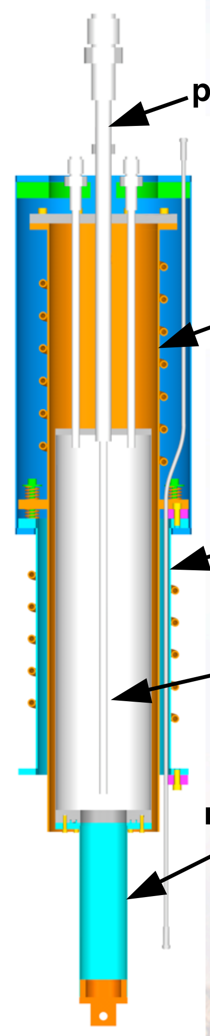




We are also testing an alternative system where the LHe cryocell is cooled by direct conduction to an expendable cryostat

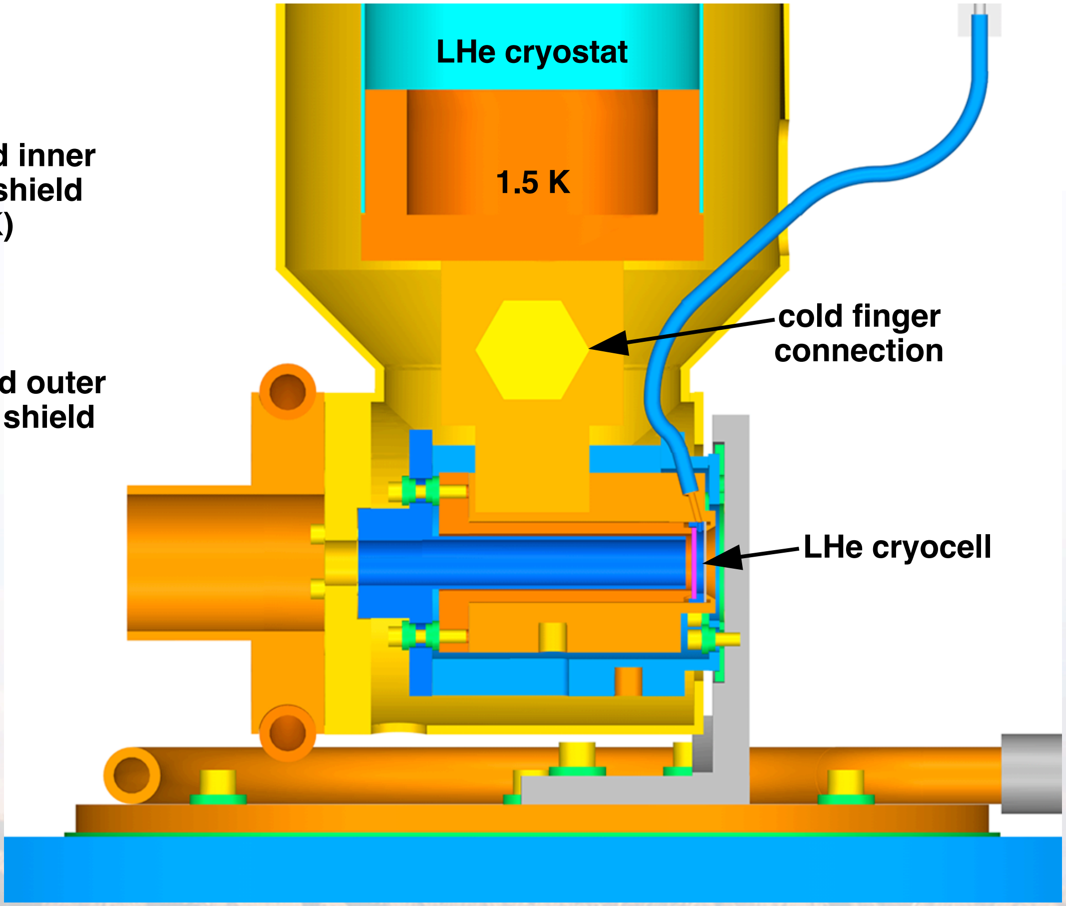


Conduction refrigerator

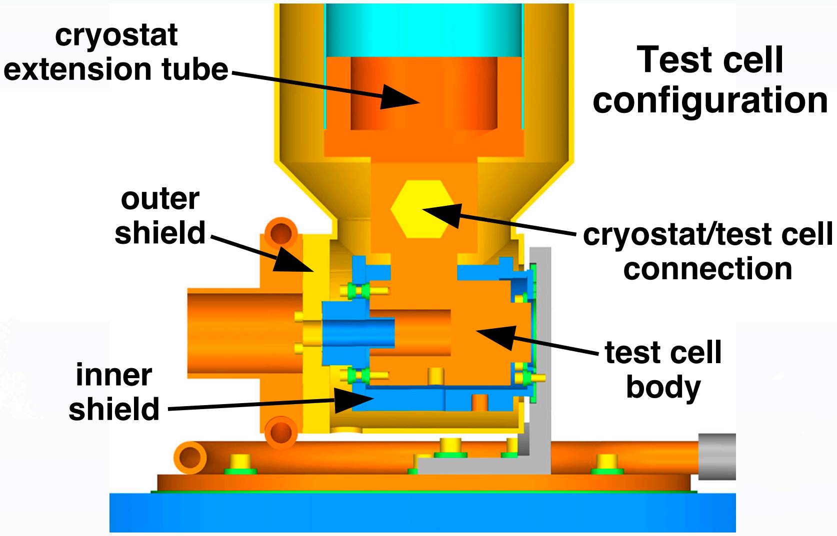


LHe cryostat

Cryocell cooled by conduction refrigerator with pumped LHe bath in expendable cryostat



The pumped-bath LHe conduction refrigerator allows relatively easy assembly, rapid cooldown, and extended operation



Test cell configuration

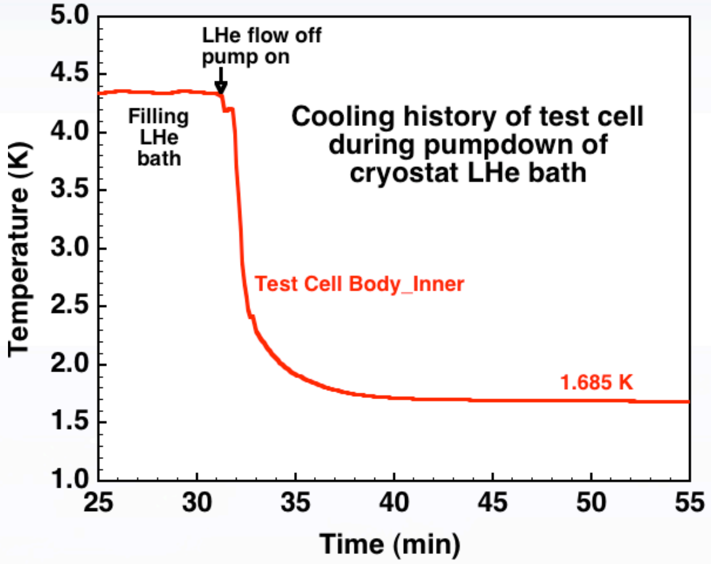
cryostat extension tube

outer shield

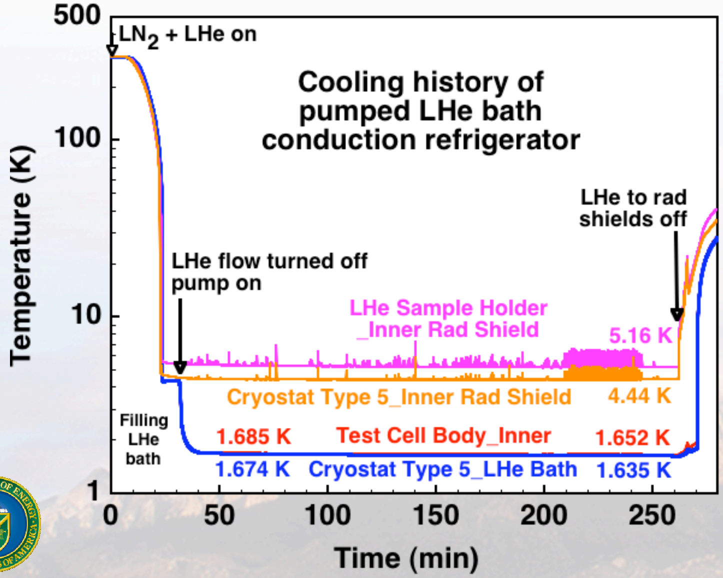
inner shield

cryostat/test cell connection

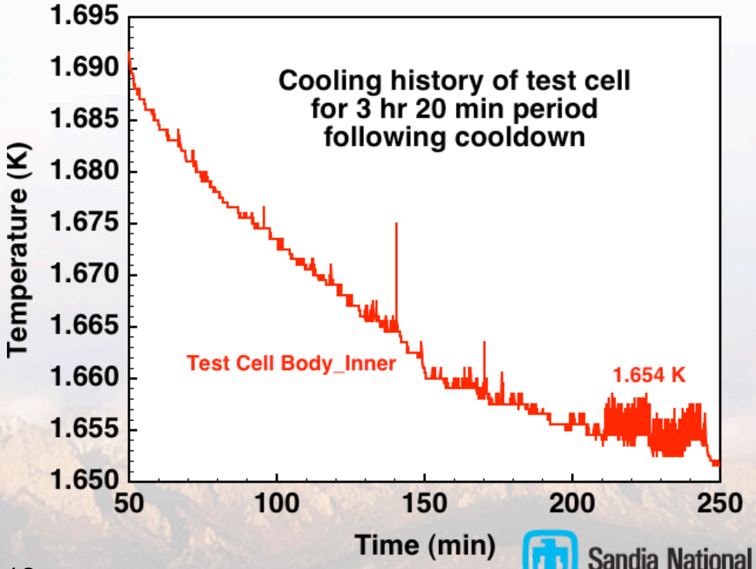
test cell body



Cooling history of test cell during pumpdown of cryostat LHe bath



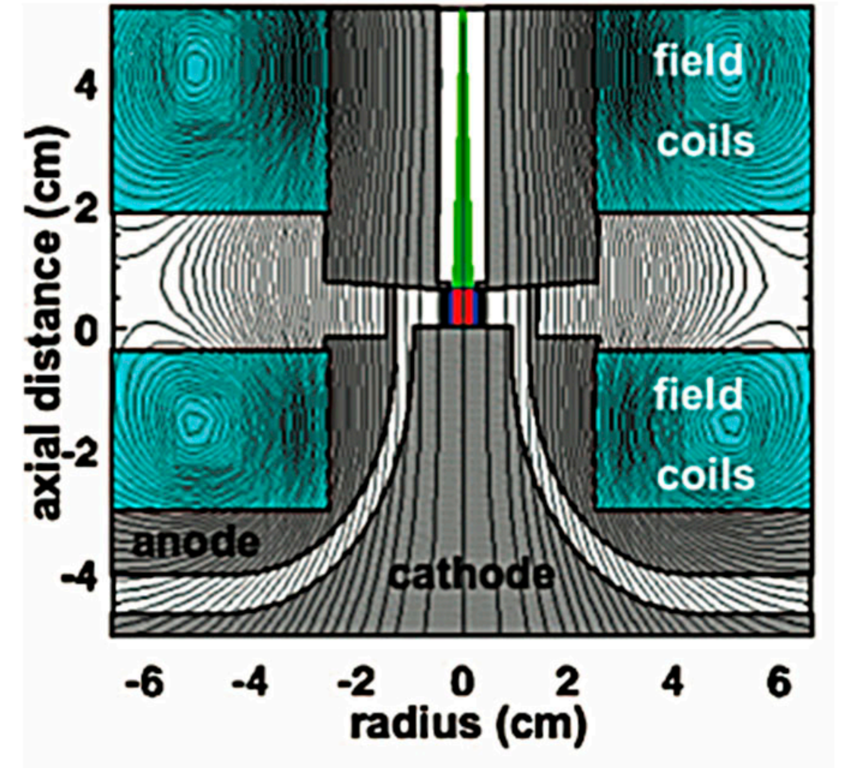
Cooling history of pumped LHe bath conduction refrigerator



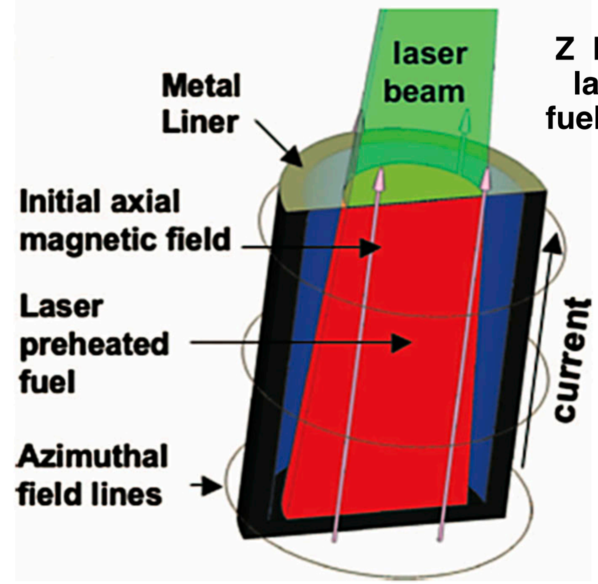
Cooling history of test cell for 3 hr 20 min period following cooldown

We are also developing LD_2 target systems to support future experiments testing the MagLIF (Magnetized Liner Inertial Fusion) concept on Z

Geometry of MagLIF concept including field coils, electrodes and laser entrance path



See S. A. Slutz *et al.*, "Pulsed-power-driven cylindrical liner implosions of laser preheated fuel magnetized with an axial field", Phys. Plasmas 17, 056303 (2010)



Z Beamlet laser for fuel preheat

Z current driver

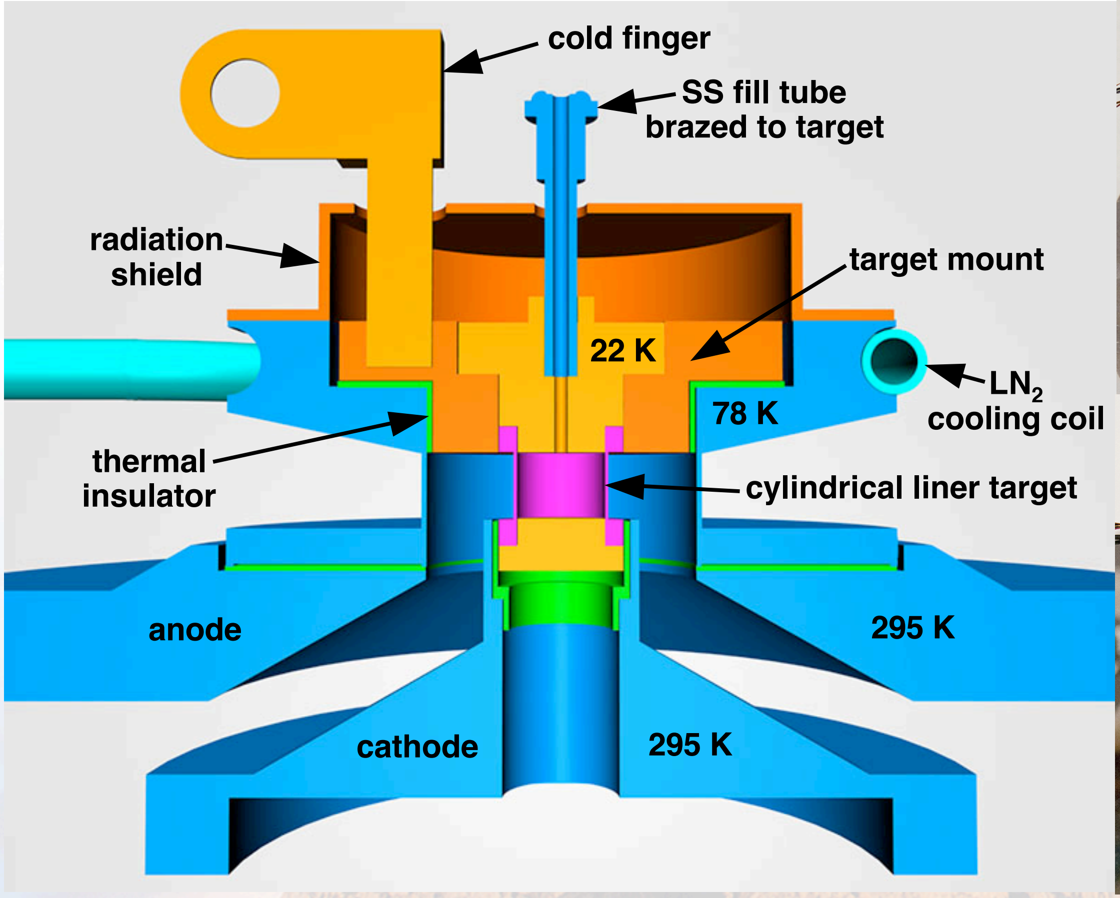
The MagLIF concept involves efficiently imploding a cylindrical metal liner to compress D-T fuel in form of gas preheated to reduce required compression and magnetized with an axial magnetic field to inhibit thermal conduction and enhance alpha particle deposition

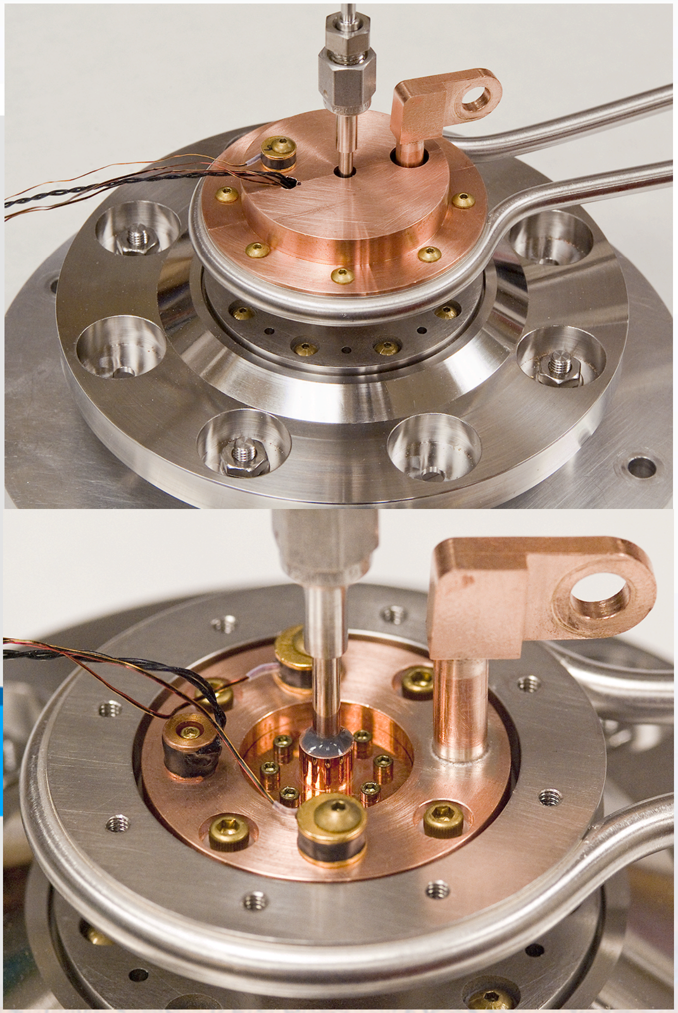
High gain MagLIF concepts require a cylindrical cryogenic D-T shell (liquid or ice) surrounding the preheated fuel

As a first step toward developing wetted-foam annular layers for this application (a partial fill problem), we adapted cryogenic systems from our DMP work to fill metal liners with LD_2 in a Z load geometry

We tested a simple Z target configuration - a cylindrical metal liner completely filled with LD_2 - in preparation for wetted-foam shell development

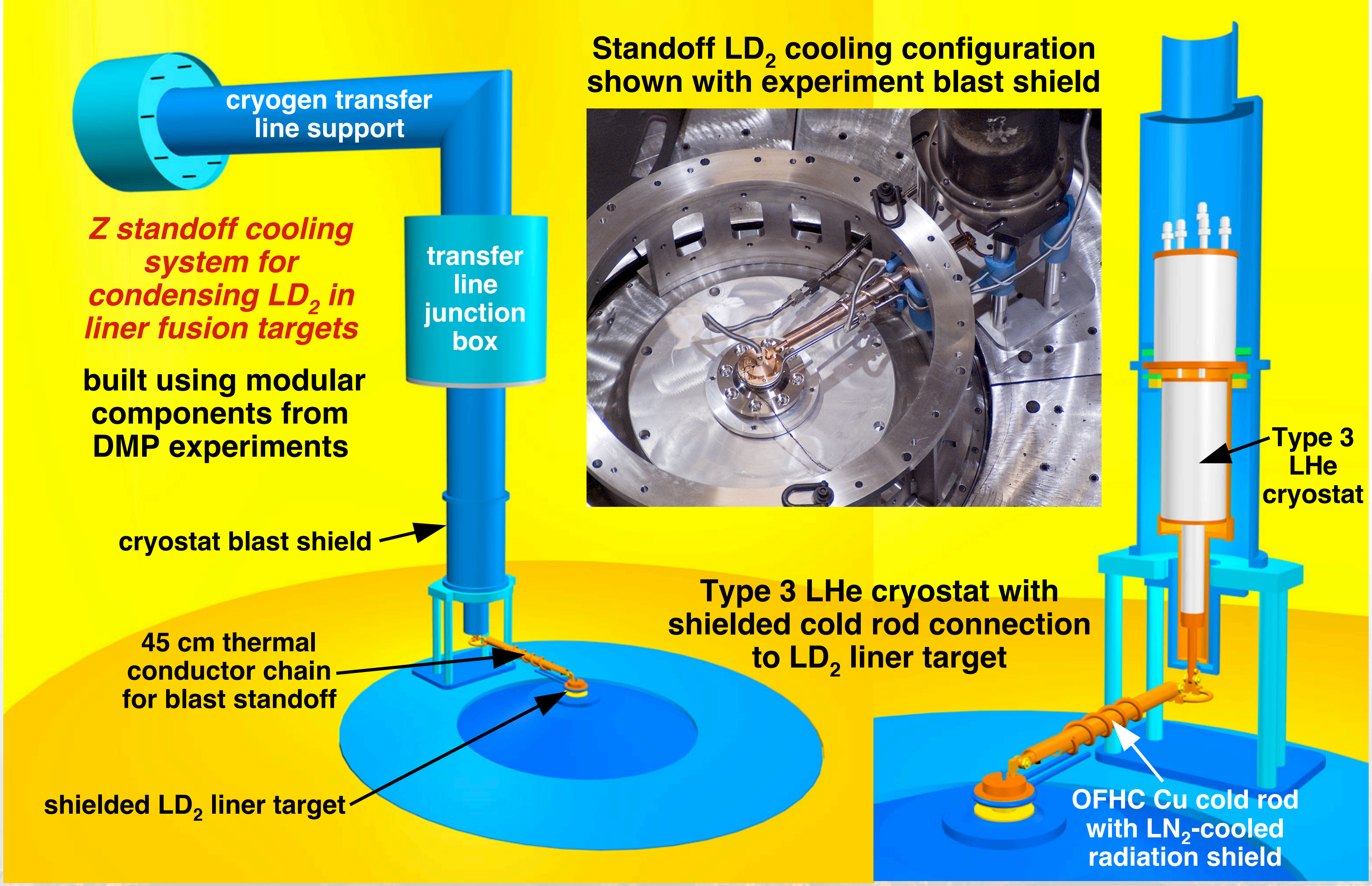
Cryogenic cylindrical liner target and radiation shield integrated with Z power feed





This initial thermal test configuration will require some modifications to accomodate top-mounted laser access and an axial magnetic field

The radiation-shielded metal liner target has a lower heat load than the unshielded DMP cryocell, permitting cryostat standoff for increased survivability



cryogen transfer line support

transfer line junction box

Z standoff cooling system for condensing LD_2 in liner fusion targets

built using modular components from DMP experiments

cryostat blast shield

45 cm thermal conductor chain for blast standoff

shielded LD_2 liner target

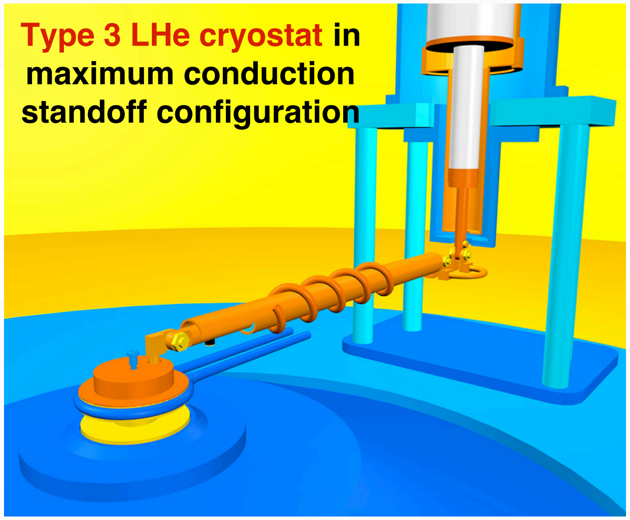
Standoff LD_2 cooling configuration shown with experiment blast shield

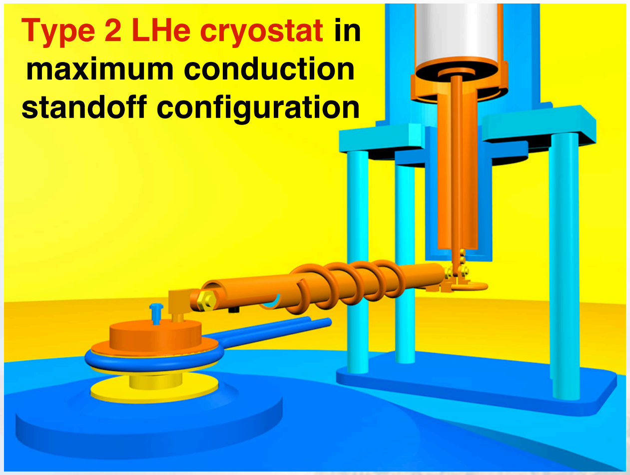
Type 3 LHe cryostat with shielded cold rod connection to LD_2 liner target

Type 3 LHe cryostat

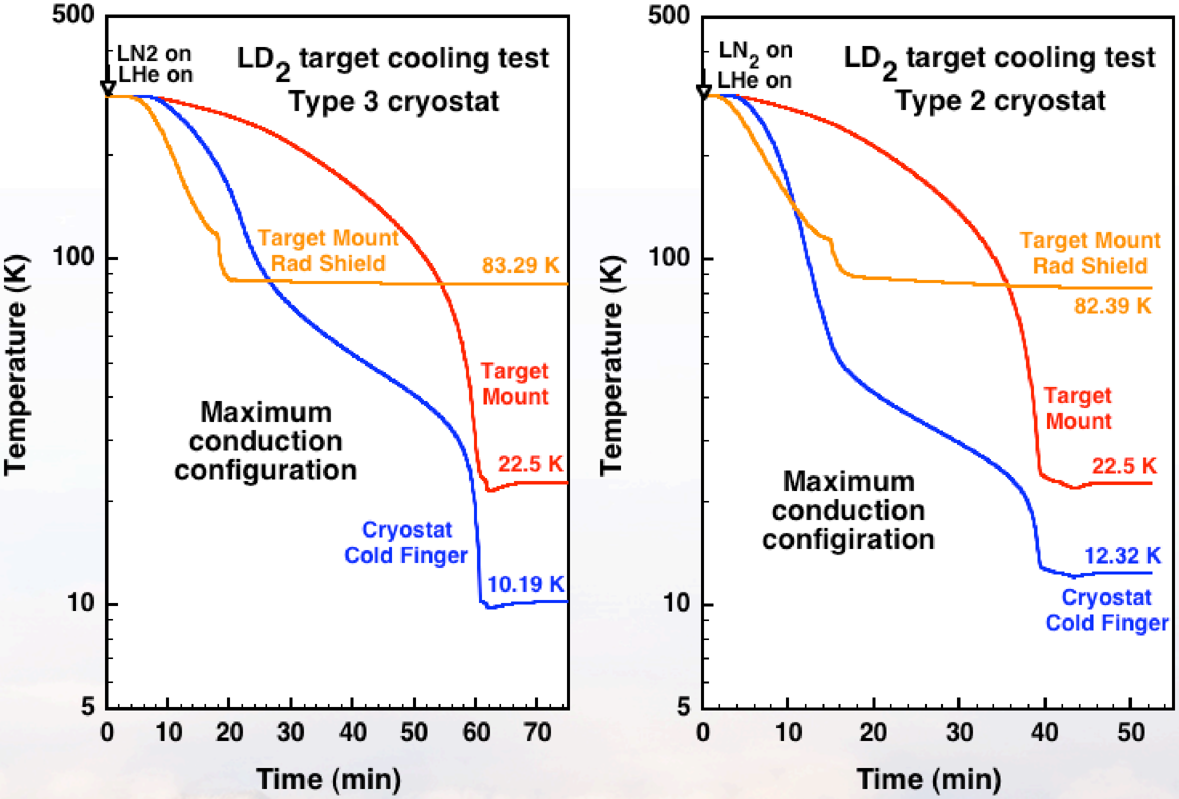
OFHC Cu cold rod with LN_2-cooled radiation shield

Cooldown of the metal liner test target in the standoff configuration requires longer than DMP cryocells with close-coupled cryostats





The Type 3 cryostat provides more cooling power at the target but the Type 2 cryostat configuration cools down more quickly

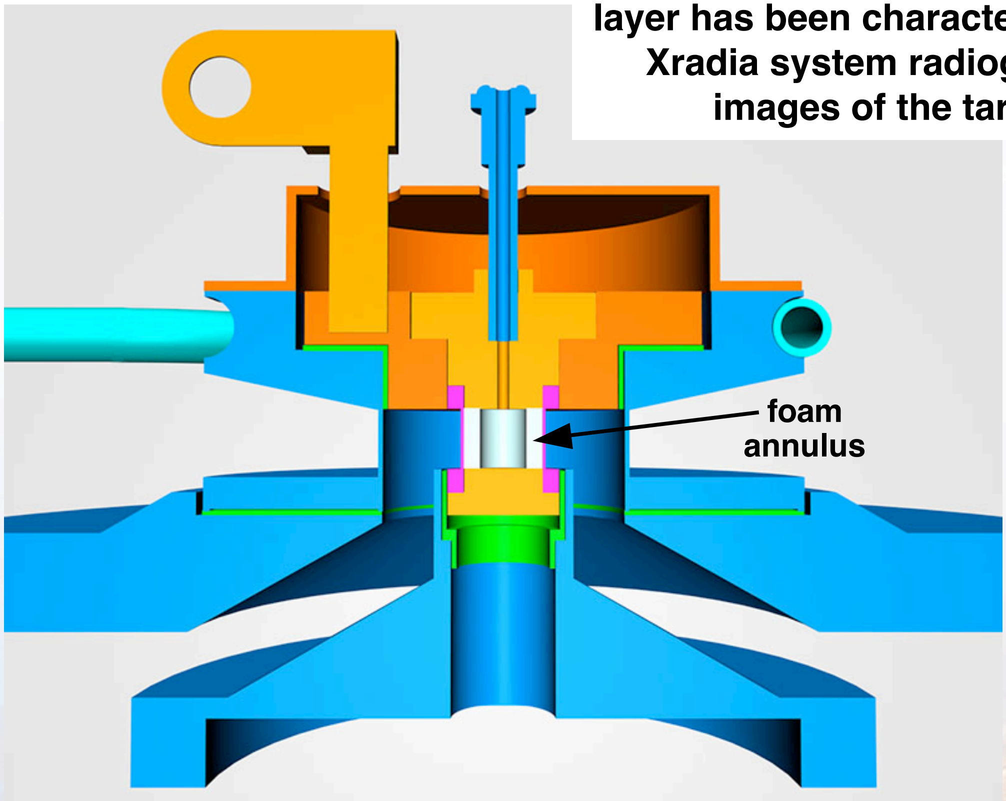


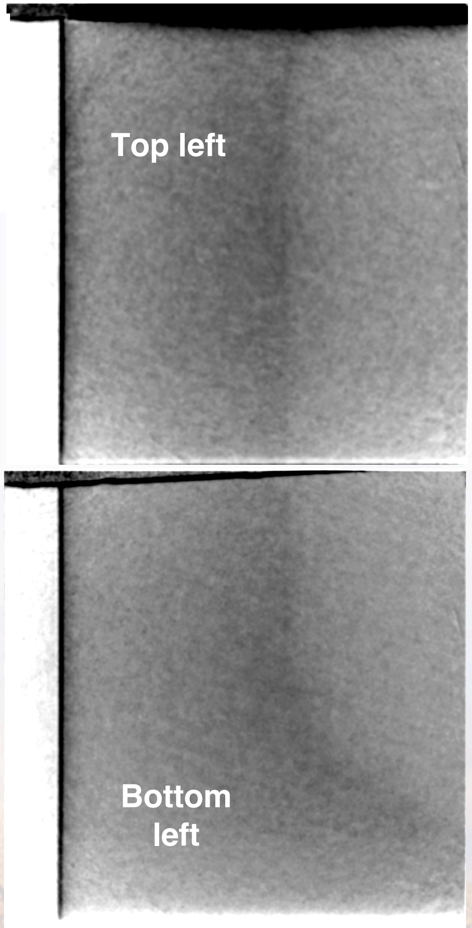
Both systems, when operating in the LD_2 target T range of 20-26 K at 18 psi fill pressure, use only the the target mount heater for temperature control

Simulations indicate high-gain MagLIF is possible with a dense layer of D-T fuel inside the metal liner surrounding the magnetized preheated gas

An initial step in meeting this requirement has been achieved in development testing by wicking LD_2 into an annular foam layer on the inside surface of the metal liner

The wetted-foam annular LD_2 fuel layer has been characterized with Xradia system radiographic images of the target





See A. J. Lopez, “Advanced Wetted-Foam Technologies at the Z Facility”, poster, this conference

Summary

- We have demonstrated the capability to generate cryogenic target samples on the SNL Z accelerator for a wide range of dynamic material properties and fusion experiments
- A new Cryogenics Development Laboratory allows cryogenic target system prototypes to be thoroughly tested before fielding on Z
- We have developed a toolkit of modular cryogenic components and Z load hardware modifications together with a flexible LabVIEW-based cryogenic data acquisition and control system to allow rapid planning and execution of cryogenic experiments on Z
- Cryogenic target systems spanning the temperature range from 10 to 190 K have been used to condense liquid samples for Z experiments
- Cryogenic target systems are under development to condense superfluid liquid ^{4}He samples for He EOS measurements and to condense annular fuel layers inside cylindrical metal liners for future MagLIF experiments