



Zero Resistance Zone

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Cryo-Engineering for SRF

Fifty-Five Years of Inextricable Success

Superconducting Radio Frequency (SRF) cavities are vitally central to SRF accelerators, boasting a Q factor about 10^5 times higher than copper cavities and the capability to produce accelerating fields (Eacc) on an order of magnitude greater than copper in CW. In the 1960s, SRF cavities were delicate instruments used by pioneering scientists in several prestigious labs. Over the past 55 years, the synergy between cryogenics and SRF accelerators has consistently proven mutually beneficial and successful. Today, the landscape has evolved significantly, with potential markets for industrial electron beams reaching \$10 billion annually. Various SRF cavities mainly made from Nb (Figure 1)^[1-2] are widely used in high energy physics, nuclear science, FEL, XFEL, synchrotron lights, computer chips, and medical and industrial applications.

Theoretical Performance

Unlike DC applications, where a superconductor (SC) has zero electric resistance, SC in RF fields have a specific surface resistance (R_s) and allow magnetic fields to penetrate their surface to a depth (δ). In the SRF cavity, Eacc runs along the central axis. Near the cavity wall magnetic fields H are parallel to the cavity surfaces, with the highest H_{max} around the cavity's equator. Electric fields are vertical to the surfaces, with the maximum E_{max} near the iris. Simplified formulas below can be used to derive several theoretical cavity performances.

Ideal (theoretical) Q_0 .

The power dissipated P_d is given by the integral of resistive wall loss over cavity surface. Q_0 is the ratio of energy restored in the cavity (ωU) to the energy loss P_d . G-cavity geometry factor and determined by its shape only, μ_0 - permeability of free-space and ω - frequency.

$$U = (\mu_0 / 2) \int H^2 dV$$

$$P_d = (R_s / 2) \int H^2 dS$$

$$Q_0 = \omega U / P_d = G / R_s$$

$$R_{BCS} = D f^2 (e^{-17.87/T}) / T$$

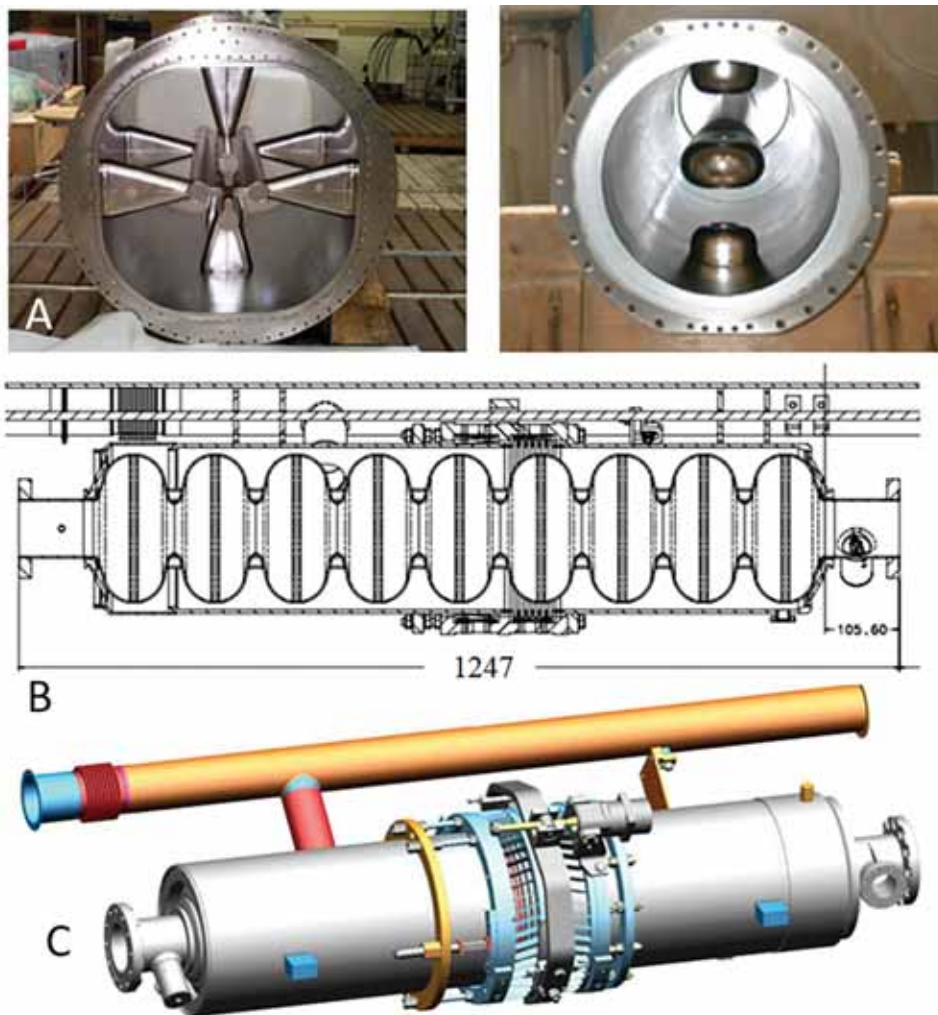


Figure 1. A- Low β Nb cavities,^[1] B- TESLA style cavity, and C- Cavity in LHe vessel.^[2] Credit: A. Lombardi et al. and C. Pagani

The $R_s = R_{BCS} + R_{res}$. R_{BCS} is the ideal minimum resistance by BCS theory. R_{res} depends on materials' purity, external H , etc. For example, a 9-cell TESLA cavity (Nb) has $G=270$ at 1.8 K and 1.3 GHz: $R_{BCS}=4.55n\Omega$, $R_{res}=R_{H_1}(\text{earth } H) = 3.42n\Omega$, $R_s=7.97n\Omega$, so the ideal $Q_0 = 3.4 \times 10^{10}$. However, for a copper cavity at 300 K and 1.3GHz, $Q_0(\text{Cu})=3 \times 10^4$.

Ideal (theoretical) Eacc.

Currently, the Type II superconductor Nb is the most popular cavity material and has a magnetic quench field H_{c2} about 2400-Oe at 1.8 K. Therefore, for this cavity, the ideal maximum Eacc is about 56MV/m, corresponding to the H_{c2} .

Journey to Ideal Performance

Q_0 vs. E curves are the primary measure of SRF cavity performance. Ideally, the cavity's Q_0 should remain constant as the accelerating field E rises, up to the magnetic quench field, as shown by the "ideal" green line in Figure 2. However, in practice, the Q vs. E curve falls below the ideal due to various factors. Thanks to advancements in cavity fabrication, including shape design, high RRR Nb, e-beam welding, BCP, and RF processing, issues related to multipacting and thermal breakdown in cavities have been successfully addressed. Consequently, Cavity Eacc ranged to 7-12 MV/m with $Q \sim 10^{10}$.

in the 1980s. This progress laid the foundation for SRF accelerator projects like KEK, HERA, LEP, and CEBAF.

However, as Eacc exceeds 10-15 MV/m, field emission (FE) becomes the primary limiting factor.^[3-4] FE significantly reduces the cavity Q_0 due to the exponential increase in electron currents from FE origins. Extensive studies at Cornell, Wuppertal, KEK, Jlab, and DESY aim to understand and mitigate FE to reach higher Eacc. Various cavity treatment techniques, including thermometer mapping, He-RF processing, high-T treatment with Ti protection, and HPP, have been employed. These efforts culminated in achieving the Eacc of about 30 MV/m at Cornell in 1989-90,^[3,4] generally meeting the TESLA requirement, as depicted in Figure 2. These achievements have helped make significant progress at TESLA, Jlab, FLASH, SNS, and LEP-II.^[5]

The emergence of the Q-disease presents new, serious challenges for SRF cavities after FE reduction. Fresh efforts involving the development of large/single crystals of Nb, EP, HPR, and mild-temperature treatments (up to 120 °C) have yielded impressive results. In 2017-18, researchers at FNAL achieved a milestone with an Eacc of 48 MV/m and a Q above 10^{10} .^[6] Since 2010, more XFELs and additional upgrades to SRF accelerators have been developed.

SRF Cryomodules

The SRF cryomodules demonstrate seamless collaboration between cryogenic techniques and SRF cavities, playing a vital role in ensuring the success of SRF accelerators. The SRF cavity is cooled within a LHe-II container, thermally isolated from room temperature using MLI blankets and the low thermal conductance support system within the cryomodule vacuum. The cryomodule also serves as the hub for high RF power to the cavities, cryogen distribution, and technical data collection.

The TESLA Collaboration, led by DESY, initially aimed to develop a 20 km e-e- linear collider but faced financial constraints that halted the project. However, core technologies from TESLA have since advanced worldwide.^[7] Figure 3 illustrates a partial section of the TESLA/ILC cryomodule,^[2] which spans about 12 meters and houses eight SRF cavities. Thermal shields are used to reduce radiation heat, featuring 30-40 MLI layers at around 65 K and 10 MLI layers at approximately 2 K. The low thermal conductivity posts are anchored

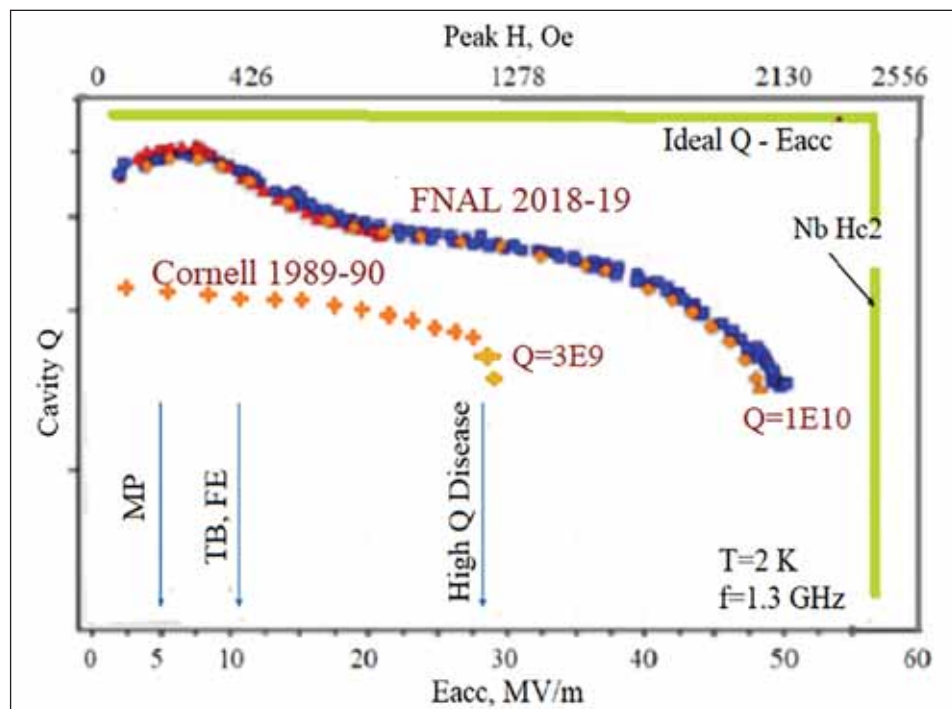


Figure 2. Simplified Q-Eacc plots used to showcase a few historical performances of the best cavities. Precise scaling in references: Cornell^[3] and FNAL.^[6] Credit: Q. S. Shu et al. and A. Grassellino et al.

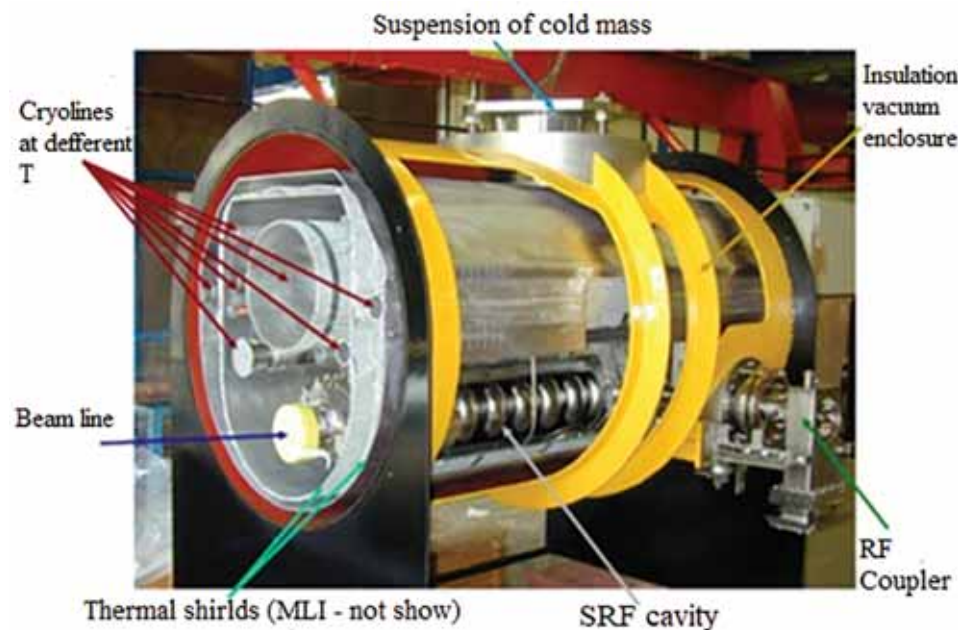


Figure 3. A mock-up of TTF3 style XFEL cryomodule.^[2] Credit: C. Pagani.

at 50-65 K and 6 K. Each cavity has a sophisticated RF coupler for transferring high RF power to the cavity and a HOM coupler to extract unwanted RF fields. A large, cold He return pipe (HGRP, 300 mm) is necessary to minimize pressure drop and can also serve as the primary structural support for the module cold mass. Typically, a cryogenic unit consists of about 10 cryomodule strings, contingent on the specific cryogenic cooling system of the accelerator design.

Cooling of SRF Cryomodules

To build an SRF accelerator, it is crucial to further improve SRF cavity cooling, which involves two key aspects: 1. Enhancing the quality factor (Q_0) and improving heat transfer on the cavity surfaces to reduce Kapitza resistances. 2. Designing and developing a highly efficient cryogenic liquefier/refrigeration system capable of supplying sufficient LHe and cold He gas to cool the cavities and associated components in all cryomodules within the

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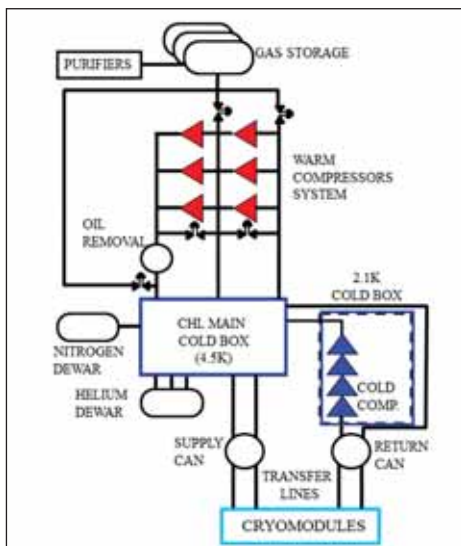


Figure 4. Diagram of the CHL at ORNL.^[9] Top of form.
Credit: M. Howell et al.

accelerator. The measured static and dynamic heat loads of an XFEL cryomodule at 16.5 GeV operation are summarized as follows^[8]: Static- 2K 6.1 W, 5/8 K 8 W, and 40/80 K 102 W. Dynamic- 2 K 7.2 W, 5/8 K 2 W and 40/80 K 32 W. These values are comparable with XFEL design.

The Spallation Neutron Source (SNS) at ORNL serves as another exemplary SRF accelerator, providing a 1 GeV, 2 MW beam for experiments. Its linac comprises over 80 SRF cavities (805 MHz) housed in a total of 23 cryomodules operating at 2.1 K. Figure 4 illustrates the central He liquefier as a highly automated and reliable system.^[9] The CHL employs a group of cold compressors to force cold He vapors into the heat exchangers of the cold box.

SRF Accelerator and Cryogenic System

SRF linear accelerators have diverse applications as “user” machines, such as proton linac (e.g., SNS and ESS), heavy ion linacs (like FRIB, ATLAS, ISAC-II), linac/ER-linac-based FELs (like FLASH, XFEL, Jlab-FEL/ERL), and future projects like Shanghai HRR-XFEL and the possible International Linear Collider (ILC). Due to space limitations, we will briefly discuss only two SRF accelerators. The European XFEL spans 3.4 km, reaches electron beams of about 18 GeV, and delivers X-rays from 0.25 keV up to 25 keV. It comprises 96 cryomodules (approximately 800 cavities with an average of over 25 MV/m and $Q \sim 10^{10}$), operating at 1.3 GHz with a 10 Hz repetition rate. These cryomodules run at 2 K, cooled by a cryogenic system with a 4-stage set of cold compressors (CC) that compress the cold helium vapor from 2400 Pa to about 110 kPa at a



Figure 5. SRF accelerator in tunnel of European XFEL.^[10] Credit: Reschke et al.

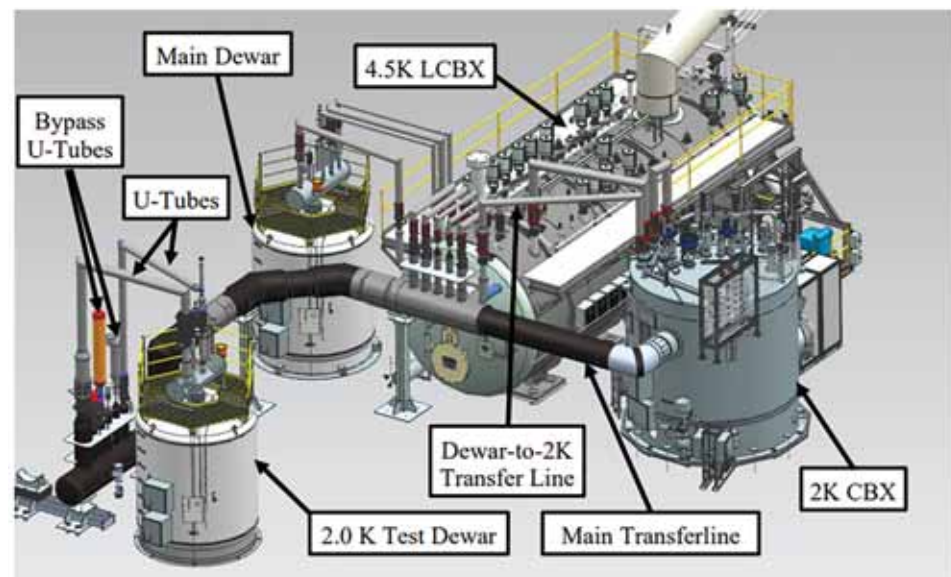


Figure 6. LCLS-II CHL system model.^[11] Credit: R. Bhattacharya et al.

mass flow of up to 100 g/s. Figure 5 shows the XFEL in a tunnel with SRF cryomodules suspended from the ceiling and RF infrastructure on the floor.^[10]

The Linear Coherent Light Source (LCLS-II) developed at the SLAC National Laboratory has 37 LINAC cryomodules operated at 2 K to accelerate a 4 GeV electron beam, generating hundreds of watts of intense X-ray laser light. The cryoplant includes two helium refrigerators, each with an equivalent 4.5 K cold box, 18 kW, and 2 K cold box 4 kW. Two five-stage cold compressors are used to compress the cold He vapors as shown in Figure 6.^[11]

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