Part I
Science

1
Introduction

1.1
RF Superconductivity Benefits

Superconducting rf (SRF) cavities excel in applications requiring continuous wave (cw) or long-pulse accelerating fields above a few million volts per meter (MV/m). We often refer to the accelerating field as the “gradient”. Since the ohmic power loss in the walls of a cavity increases as the square of the accelerating voltage, copper cavities become uneconomical when the demand for high cw voltage grows with particle energy. A similar situation prevails in applications that demand long rf pulse length, or high rf duty factor. Here superconductivity brings immense benefits. The surface resistance of a superconducting cavity is of many orders of magnitude less than that of copper. Hence the intrinsic quality factors (Q_0) of superconducting cavities are usually in the 10^9 to 10^{10} range (Q_0 is often abbreviated as Q). Characterizing the wall losses, the Q_0 is a convenient parameter for the number of oscillations it takes the stored energy in a cavity to dissipate to zero. After accounting for the refrigerator power needed to provide the liquid helium operating temperature, a net gain factor of several hundred remains in the overall operating power for superconducting over copper cavities. This gain provides many other advantages.

Copper cavities are limited to gradients near 1 MV/m in cw and long-pulse operation because the capital cost of the rf power and the ac-power related operating cost become prohibitive. For example, several MW/m of rf power would be required to operate a copper cavity at 5 MV/m. There are also practical limits to dissipating high power in the walls of a copper cavity. The surface temperature becomes excessive causing vacuum degradation, stresses, and metal fatigue due to thermal expansion. On the other hand, copper cavities offer much higher accelerating fields (≈ 100 MV/m) for short pulse (μs) and low duty factor ($<0.1\%$) applications. Still, for such applications it is still necessary to provide abundant peak rf power (e.g., 100 MW/m) and to withstand the aftermath of intense voltage breakdown in order to reach the very high fields.

There is another important advantage that SRF cavities bring to accelerators. 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,

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or even the maximum current. Because of their capability to provide higher voltage, SRF systems can be shorter, and thereby impose less disruption. Due to their high ohmic losses, the geometry of copper cavities must be optimized to provide a high electric field on axis for a given wall dissipation. This requirement tends to push the beam aperture to small values, which disrupts beam quality. By virtue of low wall losses, it is affordable to design an SRF cavity to have a large beam hole, reduce beam disruption and provide high quality beams for physics research.

For low velocity, heavy-ion accelerators, a major advantage of superconducting resonators is that a cw high voltage can be obtained in a short structure. The linac to boost ion energies can be formed as an array of independently phased resonators, making it possible to vary the velocity profile of the machine. The superconducting booster is capable of accelerating a variety of ion species and charge states. An independently phased array forms a system which provides a high degree of operational flexibility and tolerates variations in the performance of individual cavities. Superconducting boosters show excellent transverse and longitudinal phase space properties, and excel in beam transmission and timing characteristics. Because of their intrinsic modularity, there is also the flexibility to increase the output energy by adding higher velocity sections at the output, or to extend the mass range by adding lower velocity resonators at the input.

1.2
Overview of Chapters

This book is divided into three parts.

Part I (Science) will start with a review of fundamental design principles to develop cavity geometries for accelerating velocity-of-light particles ($\beta = v/c = 1$), moving on to corresponding design principles for medium-velocity (medium-β) and low-velocity (low-β) structures. There is an in-depth presentation of several new geometries that have evolved in the last decade, such as the re-entrant and low-loss shapes for high-β cavities, compressed-elliptical cavities for medium-β applications and spoke resonators for intermediate-β, bridging the medium- and low-β regimes. For ultralow velocities, a superconducting radiofrequency quadrupole (RFQ) has been developed to combine acceleration and strong focusing. The last part of Chapter 2 touches upon mechanical aspects of cavity design including Lorentz-force detuning and vibrations. Wherever appropriate, the chapter mentions various electromagnetic field calculation codes available for cavity design.

Chapter 3 delves into recent theories and experiments that address the fundamental aspects of rf surface resistance. Since the main aspects of the Bardeen, Cooper, Schrieffer (BCS) resistance are covered extensively in [1], we concentrate on the low-field and medium-field dependence of surface resistance, referred in the SRF community as medium-field Q-slope and low-field Q-slope. The chapter also updates recent findings about residual resistance. The rest of the chapter addresses developments defining fundamental limits for the maximum expected gradients based on the maximum expected surface magnetic fields. Chapter 4 discusses progress in studying electric field dependent phenomena that determine the maximum gradient and Q_0 of cavities. Multipacting and field emission have been successfully reduced but challenges remain in both arenas. High-pressure water rinsing has played a major role in reducing field emission. There has also been substantial progress in understanding the basic mechanisms involved in rf processing. Chapter 5 discusses progress in studying magnetic field dependent phenomena that determine the maximum gradient and Q_0 of cavities. Techniques such as electropolishing and mild baking (120 °C, 48 h) play a major role in achieving the best cavity performances, raising regularly achievable gradients above 25 MV/m, and the best gradients above 50 MV/m. The phenomena of high-field Q-drop have been extensively studied and various models have emerged, but none with complete success. Surface studies have made major contributions to understanding the origin and reduction of the Q-drop. Several of the prevailing models will be discussed to account for the performance improvements with new preparation techniques.

In **Part II** (Technology), Chapters 6 and 7 cover cavity fabrication and treatment advances. High-performance demands excellent control of niobium material properties, purity, fabrication stages (forming and welding) surface smoothness, and surface cleanliness. Techniques for fabrication and surface treatment have evolved considerably over the last decade to achieve the desired levels of control. Advances are discussed in depth, along with the performance levels achieved. The performance of low- and medium-velocity structures is also covered. New techniques for fabricating seamless cavities, such as monolithic spinning and hydroforming continue to make progress. Previous efforts continue to deposit thin superconducting films onto a copper substrate, and new approaches are underway to improve the quality of films. If successful, the seamless and thin film approaches will allow a cost reduction of future facilities. Although the tantalizing subject of new materials, such as Nb_3Sn, YBCO, and MgB_2, remains of great interest, there has been little progress in cavity results over the last decade. Hence the scope will exclude this topic.

The next three technological chapters (Chapters 8 to 10) deal with input couplers, higher order mode extraction couplers and absorbers, and tuners of both the slow and fast varieties. There have been substantial advances in the average and peak power capability of input couplers. Chapters 8 and 9 discuss electromagnetic, mechanical, and thermal design principles and implementation, culminating in a presentation of several popular coupler designs and variants. Multipacting issues are covered for both types of couplers. Chapter 10 presents the advantages and disadvantages of a remarkable variety of slow mechanical tuner designs. Piezo techniques to control Lorentz force and microphonics detuning are covered.

Part III (Applications) describes SRF systems at major accelerators and briefly discusses the operating experience which demonstrates that SRF is a robust technology. The Argonne Tandem Linear Accelerator System (ATLAS) has been operating for nearly three decades as a national user facility for heavy ion, nuclear and atomic physics research, logging well over 100 000 h of beam-on-target operation. CEBAF at Jefferson Lab (JLab) has been operating for a decade. Jefferson Lab is developing high gradient cavities and cryomodules to upgrade CEBAF's energy to 12 GeV. Doubling the beam energy is an important priority for advancing understanding of the strong force and its manifestation in gluonic matter. The FEL at Jefferson Lab, LEP-II at CERN (now decommissioned for LHC installation), HERA and TTF at DESY, CESR at Cornell, KEK-B factory in Japan, provide a few among many excellent examples of systems and operations.

As a natural outcome of the LEP-II Nb–Cu technology, superconducting cavities and cryomodules are ready to meet the voltage and high current demands of the large hadron collider (LHC) at CERN. The spallation neutron source (SNS) at Oak Ridge National Laboratory has been completed and commissioned. Neutron scattering is an important tool for material science, chemistry, and life science. SNS will provide 1.4 MW of beam power on target to produce a neutron flux comparable to the average flux of the Grenoble reactor, the largest neutron science facility. SNS switched to superconducting technology in 2000 for a shorter linac due to the higher operating gradient possible with superconducting cavities, a large savings in the rf installation, and the potential of reduced activation due to large beam holes of superconducting structures.

Electron storage rings as light sources have an enormous impact on materials and biological science. Superconducting cavity accelerating systems have upgraded light sources, such as CHESS at Cornell, and the Taiwan Light Source. New light sources such as the Canadian Light Source and DIAMOND in UK have adopted SRF. The Swiss Light Source and ELETTRA in Treiste have installed higher frequency (third harmonic) superconducting cavities to improve beam lifetime and stability.

The Jefferson Lab FEL has generated 14 kW of cw laser power in the infrared, and demonstrated energy recovery by recirculating nearly 1 MW of beam power. This is an important milestone toward energy recovery linacs (ERL) for future light sources and electron beam cooling applications. An upgrade to ultraviolet is underway.

High gradient SRF technology developed at the TESLA Test Facility (TTF) at DESY will drive the European XFEL, a linac-based free electron laser to provide Angstrom wavelength x-ray beams of unprecedented brilliance. The brilliance, coherence, and ultrashort pulses will open a wide range of novel experiments not possible with present x-radiation sources. TTF will continue as FLASH to serve users of ultraviolet radiation, as a test bed for the XFEL and continue its vital role as a proving ground for the technology needed for the future International Linear Collider (ILC).

In the low-β arena, ALPI at Legnaro has a new injector PIAVE based on a superconducting RFQ followed by a string of quarter-wave resonators (QWRs). Heavy-ion linacs in New Delhi and Mumbai have come on-line. TRIUMF in

Canada is expanding its radioactive beam facility (ISAC) by adding a superconducting heavy-ion linac supplying more than 40 MV. Among other fundamental questions, radioactive beams will provide basic insight into the origin of the heavy elements. With the SPIRAL2 project, GANIL in France aims to make an intermediate step between existing radio isotope beams (RIB) facilities and future projects like EURISOL.

Chapter 12 moves on to cover new accelerators under construction and planning. Designs for the nuclear astrophysics Rare Isotope Accelerator (RIA) are able to call on advanced preparation techniques that deliver high performance cavities. A future US facility will use superconducting structures suitable for particle velocities ranging from a few percent to about 70% the speed of light. Record radioactive beam intensities will allow the study of a large number of exotic isotopes that will provide quantitative information necessary for theories of stellar evolution and the formation of elements in the cosmos. In Europe, EURISOL and its first stage SPES are similar facilities also under study.

A variety of new applications are under study for linac-based light sources, such as high-power free electron lasers (FEL) and high-brilliance ERL. FEL and ERL studies are flowering around the world. Cornell University, Argonne National Labs, MIT, University of Wisconsin, Lawrence Berkeley Laboratories, BESSY in Berlin, FZ Rossendorf and the Cockroft Institute in Daresbury are all conducting a wide range of activities. High intensity beams of ERL have spurred explorations for electron cooling applications and for electron–ion colliders, for example to upgrade RHIC at Brookhaven.

High-intensity proton linacs will likely fulfill future needs in a variety of arenas: upgrading the injector chains of proton colliders and accelerators, heavy-ion radioactive beams for nuclear physics, medical therapy, industrial applications, high intensity spallation neutron sources, transmutation applications for treatment of radioactive nuclear waste, nuclear energy production using thorium fuel, neutrino beam lines, neutrino factories, and muon colliders. Fermilab is studying 1–2 MW beam power superconducting linac proton driver to upgrade its injector and provide intense neutrino beams. Prototype work is underway at CERN for the superconducting proton linac (SPL), at KEK for upgrading the Japan Proton Accelerator Research Complex (JPARC) facility, at the Korea Multipurpose Accelerator Complex (KOMAC). A consortium of European laboratories is conducting Design Studies for an eXperimental Accelerator Driven System (XADS) for transmutation of nuclear waste. With abundant thorium resources, India is interested in development of ADS systems for nuclear energy production using thorium fuel. A multitask facility, including an ADS and a neutron spallation source, is envisioned at RRCAT Indore.

In August 2004 the International Technology Recommendation Panel (ITRP) recommended the superconducting option for the next linear collider. Complementing the LHC at CERN, the linear collider will start with 500 GeV energy to be upgraded eventually to 1 TeV. The collider will provide new insights into the structure of space-time, matter, and energy. Among the discoveries expected from the multibillion dollar project are new particles to explain the origin of mass, the mystery of dark matter, and the possibility of extra spatial dimensions. Some of the main features that stem from the choice of a superconducting linac are: lower operating power, better conversion efficiency of ac power to beam power, and the ability to use long-wavelength (larger beam opening) structures than possible for the warm structures. The larger beam aperture of the cold structure reduces electromagnetic wakefields which disrupt the beam quality. The chosen design gradient is 31.5 MV/m. As proof-of-principle, individual 1 m long cavities have been successfully operated in cryomodules at 35 MV/m and in FLASH at 31.5 MV/m. Several tens of meters of superconducting cavities in accelerator modules have been operated at the 25 MV/m level.

In conclusion, superconducting cavities have been operating routinely in a variety of accelerators with a range of demanding applications. With continued progress in basic understanding, cavity performance has steadily improved to approach theoretical capabilities. Niobium cavities have become an enabling technology offering upgrade paths for existing facilities, and pushing frontier accelerators for nuclear physics, high energy physics, and materials and life sciences.