Challenges and opportunities of SRF theory for particle accelerators.

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Recent advances in the superconducting Nb cavity technology have produced resonant cavities with unprecedented quality factors up to 10^{11} and accelerating field gradients over 50 MV/m at 1-2 GHz and 1.5-2 K. These accelerating gradients are limited by the RF breakdown magnetic fields which for the best Nb cavities, approach the dc superheating field at the equatorial cavity surface. New technologies of infusing niobium with nitrogen, titanium and other impurities developed at FNAL, JLab, Cornell and other institutions have produced cavities which exhibit a significant extended increase of the quality factor with the RF field [1-6]. It is important to understand the physics and materials science behind these phenomena and attest how far the SRF performance of Nb cavities can be further improved by the materials treatments, impurity management and surface nanostructuring. Development of the next generation high-performance accelerator cavities also includes the use of new SRF materials like Nb_3Sn and others. Coating the inner surface of Nb cavities by thin films or multilayers of superconductors with higher critical temperatures and magnetic fields can produce composite accelerator cavities which can outperform the best Nb cavities and achieve lower RF losses and higher accelerating gradients exceeding 100 MV/m.

Currently it is unclear how far the parameters of the state-of-the-art Nb accelerating cavities are from the theoretical performance limits because these limits are largely unknown. The fundamental limits of surface resistance and the maximum accelerating gradient set by the dynamic superheating field in a nonequilibrium superconducting state at GHz frequencies have not yet been addressed by the established microscopic theory of superconductivity. Common estimates of these limits by extrapolations of different models far outside their applicability limits may significantly underestimate the actual SRF performance limits. These issues are ultimately related to the long-standing fundamental problems of microscopic theory of nonequilibrium superconductivity. The key outstanding issues of SRF theory are outlined below.

1. Theory of the dynamic superheating field and its dependences on temperature and RF frequency.
2. How far can the dynamic superheating field be increased by surface nanostructuring and tuning concentration of impurities?
3. Theory of nonlinear surface resistance in a nonequilibrium Meissner state driven by strong RF magnetic fields. The goal is to obtain dependencies of the nonlinear surface resistance on temperature, RF field amplitude and frequency.
4. Nonlinear dynamics and RF losses of trapped magnetic vortices driven by extremely strong surface rf currents.
5. Transparency of grain boundaries to strong rf currents in SRF cavities. The detrimental effect of current-blocking grain boundaries on the cavity performance can be particularly pronounced in such promising SRF materials as Nb_3Sn or high-temperature pnictide superconductors.

Several groups have started theoretical work on these issues [7-14], yet many crucial issues, particularly the effect of kinetics of nonequilibrium quasiparticles on the field-dependent surface resistance, and the extreme nonlinear dynamics of superfast vortices driven by strong surface Meissner currents in SRF cavities remain unresolved. Beside advancing the fundamental physics of nonequilibrium superconductivity and nonlinear electromagnetic response of a superconductor under a strong RF field, the theory can identify the essential materials parameters which can be tuned to increase the quality factor and the maximum accelerating gradient. This work can also suggest new ways of boosting the SRF cavity performance by surface nanostructuring and impurity management in the ongoing development of high-performance accelerator cavities.

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