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Cold Facts

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Zero Resistance Zone

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Superconducting Superfluids Meet Machinery

The superconductor (SC) and liquid helium (superfluid He II & He I) are two vital materials in cryogenic engineering, playing crucial roles in various applications. They both exhibit miraculous zero resistance and other fascinating quantum behaviors at the large macroscopic level. **Superconducting electrons show fermionic performance due to their half-integer spin**, governed by the Pauli exclusion principle. In a SC below its critical temperature (T_c), electrons form Cooper pairs, which move without scattering or dissipating energy as heat and electrical resistance is completely absent. **He II consists of bosons with integer spin values**. Superfluidity in He II occurs when it is cooled to ~ 2 K, and a significant fraction of **helium atoms undergo a phase transition to Bose-Einstein condensate (BEC) state**. Due to excellent thermal conductivity and cooling capability, liquid He is the only practical cryogen for large SC machines (exclusion of HTS), while LN_2 is often used for precooling and thermal shields.^[1-4] The Large Hadron Collider (LHC), NbTi magnets cooled by subcooled-superfluid He II at 1.8 K (Figure 1), and the ITER Tokamak Nb_3Sn magnets cooled by supercritical He I at ~ 3.7 K to 4.5 K (Figure 2),

are two exceptional scientific projects respectively demonstrating these technical achievements. Consequently, a range of helium liquefaction/refrigeration systems with varying capacities and multiple temperatures have been developed for various superconducting applications.

Advancements of LHe and SC Machinery

The applications of superconductors not only depend on LHe cooling, but also significantly contribute to the advancement of LHe technologies. Thanks to the unique and irreplaceable advantages of both SC magnets made of NbTi and Nb_3Sn , as well as superconducting radio-frequency (SRF) cavities, more large-scale SC machinery has been successfully developed and operated.^[1, 3-4] For example, the LHC operates at 1.8 K, requiring a 20-kW cooling power and holding a 130-ton inventory of LHe across its 27 km SC accelerator.^[5]

Furthermore, SC applications that involve high magnetic fields (H) and high accelerating fields (E_{acc}) have consistently required lower operating T . As illustrated in Figure 3, the widely adopted NbTi cable

demonstrates the capability to operate from 7 Tesla at 4.5 K to 10 Tesla at 1.8 K, maintaining the same current density (J_c).^[5] The dynamic cryogenic loss of SRF cavities primarily arises from the BCS RF surface resistance R_{BCS} . This resistance exhibits both as a function of RF frequency and an exponential dependence on the ratio of the operating temperature to the critical temperature, as shown in Figure 4.^[6]

Best SC Operational Points vs. He Liquefier Cost Realities

Researchers and engineers have constantly explored the optimized LHe operation points for best cooling of SC machines. Figure 5 delicately illustrates the He phase diagram (T-P): LHe is divided by the green λ -line into normal He I and superfluid He II. The λ transition is 2.17 K at one atm. Between LHe and He vapor is the blue saturation line, where liquid and vapor coexist with the critical point at 5.2 K & 2.25 atm. LHe above the saturation line is referred to as subcooled He, also called as pressurized LHe or supercritical He. While SC magnets and SRF cavities excel in lowering operating T , it's crucial to note that refrigeration efficiency increases from approximately 280



Figure 1. LHC SC magnets cooled by subcooled, superfluid He II at ~ 2 K in the accelerator tunnel. Credit: CERN

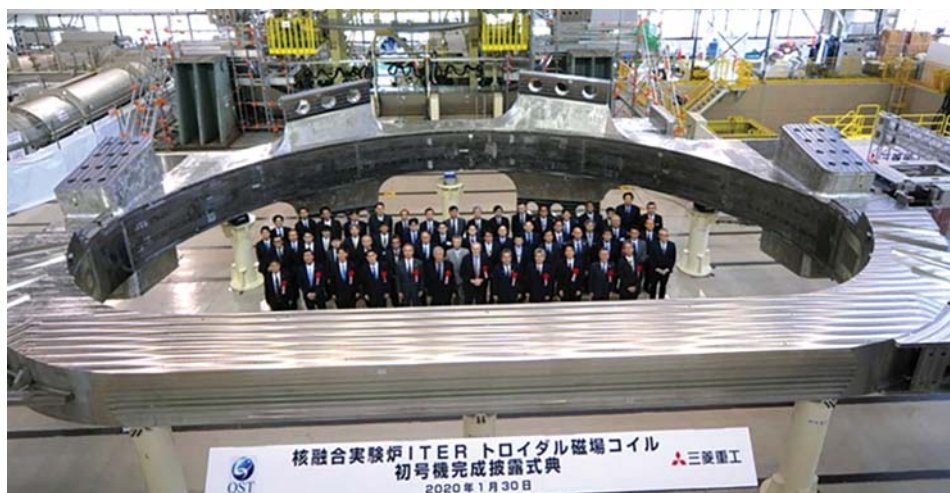


Figure 2. A 360-ton SC magnet with the D-shaped toroidal field coil cooled by supercritical He I at ~ 3.7 to 4.5 K (constructed by Japan for the ITER Tokamak). Credit: ITER

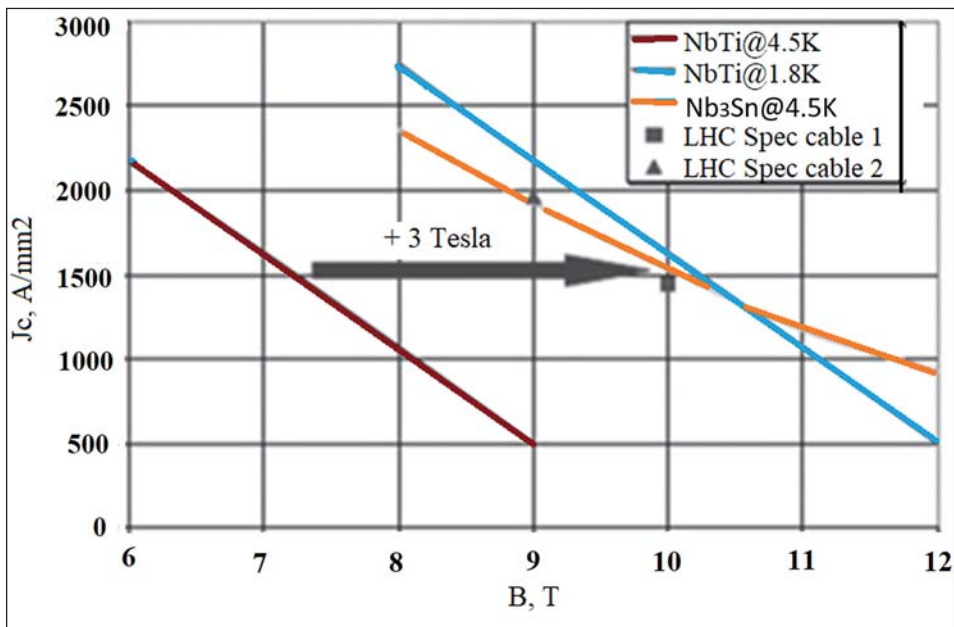


Figure 3. LHC cable specs and Critical B vs Jc of NbTi & Nb3Sn at 4.5 and 1.8 K.^[5] Credit: Ph. Lebrun

W/W at 4.5 K to about 900–1,100 W/W at 1.8 K.

Accordingly, designing helium liquefier/refrigeration systems involves balancing technical benefits and cost considerations by selecting optimal temperature (T) and pressure (P) points for liquid and gaseous helium. Efficient use of all helium's cooling capacity during circulation to cool thermal shields, anchors etc. is crucial, with designs evaluated on a case-by-case basis.^[1-4] Key thermodynamic parameters of He I and He II at critical operating conditions are outlined in Table 1, commonly used for initial estimations when designing cryogenic systems for SC machinery.

Cooling SC Devices: Saturated LHe vs Supercritical He I

Saturated 4.2 K LHe at 1 atm finds diverse applications in cryostats, particularly with SC magnets in fields like physics, materials science, and MRI. Its temperature can be finely tuned between 4.2 K and 2 K (Figure 5, points A to C) using a pumping system to regulate vapor pressure. Also, saturated 4.2 K He I can effectively cool SRF accelerating cavities in cryomodules, ensuring both effective removal of RF heat and stable temperatures to maintain cavity frequency, as seen in projects like **LEP**, **KEKB**, **CESR**, and **MRI** (Figure 5, point A).^[1] In saturated LHe cooling, the cooling power is directly proportional to the mass of LHe vaporized,

Status	T K	P Pa	Lv J/kg	ρ kg/m ³	Cp J/kg·K	S J/kg·K	H J/kg	K W/m·K
Saturated, L	4.2	99230	2.1×10^4	125.4	5170	3551	9901	0.0186
Saturated, G	4.2	99230	-	16.49	9033	8504	3074	0.0089
Saturated, L	2	3129	2.3×10^4	145.7	5187	957.8	1642	-
Saturated, G	2	3129	-	0.794	5975	1258	2504	0.0038
Supercritical	4.5	2 bars	-	124	5434	3755	1159	0.0195
Supercritical	5	2 bars	-	102.4	1658	4608	1568	0.0193
Subcooled	2	99230	-	147.5	5249	965.7	2319	-

L – liquid, G – gas, Lv – latent heat, 1 atm ~ 99230 Pa ~ about 1 bar

Table 1. Key parameters of He I & He II at important operational T & P of SC Machinery. Edited: Q-S Shu & J. Demko

denoted as $Q1 = m \cdot Lv$. Where Q1 – heat transferred (J), m – mass of LHe vaporized (kg), and Lv – latent heat of LHe at corresponding P and T (J/kg) as listed in Table 1.

Forced-flow of subcooled/supercritical He I (Fig. 5, point B) is crucial for cooling SC magnets in large-scale particle accelerators and Tokamak, such as for **Tevatron** (4.5 K, 2.5 bar), **HERA** (4.5 K, 2.5 bar), **RHIC**, **SSC** and **ITER**.^[7-8] It offers superior heat transfer properties and less sensitivity to heat inleak compared to saturated He I. This supercritical phase enables more efficient cooling in penetrating the magnets to remove AC-ramping heating, providing flexibility

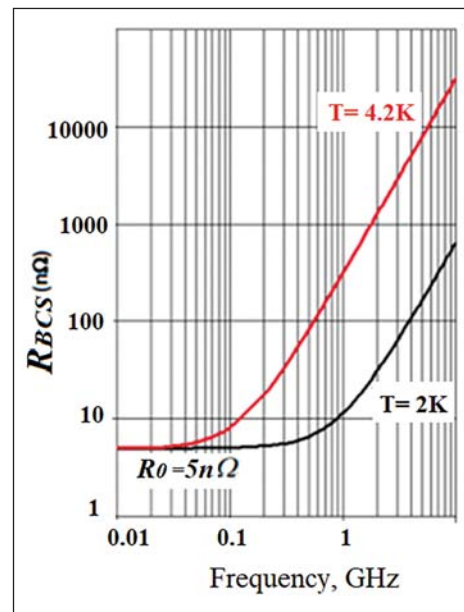


Figure 4. RF surface resistance (BCS) of Nb as function of RF frequency and operation T.^[6] Credit: P. Duthil

in operation and cost-effectiveness. In supercritical LHe cooling, the cooling power is determined by mass and specific heat (Cp) of LHe at corresponding P and T (Table 1). $Q2 = m \cdot Cp \cdot \Delta T$, where Q2 – heat transferred (J), m – mass (kg), Cp – specific heat of LHe (J/kg·K), and ΔT – temperature changes.

At Tevatron of 6.5 km, the largest SC accelerator, supercritical He I is utilized to cool its numerous dipoles (Figure 6), quads, and correction elements. The single phase He (input at 3.5 atm, 4.6 K & output 2.8 atm, 5.5 K) is cooled by the two phase LHe. As another example, eighteen "D"-shaped toroidal field

► continues on page 30

magnets (Nb_3Sn) are placed around the ITER vacuum vessel and cooled by force-flow supercritical He I. The maximum magnetic field is 11.8 tesla, capable of storing 41 giga-joules of energy.

Nb sheet is the optimal material for SRF cavity due to its high T_c (9.2 K), high RF critical magnetic field $H_c(\text{RF}) = 200$ mT at 2 K, low surface resistance (R_s), and excellent thermal/mechanical properties. For frequencies at or above 325 MHz, using saturated He II at 2 K ($P \sim 0.031$ atm) balances low temperature with cryogenic costs. Below 325 MHz, 4.2 K He I at 1 atm is preferred. Thus, saturated superfluid He II (Figure 5. Point C) is chosen for applications like CEBAF, TTF, SNS, XFEL, and LCLS-II.^[1,4,6] Figure 7 depicts an SRF cavity cooled in a saturated He II container within a cryo-module for TESLA/TTF.^[9]

SRF cavities dissipate significant power due to their large surface area (1-2 m^2), reaching up to 20 W at 2 K. However, they have a relatively low stored energy. Efficient

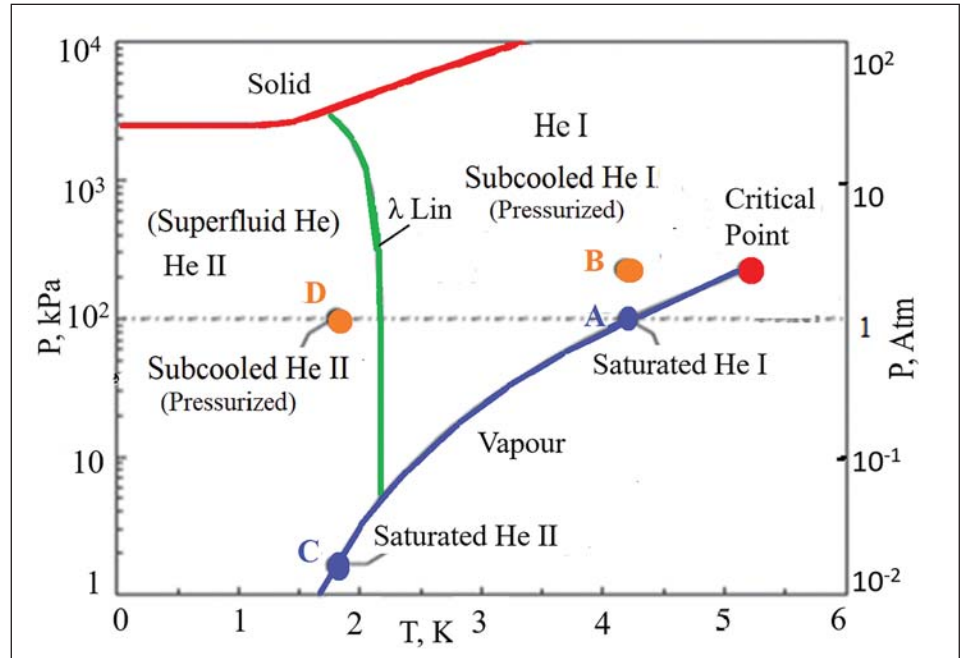


Figure 5. Operation points in He phase diagram (P vs T). Points A, B, C & D represent typical operational parameters of large superconducting machines worldwide. Edited: Q-S. Shu & J. Demko

heat transfer is vital, especially for managing local hot spots. In a pumped LHe II pool, pressure changes are minimal (~ 1 mbar),

favoring cavity frequency stability. The small hydrostatic pressure head enables operation in a slightly pressurized state, absorbing heat

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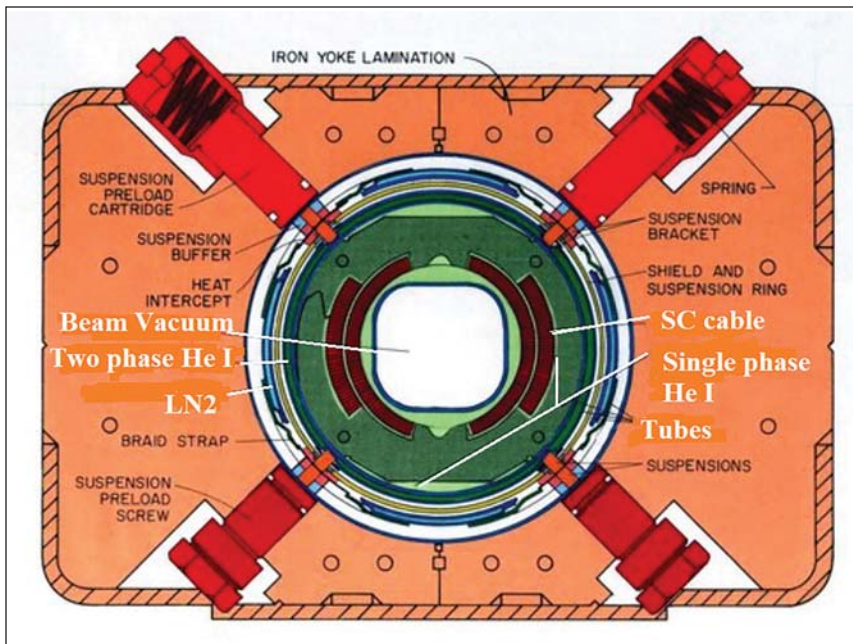


Figure 6. Tevatron SC magnets cooled by forced flow of supercritical LHe I. Credit: Fermilab

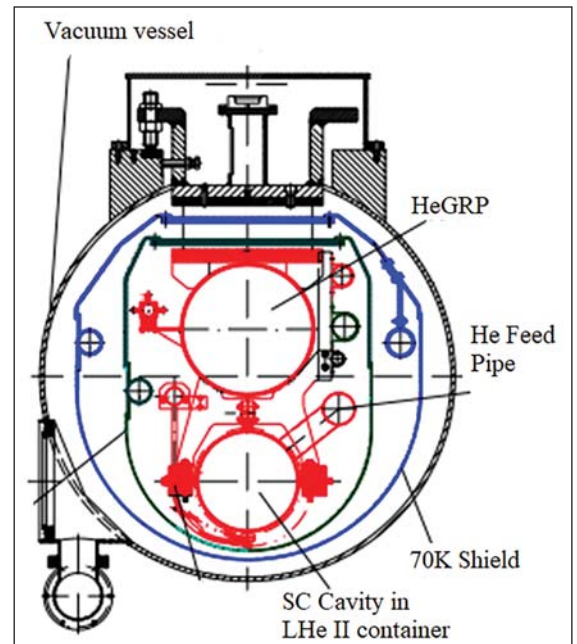


Figure 7. TESLA/TF SRF cavity pool-cooled by saturated LHe II in cryomodule.^[9] Credit: C. Pagani

from the Nb surface without phase change until crossing the saturated line.

Subcooled Superfluid He II for SC-Magnets-Based Machine

Accelerator SC magnets are often cooled with subcooled He II (Fig. 5, point D), particularly working near the B-Jc limit of the SC cable with large, stored energy. Forced-flows cooling of subcooled/pressurized He II require an additional level of heat transfer from a subcooled He II to saturated He II, but they offer several significant technical advantages, as demonstrated with LHC and Tore-Supra.^[10]

The distinctive aspect of subcooled He II in SC magnet operations are briefly summarized as follows: Improving stability and heat transfer of subcooled helium flows (He II or He I) come from providing maximum penetration of helium mass in magnet coils. Subcooled He II can absorb heat deposition in its bulk, up to the temperature at which the lambda line is crossed. Local boiling starts only then, due to the low thermal conductivity of He I. Avoiding low-pressure operation in extensive cryogenic systems mitigates the risk of air inleaks. Although heat flow results in a temperature rise in subcooled He II, SC magnets are not as sensitive to it as SRF cavities. Figure 6 depicts an LHC SC magnet.^[5] In the case of supercritical LHe II cooling, the cooling power directly for

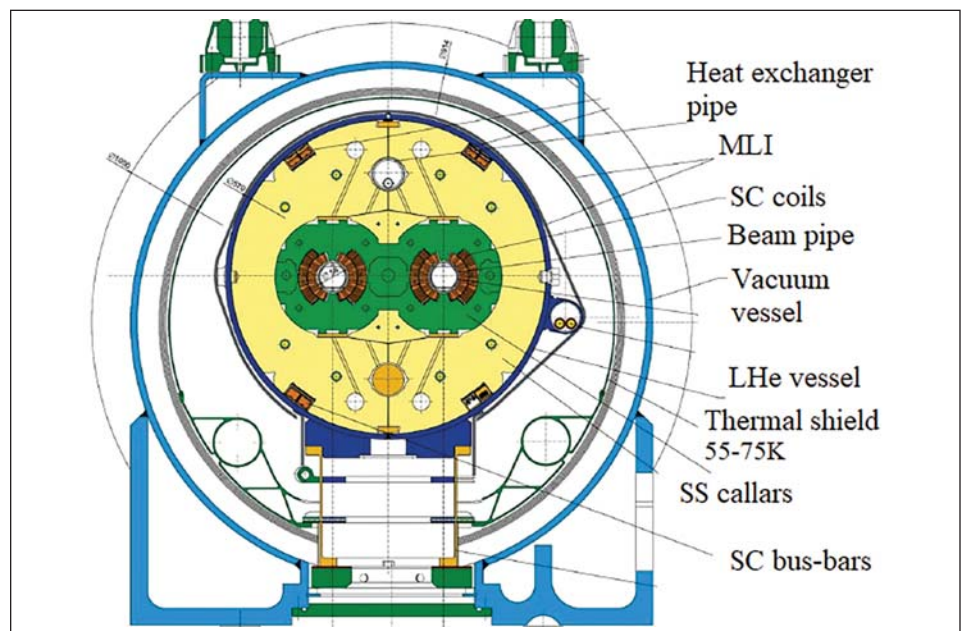


Figure 8. LHC SC magnet cooled by force flow of subcooled He II. Credit: Ph. Lebrun

superconducting components: $Q = m \cdot C_p \cdot \Delta T$, and C_p data are presented in Table 1.

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