CPC(HEP & NP), 2009, **33**(10): 922—926 Chinese Physics C Vol. 33, No. 10, Oct., 2009

Recent progress on RF superconducting cavities*

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Abstract RF superconducting (SRF) cavities can work in continuous wave mode or long pulse mode. SRF technology has been developing rapidly since the end of the last century. RF superconducting technology is widely used in particle accelerators around the world. As the key elements, research on superconducting cavities is carried out worldwide. Besides Europe, the United States and Japan, many countries have already started SRF projects, such as Canada, India, Korea, etc. Great improvements on SRF technology have been made in China in recent years. Progress in SRF cavities is introduced in this paper.

Key words superconducting cavities, SRF, accelerating gradient

PACS 74.25.Nf, 81.65.Ps, 29.20.Ej

1 Introduction

The most attractive aspect of RF superconducting (SRF) cavities is that they can run in continuous wave (CW) mode or long pulse mode and provide a high accelerating gradient due to low heat loss. The quality factor of SRF cavities is very high since the surface resistance of SRF cavities is 5 orders lower than copper cavities. SRF technology is widely used in particle accelerators around the world. Based on SRF technology, a lot of achievements have been made in the fields of FEL, THz sources, storage rings, etc. In 2004, SRF technology was recommended for the International Linear Collider (ILC). Encouraged by this, research on SRF cavities is carried out all over the world.

The developments of SRF cavities will be introduced in the following sections.

2 Developments of SRF cavities in the world

2.1 North America

SRF technology has been developed greatly in the United States. The first superconducting accelerator (SCA) in the world was commissioned at Stanford in the 1970s. The average 10 kW output for IR FEL was realized at Jefferson Lab (Jlab) in 2004. In the new century, research on SRF cavities mainly takes place at Fermilab (FNAL), Argonne National Lab (ANL), Jlab and Cornell University.

A collaboration between FNAL and ANL was established to develop and operate a complete SRF cavity processing and clean assembly facility located at ANL[1]. The Buffered Chemical Polishing (BCP) system has been designed, assembled and is being commissioned. The control system and recipe programming for 9-cell ILC cavities are nearly complete. The Argonne electropolishing (EP) system is commissioned with a one-cell cavity. The cryomodule assembly infrastructure at FNAL is now fully operational. The first cryomodule is finished and ready for testing. The vertical test stand is complete and the first 9-cell cavity was tested in September 2007. A new EP system at ANL has been used with six quarter-wave resonators (QWRs) to be installed in the ATLAS superconducting ion linac[2]. The uniformity of the polishing is improved through the use of a custom rotating cathode that also stirs the acid over the entire length of the cavity, minimizing temperature gradients in the electrolyte.

An SRF injector with a 2-cell cavity for the energy recovery linac (ERL) is being designed and fabricated at Cornell University[3]. The injector is designed to accelerate a CW beam with 2 ps bunch

Received 17 December 2008

* Supported by Major State Basic Research Development Program (2002CB713600, 2008CB817706)

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length and 100 mA average current from an input energy of 0.3 MeV to an output energy of 5—15 MeV while preserving an emittance of 1 mm·mrad. The Cornell ERL injector cryomodule is installed in the ERL injector prototype and the cryomodule is finished. 1.8 K CW operation is possible. The E_{max} for CW operation is 9.5 MV/m, which is limited by power dissipation at Q_0=1.5×10^9. For pulsed operation, the E_{max} is 13 MV/m.

Research and development on SRF cavities was started very early at Jlab and is continuing. 30 cycles of EP and vertical tests are achieved per year at the moment. Four 9-cell cavities got the best gradients of 31—42 MV/m. Quench behavior with material removal has been studied at Jlab. 3 cavities show that the quench limit gradient improves with more material removal (e.g. 20 μm) while the gradient of 2 cavities deteriorates with 20 μm material removal. To find the quench location, a temperature-mapping study with thermometers was carried out at Jlab as well as FNAL[4] and LANL[5]. Research on large grain/single crystal SRF cavities is done at Jlab. Reproducible tests show that the E_{acc} for single-cell large grain cavities is comparable to fine grain cavities while the former cavities are treated only with BCP instead of EP. The gradients of two 9-cell large grain cavities are 20 and 23 MV/m with standard BCP[6].

2.2 Europe

SRF technology at DESY, Germany is advanced in the world. The TESLA technology is used widely based on tens of years' accumulation. The highest E_{acc} of TESLA 9-cell cavity reaches 40 MV/m. Installation and testing of 7 cryomodules for TTF (FLASH) are finished. The highest operational gradient of FLASH is 27 MV/m of module 6. The European XFEL project is now under construction. TESLA 9-cell cavities are adopted for the main accelerator. Industrialization of EP is necessary. 2×10 cavities are industrially electropolished and the processing works well. The 6th cavity production, the final production series before XFEL, is done and the cavities show good performance. The E_{acc} of most cavities is above 25 MV/m and that of some is more than 35 MV/m.

Seamless technology for SRF cavities has been developed at INFN (spinning) and DESY (hydroforming) over several years. 3-cell units were fabricated and three 3-cell units were combined to a 9-cell cavity at DESY[7]. The 9-cell seamless cavity was tested at DESY and the E_{acc} is 30 MV/m. The quench limit has not yet been reached because of Q-drop and the 120 ℃ bake is underway.

A 120—150 ℃ bake is commonly used for EP/BCP cavities to eliminate Q-slope. An open argon-bake has been studied at DESY and the tests were successful[8]. This will simplify the cavity preparation sequence before final high pressure rinsing (HPR) and no additional vacuum handling of the fully assembled cavity is needed.

At CEA-Saclay, France, argon fast baking is also studied. The KEK Ichiro cavity IS#8 was electropolished at KEK. After one hour 145 ℃ fast argon baking, the E_{acc} was increased from 40 MV/m to 50 MV/m. The XFEL Clean Room at Saclay has been designed and constructed. It will be in operation in beginning of 2009.

At INFN-LNL, Italy, a fluoride-free Nb EP method is studied. The first success on Nb uses a mixture of choline chloride, urea, and NH_4F at 80 ℃. Now a totally fluoride-free solution has been developed by substituting NH_4F with NH_4Cl. At INFN-Milano, a β = 0.47 elliptical cavity for ADS is studied. The E_{max} is 17 MV/m with Q-slope and E_{acc} = 8.5 MV/m at Q_0 = 10^{10}. INFN-Milano also studies the new end groups for SRF cavities.

2.3 Asia

SRF technologies have been developed for a long time in Japan. Superconducting cavities were successfully used at the TRISTAN and KEKB factory at KEK. SC QWRs were installed in the heavy ion linac at JAEA (formerly JAERI). The electropolishing method for SRF cavities was developed at KEK and has become a standard procedure for high gradient cavities.

In the new century, more research and development on SRF cavities is being carried out at KEK. The research is mainly focused on ILC cavities, ERL cavities and crab cavities. The SRF Test Facility (STF) was established at KEK for cold testing of SRF cavities and cryomodules. Infrastructures such as flange-chemical polishing, EP, degreasing, HPR, pre-tuning, inner surface inspection, baking devices as well as a class 10 clean room and vertical test stand have been installed for STF. Cryomodule tests in STF phase-1.0 are available. String assembly of four TESLA-like cavities and cryomodule assembly were carried out in January to March, 2008. An average E_{acc} of 22.7 MV/m for vertical testing was obtained. For cryomodule testing, the average E_{acc} is 23.0 MV/m. For the best cavity STF-BL#2, the accelerating gradients for vertical and cryomodule tests are 29.4 MV/m and 28.1 MV/m, respectively.

KEK aims at realizing an ERL-based hard X-ray source in Japan and is currently developing superconducting cavities for both the injector and the main linac[9, 10]. A new 2-cell cavity is designed for the ERL injector. The cavity has double power couplers to reduce the power per coupler and helps to keep a symmetric field configuration around the coupler ports. The injector will consist of three 2-cell cavities and accelerate electron beams of 100 mA up to a beam energy of about 10 MeV. A 9-cell cavity is designed and fabricated for the ERL main linac. The designed $E_{\rm acc}$ is 20 MV/m with Q_0 of 1×10^{10}. Center-type and end-type single-cell cavities were tested and the gradients were 38 MV/m and 30 MV/m. Both single-cell cavities are better than the specification. The 9-cell cavity is under post treatment and testing at KEK.

SRF activities have been developed in Korea in recent years. An SRF project at PEFP (Proton Engineering Frontier Project) is proposed at Korea Atomic Energy Research Institute (KAERI). The goal is to develop an SRF linac to accelerate a proton beam from 100 MeV at 700 MHz. The first low loss 9-cell cavity was fabricated at PAL and tested at KEK.

Research and development on SRF technology has been carried out in India. SCRF technology has been developed and used for installation of a superconducting heavy ion LINAC booster accelerator at IUAC, New Delhi. The first linac module has 8 QWRs with an average $E_{\rm acc}$ of 3.6 MV/m[11]. Development of SRF cavities and associated technology has been made at RRCAT, Indore. New additional facilities including deep drawing, electron beam welding, EP/BCP/BP (barrel polishing), HPR, clean-room and vertical tests are under construction. RRCAT is now embarking on SC technology with a TESLA cavity. RRCAT is developing the required technology and man-power training for coming projects with inter-laboratory-industry collaboration.

3 Developments of SRF cavities in China

RF superconductivity was first explored in China in the early 1970s. Great progress on SRF technology has been made since the first SRF laboratory was founded at Peking University at the end of 1980s. Now research and development on SRF cavities is widely carried out at laboratories in China, such as Peking University (PKU), Institute of High Energy Physics (IHEP), Shanghai Institute of Applied Physics (SINAP), China Institute of Atomic Energy (CIAE) and China Academy of Engineering Physics (CAEP).

Collaborating with KEK, IHEP started the design of a 499.8 MHz superconducting cavity in 2001. The resonant frequency was low compared with the KEKB cavity by elongating the cell equator to meet the needs of BEPCII. Two Nb cavities together with cryostats, couplers and the dampers were fabricated from 2003 to 2005 by KEK in Japan. The cavities were assembled, processed and tested at KEK. After being reassembled at IHEP, the horizontal test of two cavities was carried out in 2006. It is shown that an energy gain of 2 MV is obtained at Q_0 of 0.99×10^9 and 0.55×10^9 for the two cavities. The Q_0 in each case exceeds the design requirement of 0.5×10^9. Fig. 1 gives the test result of the IHEP-#1 cavity.

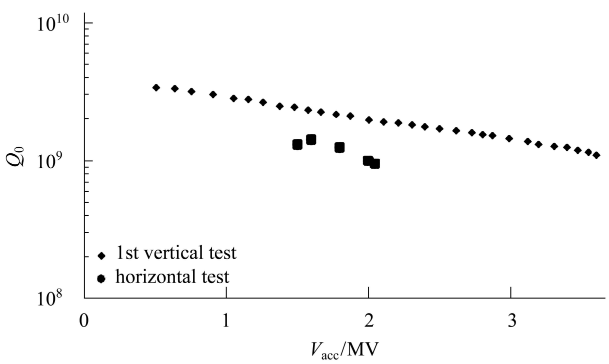

Fig. 1. The test results of the IHEP-#1 cavity for BEPCⅡ.

In addition, IHEP is doing research and development on low and mid-beta 700 MHz and 1.3 GHz superconducting cavities for proton acceleration for China SNS. IHEP has also made efforts on large grain superconducting cavities. Two single-cell KEK ICHIRO shape cavities were treated and tested at KEK. The gradients are 47.9 MV/m and 43.2 MV/m with Q_0 of 1×10^{10} respectively[12].

Three CESR type single cell SRF cavities fabricated by ACCEL are being installed in the Shanghai Synchrotron Radiation Facility (SSRF) storage ring. The cavities are used for establishing 3—6 MV accelerating voltage and providing up to 600 kW to the stored beam[13]. The vertical test results are shown in Fig. 2. Two cavities passed the acceptance tests in June and August 2008. The accelerating voltages are 2.1 MV and 2.03 MV, which exceed the guaranteed 2.0 MV. The dissipated power at 2.0 MV is 60 W and 46 W, which is below the guaranteed 70 W. At the same time, infrastructures for cavity processing and performance tests are being built.

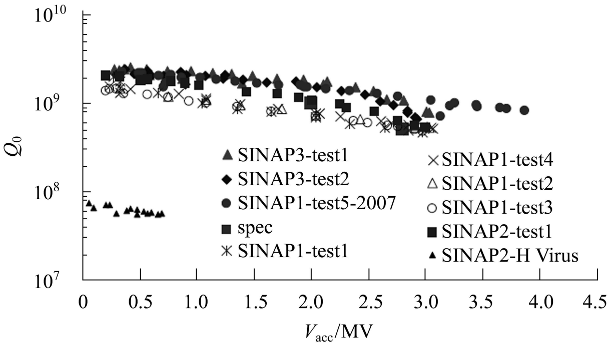

Fig. 2. The test results of SSRF superconducting cavities.

Peking University has done SRF research for 20 a. Peking University successfully fabricated the first niobium cavity and the first niobium-sputtered cavity (QWR) in China in the 1990s. From 2000, PKU started to make efforts on SRF cavities for a free electron laser facility.

Research and development on large grain niobium cavities has been carried out with the collaboration of PKU and Ningxia OTIC Company since 2006. To examine the features of large grain niobium material as well as the SRF cavity fabrication technology in China, the PKU SRF group has designed and manufactured a single-cell 1.3 GHz TESLA type cavity with Ningxia large grain niobium material. After an 800 ℃ heat treatment, the cavity was sent to Jlab for vertical testing. After a total of 120 μm BCP, 1250 ˚C purification and 120 ℃ baking, the E_{acc} reached 43.5 MV/m[6, 14], which is very close to the limit of a TESLA type cavity.

Research on multi-cell superconducting cavities has started at PKU in collaboration with Ningxia OTIC and Harbin Institute of Technology since the end of 2005. Studies on deep drawing, precise machining, RF measurements of dumbbells, niobium surface polishing, electron beam welding and post treatments have been done. After lots of hard work, the first 5-cell niobium cavity in China was finished in October 2007. This qualified the Chinese material and the fabrication procedure of multi-cell cavities. After some modifications of fabrication techniques, the first 9-cell niobium cavity in China was completed in March 2008. After leak checking and pre-tuning, the 9-cell cavity was sent to Jlab for cold testing. After 600 ℃ heat degassing treatment and 150 μm BCP, the E_{acc} is near 20 MV/m unless poor vacuum pumping and power failure occurs. After additional material removal by 50 μm BCP, the E_{acc} increased to 23 MV/m without quenching, see Fig. 3. Further baking might be used to get rid of the Q-drop starting around 20 MV/m.

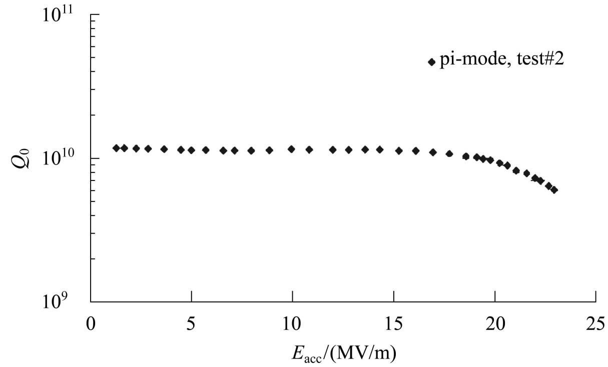

Fig. 3. The test result of the first 9-cell TESLA type cavity at PKU.

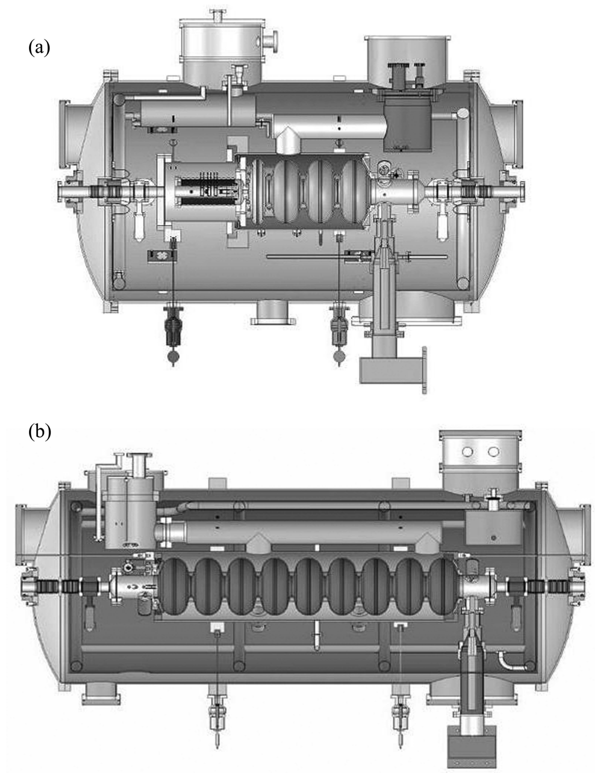

Fig. 4. The layout of the superconducting injector (a) and accelerator (b) for PKU-FEL.

Peking University Free Electron Laser (PKU-FEL) Facility[15] is under construction. The PKU-FEL facility includes superconducting injector, superconducting accelerator, driven laser, compressor, undulator and diagnostic system. The superconducting injector and accelerator are two of the most important elements for PKU-FEL. The upgraded 3+1/2 cell, 1.3 GHz DC-SC photoinjector[16, 17] will be adopted as the superconducting injector. A cryomodule including one 1.3 GHz 9-cell TESLA cavity will be used for the main accelerator. The design of the cryomodules is finished and they are being manufactured. Fig. 4 shows the structure of the two cryomodules. The fabrication of a 3.5-cell SC cavity for the injector is finished with Ningxia large grain niobium sheets. The 9-cell cavity with end groups will be finished soon.

4 Summary and outlook

Great progress in SRF technology has been achieved in recent years. Research on new shapes and new materials for superconducting cavities is carried out throughout the world. With the encouragement of ILC, post treatment procedures to obtain high gradient 9-cell cavities are studied and 35 MV/m at vertical testing can be obtained with electropolishing. But this is not so easy. In addition to the high cost of EP devices, there are other problems. For example, there might be sulfur dissipation on the surface of niobium cavities after EP. The whole procedure must be controlled precisely. The industrialization of multi-cell cavities is in progress and there is still a long way to go. The broad requirements of superconducting cavities for new scientific projects will make SRF technology more prosperous.

References

1 Rowe A, Assell D, Elementi L et al. BCP system for the ANL-FNAL SCPF. Proc. of 13th International Workshop on RF Superconductivity. Beijing, China, 2005. WEP47

2 Gerbick S, Kelly M P, Fuerst J D. A New Electropolishing System at ANL for Superconducting Quarter-Wave Resonators. Proc. of 13th International Workshop on RF Superconductivity. Beijing, China, 2005. TUP36

3 Chojnacki E P, Belomestnykh S A, Conway Z A et al. Design and Fabrication of the Cornell ERL Injector Cryomodule. Proc. of EPAC08. Genoa, Italy, 2008. 844—846

4 Dhanaraj N. http://ilc.fnal.gov/new/dhanaraj.ppt

5 Tajima T, Canabal A, Harden T A et al. Proc. of EPAC08. Genoa, Italy, 2008. 883—885

6 Kneisel P, Progress on Large Grain and Single Grain Niobium. Proc. of 13th International Workshop on RF Superconductivity. Beijing, China, 2005. TH102

7 Singer W, Jelezov I, Matheisen A et al. Preliminary Results from Multi-cell Seamless Niobium Cavities. Proc. of LINAC2008. Victoria, Canada, 2008. THP043

8 Reschke D, Ziegler J. Open 120C Bake in Argon Atmosphere: A Simplified Approach for Q-drop Removal. Proc. of LINAC2008. Victoria, Canada, 2008. THP015

9 Umemori K, Furuya T, Sakanaka S et al. Design of L-Band Superconducting Cavity for the Energy Recovery Linacs. Proc. of APAC2007. Indore, India, 2007. 570—572

10 Sakanaka S, Agoh T A, Enomoto A et al. Progress in R&D Efforts on the Energy Recovery Linac in Japan. Proc. of EPAC08. Genoa, Italy, 2008. 205—207

11 Prakash P N, Sonti S, Mistri K K et al. Superconducting Niobium Resonator Fabrication and Testing at IUAC. Proc. of APAC2007. Indore, India, 2007. 500—502

12 ZONG Zhan-Guo, GAO Jie, Saito K et al. Chinese Physics C (HEP & NP), 2008, **32**(2): 151

13 ZHAO Z T. Private Communication

14 HAO Jian-Kui, ZHAO Kui, ZHANG Bao-Cheng et al. Chinese Phyics C (HEP & NP), 2008, **32**(s1): 181

15 ZHAO Kui, HAO Jian-Kui, HUANG Sen-Lin et al. Progress Report on RF Superconductivity at Peking University. Proceedings of 12th International Workshop on RF Superconductivity. Ithaca, USA, 2005. 538—540

16 HAO Jian-Kui, LU Xiang-Yang, DING Yuan-Tao et al. Nucl. Instrum. Methods A, 2006, **557**: 138—141

17 ZHU Feng, QUAN Sheng-Wen, XU Wen-Can et al. HEP & NP, 2007. **31**(5): 496—500 (in Chinese)