Fundamentals of cryogenics (for Superconducting RF)

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Cryogenics and CAS

• Two CAS courses
    • Superconductivity in Particle Accelerators
    • Superconductivity and Cryogenics for Accelerators and Detectors

• Many topics involved:
  – Theory side
    • Thermodynamics
    • Superconductivity (& Superfluidity)
  – Technology side (non-exaustive list)
    • Materials issues
      – Be it for magnets, for cavities… and around them
    • Heat transfer mechanisms (and their handling)
    • Vacuum
    • Producing and using cryogens
Summary

• In the following I will mostly illustrate a few key concepts and provide some some “practical engineering considerations”
  – concentrated on superconducting RF linacs
  – SC in magnets is another broad topic, less relevant to High Power Hadron Machines and covered in previous CAS courses

• Lecture deals with two broad topics
  – Cryogenic concepts in general
  – Cryostats and cryogenics for SRF linacs

• This lecture is obviously incomplete in many areas (e.g. cryogenic instrumentation) and intentionally “light” on topics that could easily require an entire course to deal with the details
Why SCRF? RF losses in a RF resonator

- Power is dissipated on the cavity walls, according to their surface resistance $R_s$

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

- For a normal conductor, where $\delta$ is the skin depth (which depends on $f^{-1/2}$)

\[ R_s = \sqrt{\frac{\pi f \mu_0}{\sigma}} = \frac{1}{\sigma \delta} \]

- For a superconductor, BCS theory
  - Fit for
    - Nb
    - $T < T_c/2$
    - $f << 1$ THz

Unlike DC conditions, with RF fields a SC cavity still dissipates power. Not all $e^-$ are in Cooper pairs. Surface resistance does not drop to 0!
Superconducting RF “advantage”

Q: Good, are we going to gain 5-6 order of magnitudes for free?
A: No!

- Power is deposited at the (extremely low) operating temperature
- Implications:
  - Many material & procedure issues to guarantee good $R_s$
    - Topic: “SCRF Cavity fabrication technology”
      - High grade Niobium.
      - Clean joining technology (electron beam welding)
      - Aggressive chemistry (BCP/EP) to remove surface layer damaged by fabrication (rolling, forming, milling, turning, ...)
      - Final treatments in clean room conditions
      - ...
  - We also need to take special measures to guarantee and preserve the low temperature environment
    - i.e. we need a technological complication: a cryogenic infrastructure for the production and handling of the coolant, and for the removal of all heat deposited at low temperatures

$$R_s = R_s^{BCS} + R_s^{mag} + R_s^{residual}$$
We need a Cryoplant

- The cryoplant is a thermal “machine” that performs work at room temperature to extract heat at low temperatures
  - It cools the devices to the nominal temperatures and keep them cold by extracting all heat loads generated at cold
  - Surely we can’t beat thermodynamics and the Carnot cycle!
    - Actually we are lucky if we get to 20-30% of Carnot...
    - Overall, $1 \text{ W} @ 2 \text{ K} \Rightarrow 750 \text{ W} @ 300 \text{ K}$
  - But, even taking into account this factor, there is still a good advantage for superconductivity at moderate frequencies

- Nb critical temperature is 9.2 K, so there is not really a choice for coolants

<table>
<thead>
<tr>
<th></th>
<th>$^4\text{He}$</th>
<th>$\text{H}_2$</th>
<th>$\text{Ne}$</th>
<th>$\text{N}_2$</th>
<th>$\text{Ar}$</th>
<th>$\text{O}_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal boiling point</td>
<td>4.22</td>
<td>20.28</td>
<td>27.09</td>
<td>77.36</td>
<td>87.28</td>
<td>90.19</td>
</tr>
</tbody>
</table>
Sadi Carnot (1796-1832)

Work is needed at higher temperatures to remove the heat deposited at lower temperatures

\[ W \geq Q_{in} \cdot \frac{T_h - T_c}{T_c} \]

\[ Q_{in} = \eta_{tot} W = \eta_{th} \eta_c W \]

\[ \eta_c = \frac{T_c}{T_h - T_c} \approx \begin{cases} 1/70 & \text{for } T_h = 300 \text{ K}, T_c = 4.2 \text{ K} \\ 1/150 & \text{for } T_h = 300 \text{ K}, T_c = 2 \text{ K} \end{cases} \]

\[ \eta_{th} = \begin{cases} 25 - 30\% & \text{at } T = 4.2 \text{ K} \\ 15 - 20\% & \text{at } T = 2 \text{ K} \end{cases} \]

Power to maintain the low temperature environment

– This include ideal Carnot cycle efficiency
– Efficiency of the real thermal machine

Applies to all heat inleaks from the environment to the cold region and cryofluids, not just RF losses

To remove 1 W at 4.2 K we need to use \( \sim 250 \text{ W at 300 K} \)
To remove 1 W at 2 K we need to use \( \sim 750 \text{ W at 300 K} \)
Entropy is the function of state that allows understanding cryo devices.

Cryogenic systems are entropy pumps, which move entropy from the cold devices into a warmer environment.

- If we provide them energy.

All nonidealities (entropy sources associated to the thermal machine) lead to higher work needed.

- Spurious heat transfers, entropy changes due to compression, expansion, heat exchangers, gas leaks, etc.
What is our non ideality level?

\[ W = Q_{\text{out}} - Q_{\text{in}} \]

**Reversible**

\[ S_{\text{in}} = \frac{Q_{\text{in}}}{T_{\text{in}}} \quad S_{\text{out}} = \frac{Q_{\text{out}}}{T_{\text{out}}} \]

**Entropy Source**

**Irreversible**

\[ S_{\text{out}} = \frac{Q_{\text{out}}}{T_{\text{out}}} > \frac{Q_{\text{in}}}{T_{\text{in}}} \]

**Entropy x 5**

\[ 2 W/K \quad 1 W \]

**Hot**

\[ Q_{\text{out}} \]

\[ T_{\text{out}} \]

\[ 300 K \]

\[ 749 W \]

\[ 149 W \]

**Cold**

\[ Q_{\text{in}} \]

\[ T_{\text{in}} \]

\[ 2 K \]

\[ 300 K \]

\[ 750 W \]

\[ 2 K \]

\[ 1 W \]
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
The He refrigerator, conceptually

Compression stage:
This is where we have to do work, providing power

Expansion stage:
This is where we cool the fluid in an adiabatic expansion (and do some small amount of work)

High pressure Gas

Water cooled Heat Exchanger (release Heat to ambient)

Counterflow Heat Exchanger (uses cold gas out of device)

Cold Gas (at low pressure)

RF dissipates power

Cold liquid
Linde 1895, first industrial liquefaction of air

- Breakthrough with respect to the “cascading” liquefaction experiments
- Use the fact that inversion temperature of air is above ambient temperature, and at sufficiently high pressure an expansion leads to appreciable temperature decreases
  - Joule Thomson effect
- The expansion-cooled gas is then used to pre-cool in counterflow the high pressure gas before the valve
- Gradually decreasing temperature upstream JT, until leading to liquefaction
• Understood from T-S diagrams
  – A real gas undergoing an isoenthalp expansion can either cool or warm, depending on the Joule-Thomson effect and the inversion temperature at a given pressure
    • \( H = U + PV \)
  – Below inversion temperature the expansion lead to cooling
  – Above inversion temperature the expansion lead to warming

– \( N_2 \ T_{\text{inv}} = 621 \ \text{K} \)
– \( \text{He} \ T_{\text{inv}} = 51 \ \text{K} \)
He T-S diagram

- At point A the expansion leads to warming of the gas.
- At point B the expansion cools the gas.
- At point C it is possible to liquefy the gas to crossing the saturation line (bold) separating one phase domain from the two-phases domain.
A real cycle adds just more components

- Several stages of heat exchanges in the flow

- One or more expansion stages, either using pistons (small systems, versatile) or turbines (bigger plants, efficient at nominal speed and flow)
  - variants with expansion stages in parallel or series
  - not practical to use the work produced by expansion, usually dissipated at ambient temperature

- The last stage is always the isenthalpic expansion to generate the liquid form (Joule-Thompson valve)
Heat removal by He

• Generally speaking, heat is removed by increasing the energy content of the cooling fluid (liquid or vapor)
  – Heating the vapor
  – Spending the energy into the phase transition from liquid to vapor
    • In the pool boiling mode this is the mechanism, heat is absorbed by evaporation in isothermal conditions

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

• The rest is “piping” (engineering) design to ensure the proper mass flow, convective exchange coefficient, pressure drop analysis, …
Heat removal by He

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

<table>
<thead>
<tr>
<th>Temperature level</th>
<th>40 K to 80 K</th>
<th>5 K to 8 K</th>
<th>2 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>(module)</td>
<td>(module)</td>
<td>(module)</td>
<td></td>
</tr>
<tr>
<td>Temp in (K)</td>
<td>40.00</td>
<td>5.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Press in (bar)</td>
<td>16.0</td>
<td>5.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Enthalpy in (J/g)</td>
<td>223.8</td>
<td>14.7</td>
<td>4.383</td>
</tr>
<tr>
<td>Entropy in (J/gK)</td>
<td>15.3</td>
<td>3.9</td>
<td>1.862</td>
</tr>
<tr>
<td>Temp out (K)</td>
<td>80.00</td>
<td>8.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Press out (bar)</td>
<td>14.0</td>
<td>4.0</td>
<td>saturated vapor</td>
</tr>
<tr>
<td>Enthalpy out (J/g)</td>
<td>432.5</td>
<td>46.7</td>
<td>25.04</td>
</tr>
<tr>
<td>Entropy out (J/gK)</td>
<td>19.2</td>
<td>9.1</td>
<td>12.58</td>
</tr>
</tbody>
</table>

From: T. Peterson, ILC Cryogenic system design spreadsheet, FNAL

- From the assessment of heat loads at the various circuit levels, one can compute the needed mass flows
He: the fluid for SC accelerators

- Unique feature, melting line and saturation line do not intersect, they are separated by the “Lambda” line, separating the superfluid state
  - Critical point: 5.195 K @ 227.5 kPa
  - Normal boiling point: 4.222 K
  - “Lambda” point: 2.177 K @ 5.0 kPa
- Large accelerators use a few “regions”, i.e. cooling modes
  - Pool boiling He I
    - LEP, KEKB, HERA SRF
  - Saturated He II
    - CEBAF, FLASH, XFEL, SNS, ILC, ESS, …
  - Force flow supercritical He I
    - Tevatron, HERA, SSC, …
  - Pressurized He II
    - LHC

Helium phase diagram
Operation mode: pool boiling

• SCRF Cavities operate in the **pool boiling mode**, on the saturation curve, either at ambient pressure or below the lambda point
  – Ideally *isothermal* mode of operation, with good local heat transfer
  – Cavities are thin-walled high-Q resonators, very sensitive to environment pressure, so it is the preferred mode
  – Saturated He II
    • besides a lower temperature, gives the advantage of good heat transport (vapor coming from the surface in 2 Phase He II flow) and low pressure conditions (30 mbar) lead to quiet environment
• **but:**
  – requires pumping on the bath,
  – is subject to risks of air inleak
  – the operation close to the minimum of the Paschen curve complicates the operation of electrical and RF feedthroughs (especially true for instrumented vertical test facilities)
Operation modes

- Generally magnets are cooled with a **single phase**, either He I or He II, for good penetration of He in the coils
  - Pressurized He II
    - has excellent heat conduction capabilities
      - thermal conductivity three orders of magnitude higher than OFHC copper
    - No possibility of air inleaks!
  - Cryogenic stabilization
  - **but**
    - Cooling in non-isothermal conditions, with a temperature gradient
    - Requires an additional pressurized-to-saturated He II heat exchanger, where evaporative cooling carries heat away from the cold mass
    - The pressure conditions discourages to use this cooling method for the high-Q RF resonators
Evaporative cooling

• In any cooling mode ultimately heat is carried away from the cold region by evaporating vapor from a saturated bath and carrying it away
  – LHe (subatmospheric 2 phase 2 K or 1 bar boiling 4.2)
    • $\Delta H \sim 20 \text{ J/g}$ [23.4 J/g - 20.8 J/g]
  – Boiling LN2 at 77 K
    • $\Delta H = 200 \text{ J/g}$
  – Water... at 100 °C
    • $\Delta H = 2200 \text{ J/g}$

• Therefore, beware, big heat deposition at cold 2 K imply
  – big mass flow of low pressure gas
  – large volume flow
One additional component for Saturated He II

- Temperatures lower than 4.2 K mean 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:
  - again, latent heat of evaporation is only approximately 20 J/g
  - 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
## He cycle efficiency in big plants

<table>
<thead>
<tr>
<th>Equivalent capacity at 4.5 K (kW)</th>
<th>RHIC</th>
<th>CEBAF</th>
<th>HERA</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power required (W/W)</td>
<td>450</td>
<td>350</td>
<td>285</td>
<td>230</td>
</tr>
<tr>
<td>Efficiency</td>
<td>16%</td>
<td>20%</td>
<td>25%</td>
<td>30%</td>
</tr>
</tbody>
</table>
Cooling accelerator components

• Usually physicist and engineers designing an accelerator concentrate on the component design (cavities/magnets)
  – Then “jacket” them into helium tanks and cryostats
  – Finally specify and go out to buy a cryoplant

• The cooling mode, heat transfer mechanisms, fluid pressure drops, cooldown and warmup procedure, transient operation conditions need to be considered early in the component design
  – They can affect the complexity of the cooling system

• The cooled system has to be viewed as part of the overall cryogenic system
  – especially for big machines, where tradoff need to be made between components and support infrastructure
Heat transfer mechanisms

• One important issue in the design of accelerator components operating at cold temperatures is the **understanding and management of heat transfer processes**

• Once again, power deposition at cold temperatures implies the following r.t. power consumptions:
  - ~ 750 W/W at 2 K
  - ~ 250 W/W at 4.5 K
  - ~12 W/W at 70 K

• It is therefore crucial to intercept thermal fluxes from the room temperature environment before they reach the coldest temperatures
  - Deal with all heat transfer modes!
Provide thermal insulation!

• Three mechanisms for transferring heat
  – Conduction
    • Heat is transported inside solid or stagnant fluids, by processes at the atomic scale
  – Convection
    • Macroscopic fluid movement is responsible of heat transfer from the wet surfaces
  – Radiation
    • Heat is transported in the form of electromagnetic radiation emitted by surfaces, without requiring any supporting fluid or medium

• Besides loads intrinsically generated at the cold temperature for the device operations (e.g. the dissipated power on the SC RF cavities), we have to deal with heat leaking from the environment due to these three mechanisms
Heat losses issues: Physical mechanisms

• Heat conduction
  – The SRF cold mass has many penetrations 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 (small $S$, big $L$)

• Convection
  – Convective exchange from r.t. is managed by providing insulation vacuum between the room temperature vessel and the cold mass

• 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
Conduction

- Obeys Fourier law
  \[ \dot{Q} = k(T) S \nabla T \]
- For a 1D steady state conduction problem of flow through an area \( S \) over a length \( L \) with fixed temperatures \( T_{\text{hot}} \) and \( T_{\text{cold}} \), we can write it in the form

\[
\dot{Q} = \frac{S}{L} \int_{T_{\text{cold}}}^{T_{\text{hot}}} k(T) dT = \frac{S}{L} \left( \int_{T_{\text{reference}}}^{T_{\text{hot}}} k(T) dT - \int_{T_{\text{reference}}}^{T_{\text{cold}}} k(T) dT \right) = \\
= \frac{S}{L} \left( K_{\text{int}}(T_{\text{hot}}) - K_{\text{int}}(T_{\text{cold}}) \right)
\]

- Thermal conductivity integrals tabulated in literature
- Varies greatly with temperature and with materials, proper choice of material and thermal intercepts for conduction paths to the cold environment is necessary
Temperature dependent thermal conductivity

From CRYOCOMP Package
Thermal conduction integral, from 2 K

The graph shows the thermal conduction integral for different materials as a function of temperature (T [K]). The materials compared are CU, AL, 6061, 5083, SS, and G10. The y-axis represents thermal conductivity (k [W/m]), while the x-axis represents temperature (T [K]).
Thermal contact at interfaces

- Contact between surfaces is made only at discrete locations, not over the full areas
  - Thermal conductance of pressed contacts depend on the applied force (not pressure!) and surface finish
  - Oxyde layers on the surface increase the thermal resistance
  - Indium foils or high thermal conductance grease (Apiezon-N) may be used to enhance the thermal contact
- Important issue when making provision for thermal intercepts to prevent heat leaking into cold environment
  - Indium foils most common
Convection

- Convection is one of the physical mechanism by which we are able to extract heat from our devices and to route it to the cooling fluids flowing in the cryogenic piping
  - Analysis of the convection exchange is necessary to make proper provisions for the cooldown and warmup procedures and for the good work of the thermal intercepts preventing conductive heat leaks

- But also, we need to prevent convective exchanges from the ambient temperature environment to the cold region
  - That’s why all the cold devices are ultimately placed in a vacuum vessel, where a pressure of $10^{-4}$-$10^{-3}$ mbar prevents convective exchange to the low temperature regions
  - i.e. remove the fluid to prevent convective exchanges...
Convection heat transfer

• Heat transfer between a bulk fluid at temperature $T_b$ and a surface of area $S$ at temperature $T_w$ is described by

$$\dot{Q} = S \ h \ (T_w - T_b)$$

• Determination of $h$ can be challenging, and is usually done from experimental correlations, via the dimensionless groups

$$Nu = \frac{hD}{k_{th}} \quad \text{(convection and conduction exchanges)}$$

$$Re = \frac{\rho \ \nu \ \frac{D}{\mu}} \quad \text{(inertial and viscous forces)} \quad \text{Laminar (}<2000\text{) or turbulent (}>10^4\text{) flow}$$

$$Pr = \frac{C_p \ \mu}{k_{th}} \quad \text{(momentum/thermal transport)} \quad \text{Fluid related}$$
Correlations

- Generally
  \[ Nu = f(Re, Pr) \]

- Except for the case of HeII, frequently the same correlations used for non-cryogenic fluids can be used.

- But correlations are valid for given flow conditions, and the fluid properties need to be evaluated at the proper temperature and pressure conditions.

- Many correlations exist in literature, for various geometrical flow configurations and regimes:
  - Natural convection
  - Liquid and Gas monophase flows

- **Recipe**: Evaluate regime via \( Re \), then \( Pr \) through fluid properties, and compute \( Nu \) from correlation:
  \[ Nu = 0.023 \ Re^{0.8} \ Pr^{0.4} \]

- Calculate \( h \) from \( Nu \).
Radiation heat exchange

- Total radiated flux emitted by a body of emissivity $\varepsilon$ at $T_h$ and received at negligible temperatures

\[ \dot{q} = \varepsilon \sigma_{SB} T_h^4 \]

amounts to 500 W/m$^2$ at 300 K and 2 W/m$^2$ at 77 K for $\varepsilon=1$

- Flux collected by a surface with emissivity $\varepsilon$ and temperature $T_c$ from a black body at $T_h$ is

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

- Emissivity depends on the temperature and surface finish

  - Examples
    - surface as fabricated
      - from RT to 77 K, SS $\varepsilon=0.34$, Al $\varepsilon=0.12$
      - from 77 k to 4 K, SS $\varepsilon=0.12$, Al $\varepsilon=0.07$
    - polished surfaces
      - from RT to 77 K, SS $\varepsilon=0.10-0.12$, Al $\varepsilon=0.08-0.10$
      - from 77 k to 4 K, SS $\varepsilon=0.07$, Al $\varepsilon=0.04-0.06$

See G. Vandoni in CAS 2004-08 for more data
Management of radiative load

• The first measure is to intercept the thermal flux impinging on the cold surfaces from the room temperature environment with one (or more) thermal screen at actively cooled at higher temperatures
  – E.g. 40 to 80 K Cu or Al shield in all designs for magnets and SRF cavities

• A second effective way to protect the surfaces from radiation load is to wrap them with many “floating” (i.e. radiation cooled) reflective screens
  – Multi Layer Insulation (MLI)
    • Reflective aluminum foils (or aluminized/double aluminized polyester films) separated by an insulating spacer material (a glass-fiber or polyester net or paper foil)
    • Packing density of the layers affects performances, but even more important are the installation procedures
      – don’t leave holes and don’t short circuit layers!
Practical MLI

• With proper care MLI can reduce radiative loads to
  – 0.5-1.0 W/m² from Room Temperature to 80 K level
  – 0.05-0.1 W/m² from 80 K to negligible temperatures

• Any small hole in the shielding that is needed to accommodate for pumping lines, current leads, RF feeds, cabling should be avoided with care in order not to expose a direct line of sight from the room temperature surfaces to the cold region
  – Remember that RT blackbody radiation is as high as 500 W/m²!

• When joining MLI blankets it is necessary to avoid thermal short circuits, putting in contact inner layers with the outer ones, impairing the “floating” screen concept
Don’t do this!

Cold Surface

Do this!

Cold Surface
Material contraction at low temperatures

- Materials have huge differences in the thermal contraction coefficients, and high stresses can be induced if relative movements are constrained.

- Nb half SS!
- Nb = Ti
- Invar ~ 0
- Al large!
Warmup and Cooldown

• Need to be foreseen in the design

• Cooling down
  – A single fill line from the top of the device (or from one end) will not easily work due to the possibility of interruption of the incoming liquid flow by the generated vapors
    • Either vent the vapor or have separate bottom fill lines

• Warming up
  – Helium flow will stratify with a thermal gradient. Bottom regions will be slow to warm up
    • Provide means of heating lower parts of the cold mass, e.g. electrical heaters or warmup lines bringing warm vapors
Pressure drop

• In a pipe of diameter $D$ and length $L$ where a fluid with density $\rho$ and velocity $v$ flows at a mass flow rate $m'$ in the turbolent regime

$$\Delta P = \frac{8}{\pi^2} \frac{m'^2}{\rho D^5 L f}$$

no elevation change, no fluid density variations

• where $f$ is the fluid friction coefficient (depending on geometry, flow and roughness)

• This pressure drop (increase!) is particularly important for the exhaust circuit removing the 2 K vapors from the cavities, since the mass flow can lead to pressure increase at the cavities
  – In a saturated bath $T=T(P)$, therefore an insufficient diameter would lead to inability to maintain operating temperature!
The cavity cryomodules

- All the cryogenic engineering considerations briefly discussed in the previous slides need to be addressed when designing one important item in a Superconducting RF linac: the cryomodule
- The cryomodule is the modular building block of the accelerator, it needs to provide
  - the mechanical support of the cavities (and possibly focussing elements)
    - need to address cavity alignment tolerances as well
  - the cold environment needed for operation
    - and adequate protection against spurious heat leaks to the cold region not to affect efficiency
- The cryomodule is an important part of the cryogenic plant, since it is the region where the important heat loads are located
“Cartoon” view of the system

To He production and distribution 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)
Engineering practices for cryomodule design

• Thermal design
  – Minimization of spurious heat loads at the coldest temperatures
  – Heat removal at various temperature levels (for the device operation and for the thermal intercepts)
  – Add provisions for cooldown and warmup, where the large enthalpy content of the cold mass need to be carried away

• Mechanical design
  – Support the devices with minimal heat losses
  – Support gravity, vacuum and pressure loads
  – Deal with stresses due to thermal gradients during transient conditions and operation
  – Implement alignment of the sensitive components, and their preservation under differential thermal contractions

• “Hydraulics” design
  – Integrate cooling circuits in the cryogenic system
Case Study, TTF (XFEL & variants) modules

• The TTF cryomodules represent the state of the art of low losses cryomodules for 2 K SRF cavities
  – Design conceived for the TESLA linear collider
  – Used for XFEL linac 1.3/3.9 GHz modules, with minimal modifications
  – Baseline for ILC modules
  – Concept followed in other current or proposed projects (e.g. Cornell ERL)

• The module design is illustrated here to “summarize” the interplay of design issues at various system levels for the linac/cryosystem and cryomodule
Initial requirements

• High **filling factor**
  – maximize ratio between real estate gradient and cavity perfs
  – 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
  – low static losses, for operation costs (TESLA > 30 km)

• Effective **cold mass alignment strategy**
  – room temperature alignment preserved at 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
• The 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 or cryogenic feed into the module requires space and introduces additional losses

• Thus, **long cryomodules, with many cavities** (and magnets) are preferred, cryogenically connected, to form **cryo-strings**, in order to minimize the # of cryogenic feeds
  
  – Limit to each cryomodule unit is set by fabrication 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
(12) Modules are connected in “Strings”

12 m modules / 8 cavities

- 12 modules (~150 m)
- Shield cooling
- 70 K return
- 70 K forward
- 5 K return
- 5 K forward
- Fill Line
- Vapor recovery

- Thermal anchor couplers
- Coupler & Adsorber heat intercepts
- Co 9-cell cavities
- TT Temperature sensor
- Current lead heat intercepts
- Q SC quadrupole
- LT SC level sensor
- Screens or shieds
- Heater

12 modules (~150 m)
Consequences/II

• The cryogenic distribution for the cryo-string is integrated into the cryomodule, again to minimize static losses
  – Several cryogenic circuits along the cold mass to provide the coolant for the cavities and for the heat interception at higher T

• To take out the RF power dissipated along the long cryo-string formed by many cryomodules 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 hangs from the vacuum vessel by means of low thermal conduction composite suspension posts
Cross Section: 2 shields at 5 K and 70 K

- Alignment holder
- Support post
- Helium Gas Return Pipe
- Structural Backbone
- 5/70 K shield cooling
- Thermal shields
- Coupler port
- Cavity helium tank
- Sliding supports
- Suspension Bracket
- Vacuum Vessel
- Pressurized 2 K helium feeding
- 5/70 K gas forward
- Invar Rod
- Two phase flow
the TESLA module provides

- **cryogenic environment** for the cold mass operation
  - cavities/magnets in their vessels filled with sub atmospheric He at 2 K
  - contains He coolant distribution lines at required temperatures
  - collect large flow of return gas from the module string without pressure increase
  - Low losses penetrations for RF, cryogenics and instrumentation

- **shield “parasitical” heat transfer**
  - double thermal shield

- **structural support** of the cold mass
  - different thermal contractions of materials
  - precise alignment capabilities and reproducibility with thermal cycling

12 m, 38” diameter, string of 8 cavities and magnet
Strings are connected in Cryo-units

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

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

- All string piping connection are welded (no joints!)
String and Cryogenic unit length limitations

• Strings of 12 modules are also the vacuum segmentations
  – 2 phase line feeding 12*8 cavities runs over the full string
  – String length limit is pressure drop and He level change in the 2 phase line

• Strings are then connected into one cryogenic unit
  – Limit or one cryo-unit is plant size: 25 kW equivalent 4.5 K capacity
    • LHC+20%
    • Heat exchanger sizes
    • Over-the-road sizes
    • Experience
  – Also limited by cold compressors, pressure drops, etc.

• ILC uses 5 units per 250 GeV linac
• XFEL overall is 1 unit of 10 strings (1.7 km)
each module contains all cryo piping
- each cavity tank in module connected to two phase line
- vapor is collected from 2 phase line once per module in the GRP

several modules are connected in strings
- single two phase line along the string
- a JT valve once per string fills two phase line via subcooled 2.2 K line

strings are connected into units
- each unit is fed by a single cryogenic plant
### ILC Cryogenic unit spreadsheet

From: T. Peterson, ILC Cryogenic system design spreadsheet, FNAL

<table>
<thead>
<tr>
<th>Temperature level</th>
<th>40 K to 80 K</th>
<th>5 K to 8 K</th>
<th>2 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>(module)</td>
<td>(K)</td>
<td>(module)</td>
<td>(module)</td>
</tr>
<tr>
<td>Temp in</td>
<td>40.00</td>
<td>5.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Press in</td>
<td>16.0</td>
<td>5.0</td>
<td>1.2</td>
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<tr>
<td>Enthalpy in</td>
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<td>14.7</td>
<td>4.383</td>
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<tr>
<td>Entropy in</td>
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<td>1.862</td>
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<tr>
<td>Press out</td>
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</tr>
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<td>Enthalpy out</td>
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<td>19.2</td>
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<thead>
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<th></th>
<th>40 K to 80 K</th>
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<tbody>
<tr>
<td>Predicted module static heat load</td>
<td>(W/module)</td>
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<td></td>
</tr>
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<td></td>
</tr>
<tr>
<td>Number of modules per cryo unit (8-cavity modules)</td>
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<tr>
<td>Non-module heat load per cryo unit</td>
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<tr>
<td>Total predicted heat per cryogenic unit</td>
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<tr>
<td>Heat uncertainty factor on static heat (Fus)</td>
<td>(kW)</td>
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<td>1.10</td>
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<td>(kW)</td>
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</tr>
<tr>
<td>Efficiency (fraction Carnot)</td>
<td></td>
<td>0.28</td>
<td>0.24</td>
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<tr>
<td>Efficiency in Watts/Watt</td>
<td>(W/W)</td>
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<td>197.94</td>
</tr>
<tr>
<td>Overcapacity factor (Fo)</td>
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<td>1.40</td>
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<tr>
<td>Overall net cryogenic capacity multiplier</td>
<td></td>
<td>1.54</td>
<td>1.54</td>
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<tr>
<td>Heat load per cryogenic unit including Fus, Fud, and Fo</td>
<td>(kW)</td>
<td>46.92</td>
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<tr>
<td>Installed power</td>
<td>(kW)</td>
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<td>934.91</td>
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<tr>
<td>Installed 4.5 K equiv</td>
<td>(kW)</td>
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<tr>
<td>Percent of total power at each level</td>
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<td>21.8%</td>
</tr>
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</table>
TTF module summary

• Cooling of the cold mass by evaporation of He II
  – 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 (no radiation load at 2 K)
  – 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”

• Include provisions for warmup/cooldown
  – A small diameter warm-up/cool-down line connects the bottoms of the He vessels (primarily for warm-up)
Several cryogenic lines at different temperatures

Suspension supports of the cold mass

Insulation vacuum enclosure

Beam Line

Cavity

RF Coupler

Thermal shielding and heat interception
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) have a sliding connection with the HeGRP
  - 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
Thermal contraction depends from the material: SS=0.31% Nb&Ti=0.15%

- The HeGRP is the backbone
- HeGRP provides Cavity alignment
- Invar Rod for independent z
  - Independent cavity z position
  - Semi-rigid couplers allowed
  - Less demanding on coupler bellows

Shown, XFEL 3.9 GHz module
Longitudinal behavior: Decoupling contractions

Position of cavity follows invar rod...

INFN module for ILC S1 Global @ KEK
Evident comparing with GRP

Longitudinal cavity position decoupled from GRP, follows invar

INFN module for ILC S1 Global @ KEK
Composite Support Posts

- Designed to sustain the active items to the HeGRP
- Support posts are qualified for a 5000N tension force on all flanges with a limited thermal conductivity
- SS and Al flanges are connected to the Fiberglass (G10) body by thermal shrink fit
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
  – “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 ~ 500 W/m² for ε=1!

<table>
<thead>
<tr>
<th>Effective Heat Flux (CERN Data)</th>
<th>W/m²</th>
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<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

Thermal contact cannot rely on surface contact

Welding the shield

30 MLI layers on shield
Thermal gradients

Conduction path only through welded fingers
(worst case of no thermal contact between mating surfaces and strong choking of thermal flux)
Structural analysis, stresses

Finger weld scheme to relieve shield structure from stresses (by design)

INFN module for ILC S1 Global @ KEK
String inside the Clean Room
String in the assembly area
Cavity interconnection detail
String hanged to HeGRP
Module assembly picture gallery - 5

String on the cantilevers
Close internal shield MLI
Module assembly picture gallery - 7

External shield in place
Module assembly picture gallery - 8

Welding “fingers”
Sliding the Vacuum Vessel
Complete module moved for storage
• ANSYS FEA against measured CMTB data at DESY

70 K shield

5 K shield
Different design: SNS Cryomodule
Design Rationales

- Fast module exchange and independent cryogenics (bayonet connections)
  - 1 day
  - 2K production in CM
- Warm quad doublet
  - Moderate filling factor
- Designed for shipment
  - 800 km from TJNAF to ORNL
- No need to achieve small static losses
  - Single thermal shield
Design for shipment (TJNAF to ORNL)

Spaceframe concept
Helium to cool the SRF linac is provided by the central helium liquefier.
He then piped to the 4.5K cold box and sent through cryogenic transfer lines to the cryomodules.
Joule Thomson valves on the cryomodules produce 2.1 K (0.041 bar) LHe for cavity cooling, and 4.5 K He for fundamental power coupler cooling.
Boil-off goes to four cold-compressors recompressing the stream to 1.05 bar and 30 K for counter-flow cooling in the 4.5K cold box.
SNS He Flow

He Supply 4.5 K

He Return

Coupler and flange thermalization with 4.5 K flow

50 K Shield

2 K

He Flow

He Supply 4.5 K

He Return

Coupler and flange thermalization with 4.5 K flow

50 K Shield
SNS $\beta=0.61$ Cryomodule Assembly -1

Cavity string in Clean Room
SNS $\beta=0.61$ Cryomodule Assembly -2

Internal magnetic shield and MLI
SNS $\beta=0.61$ Cryomodule Assembly -3

Thermal shield and spaceframe
SNS $\beta=0.61$ Cryomodule Assembly -4

String in spaceframe
SNS $\beta=0.61$ Cryomodule Assembly -5

Vacuum vessel
SNS $\beta=0.61$ Cryomodule Assembly -6

Spaceframe with external magnetic shield
Sliding the Vacuum Vessel
Alignment strategy

- Cavity string is supported by the spaceframe
- Each target sighted along a line between set monuments (2 ends and sides)
- The nitronic rods are adjusted until all the targets are within 0.5 mm of the line set by the monuments
- Cavity string in the vacuum vessel: the alignment is verified and transferred (fiducialized) to the shell of the vacuum vessel.

- Indexing off of the beamline flanges at either end of each cavity
- Nitronic support rods used to move the cavity into alignment
- Targets on rods on two sides of each flange.
Project-X baseline cryogenics

- 2-phase He at 4.5 K
- Strings are fed in parallel
  - first string SC solenoids, warm RF
  - second string SSR/TSR modules
- Cryomodules are fed in series
- Revised TESLA cryo string concept
- 2 phase He line at 2 K
  - concurrent liquid supply and vapor return flow in the string
- Double thermal shielding in strings to limit radiation flow at 2 K
## Project X ICD

<table>
<thead>
<tr>
<th>Item</th>
<th>Qty [#]</th>
<th>2K Static</th>
<th>2K Dynamic</th>
<th>4.5K Static</th>
<th>4.5K Dynamic</th>
<th>5K Static</th>
<th>5K Dynamic</th>
<th>40K or 80K Static</th>
<th>40K or 80K Dynamic</th>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>1000</td>
<td>-</td>
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</tbody>
</table>

- **Estimated, [W]**
  - 222
  - 193
  - 338
  - 160
  - 502
  - 211
  - 9787
  - 5566

- **Design Capacity, [kW]**
  - 0.8
  - 1.0
  - 1.4
  - 29.9

- **4.5K Eqv [kW]**
  - 8.2

- **Plug Power, [MW]**
  - 2.3
Project-X cryo r&d plan

- **cryo distribution and segmentation**
  - study existing cryomodules thermal cycling experience
  - stationary, transient, fault, maintenance and commissioning scenarios
  - component over pressure protection study
  - define **cryogenic string size** limits and segments
  - liquid **helium level** control strategy development
  - development of tunnel ODH mitigation strategy

- **capital and operational cost optimization**
  - lifecycle cost optimization & Cryogenic Plant Cycle
  - heat shields operating parameter optimization

- **heat load analysis**
  - static and dynamic loads analysis for components/sub systems
  - define overcapacity and uncertainty factors
  - fault scenarios heat flux study
HINS - SSR1 conceptual cryomodule layout

- String on strongback, dressed, aligned, shielded
- Vessel replicates assembly table supports
strongback concept

Support lugs

Support post pockets
spoke/solenoid mounting scheme

Analysis of the strongback deflections under dead loads with support optimization

30/5/2011

P. Pierini
Vacuum vessel with internal strongback supports
Conclusive remarks

- The design of the “noble” device (the RF cavity) is not the end of the game
  - A lot of physics considerations and detailed engineering goes in its supporting systems that have to provide the operating conditions

- Considerations on the overall linac design choices (especially for large machines) have strong implications on the design on the cryomodule

- Plans for providing adequate mechanism for cooling to nominal levels, heat removal during operation, control of alignment, countermeasures for thermal stresses and spurious heat leaks should be developed early
References & Acknowledgements

- Hasan Padamsee
  - RF Superconductivity for Accelerators
    - Wiley-VCH 2° Ed., 978-3527408429
  - RF Superconductivity Volume II
    - Wiley-VCH, 978-3527405725

- J. G. Weisend II
  - Handbook of Cryogenic Engineering
    - Taylor and Francis, 978-1560323327

- R. F. Barron
  - Cryogenic Heat Transfer
    - Taylor & Francis, 978-1560325512

- Tom Peterson, providing an almost endless repository of smart material to feed my curiosity and my slides
  - http://tdserver1.fnal.gov/peterson/tom

- B. Petersen, DESY
• Backup slides with reference data
Role of material properties

- **Differential contraction** can be big!
  - Can lead to unacceptable stresses if not taken into account
  - Choose proper combination of materials/bellows
    - e.g. Nb/Ti vs Nb/SS

<table>
<thead>
<tr>
<th>Material</th>
<th>$(L_{300} - L_2)/L_{300}$</th>
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<tbody>
<tr>
<td>Nb</td>
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<tr>
<td>Ti</td>
<td>0.159%</td>
</tr>
<tr>
<td>Stainless Steel (304)</td>
<td>0.310%</td>
</tr>
<tr>
<td>Al 6061</td>
<td>0.419%</td>
</tr>
<tr>
<td>Invar</td>
<td>0.038%</td>
</tr>
<tr>
<td>G10 composite</td>
<td>0.274%</td>
</tr>
</tbody>
</table>
Thermal radiation from hot surfaces to cold mass

<table>
<thead>
<tr>
<th>Temperature (radiating surface)</th>
<th>Specific heat flux [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 K</td>
<td>460 W/m²</td>
</tr>
<tr>
<td>70 K</td>
<td>1.4 W/m²</td>
</tr>
<tr>
<td>4.5 K</td>
<td>$22 \times 10^{-6}$ W/m²</td>
</tr>
</tbody>
</table>

With MLI Insulation

<table>
<thead>
<tr>
<th>Temperature (radiating surface)</th>
<th>Specific heat flux [W/m²] at low T</th>
</tr>
</thead>
<tbody>
<tr>
<td>From 300 K, 30 layers</td>
<td>1.2 W/m²</td>
</tr>
<tr>
<td>From 80 K, 10 layers</td>
<td>0.06 W/m²</td>
</tr>
</tbody>
</table>
Thermal conduction integrals

\[ \dot{Q} = \frac{S}{L} \int_{T_c}^{T_h} k_{th}(T) \, dT \]

<table>
<thead>
<tr>
<th>Thermal conduction integral: 2 to 4.5 K [W/m]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>G10 composite</td>
<td>0.134</td>
</tr>
<tr>
<td>Steel</td>
<td>0.453</td>
</tr>
<tr>
<td>Aluminum (6061)</td>
<td>19.3</td>
</tr>
<tr>
<td>Copper</td>
<td>471</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermal conduction integral: 4.5 K to 70 K [W/m]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>G10 composite</td>
<td>16.8</td>
</tr>
<tr>
<td>Steel</td>
<td>270</td>
</tr>
<tr>
<td>Aluminum (6061)</td>
<td>5000</td>
</tr>
<tr>
<td>Copper</td>
<td>55000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermal conduction integral: 70 K to 300 K [W/m]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>G10 composite</td>
<td>150</td>
</tr>
<tr>
<td>Steel</td>
<td>2800</td>
</tr>
<tr>
<td>Aluminum (6061)</td>
<td>31300</td>
</tr>
<tr>
<td>Copper</td>
<td>93700</td>
</tr>
</tbody>
</table>