THE FUTURE OF SUPERCONDUCTING TECHNOLOGY FOR ACCELERATORS

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Abstract

Superconducting technology has been inevitably required for guiding and accelerating particle beams in energy/intensity frontier particle accelerators. Based on a long history with NbTi superconductor, accelerator magnet technology has much progressed to realize higher magnetic fields above10 T by using Nb_3Sn superconductor. It has been applied to specific magnets for the HL-LHC project at CERN and further effort to increase the field to with increasing the current density is being investigated for future frontier accelerators. Superconducting RF technology has much advanced with pure Nb superconductor and the completion of European XFEL accelerator is a very important milestone for future large-scale SRF accelerator applications. Thin-layer SRF technology will become critically important for further advances in the field-gradient and quality performances. This report will cover the progress and future of the superconducting technology for accelerators.

INTRODUCTION

Superconducting magnet (SCM) and radio-frequency (SRF) technologies have been essentially contributing to energy/intensity frontier particle accelerators respectively for guiding and accelerating particle beams [1-3]. The SCM application may work in the "mixed state" of the superconductivity, up to the higher critical magnetic field, B_{c2} in the type II superconductor [4, 5]. In contract, the SRF application needs to stay in pure superconductivity condition so called "Meissner state", below the lower critical magnetic field, B_{c1}, and more critically limited with the thermal balancing limit, B_{sh}, a little higher than B_{c1} with the RF superconductivity [6, 7]. Table 1 summarizes these type-II superconductor characteristics constraining the accelerator applications.

Table 1: Characteristics of Type-II Superconductors in Applications for Particle Accelerator

Material	Tc [K]	B_{c1} [T]	B_{sh} [T]	B_{c2} [T]	applied for
Nb	9.2	**0.18**	**0.21**	0.28	SRF
NbTi	9.2	0.067	--	**11-14**	Magnet
Nb_3Sn	18.3	0.05	**0.43**	**28-30**	Mag./SRF
MgB_2	39	0.03	0.31	39	Link/Mag.
YBCO	92	0.01	--	100	Magnet
B-2212	94	0.025	--	>100	Magnet
B-2223	110	0.0135	--	> 100	Magnet

For the SCM applications, NbTi has been widely used in the field below 10 T, and Nb_3Sn is required to extend the applications above 10 T. High temperature superconductor will be inevitable to realize higher field toward ~ 20 T. It may be well understood that Nb is the superconductor adequate for the SRF cavity application, and Nb_3Sn may have a potential for higher gradient cavities in future. Table 2 summarizes superconducting accelerators based on SCM and SRF technologies [1-11].

Table 2: Superconducting Colliders and Accelerators

Project	Energy [GeV]	Field B/E	SC material	Operation [years]
SCM (hadron acc.):		[Tesla]		
Tevatron	2x980	4.0	NbTi	1983-2011
HERA	920	4.68	NbTi	1990-2007
RHIC	2x100	3.46	NbTi	2000 -
LHC	2x3500 ~2x7000	4.18 ~8.36	NbTi	2009 -
FAIR	29	1.9	NbTi	(2018)
HL-LHC	2x7000	11	Nb_3Sn	(2025)
HE-LHC	2x14000	16	Nb_3Sn	(study)
FCC-hh	2x5e4	16	Nb_3Sn	(study)
SppC	2x≥5e4	16-20	Nb3Sn/HTS	(study)
SRF (hadron acc.):		[MV/m]		
SNS	1.25	15	Nb	2007 -
LHC	2x3500 ~2x7000	5	Nb/Cu	2009 -
FRIB	0.2/u	5~8	Nb	(2022)
ESS	2	9-20	Nb	(2023)
PIP-II	0.8	10-20	Nb	(2025)
FCC-hh	2x50,000	tbd	tbd	(study)
SppC	2x50000	tbd	tbd	(study)
SRF (lepton acc.):		[MV/m]		
CEBAF	6→12	5-12	Nb	1985 -
Tristan	2x30	5	Nb	1986-1995
LEP	2x105	5	Nb	1989-2000
HERA	27.5	n/a	Nb	1990-2007
KEKB	3.5+8	5	Nb	1998-2010
BEPC-II	2x1.89	5	Nb	2008 -
S-KEKB	4+7	5	Nb	2016 -
E-XFEL	14	24	Nb	2017 -
LCLS-II	4	16	Nb	(2020)
ILC	2x500	31.5	Nb	(plan)
FCC-ee	2x350	10-20	Nb/Cu	(study)
CEPC	2x240	5-20	tbd	(study)

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SUPERCONDUCTING MAGNETS

Magnetic Field Progress in Accelerators

After the long experiences integrated with the superconducting magnet development and operation, based on NbTi superconductor, in Tevatron, HERA, RICH, and LHC projects, the accelerator magnet technology with Nb3Sn superconductor above 10 T needs to be advanced for energy/intensity frontier accelerators, as shown in Fig. 1 [1].

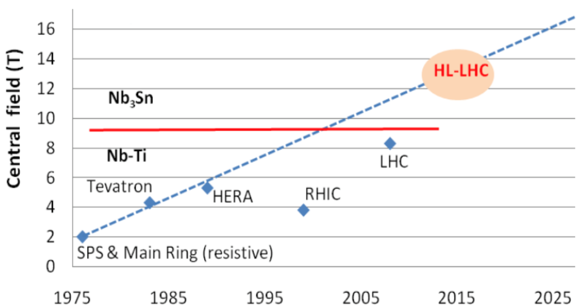

Figure 1: Progress in dipole field with NbTi superconductor for collider accelerators, and the prospect with the Nb_3Sn superconductor.

Advances in Nb_3Sn Magnets

The high-luminosity LHC (HL-LHC) accelerator project is pioneering to apply the Nb_3Sn high-field magnet with a usable magnetic field level of 11~12 T in two specific objectives of beam focusing at the beam interaction regions (IRs), and bending at a specific arc section [12]. Figure 2 shows cross sections of the 11 T dipole and the IR quadrupole, using Nb3Sn superconductor, being developed for the HL-LHC project at CERN [13 - 15].

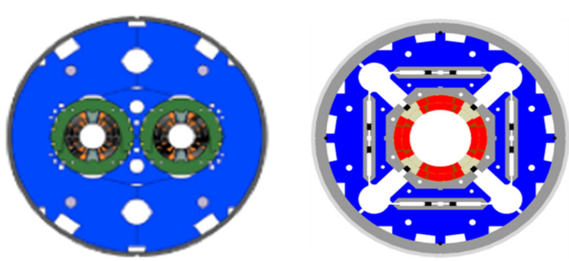

Figure 2: Cross sections of a 11 T dipole and an IR quadrupole with Nb3Sn conductor for the HL-LHC.

Both short model magnets have reached the design field and field gradient for the HL-LHC project within reasonable training quenches, after long effort between CERN and US-LARP collaboration [16]. The US-LARP Collaboration has been taking a pioneering role to develop accelerator quality Nb_3Sn superconductor and to demonstrate the Nb_3Sn accelerator magnet technology, having controlled the brittle feature with bladder technology introduced to manage strong magnetic pressure proportional to B^2. CERN has been leading the international effort to realize the Nb_3Sn accelerator-quality magnet technology applied for the HL-LHC project, as an important milestone for the future.

As a next step, it will be very important to increase the current density of Nb3Sn conductor with a level of 50% to be ~ 1,500 A/mm^2 at 16 T, 4.2 K, as shown in Fig. 3 [17]. It will be inevitably required to realize accelerator quality high-field magnets with a level of 16T, for the Future Circular Collider being study at CERN [18, 19]. Global cooperation has been formed to realize it. Various magnet design studies for the FCC are being carried out under frameworks of EuCard-2/ARIES, EuroCircol, US Magnet Development Program (MDP) [20-22] (Fig. 4).

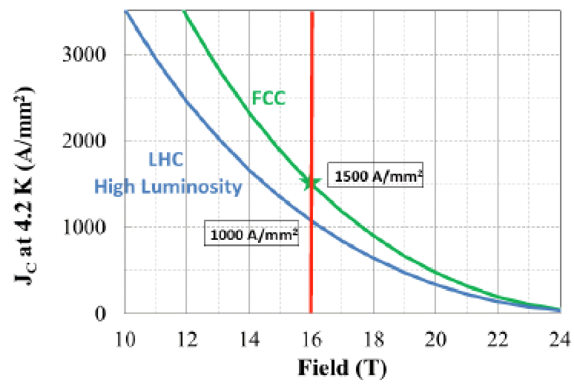

Figure 3: Critical current density improvement required for 16 accelerator magnets to be realized for Future Circulator Collider (FCC).

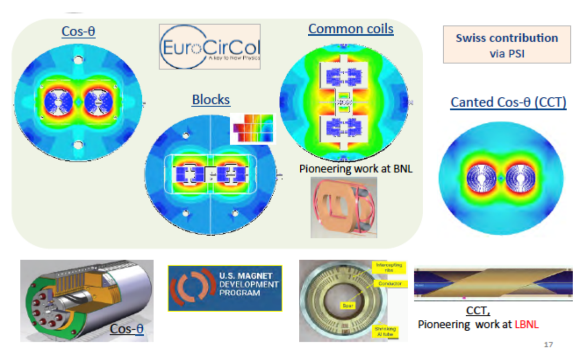

Figure 4: Various high field magnet designs being studied for the FCC.

Prospect for High-field Magnets beyond 16 T

It will be inevitable to apply HTS superconductor such as YBCO/ReBCO to realize high field magnet beyond 16T. A unique effort for future high-field magnet using the Roebel (fully transposed) cable is being developed, with an aligned-block coil configuration as shown in Fig. 5 [23].

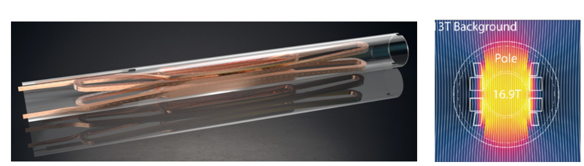

Figure 5: An aligned block model coil configuration under development by using the ReBCO Roebel cable.

SUPERCONDUCTING RF

Advances in SRF Technology

Superconducting RF (SRF) technology for beam acceleration has been much advanced, since pioneering works realized with CEBAF at JLab, Tristan at KEK and LEP-II at CERN in 1980s as summarized in Table 1, and shown in Fig. 6 [24].

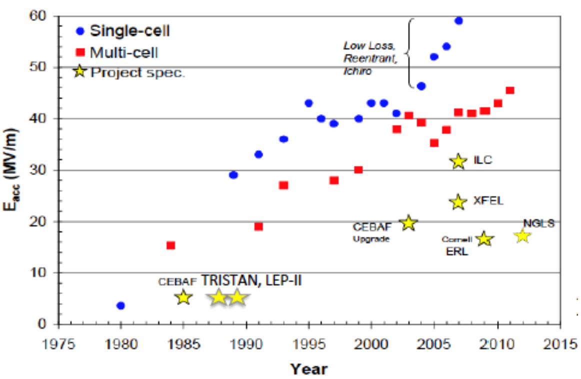

Figure 6: Progress of field gradient in single and multicell SRF cavities.

It should be noted that European X-ray Free Electron Laser (XFEL) SRF accelerator has been completed, as the installation in to the tunnel shown in Fig. 7, and successfully started beam acceleration by using ~ 800 multi-cell SRF cavities in pulsed operation at 1.3 GHz, 2 K, and to create the first light for new photon science experiments to start in near future [25, 26].

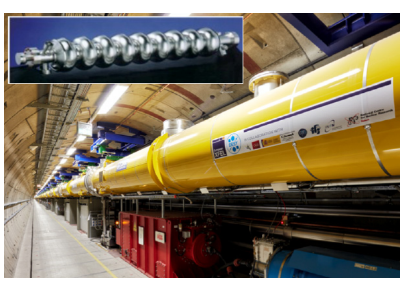

Figure 7: The European XFEL accelerator with 1.3 GHz superconducting 9-cell cavities.

Figure 8 shows statistical results of the ~ 800 9-cell SRF cavities industrially produced and tested at DESY including additional surface rinsing in some fraction to reach this result, reaching quality factor, Q_0 of $1x10^{10}$, as

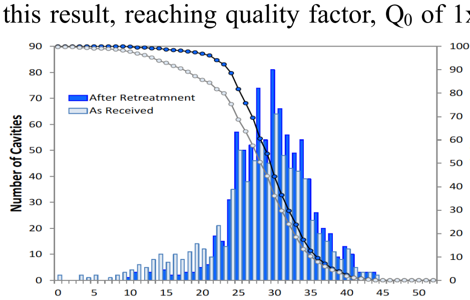

Figure 8: Field gradient distribution for the European XFEL cavities from their individual test.

usable cavities [27,28].

It should be also noted that three major SRF accelerator projects of LCLS-II at SLAC in cooperation with Fermilab and JLab, FRIB at Michigan State University, and European Spallation Neutron Source at ESS are under construction to start their operations for science, in a time range of 2020 – 2025 [29-31]. The International Linear Collider (ILC) is being prepared as a global project to be realized in 2030s [32-34].

Prospects for SRF Technology

The SRF cavity performance, the field gradient and quality factor (Q_0), will strongly depend on the cavity surface conditions such as material, physical conditions, surface treatment, and cleanness. Thin-film doping/infusion and/or coating technology should be an important to figure out some breakthrough for improving the performance.

A nitrogen doping (N-doping) technique has been discovered and demonstrated at Fermilab as shown in Fig. 9 [35, 36] and it has been a very important breakthrough to improve the quality factor Q_0 resulting in the cryogenics power saving. It has been well established, transferred to industry, and applied for the LCLS-II SRF project.

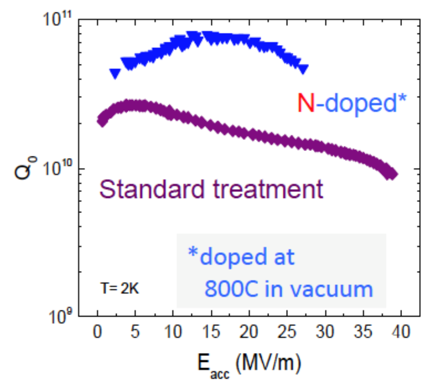

Figure 9: Effect of nitrogen doping to improve Q_0.

Further discovery of the "nitrogen infusion" technique has been also made at Fermilab [37]. It consists of infusing very thin-layer on the cavity surface with nitrogen, at a lower temperature in vaccum. to control the nano-metric diffusion depth, as shown in Fig. 10 [38]. It has resulted in a gradient of 45.6 MV/m with achieving Q_0 of $2x10^{10}$.

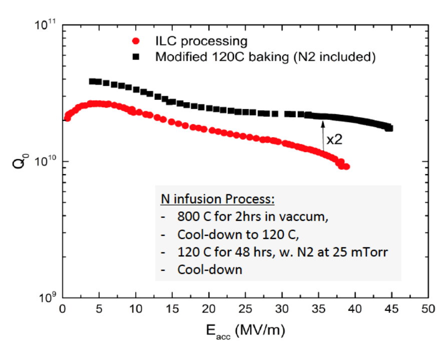

Figure 10: "Nitrogen infusion" process demonstrated a Fermilab, resulting in high-Q and high-G.

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Global efforts are being carried out to confirm this process and the performance improvement. It will critically contribute to the energy frontier collider project such as ILC.

Theoretical efforts have been also carried out to understand the scientific background, and the effort for the thin-layer and/or thin-film are major subjects for future SRF cavity advances [39-43]. In this direction, Nb3Sn or MgB_2 thin-layer coating on Nb-bulk or other material will be a very interesting approach for future [44], because of their much higher B_{sh} for the practical upper limit of the magnetic field for the SRF cavities. Further prospects including cavity shape optimization are discussed in references [2, 3, 45].

SUMMARY

Superconducting technology will be inevitable to approach any energy/power frontier particle accelerators, increasing energy and saving power consumption, (Green Accelerators).

High-field (11-12T) magnet technology is being matured with Nb_3Sn superconductor, to be applied in real projects, and further R&D effort to increase available current density and cost-saving will be inevitably required for future energy/power frontier accelerators. HTS needs to be matured in magnet technology and the cost saving in mass production will be a key for future accelerator application.

SRF technology has been much advanced in past 20 years, with bulk Nb technology. Thin-film science and technology will be a key for extending the field gradient and for saving cooling power in future application expansion, as well as ERL SRF technology.

The superconducting technology will be extended to wide range of science and technology including photon science, material science with spallation neutron sources, medical applications, and further industrial applications.

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