SCRF upgrades

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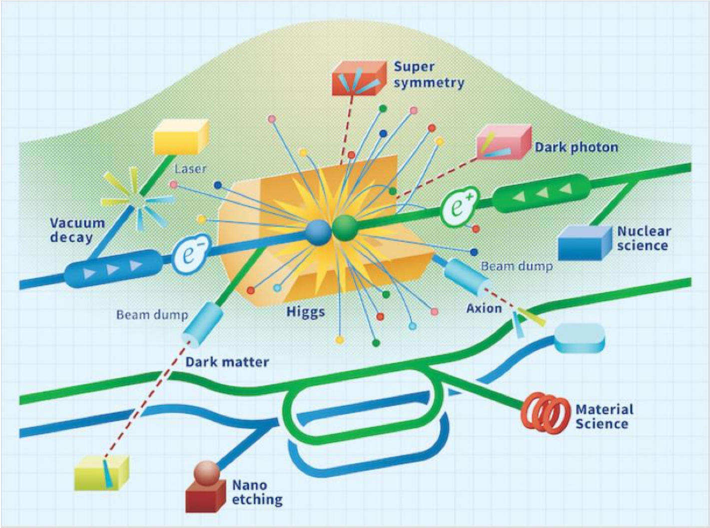

Outline

In this presentation we consider Superconducting RF (SCRF, or SRF) R&D needed for potential energy upgrades of a superconducting linear collider that might be implemented on 5-year, 10-year, and longer timescales. Accordingly, the presentation outline is

- Introduction
- Strategic trends in SRF
- What can be done with bulk Nb within a 5-year horizon?
- Traveling wave SRF: Prime-time ready on a 10-year timescale
- R&D on advanced SRF superconductors (Nb_3Sn, thin films, mutilayers)
- Summary

Introduction

The **performance limit of SRF cavities by the two key parameters**: the RF critical (superheating) magnetic field B_{sh}, which determines the rate of acceleration, and the surface resistance R_s, which determines the SRF efficiency.[1]

Recent advancements in surface tailoring techniques[2] for cavities made with bulk Nb have led to groundbreaking results, as laboratories have successfully introduced nitrogen, oxygen, and other impurities into the niobium lattice. These innovative procedures have yielded increasing efficiency of cavities by a factor of 2 to 3 at medium accelerating fields (20-30 MV/m) and pushing the practically achievable gradients toward 50 MV/m. The new surface treatments most relevant for a superconducting LC are nitrogen infusion, a combination of cold electropolishing and two-step baking (75/120◦C), and a medium temperature (mid-T) baking.

Here are the most recent achievements:

- The superheating field of approximately **210 mT at 2 K** was reached experimentally on single cell cavities, resulting in an accelerating field of about **50 MV/m** for TESLA-shape cavities. To date, the experiments show that only **low-temperature surface treatments** are beneficial for increasing of RF critical field. Mid-T bake and nitrogen doping tend to lower the achievable quench field of SRF cavities.
- The best results achieved to date at **30 MV/m** (via mid-T bake) are limited by ~ 5 nOhm R_{BCS}[3] at 2 K that results in a quality factor Q_0 of $\mathbf{5 \times 10^{10}}$ at an operating frequency of 1.3 GHz. At 40 MV/m, either two-step baking or a mid-T/low-T procedure allows for 2×10^{10}. At 50 MV/m the quality factor is still limited to $\sim 10^{10}$ at 2 K.

1) These parameters translate into the SRF accelerating gradient and intrinsic cavity quality factor as $E_{acc} = B_{sh}/k_M$ and $Q_0 = G/R_s$, where the constants k_M [$= 4.26$ mT/(MV/m) for ILC cavity] and G [the geometry factor, ≈ 270 Ohm for ILC cavity] are determined only by the cavity shape and are independent on its dimensions. The power dissipation in cavity walls is $P \propto E_{acc}^2/(R/Q \cdot Q_0)$, where R/Q is the geometric shunt impedance, also determined by the cavity shape only.
2) As the SRF penetration depth is very small (the London penetration depth for pure Nb is about 40 nm), the surface layer of only ~100 nm determines the performance of SRF cavities.
3) The surface resistance R_s consists of two parts: R_{BCS} predicted by BCS theory and the residual resistance R_{res}.

Strategic trends in SRF

The European Strategy for Particle Physics - Accelerator R&D Roadmap and Snowmass'2021 emphasized strategic trends in SRF development.

In particular, the former stated:

In SRF the development is focused in two areas, bulk niobium and thin-film (including high-T_c) superconductors. In bulk SRF new treatments are allowing niobium cavities to exceed previous record Q factors and avoiding degradation with increasing gradients. This includes nitrogen infusion and doping, and two-step baking processes. There is also an emphasis on limiting field emission. For thin-films the community is investigating creating coated cavities that perform as good as or better than bulk niobium (but with reduced cost and better thermal stability), as well as developing cavities coated with materials that can operate at higher temperatures or sustain higher fields. One method of achieving this is to use multi-layer coatings. Innovative cooling schemes for coated cavities are also being developed. Coupled to the cavity development is improvement in the cost and complexity of power couplers for SRF cavities.

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RF Accelerator Technology R&D

Report of AF7-rf Topical Group to Snowmass 2021

AF7-rf Conveners:
Sergey Belomestnykh[1,2], Emilio A. Nanni[3,4], and Hans Weise[5]

Accelerator Frontier

Frontier Conveners: S. Gourlay[1], T. Raubenheimer[2], V. Shiltsev[3]

Topical Group Conveners: G. Arduini[4], R. Assmann[5], C. Barbier[6], M. Bai[2], S. Belomestnykh[3], S. Bermudez[4], A. Faus-Golfe[7], J. Galambos[6], C. Geddes[1], G. Hoffstaetter[8], M. Hogan[2], Z. Huang[2], M. Lamont[4], D. Li[1], S. Lund[9], R. Milner[10], P. Musumeci[11], E. Nanni[2], M. Palmer[12], N. Pastrone[13], F. Pellemoine[3], E. Prebys[14], Q. Qin[15], G. Sabbi[1], Y.-E. Sun[16], J. Tang[17], A. Valishev[3], H. Weise[5], F. Zimmermann[4], A.V. Zlobin[3], R. Zwaska[3]

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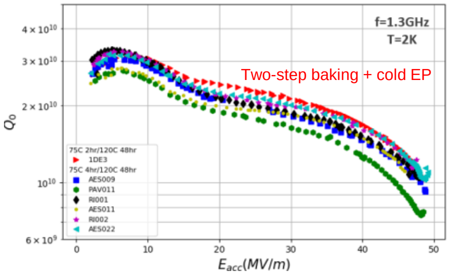
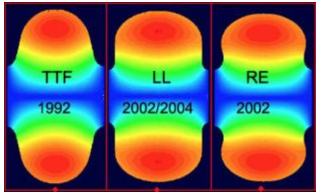
What can be done with bulk Nb within a 5-year horizon?

On a short timescale of about 5 years, the **focus** shall be on **improving the reliability and repeatability** of the selected technologies and **demonstration of their industrialization**.

- The most relevant for ILC recently developed surface treatment is a combination of cold electropolishing and two-step baking ($75/120$°C). It paved the way for gradients near 50 MV/m in single-cell TESLA-shape cavities. Combining this advanced treatment with developed earlier improved shape standing wave SRF cavities holds the prospect of gradients close to 60 MV/m in single-cell cavities and 50-55 MV/m in 9-cell cavities in a cryomodule.
- Applying these advances in accelerating gradients to ILC upgrades must be accompanied by 1) R&D on improving Q_0 at high gradients to avoid increase of the collider power consumption, and 2) developing methods to mitigate field emission during cryomodule assembly (e.g., robot-assisted automation) and after installation, e.g., plasma processing.
- Equally important is the continuation in development of "companion" technologies, such as high-efficiency high-power RF sources, modern LLRF with AI/ML tools (including precise cavity resonance control at high gradients), robust RF power distribution network.

If **50 MV/m** can be **reliably achieved in cryomodules**, the ILC can be upgraded to collisions at **380 GeV** center of mass energy within the ~ 20 km facility site. With an improvement of the cavity quality factor to 2×10^{10}, the overall site power will be **about 135 MW**, as compared to 111 MW for ILC250. New high-efficiency klystrons would reduce the overall site power.





Examples of optimized cavity geometries

Fastening coupler flange after insertion with a robotic arm

Traveling wave SRF: Prime-time ready on a 10-year timescale

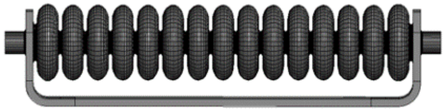
Further improvements in accelerating gradients of bulk Nb structures are possible but require developing an alternative approach, utilizing a traveling wave (TW) in a resonant ring configuration. The SRF TW structure has several advantages compared to the standing wave structures. The most salient advantages are :

- Substantially lower k_M promises achieving higher E_{acc} at the same magnetic quench limit.
- Approximately a factor of 2 higher R/Q (even at lower G) would ensure lower cryogenic losses.
- In addition, the TW structure provides high stability of the field distribution along the structure with respect to geometrical perturbations. This allows for much longer accelerating structures than ILC cavities, limited by the manufacturing technology only.

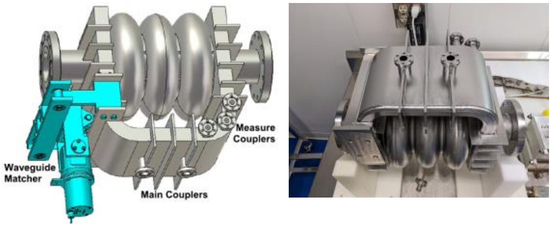
Assuming the accelerating gradient of **65 MV/m** and the quality factor of 1.4×10^{10} (for the surface resistance corresponding to $Q_0 = 2 \times 10^{10}$ of ILC cavity), the superconducting collider built with TW cavities could reach **500 GeV** center of mass collision energy within the **20 km** footprint. The total site power is estimated at **168 MW**.

P.S. *Presently the progress towards proof-of-principle experimental demonstration on a 3-cell structure and developing a longer structure is slow due to intermittent funding. Proper investment in this technology could bring it to "prime time" readiness – demonstrated performance in a full-scale cryomodule – on a 10-year time scale. After that, a TW-based linear collider should be feasible.*

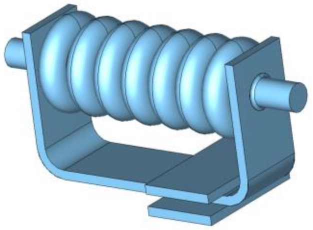
ILC (TESLA) 9-cell standing wave cavity



Traveling wave 15-cell SRF cavity



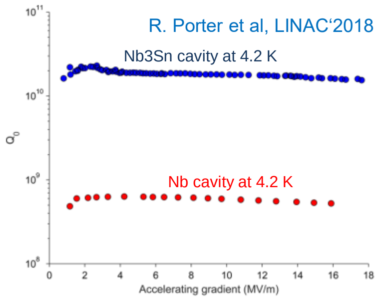
Proof-of-principle 3-cell cavity

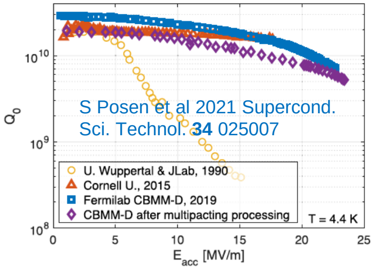


3D model of a 7-cell TW cavity

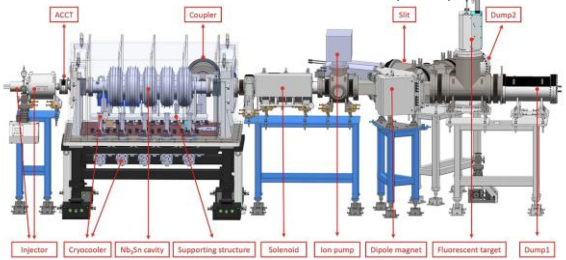
R&D on advanced SRF superconductors: Nb_3Sn

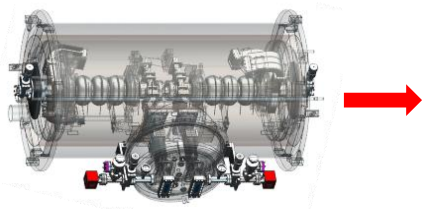
- The most developed alternative SRF superconductor is Nb_3Sn. SRF Nb_3Sn cavities have a potential to be a game changer, bringing **higher gradients at higher cryogenic efficiency**: Nb_3Sn has higher T_c of 18.3 K, compared to the 9.2 K of Nb, and higher DC superheating field (B_{sh}), approximately twice that of Nb.
- 1.3 GHz Nb cavities must operate at 2 K to have $Q_0 > 1 \times 10^{10}$. 2 K cryogenic systems are inefficient, $\mathrm{COP} \approx 800$ W/W. Nb_3Sn can have similar Q_0 but at 4.2 K where the cryogenic efficiency ~3 times better.
- Nb_3Sn cavities might reach 90-100 MV/m with good system efficiency at the same time. However, despite continuous efforts, the accelerating gradients achieved to date remain ≤ 24 MV/m.
- First applications are in compact accelerators, including conduction-cooled. If the technology will mature even at this gradient level, it could be useful for an ERL-based LC.
- The most progress to date has been made with the vapor diffusion process. Other processes of making Nb_3Sn are under investigation: electroplating, CVD deposition, magnetron sputtering... As these techniques mature, we should expect further progress. If there is a breakthrough, one could potentially apply Nb_3Sn to traveling wave structures, making even higher accelerating gradients reachable.



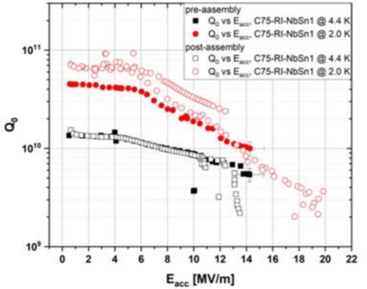


Demonstration of beam acceleration at IMP (China)



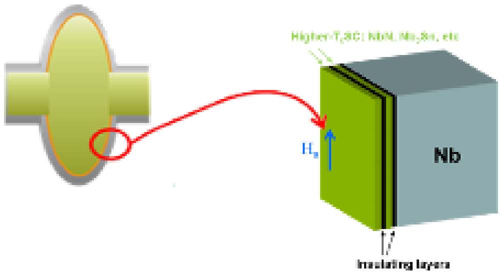


Two 5-cell Nb_3Sn cavities in a cryomodule at JLAB



R&D on advanced SRF superconductors: multilayers

- A concept to overcome limitations of Nb is to create a multilayer structure called S-I-S.
- It is achieved by coating the cavity surface with alternating insulating and superconducting thin films (hence SIS) with thickness d thinner than the London penetration depth λ.
- Theory suggests increase of max. E_{acc} because magnetic shielding improvement, caused by counter currents at each interface, and the Meissner state can be maintained at a magnetic field much higher than the bulk critical magnetic field. However, surface defects, grain boundaries, etc. can allow for flux penetration at field levels below B_{sh}.
- RF field is dominant in the top superconducting layer with higher energy gap Δ compared to Nb. This will reduce losses because $R_{BCS} \propto \exp(-\Delta/k_B T_c) \rightarrow$ higher Q_0.
- **Technological readiness level is still low** – successful sample studies need to be transferred to cavities.
- Teams in Asia, Europe and America are working on several materials (NbTiN, NbN, Nb_3Sn), using various deposition techniques (sputtering, ALD, CVD, PVD) and applying different post-deposition processing steps.
- A sustained investment into the basic R&D studies, infrastructure, analytical instruments is needed before we can expect first practical multilayer SRF cavities.
- **Goal is to achieve ~ 70 MV/m with a Q_0 of 10^{10}** (optional: at 4K) **on single cell cavities within next ~10 years.**



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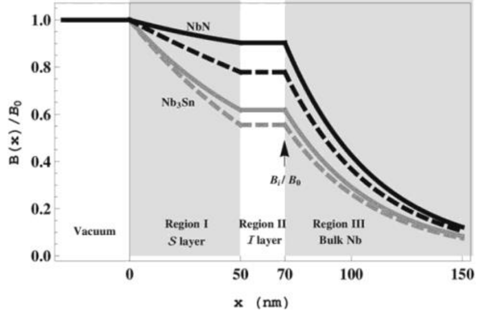

Summary

- SRF technology has made significant progress over the last decades finding applications in many modern particle accelerators (colliders, light sources, FELs, proton and ion linacs). Machines like E-XFEL and LCLS-II are recent demonstrations of using the technology on a scale relevant to linear colliders.
- The baseline ILC utilizes the SRF technology developed in late 1990s-early 2000s. Meanwhile R&D efforts on improving performance of SRF cavities continues producing new results and opening new exciting possibilities.
- With additional investments, further developments in the standing wave bulk niobium SRF technology could be impactful for the ILC upgrades on a 5-year time scale, making an energy of 380 GeV center of mass feasible for a 20-km facility size.
- On a longer time scale, about 10 years, traveling wave SRF structures could be developed to bring the gradient to > 60 MV/m. A superconducting linear collider based on the TW technology could potentially reach 500 GeV center of mass energy within the 20-km collider footprint.
- Finally, if there is a breakthrough, thin films and superconductors beyond niobium could potentially bring higher accelerating gradients, higher quality factors at 4 K, or both. This would open a horizon to more efficient (e.g., ERL-based) and higher energy linear collider options. While potential of these technologies is high, it is too early to speculate about what upgrades would be possible, as the research is still in its initial stage.
- It is important to note that any increase of accelerating gradient must be accompanied by measures to mitigate field emission in SRF cavities and development cost- and power-saving companion technologies.