Cooling The LSST Camera

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LSST
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†A special acknowledgement is due to Gordon Bowden (SLAC), Prof. William Little (MMR) and Samuel Spektor (MMR), who pioneered this program and the SLAC team (J. Langton, Jacob Powers, Owen Saxton), and the technical team (Howard Rogers, Jeff Aldrich, Jeff Garcia and many more….) who actually made it happen.

Every Story Has Its Beginning…..

- **When I came on-board the project, it was clear that perhaps the three biggest challenges we faced were:**
  - **Development and production of the image sensors**
  - **Assembling and maintaining the focal plane flatness**
  - **Cooling the sensors and proximate readout electronics with minimum impact on the telescope and dome environment**

These were all unprecedented challenges compared to previously constructed instruments and each has lead us down a long road of R&D

Early Trades Study Lead Us To The Choice of “Mixed Refrigerants” To Address Our Requirements:

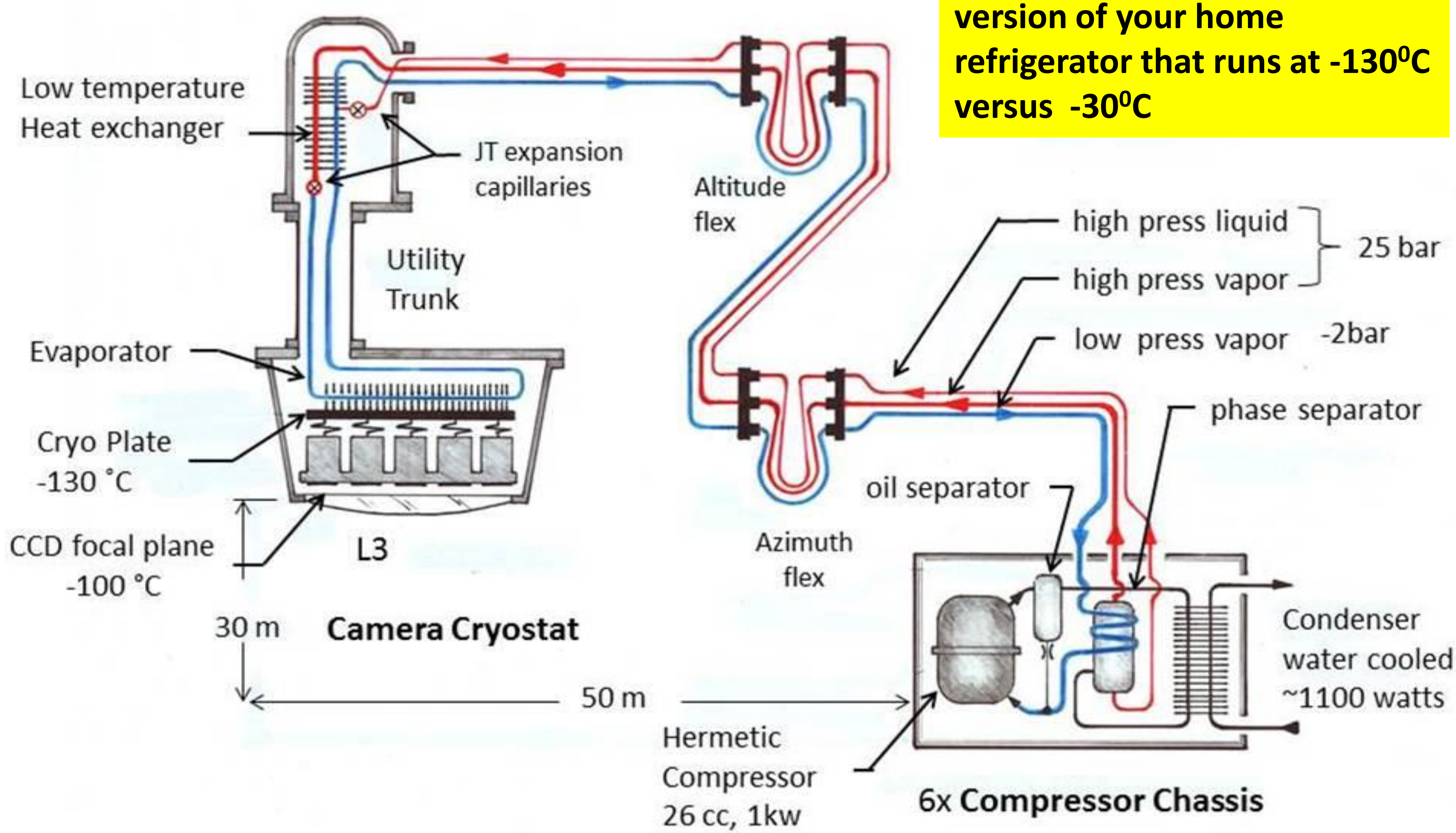
- Unprecedented heat load (at the time of CD-1) >700W at -130^{0}C and 580W at -40^{0}C).
  - Significantly larger than any previous cameras
- A 100m separation between Utilities room and Camera with a 30m change in elevation
- Survey operations requiring ~10^4 mount rotations/year (long flexible transfer lines)
- Requirement not to disturb the dome environment

Option:	LN_2 Boil-off Refrigerant	Circulating Mixed Cryo-Refrigerant (Polycold) -or- Recirculating Saturated LN_2 (DECam)	Cryocoolers: Gifford-McMahon, Pulse Tube, and Stirling Refrigerators	On-Camera Mixed Refrigerant System (MMR)
Cons:	- Large & heavy dewar - Need >217kg /day LN2 - Flexible vac insulated Cryo lines - Large stored energy	- Cryogenic Pumps - Flexible Vacuum Insulated Cryo lines (both directions) - Large stored energy - High excess heat loads	- Large and heavy - Significant low frequency vibration	- New mixed refrigerants - Sensitivity to plugging of capillaries from water or oil contamination
Pros:	- Familiar refrigerant - Low pressures	- Fairly Conventional Engineering	- Commercially Available to hundreds of Watts	-Small diam. ambient temp. refrigerant lines -Redundant parallel circuits -High thermal efficiency -Small stored energy

“Cascade Cooling”

Concept of Current LSST Mixed Refrigerant System
6 Circuits of ~85W @ -130^{0}C

A somewhat more complex version of your home refrigerator that runs at -130^{0}C versus -30^{0}C



Plan For Developing an LSST Specific Mixed Refrigerant System Emerged With Three Specific Thrusts

- Mixed Refrigerants
- Compressor System
- Counter - flow Heat Exchanger

This work primarily at MMR

These efforts were to start at MMR and transition to SLAC

Initially naïve to the fact, we learned fairly quickly that while these each represented "separate" technological challenges, they quickly became quite intimately connected by the unique requirements of the LSST Camera and Telescope system

- **Indeed, while "lab" scale "cryocoolers" are straightforward, almost none of the features required by the LSST camera & telescope implementation had ever been built– by anyone**
  - Cryogenic Nonflammable Refrigerants
  - Long Ambient Temperature Transfer Lines Separating the Compressor and HeX
  - Significant Elevation Change, and Flexibility for Articulations
  - Separation of the Evaporator (Cryoplate) from The HeX
  - Motion/Reorientation and Accelerations of the HeX

Mixed Refrigerants are Critical To LSST and Work Continues MMR to Optimize a Mix for LSST

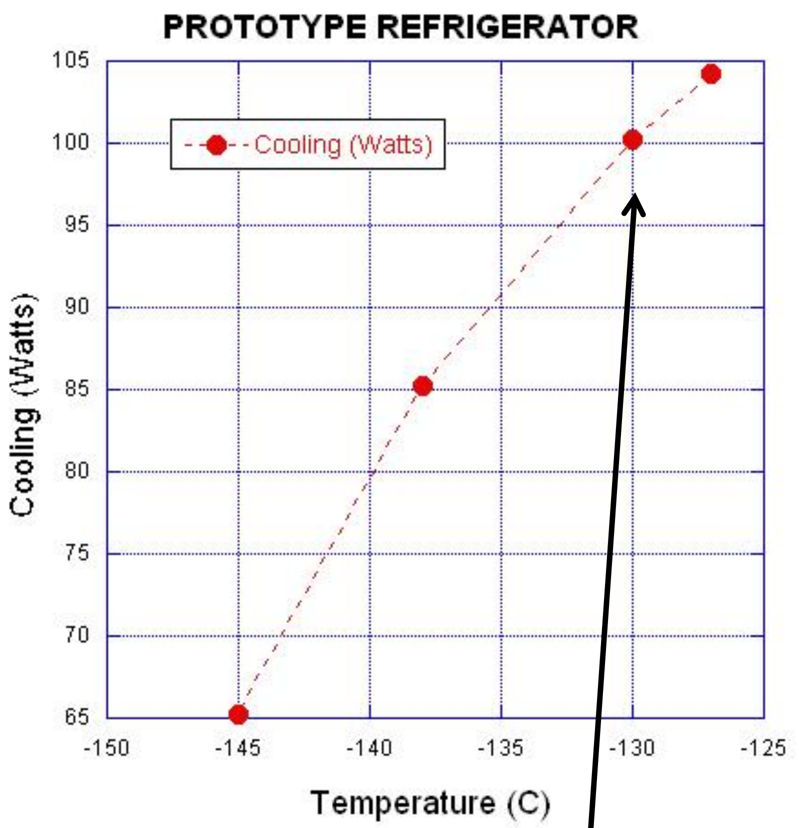
- First observed by A.P.Kleemenko in 1960, the thermodynamic properties of refrigerant mixtures are markedly different from single component refrigerants used in conventional refrigeration systems
  - Mixtures extend cooling down to cryogenic temperatures (-130^0C) required for LSST
- By combining higher boiling point organics or fluorocarbon refrigerants (R14, R123, R143a…) with cryogenic gasses (Ar, N_2, Kr ...) you can greatly expand the range of temperatures and pressures over which liquid and vapor are in equilibrium.
  - Conventional refrigerants (higher boiling point components) which, in their pure state would be frozen at cryogenic temperatures do not freeze out in mixtures.
  - Boiling can extend over broad range of temperatures and pressures so evaporative heat transfer can be large all the way down from ambient temperature to the cryogenic temperatures we require.
  - Development of mixed refrigerants for a specific temperature range starts with a computer model, but then requires much empirical testing.

In 2011, First Mix Developed for LSST by MMR: LSST-3N (5 components) – "Proof of Principle"

Flammable mixes generally have higher cooling capacity than non-flammable ones but are prone to freezing without operating heat load. This mix was only run at MMR.

Component	Common Name
Argon	Ar
C_2H_6	Ethane
tetrafluoromethane	R14
triflouromethane	R23
Iso-Pentane**	R601A

**Iso-Pentane is a flammable liquid at room temperature and needs to be injected when the system starts running under pressure and warms up --



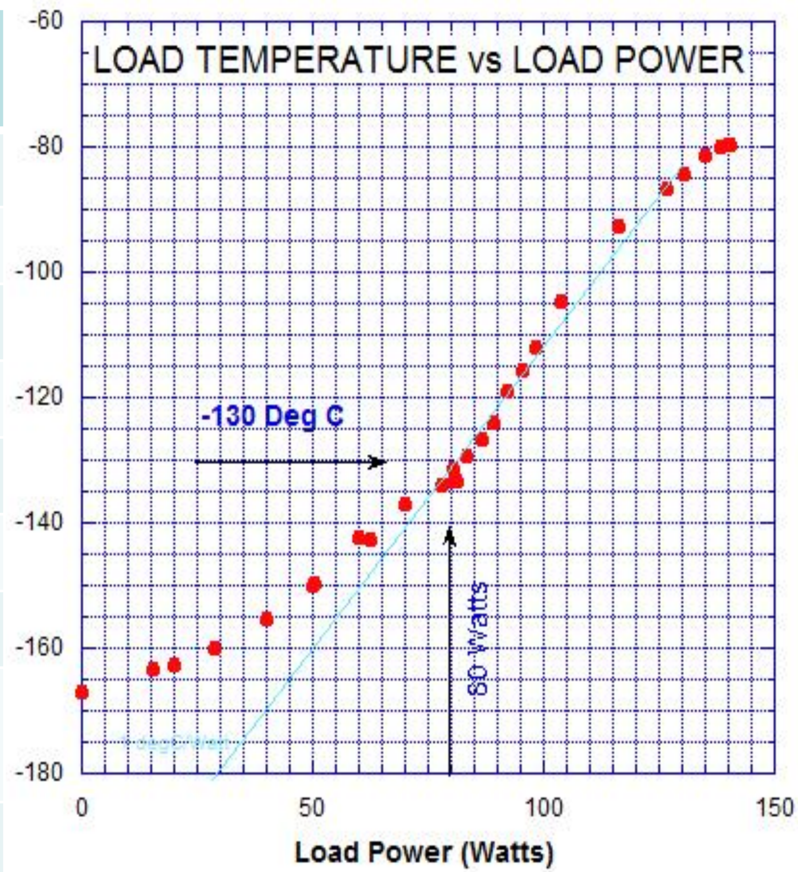
This flammable mix produced >110W at -130^{0}C (Incl. parasitic load) and meeting our requirement on temperature and capacity.

In 2012 We Moved to the Non-Flammable KR-15 Mix (9 components)

In moving the refrigerator development to SLAC, the KR-15 mix was developed as it is non-flammable. Most of the "Long Lines Tests" in 2013 was done using this mixture.

Component	Common Name	%
Argon	Ar	34%
Krypton	Kr	1.7%
tetrafluoromethane	R14	19%
triflouromethane	R23	14.%
chlorotetrafluoroethane	R124	8%
Trifluoroethane*	R143A	11%
pentafluoroethane	R125	7%
-1,1dichloro-2,2,2-trifluoroethane	R123**	5%
-1,1,1,2-tetrafluoroethane	R134A	0.51%

**Liquid R123 must be injected when the system starts running under pressure (R123 → GHG)



This non-flammable mix produced >90W at -130^{0}C (Incl. Parasitic Load)

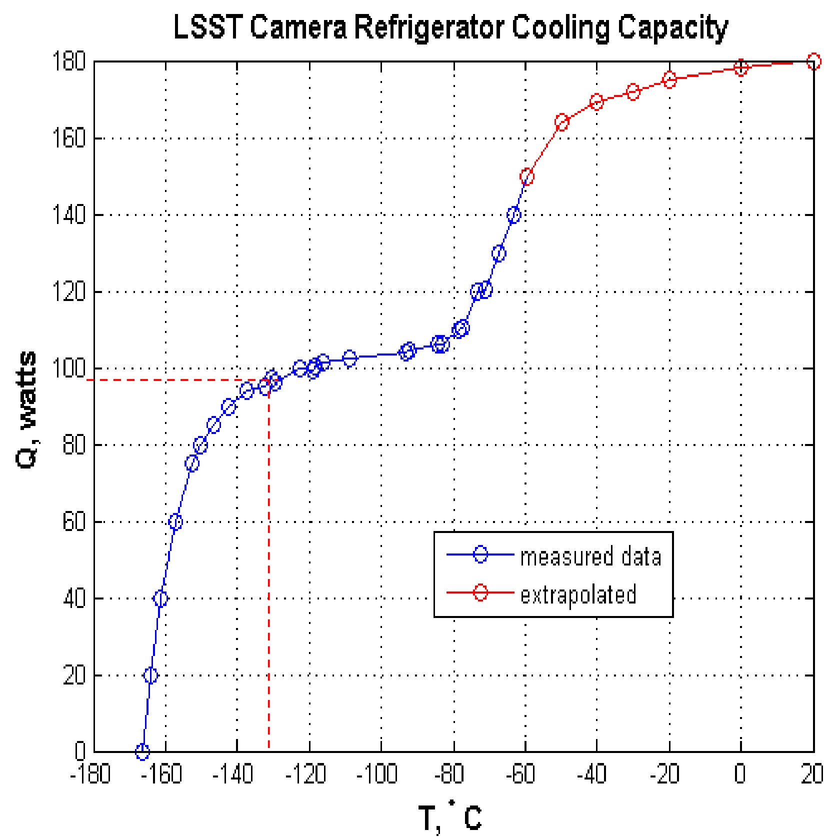
Finally in 2014 Switched Refrigerant to MX19-18 and Variants

This non-flammable mix is based on R218 with the advantage of being prepared & stored as vapor at room temperatures** - it requires no special liquid injection when charging system

Component	Common Name	Molar %
Argon	Ar	36%
octofluorpropane	R218	21%
tetrafluoromethane	R14	20%
60% Chlofluoromethane + 38% Pentafluoromethane + 2% Propane	R402B	13%
chlorotetrafluoroethane	R124	5%
1,1,1,3,3-Pentafluoropropane	R245fa	5%**

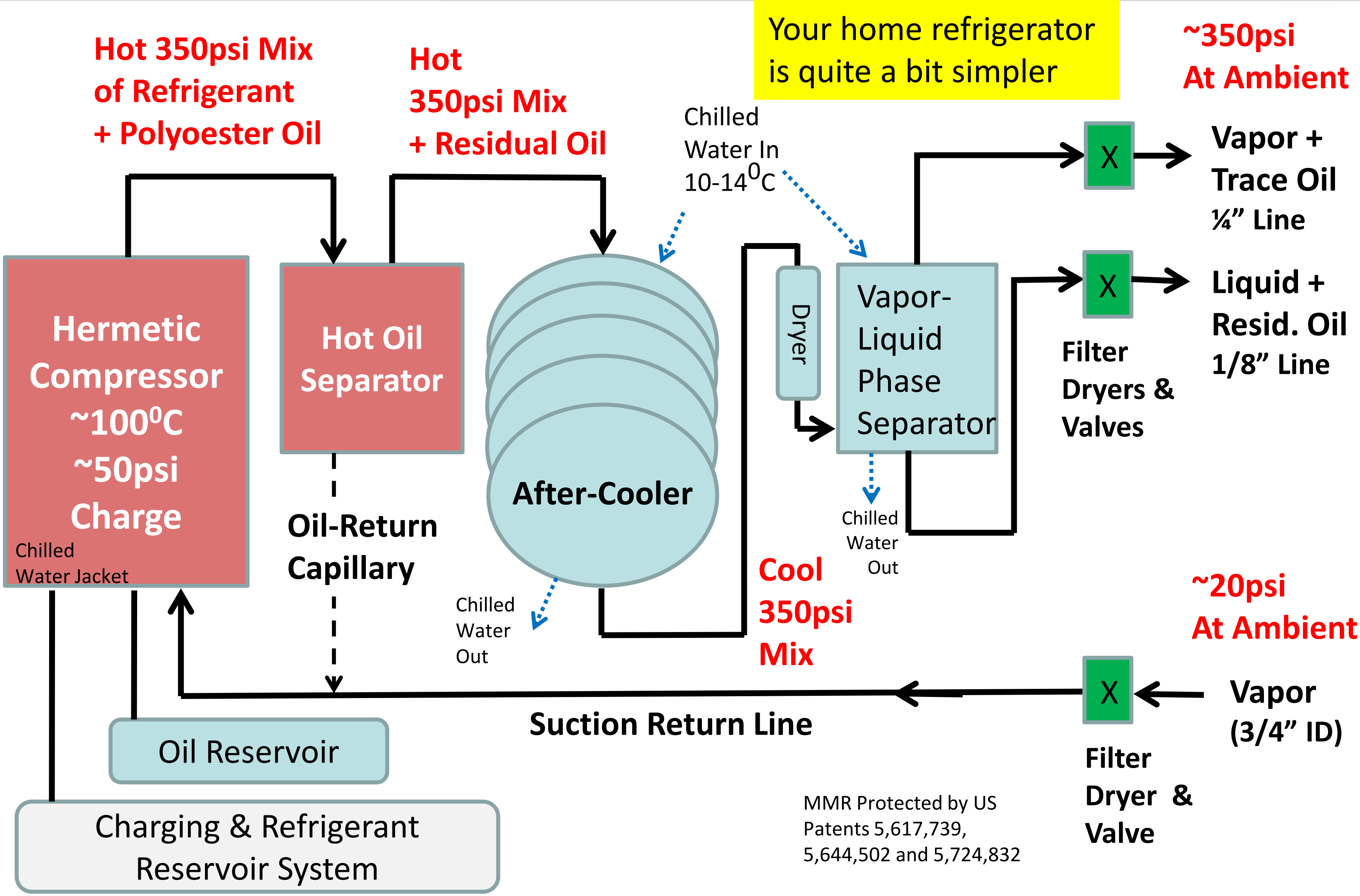
**In this mix the liquid R123 (BP 28^0C) is replaced by the lower BP (15^0C) R245fa which liquefies under pressure. It reduces the cooling capacity somewhat making it more sensitive to operating conditions in the hall.

Variations in mix designation reflect % changes in liquid components to accommodate experimental arrangement



This non-flammable mix gave ~100W at -130^0C (Incl. parasitic load) with more efficient heat transfer in the HeX

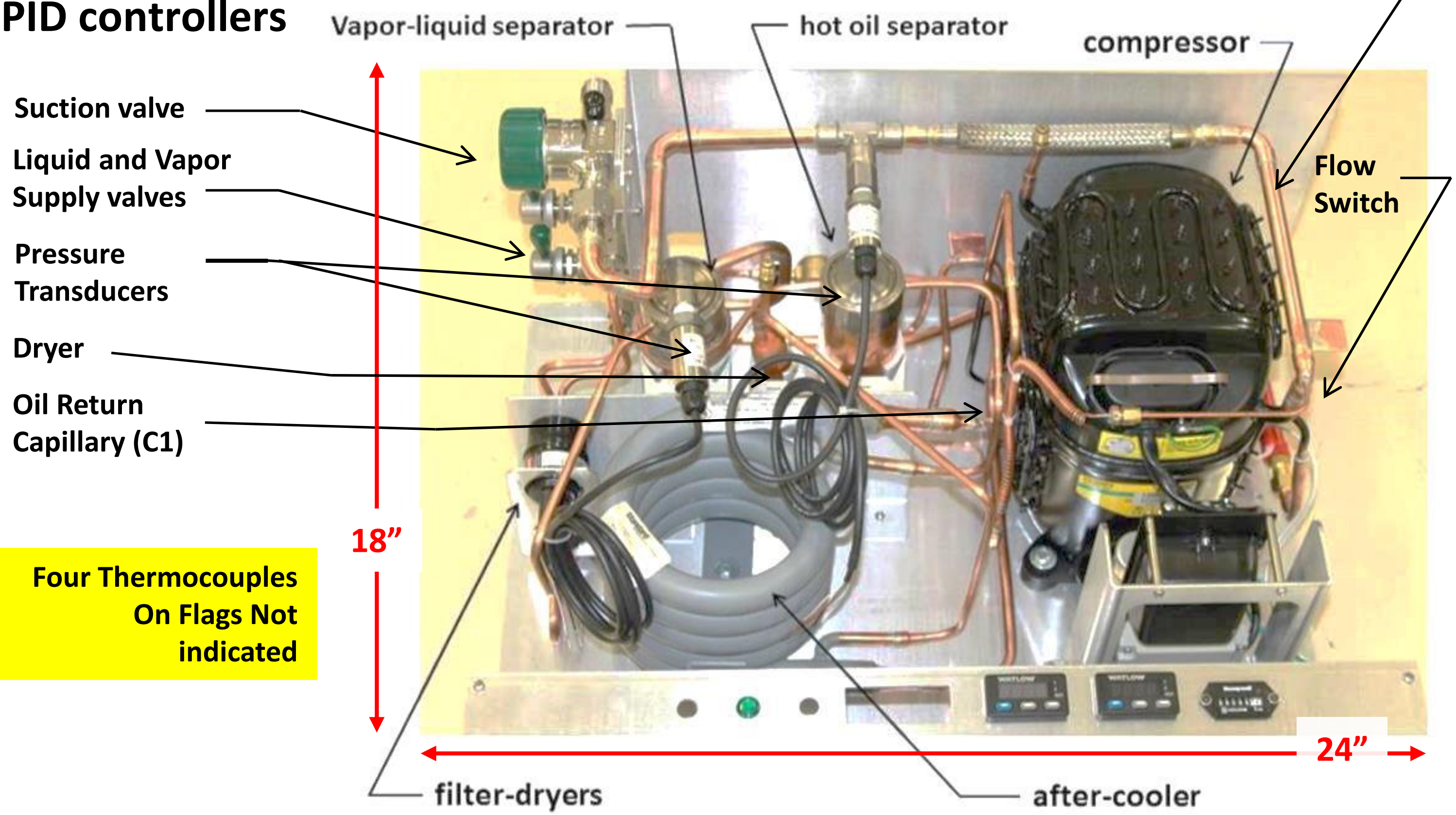
The Compressor Circuit – Unique Dual Phase System Enabling "Cascade Cooling" in a Single System



MMR Protected by US Patents 5,617,739, 5,644,502 and 5,724,832

Compressor Module (2nd Generation)

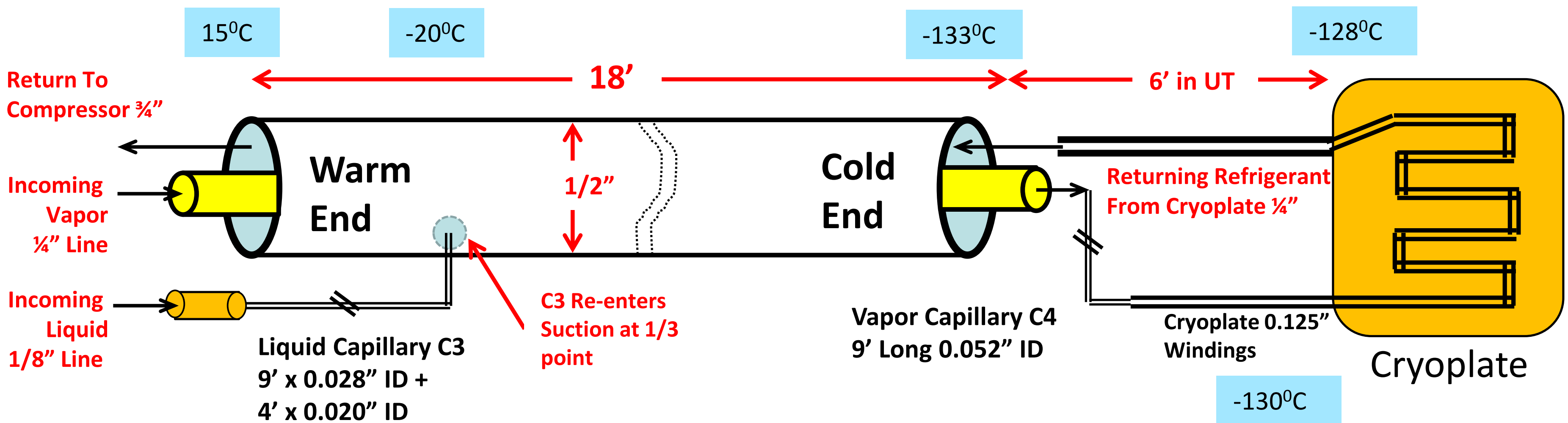
- Compressor is "off the shelf" Danfoss 26cc 220V 50Hz – Hermetically Sealed – Filled with ~0.8 liters of OPE lubricating oil.
- Copper shell + chilled-water cooling loops (~10^{0}C) stud welded +thermal epoxied on
- 3rd Generation to have "external oil reservoir" and oil level sensor
- 3rd Generation to have "smart" compressor control, protection & monitoring module replacing PID controllers



Four Thermocouples On Flags Not indicated

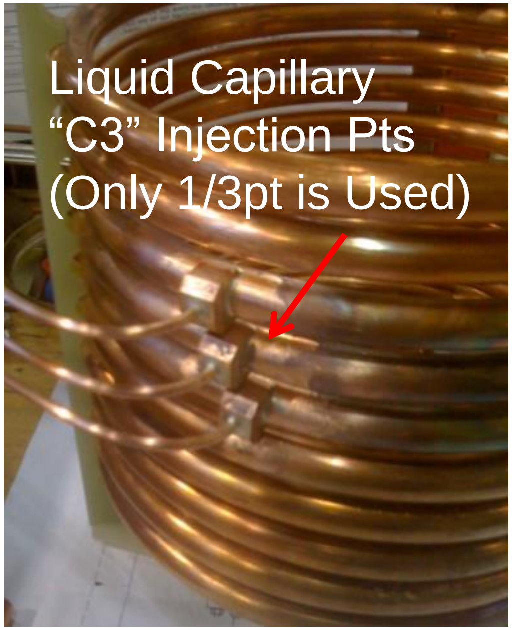
The Last Elements are the Counterflow Heat Exhanger and the Cryoplate – Both are Up at the Camera

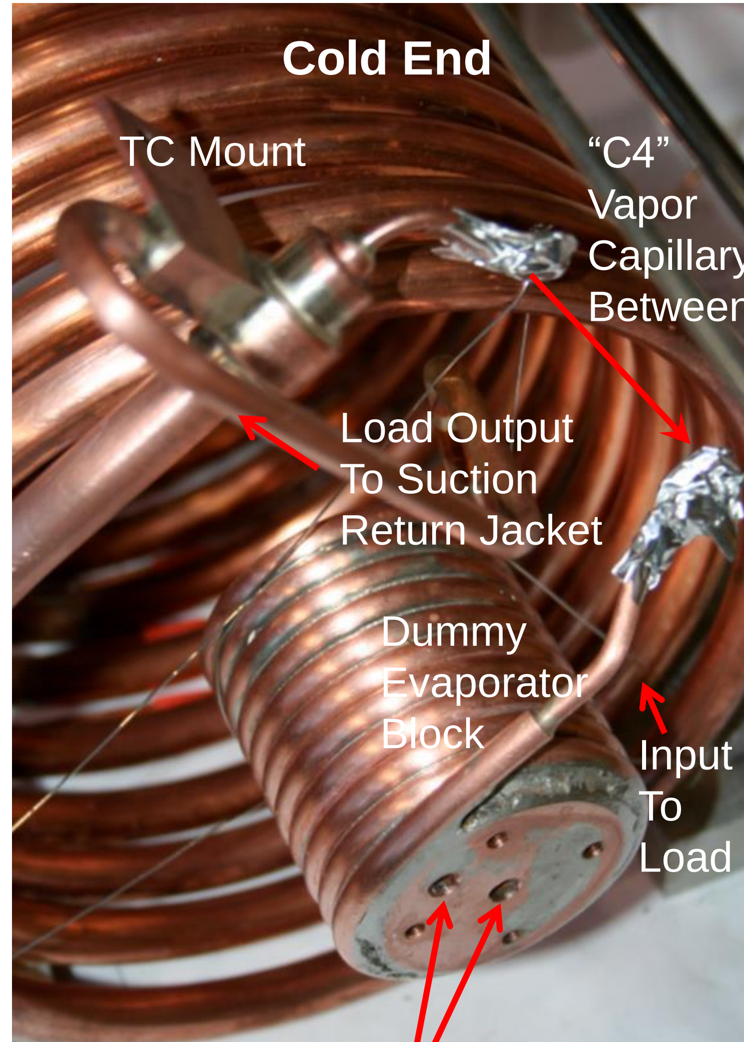
- **Unique to the MMR design is the counterflow HeX where both high pressure liquid and vapor streams are expanded to low pressure thru two distinct capillaries (C3 & C4) located along a single heat exchanger. C3 and C4 also control the flow rate.**
  - **High boiling pt condensed liquid is expanded in C3 and used in 1st third of HeX to pre-cool incoming lower boiling pt vapor before returning to the compressor.**
  - **Incoming vapor is further cooled travelling along the HeX by the cold return flow and finally condensed at the cold end of HeX and expanded into the cryoplate by C4.**



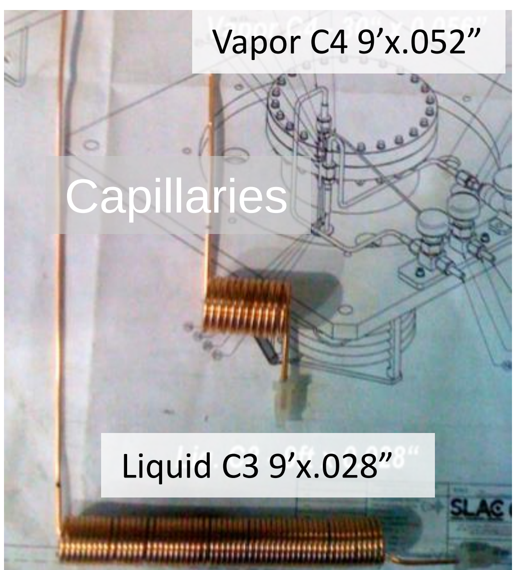
- **Two advantages of MMR system are:**
  - **Separated refrigerants can be better matched to heat transfer conditions which vary along the length of the heat exchanger**
  - **The phase separator washes most of the oil into the liquid. There the oil never gets cold enough to freeze and plug up C3. Any trace oil in the vapor phase is small enough to not plug C4**

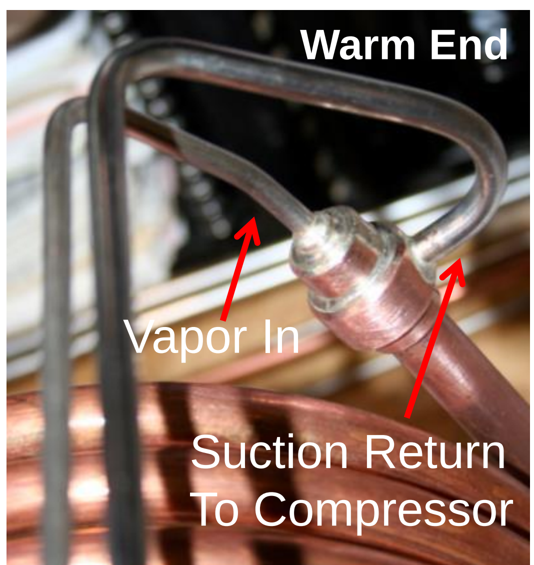
In Real HeX Incoming Vapor is Distributed at the Warm End into 7 Small 18 ft Long Tubes Increasing Surface Area /Turbulence /Heat transfer with the Cold Return Flow





Heater and RTD
Mount to Evaporator



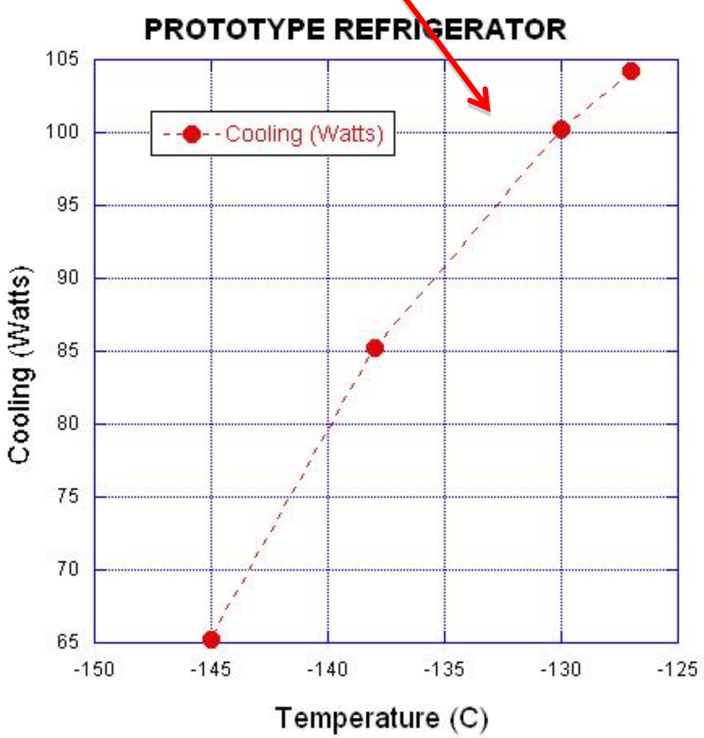


Weak Point of Refrigerators are the Capillaries Where Pressure Drops ~Linearly Along Length While Expanding the Refrigerant

- Capillaries are critical to the functioning of almost all refrigerators
  - Their long length (9') and small diameter (0.020") make them susceptible to plugging
- There are three possible sources and each have mitigations:
  - Particulate contamination from machining & brazing assemblies
    - Care and cleaning during fabrication and assembly
    - Introduction of filters on inlets and outlets
  - Moisture carried by the refrigerant/oil (or leaks) can freeze up.
    - Go to all metal lines (incl flex) with VCR fittings
    - Everything flushed & dried before assembly – especially long lines with lots of surface area
    - Dessicators introduced on compressor inlets and outlets
  - Trace Polyoester compressor oil carried by the refrigerant can build up and freeze up at the lowest temperatures
    - Liquid refrigerant itself helps to flush this (but not as well with Polyoester)
    - Long lines help to reduce oil that reaches HeX, but must not have "traps"
    - Because depletion of oil in compressor (the lubricant) is itself bad

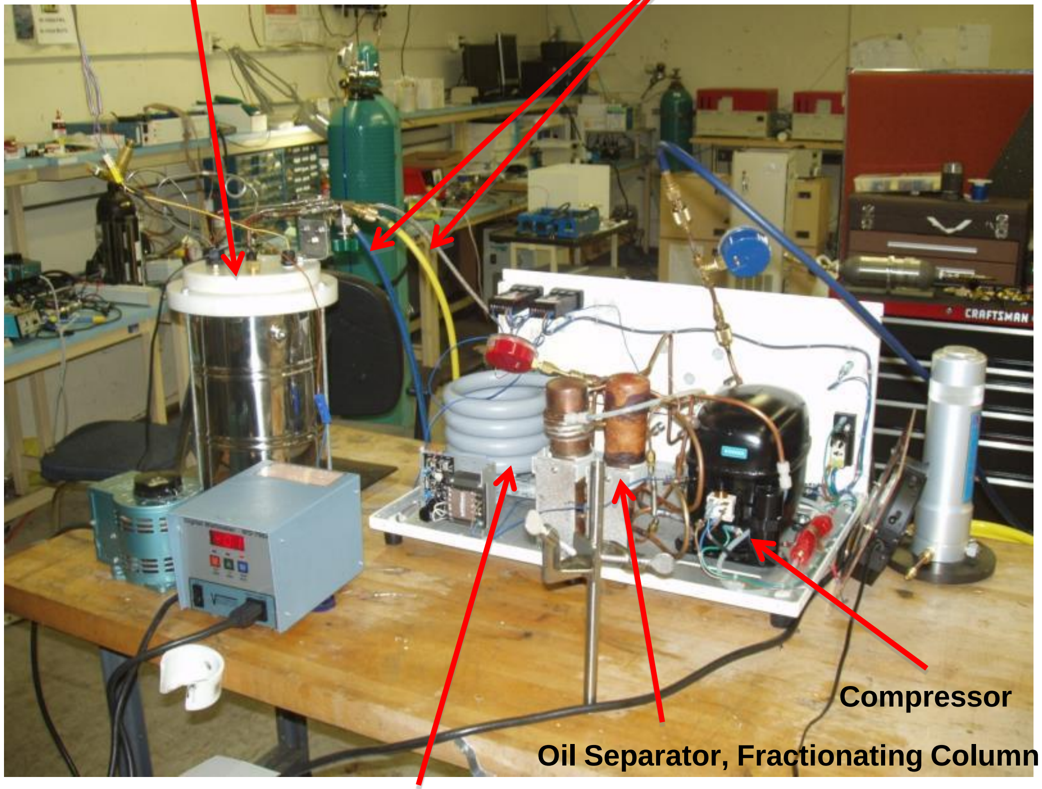
Mixed Refrigeration Development Started in 2010:

- **Mixed Refrigeration Development Phases 1 & 2, completed in 2011 at MMR**
  - **Fabrication and test of bench top prototype system.**
  - **Demonstration of 100 Watt at -130^{0}C cooling employing a flammable mix**



Dewar With Counter-Flow Heat exchanger

Plastic Refrigerant Lines



Compressor

Oil Separator, Fractionating Column

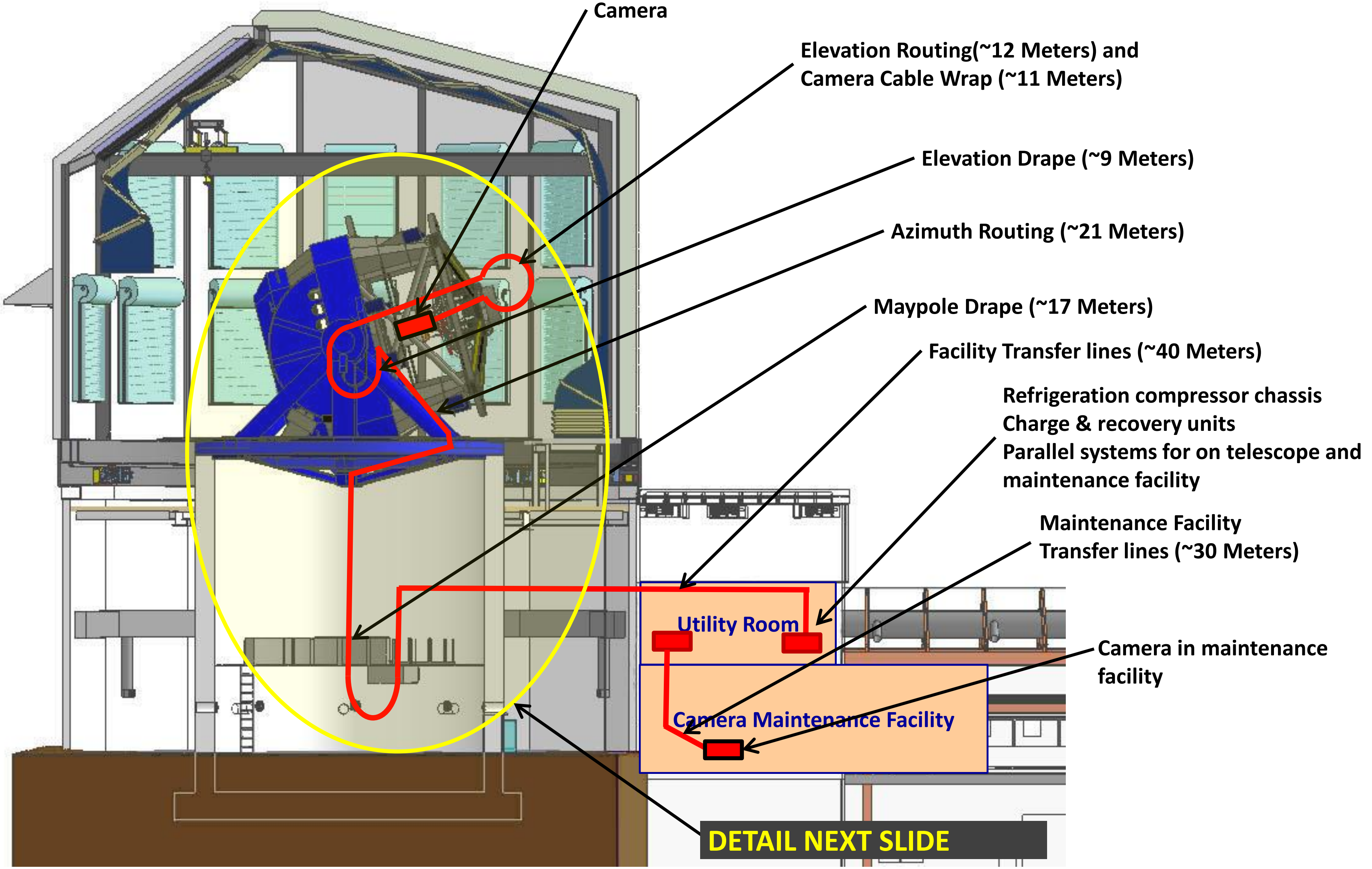
Water Cooled Condenser

Phase 3 – The Installation and Test of a Prototype System at SLAC in 2012/2013 "Long Lines Test"

- The goals of Phase 3 were:
  - Transfer knowledge and operational experience from MMR to SLAC
  - Develop LSST specific hardware at SLAC
- First test and validate "on-telescope" long refrigerent line length and elevation effects.
  - Follow by longer duration test runs to evaluate reliability and equipment suitability.
  - Understand required monitoring and control instrumentation
- Continue development and optimization of HeX at SLAC using vacuum insulated system rather than a Dewar
- Refrigerant mix optimization (Flammable -- > Nonflammable) at MMR

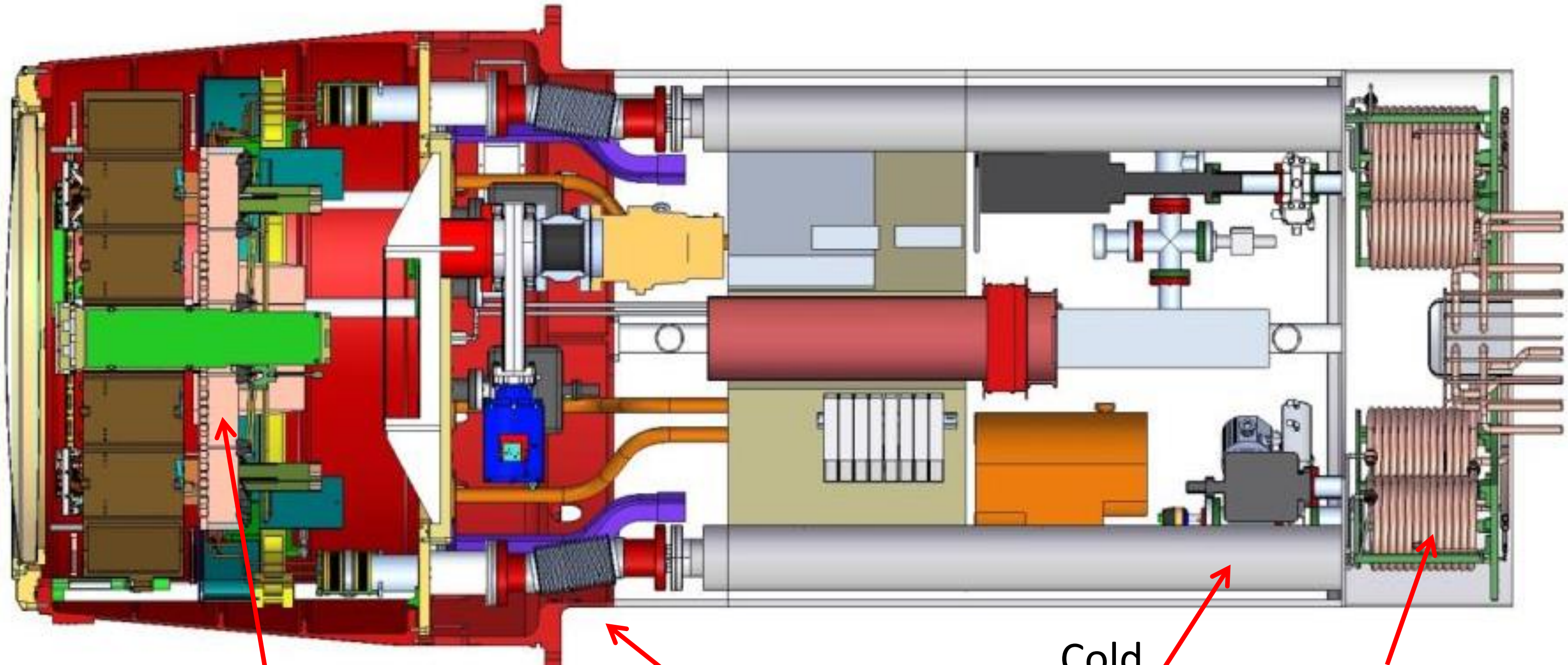
This work was largely completed last year and many valuable and practical lessons learned

In Real Facility there is 110 m From Compressor to HeX – Our Concerns Were Line Volume, Elevation Effects & Refrigerant/Oil Traps



And once inside the camera ….. Evaporator or Cryoplate Is Separated from the Heat Exchanger by 3m

3 meters

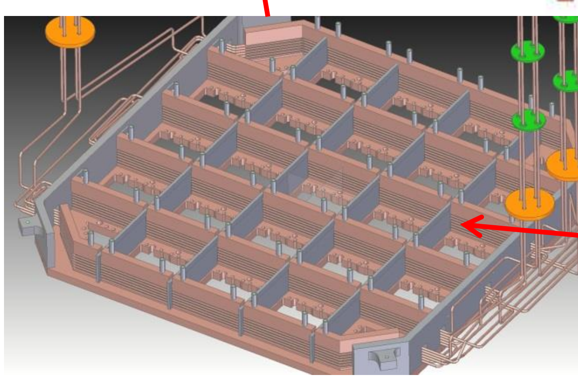


Cryogenic Feedthroughs

Cold Transfer Under Vacuum

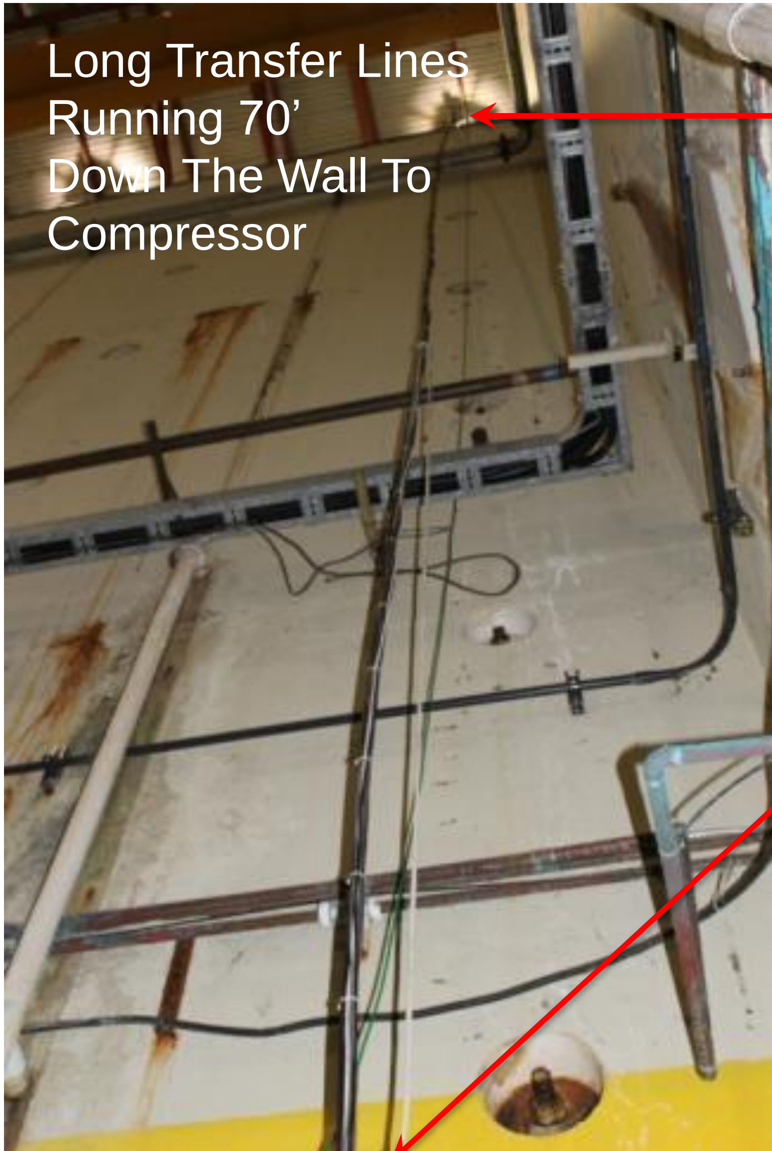
Heat Exchangers Under Vacuum

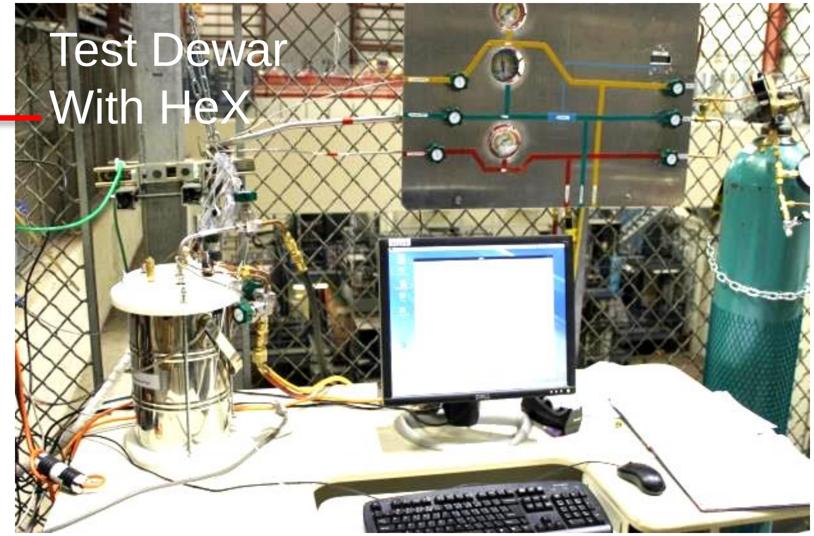
Supply & Return



Cryoplate or Evaporator With Raft Heat Load

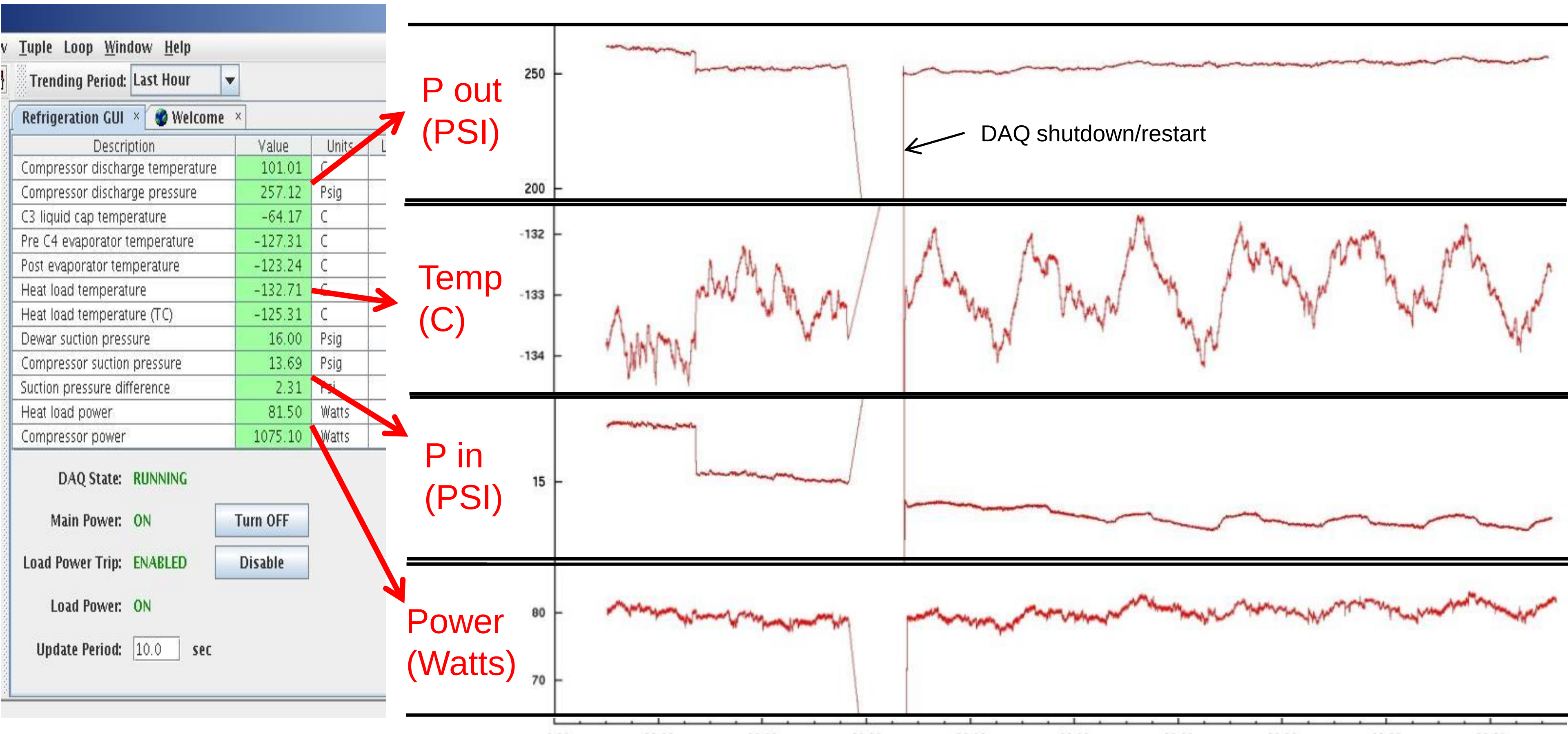
"Long Lines Test" System Installation at SLAC To Test Long Transfer Lines and Elevation Effects





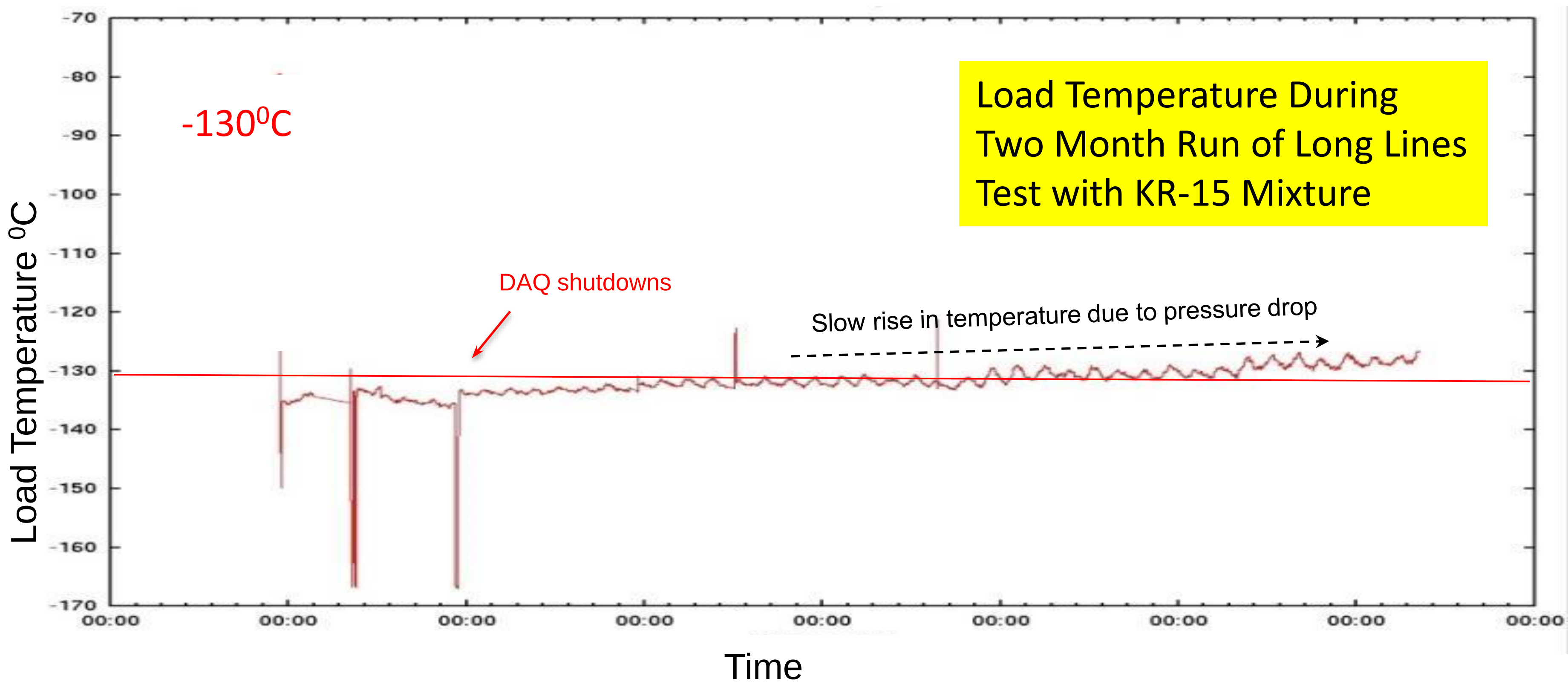
Early 2013 Endurance Run at SLAC Demonstrates Stability and Reliability as well as Prototype DAQ System

- **Continuous running with DAQ monitoring 12 parameters.**
- **System shows small (+/- 1^{0}C) diurnal response correlated to ambient temperature swings**
- **Otherwise, excellent stability considering we have no active feedback control.**



Long Term Stability Demonstrated: Two Month Run through Mid-April 2013

- **Load (80 watts+10W parasitic) and temperature (-130^{0}C) was stable for majority of two month long run.**



End 2013 Through Present – Optimize HeX / Mix and Test With a More and More Realistic System

- Fabricate Three new HeX(s) at SLAC now housed in a vacuum dewar

Initial tests done and satisfactory

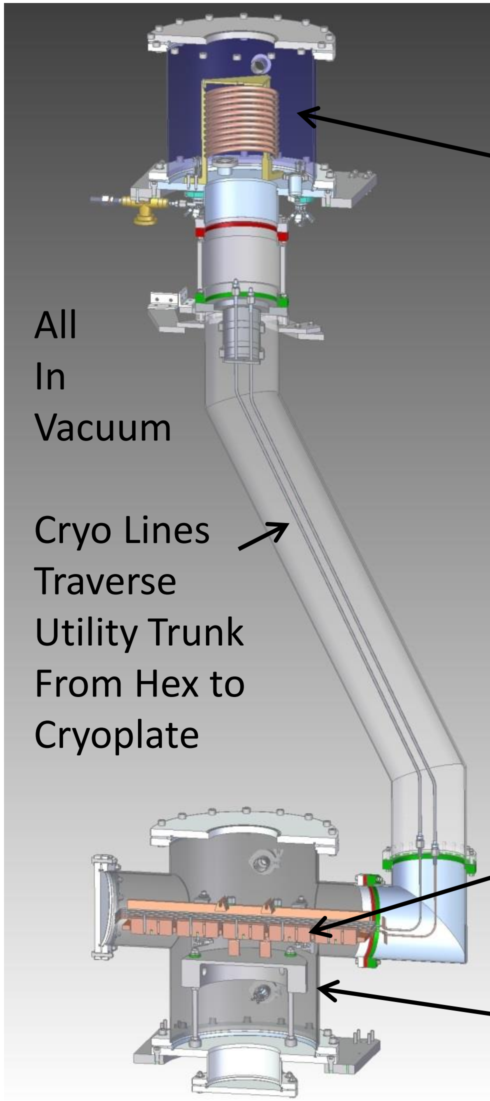
- Three new Compressor Modules incorporating lessons of Long-Lines tests

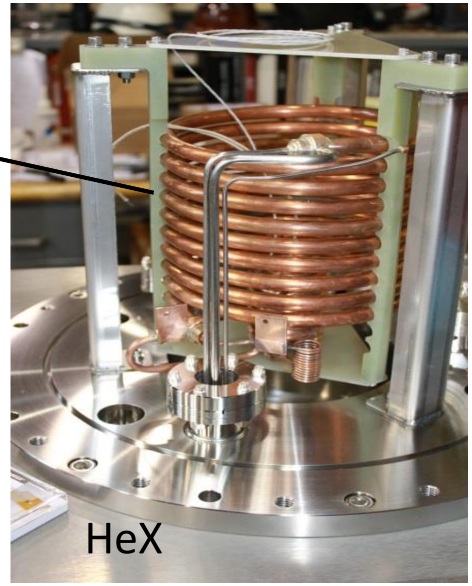
Last one is being tested now at MMR with the extended features

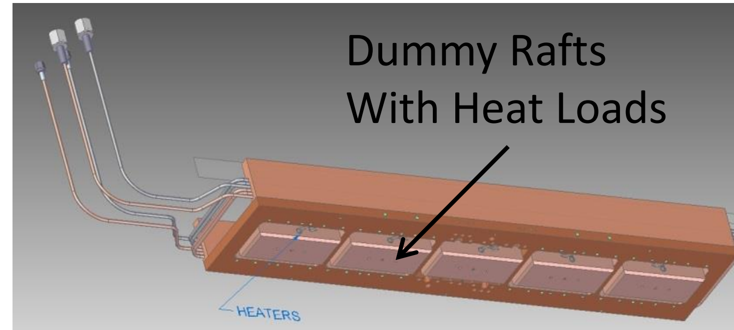
- Construct extended vacuum system to include more camera-like hardware and geometry, candidate transfer lines and articulations.
  - Build subscale (1/5) cryoplate (prototype fabrication, performance issues (temp uniformity etc.) Include simulated Grid and simulated Rafts
  - Separate HeX from cryoplate after the vapor capillary (C4) and test performance
  - Add long flexible transfer lines and final rotation / articulation behind Utility Trunk
  - Continue orientation tests and conduct extended runs
  - Test feedback algorithm for temperature control of cryoplate via trim heaters

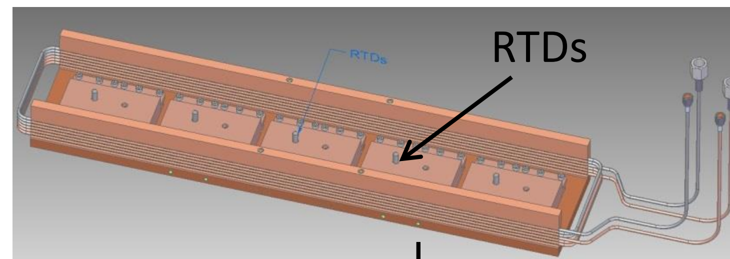
Initial “Sub Scale” Tests Began in June

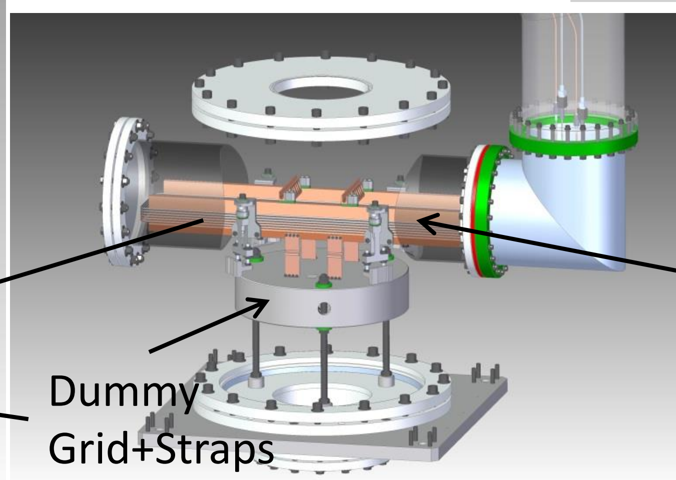
Subscale Test Simulates Camera/UT Geometry, Final Cable Wrap, Thermal Masses, Heat Loads, Separation of Cryoplate From HeX & Orientation Effects

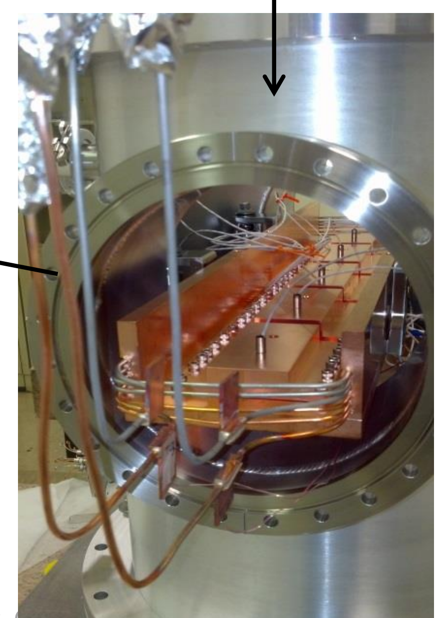










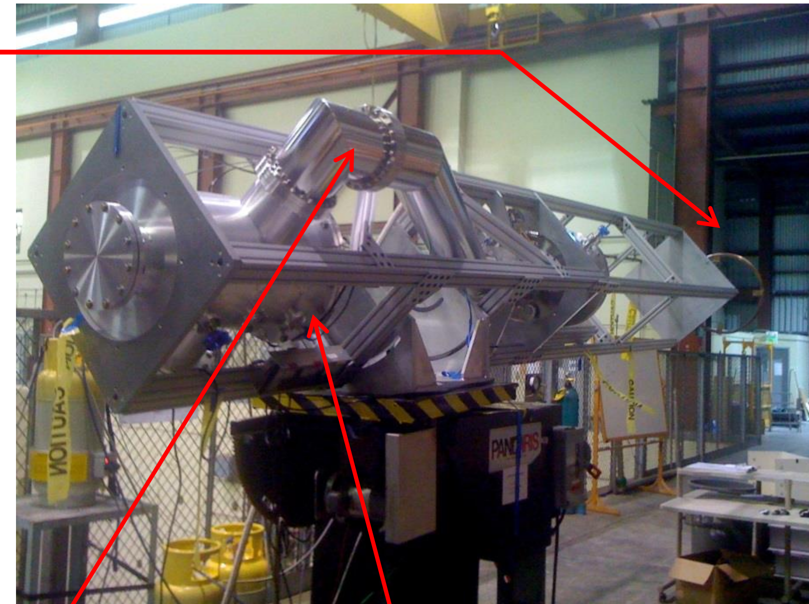


1/5th
Cryoplate
With
Dummy
Rafts
(Heaters)

Assembly Started in March 2014

Includes Ability to Tip, Tilt & Rotate & Top End Cable Wrap Simulation &

Top End Cable Wrap



Compressor
With ~15m
Flex Lines

Cryoplate
Grid
Dummy Rafts

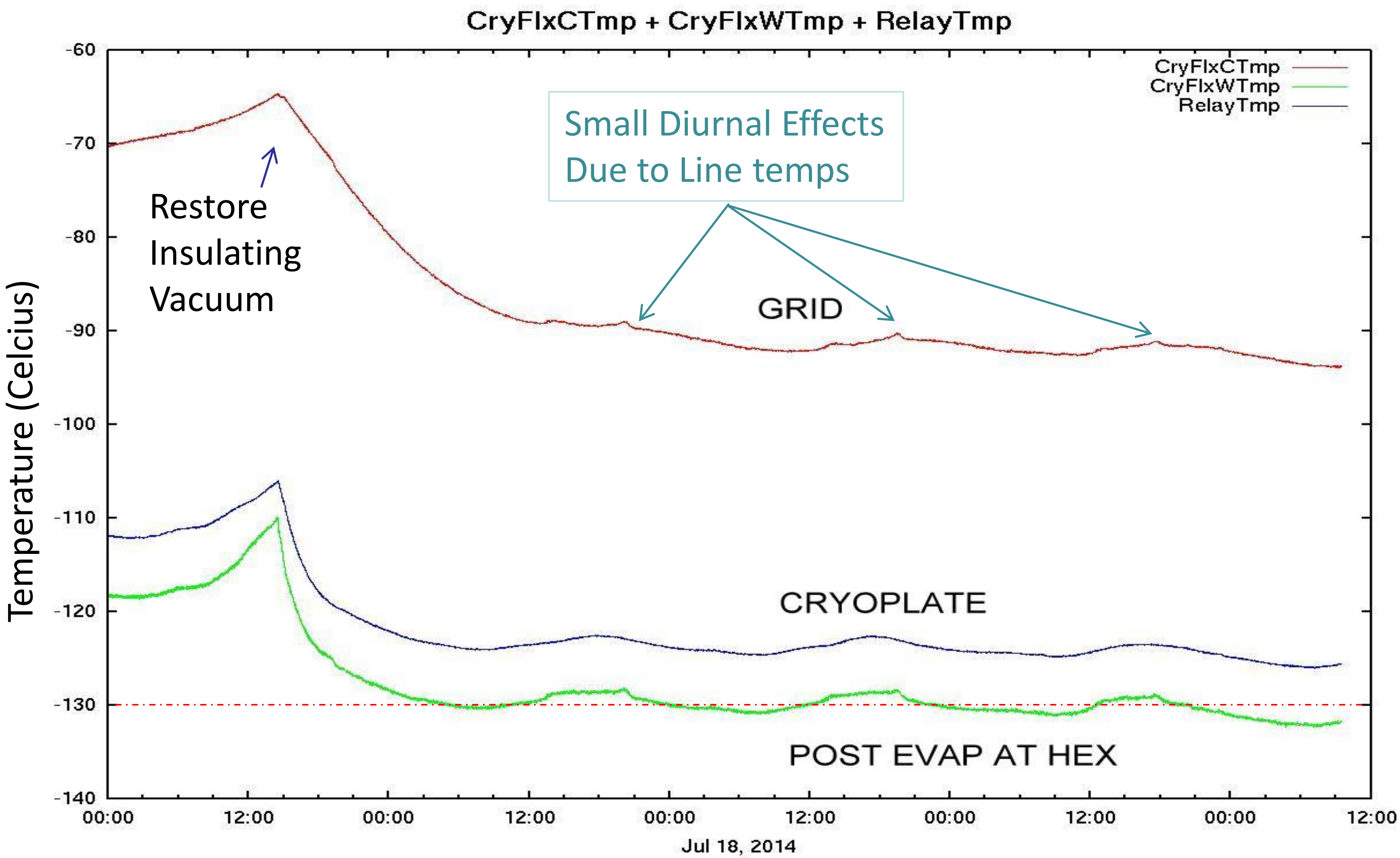
Refrigerent
Lines Traverse
Utility Trunk

Cryoplate Evaporator,
Dummy Raft Heat Loads
and Grid In Cryostat

Compressor
Control &
Monitoring
Module

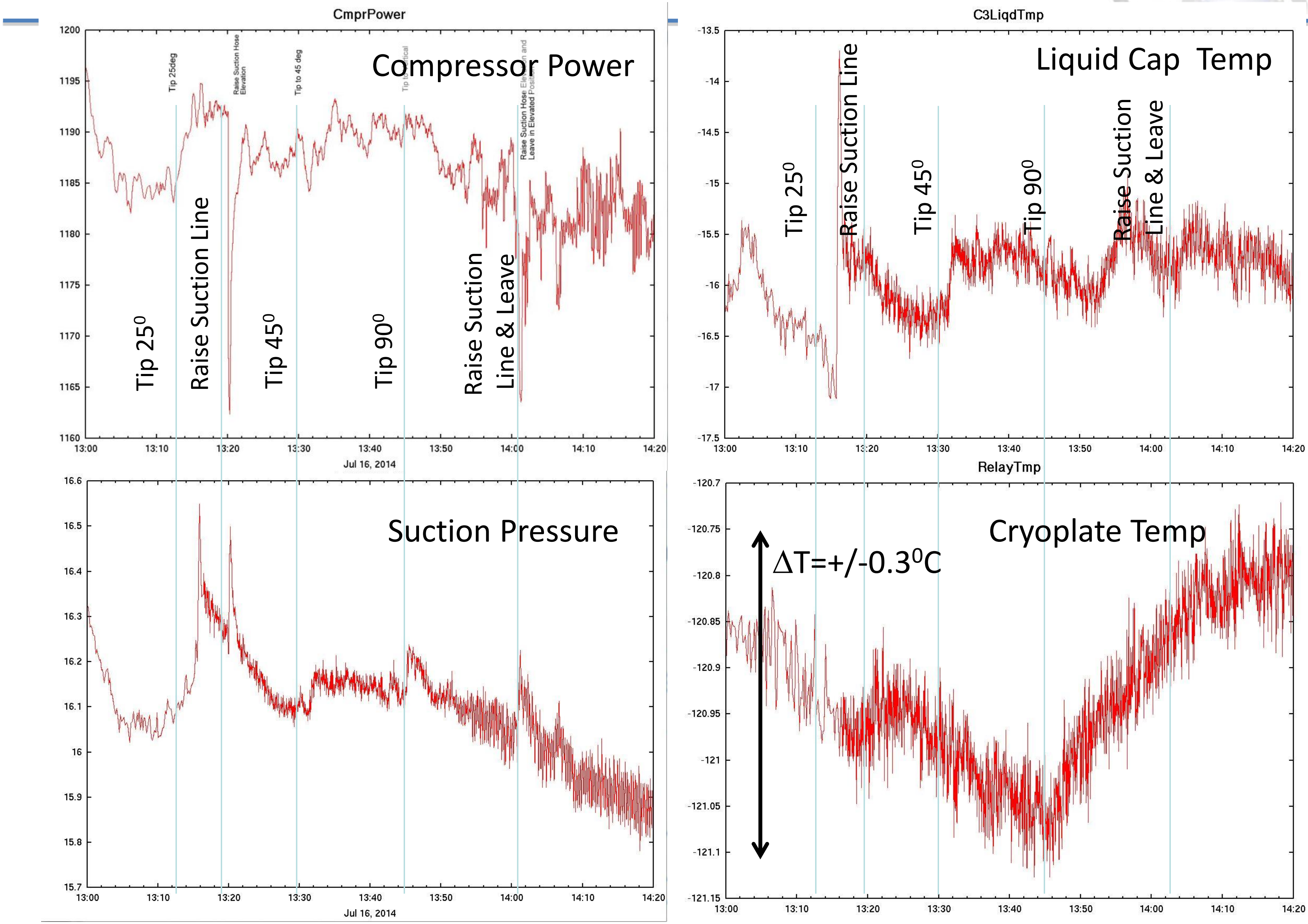
Single Bay
Camera DAQ
Module

Started Running In End of June 2014.
Temperatures During 5 Day Period (System in Horizontal Position)

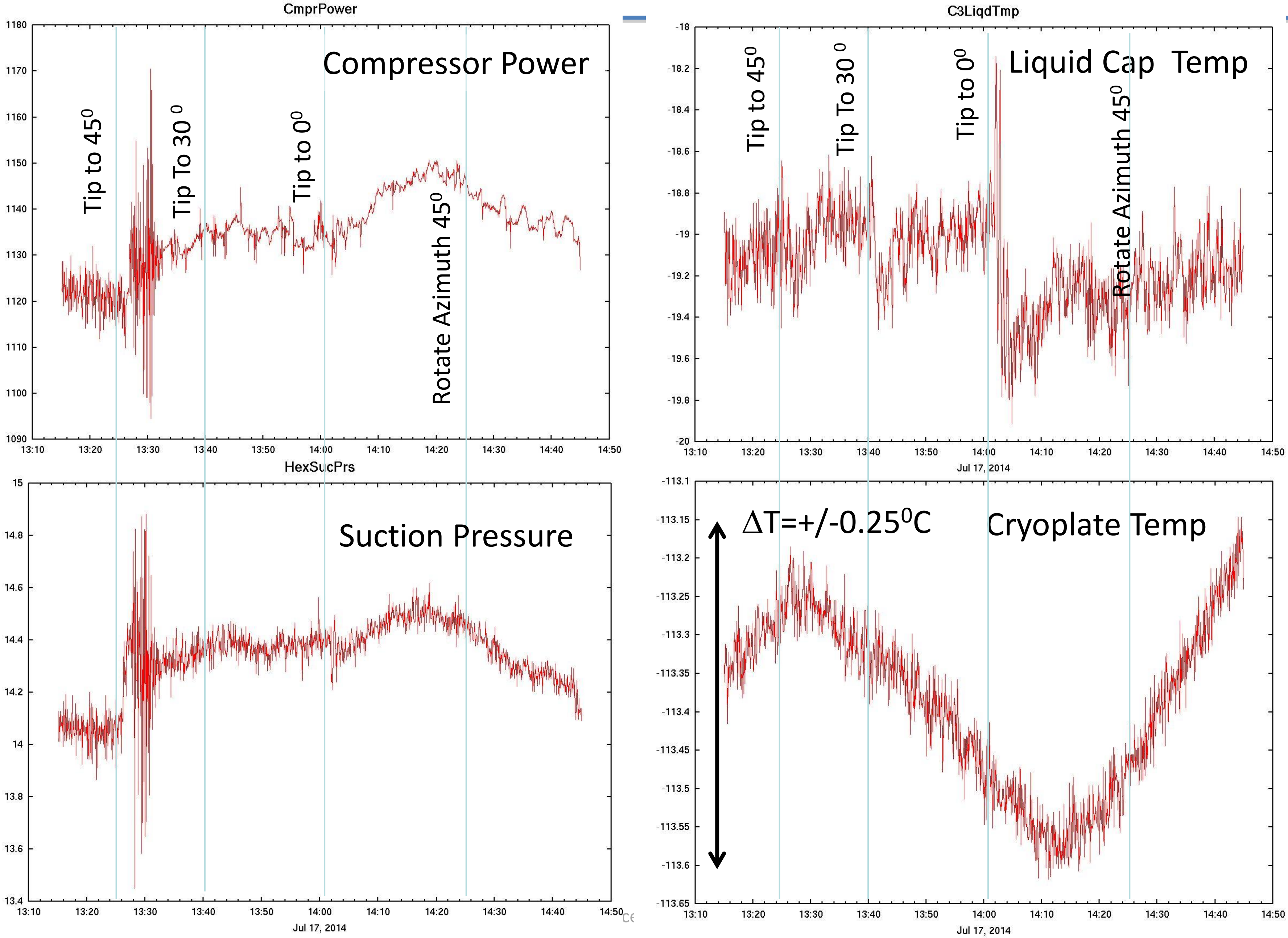


Mix Yielded Temperatures a ~5^{0}C Warmer Than Seen In Standard Test Setup Which Did Not Have The Large Hex to Evaporator Distance Nor the Larger Radiation Load.

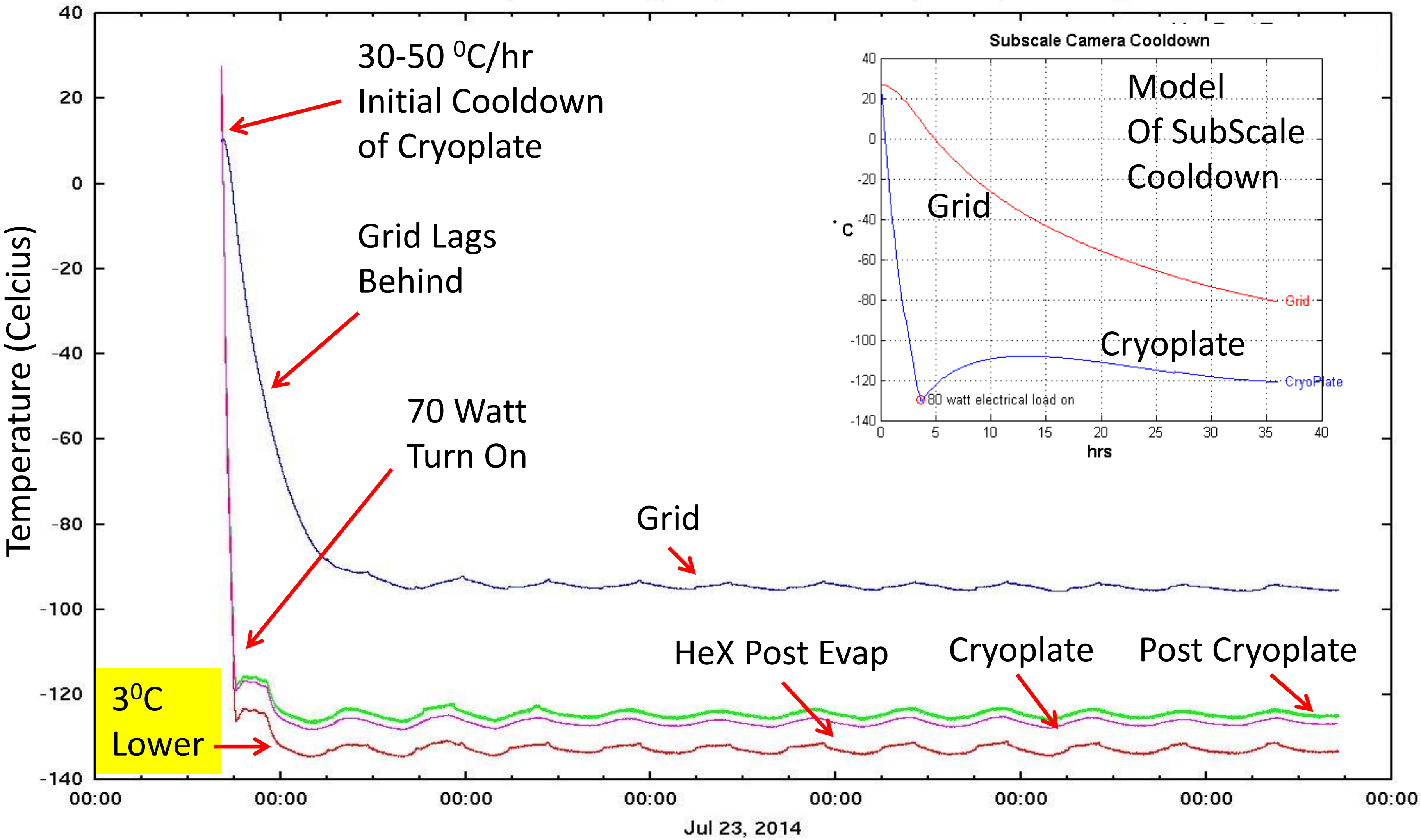
Slow Tip-Tilt Study (July 16th 2014) Horizontal To Vertical



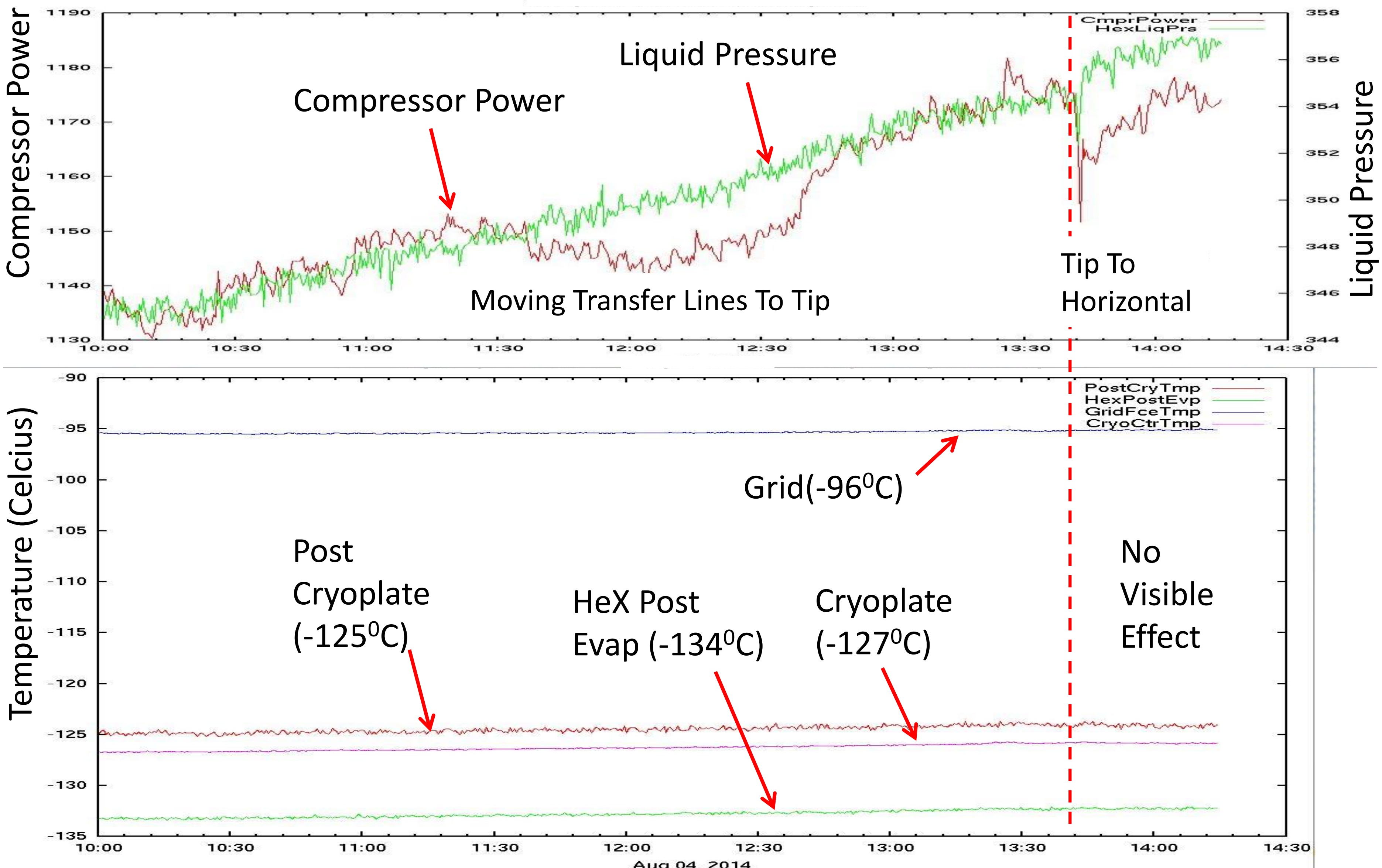
Slow Tip Tilt Study (July 17th 2014) Vertical to Horizontal & Then 45^{0} Azimuthal Rotation Around Camera Axis



Continue Run Til July 22, Warmed Up System & Adjusted Liquid Refrigerant Mix To Improve Temps, Cooled Down and Ran Again Until August 4th

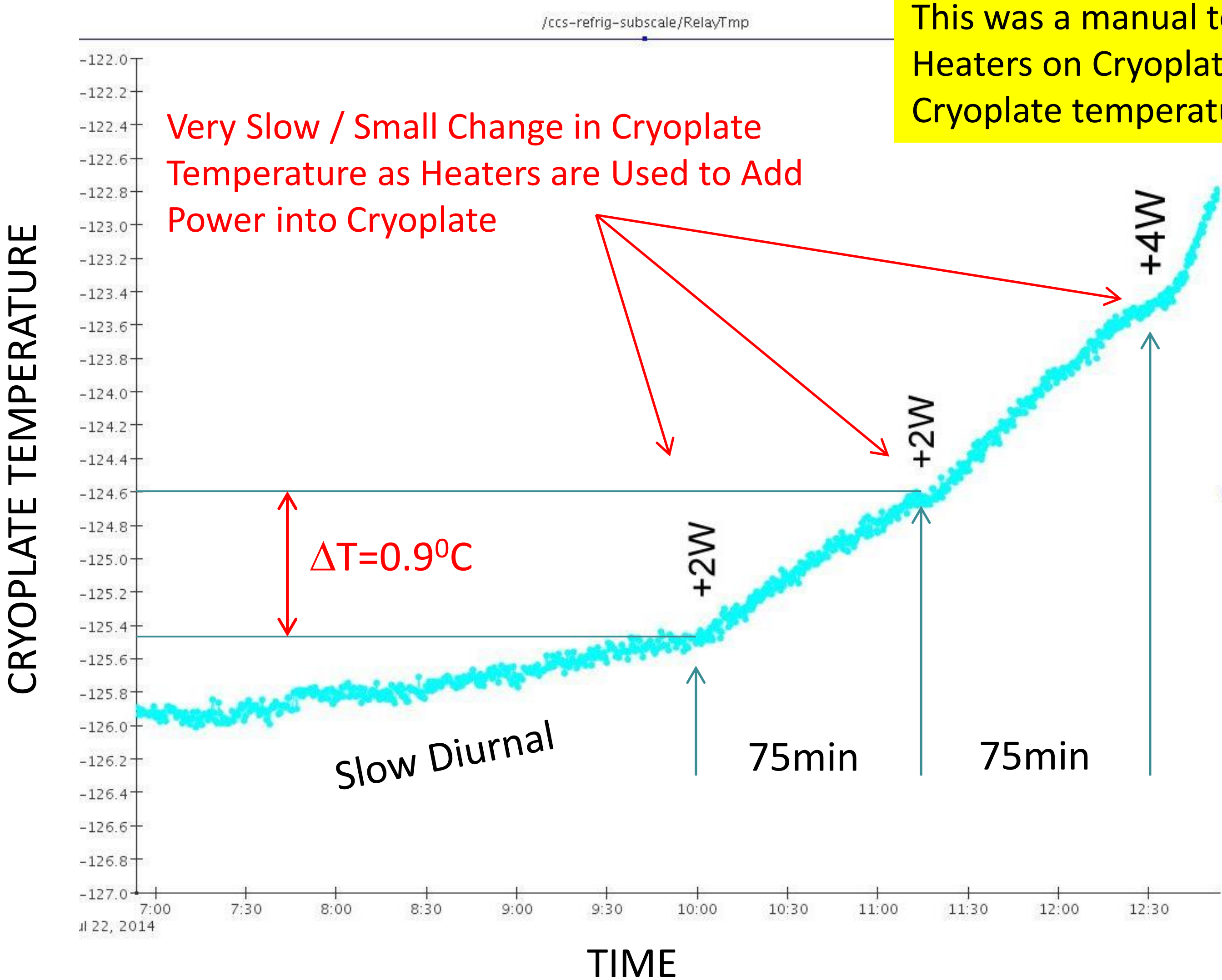


August 4th Tipped From Vertical To Horizontal In One Fast Step



Testing Cryoplate Thermal Control Algorithm With Feedback Software

This was a manual test -- adjusting Trim Heaters on Cryoplate and watching Cryoplate temperature response



Whats Next? Much To Do Over Next Two Years !

- **Multiple Parallel Efforts:**
  - **Bring HeX Vacuum Test Stand back into operation for HeX studies and commission it with the 3rd generation Compressor Module**
    - Oil reservoir and oil level monitoring
    - Compressor Control and Monitoring Chassis with Protection System
  - **Operate Sub Scale Camera System to verify all features of real Refrigeration System**
    - Long endurance run of current system with further tip/tilt testing while preparing to
    - Relocate compressor to CEH floor and reconnect with Long Lines and realistic drapes to simulate observatory system
    - Add Filter/Dryer Bypass Panel to compressor system to improve control of moisture
    - Add long line insulation/heaters and feedback to reduce diurnal effects
    - Add the second compressor/refrigerator circuit to existing cryoplate (its already plumbed) to understand realistic operational issues (circuit interplay, warm-cold startup / shutdown)
    - Add cryogenic feedthrough prototype, Single Bay Grid and Realistic Raft Tower simulator
  - **Setup lifetime tests for verifying wear and reliability of flexible metal parts of the system and test connect/disconnect service options**
  - **Build and test the conventional "Cold" system (in HeX Vac Test Stand)**

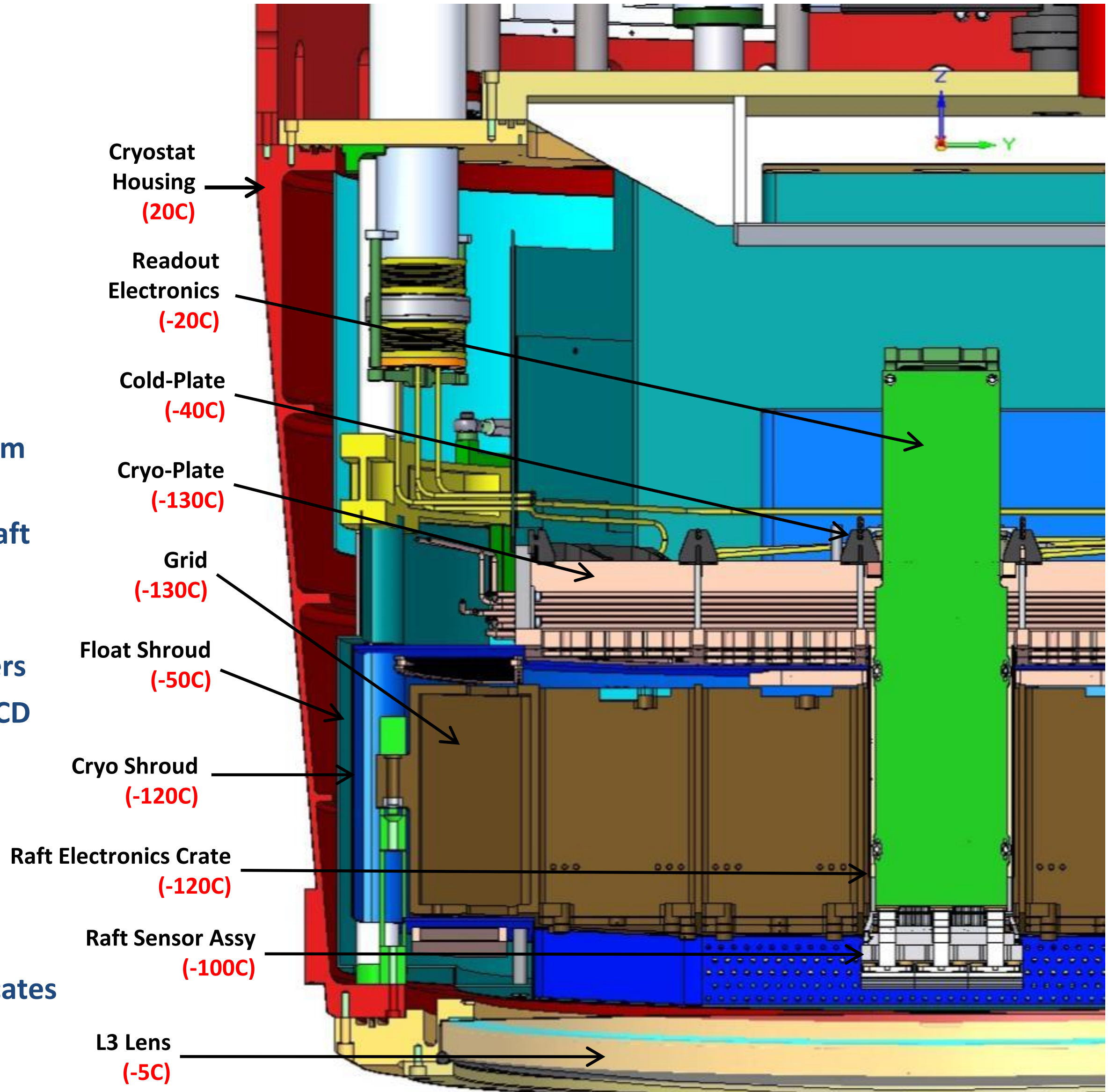
End of Presentation

Cryostat Thermal Design and Control Approaching CD-2

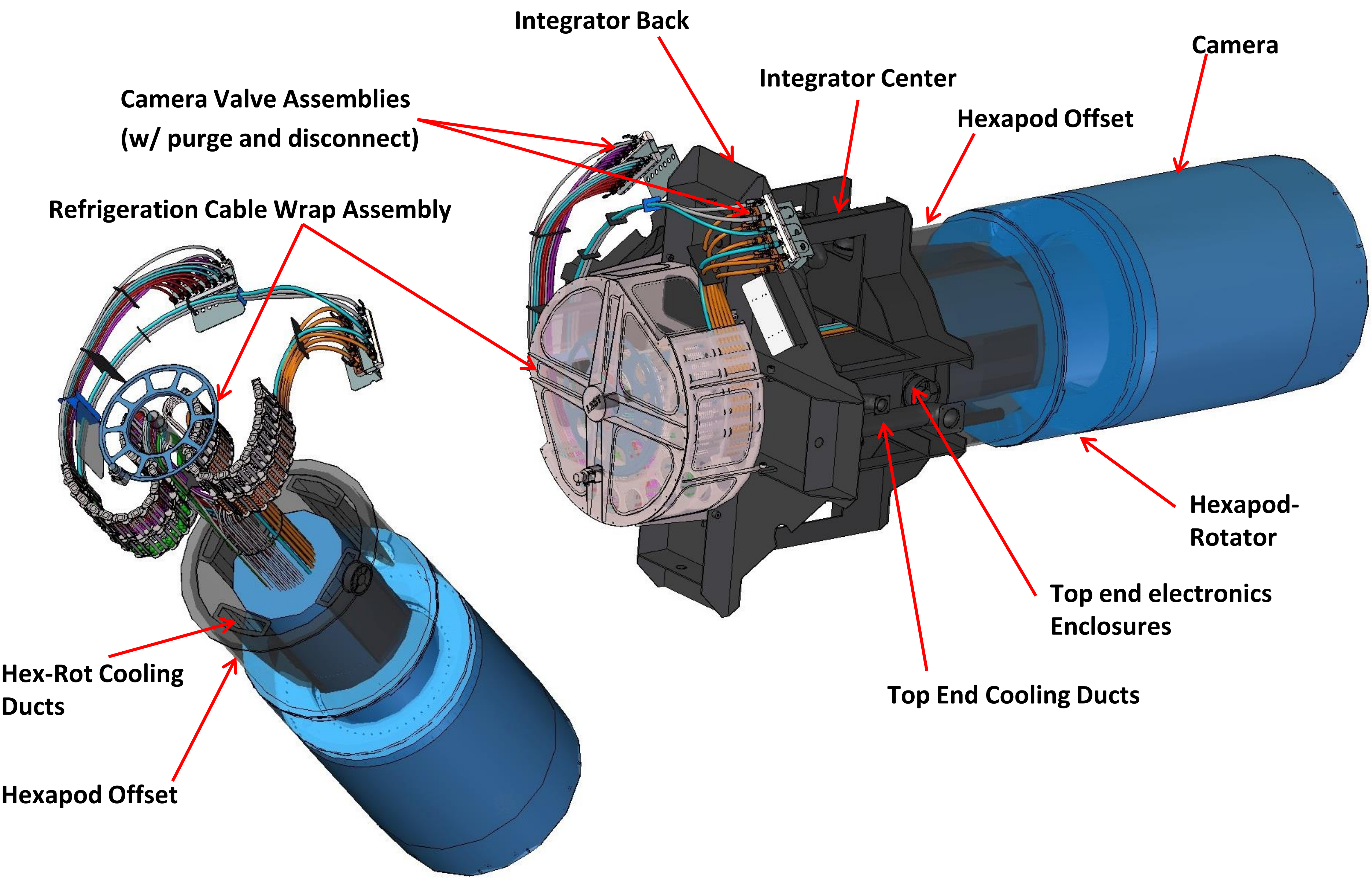
- **Requirement:**
  - Cryo-plate **> 700 W at CD-1**
    - 520 Watts at -130C, stability <2^{0}C at RSA
    - Mechanical support of ~200kg REC crates
    - Temperature uniformity of Grid (~0.5^{0}C)
  - Cold-plate **> 580 W at CD-1**
    - 1000 Watts at -40^{0}C, stability TBD

- **Functionality:**
  - Turbo / Ion pumps provide insulating vacuum
  - Cryo-plate sinks radiant & conductive heat sources and provides thermal stability of Raft Science Array & Raft Electronics Crate
  - Cold-plate provides thermal stability of REB
  - Coarse temp. ctrl via compressor trim heaters
  - Raft provides fine temperature control of CCD

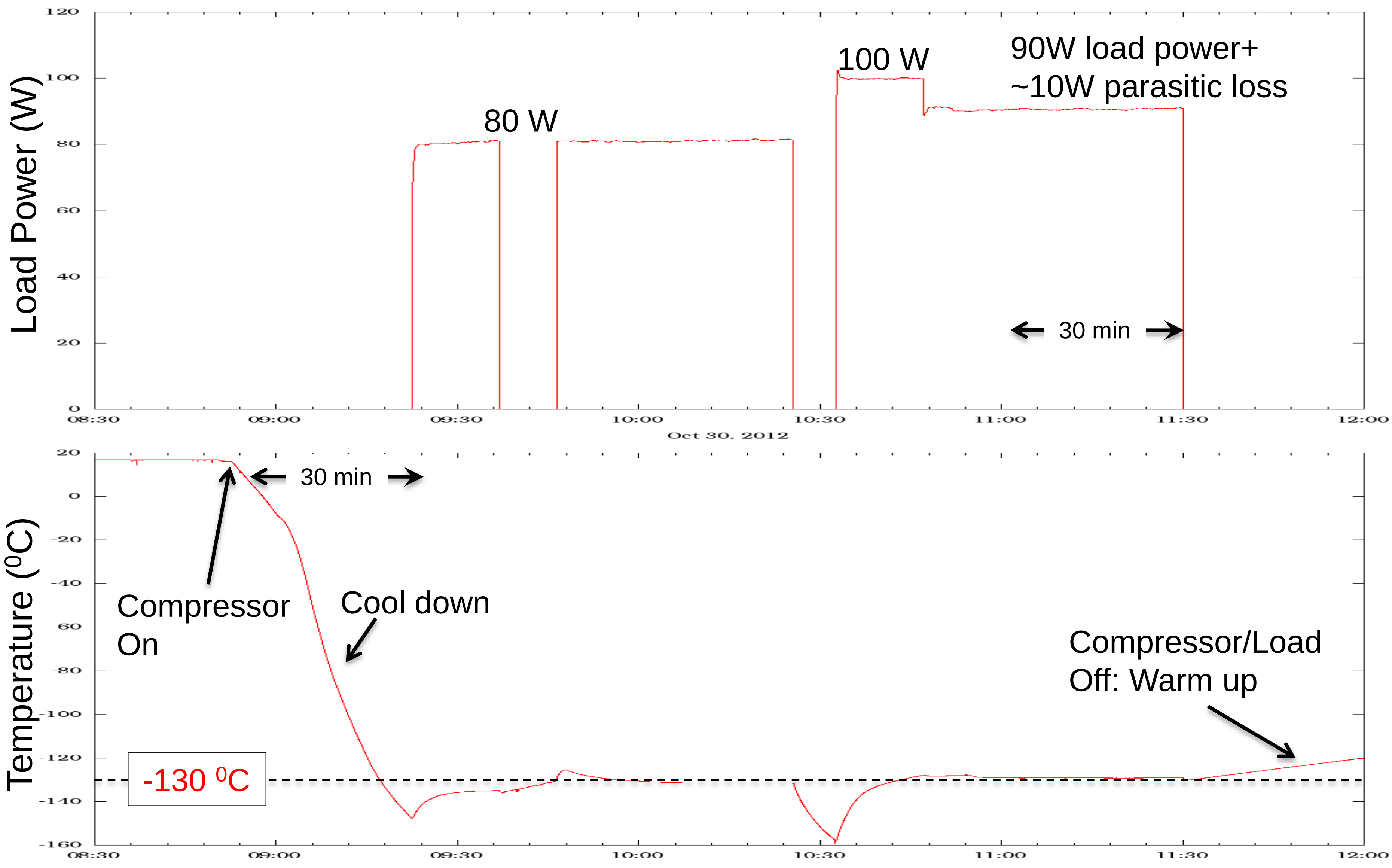
- **Status:**
  - All heat sources well understood
  - Thermal analysis indicates all components satisfy requirements
  - Structural analysis of cold & cryo plate indicates that they satisfy stiffness requirements



Once You Are Up There:
The Top End Camera Assembly Requires Final Rotation

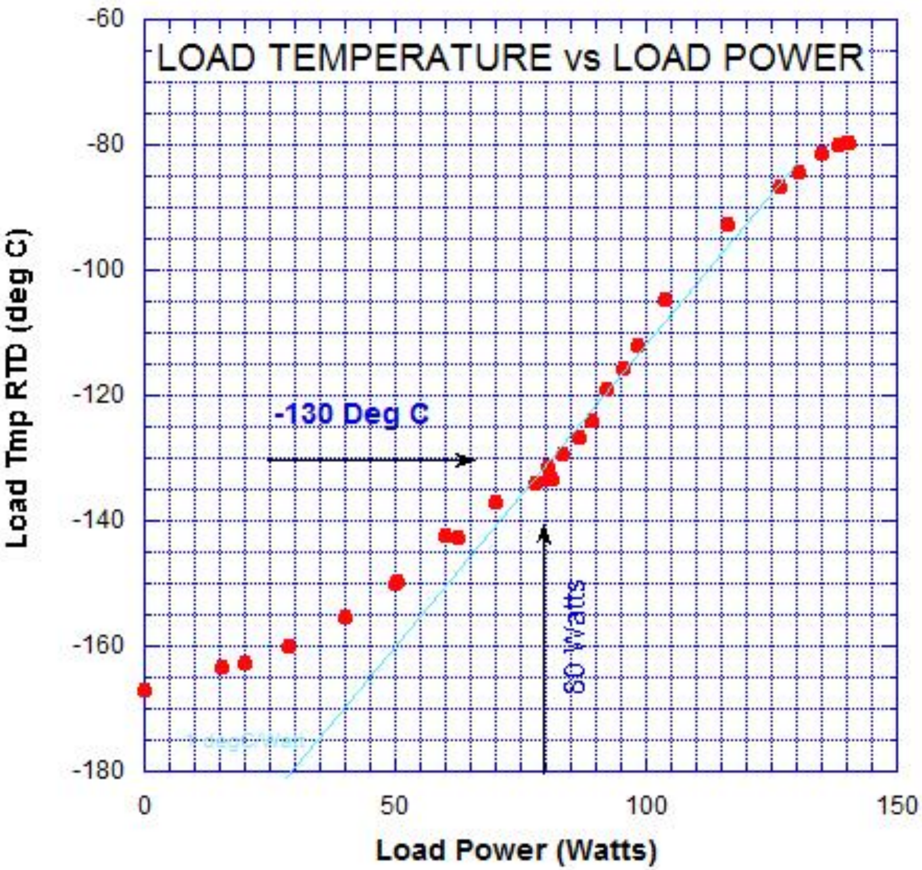


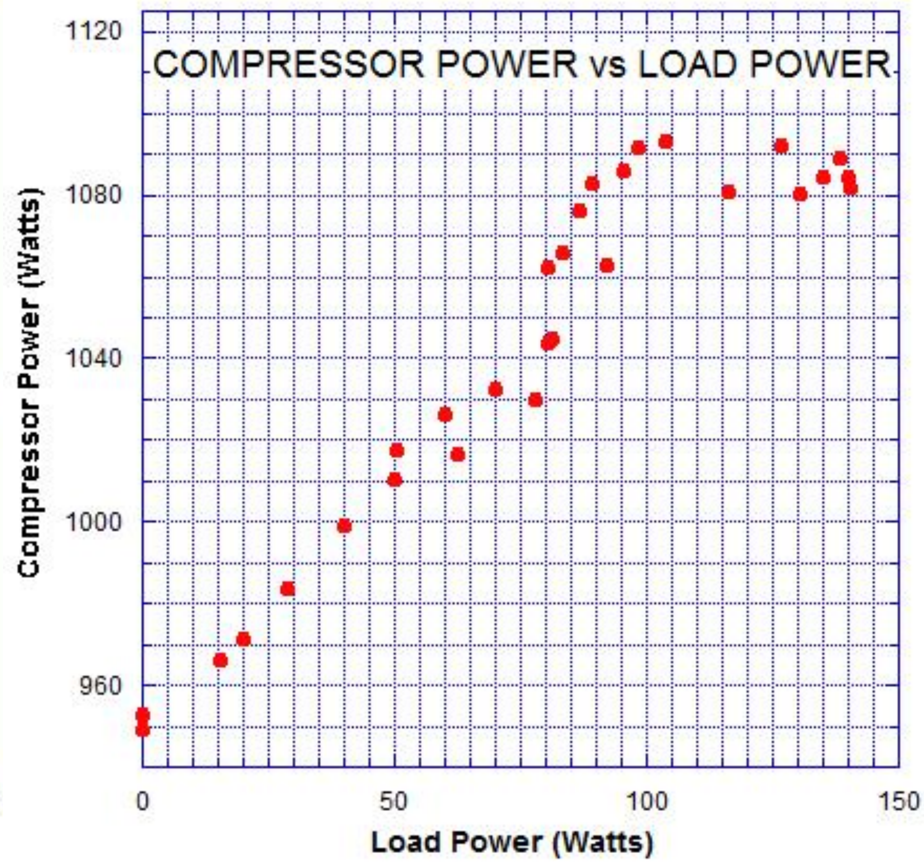
End 2012 First Run with KR-15 Mix Demonstrates Required Cooling Capacity and Temperature at SLAC



Measurements of Response to Load Variations (KR-15)

- **System has excellent response to load variation and overload tolerance.**





Around operating temperature the load temperature varies by ~1 Watt/Deg C

Slow rise in compressor power as load increased… ~8% efficient

End 2013 Through Present – Optimize HeX/Mix and Test With More and More Realistic System

- **Construction of new HeX(s) at SLAC now housed in a vacuum dewar. Include associated hardware to evaluate all orientation effects due to camera pointing & accelerations and optimize HeX design.**

Initial tests done and satisfactory

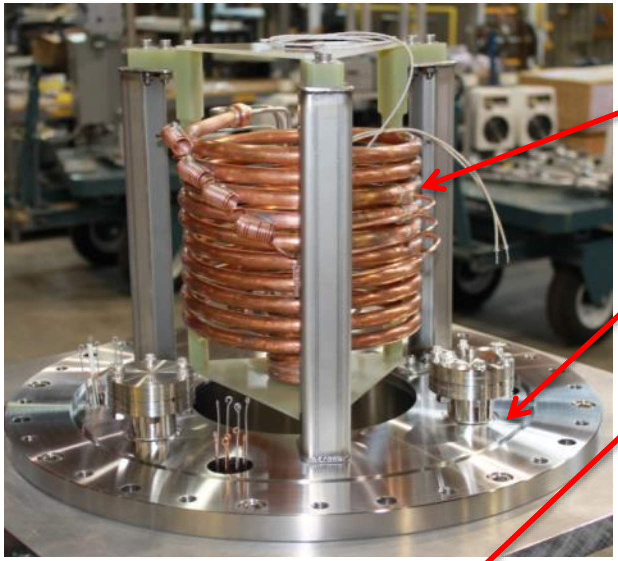
- **Construct 3 new Compressor Modules incorporating lessons from Long-Lines tests**
  - **Prototype the Hardware Control Unit [HCU] and software for compressor.**
    - Flow, over temperature, and protection system safety interlocks
    - DAQ monitoring of supply and return temperatures and pressures and compressor power

Last one is being tested now at MMR with the extended features

- **Design of extended vacuum Dewar system to include more camera representative hardware and geometry, candidate transfer lines and articulations.**
  - **Build subscale (1/5) cryoplate (prototype fabrication, performance issues (temp uniformity etc.) Include simulated Grid and simulated Rafts**
  - **Separate HeX from cryoplate after the vapor expansion capillary (C4) and test performance**
  - **Add long flexible transfer lines and final rotation / articulation behind Utility Trunk**
  - **Continue orientation tests and conduct extended runs**
  - **Test feedback algorithm for temperature control of cryoplate via trim heaters**

Initial Tests Began in June

7-Tube HeX In First Vacuum Dewar on Tip-Tilt Stage For Orientation Tests and Continued HeX Optimization



- **Heat Exchanger on insulating supports.**
- **On the Dewar flange.**
- **Inside a Vacuum enclosure.**
- **Plumbed with coils of rigid tubing for strain relief**
- **Mounted to rotator**
- **That is on a tipping platform**
- **To simulate camera motions**

System operated in late 2013 but shutdown in December awaiting new compressor chassis, filter/drying panel, new DAQ and extensive re-plumbing