ISAC-II SC-Linac Cryogenic System at TRIUMF

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TRIUMF, Canada

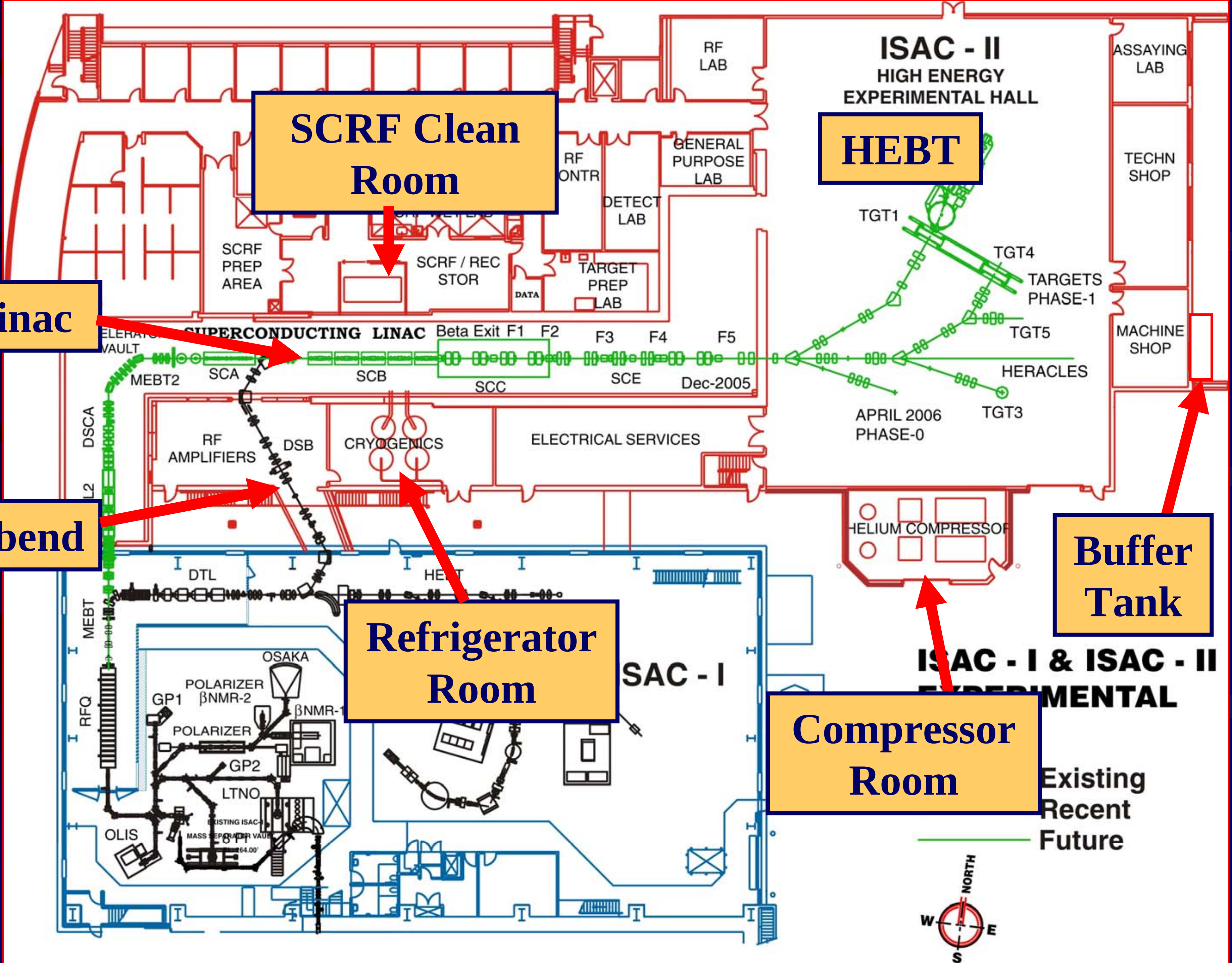
Cryogenics Operations Workshop
May, 2006

Outline:

- Overview
- Cryogenic Design
- Cryomodules
- Refrigerator Commissioning
- Beam Acceleration with one Cryomodule
- SC-Linac and He-Distribution Installation
- SC-Linac Commissioning – Beam Acceleration
- Summary and Future

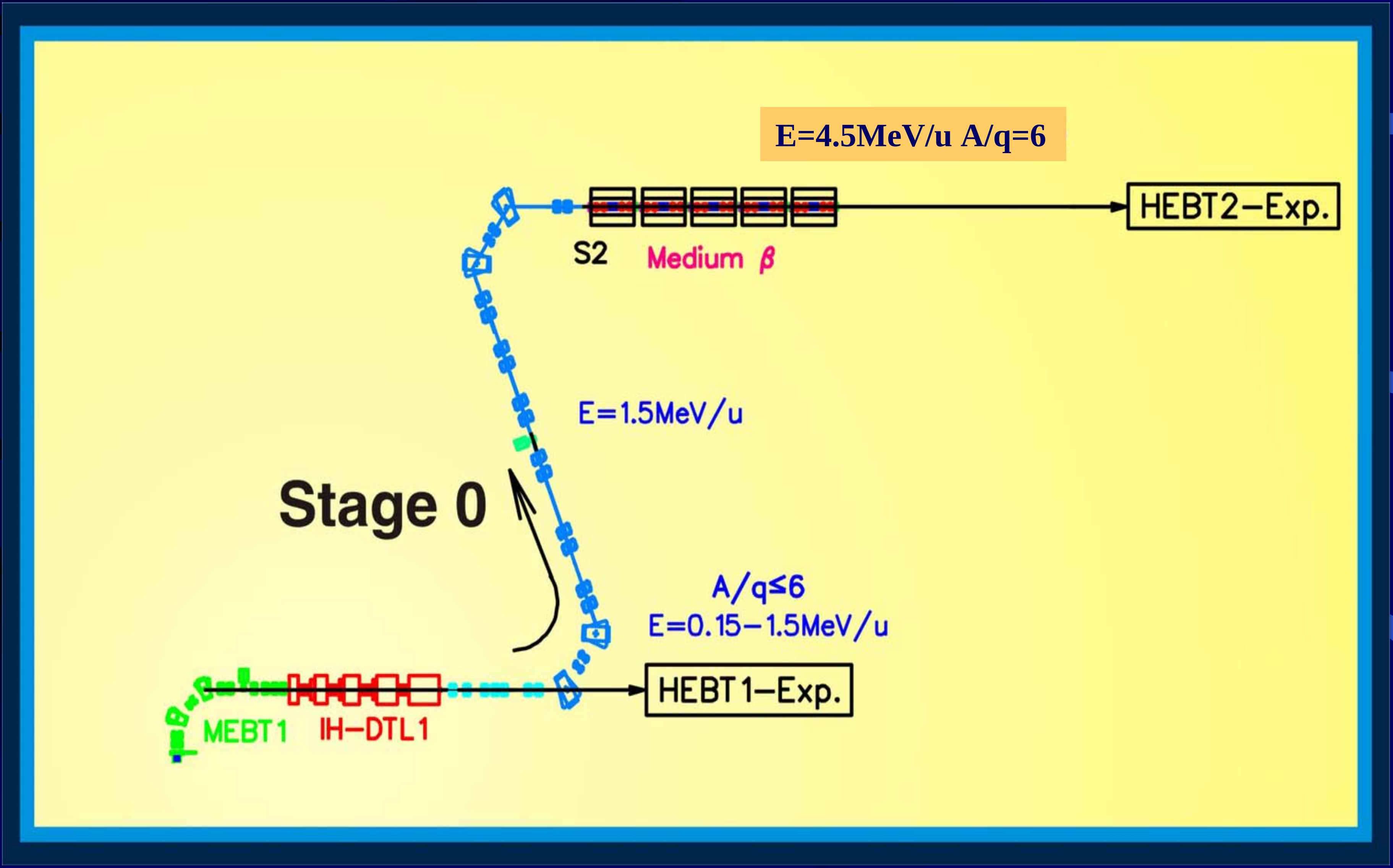
Overview

Cryogenics at TRIUMF

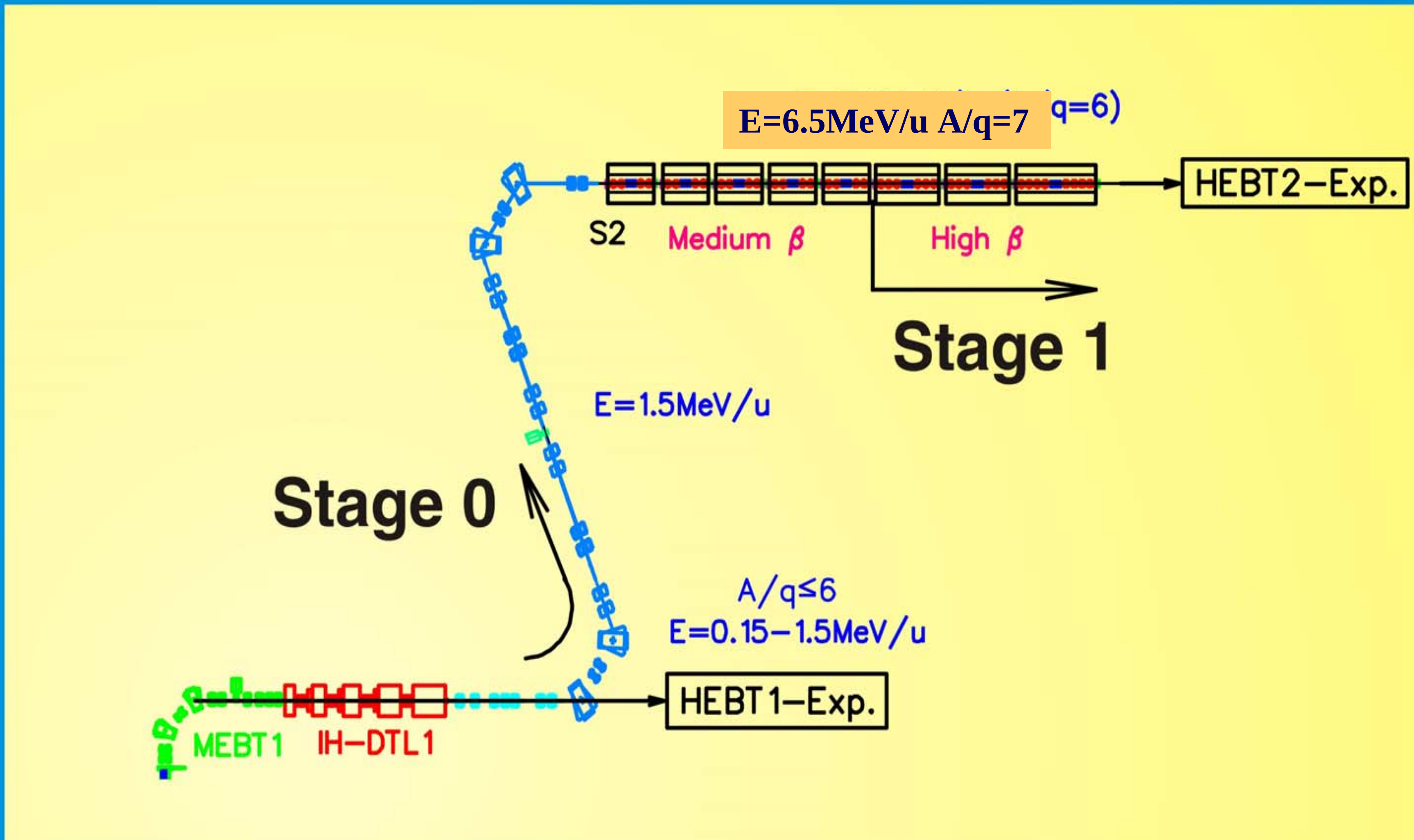


SCRF Clean Room
HEBT
Linac
S-bend
Refrigerator Room
Compressor Room
Buffer Tank
ISAC - II
HIGH ENERGY EXPERIMENTAL HALL
RF LAB
ASSAYING LAB
TECHN SHOP
MACHINE SHOP
GENERAL PURPOSE LAB
DETECT LAB
TARGET PREP LAB
SCRF PREP AREA
SCRF / REC STOR
DATA
SUPERCONDUCTING LINAC
Beta Exit F1 F2 F3 F4 F5
SCA
SCB
SCC
SCE
Dec-2005
MEBT2
DSCA
DSB
RF AMPLIFIERS
CRYOGENICS
ELECTRICAL SERVICES
TGT1
TGT4
TARGETS PHASE-1
TGT5
HERACLES
TGT3
APRIL 2006 PHASE-0
HELIUM COMPRESSOR
DTL
MEBT
RFQ
OSAKA
POLARIZER βNMR-2
GP1
βNMR-1
POLARIZER
GP2
LTNO
OLIS
ISAC - I
ISAC - I & ISAC - II EXPERIMENTAL
Existing
Recent
Future
NORTH
W
E
S

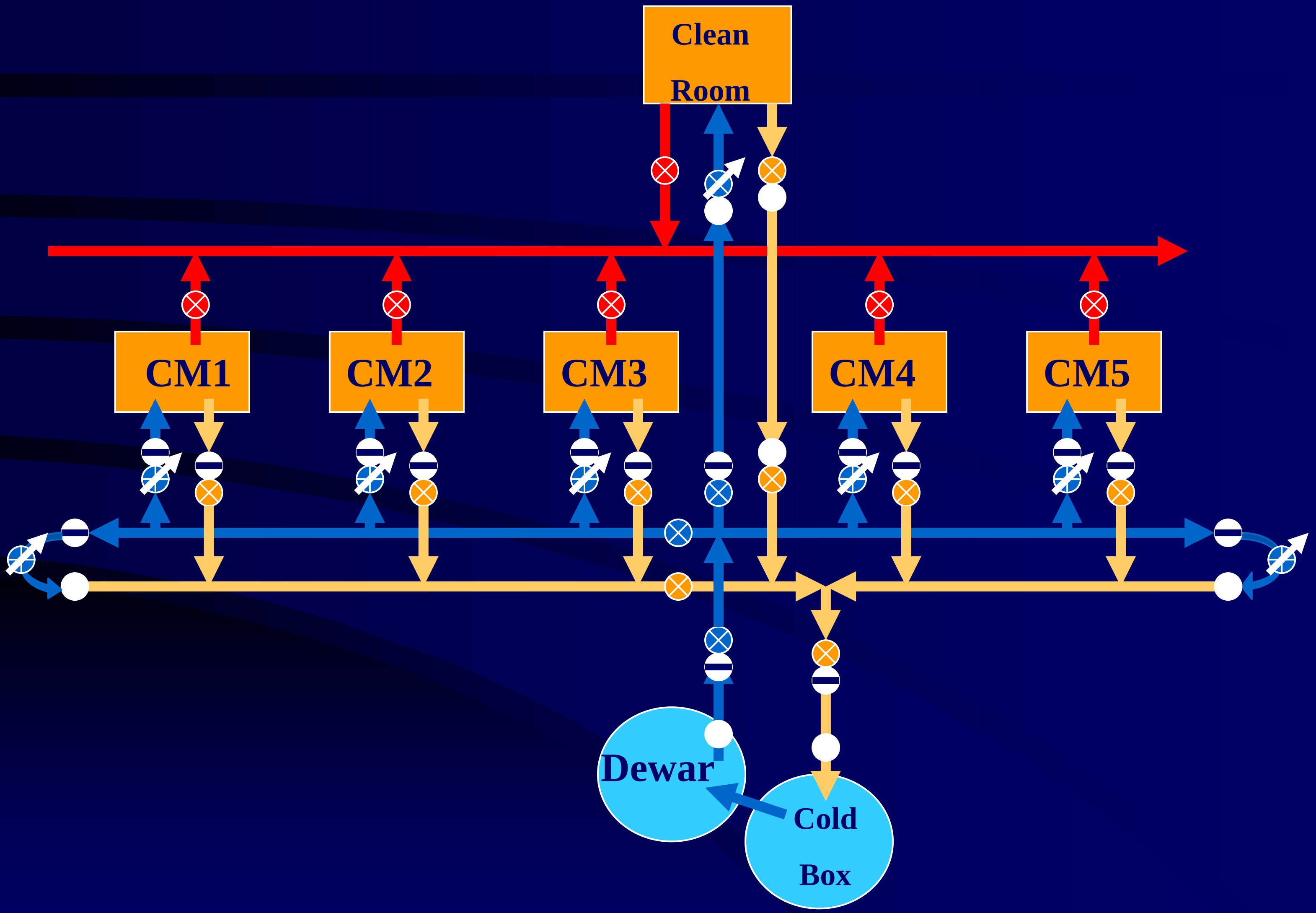
Stage 0 - 2005 (Commissioned April, 2006)



Stage 1 - 2008

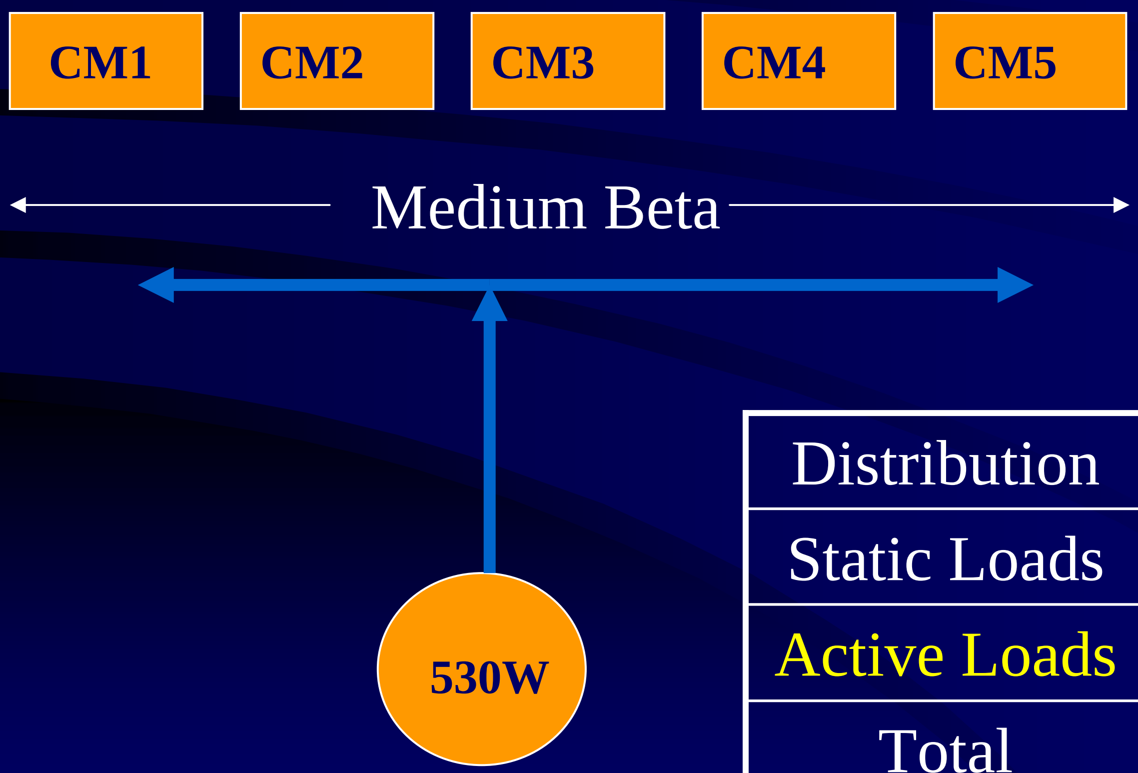

E=6.5MeV/u A/q=7
q=6)
HEBT2–Exp.
S2
Medium β
High β
Stage 1
E=1.5MeV/u
Stage 0
A/q≤6
E=0.15–1.5MeV/u
HEBT1–Exp.
MEBT1
IH–DTL1

Cryogenic Design



Cryogenic Loads (Phase 1)

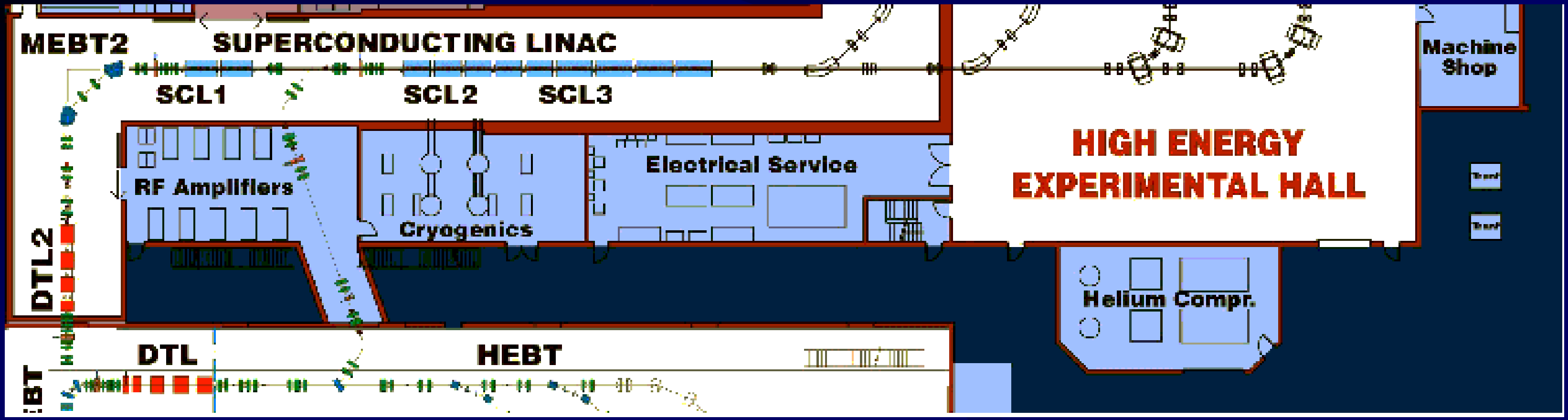
13W	13W	13W	13W	13W	Static Loads
32W	32W	32W	32W	32W	Active Loads



Distribution	< 72W	< 4.0gm/sec
Static Loads	65 W	3.6gm/sec
Active Loads	160 W	8.9gm/sec
Total	300W	16.5gm/sec

Phase-1 Refrigerator (530W)

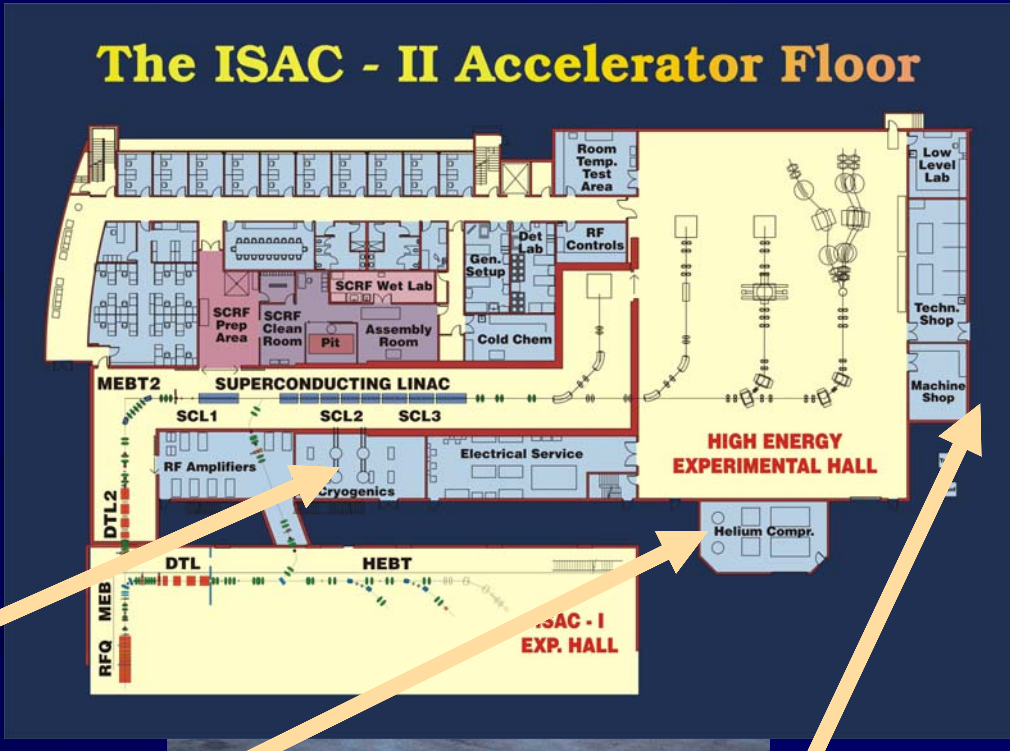
- Linde TCF50
  - 530W @ 4.5K and 0.7gm/sec liquefaction with LN2 pre-cooling
- Choice based on the following specification:
  - Expected Normal Loads
    - 140W static and 160W active → 300W
  - Cooldown mode (maximum liquefaction)
    - Phase 1 – 5.2gm/sec (150liq-ltr/hour)
  - Pressure variation specification
    - $dP/dt < 1$ Torr/sec
    - $\Delta P < \pm 10$ Torr



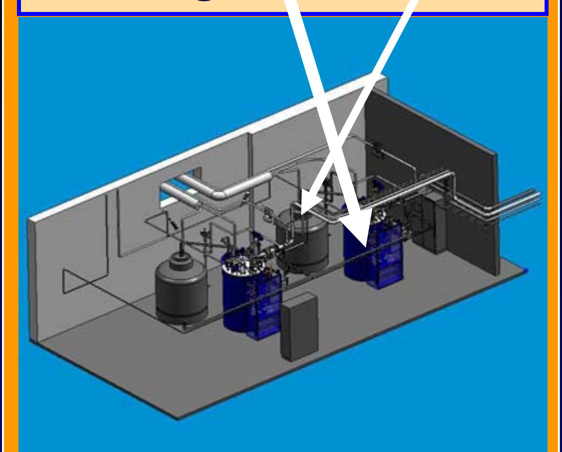
ISAC-II Cryogenics

Cold Box

LHe Dewar



Refrigerator Room



Compressor Room

Buffer Tank

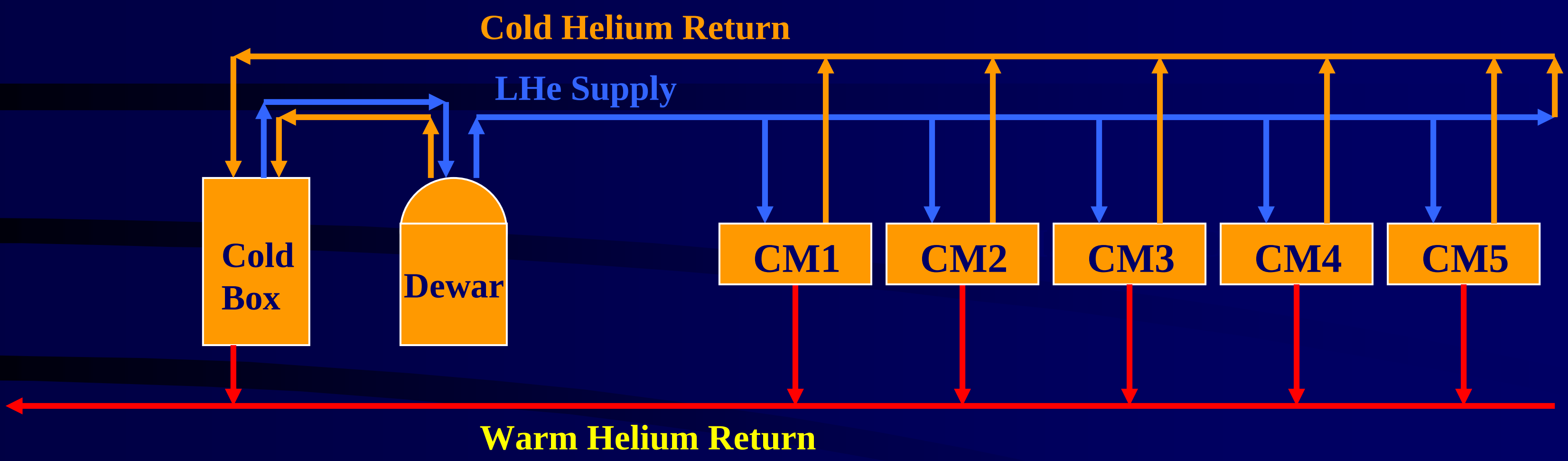
Phase-1 Refrigeration (530W)

- LINDE supply
  - ✓ Cold box
  - ✓ Main compressor
  - ✓ Recovery compressor
  - ✓ ORS and gas management system
  - ✓ Commissioning – March, 2005

- TRIUMF supply
  - ✓ Installation of Linde components
  - ✓ Helium dewar – Chalk River
  - ✓ Buffer tank – 30000 USgallon
  - ✓ Warm piping
  - ✓ Cold distribution (DeMaCo)
  - ✓ Helium purity meter

LINDE TCF50 Commissioned (Feb. 2005)

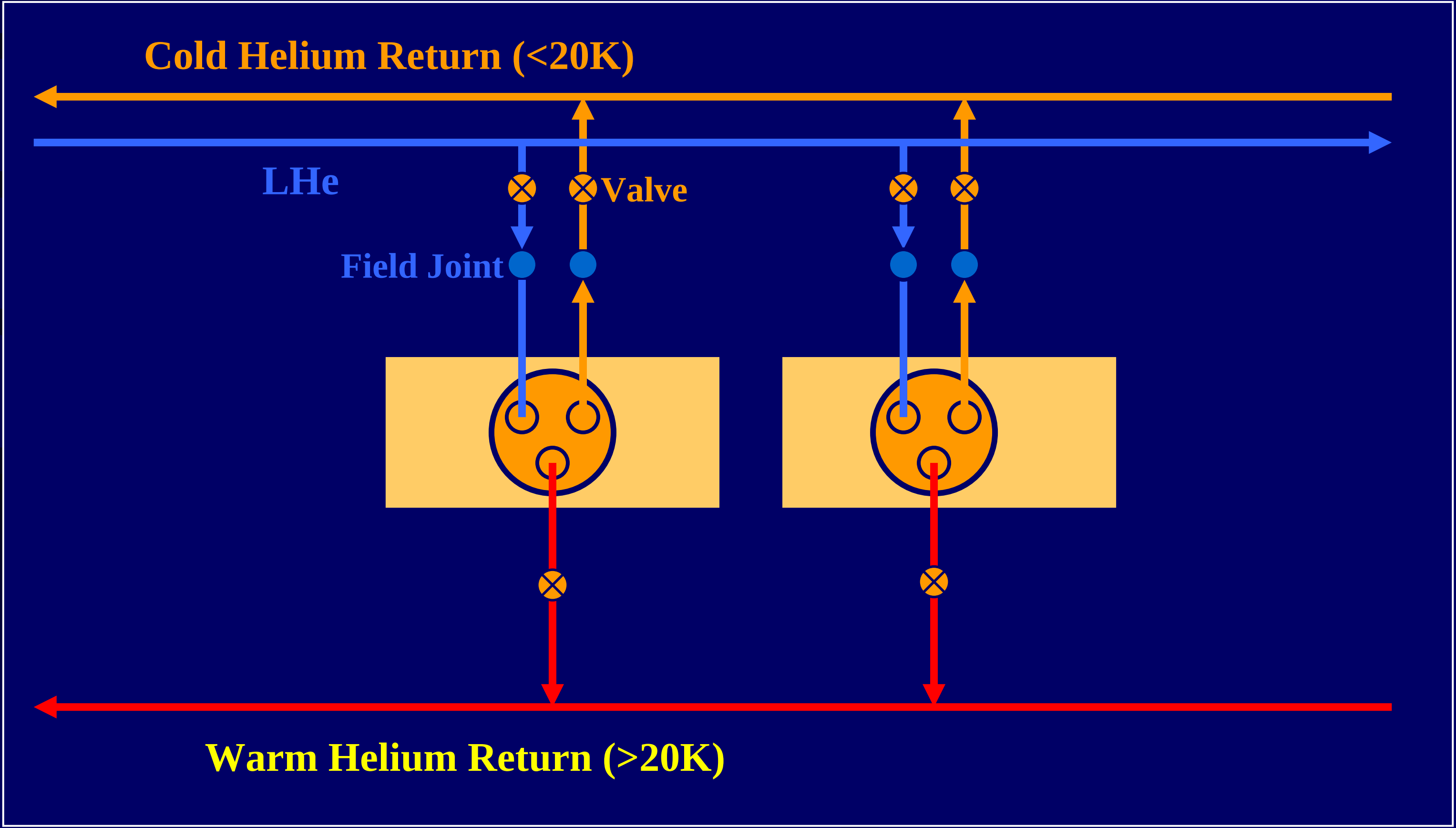
Cold Distribution



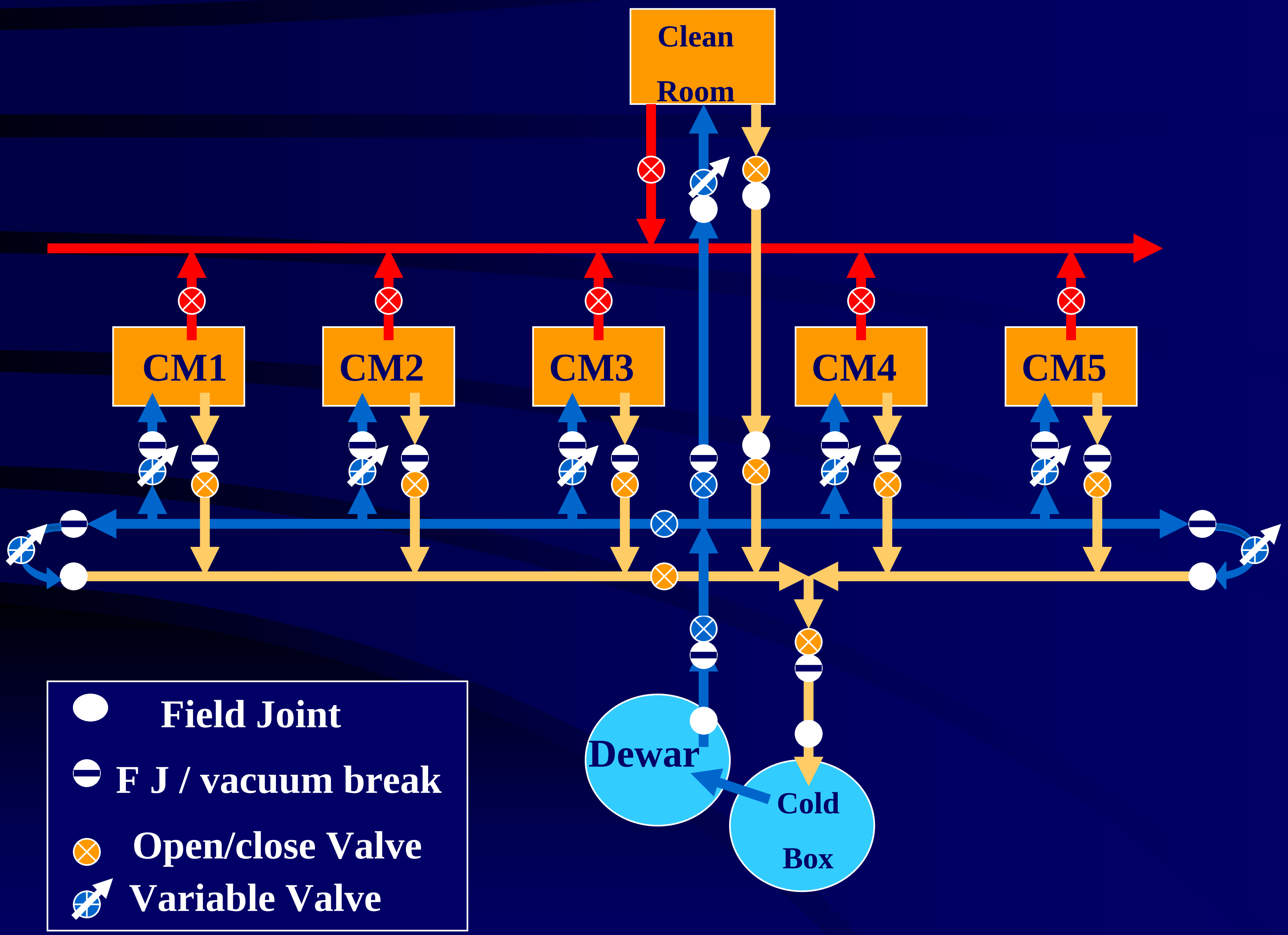
- Parallel supply feed from dewar through main header (4.5K)
- Cold helium return (<20K) during normal operation
- Warm helium return (>20K) to compressor suction used during cooldown

He Cold Distribution – Cryomodule

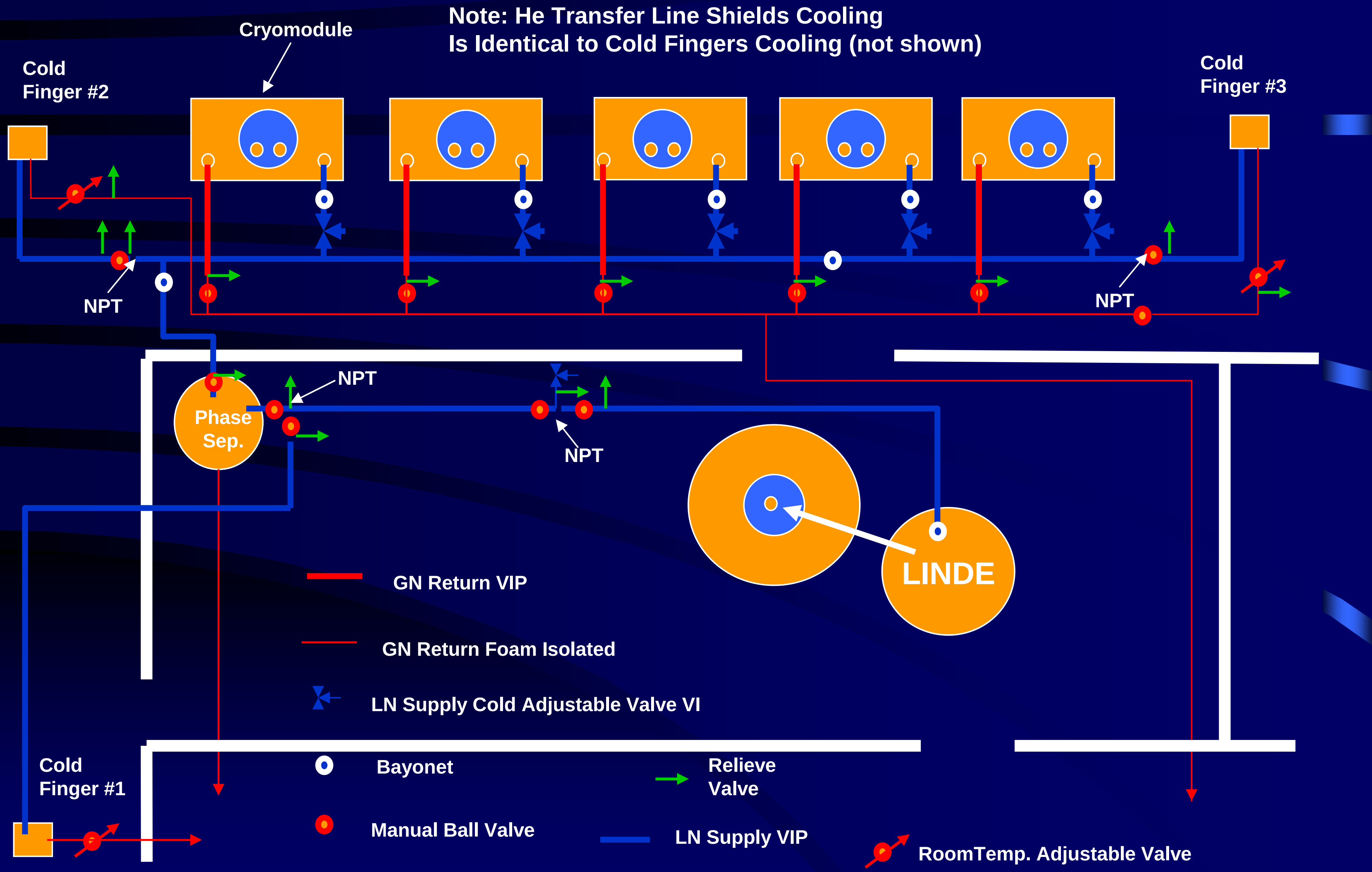
- Individual, vacuum jacketed, LN2 cooled lines for supply and return
- Field joints used to join supply and return for cryomodule to main trunk-line



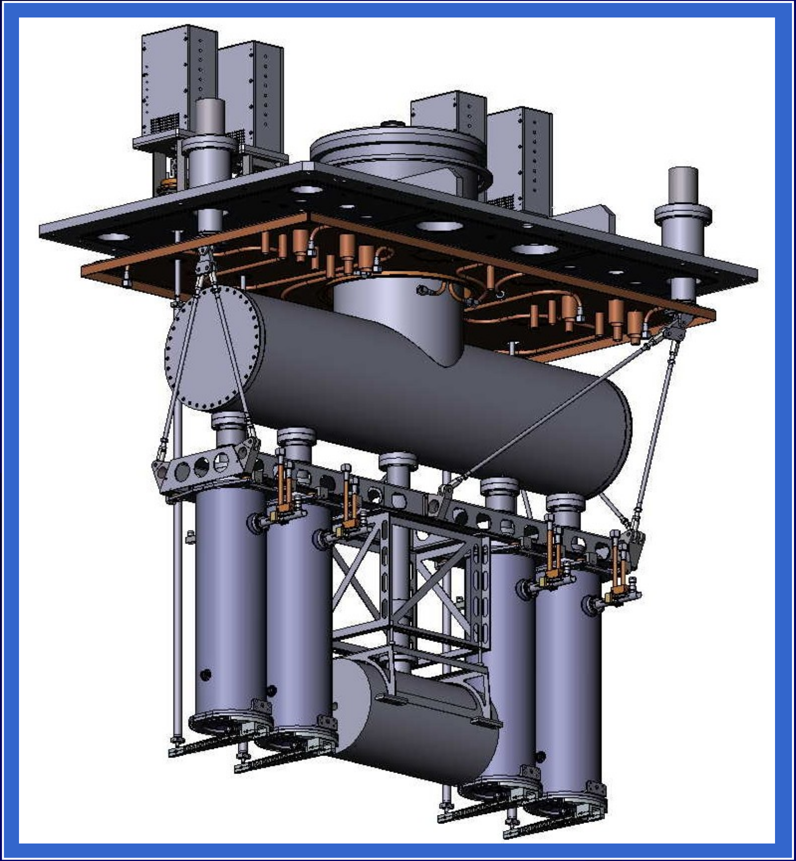
Cold Distribution (Phase-1)



Nitrogen Distribution

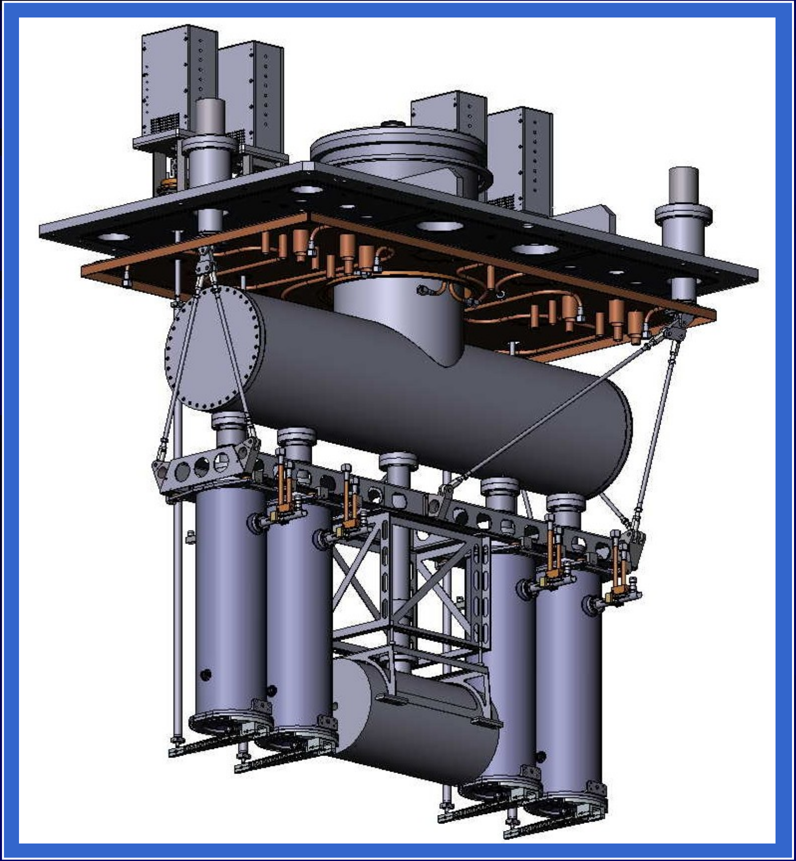


Medium Beta Cryomodules



Medium Beta Cryomodule

- Cold mass suspended from lid
- LN2 cooled thermal shield, mu metal liner
- 120 L helium reservoir
- Single vacuum space for RF and thermal isolation



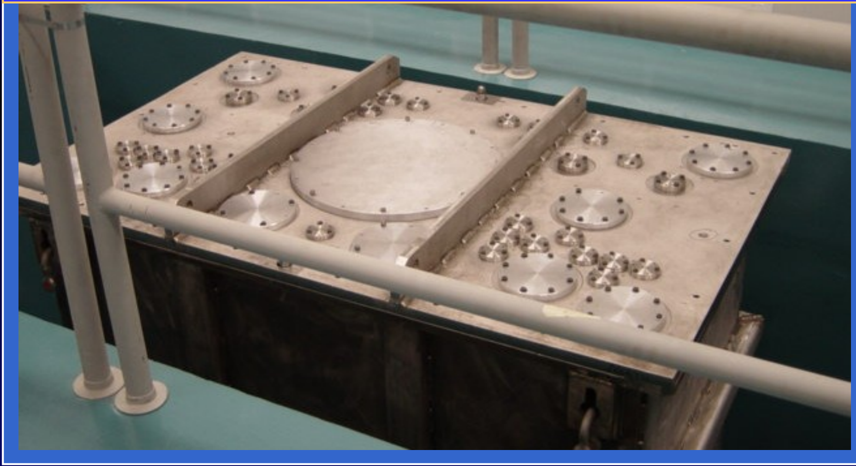
Lid Assembly in Assembly Frame

Vacuum Tank

- 1.9cm thick stainless steel (316L) with external reinforcing ribs
- L=176cm, W=99cm, H=196cm
- All services through 44 flanged ports on lid

Cryomodule Vacuum Tank

Cryomodule Top Plate



Assembly Frame

- For clean room assembly of cryomodule lid and contents including RF cavities and solenoid
- Top mounting surface and end plates mimic the vacuum tank top flange and beam ports for pre-alignment of cavities

Cryomodule Assembly Frame

Nitrogen Heat Shield

- 10mm ID copper tube soldered to copper sheet arranged in a box-like structure
- Copper, nickel-plated to reduce emissivity
- Solder applied on hot table without flux in inert gas environment
- Copper cooling tubes run in series
    - L=36m
    - ΔP=1.9PSI warm and 0.1PSI cold

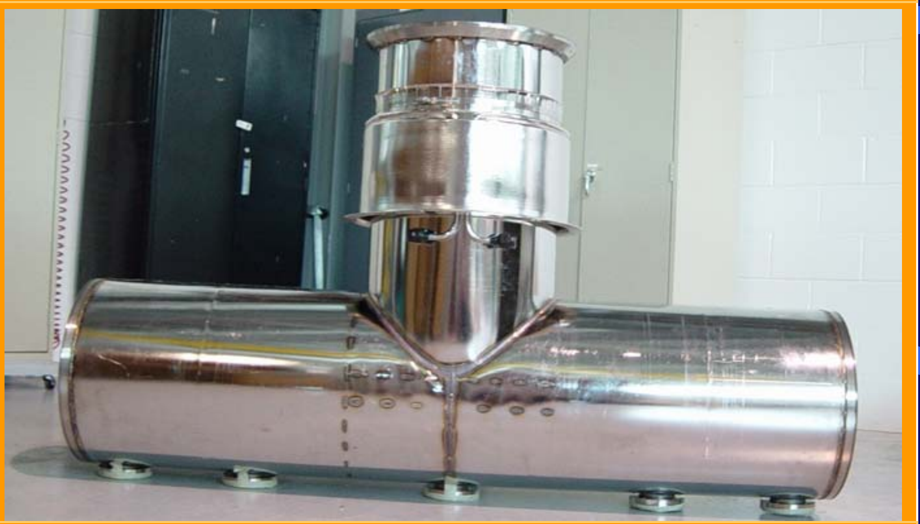
Hot Table for Fluxless Soldering

LN2 Box being lowered into Cryomodule

Helium Reservoir and Mounting Frame

- Helium reservoir
  - 120 Ltr
  - 316L electropolished stainless steel
- Mounting frame
  - 316L electropolished stainless
  - Supports cavities and solenoid
  - Suspended from struts on lid

Helium Reservoir



Mounting Frame and Support Struts

Medium Beta Cavity

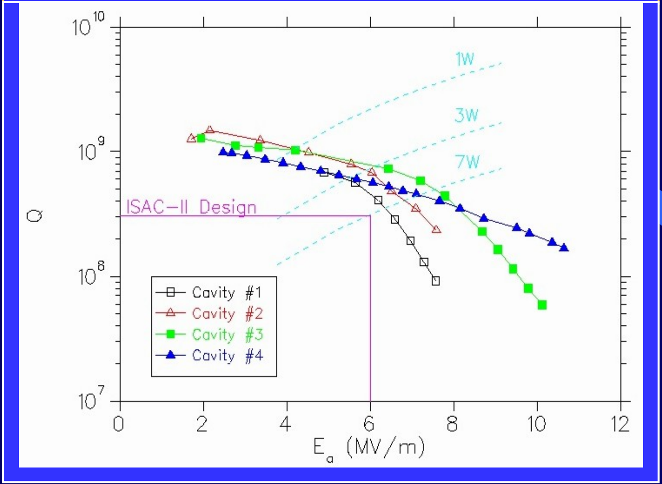
- Prototype developed in collaboration with LNL, Italy and fabricated at Zanon, Italy
- Twenty cavities manufactured by Zanon
- Four cavities chemically polishing at CERN
- Remaining 16 cavities polished at JLAB
- All cavities tested at TRIUMF

Chemical Polishing at CERN

Prototype Cavity

Frequency Measure at Zanon

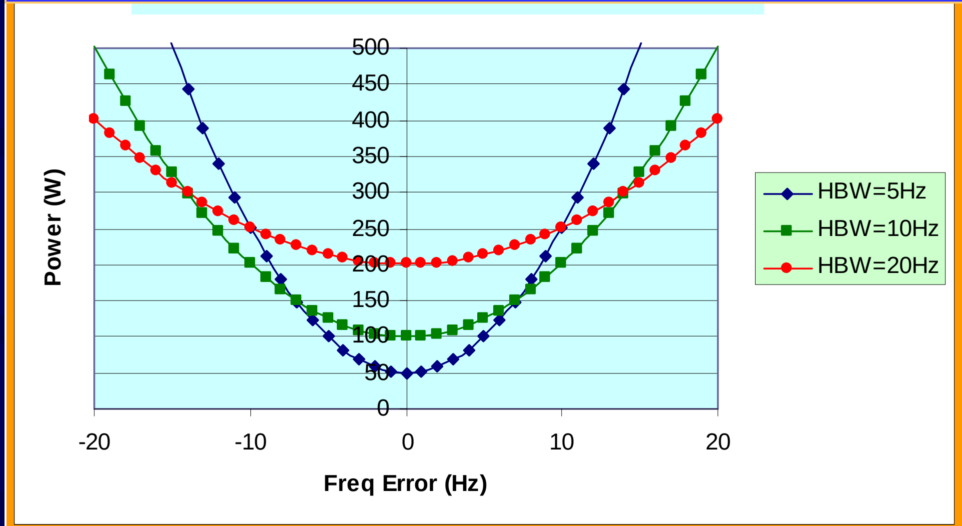
Four Cavities at TRIUMF



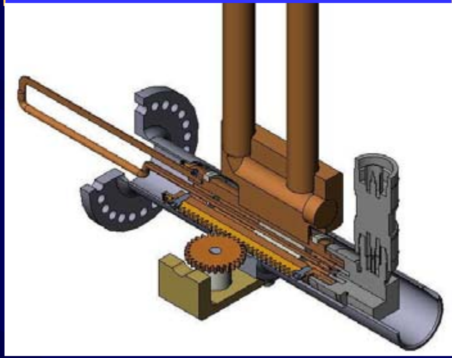
RF Systems

- ❑ RF power
  - ➢ Provide useable bandwidth by overcoupling
  - ➢ Require P_f =200W at cavity for f $_{1/2}$=20Hz at E_a=6MV/m, β=200
- ❑ Coupling loop
  - ➢ Developed LN2 cooled loop
  - ➢ <0.5W to LHe for P_f=250W
- ❑ Mechanical tuner
  - ➢ Precise (0.3~Hz), fast (>50Hz/sec) tuner with dynamic range of 8kHz and coarse range of 32kHz
- ❑ Tuning plate
  - ➢ Spun, slotted, `oil-can' tuning plate to improve tuning range

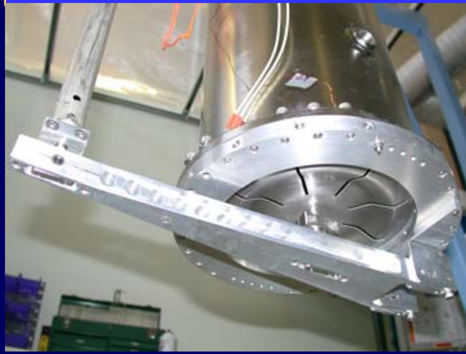
Forward power required for Ea=6MV/m and given bandwidth



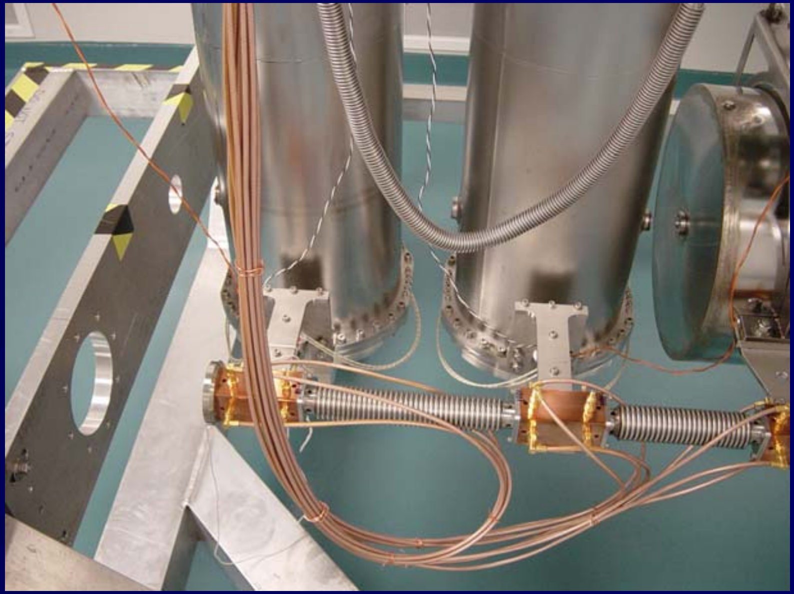
Coupling Loop

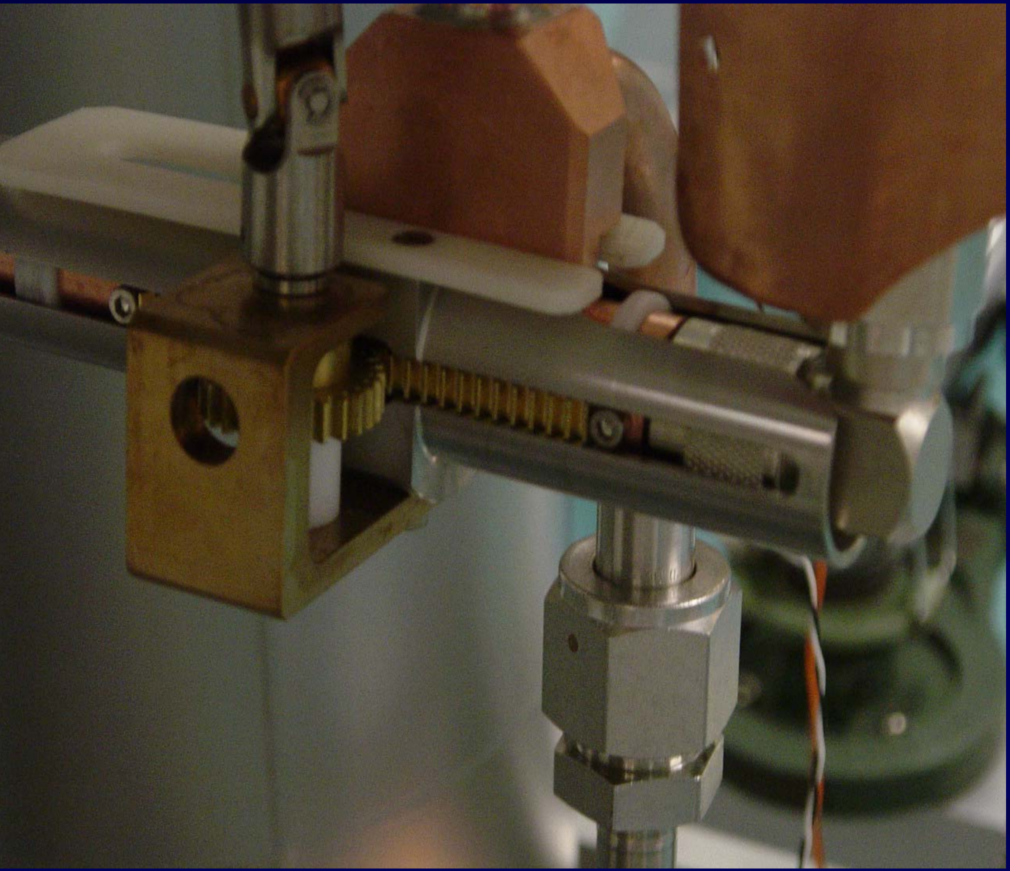


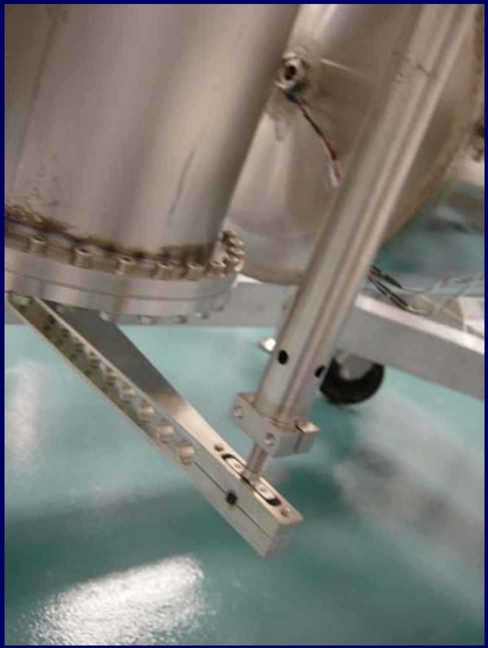
Mechanical Tuner



Cryomodule Components



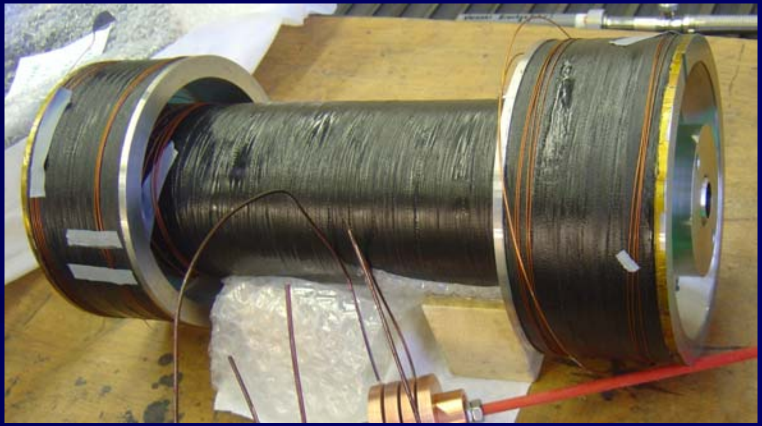




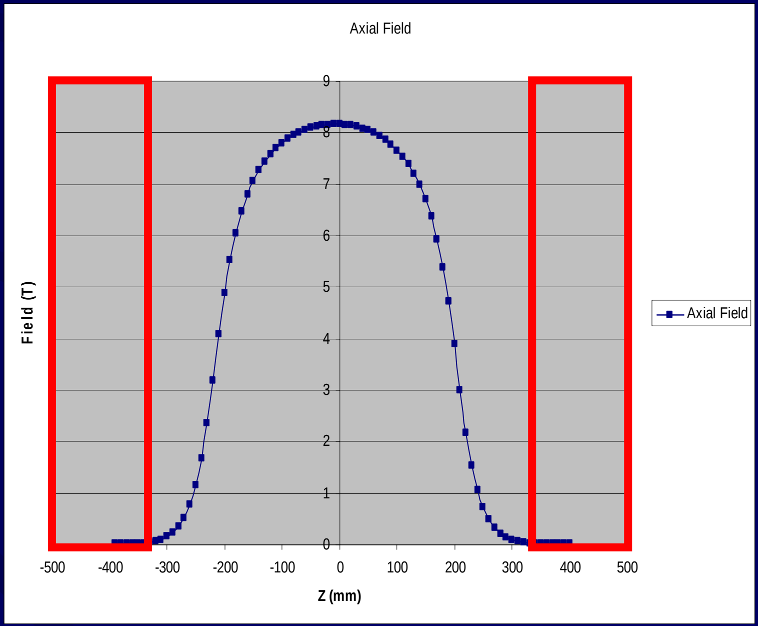
Superconducting Solenoids

- Beam Focusing in the SC-Linac is provided by superconducting solenoids (B≤9T)
- End fringe fields controlled with active `bucking' coils (B_{cavity}≤0.1T)
- Solenoids for Medium and High-beta Cryomodules fabricated at Accel, Germany
  - See table for specifications

Prototype Solenoid at Accel



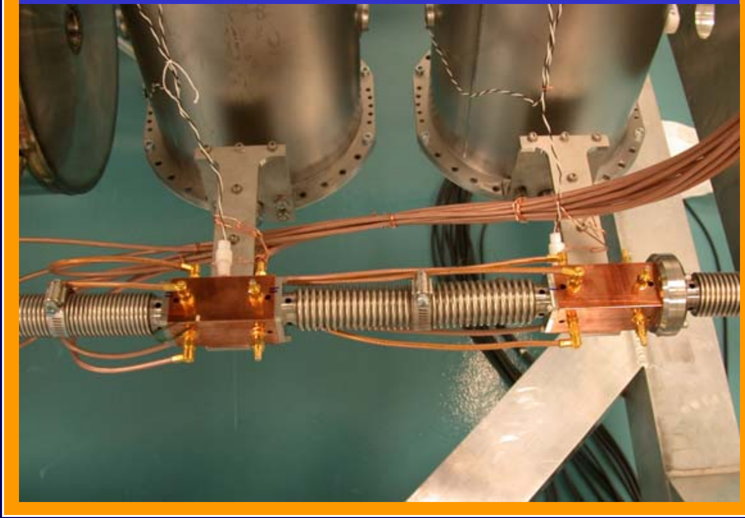
	Low β	Med β	High β
Field	9T	9T	9T
Bore	26mm	26mm	26mm
Number	4	5	3
Eff. Length	16cm	34cm	45cm

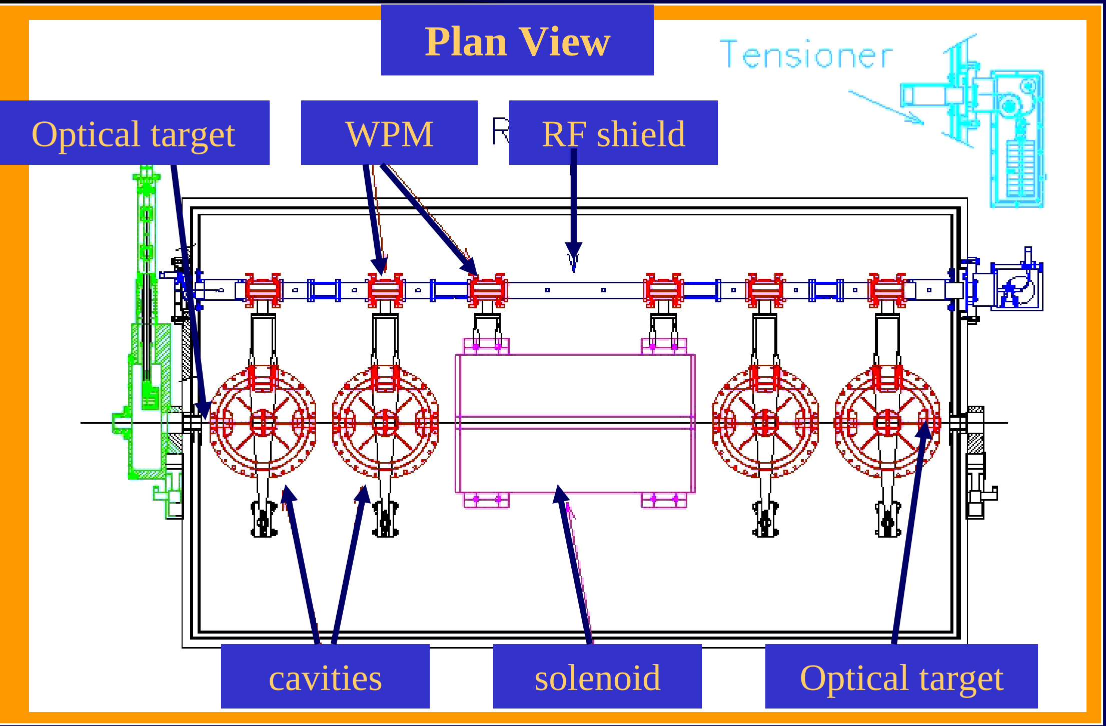


Cryomodule Alignment

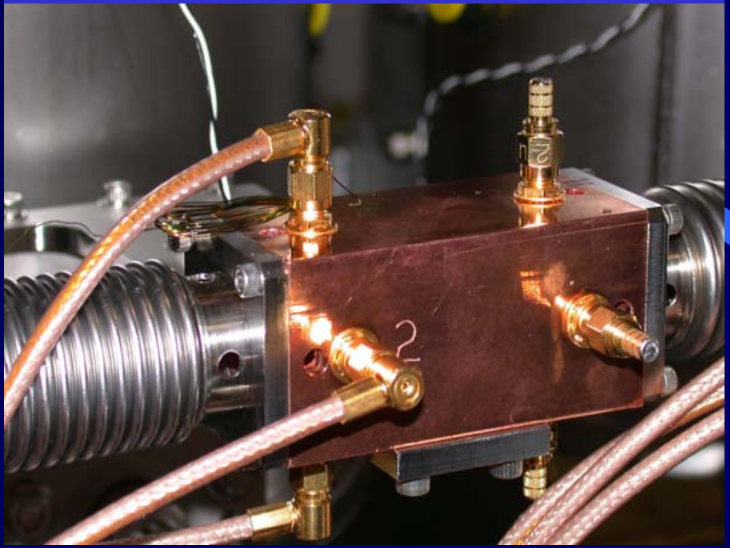
- **the tolerance on solenoid and cavity misalignments are ±200 µm and ±400 µm respectively**
- collaboration with INFN, Milano, Italy on the development of a Wire Position Monitor for cold alignment measurement with precision of 20 **µm**
  - Stripline monitor attached to each device driven by RF signal along a reference wire

WPM Monitors on Cavities



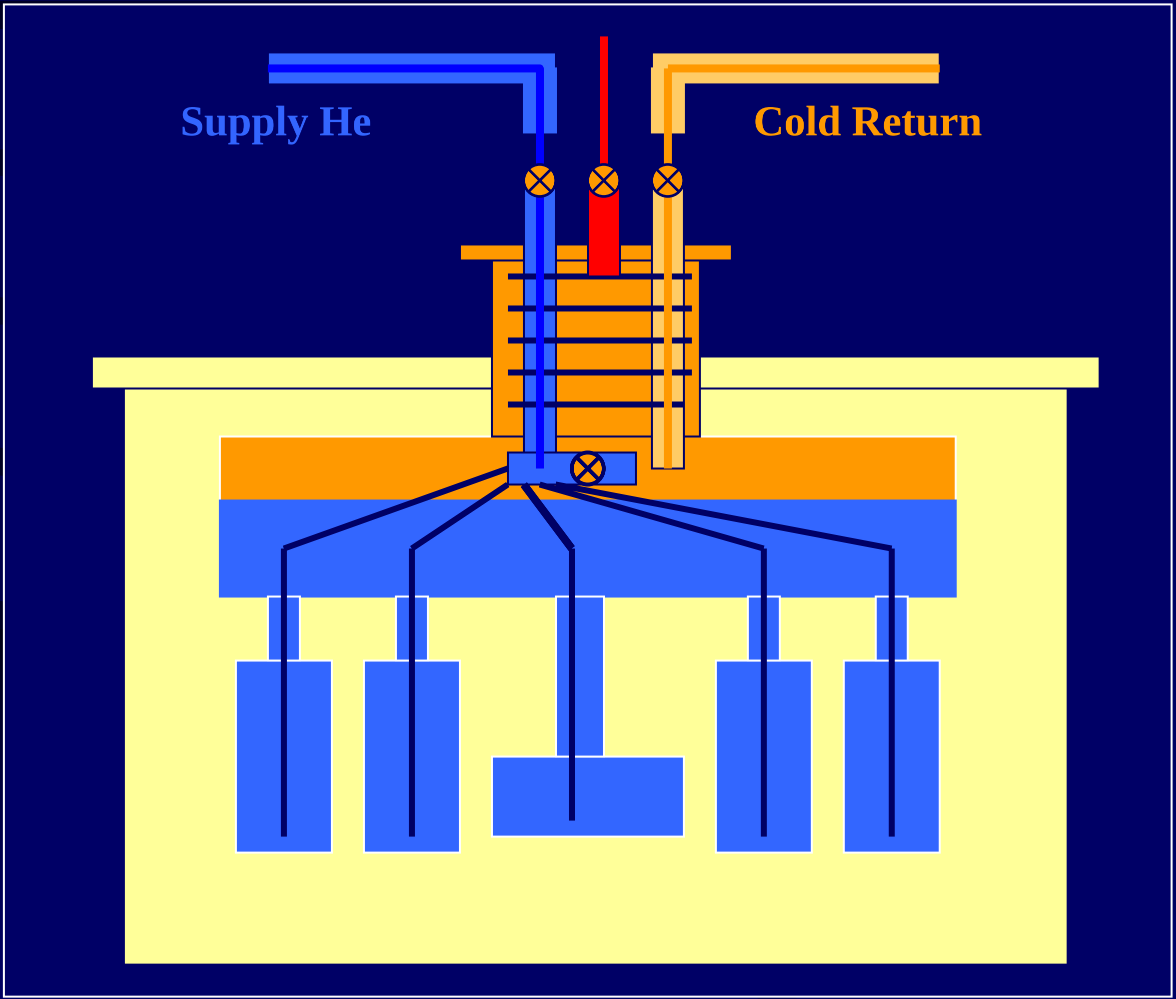


Wire Position Stripline Monitor

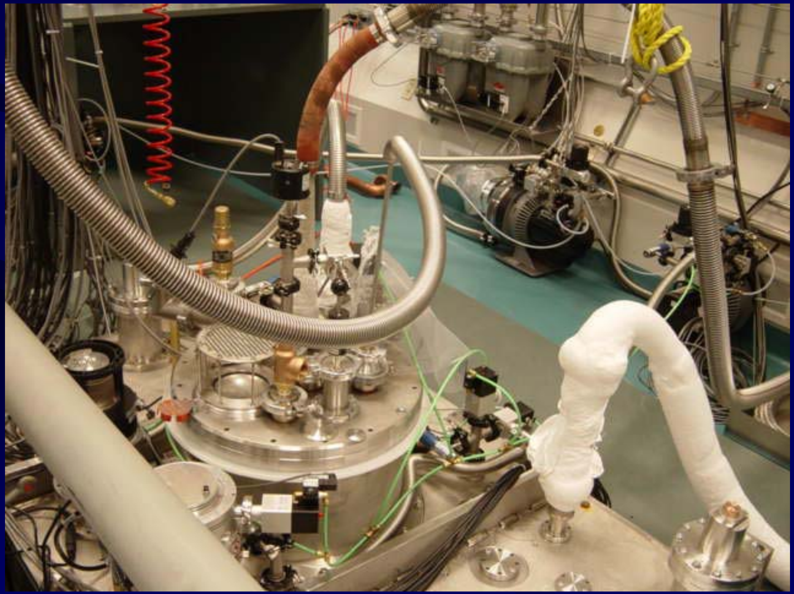


Cryomodule Distribution

- Cryomodule cooled by forcing helium to bottom of each cold element through a distribution spider

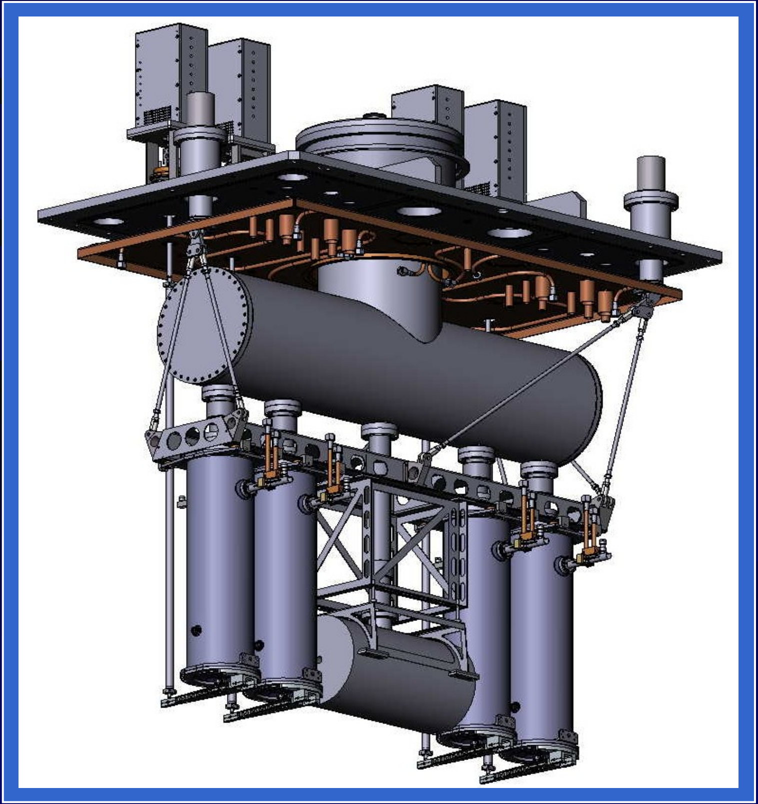


Cryomodule Cold Tests

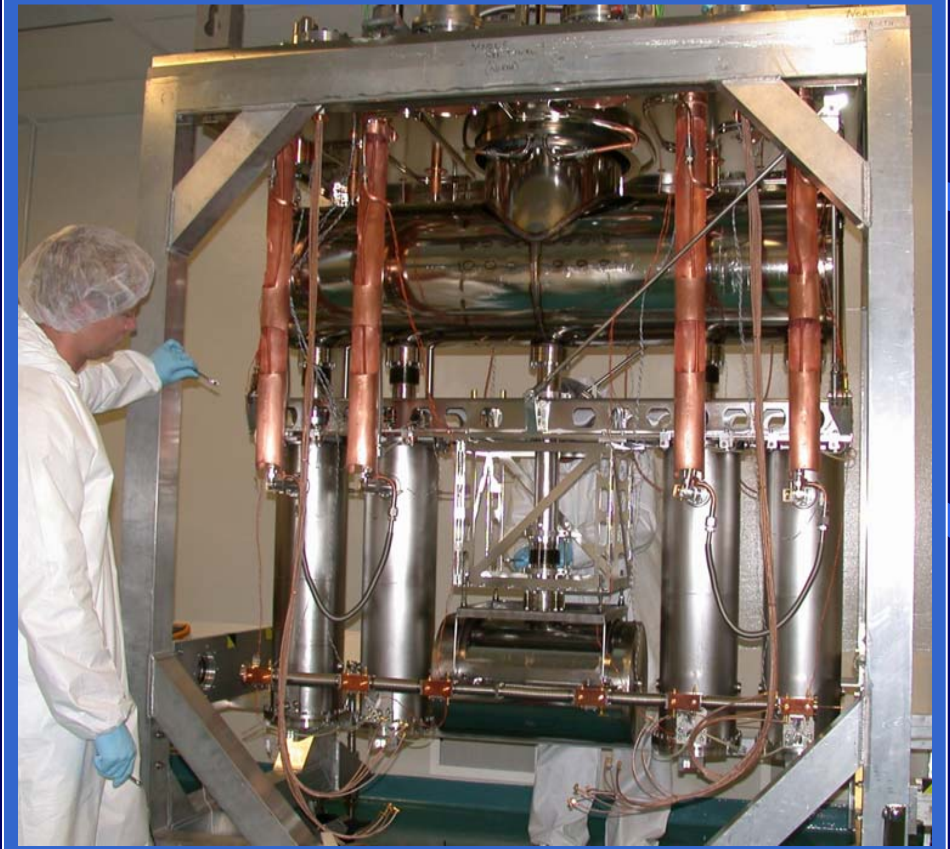


Medium Beta Cryomodule

- Cryogenic alignment tests
- RF cold tests
- Acceleration test - Clean Room - Nov, 2004
- Acceleration test - Vault - June, 2005

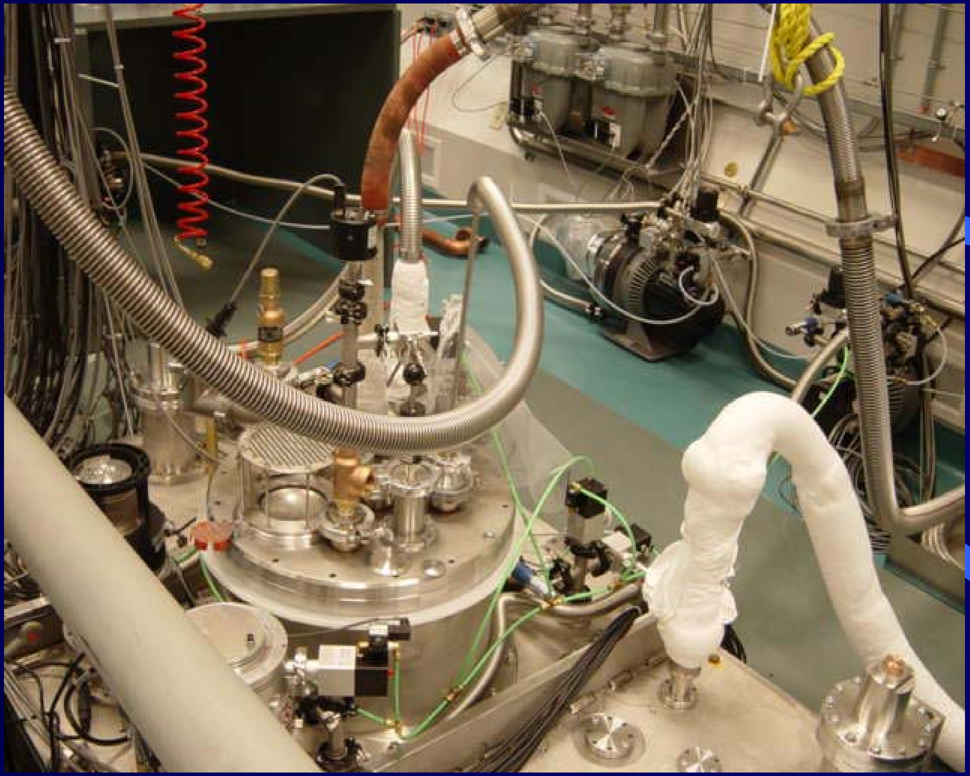


Cryomodule Assembly in Clean Room



CRYOMODULE Assembly in ISAC-II Clean Room

CRYOMODULE Cold Test in ISAC-II Clean Room

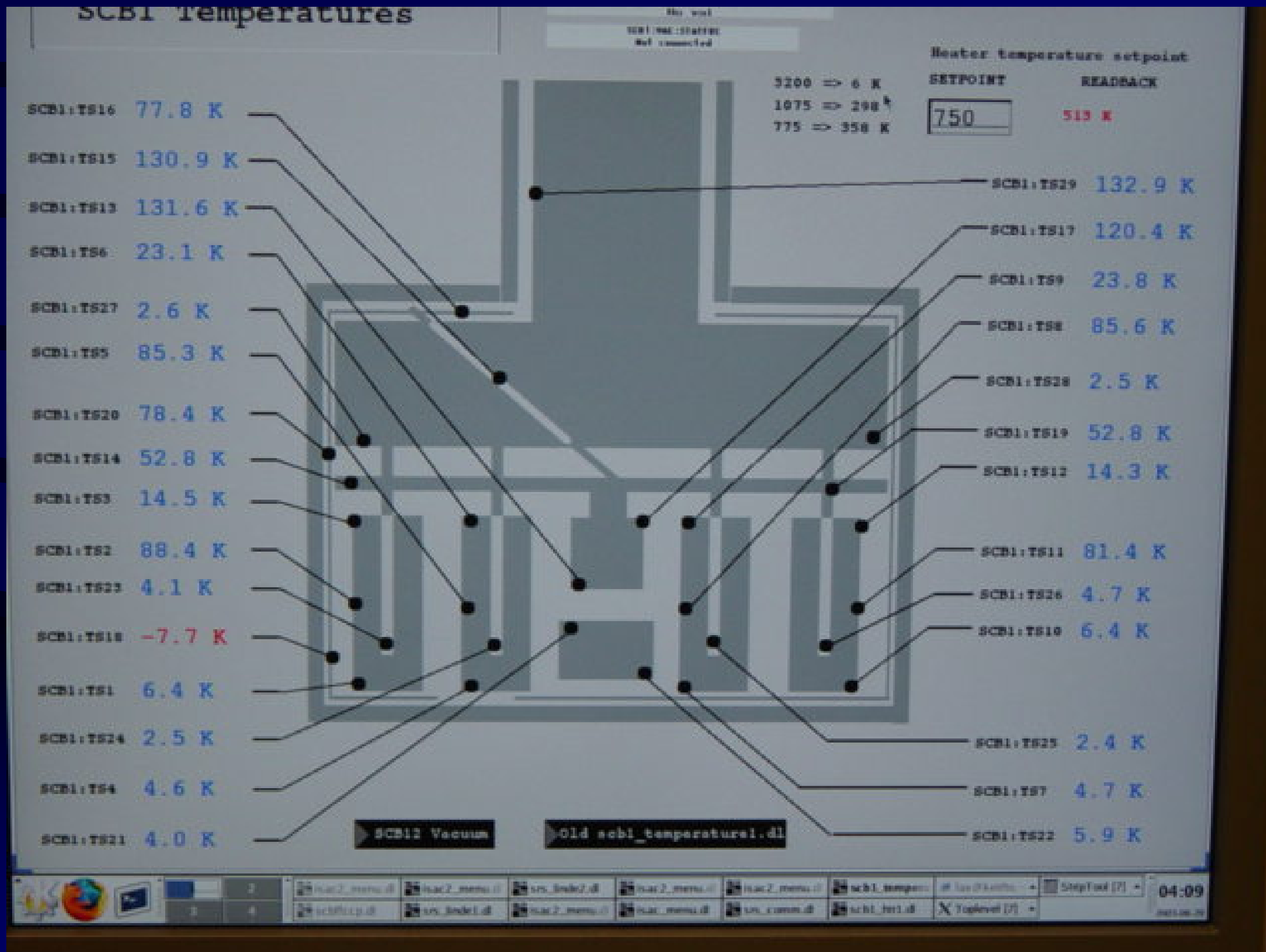


He & N2 Gas Flow Meters

Vaporizers

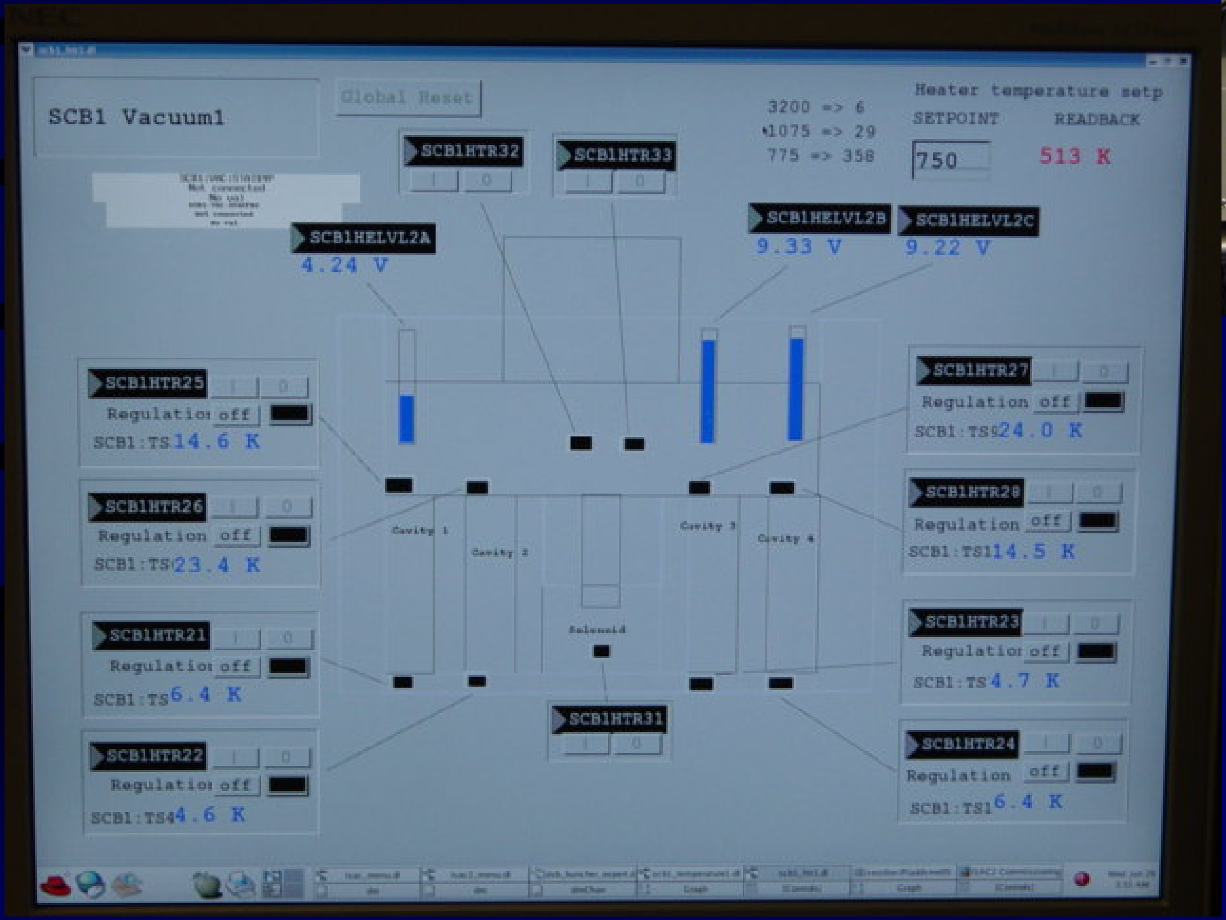
Medium Beta Cryomodule

- Thermometry (29 Lakeshore silicone diodes)



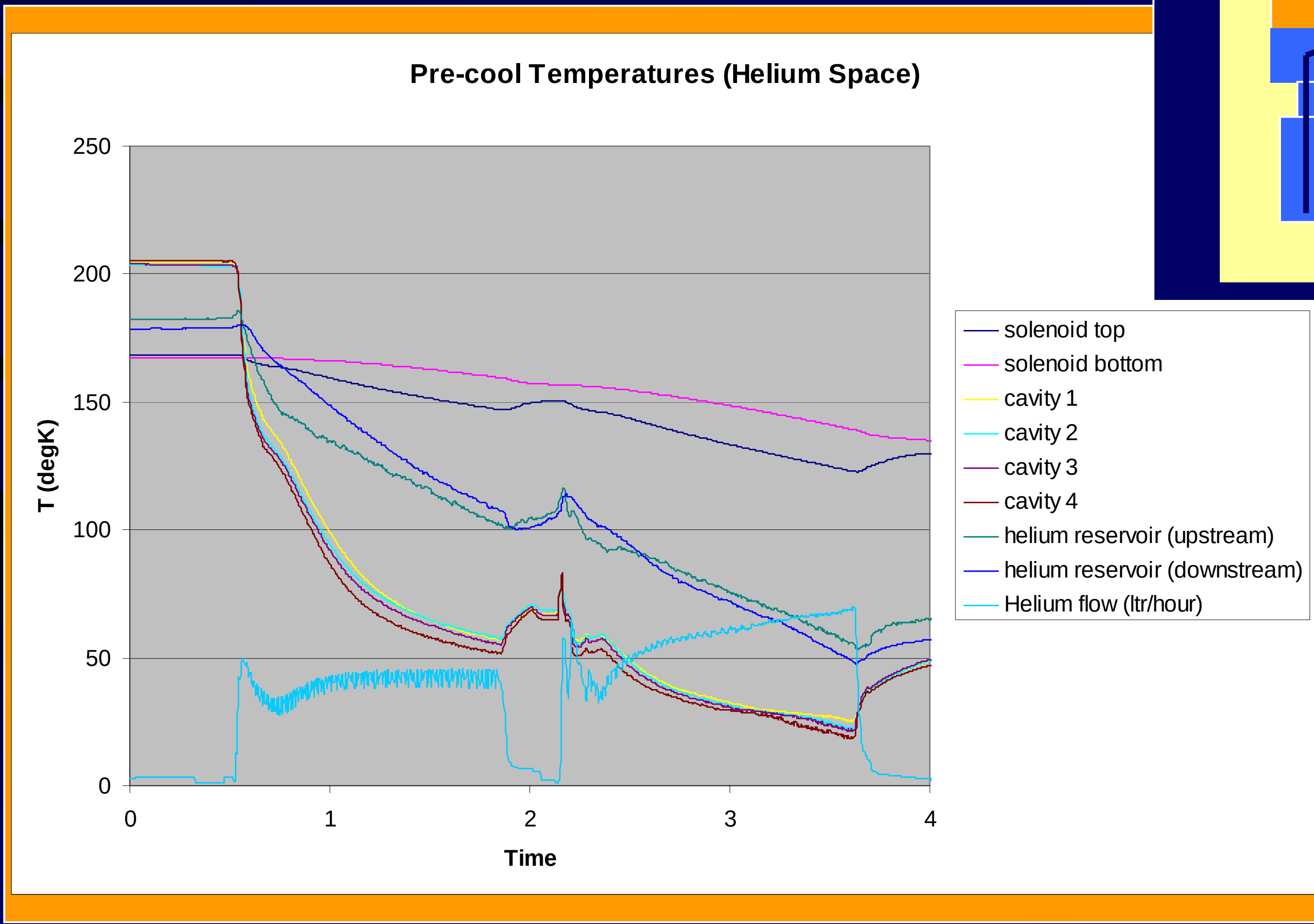
Medium Beta Cryomodule

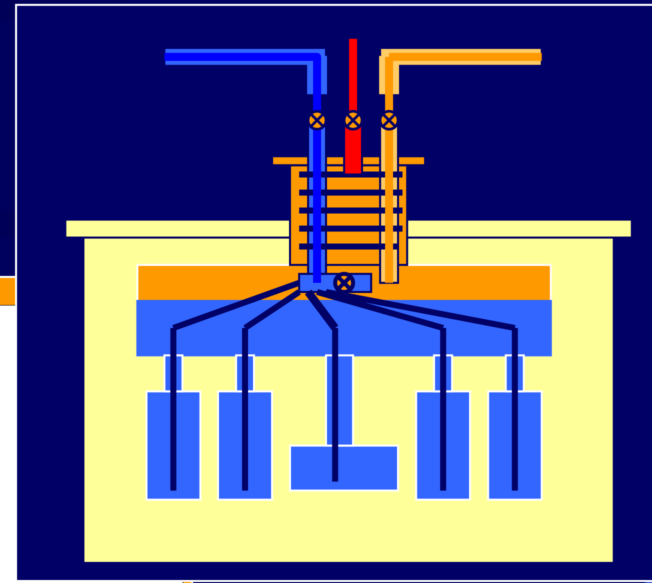
- ❑ Helium Level Probes, Heaters, Thermometry



Cryomodule Pre-cool Test

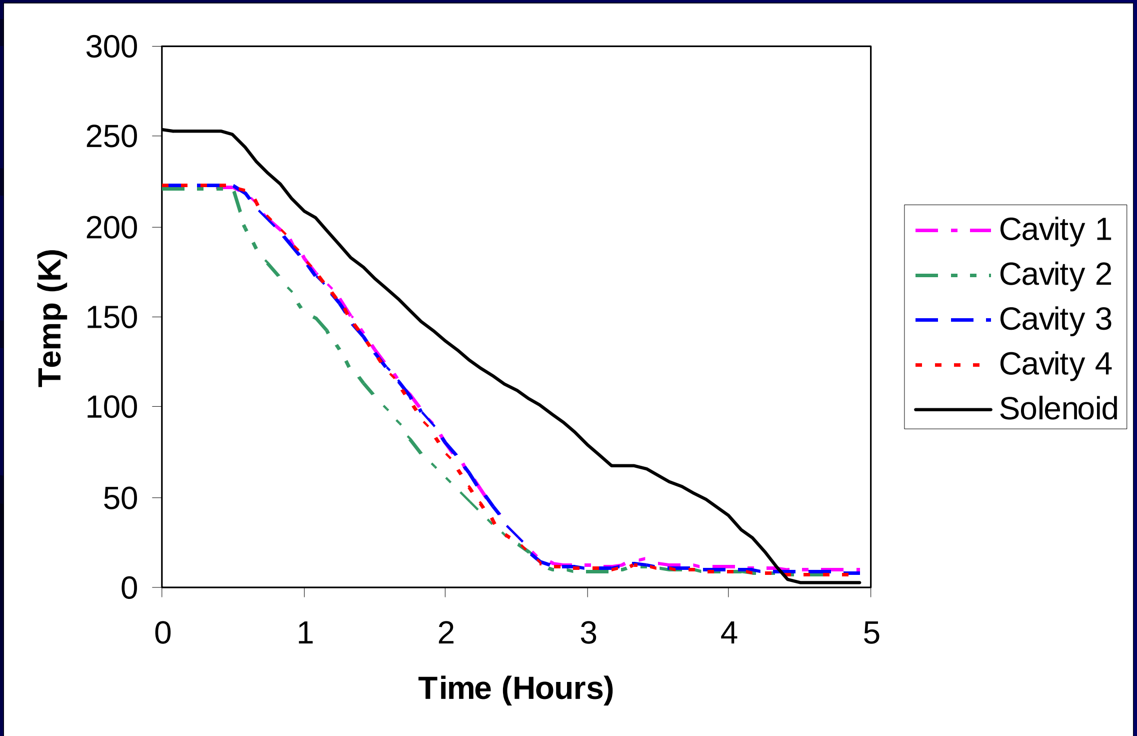
- Cryomodule cooled with Helium April 23, 2004
- Pre-cool manifold and `spider' worked well to cool cavities and solenoid uniformly





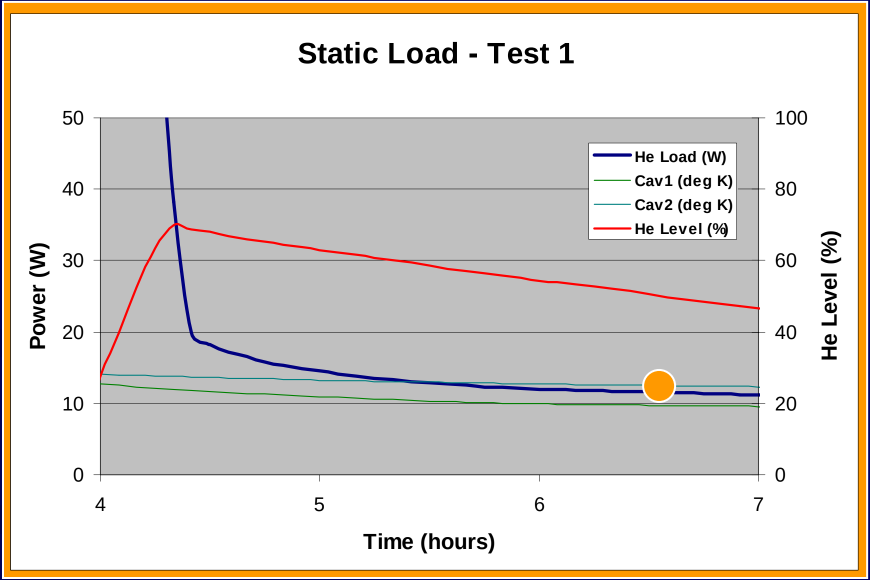
Cryomodule Cooldown Data (Aug. 2005)

- Cryomodule (SCB1) cooled with LINDE TCF-50
- Three-position valve on `spider' worked well to cool cavities and solenoid

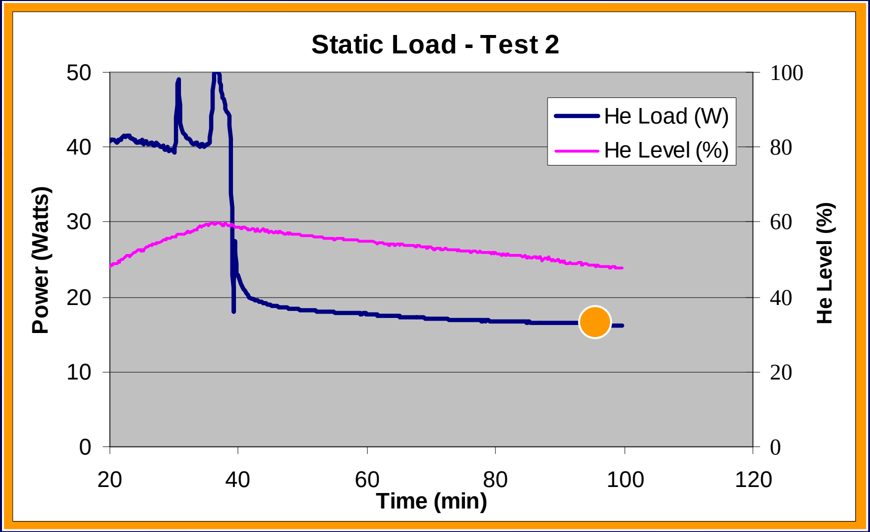


Cryomodule Static Load – Test 1, 2

- April 25, 2004 – First cooldown
  - After thermalization, boil-off equivalent to **11W** static load

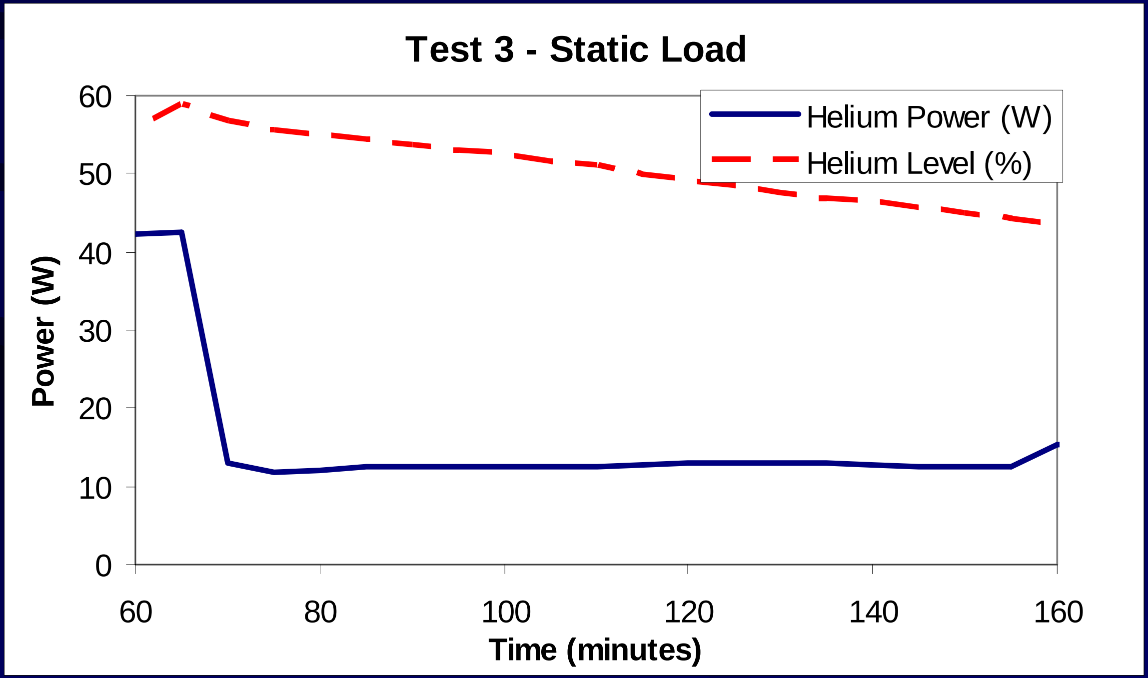


- July 2, 2004 – Second cooldown
  - After thermalization, boil-off equivalent to **16W** static load



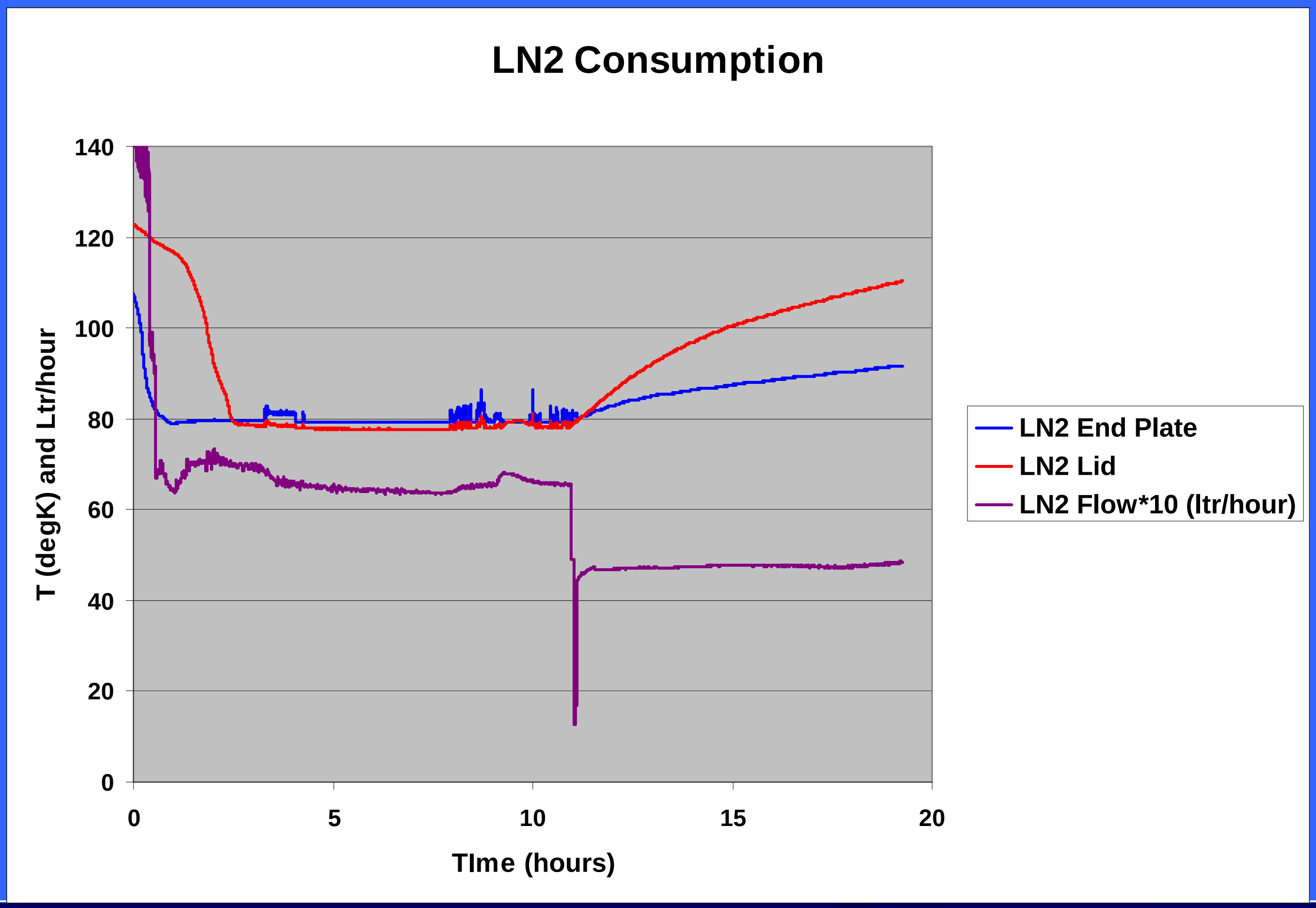
Cryomodule Static Load – Test 3

- Nov. 3, 2004 – Third cooldown
  - 180ltr LHe accumulated in cryomodule
  - After thermalization boil-off equivalent to **13W** static load



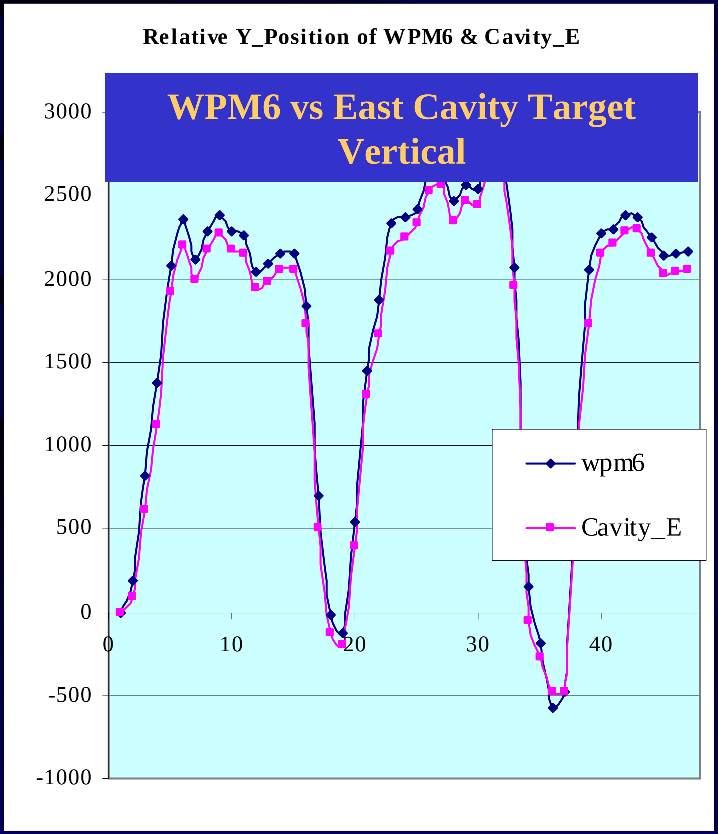
LN2 Consumption

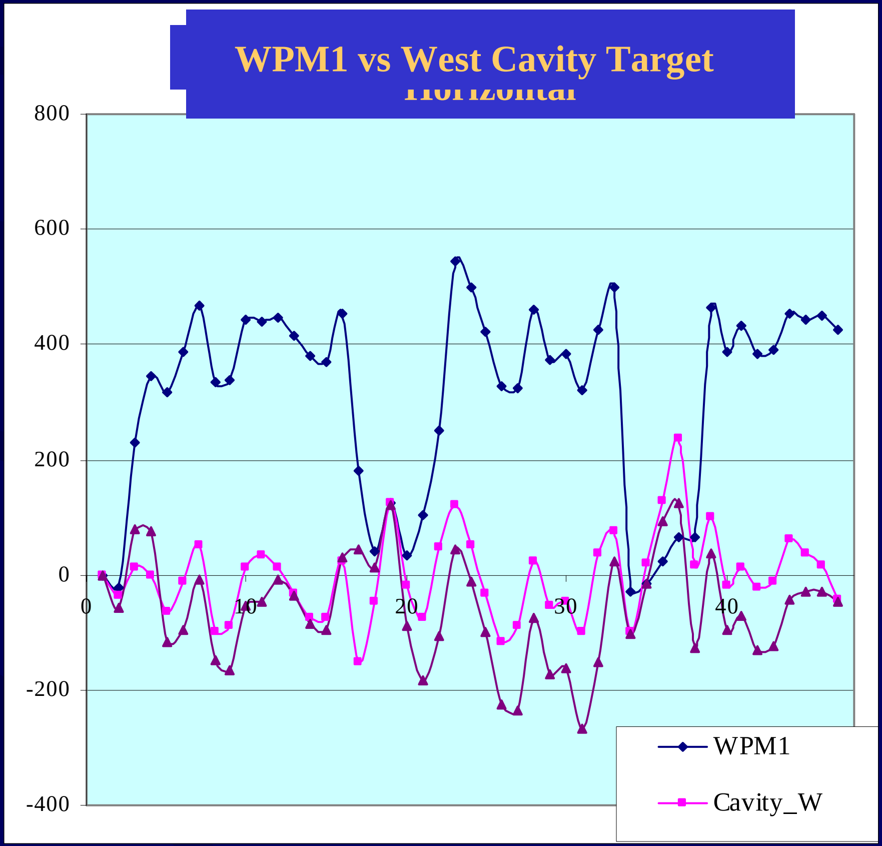
- Regulated exhaust flow at constant pressure
  - 6.2 Ltr/hr produced 80K shield
  - 4.7 Ltr/hr warmed shield to about 120K



Alignment Calibration

- Optical targets in first and last cavity were periodically measured with telescope to calibrate the temperature contraction of WPM brackets

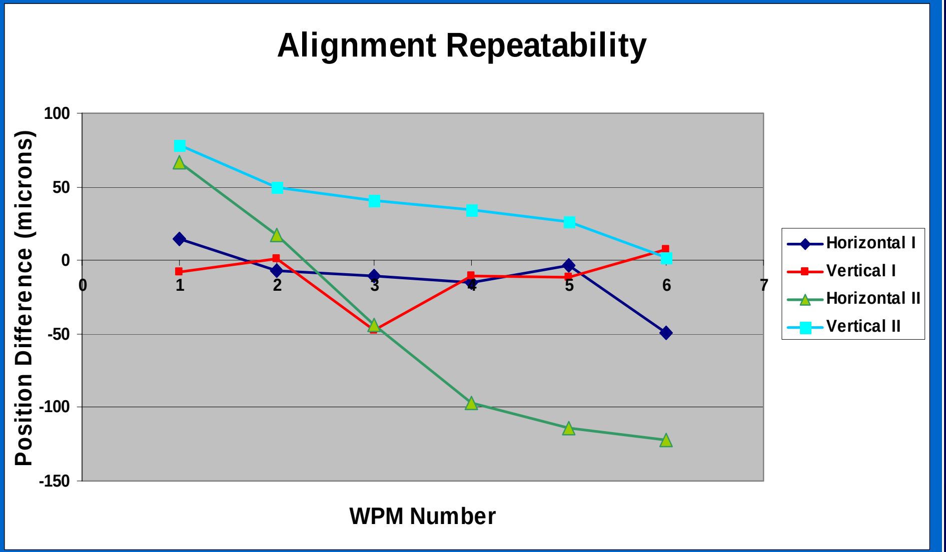




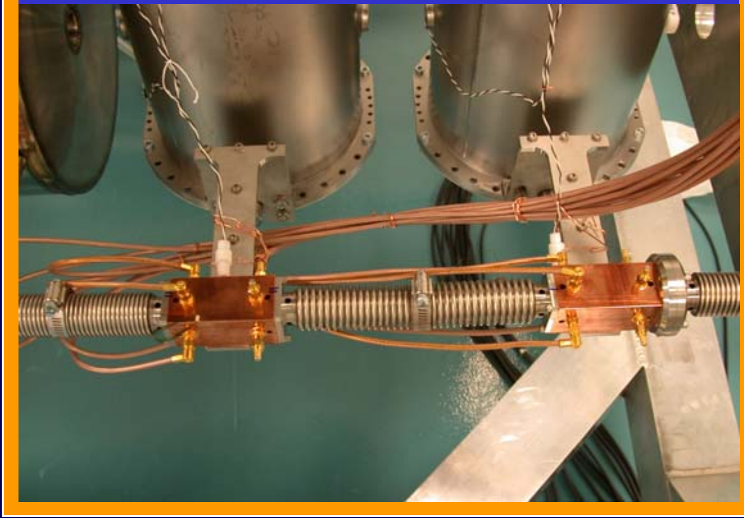
Alignment Repeatability

•Cryomodule thermally cycled three times from room temperature to LN2 temperature

- •WPM data analyzed to note repeatability of alignment at cold temperatures
- •Alignment repeatable to within 80 microns vertically and to within 120 microns horizontally

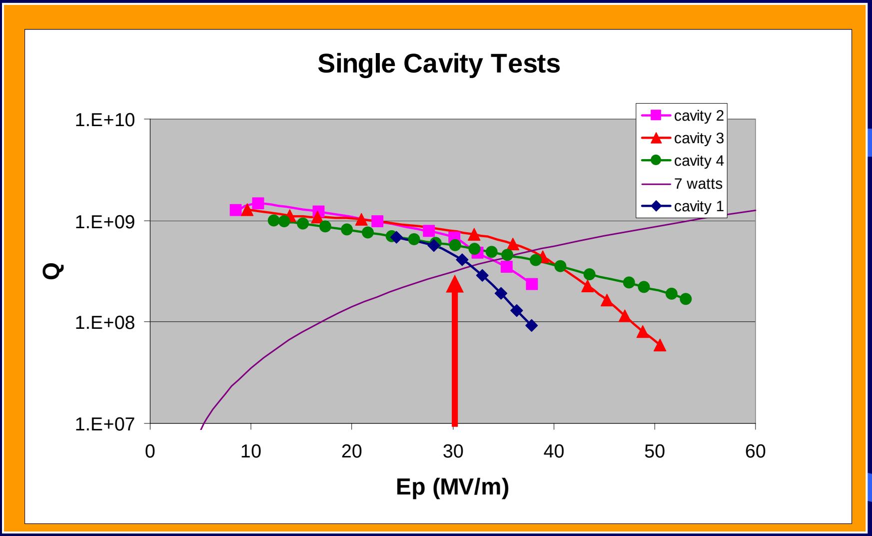


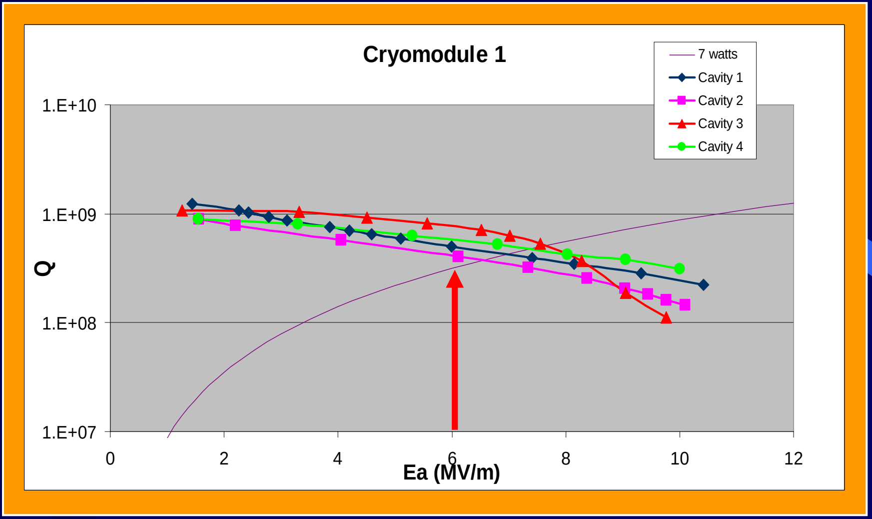
WPM Monitors on Cavities



Cavity Performance

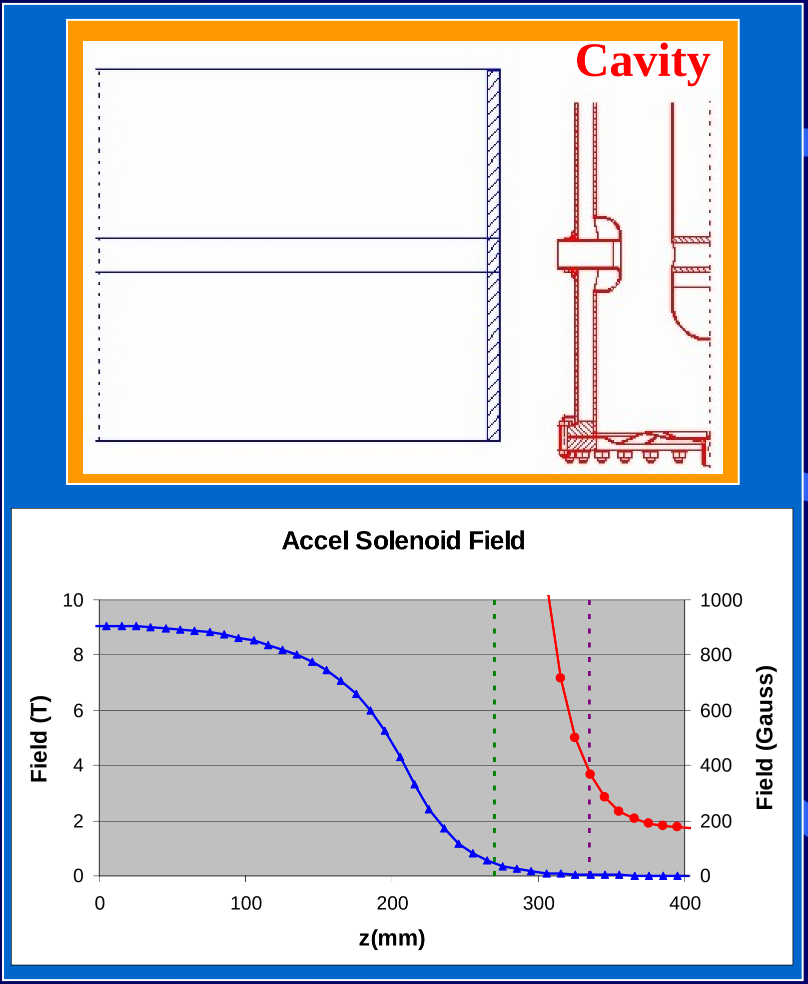
- All cavities locked simultaneously at ISAC-II specifications (6 MV/m and 106.08 MHz)
- Low level Q values all >1e9
    - Mu metal field reduction is adequate
- Cavity performance matches single cavity tests with high pressure rinsing and clean techniques during assembly





Solenoid Test

- Base Q's measured before solenoid test
- Ramp up solenoid to 9T
    - Cavities 2 and 3 on
    - No quench of cavities or solenoid
    - No change in cavity Q
- Cold mass warmed above transition
- Q's measured after second cooldown
    - No change; Q>1e9
    - Residual field tolerable

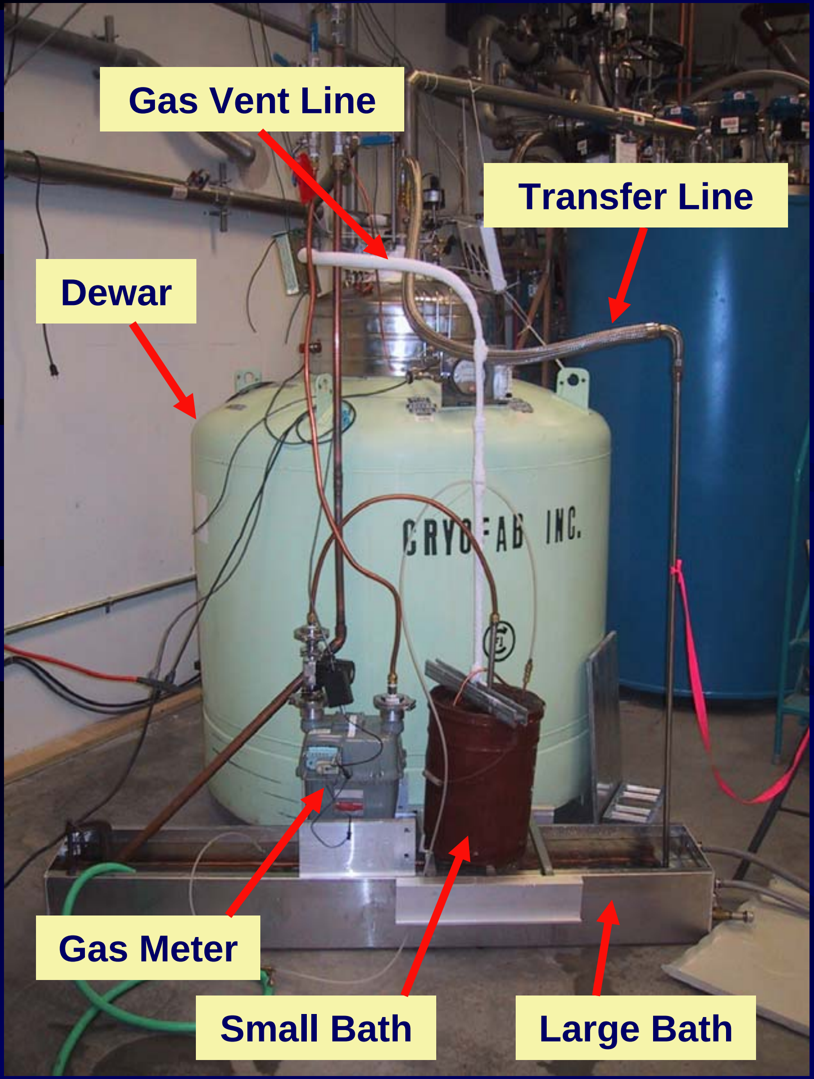


No negative impact on cavities from operation of solenoid

Refrigerator Commissioning
Feb – March, 2005

Helium / Water Heat Exchanger

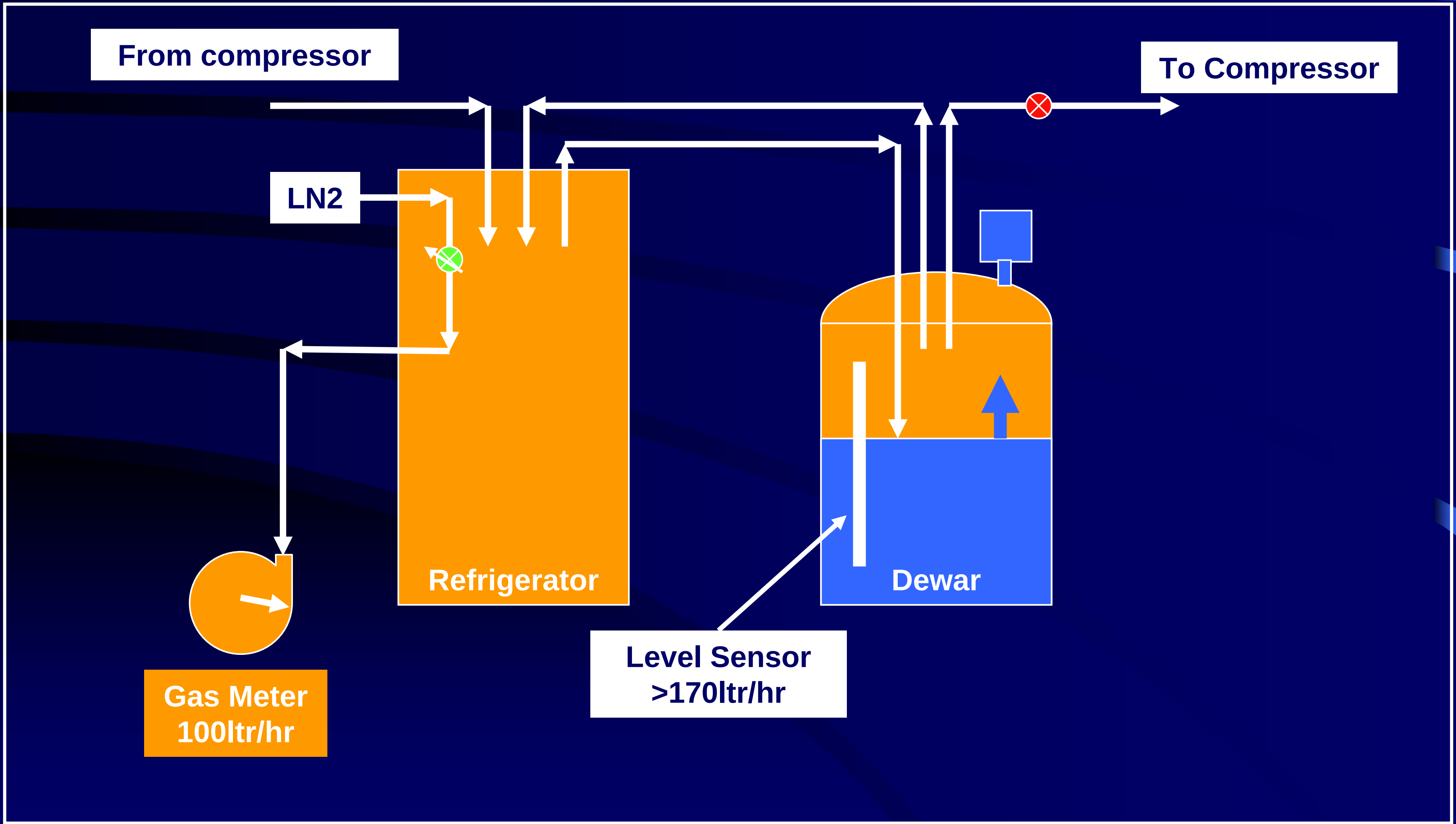
Commissioning Hardware



- Transfer line
  - For liquid removal/recovery test
  - Liquid goes through large water bath heat exchanger and back to compressor suction
- Gas vent line
  - For measured liquifaction load
  - Gas is drawn off through smaller water bath heat exchanger, then through gas meter and flow valve and back to compressor suction
- Dewar equiped with 650W heater and level probe
  - Dewar static loss less than 0.5W (25 year old Cryofab dewar)

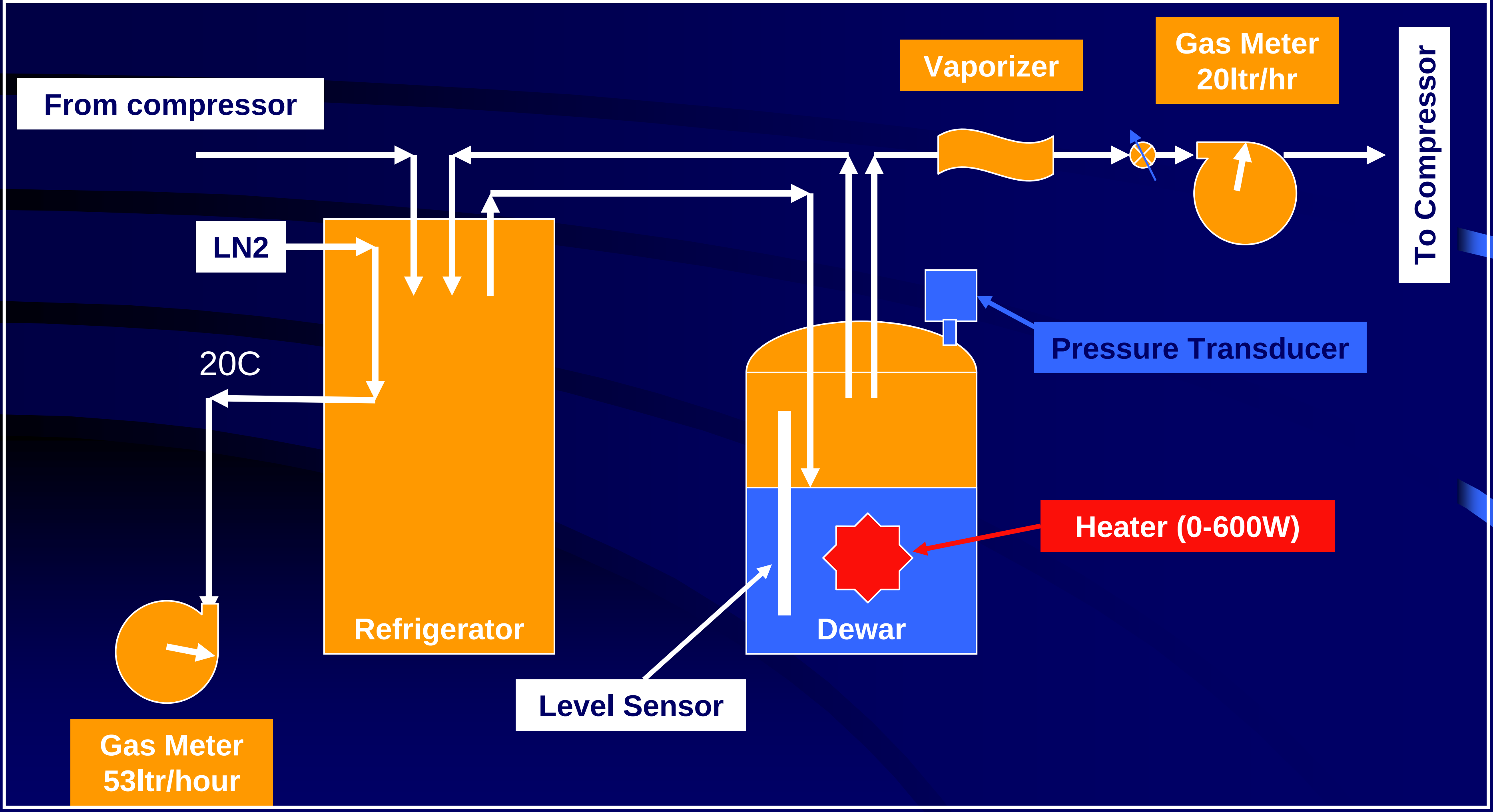
Liquefaction Test

- Measure rise in level while monitoring dewar pressure (want 1.3Bar – 990 Torr)
- Displaced vapour returned back to cold box and enhances liquefaction



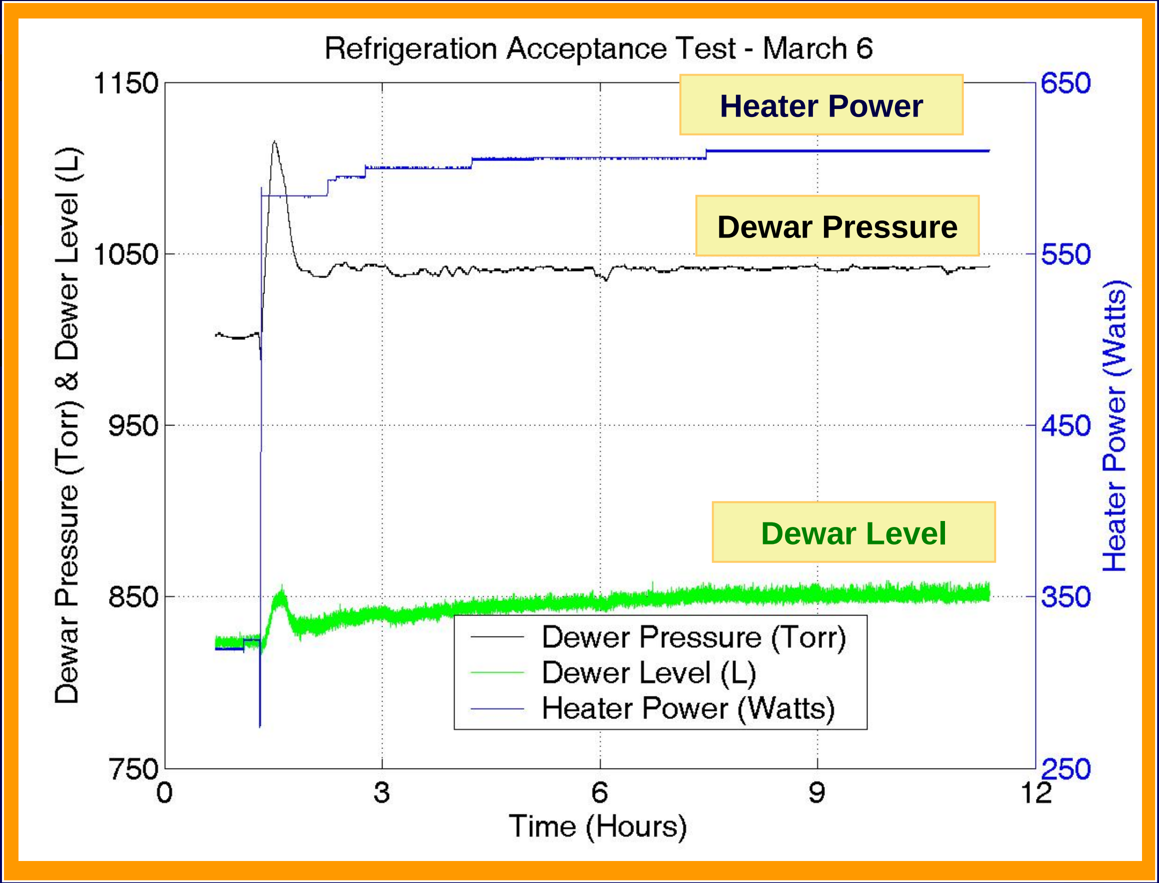
Refrigeration Test

- Measure heater power required to maintain constant level
  - Adjust bleed valve to set liquefaction load (20 Ltr/hr)
  - Maintain constant dewar pressure ~ 1.3 Bar



Refrigeration Acceptance Test

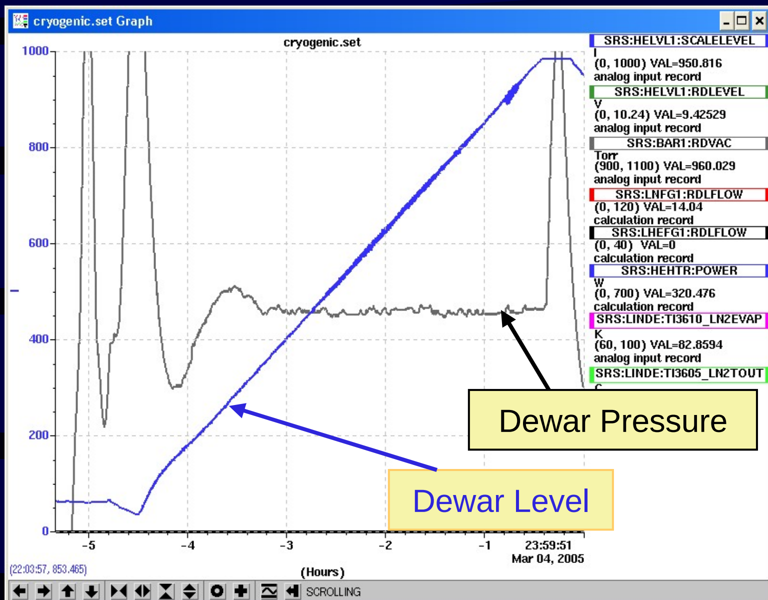
•Dewar heater power is raised until a constant level is reached at a constant dewar pressure.

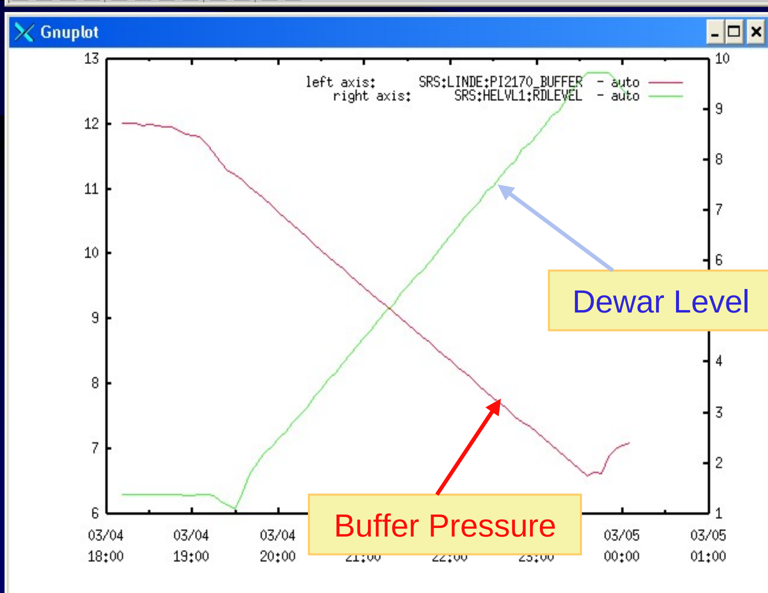


Parameter	With LN2
Refrigeration (W)	610
Guaranteed	530
Liquifaction (g/s)	6
Time (hr)	24
LN2 (l/hr)	55
Pressure (Torr)	1045

•Refrigeration is 350W without LN2 and no liquefaction load

Liquefaction Test in Normal Mode





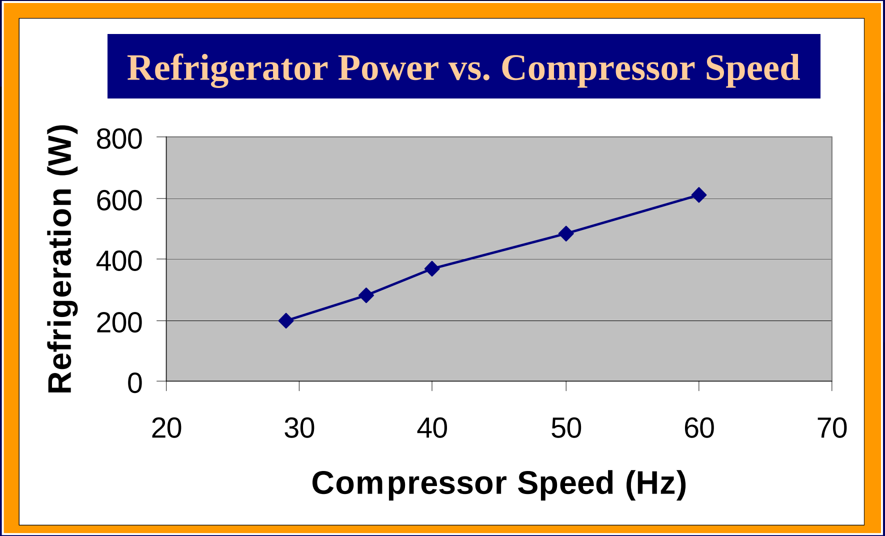
Acceptance test

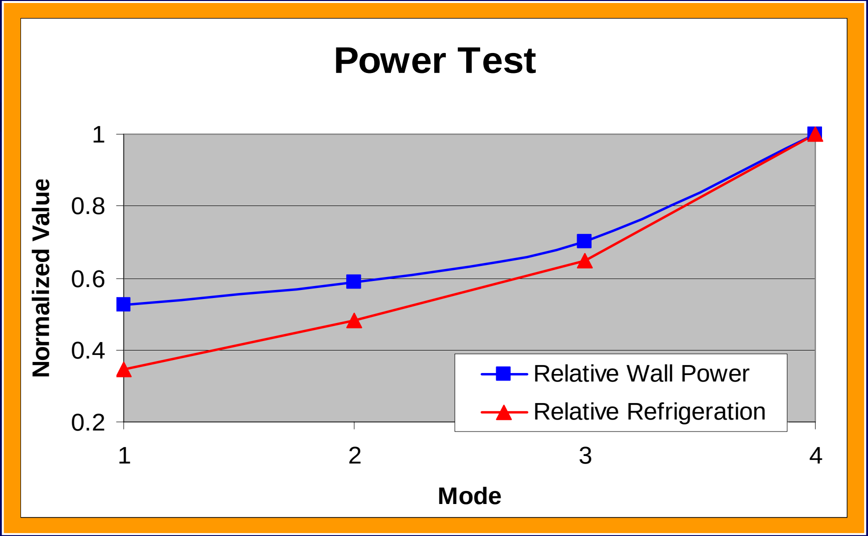
- Demonstrated 225 Ltr/hr based on rising level in the dewar
- Collected a total of 825ltr for 221min
- Linde guaranteed 180 Ltr/hr

Parameter	With LN2
Rising level (l/hr)	225
Rising level (g/s)	7.5
Time (min)	221
LN2 (l/hr)	80
Pressure (Torr)	991

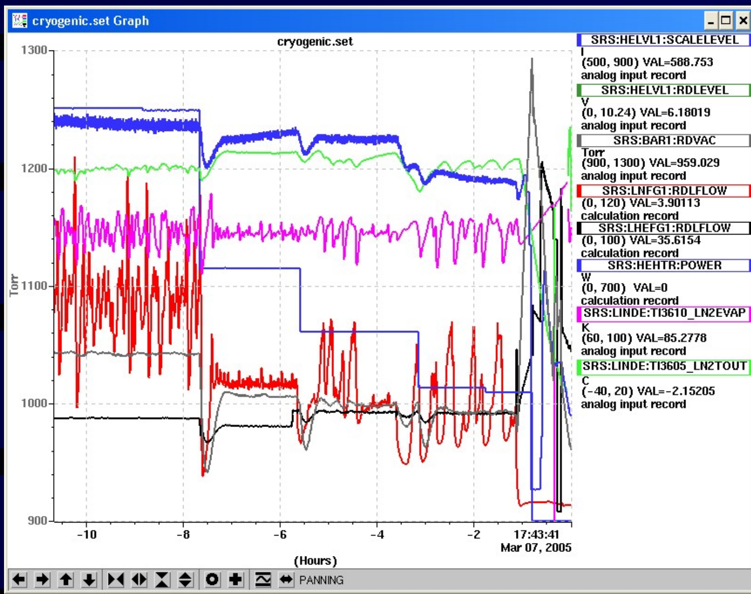
Power Saving Modes (with LN2)

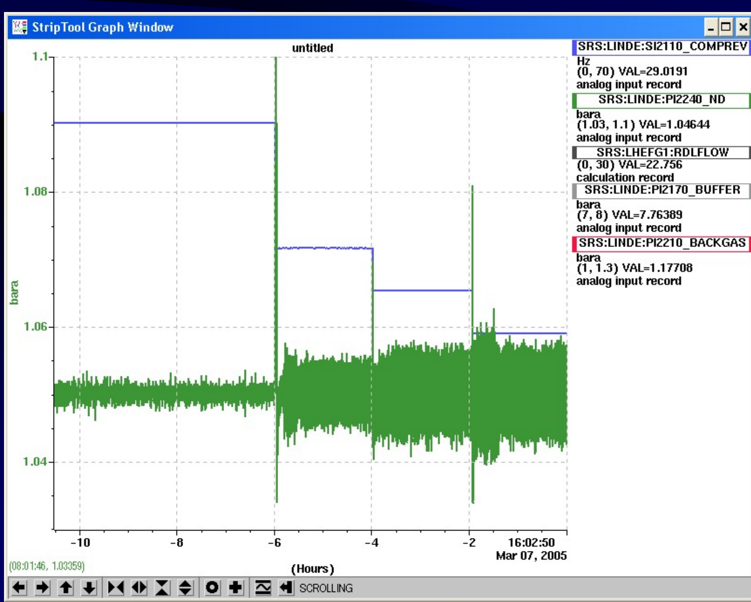
Mode	Refrig (W) or (6g/s)	Freq (Hz)	Discharge P (Bar)	Wall Power
Normal	610	60	13	1.0
Eco1	375	40	13	0.70
Eco2	280	35	11.8	0.59
Standby	190	29	11.5	0.53





Mode Switch Test





<u>Measurements</u>

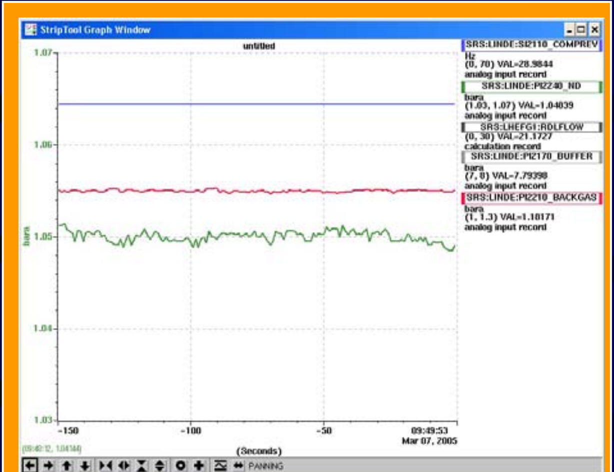
- Starting from normal mode the plant was switched to Eco1 then Eco2 then Standby stopping for two hours in each mode.

- Each mode was achieved without excessive transient

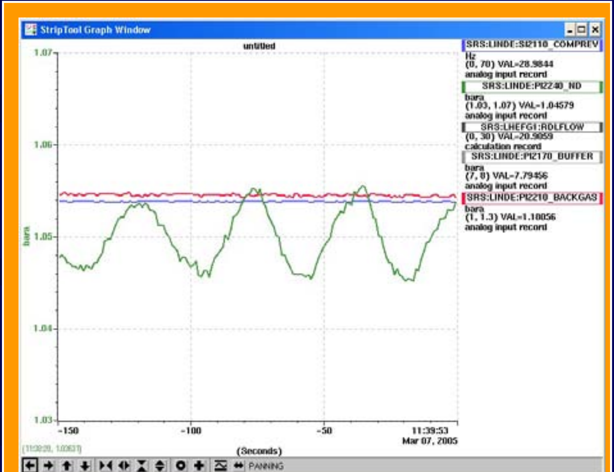
- Equilibrium was established after ~1/2 hr

- An instability in the suction pressure was observed for the three low power modes up to a maximum of +/- 10 mbar for Standby mode

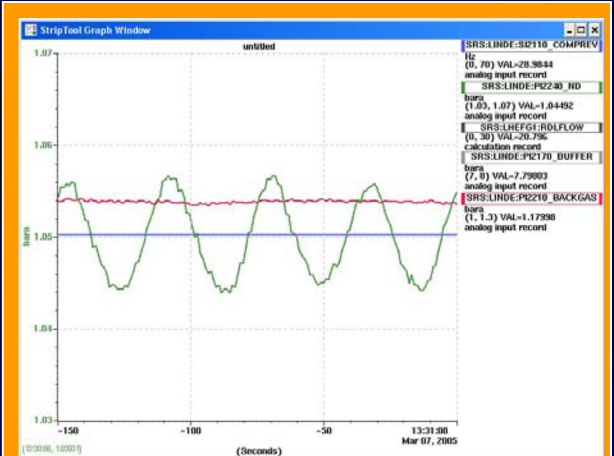
Suction Pressure Stability



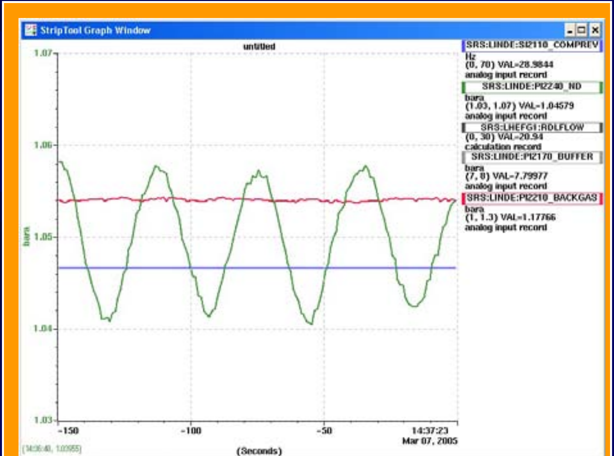
Normal Mode ±1.5mbar



Eco1 Mode ±4.5mbar



Eco2 Mode ±6mbar



Standby Mode ±7mbar

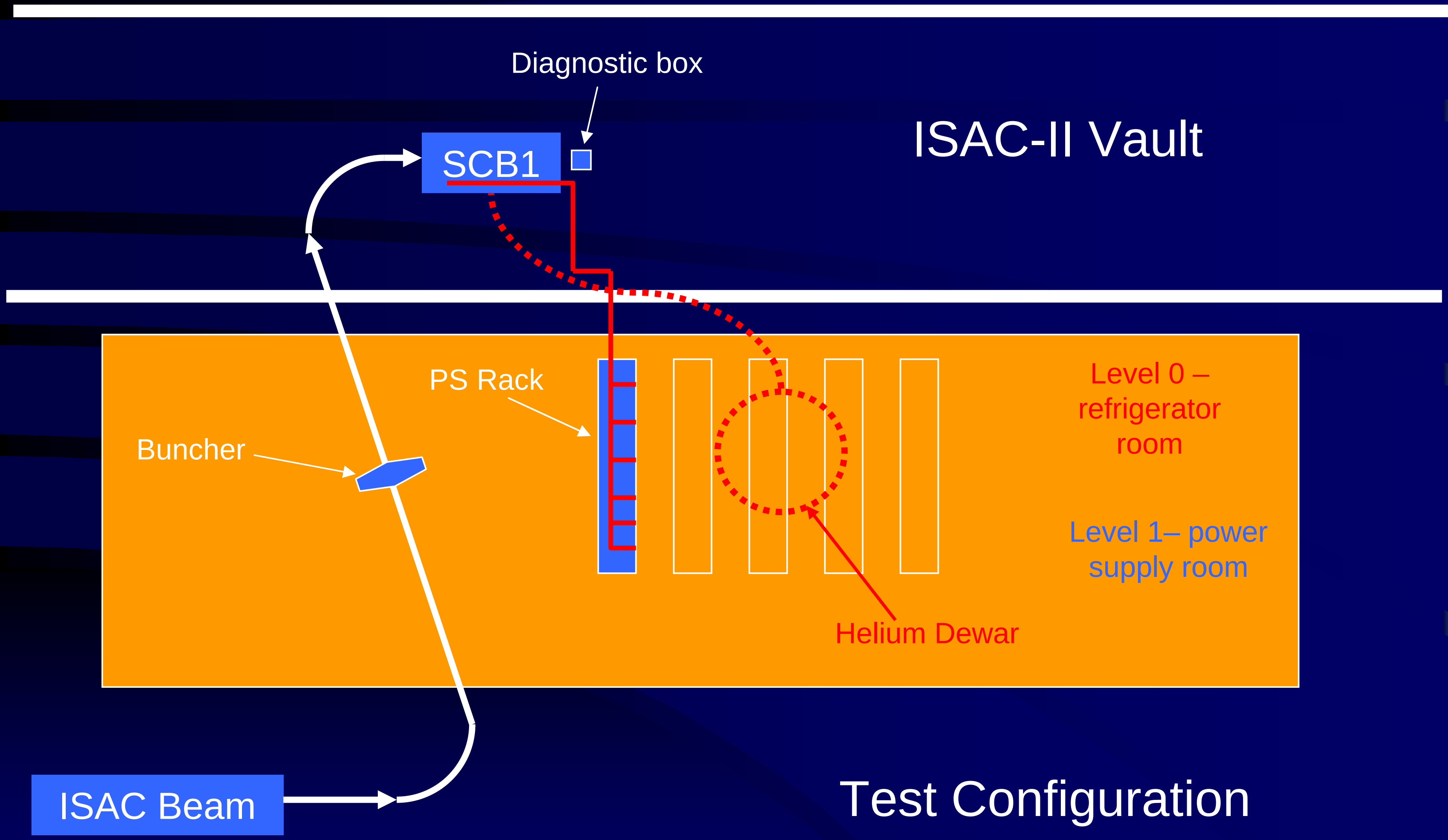
- Modulation in suction pressure was observed for the three lower power modes
- Frequency of modulation ~1/40 Hz
- Linde improved instability in the suction pressure by correcting the main compressor settings

March 8, 2005

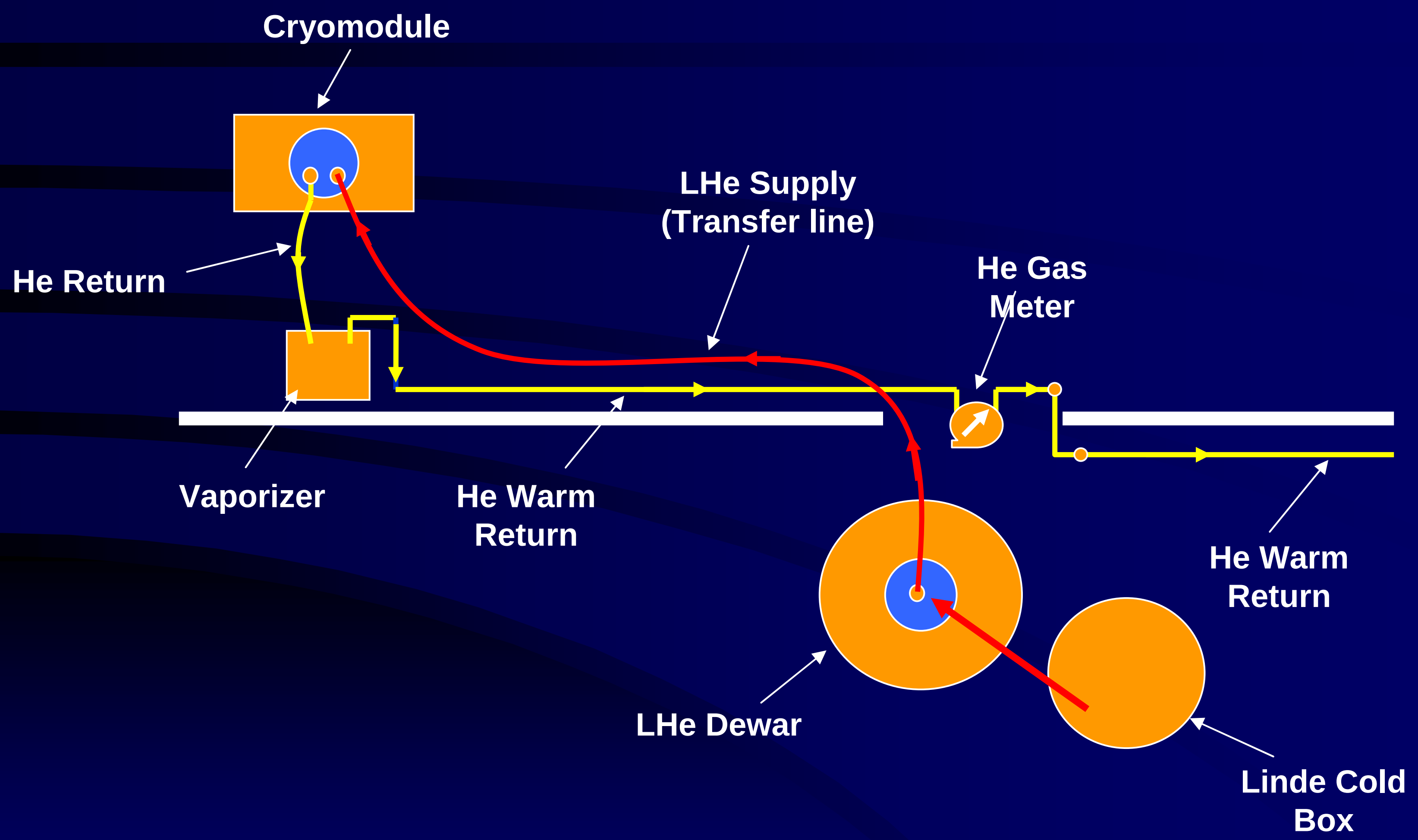
Nice cold champagne!

ISAC-I Beam Acceleration with one Cryomodule (Vault Test – June, 2005)

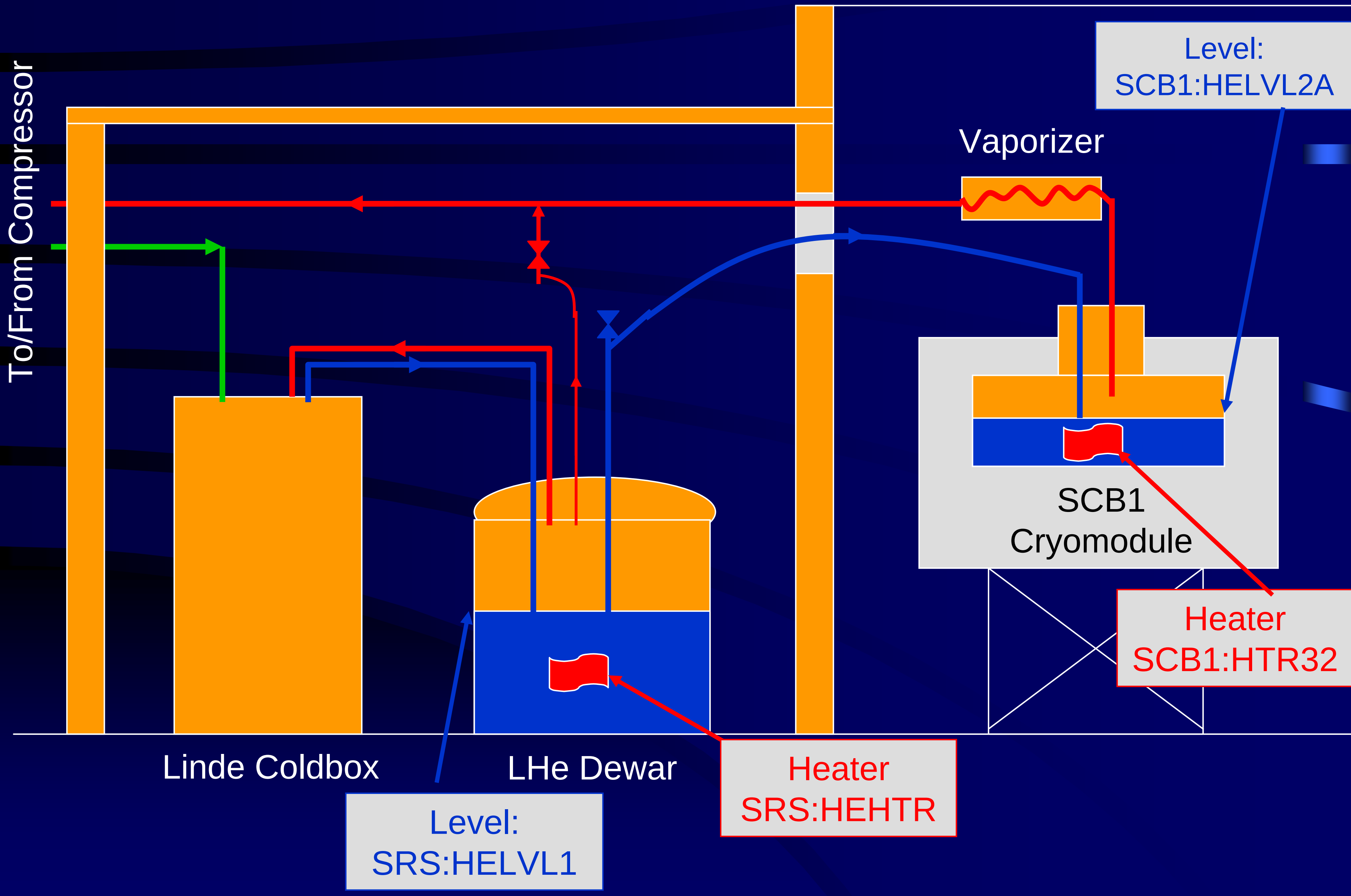
SCB1 Vault Test



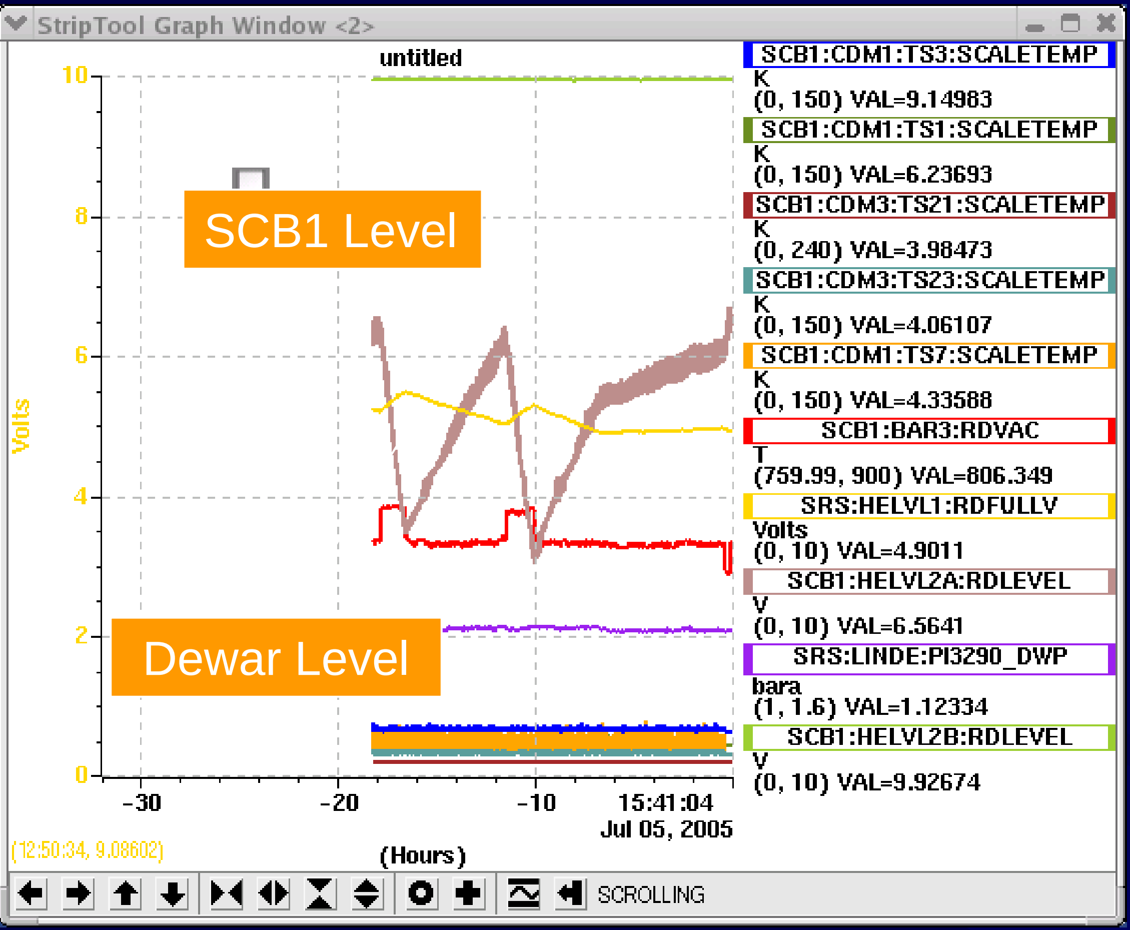
Vault Test Plumbing



Helium Flow Schematic



Refrigerator Operation



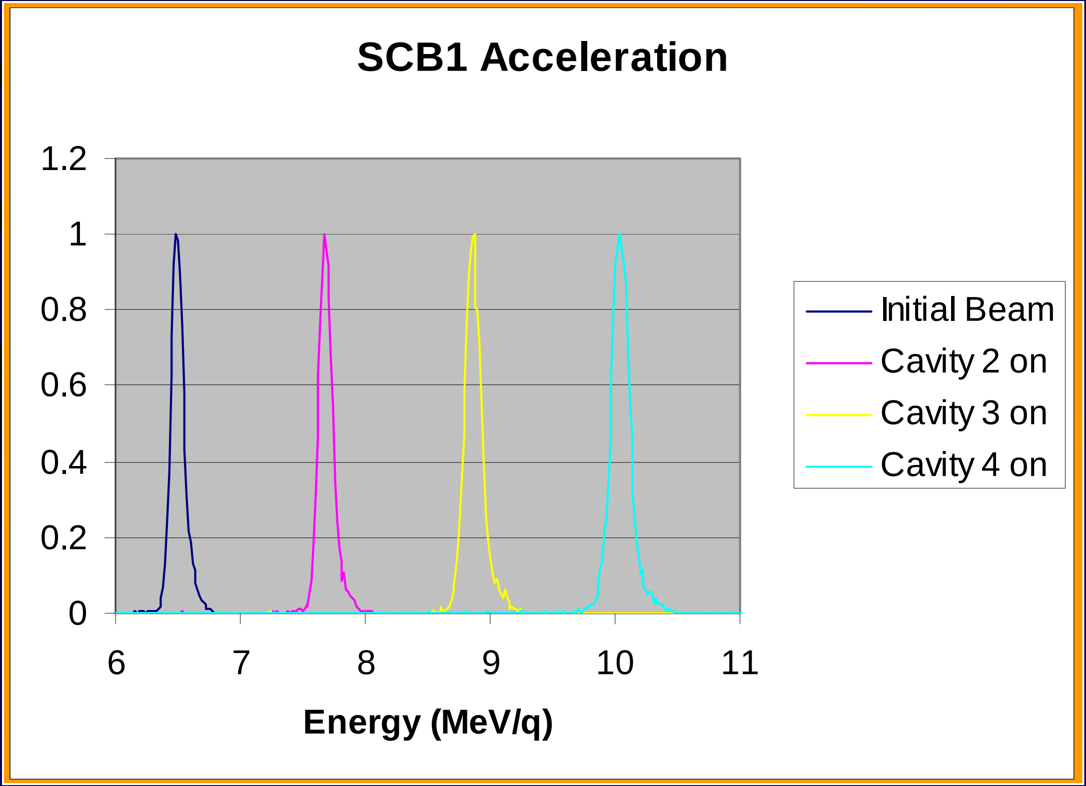
Refrigerator operated in continuous mode after an initial startup period.

LHe level in cryomodule and supply dewar regulated manually by supply transfer line valve and heaters in each volume

Refrigerator warmed up after two-week successful run

Acceleration – July 7, 2005

- Injected $^{26}Mg^{6+}$ from ISAC at 1.5MeV/u into SCB1
- Measured final energy with Si detector
- Achieved 3.5MV acceleration from three cavities
  - Corresponds to average values of Ea=7.4MV/m and Ep=37MV/m
  - One cavity not operational



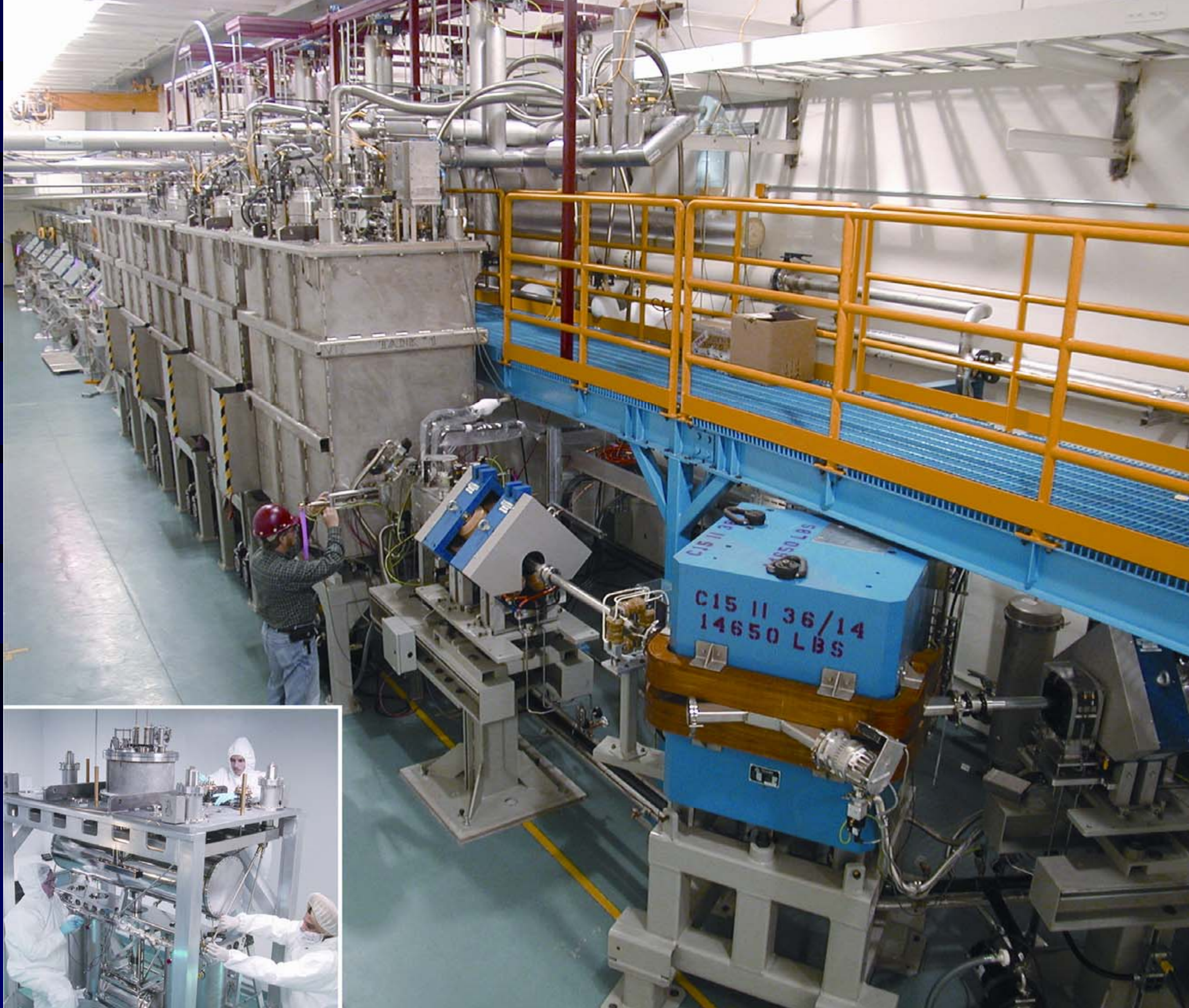
SC-Linac
and
Helium Distribution System
Installation

ISAC–II SC-Linac Installation (Nov, 2005)

He-Distribution Installation (Nov, 2005)

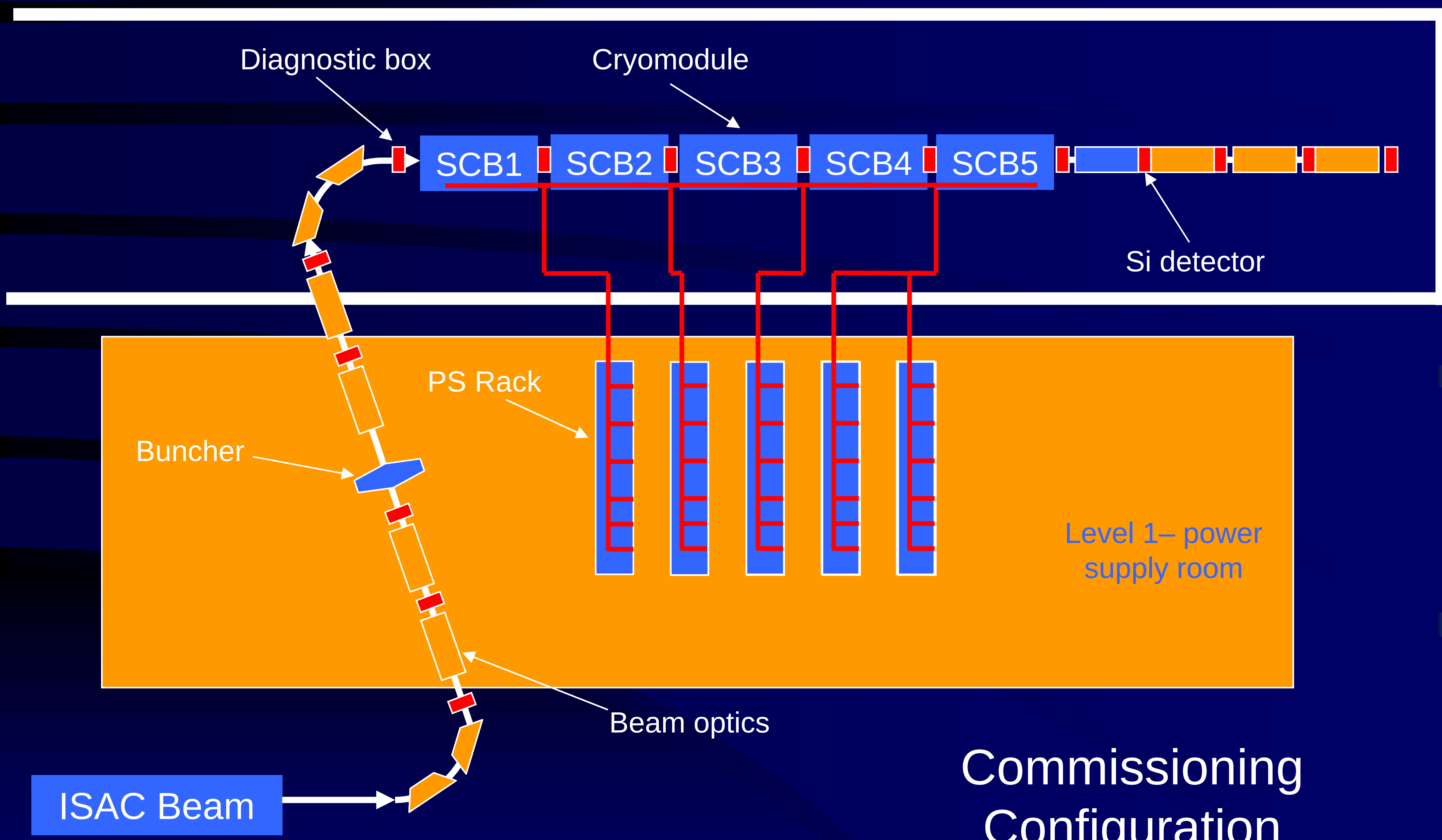
Field Joint

I. Sekachev, *Cold Tests of the ISAC-II Medium Beta Cryomodule,* CEC - 2005, Colorado


C15 II 36/14
14650 LBS

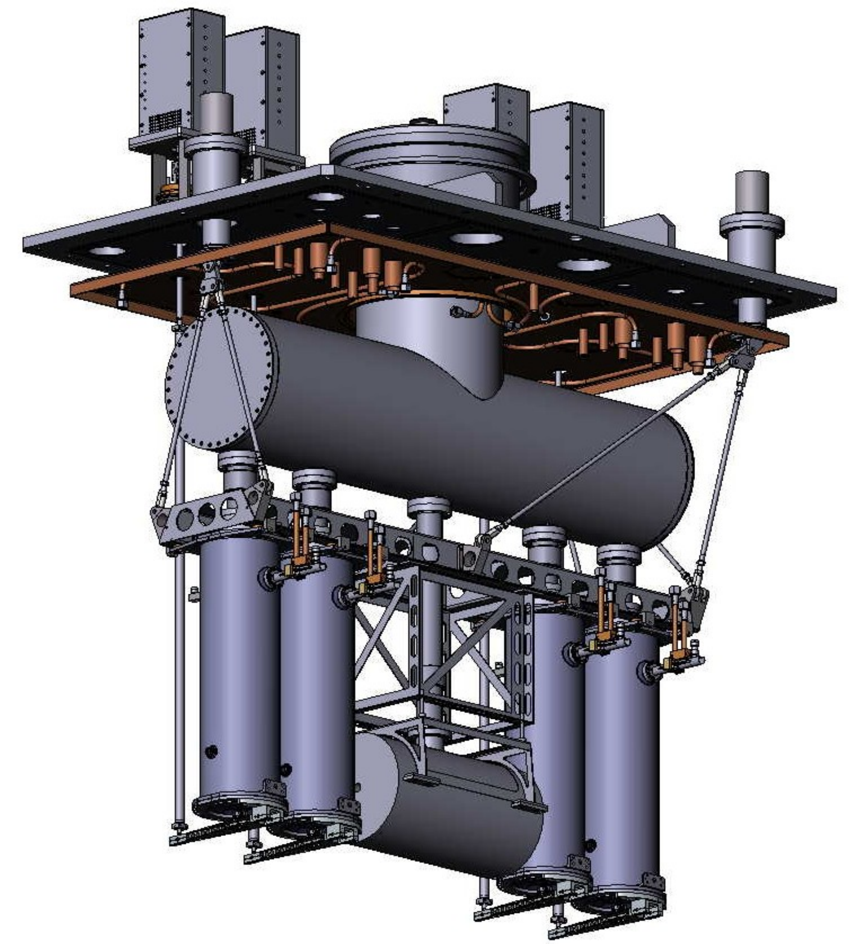
SC-Linac Commissioning

LINAC Commissioning, April 2006



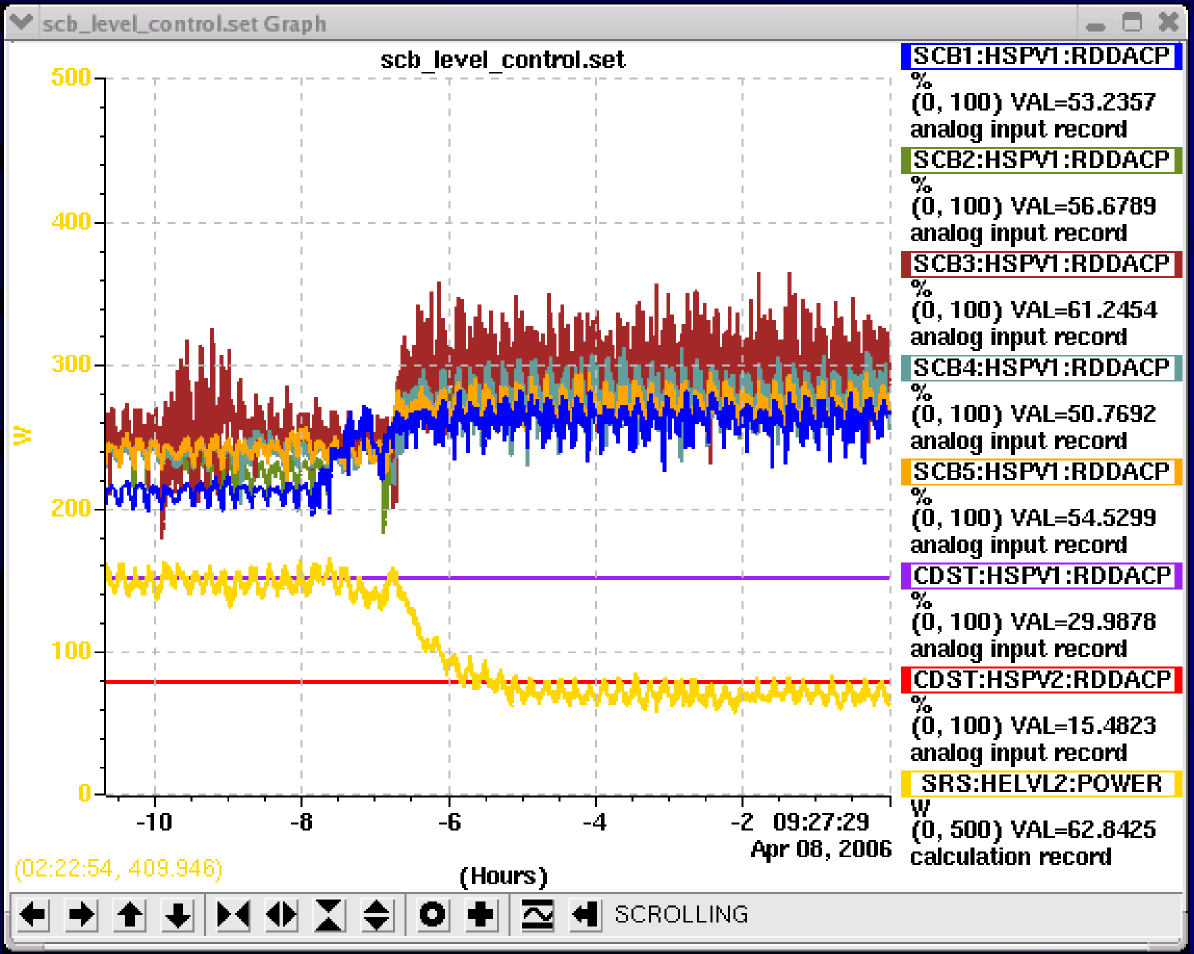
Commissioning Configuration

Medium Beta Cryomodule



Lid Assembly in Assembly Frame

Helium Control

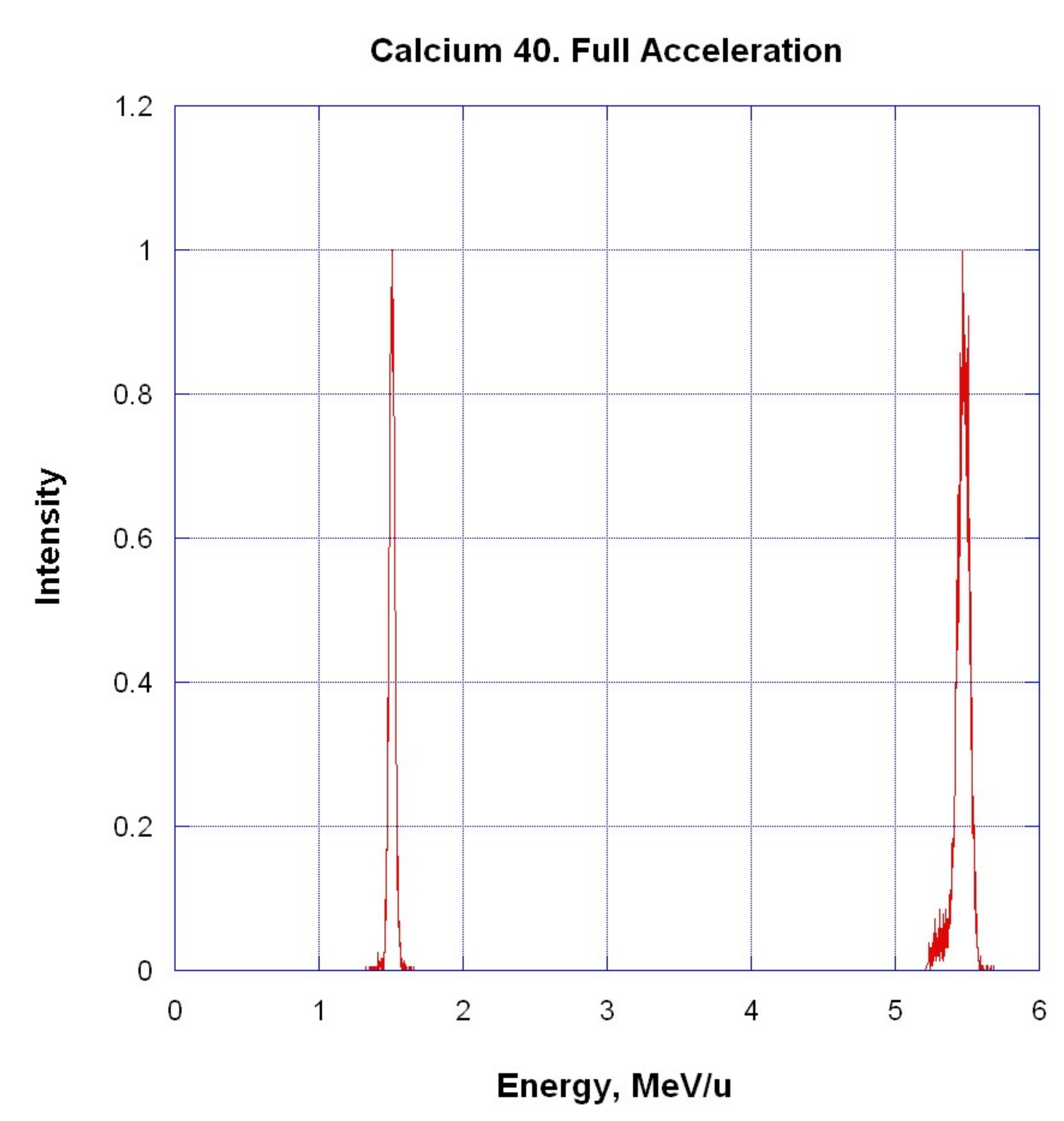


- Dewar heater power is used to calibrate the rf power required for acceleration
- Helium supply valves for each module regulate on the level in each module
- Dewar heater used to regulate level in the supply dewar
- Dewar heater reduced by 80W when cavities turned on

The Good News

- All cavities locked with most requiring only automated start-up
- Set-point of 1800 gives an average gradient of 5.6MV/m at 80 of RF power (4W/cavity)
- Set point of ~2000 should give an average gradient above 6MV/m for ~7W/cavity
- First acceleration demonstrated with over 220MeV Ca40

First Beam Acceleration Results



- 40Ca beam at 10+ is accelerated through ISAC-DTL to 1.5MeV/u
- Beam is accelerated through the twenty ISAC-II superconducting cavities to reach a final energy of ~5.5MeV/u or a total energy of 220MeV
- Average cavity gradient is 5.6MV/m with an average rf power consumption of 4W/cavity – a total RF power of 80W

Summary of Cold Tests

- ❑Cryomodule cold tests very successful
  - ➢Established cold alignment
  - ➢Proved cryogenic and RF integrity
  - ➢Pre-test for linac controls and acceleration
- ❑Highlights
  - ➢All cavity Q's >1e9
  - ➢20 cavities locked simultaneously at ISAC-II specifications (Ea=6MV/m, Ep=30MV/m at 106.08MHz)
  - ➢9T solenoids operated without effecting adjacent cavities
  - ➢Static load is within design limits (13W) for all 5 Cryomodules
  - ➢Accelerated 2.8MeV alphas to 9.4MeV (Nov, 2004)
  - ➢Accelerated beam 26Mg6+ delivered from ISAC-I (June, 2005)
  - ➢ Accelerated beam 40Ca10+ to 220 MeV with SC-Linac (Apr, 2006)

Summary

•LINDE TCF50 installed, commissioned and now operational with He distribution system, supplied by DeMaCo.

•SC-Linac (fist stage) commissioned in April, 2006. The first beam accelerated.

•Second stage of SC-Linac and second 500W class refrigerator planned for installation in 2007 - 2008.

Thank You