

# **NCSX Cryogenic Systems Peer Review/Workshop**

**April 23, 2008**

**Steve Raftopoulos**  
*NCSX Cryogenic Systems WBS(17 & 62) Manager*

# Goals of this review



- **We have been charged to bring the design of the NCSX Cryogenic Systems to a level of greater maturity/lower risk.**
- **Our goal is to be at the Preliminary Design Review (PDR) level by the end of August 2008. That's only ~4 months!!!**
- ***This peer review is the starting point of this effort. Goals:***
  - ***To gain expert opinions concerning the Cryostat, LN2 distribution system, cool-down and methods proposed for both coil cooling and cool-down.***
  - ***To develop the framework for Statements of Work to provide NCSX with technical support for this effort with participants such as you.***

# Specific tasks which we need to complete by August



## Bringing the systems to Preliminary Design level requires:

- **Systems requirements** defined.
- **Analyses** (thermal, mechanical, etc) necessary to support current elements of design and indicate changes are not necessary.
- **Interfaces** defined.
- **ES&H requirements defined** – Show that implementation of this design (through Installation & Operation) conforms with all PPPL, DOE, State and Local ES&H directives.
- **Models/Drawings** – Sufficient to support developmental design and analytical evaluation of the inherent ability of the design to attain the required performance. Drawings shall be sufficient to develop manufacturing & construction/installation approaches and cost estimates.
- **FMEA/Risk Analyses** – Failure Modes and Effects Analysis completed at the component and function level.
- **Manufacturability** – Design's manufacturability has been validated.
- **Constructability** – Demonstrate that design can be constructed/installed.
- **Operations** – Demonstrate confidence that the design will function reliably when placed into service.
- **Cost/Schedule** – Develop cost & schedule estimate with high level of confidence.

# Scope & status of the NCSX cryogenics system elements



- Design of the Cryostat for the NCSX Stellarator
  - Baseline design developed through PDR in '05.
- Design & analysis of the Cooling System (LN<sub>2</sub> and/or GN<sub>2</sub> distribution) that cools contents of the Cryostat (initial cool-down & during operation)
  - Currently pre-conceptual.
- Design of the magnet LN<sub>2</sub> distribution system.
  - PDR scheduled for June 3.
- Design of the LN<sub>2</sub> supply system.
  - Currently pre-conceptual.

# Salient Issues

- Can we successfully operate with a cryostat that is constructed with a modular, panelized design and has 125+ penetrations?
  - Seals between panels & at ports are of particular concern.
- Recommendations for effectively (and evenly) cooling the contents of the cryostat to minimize thermal stresses?
- Have we adequately addressed the LN<sub>2</sub> distribution system & flow balancing of LN<sub>2</sub> through the multiple coil cooling passages?
- Are there any obvious things that we've missed?
- Are there any safety related items & Code requirements that you would pass onto us?

# Areas where we feel we need expert support



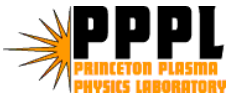
- It is our intention to seek formal agreements for technical support. The tentative list below is our current thoughts as we begin this review. We hope to refine it based on our discussions and review our refined thoughts with all of you this afternoon with more specific details:

## SOW 1 - Cryostat and GN2 cryostat cooling

- Develop new or validate current concepts.
- Develop concepts for panels and penetrations into viable designs.
- Design cooling system that includes the hardware and the process for cooling the contents of the cryostat per the requirements.
- Establish cost estimates for fabrication.

## SOW 2 for the LN2 distribution and control

- Verify current and perform additional flow calculations.
- Develop controls logic.
- Develop flow diagrams & schematics.
- Specify components.



# What are we asking for? (end of day)



- Today (**Move to closing discussion**)
  - Give us candid critique of our current design plan(s)
- Immediate Future
  - Are you interested in possibly being involved in follow-on work ? Alternatively, can you point us to resources that may be experts in the areas needed.
    - Please let us know if you have questions on contractual arrangements that might be possible for this phase.
  - Even if you do not participate in the engineering/design follow-on work, would you be willing to participate in future design reviews or technical discussions?
- Not-so-Near Future
  - Fabrication. We will need to openly compete the fabrication contract(s). Please let us know if you'd be interested in receiving a Request for Quotation when it is issued.



# NCSX Cryostat and Cooling of Stellarator Core

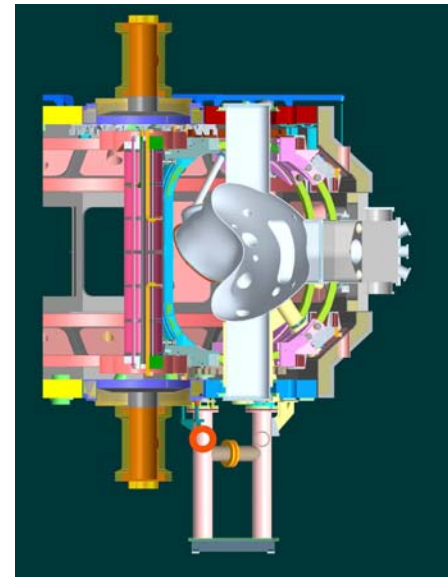
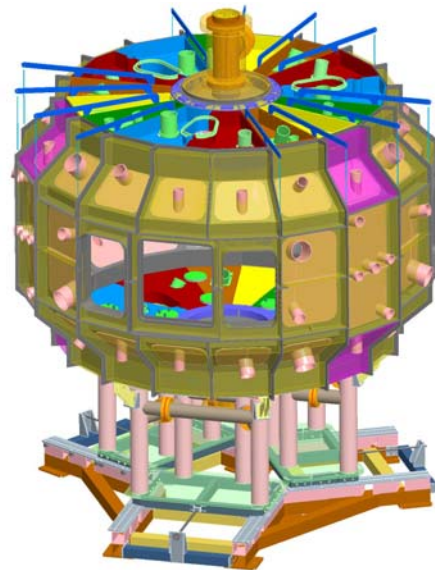
Steve Raftopoulos  
*NCSX Cryostat WBS(171+623)*



# Introduction

The cryostat (WBS 171) is an insulating, semi-hermetic barrier that will allow the surrounding of the stellarator core with a cold nitrogen atmosphere down to a temperature of 77K.

The semi-hermetic nature of the cryostat excludes the components of atmosphere from approaching the stellarator core in the design temperature range (77K to 311K).



# Requirements WBS 171 (cryostat)



- Must be gas-tight to internal positive pressure.
  - Small leaks are a nuisance, large leaks are expensive, very large leakage may risk ability to operate stellarator, in-leakage of air may damage components.
- Must provide penetrations for vessel extensions, electrical & hydraulic lines, stellarator supports, etc.
  - Shall be have provisions for custom configuration, i.e. future penetrations.
- Shall allow access to internal volume for stellarator maintenance
  - Demountable design
  - Removable panels.
- Shall withstand vacuum vessel displacements ( $\sim 1/4$ " radial) due to thermal expansion/contraction.
- Shall withstand displacements ( $\sim 1/4$ " radial) due to movement of the coil/coil support structure during magnet pulse and cooldown.
- The cryostat design, including penetrations and joint sealing, shall limit the influx of ambient heat to about 14 kW.
  - In order to limit LN2 usage to  $\sim 2$  trailers per week.

# Requirements WBS 171 (cryostat)

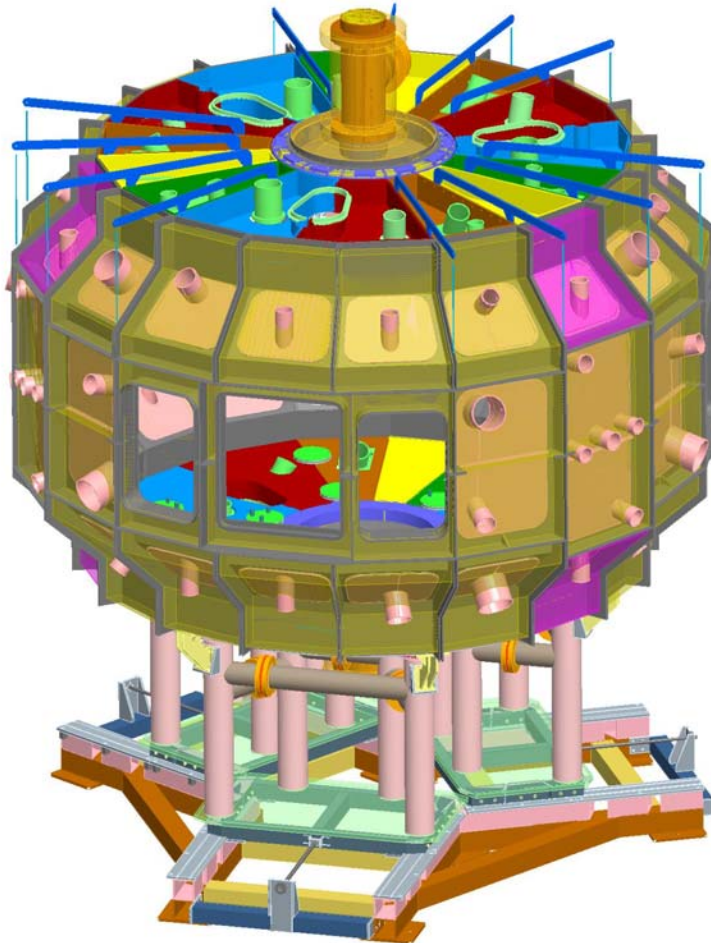


- Cryostat panels shall contain a feature allowing the admission of ambient temperature nitrogen gas.
  - Inhibits the oxygen enrichment of the panel system
  - Retards frost build up.
- Ability to relieve overpressure situation.
  - Pressure monitoring, LN2 isolation
- Shall be compatible with all indentified ES&H requirements and best practices.

# Interfaces

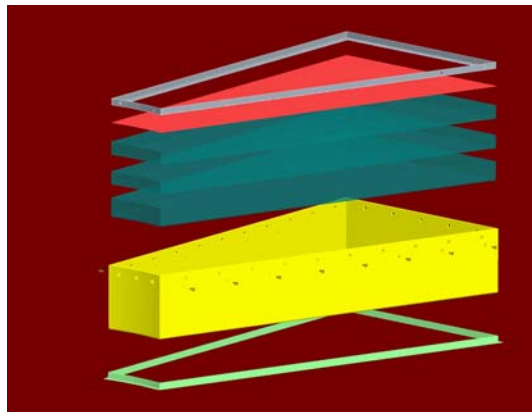
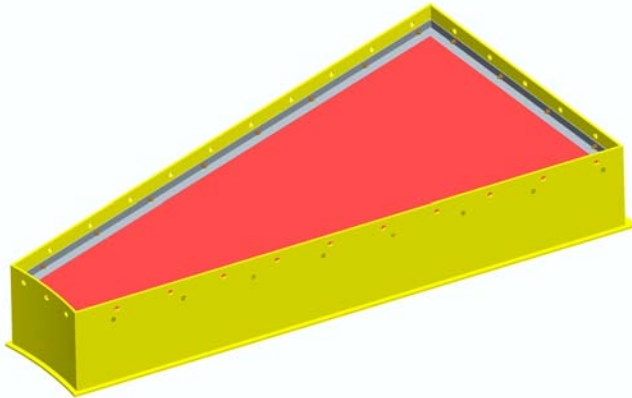
- **MECHANICAL**
  - EVERYTHING is either within or passes through the cryostat. A system interface document will address all interfaces, including planned (and unplanned) maintenance.
- **ELECTRICAL**
  - Coil buss work
  - Signal and control cabling
- **ENVIRONMENTAL/SAFETY**
  - Test cell (maintain environment safe for occupation)
    - Oxygen deficiency in Test Cell and Test Cell Basement must be addressed
    - Oxygen enrichment must be avoided.
  - HVAC (nitrogen gas must be vented outside via ducting).

# Cryostat Design



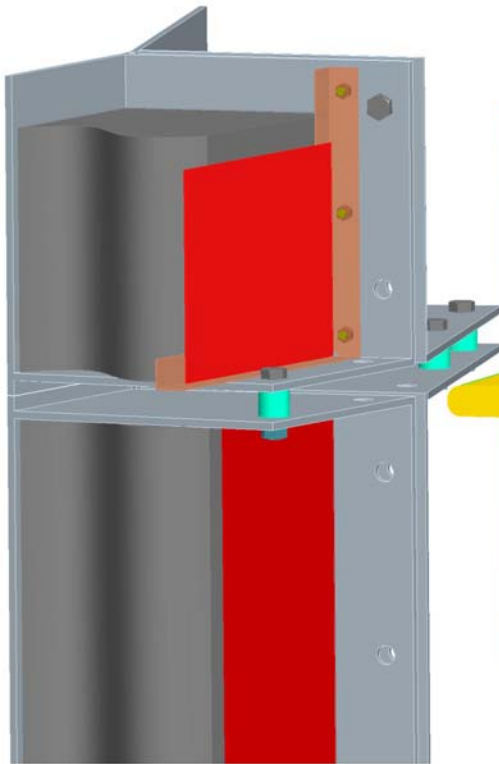
- It arrives at the Test Cell in finished sub assemblies
- Keeping with the modular concept, the cryostat is an array of panels edge-bolted together.
- The tubs have gas seals at their joining edges
- An alternative is to “foam-in-place” for the gaps between panels.

# Cryostat Panel

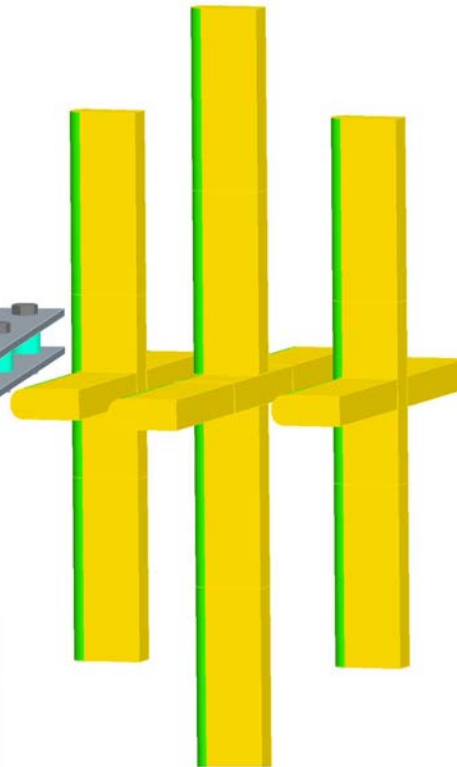


- The simple yellow panel is shown here with its cover in place.
- The cover, properly installed, results in leak-tight (1-in Water, bubble check) module.
- The module will be provided with a purge fitting for low press N2 gas to keep moisture out.
- The panel is loaded with 17 cm of closed cell polyisocyanurate board stock in layers. Any joints in the layers are staggered by several inches.
- The green 2 x 1 cm unequal leg angle is bonded in place to serve as a seal limiter for the inter-panel packing.
- The flat-head screws for the cover are insulating material (for accidental drops).

# Panel seal system



**Intersection of 4 panels.**



**Foam seal system  
(solomide + kapton)**

- Adjacent panels are joined with screw-bushing-nylok nut combinations.
- The bushings will be of insulating materials in case of accidental drop-in.
- This method of joining the warm edges of the panels together with a controlled gap between adjacent seal limiters will tolerate dimensional change in the cryostat during cool-down and warm-up cycles.
- Layers of over-thick resilient foam with PTFE tape on the edges serve as the packing for joints and for MOST penetrations
- Multiple PTFE (or kapton) membranes end reliance on a single inboard seal
- This scheme is fully serviceable from the outside of the cryostat.
- A final circular bead (not shown) seals the joint from atmosphere

# Thermal Characteristics of Candidate Materials

Material	Thermal Conductivity	Coeff of Thermal Expansion
Dow Trymer 2000 Closed Cell Foam	0.027 W/mK @ 293K	9e-5 /K @ 300K Unknown @ 77K
Inspec Solimide Open Cell Foam	0.040 @ 293K	Resilient at all temperatures of interest
G-10 Warp Direction (Inconel 718 is similar)	0.85 W/mK @ 300K 0.30 W/mK @77K	1.16e-5 /K @ 300K 5.5e-6 /K @ 77K
Teflon	0.26 W/mK @ 300K 0.23 W/mK @77K	4.2e-5 /K @ 300K 3.4e-5 /K @ 77K
304 SS	14.9 W/mK @ 300K 8.2 W/mK @77K	1.6e-5 /K @ 300K 7.5e-6 /K @ 77K



# Partial Parasitic Heat Load



- The 0.027 W/mK associated with the candidate closed cell foam suggest a constant heat load of about 5 kW through the panels only.
- 5 kW suggests the vaporization of
  - 4900 gallons of LN2 or
  - $\frac{3}{4}$  trailers per week
- The GRD offers a non-bakeout parasitic load of 2.12 trailers per week
  - The panels claim 36% of this number

# Differential Thermal Expansion

	R = 152 cm Vertical Port	R = 193 cm Outboard Leg	R = 320 cm Midpland Diag Cover
<b>Cryostat, G-10 300K to 80K</b>	-0.35cm	-0.44 cm	-0.74 cm
<b>Vessel and Graded Extensions, Inconel 300K to 650K</b>	0.65 cm		~0.8 cm (assuming some gradients in ports & ext.)
<b>Machine Base, 300 Series SS 300K to 80K</b>		-0.56cm	

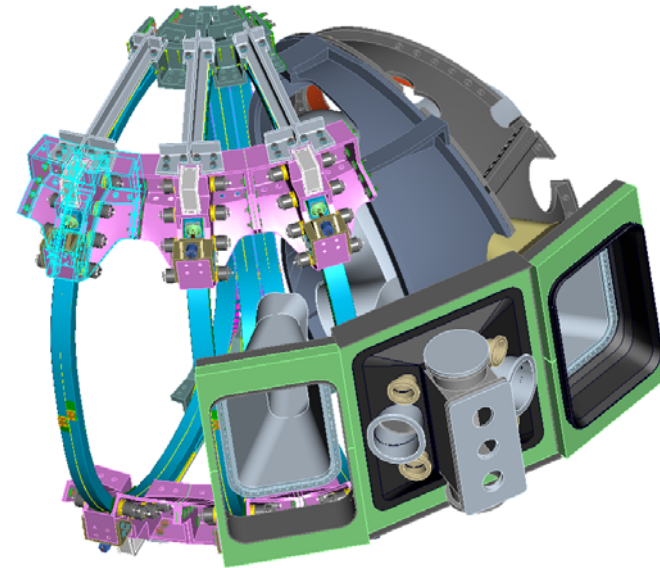
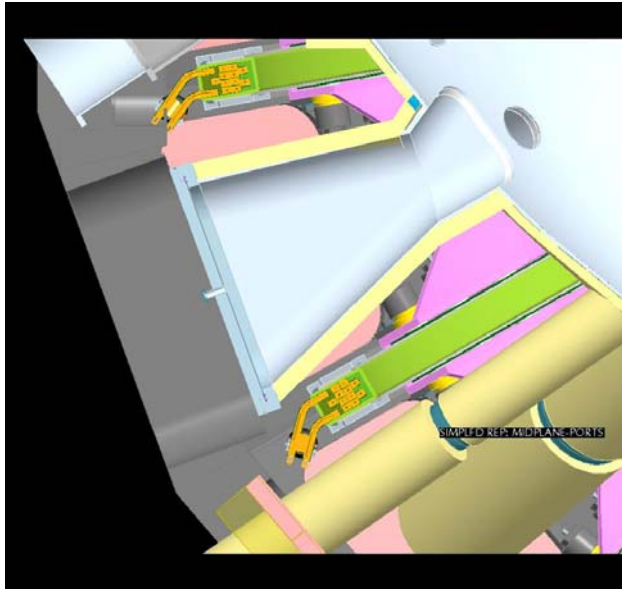
Differential expansion between the vessel and the penetrations is not trivial at 1 cm & 1.5 cm!

The cold inboard seal must tolerate this displacement AND this assumes no asymmetric vessel constraints (NB tugging vs. diags)

# Design considerations

- Pros
  - Modular panel design, allows access to stellarator as required.
  - Rigid panelized system, fabricated in relatively small sections that are easy to transport and handle.
  - Readily repairable in-situ if damaged.
  - Preliminary mechanical and thermal analysis has been done.
- Cons
  - Incorporates many linear feet of seals.
  - Unproven sealing technique – needs prototyping/proof of principle (or validation by cryo experts)
  - Panelized base of cryostat may not contain LN2 if gas condenses and accumulates as liquid.

# Special area of concern

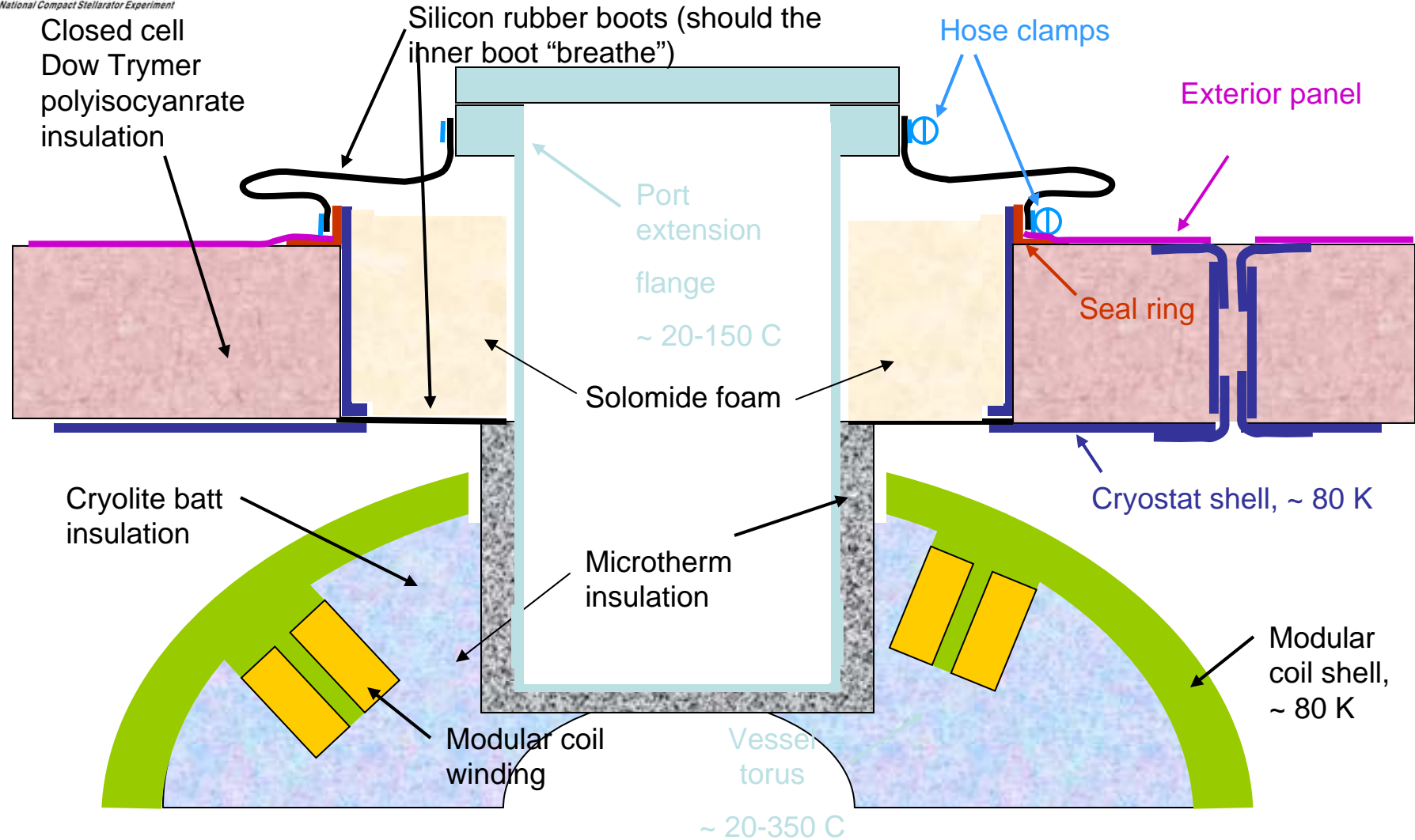


- The large VV ports intersect the volume space otherwise allocated for the cryostat. Cannot install the desired thickness of insulation.
- NB and large port seals need further development.
- We could consider a vacuum-jacketed solution in these areas.

# Design Alternatives

- A simpler cryostat (like the Alcator C-Mod), that uses a upper/lower “dome” and minimally segmented cylinder.
- One derivative of this approach would be to increase the diameter to allow access for an individual to maneuver within the cryostat
  - Pros
    - More easily sealable, reliable
    - Lower, one-piece dome would contain liquid.
  - Cons
    - Loose a large degree of accessibility
    - Adds length to the port tubes used by diagnostics (reduced aperture)
- Instead of pliable foam seal, we could “foam-in” the joints and cut them out when access is needed.

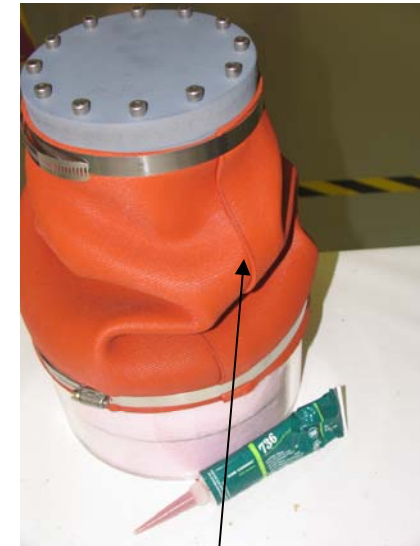
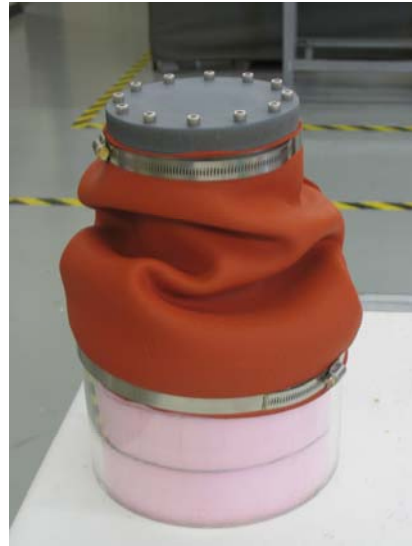
# Penetration Sealing Schematic



# Penetration Basics

- Inner boot is historically fiberglass cloth impregnated with Dow silicone compound
- The penetrations be entirely serviceable from the exterior of the machine
  - Our ever-growing concern about confined spaces AND time-for-rescue tends to call for exterior serviceability
- Inboard travel limiter to prevent packed joint seals from falling in
  - Limiter included in basic tub would be expensive
  - A value-minded engineer might glue non-conductive angle on the tub

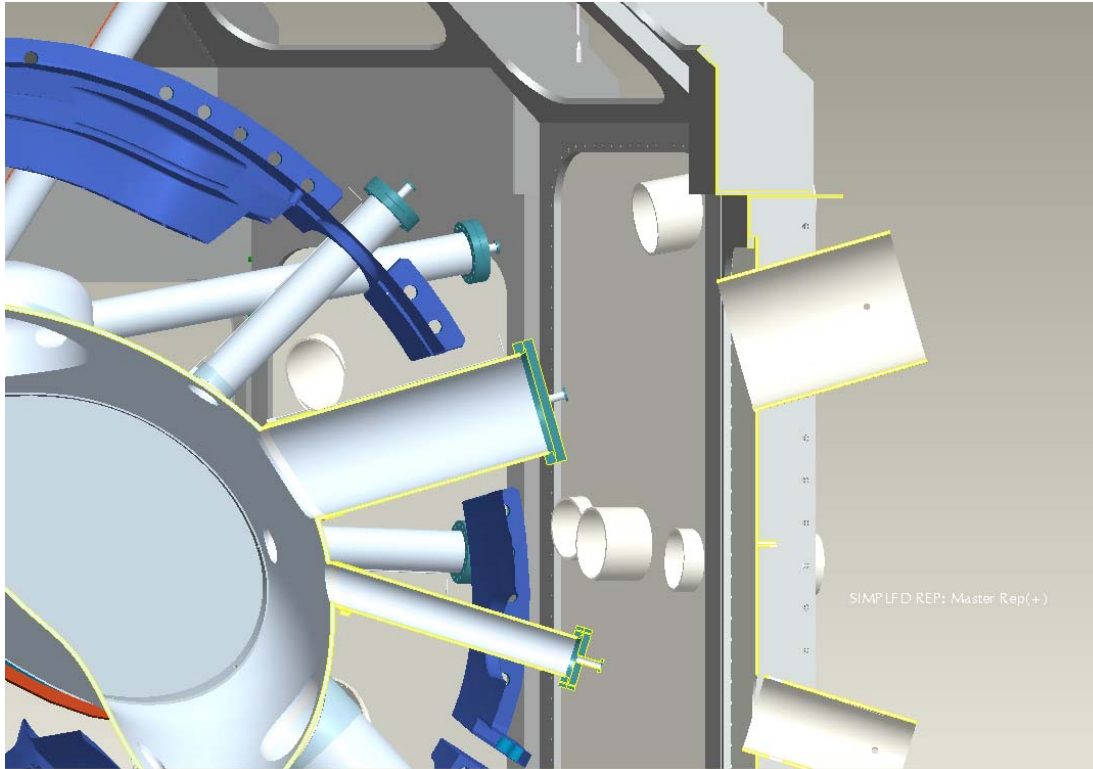
# Penetration (bag) sealing prototypes



seam glued with dow  
corning RTV 736



# Diagnostic Ports



- **Diagnostic ports penetrate at varying angles, trapping the cryostat panel.**

- **Diameter of cryostat port will have to be large enough to allow workers to access flange**

# Cooling the Contents of the Cryostat

# Cooling the Contents of the Cryostat - Requirements



- Cool the stellarator in 96 hours (soft requirement)
- Cool stellarator without introducing thermal stresses or compromising dimensional control. Limit  $\Delta T$  to 50K
- Cool the coils at the same rate as the surrounding environment.
  - May need to control the flow of cold fluid through conductors' cooling channels to ensure this is met.
- GRD also asks for the ability to warm the coils to room temperature in 96 hours

# Concerns

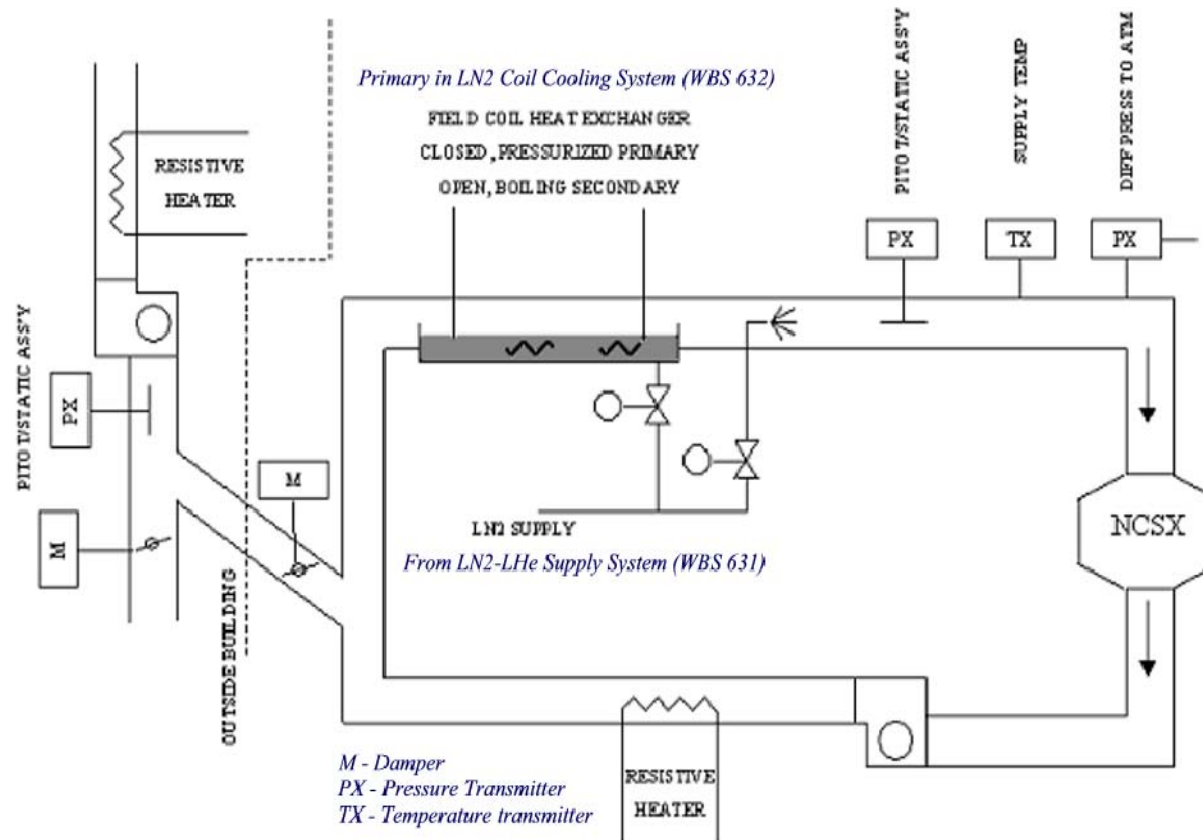
- Stratification of GN2 temperatures may result in uneven cooling of the structures.
- Cool down and warm up of system in a reasonable timeframe and without creating temperature variations.
- Cooling the coils and the structure at the same rate.
- Using LN2 for cooling may result in accumulation/condensation of liquid at bottom of cryostat. This may cause sealing issues resulting in LN2 and cold gas leaks.

# Cooling the Contents of the Cryostat - Considerations



- The Modular, Poloidal Field and Toroidal Field coils (total weight ~50,000 lb) are actively cooled via cooling channels either within or bonded to the magnet.
- The rest of the structure (~100,000 lbs in modular coil shell, and 100,000 lbs widely distributed mass) must be cooled via secondary system.
- The interface between the modular coil pack and the winding form (shell) was designed to be thermally decoupled, so conduction from the 18,000 lbs of cooled copper and 100,000 lbs of stellaloy (300 series SS derivative) is limited.
- Coil Test Facility's cryostat showed that without any mechanism to actively "mix" the cold gas, temperature stratification will result – we should expect the same result for the stellarator cryostat.
- Temperature stratification may result in temperature gradients between or across structural components and magnets. This could result in mechanical stresses and/or displacements of coil centroids which are painstakingly fabricated and positioned with very precise dimensional control. **Analysis is needed here to identify limits.**
- We are considering the used of ducted cold gas, internal mixing fans, multiple LN2 spray heads as a means to minimize stratification.

# SIMPLIFIED GN2 CRYOSTAT COOLING SUPPLY



The actual cryostat attachment points for the insulated supply and return ducts have not yet been selected. Top and bottom center are favored to promote a flow pattern having radial symmetry. Dominant loads are heat leakage from bakeout and from port extension penetrations. The cryostat's nitrogen pressure will be kept slightly positive relative to the atmosphere.

# Stellarator Cool Down Process

- Introduce temperature-controlled N2 gas into the coil cooling passages and into the cryostat.
- Using thermocouple data, drive the temperature of coils and structures down in steps at approximately 2 degree/hour (average).
- When the system is sufficiently cold (this was done @ 130K for the C1 cold testing), introduce LN2 into coil coolant passages.

# Possibilities??

- We could spray LN2 directly onto structures that are shielded from convective cooling.
- Fans for mixing operating within the cryostat.
- Conduction cooling via plates or tubing? (Alcator C-MOD recommendation).
  - May be feasible for the modular coil mass, but the 100,000 lbs of distributed mass will be difficult to cool this way



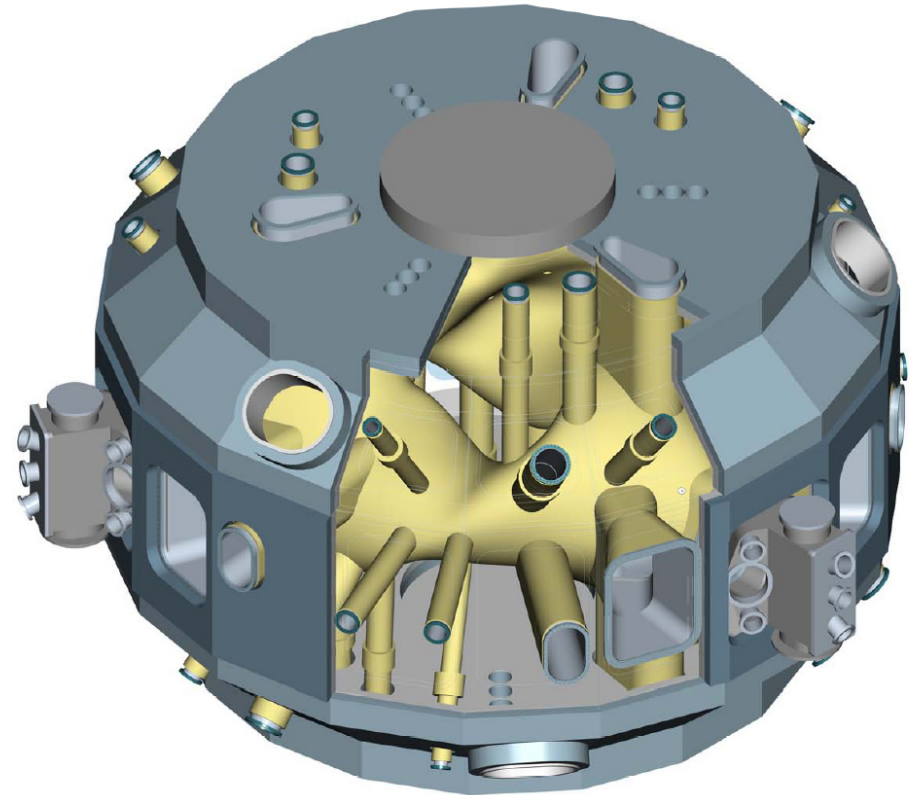
# NCSX Cryogenics Systems LN2 Distribution

Steve Raftopoulos  
*NCSX Cryogenic Systems WBS(62)*

# Overview

The stellarator core is supported by two cryogenic facility systems:

- **WBS 621** delivers LN<sub>2</sub> to the machine area.
- **WBS 622** performs heat removal from the field coils



# Requirements



- WBS621
  - Provide LN2 for distribution to:
    - LN2 Coil Cooling system
    - LN2/GN2 Structure Cooling
- WBS622
  - Provide LN2 (~210gpm @150 psig ) to coil distribution manifold (WBS16) for extracting heat from PF, TF and Modular Coils.
  - Maintain single phase flow.

# Interfaces

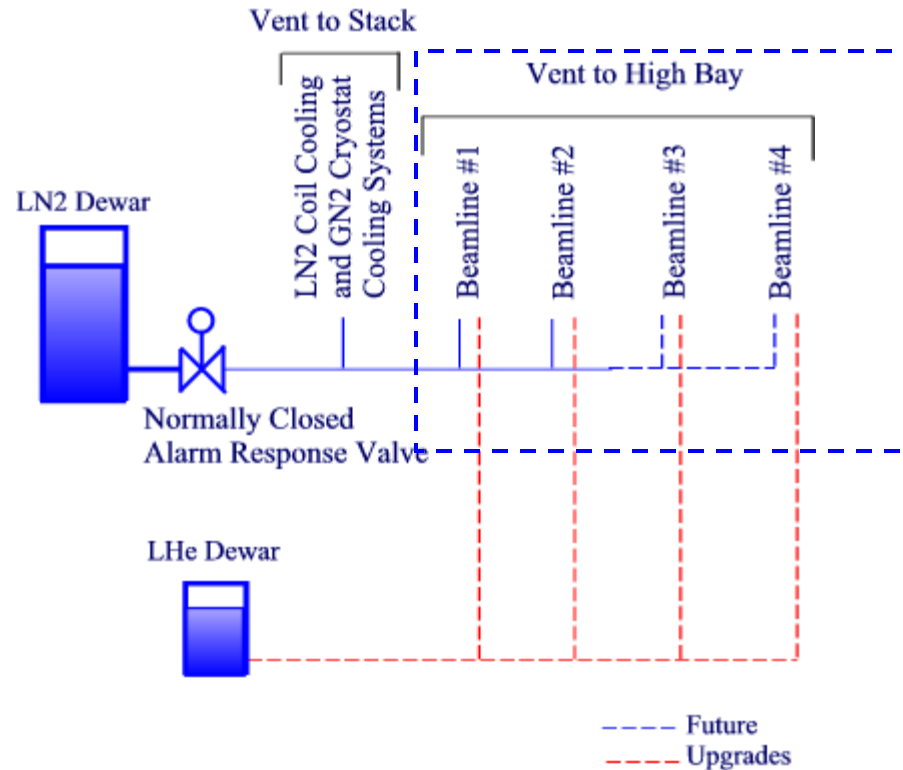
- WBS621
  - C-Site 9200-gallon LN2 tank
  - WBS-622 Coil LN2 circulation pump skid
  - WBS-623 LN2 supply to Cryostat
  - Test Cell Air monitoring system
- WBS622
  - Coil LN2 distribution manifold
  - HVAC exhaust

# Design Plans (WBS-621 LN2 supply)



- This is very straightforward.
- Flow rates, heat loads and pressure drops are already reasonably well known.
- Design will incorporate flow diagrams, and isometric piping drawings. Detailed component drawings will be minimal. This will allow many elements of the design of the system to proceed without requiring the “final” parameters.
- When final requirements for flow rates, heat loads and pressure drops are available, the components shall be procured, assembled and installed.

# SIMPLIFIED LIQUID CRYOGEN DISTRIBUTION



The cryogen distribution system makes full use of legacy equipment at C-Site. The 9200 gallon LN<sub>2</sub> dewar is ready for service. The helium off-load gear exists but requires general overhaul.

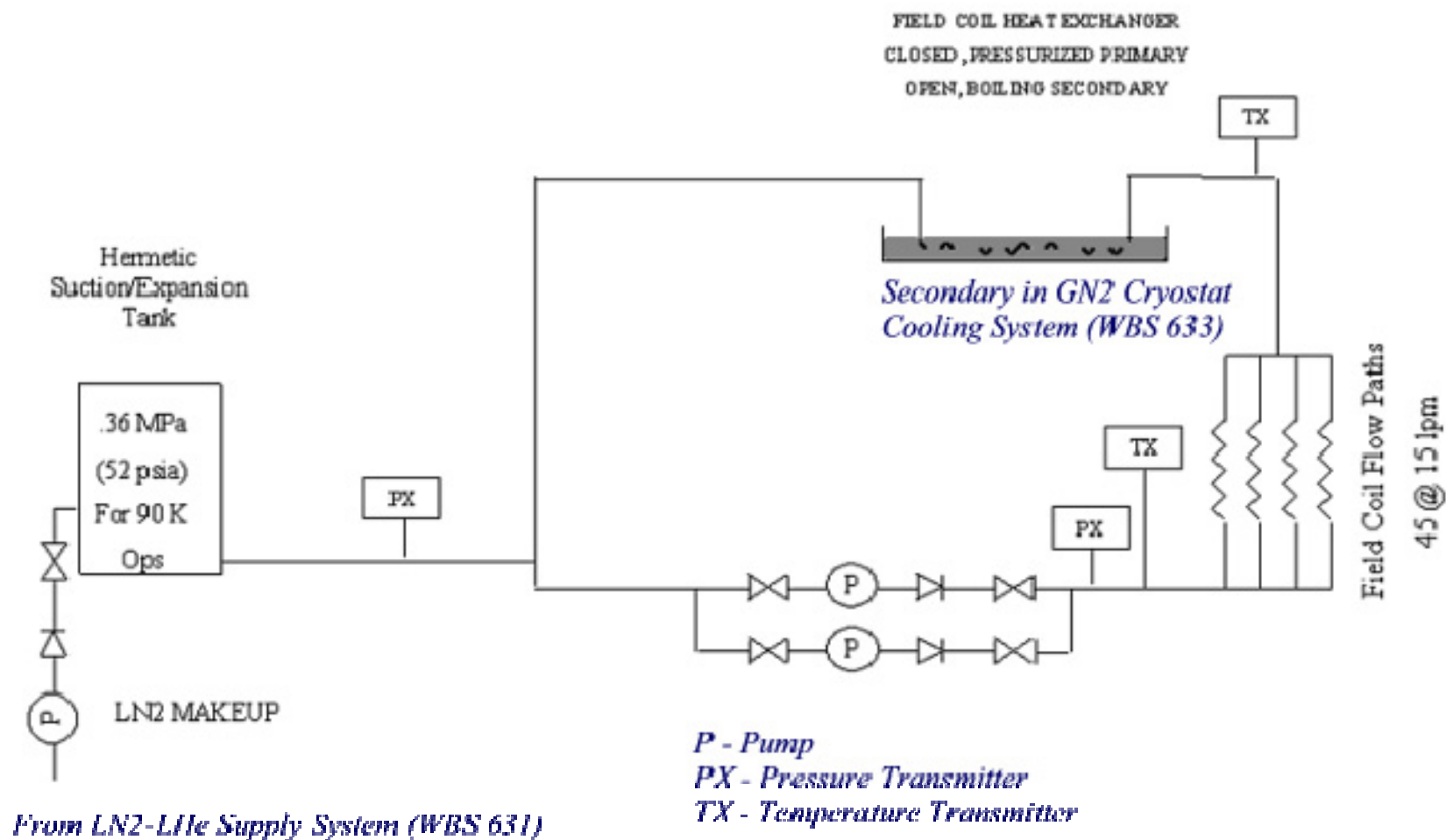
# Design Plans (WBS-622 Coil Cooling)



- A pressurized, LN<sub>2</sub> heat removal loop is planned for the field coils.
- The prototype for this loop was operated for the coil testing.
- A scaled up version of the Coil Test Facility's pump skid is required to support full field magnet requirements.
- WBS-622 scope provides system capable of removing ~50 MJ in a 15 minute recovery interval (about 56 kW avg.)

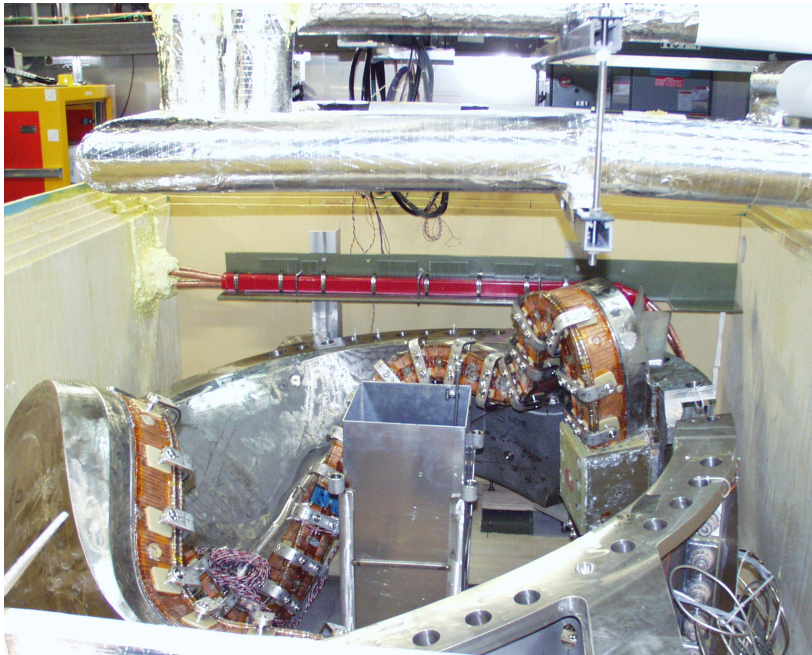


# Simplified Coil Cooling Circuit





# Design Plans (WBS-622 Coil Cooling)



- The C1 coil was cooled to the point that single phase liquid flow was established in the winding pack's coolant channels
  - A success!
  - The single phase flow approach is validated
  - Technical risk is low

# Summary



- WBS-621 LN2 supply
  - Sizing of piping is straight forward
  - Based on identified (calculated) heat loads, the capacity of existing C-site LN2 tank 9200 (gallon) is adequate.
  - Off-the-shelf components are used.
- WBS-622 Pressurized LN2 cooling for coils
  - Coil testing cooling loop validates design.
  - Full power coil heat loads have been calculated.
  - Required flow rates and pressure drops have been calculated.
  - LN2 delivery system can be sized to accommodate requirements
  - Standard industrial products make up the system.