12 GeV
Cryogenic System Planning

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What is an “Optimal” System

- One’s viewpoint can be based only on their role and focus within a project
- Easy to believe that one’s goals are mutually exclusive of others
- Many believe that maximum system efficiency occurs only at one set of fixed operating conditions
Jefferson Lab Today

2000 member international user community engaged in exploring quark-gluon structure of matter

Superconducting accelerator provides 100% duty factor beams of unprecedented quality, with energies up to 6 GeV

CEBAF’s innovative design allows delivery of beam with unique properties to three experimental halls simultaneously

Each of the three halls offers complementary experimental capabilities and allows for large equipment installations to extend scientific reach
12 GeV CEBAF

Two 0.6 GV linacs

Upgrade magnets and power supplies

Add 5 cryomodules

CHL-2

20 cryomodules

Add arc

20 cryomodules

Add 5 cryomodules

Enhanced capabilities in existing Halls

Lower pass beam energies still available

Two 1.1 GV linacs
Additional Loads of 12 GeV

- **CEBAF Accelerator** (Each of 10 new cryomodules)
  - Up to 300 W at 2.1K, Primary Load
  - Up to 300 W at 35 K, Shield Load

- **Hall D** (inclusive of cryogen distribution system)
  - 100 W at 4.5K refrigeration
  - 0.7 g/s of liquefaction (lead cooling)
CHL#2 Design Goals

System Must Meet Accelerator Refrigeration Requirements
Stable and Reliable Service, 4-5 years at a time
Unattended Operation
Minimal Capital Equipment and Operational Cost
CD-0

Depicts need of project, R+D to meet technical needs, budgetary estimates of cost and schedule, design criteria and standards, preliminary information concerning supportive systems (ex: Civil requirements)

CD-1

First Phase engineering, “PED”, Project Engineering and Design, refinement of cost and schedule, budget review to establish fixed budget and schedule toward end of CD-1 in preparation of CD-2 project stage

CD-2

Completion of engineering, “PED”, Project Engineering and Design

CD-3

Construction and procurements

CD-4

Project commissioning and deliverables
Cryogenics had extensive existing infrastructure to reduce cost
Definitions:
DSD…Design Solution Doc
SRD…System Requirements Doc
DCD…Design Control Doc
WBS…Work Breakdown Structure
P3……Master Cost and Schedule Doc
Looking at the CHL
LINAC TRANSFER LINES

NEW 12 GeV

Supply Transfer Line

Return Transfer Line

INJECTOR

NORTH LINAC

South Linac

FEL
LINAC TL CONFIGURATION

• CURRENT 6GeV:
  CHL-1 Supplies Injector, N. and S. Linacs, FEL, and 10 g/s to ESR

• NEW 12 GeV:
  CHL-1: Injector, North Linac and ESR (10 g/s)
  CHL-2: South Linac and existing FEL

NOTE: IN CASE OF A CHL-1 OR CHL-2 MAINTENANCE or FAILURE, THE LINACS CAN BE RECONNECTED TOGETHER INTO SINGLE REMAINING CRYO PLANT FOR 6 GeV BEAM OPERATION
CHL Max Capacity
Current vs. New

• Current 6 GeV (CHL #1)
  – Load: 4.25 kW @ 2.1K, 11.65 kW @ 35K
  – Capacity: 4.6 kW @2.1K, 12 kW @ 35K
  – 10 g/s liquefaction

• New 12 GeV (CHL #1 + new CHL#2)
  – Load: 7.25 kW @ 2.1K, 14.65 kW @ 35K
  – Capacity: 9.2 kW @ 2.1K, 24 kW @ 35K
  – 25 g/s liquefaction
## Load Distribution for 6/12 GeV

<table>
<thead>
<tr>
<th>Unit Loads</th>
<th>6 GeV</th>
<th></th>
<th>12 GeV</th>
<th></th>
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<tr>
<td></td>
<td>2 K</td>
<td>50 K</td>
<td>#</td>
<td>2 K</td>
</tr>
<tr>
<td>North Linac</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South Linac</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loads (#,W)</td>
<td>Static</td>
<td>Transfer Line</td>
<td>530</td>
<td>7000</td>
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<tr>
<td></td>
<td>Original CM’s</td>
<td>16</td>
<td>110</td>
<td>42.25</td>
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<tr>
<td></td>
<td>12 GeV CM’s</td>
<td>50</td>
<td>250</td>
<td>5</td>
</tr>
<tr>
<td>Dynamic</td>
<td>12 GeV CM</td>
<td>250</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>TL BAYONETS</td>
<td></td>
<td>TL BAYONETS</td>
<td>75</td>
<td>75</td>
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<tr>
<td>Totals</td>
<td>42.25</td>
<td>4248</td>
<td>11648</td>
<td>25.25</td>
</tr>
<tr>
<td>TL SECTION</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacities (W)</td>
<td>CHL#1 (W)</td>
<td>4600</td>
<td>12000</td>
<td>4400</td>
</tr>
<tr>
<td></td>
<td>% of Full Load</td>
<td>92%</td>
<td>97%</td>
<td>87%</td>
</tr>
<tr>
<td></td>
<td>CHL#2(W)</td>
<td></td>
<td></td>
<td>4400</td>
</tr>
<tr>
<td></td>
<td>% of Full Load</td>
<td></td>
<td></td>
<td>81%</td>
</tr>
</tbody>
</table>
CHL Considerations

• Existing CHL#1 is a “one of a kind” 2K refrigerator
  – Custom engineered and built, not “off the shelf”
  – ~2x as large as any other 2K refrigerator in existence

• New CHL#2 has the following considerations which had to be accounted for…..
  – Commercial custom refrigeration engineering is generally done during the construction project but creates a problem providing detailed information to civil engineering for cost estimation/design that occurs during the previous project phase of engineering. This includes such topics as….
    Building Size, Equipment Floor Loading, Ventilation, Electric and Water Cooling Requirement, Equipment Layout, LN2 usage, Crane requirements, How to get equipment into the building, door sizes, piping/electrical chases, etc. etc.
CHL Considerations

– Very large fluctuations in the foreign exchange rates during the refrigerator project (1.29 to 1.65 exchange variations). Large refrigerators of this type are of foreign origin.

– Large increases in raw materials used in the construction of the refrigerator plant inclusive of copper, carbon steel, and stainless steel.

– Ether CHL#1 or #2 could be used to support beam operations at 6GeV should one of the refrigerators go down.
Less than ideal installation conditions: Through the roof (heavy/high crane pick, pit required, stripped of end vacuum shells to save weight, complicated reassembly
Existing Equipment (CHL#1)

4600W @ 2.1K Refrigerator & 1st set of Cold Compressor (2K Cold Box), 245 g/s

Warm Helium Compressors, ~5.2 MW
Qty 3, 600 HP ; Qty 3, 2250 HP

2nd set of Cold Compressor (2K Cold Box) 245 g/s

Typical 2K Cold Box Internal Piping
Existing Transfer Line Components

Existing 42 Cryomodules, 1600 liters ea.

TL Already Has 10 Connection Bayonet Locations for the 12 GeV Expansion 300 liters ea
Other CHL Operational Modes

- Although meeting the “steady state” operational mode is important…there are many other modes which the refrigerator must practically meet

  Examples….
  - Filling the cryomodules with liquid (liquefaction rate)
  - Maintaining the cryomodules at 4.5K instead of 2K
  - Translating from 4.5 to 2.1K operations (very low refrigeration requirement)

- So these “other” modes must be mapped out to make sure that the refrigerator can cover them…(part of the procurement specification)
## CHL-2 Design Modes of Operation

<table>
<thead>
<tr>
<th>#</th>
<th>Design Mode</th>
<th>Load @ 2 K [g/s]</th>
<th>Load @ 4.5 K [kW]</th>
<th>Liquefaction [g/s]</th>
<th>Load @ 35 K-55K [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maximum capacity (CBX supporting maximum cold compressor operation)</td>
<td>&gt;238</td>
<td>0</td>
<td>&gt;15</td>
<td>&gt;12</td>
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<tr>
<td>2</td>
<td>Nominal capacity (CBX supporting nominal cold compressor operation)</td>
<td>&gt;200</td>
<td>0</td>
<td>0</td>
<td>&gt;7.5</td>
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<tr>
<td>3</td>
<td>Maximum 4.5-K liquefaction</td>
<td>0</td>
<td>0</td>
<td>&gt;150</td>
<td>&gt;7.5</td>
</tr>
<tr>
<td>4</td>
<td>Maximum 4.5-K refrigeration</td>
<td>0</td>
<td>&gt;10.5</td>
<td>0</td>
<td>&gt;12</td>
</tr>
<tr>
<td>5</td>
<td>Maximum fill (of Linac cryomodules)</td>
<td>&gt;200</td>
<td>0</td>
<td>&gt;35</td>
<td>&gt;12</td>
</tr>
<tr>
<td>6</td>
<td>Stand-by 4.5-K refrigeration**</td>
<td>0</td>
<td>&gt;2.5</td>
<td>0</td>
<td>&gt;12</td>
</tr>
</tbody>
</table>

- Load at 2.1 K means supply flow at 3.2 bar 4.5 K, with return flow at 1.2 bar 30 K
- **Mode 6 requires a minimum amount of rotating equipment while supporting the LINAC loads at 4.5-K.**
Operational high efficiencies remain fairly constant no matter the operational mode.
Old Vs. New @ Maximum Capacity
CHL Plant Comparison

<table>
<thead>
<tr>
<th>CHL#1 (Old)</th>
<th>CHL#2 (New)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Power, 6 MW</td>
<td>Electric Power, 4 MW</td>
</tr>
<tr>
<td>Liquid Nitrogen Use, 300 gal/hr</td>
<td>Liquid Nitrogen Use, 200 gal/hr</td>
</tr>
<tr>
<td>Number of compressors, 6</td>
<td>Number of compressors, 5</td>
</tr>
<tr>
<td>Cooling Water, same as electric</td>
<td>Cooling Water, same as electric</td>
</tr>
</tbody>
</table>

Key cryogenic technologies developed at JLab (Ganni Cycle, LN2 precooling efficiency, etc.) has enabled reduction of utilities used by the refrigeration systems coupled with reduced capital equipment costs
JLab CHL#1 facility had many supportive subsystems already in place needed by CHL#2 which reduced system cost substantially
Existing CHL Infrastructure

- Gaseous Helium Storage Tanks
- LN₂ Storage Dewars (twin 80,000 liter)
- Cold Compressor Sets (twin 245 g/s @ 2.1K)
- Helium Gas Purification and Contamination Monitors
- Guard Vacuum Subsystem (2.1K operations)
- Building for lower 60-4.5 K Cold Box
- Outdoor Foundation for upper 300-60 K Cold Box
- Linac Cryogen Distribution Piping (ok for double flow but cuts down on maximum refrigeration due to need for lower 2K operating pressure by 5 mbar, ie. compensation for additional piping pressure drop due to increased flow)
Needed New Equipment for CHL#2

- 4.5 K cold box and warm helium compressors
  - Two sectional 4.5K cold box, (300-60K, 60K-4.5K)
  - Design baseline is JLab’s Ganni Helium Process Cycle
  - Capacity, 4600 W @ 2.1 K and 12 kW at 35 K plus 25 g/s

- Compressor oil removal system
- Gas Management System
- Computer distributive control system
- 10 kL helium dewar

New Facilities and Utilities

- Cooling Water System (twin 15,200 l/min)
- Electrical Power (twin 5 MW, 4160V)
- 4800 ft² compressor building
Existing CHL#1 Building
New CHL #2 Compressor Building

CHL #2 Building
(August 09)

CHL #2 Building
(March 10)
CHL #2 Compressor Building
Foundation and Electrical Conduits
(before the compressors were purchased)
CHL Major Equipment Procurements

CHL Warm Helium Compressors (5)

Compressors & 4.5K Cold Box ~73% of the cost

Upper 300-60K Cold Box

Lower 60-4.5K Cold Box

CHL 4.5K Cold Box
Typical CHL#2 Compressor Assembly

JLab DESIGN BASIS
- “Lessons Learned” from existing commercial designs
- Lower Cost Goal
- Better Maintainability
Compressor Flow Schematic

A/C….Gas Discharge After-cooler Heat Exchanger
BOS…Bulk Oil Separator Vessel
O/C….Oil Cooler Heat Exchanger
Compressor Skid Assembly Underway At Vendor’s Facility
JLab Designed BOS

3x more effective oil separation
JLab Bulk Oil Separator Internals
CHL#2 Compressor Building Layout

- 4 800 HP
- 1 2500 HP
- Trench Piping
- Cooling Water
- Helium Gas
- Electrical/Control
- Under Slab

~4 MW USAGE
CHL#2 He and Cooling Water Trench Piping Installation Underway
CHL#2 Final Oil Removal Vessels
New CHL#2 4.5K Cold Box Design Considerations

- Moves large upper temperature section (>60K) out-of-doors for smaller indoor system foot print and easier field construction and facility cost reduction, eliminates special building feature requirements such as large building access doors and cold box insulating vacuum floor pits, enabled use of existing JLab building without modifications.

- Has lower temperature (<60K) section indoors which contains turbines, valves, etc. which require personnel access and controlled work environment.
Cold Box Under Construction

Upper Cold Box Heat Exchangers

Lower Cold Box Heat Frame and Vacuum Shell Top Assembly
CHL 4.5K Cold Box Assembly

“Top Hat” and Cold Box Frame

Internal Heat Exchangers
Existing 2K Cold Compressor Box
(to be used with CHL#2)
CHL #2 Installation Plans

CHL 4.5K Cold Boxes Installed
In Existing Building
Hall D Rendering

- Hall D
- Counting House
- Cryo Bldg
A Look at the Hall D Refrigerator
HALL-D Cryogenic System

Hall D 4.5K Refrigerator (Built 1980)

200W @ 4K Refrigeration or 2 g/s Liquefaction Capacity

Hall-D Mixed Load…0.7 g/s liquefaction + 100W Refrigeration
(includes transfer line load)
Hall D Refrigerator Equipment “On Hand”

- Two CTI Cryogenics Helium RS Compressors
- CTI M2800 200W 4.5 K Helium Refrigerator
- LHe Subcooler Dewar
- Motor Starters, 480V
Other Hall D Cryogenic Equipment Requirements

- Gas Management Valve Control Rack
- LN2 storage, 10,000 liter dewar
- One 4000 cf Helium Gas Storage Vessel
- Integrated Refrigerator Computer Controls
- Instrument Air System, 15 scfm
- Purification Loop Piping to the CHL via N. Linac
- 640 ft² building
- Compressor/Turbine Cooling Water
- 480V, 300 kW compressor power
Hall D 4,000 Cuft Gas Storage Tank
<table>
<thead>
<tr>
<th>Date Range</th>
<th>Event Description</th>
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<tbody>
<tr>
<td>October 2006 – October 2008</td>
<td>CD-2, Project Engineering and Design Status</td>
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<tr>
<td>October 2008</td>
<td>CD-3, Project Construction Status</td>
</tr>
<tr>
<td>April-Sept 2009</td>
<td>CHL#2 Major Component Purchase</td>
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<tr>
<td>December 2009</td>
<td>CHL#2 Building Construction Complete</td>
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<tr>
<td>October 2010</td>
<td>CHL#2 Utilities Construction Complete</td>
</tr>
<tr>
<td>October 2010-July 2011</td>
<td>CHL#2 Major Equip Delivery/Installation</td>
</tr>
<tr>
<td>Oct 2011-March 2012</td>
<td>Hall D Refrigerator Installation</td>
</tr>
<tr>
<td>Oct 2011 -June 2012</td>
<td>CHL#2 Commissioning</td>
</tr>
<tr>
<td>March-April 2012</td>
<td>Hall D Refrigerator Commissioning</td>
</tr>
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Current Cryogenic Status

• Construction Phase, CD-3, Sept 2008
• CHL Civil Design ~100% Complete
• Hall D Cryogenic Civil Design ~100% Complete
• Major Cryogenic Specifications Developed
• CHL 4.5K Refrigerator Fabrication Underway
• CHL Compressor Skid Fabrication Underway
• All Major Procurements have been placed
• CHL Field Installation Piping and Controls On-going
• On Schedule and Budget
Thank You for Your Kind Attention

May We Answer Your Questions?
Backup Slides of Ganni Cycle Description
Compressor Characteristics

**FIGURE 1.3** BRV=2.2 1st Stage

**FIGURE 1.4** BRV=2.6 2nd Stage
Standard Cycle

16 or 21 ATM

Pressure Ratio
Pr~ 5.3 or 7

3 ATM

Pressure Ratio
Pr~ 3

1 ATM

C1

TURBINE

RECYCLE

FLOW

C2

Pressure Ratio
Pr~ 5.3 or 7

T

COMPRESSORS

REFRIGERATION LOAD

STANDARD INDUSTRIAL
HELIUM REFRIGERATION SYSTEM

COLD BOX

FROM REFRIGERATED LOAD

TO REFRIGERATED LOAD
Ganni Cycle

GANNI CYCLE (FLOATING PRESSURE)
HELIUM REFRIGERATION SYSTEM

12 TO 16/21 ATM

Pressure Ratio Pr~ 3.5

Pr~ 3.5

1 ATM

C1

TURBINE
RECYCLE
FLOW

C2

Pressure Ratio Pr~ 3.5

3.5 - 6 ATM

T

COMPRESSORS

SMALLER 2ND STAGE COMPRESSORS

SMALL LOAD COMPRESSOR

1- 1.75 ATM

COLD BOX

FROM REFRIGERATED LOAD

TO REFRIGERATED LOAD

REFRIGERATION LOAD

HELIUM REFRIGERATION SYSTEM

FROM REFRIGERATED LOAD

REFRIGERATED LOAD

FROM REFRIGERATED LOAD

REFRIGERATED LOAD