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Introduction

Discovered in 1911, superconductivity is a fascinating phenomena of modern physics with marvelous scientific and technological applications, such as powerful magnets for medical imaging (magnetic resonance imaging [MRI]), for high energy physics, in particular, the large hadron collider (LHC), for nuclear fusion, and a wide range of modern applications.

The first major milestone in the history of superconductivity was the discovery by Kamerlingh Onnes [1, 2] that the electrical resistance of various metals, such as mercury, lead, and tin disappears when the temperature is lowered below some critical temperature value, T_c. Zero electrical resistance allows persistent currents in superconducting rings. These currents flow without any measurable decrease up to one year, allowing a lower bound of 10^5 years on their decay time. Compared to good conductors, such as copper, which have a residual resistivity at low temperature of the order of 10^{-6} Ω-cm, the resistivity of a superconductor is lower than 10^{-23} Ω-cm.

Subsequently, Meissner and Ochsenfeld [3] discovered perfect diamagnetism in superconductors. Magnetic fields are excluded from superconductors. Any field originally present in the metal is expelled from the metal when lowering the temperature below its critical value. Expulsion of magnetic field from walls of superconducting cavities via the Meissner effect will be an important topic in Chapter 4.

Starting with pioneering efforts in the 1960's, RF superconductivity (SRF) finally catapulted to an enabling technology since the 1980's. SRF has since equipped frontier accelerators in high energy physics, nuclear astrophysics, nuclear physics, as well as light sources and neutron sources for materials and life sciences. New applications are coming on line to intense proton sources for neutrino beams, and transmutation of nuclear waste, as well as for deflecting cavities for beam tilts for higher luminosity at LHC.

The primary advantages of the SRF technology have been discussed in the two previous books [4, 5]. The most attractive features of applying SRF to particle accelerators lie in the high accelerating gradient, E_{acc}, possible in continuous wave (cw) and long-pulse operating modes, along with extremely low RF losses in the cavity walls at cryogenic temperatures. There is another important advantage. The presence of accelerating structures has a disruptive effect on the beam, limiting the quality of the beam in aspects such as energy spread, beam halo, or the maximum current. SRF systems can be shorter, and thereby impose less disruption to the beam. By virtue of

Superconducting Radiofrequency Technology for Accelerators: State of the Art and Emerging Trends,
First Edition. Hasan Padamsee.

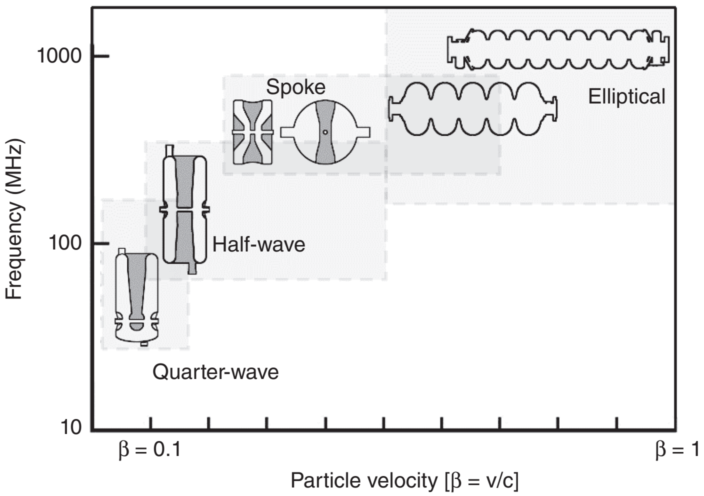

Figure 1.1 Superconducting cavities spanning the full range of particle velocities. Source: [6]/M. Kelly, Argonne National Lab/with permission from World Scientific Publishing.

low wall losses, SRF cavities can be designed with large beam holes (apertures) to further reduce beam disruption and allow higher beam currents desirable.

There are two distinct types of superconducting cavities. The first type, TM-mode cavities, is for accelerating charged particles that move at nearly the speed of light, such as electrons in a high-energy linear accelerator (linac) or a storage ring. The second type, TEM-mode cavities, is for particles that move at a small fraction (e.g. 0.01–0.5) of the speed of light, such as the heavy ions. Structures for these applications are the quarter wave resonator (QWR), the half wave resonator (HWR) and the single spoke resonator (SSR), or one with multiple spokes. At intermediate velocities, both TM and TEM types could be used, depending on the application. Figure 1.1 [6] shows practical geometry sketches, and typical RF frequencies for each cavity type, depending on the velocity of the particles spanning the full velocity range of particles.

The QWR is the compact choice for low-β applications ($\beta < 0.15$) requiring ~50% less structure with less overall RF dissipation compared to the HWR for the same frequency and β. (Here $\beta = v/c$, where v is the speed of the particle under acceleration, and c is the speed of light.) But the asymmetric field pattern in the accelerating gaps produces vertical steering that increases with velocity. The QWR is less mechanically stable than the HWR due to the unsupported end at the bottom in Figure 1.1. Hence the HWR is more suitable in the mid-velocity range ($\beta > 0.15$) or where steering must be eliminated (i.e. for high intensity). It has a symmetric field pattern and provides higher mechanical rigidity. But the HWR is larger, requires a larger cryomodule (CM), and has roughly twice the dissipation for the same β and frequency. The SSR is a more compact variant of the HWR. It opens a path to extension to several accelerating gaps along the beam in a single resonator, using multiple spokes. It provides a higher effective voltage, but with a narrower transit time acceptance.

This book will mostly focus on a review for the near velocity-of-light, or high-β accelerating cavities, and to particle accelerators that use these structures. We only briefly cover some of the latest applications of low-β structures to major facilities. For in-depth coverage of low-β cavities, we refer the reader to excellent articles [6], and tutorials at International SRF conferences [7, 8].

This book will not cover many important topics in SRF, such as input couplers, higher-order-mode couplers, tuners, and cryomodules. For latest developments in these areas, we refer the reader to many papers published in the Proceedings of the International SRF Conferences. The proceedings are available on the JACoW website [9].