SUPERCONDUCTING RF - NEW DIRECTIONS*

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Abstract

In the last two years, there has been substantial progress in superconducting accelerator technology both in long term operation at many facilities as well as in high gradients at many laboratories. These rapid advances have made RF superconductivity an enabling technology for a variety of new applications. In high energy physics, low frequency (200 – 400 MHz) cavities are envisioned to accelerate muons for intense neutrino beams and muon colliders (200 – 1300 MHz). For storage ring based light sources, superconducting cavity systems (500 MHz) will upgrade the Taiwan Light Source and provide high voltage and high power for new storage rings under construction for the Canadian Light Source (CLS), DIAMOND in England, and SOLEIL (350 MHz) in France. Similar systems are envisioned for BEPC in China and for the new Shangai Light Source. Superconducting linacs are now driving low emittance beams in a number of free electron lasers (FEL), stimulating new FEL projects and new energy recovery linacs (ERL) to generate x-ray beams. High intensity proton beams at LHC will be supported by 400 MHz superconducting systems. A high intensity (2 MW) proton linac from 200 MeV to 1000 MeV based on 800 MHz superconducting cavities will drive the U.S. Neutron Spallation Source (SNS). A large fraction of cavities will be for low velocity (beta = v/c=0.6) protons. Higher intensity (5 – 10 MW) proton linacs are under planning in Europe for neutron spallation, accelerator transmutation of waste, energy amplifier, as well as to generate muons for neutrino beams. Radioactive beams for nuclear-astrophysics will be accelerated by superconducting cavities between 58 and 700 MHz.

1 INTRODUCTION

This is an exciting period for RF superconductivity. Besides continuing applications to High Energy Physics and Nuclear Physics, new areas are opening up in light sources and neutron sources. New cavity geometries and lower frequencies are being explored. Some of the new applications demand high beam currents, and therefore high beam power. Other applications demand the highest possible gradients. Some require CW operation, others demand pulse lengths in the millisecond range.

* Work supported by NSF

2 HIGH ENERGY AND NUCLEAR PHYSICS

Over one kilo-meter of superconducting cavities have been installed in accelerators around the world providing more than 5 GV of acceleration. For nuclear physics, CEBAF at Jefferson Lab is the largest U.S. installation with nearly 200 meters of 1500 MHz cavities, providing more than one GV. Over the period of a few years CEBAF has upgraded the in-line accelerating gradient of their sheet metal niobium cavities from the design value of 5 to more than 7 MV/m[1]. At CERN, niobium-coated-copper (Nb/Cu) superconducting cavities doubled LEP beam energies to 105 GeV per beam with 288 cavities providing 3.6 GV[2]. During its reign as the largest SRF installation, LEP-II upgraded their in-line performance of their niobium-on-copper (Nb/Cu) cavities from 6 to 7.5 MV/m. The performance upgrades at CEBAF and LEP took advantage of the intrinsic, high gradient potential of SRF cavities. Figure 1 shows Cornell/CEBAF cavities made from bulk niobium and Figure 2 shows LEP cavities Nb/Cu cavities.

Large beam hole cavities with low impedance and high gradient have been a boon to high current storage rings, such as CESR[3] and KEK-B[4], providing needed voltage with a few units, and average beam powers of 280 kW per cavity. Figures 3 and 4 show cavity systems for B-physics machines. KEK is also developing single cell crab cavities[5] to deflect crossing angle beams so they collide head on (Figure 5).

At CERN a new RF system for LHC will rely on 16 low impedance Nb/Cu single cell cavities[6]. Excellent Q vs. E performance curves (Figure 6) for LHC cavities have encouraged other large low frequency applications for muon acceleration, to be discussed below.

Improved understanding of the physics of RF superconductivity, together with technology advances are responsible for the spectacular increases in performance. The history of advances in superconducting cavities shows that, as the limiting mechanisms of multipacting, thermal breakdown and field emission were each understood, and in turn overcome, cavity performance improved steadily over time.

The first breakthrough above 25 MV/m came with 5-cell 1300 MHz cavities [7] fabricated and prepared at Cornell and tested through a collaboration between Cornell, DESY and Fermilab (Figure 7). Field emission, the dominant limitation was eliminated by destroying emitters with peak power processing above one MW. Raising gradients over 25 MV/m, SRF met its first challenge for linear colliders. The advantages of SRF for TESLA have been clear for some time since the first international TESLA workshop held at Cornell in 1990[8]. Because of low losses, SRF cavities can be filled slowly and drastically reduce peak power demands, a major cost item for a normal conducting linear collider. With low losses, high stored energy associated with low frequency becomes affordable. Low frequencies drastically reduce wakefields, allowing excellent emittance preservation for high luminosity. The TESLA approach offers the highest luminosity among various paths to the next linear collider. Finally, low losses permit long RF pulse lengths, which allows increased spacing between bunches and corresponding gains for detectors[9].

Another challenge was to lower the cost substantially. To this end, 9-cell cavities were adopted and cryomodules with high filling factors developed[10]. Today, full-scale structures, ready for beam, reach gradients over 20 MV/m[9]. 9-cell TESLA cavities now routinely reach accelerating fields of 28 – 32 MV/m (Figure 8). and single cell cavities exceed accelerating fields of 40 MV/m[11], not far from the theoretical limit of 50 MV/m imposed by the RF critical magnetic field.

As a result of concerted efforts, costs for TESLA technology have now come down to make TESLA a very attractive option for 0.5 TeV linear collider[10]. At 42 MV/m TESLA would reach one TeV in the center-of-mass. Success of TESLA technology has also opened a host of new applications and ideas to be discussed later.

Recent discovery of neutrino mass has generated excitement for a Neutrino Factory (Figure 9) to provide an intense beam of neutrinos from decaying muons[12]. Since muons generated by proton bombardment have a very high emittance, low frequencies (200 MHz) become necessary. And since muons decay rapidly, gradients above 15 MV/m are essential. For the recirculating linac accelerating muons to 20 GeV (Figure 9), about 500 meters of 200 MHz SRF are necessary, making the system somewhat larger than that installed for LEP-II. A Nufactory cryomodule will house four 2-cell units (Figure 10). The first step towards this ambitious goal will be to prove the needed gradient in a single which will be built at CERN and tested at Cornell (Figure 11).

The Neutrino factory will be a first step towards a future muon collider[12]. Being 200 times heavier than electrons, muons can be accelerated without losing energy due to synchrotron radiation, and collided without generating beamstrahlung associated background. Energies of 5 – 10 TeV in the center of mass are envisioned for the far future, after electron-positron colliders cannot grow higher in energy. For low energy acceleration, recirculating linacs will need 200 – 400 MHz cavities and the higher energy accelerators can use TESLA-like structures at 1300 MHz. Both the neutrino factory and TESLA will therefore provide key technologies for muon colliders. If both cool muons and a TESLA-like 500 GeV superconducting linac become available in the future, HEP may envision assembling a 5-turn recirculating linac to provide 2.5 TeV energy muons for 5 TeV CM collisions.

3 LIGHT SOURCES

SRF cavities developed for HEP high current storage rings make ideal accelerating systems for new light source storage rings and for upgrading existing light sources. Because of high gradient, only a few units are needed saving valuable space for insertion devices. The large beam hole means low impedance which is essential for high currents. One single cell, 500 MHz CESR SRF cavity (Figure 3) will be used to upgrade the Taiwan Light Source[13] and one cavity will fill the needs for the new Canadian Light Source[14]. Diamond plans to install three CESR cavities[15]. The technology for the CESR SRF cavity has been transferred to one industry which is gearing up now to provide turnkey systems[16]. KEK-B cavities are under consideration for upgrading BEPC as well as for the Shangai Light Source in China. In France the SOLEIL project [17] will use 350 MHz Nb/Cu cavities built and tested by a Saclay/CERN collaboration. Performance results exceed design (Figure 12).

SRF cavities are already the basis of FEL sources of IR and UV radiation at Stanford University FEL[18], JLAB [19] and JAERI[20]. JLAB has reached CW powers of more than one kilowatt. Future light sources desire higher brilliance and Angstrom wavelength which can be provided with 20-30 GeV electron beams by the SASE FEL method[21]. TESLA technology is the ideal basis for such an FEL, and the TESLA project is planning to provide such a joint facility[21].

For light source users desiring brilliance intermediate between existing storage rings and future x-ray FELs, the Energy Recovery Linac (ERL) could be a viable option[22]. Again, based on TESLA technology, such a machine would provide 5 – 7 GeV linac beam with 100 mA CW current. 500 – 700 MW of beam power would have to be recovered by recirculating the beam through the accelerating linac. Ninety percent energy recovery has already been demonstrated at SCA [23] and 99.9% recovery at the JLAB FEL[24]. A low energy prototype ERL is necessary to extend these achievements to the 100 mA current level, as well as to show the needed emittance at high current[22].

4 NEUTRON SOURCES

Over the last few years high intensity proton linac based neutron sources have started to derive benefits from SRF technology. Neutron sources are intended for studying materials and transmutation for isotope production and treating nuclear waste[25]. For such facilities, high gradient superconducting cavities reduce the peak power installation and linac length, as well as save on operating cost. Because of these advantages the 2 MW SNS project recently adopted SRF technology from 100 MeV to 1 GeV[26].

The first push for a high current proton machine was the 100 MW CW machine, APT[27]. Key technologies were developed: 700 MHz cavities with beta = 0.6, cryomodules and high power couplers. Figure 13 shows performance results for industrially produced cavities reaching twice the design gradient[28]. High power couplers have been tested at one MW[29].

Low beta cavities for the SNS project have exceeded gradients of 15 MV/m (Figure 14) and high beta cavities approach 19 MV/m[30]. High power couplers based on the KEK-B design have been constructed and are now under test[31].

5 OTHER PROJECTS

For Nuclear astrophysics, the Radioactive Isotope Accelerator (RIA) would be a unique combination of very low beta, medium beta and high beta structures (Figure 15)[32]. There is a strong incentive to develop medium beta cavities of which the spoke resonator has emerged a strong candidate. A collaboration between ANL and LANL have demonstrated gradients near 10 MV/m (Figure 16)[33].

Space does not permit discussion of several new projects underway, such as the CEBAF upgrade[34] to 16 GeV, third harmonic cavities for bunch lengthening[35] in order to raise the lifetime of storage rings under development at several laboratories, the superconducting RFQ developed at INFN[36] and the Fermilab separator for a Kaon beam line[37].

6 CONCLUSIONS

RF superconductivity is a mature science going well beyond technological know-how and trial-error approaches to genuine understanding of underlying physics.. Rapid advances in the performance of superconducting cavities have made RF superconductivity a key technology for accelerators that fulfil a variety of needs.

7 REFERENCES

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Figure 1: Cornell/CEBAF cavity pair, 1500 MHz.

Figure 2: CERN Nb/Cu cavity, 350 MHz.

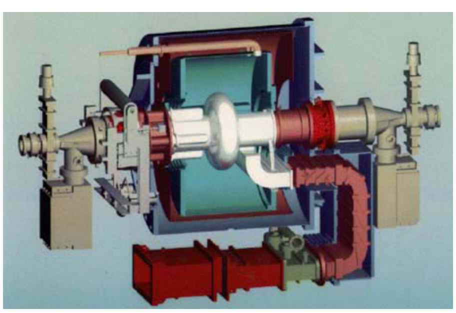

Figure 3: CESR 500 MHz cavity in cryostat.

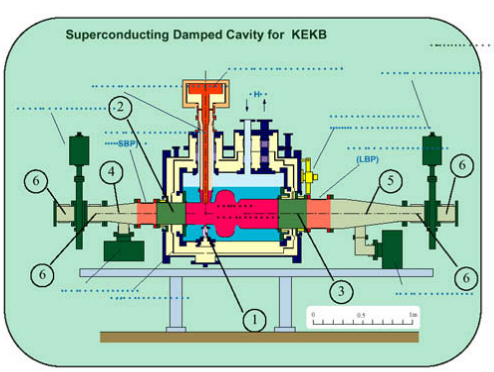

Figure 4: KEK-B 508 MHz cavity in cryostat.

Figure 5: KEK-B 500 MHz crab cavity, TM110 mode.

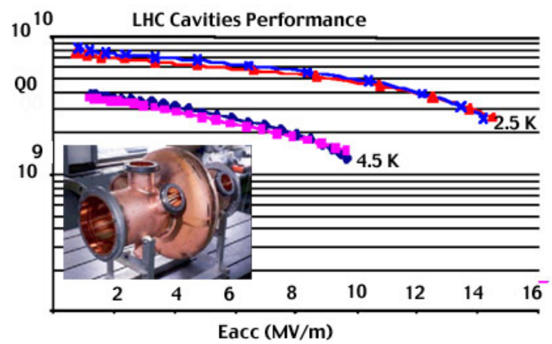

Figure 6: LHC cavity performance, 400 MHz.

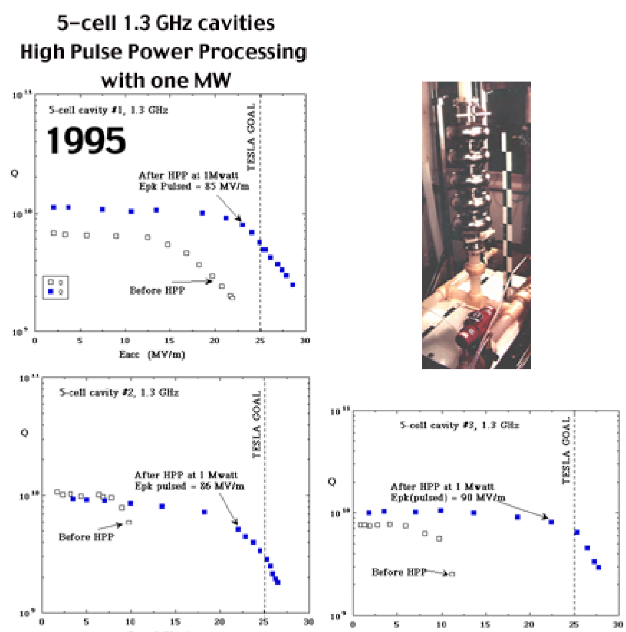

Figure 7: TESLA goal of 25 MV/m reached with one MW processing of Cornell 1300 MHz, 5-cell cavities.

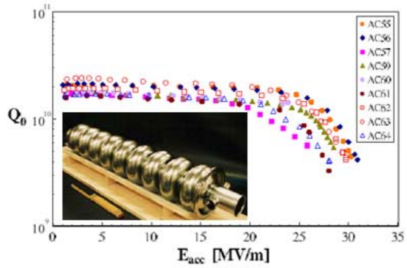

Figure 8: Performance TESLA cavities, 1300 MHz.

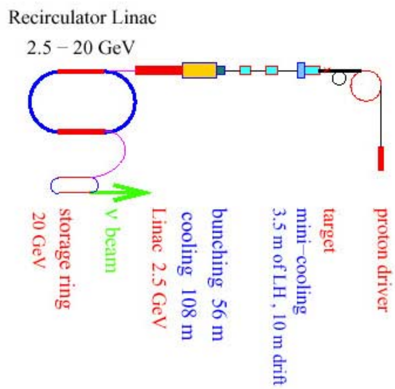

Figure 9: Neutrino Factory layout.

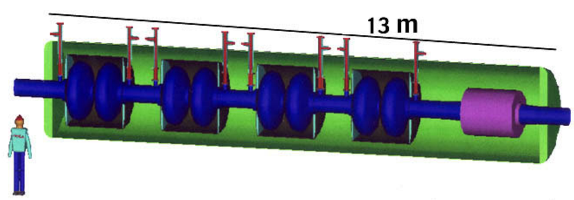

Figure 10: Schematic of Neutrino Factory cryomodule with 200 MHz cavities.

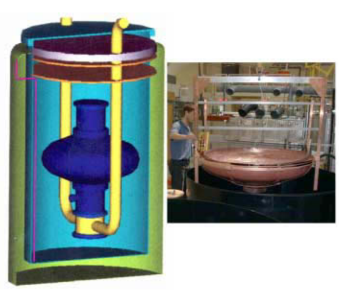

Figure 11: Single cell 200 MHz cavity produced by CERN and to be tested at Cornell.

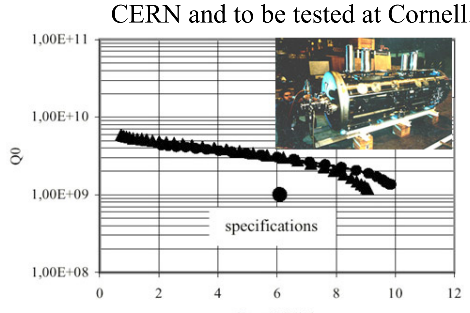

Figure 12: Two SOLEIL 350 MHz cavities in a cryomodule and their performance.

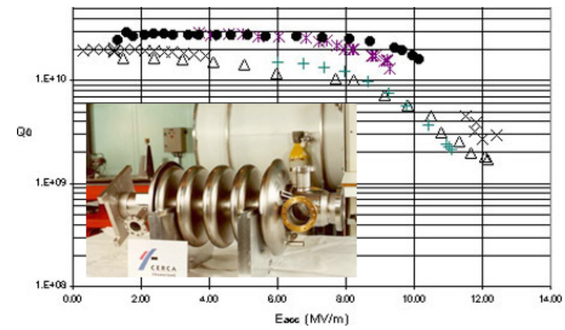

Figure 13: APT β=0.65 cavity and performance.

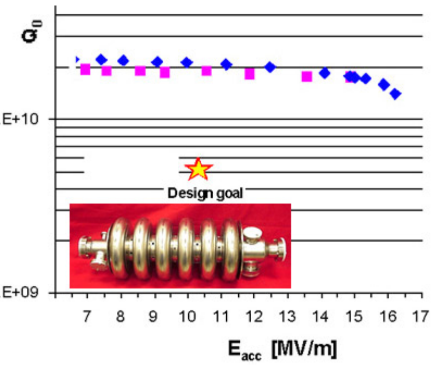

Figure 14: SNS β=0. 61 cavity, 800 MHz, and performance.

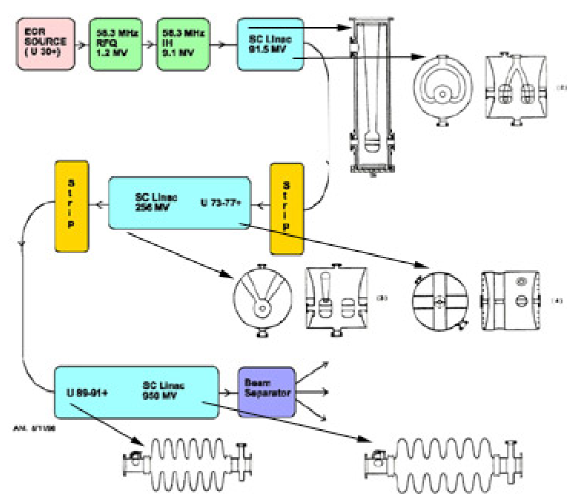

Figure 15: Layout of RIA and spectrum of cavities needed.

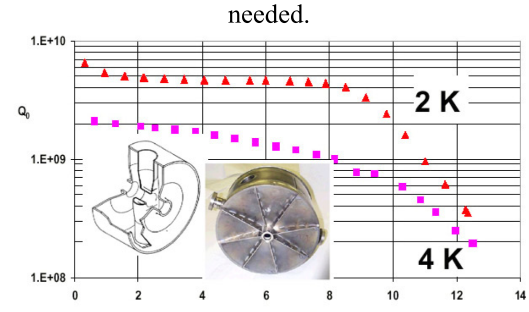

Figure 16: ANL/LANL spoke resonator and performance.