ACCELERATOR TECHNOLOGY – FROM BIG PROJECTS TO BROAD APPLICATION*

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Abstract

Accelerator technology has much progressed through processes, for realizing big accelerator projects, using such superconducting technology for magnets and/or RF cavities. In this report, we focus on the superconducting technology progressed in large-scaled, particle accelerator programs and the broad application. One is the superconducting magnet technology much advanced through the LHC project at CERN, and another is the superconducting RF cavity technology much advanced in the process for the design study and technical R&D effort for the ILC project being proposed. We discuss medical applications as representing applications of the accelerator technology.

INTRODUCTION

Advanced accelerator technology has been inevitably required to realize energy- or intensity-frontier particle accelerators with increases of the accelerator scales in recent decades. Figure 1 shows the progress in the energy frontier particle accelerators for protons and electrons. Superconducting magnet technology has been taking a crucial role in proton beam circulation, since TEVATRON at Fermilab succeeded to use it for major components, and much advanced in the following projects of HERA at DESY, and RHIC at BNL, and LHC at CERN [1-4]. Superconducting RF technology has been taking a crucial role in beam acceleration, since TRISTAN at KEK succeeded to apply it for a major acceleration component in the operation, and LEP at CERN also succeeded to apply it in the beam acceleration [1, 5]. Table 1 summarizes the progress in particle accelerators based on major application of superconducting magnet and/or RF technologies including European XFEL [6], Project X[7] and ILC [8, 9] under construction or being prepared.

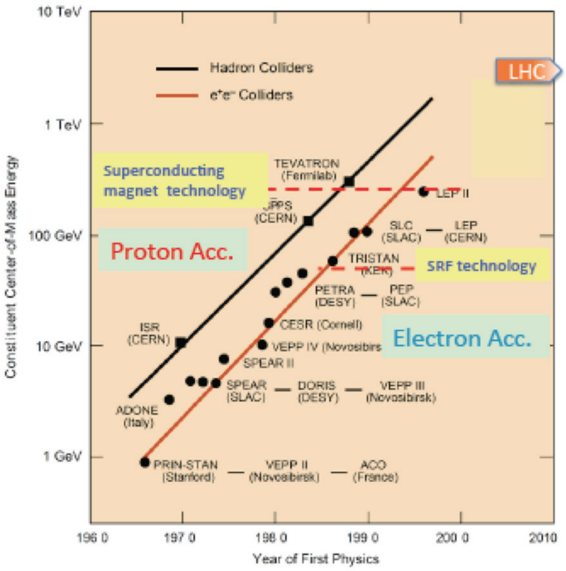

Figure 1: Progress in accelerators in particle physics and superconducting magnet and RF technologies.

Table 1: Progress in Accelerators in Particle Physics, based on Superconducting Technology

Accelerator	Beam Energy	B/E field
Proton		
TEVATRON	450 GeV	4.0 T
HERA	820	4.68
RHIC	100	3.46
LHC	(7,000*)	(8.36*)
***Electron/proton**:*		
TRISTAN	30 GeV	5 MV/m
LEP	105	5
CEBAF	6 (12*)	7 (20*)
KEKB	8	5
(EXFEL*)	(14*)	(24*)
(Project-X, SCL)	(8)	(~20*)
(ILC*)	(250*)	(31.5*)

* to be realized or proposed.

SUPERCONDUCTING MAGNET TECHNOLOGY

The relation between the momentum of charged particles, p_{beam}, and the magnetic bending field, B_{dipole}, in a circular collider with the bending radius R is given by $p_{beam} = 0.3\ B_{dipole} \cdot R$ (TeV, T, km). The requirement of high fields is evident, and the LHC main diple field is to reach a field level above 8 T by using Nb/Ti superconductor technology at 1.8 K.

After the LHC will be operating for certain years at nominal parameters, it will need to be upgraded for significantly higher luminosity, as the HighLuminosity upgrade (HL-LHC) [2]. The most direct way of increasing luminosity is to focus the beam more tightly at the collision point (and to reduce the so-called beta* parameter) which calls for a redesign of the machine optics in the beam interaction regions and a replacement of the final-focusing quadrupole magnets with a much larger aperture, resulting the peak field to exceed 10 T. An advanced superconductor such as Nb3Sn will be inevitably required to realize the luminosity-upgrade final focusing quadrupoles [10, 11]. For a further upgrade program, the High-Energy upgrade (HE-LHC) program is also under study [2]. It will require much higher magnetic field and further advanced sperconductor [11, 12]. Figure 2 shows the superconductor progress and the magnet designs under development/study [2, 10, 11].

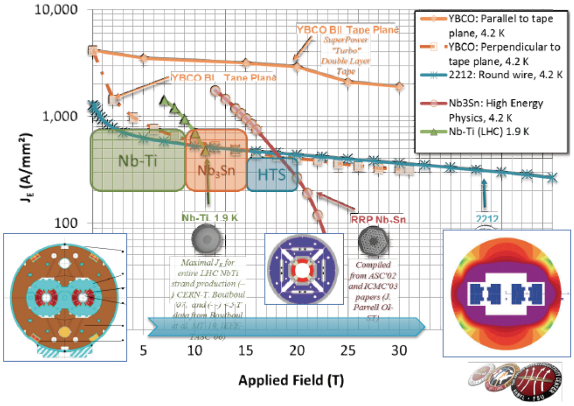

Figure 2: Advanced superconductor characteristics and magnet designs required for the LHC and the upgrades under development/study [2, 8, 9].

SUPERCONDUCTING RF CAVITY TECHNOLOGY

Linear accelerators have benefitted greatly through the use of Super-Conducting RF (SCRF) cavity technology [5, 13]. This technology, when applied in standing-wave RF operation, provides the following important advantages [14]:

- Small RF surface resistance and large quality factor, Q, resulting *long pulse operation*, with a range of 1 ms, and much higher duty factor in beam acceleration,
- Lower operational frequency with enlarged beam-apertures in the range of ~70 mm diameter, (1.3 GHz), which results in large acceptance and provides practical solutions for *very intense beams*.

The above feature of superconducting cavities are (i) the average accelerating gradient field *Eacc* and (ii) the intrinsic quality factor *Q*, that is a universal figure of merit for resonators and is defined in the usual manner as the ratio of the energy, U, stored in the cavity to the power lost in one RF period. The Q value depends on the microwave surface resistance of the metal. In general, one would like to have as high an accelerating field and as high a Q as possible.

The strongest incentive to use superconducting cavities in an accelerator is that continuous wave (CW) mode or high duty factor (> 1 %) operation is practical. For CW operation power dissipation in the walls of a copper structure is substantial and often not possible. Here superconductivity comes to the rescue. The microwave surface resistance of a superconductor is typically five orders of magnitude lower than that of copper, and therefore the Q value is five orders of magnitude higher. The above advantages may be of benefit even though superconducting technology requires low temperature (1.8 degree) cryogenic system operation, resulting additional power consumption for cooling. It should be also noted that a pulse duration in the level of msec in the superconducting cavity operation, three order magnitude longer than that of a normal-conducting cavity, would be much helpful in other linear collider sub-systems such as particle detectors and feed back systems.

Superconducting cavities are intended for use in high-energy accelerators such as EXFEL, Project-X and ILC were designed for operation at 1.3 GHz with a cell length of 115.4 mm. The 9-cell elliptical cavities were originally designed and developed for the FLASH/TESLA Test Facility program at DESY [15], and have become a standard for further programs. Figure 3 shows a photo of the FLASH/TESLA cavity.

Figure 3: TESLA type, 1.3 GHz, 9-cell SCRF cavity.

Figure 4 shows progress of SCRF cavity gradient with the requirements from various projects on-going or proposed [16]. We are expecting further improvement of the gradient with further basic R&Ds [17, 18] and efforts for the big projects. The industrialization of the ILC accelerator technology is discussed in a reference [19].

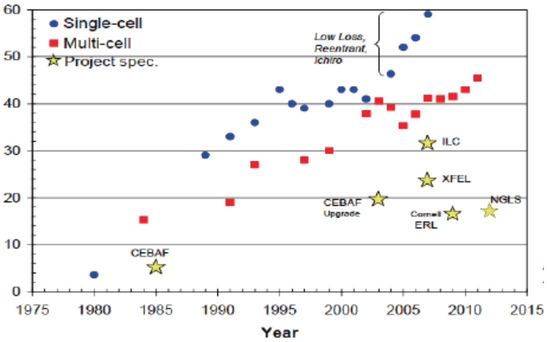

Figure 4: Progress in the SCRF cavity gradient and the requirements from various accelerator projects [16].

BROAD APPLICATION

The accelerator technology application has been broadly extended to various fields of (i) superconducting magnet technology as such as MRI, semiconductor purification, MAGLEV transportation, electric-power transmission, and undulators for photon science [20], (ii) superconducting RF technology as such as ADS [21], compact X-ray source [22], compact electron-microscope, and general microwave application, (iii) Synchrotron radiation [23] as such as material and life science application, (iv) medical therapy as such as cancer-

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therapy accelerators by using heavy-ion, proton, electron, and x-ray [24, 25], and (v) further industry accelerators [26]. The medical therapy accelerator is the most developed, practical application, and the beam handling technology has been further well progressed. Table 2 summarizes the recent worldwide progress and near future plans in medical therapy application programs focusing on heavy-ion accelerators [27], and Figure 5 shows a layout of the Heavy-Ion Medical Accelerator Complex (HIMAC) at NIRS and a new treatment facility with a gantry room and a superconducting beam transport magnet system under development [24, 28]. The heavy ion therapy accelerators have been much progressed because of the radiation localization to be significantly improved. It should be also noted that recent industry and KEK cooperation has realized "Image guided, dynamic tracking radiation therapy system", as a very compact, commercial product and application [29].

Table 2: Heavy-ion (Carbon), Accelerators in Operation and Near Future Plans for Medical Therapy Applications [27].

Accelerator	Beam Energy	Operation
Progress		
NIRS (Japan)	400 MeV	1994 ~
GSI (Germany)	400	1997 ~
HIBMC (Japan)	320	2001 ~
IMP (China)	400	2006 ~
HIT (Germany)	430	2009 ~
GHMC (Japan)	400	2010 ~
CNAO (Italy)	400	2012 ~
Plan to be in operation		
Fudan Univ. (China)	430	2013 ~
Saga-HIMAT (Japan)	400	2013 ~
PTC (Germany)	430	2013 ~

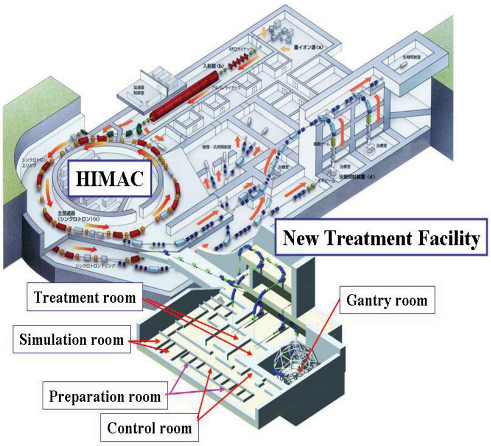

Figure 5: Layout of HIMAC with a gantry at NIRS [28].

SUMMARY

The accelerator technology and the application have been reviewed, from a viewpoint of "from big projects to broad application". We have focused on superconducting technology progressed with the big projects such as LHC and ILC (proposed) and key accelerator technologies. Broad application to various fields has been discussed, and medical accelerator application has been focused specially on hadron therapy using heavy-ions as a very promising application in our future.

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