ILC Cryomodule and Cryogenics

Carlo Pagani

University of Milano and INFN Milano
Outline

• **Preface: Accelerators need RF**
  - Superconducting RF is the ILC Technology choice
  - Superconducting RF needs cryomodules and cryoplants

• **Cryogenics fundamentals**
  - Thermodynamic efficiency
  - Sources of heat losses

• **Cryomodule, Cryo-strings and Cryo-units**
  - ILC requirements and consequences

• **Cryomodule details**
  - Basic function and features
  - The TTF cryomodule as the starting point for ILC BCD
  - Operational experience at TTF
  - Global effort for ILC
Why Accelerators need RF?

- To give energy to a charged particle beam, apart from “details”, you need to let him move across a region in which an electric field exists and is directed as the particle motion.

\[
\Delta E_{\text{particle}} = \int F_{\text{Lorentz}} \cdot d\vec{s} = q \int \vec{E} \cdot \vec{v} \, dt
\]

- In the accelerator’s world RF take care of all the variety of items that are required to accomplish this task of creating a region filled of electromagnetic energy that can be sucked by the beam while crossing it.

- An “RF power source” is used to fill, via a “coupler”, the “RF cavity”, or resonator that is the e.m. energy container from which the beam is taking its energy.

- What we ask to a good cavity?

### High \( Q \) for losses:
- \( U = \) stored energy
- \( P_{\text{diss}} = \) dissipated power

\[
Q = |\omega| \frac{U}{P_{\text{diss}}}
\]

### Small \( R_s \) for high \( Q \):
- \( R_s = \) surface resistance
- \( G = \) cavity geometrical factor

\[
Q = \frac{G}{R_s}
\]
The ILC technology choice

Stand wave: $V_{ph} = 0$ and $Vg = c$

TESLA: $f = 1.3$ GHz

The power is deposited at the operating temperature - 2 K

We need to guarantee and preserve the 2 K environment
- Cavity is sensitive to pressure variations, only viable environment is sub-atmospheric vapor saturated He II bath

We can't beat Carnot efficiency!

Remembering that the power dissipated on the cavity walls to sustain a field is:

$$P_{\text{diss}} = \frac{R_s}{2} \int_S H^2 dS$$

a pulsed operation is required to reduce the time in which the maximum allowable field is produced to accelerate the particles

Cryogenics and cryomodules
How is spent the cold advantage?

The gain in RF power dissipation with respect to a normal conducting structure is spent in different ways:

- **Paying the price of supplying coolant at 2K**
  - This include ideal Carnot cycle efficiency
  - Mechanical efficiency of compressors and refrigeration items
  - Cryo-losses for supplying and transport of cryogenics coolants
  - Static losses to maintain the linac cold

- **Increasing the duty cycle (percentage of RF field on)**
  - Longer beam pulses, larger bunch separation, but also
  - Larger and more challenging Damping Rings

- **Increasing the beam power (for the same plug power)**
  - Good for Luminosity

\[ W \geq Q \frac{T_h - T_c}{T_c} \]
The ILC Linacs: 2 x 12 km Cryomodules
LHC and ILC/TTF Cryomodule Comparison

From an LHC Status Report by Lyndon R. Evans

$\phi = 38''$

ACC 4 & ACC 5 in TTF

ACC 2 & ACC 3 in TTF
Cryogenics and Cryomodule

**Cryomodule** (it contains 8 SC Cavities)

- It’s the building block of all SC accelerators: ILC but also LHC
- The cryomodule provides:
  - cryogenic environment for the SC active elements
  - thermal shielding to mitigate static losses
  - structural support

**Cryogenics**

- Refrigeration Plants:
  - Transform plug power into cooling power at cryogenics temperatures
    - from MW to kW
    - from 300 K to few K
    - from water to Helium
- Distribution and Recovery of cryogenics coolants
"Cartoon" view of the system

All "spurious" sources of heat losses to the 2 K circuits need to be properly managed and intercepted at higher temperatures (e.g. conduction from penetration and supports, thermal radiation)

To He production and distribution system
Heat load budget for 1 Cryomodule

- Static is derived from TTF measurements (see next)

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<thead>
<tr>
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<td>Supports</td>
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<td>Input Coupler</td>
<td>TBD</td>
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<td>HOM coupler</td>
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<td>Beam tube bellows</td>
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<td>0,24</td>
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<td>HOM to structure</td>
<td></td>
<td>1,68</td>
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<td>Instrumentation cable</td>
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<td>Current leads</td>
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<td>Dark current</td>
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<td>TBD</td>
<td>71,76</td>
<td>105,25</td>
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<td>Quadrupole</td>
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<tr>
<td>sum static</td>
<td>3,5</td>
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<tr>
<td>sum dynamic</td>
<td>8,37</td>
<td></td>
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<tr>
<td>Total (static+dynamic)</td>
<td>11,87</td>
<td></td>
<td></td>
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<tr>
<td>HL per meter (W/m)</td>
<td>0,973</td>
<td></td>
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</table>

ILC (500 GeV)
RF properties 31.5 MV/m, Qo=1 E10
Operating mode 5 Hz
Cryo-module 8 cavity module, 9-cell
Cryo-module length in string (including interconnect) (m) 12,20
# TTF Cryomodule Performances

<table>
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<td>115.0</td>
<td>76.8</td>
<td>90.0</td>
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<td>81.5</td>
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<td>77,9</td>
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<td>72.0</td>
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<tr>
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<td>115.0</td>
<td>76.8</td>
<td>73.0</td>
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<tr>
<td>Module 4</td>
<td>III</td>
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<td>76.8</td>
<td>74</td>
</tr>
<tr>
<td>Module 5</td>
<td>III</td>
<td>115.0</td>
<td>76.8</td>
<td>74</td>
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<tr>
<td>Module SS</td>
<td></td>
<td>115.0</td>
<td>~76.8</td>
<td>72.0</td>
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<tr>
<td>Module 3*</td>
<td>II</td>
<td>115.0</td>
<td>76.8</td>
<td>75</td>
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<tr>
<td>Module 2*</td>
<td>II</td>
<td>115.0</td>
<td>76.8</td>
<td>74</td>
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<tr>
<td>Module 6 EP</td>
<td>Type III, EP-Cavities</td>
<td>Goal: Solution close to XFEL Modules</td>
<td>Design and estimated values by Tom Petersen 1995 -Fermilab-</td>
<td>Modules under Test in TTF2-Linac</td>
</tr>
</tbody>
</table>
Cryogenics
The helium refrigeration process

- A conceptually simple (but impractical) helium liquefier could consist of just two processes or steps
  - **Isothermal compression**
    - Reduce He entropy
  - **Isentropic expansion**
    - Removes energy as work
  - This process illustrates the derivation of the thermodynamic limits for a helium refrigerator

- Real processes just add one more feature -- heat exchangers
Ideal He process

Work in = $T_{amb}\Delta s$

Work out = $\Delta h$

Net ideal work into system: $T_{amb}\Delta s - \Delta h$ (in dimension of energy per unit mass)

Heat load absorbed by evaporation: $\Delta h = T_{liquid} \Delta s$ (isothermal load)

Ratio of applied work to heat absorbed: $T_{amb}/T_{liquid} - 1 \sim T_{amb}/T_{liquid}$

Real plants include several stages of intermediate temperature expanders (Claude process)
The thermal cycle: Efficiency

- **Thermal cycle efficiency**
  - Efficiency of the thermal cycle, to extract heat $Q$ deposited at $T_c$ we need a work $W$ at temperature $T_h$ always greater than the Carnot cycle

  \[ W = Q \cdot \frac{T_h - T_c}{T_c} \cdot \eta_{th} \]

  - including the efficiency $\eta_{th}$ of the thermal machine (20% for $T_c = 2$ K) we need 750 W at room temperature for each W dissipated at 2 K
  - All sources of parasitical heat loads need to be carefully avoided if we do not want to pay such a high price!
  - Accurate thermal design for the cryomodule in order to minimize the heat losses
    - **Static**: Always present, needed to keep the module cold.
    - **Dynamic**: Only when RF is on. Due to power deposition by RF fields.

- **N.B. at different intercept temperatures**
  - when $T_c = 4.2$ K we have $\sim 250$ W/W
  - when $T_c = 50-80$ K we have $\sim 20-10$ W/W
Heat removal by He

- Generally speaking, heat is removed by increasing the energy content of the cooling fluid (or vapor)
  - Heating the vapor
  - Spending the energy into the phase transition from liquid to vapor
    - In the 2 K bath this is the mechanism, heat is absorbed by evaporation in isothermal conditions

- Cooling capacity is then related to the enthalpy difference between the input and output helium (and directly \( \propto \) to the mass flow)

- The rest is “piping” design to ensure the proper mass flow, convective exchange coefficient, pressure drop analysis, ...

\[
P_{\text{removed}}[\text{W}] = m_{\text{flow}}[\text{g/s}] / \Delta h[\text{J/g}]
\]

<table>
<thead>
<tr>
<th></th>
<th>Temp in (K)</th>
<th>Press in (bar)</th>
<th>Enthalpy in (J/g)</th>
<th>Entropy in (J/gK)</th>
<th>Temp out (K)</th>
<th>Press out (bar)</th>
<th>Enthalpy out (J/g)</th>
<th>Entropy out (J/gK)</th>
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<td>40 K to 80 K</td>
<td>40,00</td>
<td>16,0</td>
<td>223,8</td>
<td>15,3</td>
<td>80,00</td>
<td>14,0</td>
<td>432,5</td>
<td>19,2</td>
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<td>5 K to 8 K</td>
<td>5,0</td>
<td>5,0</td>
<td>14,7</td>
<td>3,9</td>
<td>8,0</td>
<td>4,0</td>
<td>46,7</td>
<td>9,1</td>
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<td>2 K</td>
<td>2,4</td>
<td>1,2</td>
<td>4,383</td>
<td>1,862</td>
<td>2,0</td>
<td>saturated vapor</td>
<td>25,04</td>
<td>12,58</td>
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</table>

From: T. Peterson, ILC Cryogenic system design spreadsheet, FNAL
Large cooling capabilities < 4.2 K

- Temperatures lower than 4.2 K means sub atmospheric pressure conditions for the He bath where we want to extract the dissipated power.
- But with high heat loads and low pressures the gas volume flow from the bath becomes large.
  - Cold compressors are needed to increase pressure conditions before the He gas reaches room temperature conditions.
ILC Refrigerator Scheme

Compressors

Heat Exchangers

Helium Expanders

Cold Compressors

LHC Compressor Station

LHC Cold Compressor
# He cycle efficiency in big plants

<table>
<thead>
<tr>
<th></th>
<th>RHIC</th>
<th>CEBAF</th>
<th>HERA</th>
<th>LHC</th>
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</thead>
<tbody>
<tr>
<td><strong>Equivalent capacity at 4.5 K (kW)</strong></td>
<td>25</td>
<td>13</td>
<td>8.4 coolbox</td>
<td>18 coolbox</td>
</tr>
<tr>
<td><strong>Power required (W/W)</strong></td>
<td>450</td>
<td>350</td>
<td>285</td>
<td>230</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>16%</td>
<td>20%</td>
<td>25%</td>
<td>30%</td>
</tr>
</tbody>
</table>
The Big Picture: ILC Site Power ~ 200MW

Main Linacs
140MW

RF: 90MW

Cryogenics: 50MW

Injectors
Damping rings
BDS
Auxiliaries

Beam 22MW

78%
65%
60%

Carlo Pagani

ILC School
May 2006
From Cryomodule to Cryo-units
Basic Functions of the ILC cryomodule

- In SRF application the cryomodule provides:
  - **Cryogenic environment** for the cold mass operation
    - Cavities/Magnets in their vessels filled with sub atmospheric He at 2 K
    - He coolant distribution at required temperatures
    - Low losses penetrations for RF, cryogenics and instrumentation
  - **Shield for the sources of “parasitical” heat transfer** from room to cryogenics temperature produced by three mechanisms
    - thermal radiation
    - conduction
    - convection
    - (To mitigate loads at 2 K all heat fluxes need to be intercepted at higher T)
  - **Structural support** of the cold mass
    - Issues concerning different thermal contractions of materials
    - Provide precise alignment capabilities and reproducibility with thermal cycling

- The cryomodule contains a variety of complex technological objects: cavities and their ancillaries, but also magnets and BPMs
Heat losses issues: Physical mechanisms

• Thermal radiation
  - Radiated power from hot surfaces to vanishingly temperatures is proportional to $T^4$ (Stephan-Boltzmann). $\sigma_{SB} = 5.67 \cdot 10^{-8}$ [W m$^{-2}$ K$^{-4}$]
    - Reduce the surface emissivity, $\varepsilon$ (material and geometry issue)
    - Intercept thermal radiation at intermediate temperatures by means of thermal shields

• Heat conduction
  - A SRF module has many penetration from the room temperature environment (RF couplers, cables, ...)
    - Proper choice of low thermal conduction, $k_{th}$, materials whenever possible
    - Minimize thermal paths from r.t. and provide thermalization at intermediate temperatures.

• Convection
  - Convective exchange from r.t. is managed by providing insulation vacuum between the room temperature vessel and the cold mass
ILC Cryomodule specific requirements

- High filling factor
  - maximize ratio between real estate gradient and cavity performances
  - long cryomodules/cryo-units and short interconnections

- Moderate cost per unit length
  - simple functional design based on reliable technologies
  - use the cheapest allowable material that respect requirements
  - minimum machining steps per component
  - minimum number of different components

- Effective cold mass alignment strategy
  - room temperature alignment preserved once active elements are cold

- Effective and reproducible assembling procedure
  - class 100/10 clean room assembly just for the cavity string
  - minimize time consuming operations for cost and reliability

- QC and QA procedures defined at each production step
Consequences/I

- The combined request for a high filling factor [machine size] and the necessity to minimize static heat losses [operation cost] leads to integrate the cryomodule concept into the design of the whole cryogenic infrastructure
  - Each cold-warm transition along the beamline requires space and introduces additional static losses
  - Each cryogenic feed into the module requires space and introduces additional static losses
- Thus, long cryomodules, containing many cavities (and the necessary beam focusing elements) are preferred, and they should be cryogenically connected, to form cryo-strings, in order to minimize the number of cryogenic feeds
  - Limit to each cryomodule unit is set by fabrication (and cost) issues, module handling, and capabilities to provide and guarantee alignment
    - practically 10 to 15 meters
  - RF heat loads increase with the number of cavities in the module, and lead to an increase in the sizes of some cryogenic piping
Consequences/II

- The cryogenic distribution for the cryo-string is integrated into the cryomodule, again to minimize static losses
  - Several cryogenic circuits running along the cold mass to provide the coolant for the cavities and for the heat interception at several temperatures
- To take out the RF power dissipated along the long cryo-string formed by many cryomodules connected together a large mass flow of 2 K He gas is needed, leading to a big He Gas Return Pipe (HeGRP) to reduce the pressure drop
  - This pipe can be made large and stiff enough so that it can act as the main structural backbone for the module cold mass
    - Cavities (and magnet package) are supported by the HeGRP
    - The HeGRP (and the whole cold mass) hangs from the vacuum vessel by means of low thermal conduction composite suspension posts
- TESLA Test Facility cryomodule scheme:
  - 8 cavities and one magnet package, approximately 12 m long
The ILC Reference: TTF Type 3 (by INFN)

3 cryomodule generations in TTF to:

- improve simplicity and performances
- minimize costs

Required plug power for static losses ~ 5 kW/(12 m module)

He Gas Return Pipe is the structural backbone of the module cold mass

Reliable Alignment Strategy

“Finger Welded” Shields

Sliding Fixtures @ 2 K
Cryooydules installed in TTF

ACC 5  ACC 4  ACC 3  ACC 2  ACC 1
RF gun

800 MeV  400 MeV  120 MeV  4 MeV

ACC 4 & ACC 5  ACC 2 & ACC 3
Module interconnections ~ 0.4 m/each

- Warm/Cold beamline transitions kept to the minimal
- 12 Modules are connected together in strings via bellows on the vacuum vessel
- Several string (~16) are connected to form a cryo-unit (~2.3 km)
- Every 4 strings a vacuum barrier is conceived
Modules are connected in Cryo-Strings

12 m modules with 8 cavities (and 1 quad every 3 modules)

Cryomodule

Cryo-string (15 cryomodules, ~165 m)

Screens or shields

C 9-cell cavities

Q SC quadrupole

JT SC level sensor

CD CD level sensor

TT Temperature sensor

Heater

Coupler & Adsorber heat intercepts

Current lead heat intercepts

12 modules (~150 m)
Strings are connected in Cryo-units

- At each cryo-string (~150 m) there is additional space needed for cryogenic connections (several meters)

16 strings per cryogenic unit, so 192 modules per cryo unit (50 GeV)
ILC cryogenic system summary

- **Cooling of the cold mass by evaporation of HeII**
  - cavities and quads immersed in a saturated He II bath @ 2 K

- **Static losses minimization (negligible radiation effect reaching 2 K)**
  - Thermal shield @ 5 - 8 K fed by He gas
  - Thermal shield @ 40 - 80 K fed by He gas

- **Integration of the distribution lines into cryomodule**
  - Two-phase line (liquid helium supply and concurrent vapor return) connects to each helium vessel
  - Two-phase line connects to gas return once per module
  - Sub-cooled helium supply line (for the downstream modules) connects to the big two-phase line via JT valve once per “string” (12 modules)

- **Include provisions for warmup/cooldown**
  - A small diameter warm-up/cool-down line connects the bottoms of the He vessels (primarily for warm-up)
# ILC Lengths and Packing Factors

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<th>Description</th>
<th>Value</th>
<th>Notes</th>
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<tr>
<td>Cryomodule with quad</td>
<td>12543</td>
<td>1 per RF unit</td>
</tr>
<tr>
<td>Cryomodule without quad</td>
<td>11271</td>
<td>2 per RF unit</td>
</tr>
<tr>
<td>RF unit</td>
<td>35085</td>
<td>3 modules per RF unit</td>
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<tr>
<td>Extra Length at End of String (mm)</td>
<td>2000</td>
<td>4 RF units per string</td>
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<tr>
<td>String</td>
<td>140342</td>
<td>12 modules per string</td>
</tr>
<tr>
<td>Extra length at end of string (BCD)</td>
<td>1757</td>
<td>1 end box per string. Add back the 850 since separate box mea</td>
</tr>
<tr>
<td>Extra length at end of segment (ACD)</td>
<td>9271</td>
<td>Take full module length for warm-up/cool-down segmentation</td>
</tr>
<tr>
<td>Segment</td>
<td>563123</td>
<td>48 modules per segment</td>
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<tr>
<td>Extra length at end of cryo unit</td>
<td>20785</td>
<td>Take one module length for feed box and one for turnaround</td>
</tr>
<tr>
<td>Cryogenic unit</td>
<td>2273279.2</td>
<td>192 modules per cryo unit</td>
</tr>
<tr>
<td>Modules installed in 15-250 GeV region</td>
<td>960</td>
<td>5 cryo units per linac from 15-250 GeV</td>
</tr>
<tr>
<td># Required for Acceleration (15-250 GeV)</td>
<td>931</td>
<td>3% Overhead</td>
</tr>
<tr>
<td>Length of 15-250 GeV region of linac</td>
<td>11366396</td>
<td>5 degree off-crest</td>
</tr>
<tr>
<td>Length occupied by cryo boxes</td>
<td>139068</td>
<td>11.4 km long linac (15 - 250 GeV) w/o diag,</td>
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<tr>
<td>Linac Packing Fraction (%)</td>
<td>139.1</td>
<td>139.1 meters of cryo boxes in 15 - 250 GeV p</td>
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<tr>
<td>Packing Fraction w/o Extra Lengths (%)</td>
<td>70.0 %</td>
<td>70.0 % packing fraction</td>
</tr>
<tr>
<td></td>
<td>70.9 %</td>
<td>70.9 % packing fraction for modules alone</td>
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Cryoplant Layout in the ILC e-Linac

For ILC 500, total of ten 25 kW @ 4.5 K plants requiring 52 MW of AC power.
Heat load revisited
- More conservative estimates of static heat leak than in TDR
  - based on TTF measurements (all module with warm-cold transition)
- Higher operational safety margin (~ 1.4 x 1.5 instead of 1.5 total)
- Higher dynamic load due to higher gradient
- Keeping the plant sizes below 25 kW total equivalent 4.5 K capacity leads to maximum plant spacing of ~2.3 km

Cryo-segmentation every 560 m - warm or cold?
- Use segments to isolate insulating vacuum sections
  - Not necessarily a warm-cold transition
- Introduction of a cold-warm transition could be used for shortening regions that are warmed up for repair work
  - Faster cooldown
  - Could be used for Instrumentation
Cryomodule details
# Wide Operation Experience with TTF

<table>
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<tr>
<th>Type</th>
<th>Installation date</th>
<th>Cold time [months]</th>
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<tr>
<td>CryoCap</td>
<td>Oct 96</td>
<td>55</td>
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<tr>
<td>M1</td>
<td>Mar 97</td>
<td>5</td>
</tr>
<tr>
<td>M1 mod.</td>
<td>Jan 98</td>
<td>12</td>
</tr>
<tr>
<td>M2</td>
<td>Sep 98</td>
<td>44</td>
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<td>M3</td>
<td>Jun 99</td>
<td>35</td>
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<tr>
<td>M1* MSS</td>
<td>Jun 02</td>
<td>39, 8</td>
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<td>M3* M4</td>
<td>Apr 03</td>
<td>28, 28, 28</td>
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<td>M2*</td>
<td>Feb 04</td>
<td>25</td>
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20 May 2006
From Prototype to Cry 3

Extensive FEA modeling (ANSYS™) of the entire cryomodule
- Transient thermal analysis during cooldown/warmup cycles,
- Coupled structural/thermal simulations
- Full nonlinear material properties

Detailed sub-modeling of new components and Laboratory tests
- Finger-welding
- Cryogenic tests of the sliding supports
Several cryogenic lines at different temperatures

Suspension supports of the cold mass

Beam Line

Thermal shielding and heat interception

Insulation vacuum enclosure

RF Coupler

Cavity
Few Changes from TTF Type3 to ILC

► Move quadrupole to the center
  - Quad/BPM fiducialization, separate steering magnets
  - High pressure rinsing and clean room assembly issues
  - Movers and dampers if required

► Short cavity design
  - Cutoff tubes length by e.m. not ancillaries (coaxial tuner)

► Coaxial Tuner with integrated piezo-actuators
  - Parametric “Blade Tuner” or equivalent for real estate gradient
  - Integration of fast tuner (piezo actuated) underway
Towards ILC Cryomodule

- International collaborative Effort in the three regions
- Design changes are towards nailing down slot length of components
  - Costing should be straight-forward from TTF (and possibly XFEL) experience
Cold mass alignment strategy

- The Helium Gas Return Pipe (HeGRP) is the system backbone
- The 3 Taylor-Hobson spheres are aligned wrt the HeGRP axis, as defined by the machined interconnecting edge flanges
- Cavities are individually aligned wrt the aligned T-H spheres
- Cavity (and Quad) sliding planes are parallel to the HeGRP axis by machining (milling machine)
- Longitudinal cavity movement is not affecting alignment
- By design the differential thermal contractions preserve parallelism
- Variation of axis distances by differential contraction are fully predictable and taken into account
- Sliding supports and invar rod preserve the alignment while disconnecting the cavities from the huge SS HeGRP contraction
  - 36 mm over the 12 m module length cooling from 300 K to 2 K
WPMs to qualify alignment strategy

WPM = Wire Position Monitor

On line monitoring of cold mass movements during cool-down, warm-up and operation

2 WPM lines with 2 x 18 sensors
4 sensors per active element
8 mm bore radius

1 WPM lines
1 sensor per active element
25 mm bore radius

1 WPM line
7 sensors/module
25 mm bore radius

Cry 1

Module 1

Cry 2

Module 2 & 3

Cry 3

Module 4 & 5

Carlo Pagani
ACC4 & ACC5 Met Specs

- Still some work at the module interconnection
- Cavity axis to be properly defined

Table 1: Result Summary.

| TDR Specifications (rms) | | WPM results (peak) | |
|-------------------------|------------------|-------------------|
| Cavities                | x/y              | + 0.35/-0.27 mm   |
| Quadrupoles             | x/y              | + 0.35/-0.1 mm    |

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ILC School
May 2006
Sliding supports and Invar Rod

Thermal contraction depend from the material: SS=0.31% Nb&Ti=0.15%

- The HeGRP is the backbone
- HeGRP for Cavity alignment
- Invar Rod for independent z
  - Independent cavity z position
  - Semi-rigid couplers allowed
  - Less demanding bellows
Dressed Cavity: 3D Model and Dimensions
A dressed cavity into the cryomodule

The coupler represents a heat conduction path from the r.t. to 2 K, at each cavity.

Needs proper heat interception not to increase the static heat losses at 2 K to intolerable levels.

It also has dynamic heat load effects at the thermal interception stages.
**Support Posts and Brackets**

- Designed to sustain the HeGRP with the active items.
- Support posts are qualified for a 5000N force on all flanges with a limited thermal conductivity.
- SS and Al flanges are connected to the Fiberglas body using thermal expansion/contraction forces.
Thermal shields and MLI

- Roles of thermal shield at intermediate temperature:
  - The internal cold mass "sees" a surface at lower temperature than the external (r.t.) chamber, consequently heat load is reduced
  - Provides thermal interception point to all penetration (couplers, etc)
- Role of MLI (multilayer insulation)
  - "Floating" radiation shields to reduce flux

\[ \dot{Q} = S \varepsilon \sigma_{SB} \left( T_h^4 - T_c^4 \right) \]

Radiation load from 300 K to low temperatures \(\sim 500 \text{ W/m}^2\) for \(\varepsilon = 1\)!

<table>
<thead>
<tr>
<th>Effective Heat Flux (CERN Data)</th>
<th>W/m(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLI (30 layers) from 300 K, P&lt; 1 mPa</td>
<td>1-1.5</td>
</tr>
<tr>
<td>MLI (10 layers) from 80 K, P&lt; 1 mPa</td>
<td>0.05</td>
</tr>
</tbody>
</table>
The 50-70 K shield

Welding of the “fingers”

30 MLI layers on shield
Finger-Welded Shield Behavior

- Cooldown simulation of the 4.2 K and 70 K aluminum thermal shields.
- We used a simultaneous 12 hour linear cooldown.
- The maximal thermal gradient on the shields (upper left graph) is below 60 K, a safe value.
- The temperature fields show that the gradient is concentrated in the welding region, where the fingers unload the structure.
Thermo-mechanical analysis of Shields

Applying the computed temperature field, deformations and stress distribution can be easily computed.

Maximum stresses are within acceptable limits

Maximum deformations due to asymmetric cooling is below 10 mm.
Simulations verified on ACC4 and ACC5
Module assembly picture gallery - 1

String inside the Clean Room
Module assembly picture gallery - 2

String in the assembly area
Module assembly picture gallery - 3

Cavity interconnection detail
Module assembly picture gallery - 4

String hanged to the HeGRP
String on the cantilevers
Module assembly picture gallery - 6

Close internal shield MLI
Module assembly picture gallery - 7

External shield in place

Welding “Fingers”

Sliding VV on shield (MLI)
Module assembly picture gallery - 8

Complete module moved for storage
Selected Bibliography

- **CERN 2004-008**

- **Handbook on Cryogenic Engineering**
  - J. G. Weisend II, Taylor & Francis, 1998

- **TESLA Technical Design Report**: online TESLA Report 2001-23
  - http://tesla.desy.de/new_pages/TESLA/TTFnot01.html

- **ILC BCD documents**
  - bcd: main_linac:ilc_bcd_cryogenic_chapter_v3.doc