STATE-OF-THE-ART AND FUTURE PROSPECTS IN RF SUPERCONDUCTIVITY*

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Abstract

Performance of the superconducting radio frequency (SRF) cavity has been remarkably improved in the last two decades. The gradient has been reached over than 50MV/m with single cell cavities and 40-45MV/m even with 9-cell structures like ILC. The gradient is approaching the fundamental limit. This paper will review the progress in performance of SRF niobium cavity over the past 50 years and explore future directions.

SPECIFICS AND CONSTRAINS

It is important to see the specifics and constrains in SRF cavity in order to understand such a long R&D history. Fig. 1 illustrates them. When microwave is put into a cavity, surface current induced by the microwave flows on the skin surface. This surface current produces a heating by Ohmic loss mechanism by the surface resistance. The surface skin depth is several micron typically on normal conductor like copper with high electric conductivity and typically 500Å for niobium SRF cavity. This means that SRF cavity is much sensitive on the surface properties than normal conductor.

The surface resistance of SRF niobium cavity is typically 10nΩ at 2K and extremely small. On the other hand, that of normal conductor is typically a tenth of mΩ order. SRF cavity is smaller by 6th order of magnitudes than normal conductor. RF surface heating is dominant in normal conducting cavity but is not the case for SRF. In SRF cavity, the heating is dominant by unexpected phenomenon and limits the performance. As seen in Fig. 1, the heat transfer from the heating site to liquid helium is very important.

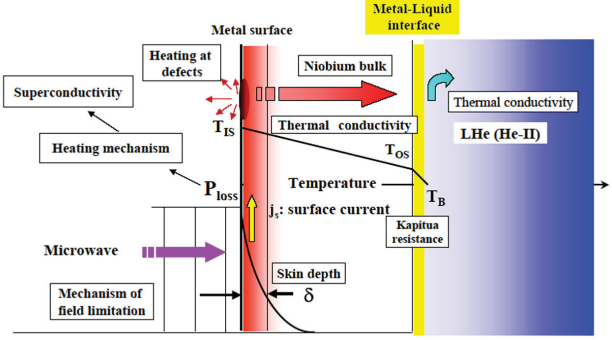

Figure 1: Specifics and constraints with SFR cavities.

Superconductor usually has a poor thermal conductivity. Temperature rises over T_C (critical temperature of SC state) breaks superconducting state. Higher thermal conductivity of niobium material or using superfluid liquid helium with very high thermal conductivity or using both allows suppression of the temperature rising and results in higher gradient. As a summary,

1) SRF cavity performance is very sensitive on the thin surface property.
2) Unexpected phenomenon limits dominantly the performance because of the very small surface. resistance.
3) Efficient cooling is critical to push up the gradient.

HISTORY OF THE SRF CAVITY R&D

The history of SRF cavity R&D could be divided into three stages; early stages of development in 1965-1980, successful its application for storage ring in 1981-2000, high gradient development for ILC (International linear collider) application. Fig. 2 summarizes the history, which is arranged mainly from cavity performance pint of view.

Early Stage of Development

The R&D of SRF cavity was triggered by Turner et al. at Stanford University around 1965. They thought to use SRF cavities to linear accelerator. In this early development, most important technologies have been developed; niobium material, electron beam welding (EBW), buffered chemical polishing (BCP) and electropolishing (EP), temperature mapping system as a diagnostics. At the begging, they used lead because it could electro-plated on copper substrate cavity. After that, they selected niobium having better superconducting performance than lead. It is surprised that surface magnetic field was already reached 1500Oe with electropolished niobium cavity, which corresponds to 35MV/m with the current SRF cavity design. Single cell cavity performance was excellent but multi-cell cavity showed a very limited performance due to multipacting (MP).

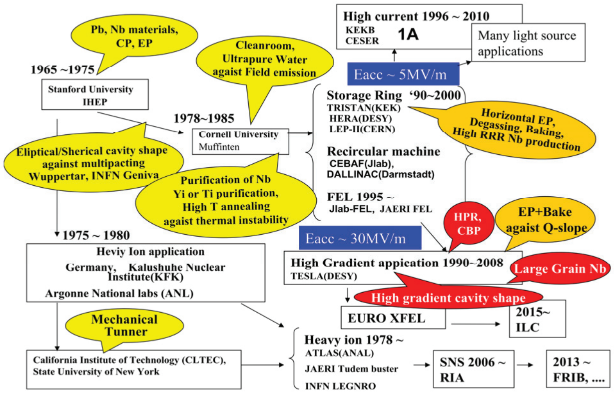

Figure 2: History of SRF cavity R&D over 50 years.

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** On leaving KEK to Michigan State University in USA

Finally they gave up SRF cavity application to LNAC, thereafter they constructed a linear accelerator well known as SLAC today by normal conducting technology .

After the Stanford University, SRF cavity activity was split into two areas for heavy ion accelerator (CW operation); Karlsruhe nuclear institute (KFK) in Germany and CALTEC in USA. EP was more studied and current oscillation method was developed at KFK under the collaboration with SEMES. They applied this method to horizontal EP method for multi-cell structure. On the other mechanical vibration issue in operation was solved at CALTEC using tuner system. The history of the early stage is seen in Hasan's book [1].

Successful SRF Cavity Application for Storage

Coming to '80, high energy physics community needed high energy colliding machines e^-/e^+ (TRISTAN, LEP) or e^-/p^+ (HERA) in order to explore new particle physics. Nuclear physics also required recirculating CW high energy electron machine (CEBAF) to describe the nuclear structure by quark freedoms. These machines are operated in CW at the gradient ~5MV/m. SRF cavity is the best choice because normal conducting cavity needs so much electricity due to the large wall heating. In a storage ring, beam is repeatedly accelerated every turn at the same cavity. So high gradient is a less issue than LNAC in which the beam is accelerated only once at the cavity. Beam instability by interaction between beam and cavity is much concerned in the storage ring. A lower frequency is preferable to mitigate this issue because the bore radius of the cavity can make larger. 500MHz in TRISTAN, HERA, and 350MHz for LEP-II were chosen, which prefer to operate cavity at 4.2K due to smaller BCS surface resistance. 1500MHz for CEABF was chosen and operated at 2K. In these cavities, cross section becomes larger and results in large SRF surface, and long EBW path in cavity fabrication. These are disadvantages. In this stage, however, as seen below many innovations appeared; cavity shape, high pure niobium material vendor production, suitable preparation processing methods for multi-cell cavities, clean assembly, and so on.

Elliptical/Spherical Shape today, elliptical or spherical shape is always applies for SRF cavity. It was discovered that these shapes can suppress multipacting [2]. Fig. 3 shows the suppression. This let it easy to realize multi-cell structures which make acceleration with a higher efficiency. Thus, MP issue at the Stanford University was removed.

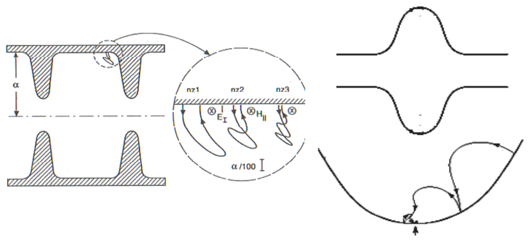


Figure 3: Multipacting in early multi-cell structure (left) and its suppression by elliptical shape (right).

High RRR Niobium Vendor Production in those days, surface imperfections like EBW defects or contamination limited the performance. Improving thermal conductivity of the cavity wall helps to push up the limit. Residual resistance ratio (RRR) is well defined instead of the thermal conductivity. RRR is the ratio between DC resistance at 300K and that of 10K for niobium material. RRR is linearly proportional to the thermal conductivity at 4.2K. It can be easily measured. To date RRR is used as the quality parameter of niobium. In early of 80' reactor grade niobium material with RRR 20~30 was only possible to use.

In end of the '70, SRF activity moved to Cornell University. There fundamental study took place to improve thermal conductivity of the niobium material. Thermal conductivity is limited by scattering between electrons and interstitial light elements in the material, especially Oxygen in niobium material. Purification methods were developed using Yttrium or Titanium. Both utilize getter reaction by higher oxidative effect than niobium and successfully pushed RRR up over 200 [1].

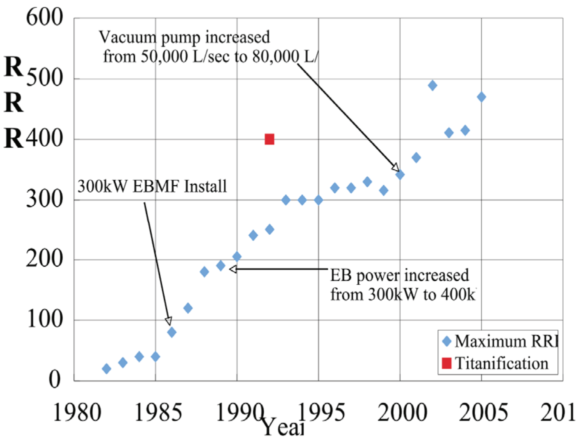


Figure 4: A history of improvement high RRR niobium.

On the other hand, such efforts influenced to niobium vendors. Fig. 4 shows a history of RRR improvement of niobium ingot in a vendor. Niobium ingot is refined by electron beam melting (EBM) in vacuum. Three methods are known to improve RRR of the ingot; wide molten pool surface namely large ingot, high vacuum of the EBM chamber, multi-repeated melting. The last one is easy because no facility change is required. By end of 80', niobium vendors have improved RRR over 200 by this method as seen in Fig. 5, by the following investment of vendors over 400, namely larger ingot production and improving vacuum pressure in the EBM chamber [3]. Recent remarkable improvement of SRF cavity performance owes to the vendor production of reliable high RRR niobium materials.

Innovation of Preparation Technology for Production target of the gradient was ~5MV/m for storage ring application because of CW operation. Such a gradient was achievable by both BCP and EP. The total EBW seam length is about 15m in a 500MHz 5-cell cavity. Defect free EBW seam was unexpected in such a long

EBW path. KEK mechanical ground every EBW seam before bulk EP. This worked as a good QA procedure.

BCP is simple and cost-effective. Many institutes preferred BCP in Europe or USA. KEK chose EP valuing the finished smooth surface. Fig. 5 shows the surface finishing of the fine grain niobium by BCP(left) and EP(right). Grain boundary steps are much smoother in EP. Suitable preparation system has been established in both cases. Especially horizontally rotated EP system was innovated by the systematic study [4]. To Date this is a baseline technology for high gradient cavity like ILC. Fig. 6 shows the horizontal EP system for TRISTAN cavity. This technology was transferred DESY and Jlab in 2000.

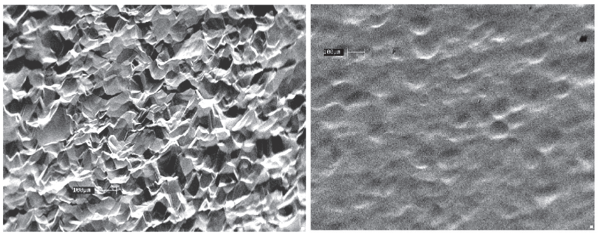


Figure 5: Surface finishing by BCP(left) and EP(right).

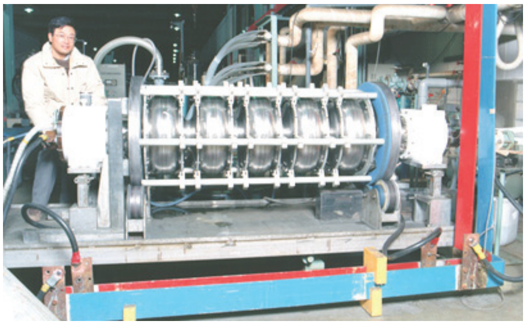


Figure 6: Horizontal continuously rotated EP system innovated in TRISTAN project.

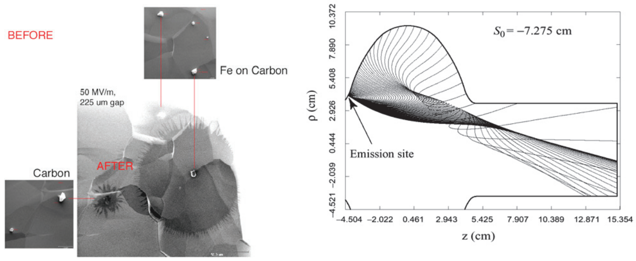


Figure 7: Field emission study at Cornell University. Courtesy of H. Padamsee.

Field Emission Study and Application of Semiconductor Technology another issue was field emission (FE) in this age. FE is a phenomena that field emitted electrons from the niobium surface are accelerated by the RF field in the cavity and bombards on the opposite cavity wall. Many theoretical studies and experiments took place on this issue, and especially Cornell University has made systematic investigation with simulation and RF measurement with temperature mapping as seen in Fig. 7 [1]. It shows the particle evaporation after RF processing and the trajectory of emitted electrons, which suggests particle is a seed of FE. Thus it was understood that dust free clean surface is essential. Semiconductor technologies were applied to make clean surface. Ultra-pure water, which is highly controlled in dusts and impurities in the water, came to be used for water rinsing in cavity surface treatment process. Clean-room also came to be applied in cavity assembly. To date these two are baseline technology for SRF cavity.

Cavity Performance of Storage Ring Cavities it should emphasize that cavity surface is very large, for instance ~ 4m^2 with TRISTAN cavity. Statics of cavity performance was 9.6±0.5MV/m and Qo=(2.8±0.3) x10^9 with 32 cavities totally [4]. The target performance: Q=2x10^9, Eacc > 5MV/m was well certificated. As a summary, by the following baseline technologies:

1) Application of elliptical or spherical shape,
2) Reliable high RRR niobium material production in vendors,
3) Suitable preparation technologies both BCP and EP,
4) Application of Ultra-pure water and Clean-room, well certificated performance was achieved for the storage ring SRF cavities.

High Gradient Cavity Development

After the successful large scale SRF cavity applications for the storage rings, the R&D path divided into two ways; high current application for high luminosity e^-/e^+ collider and high gradient one for linier collider. As seen in Fig. 2. High current application does not require to upgrade cavity performance itself but needs to damp strongly higher order modes (HOMs) excited by the high current beam. This needs to use single cell cavity. They successfully developed the damper using RF absorber, the succeeded to accelerate electron beam over 1A as KEKB [5]. Hereafter this paper concentrates on R&D on high gradient cavity.

High Pressure Rinsing since 1990 SRF R&D for linear collider (TESLA) has been started at 1.3GHz. The target gradient was 24MV/m. FE was still an issue in such a high gradient. High pressure rinsing (HPR) was innovated for Nb coated cavity by D. Bloss at CERN in 1990 [6] and was successfully practiced for Nb bulk cavities in 1995 by P.Kneisel and K.Saito [7]. Particle free water jet hits SRF surface and eliminates particle contaminations. HPR had brought the first breakthrough in the high gradient R&D as seen in Fig. 8.

Superiority of EP on the High Gradient since 1995 the gradient of 40MV/m was reached constantly at KEK as seen in Fig. 8. KEK has been used the combination of mechanical grinding, EP, HPR and 120°C baking during vacuum evacuation. Other laboratories have been used just BCP and HPR but the gradient was often limited below 30MV/m. K.Saito at KEK asserted the superiority of EP over BCP on high gradient in the SRF workshop '97, Abano in Italy [8]. This changed the flow hereafter on the high gradient SRF cavity R&D.

High Gradient Q-Slope and Baking Effect after the Kenji's assertion above, DESY has tried EP immediately and found the high gradient Q-slope. The gradient was limited below 30MV/m by a Q-drop very similar to FE but without any X-ray. This was a new phenomenon. However, KEK has no Q-slope. DESY carefully studied KEK procedure and found out the baking. They put baking after EP and reached the similar result as KEK [9]. Meanwhile the baking effect on BCP'd cavities was also studied and found the effect partially emerges with BCP'd fine grain cavity case. The behind physics of the Q-slope might be flux entry at grain boundaries. Thus, SRF community have the baseline technology in hand for the high gradient in 1997-2000.

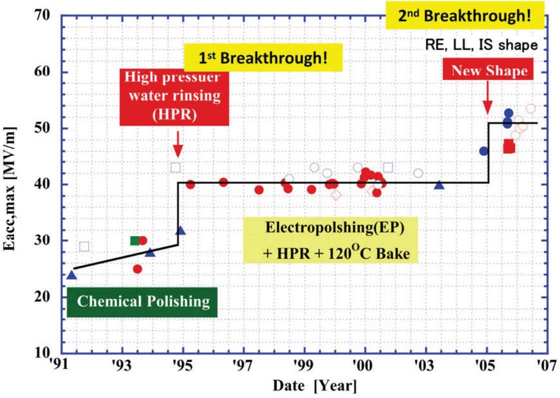
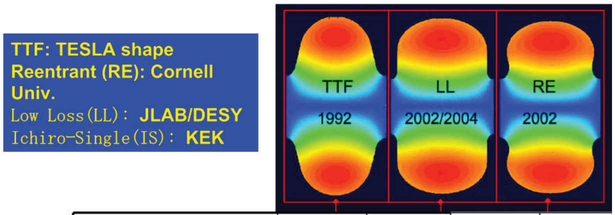


Figure 8: The best gradient since 1991 in TESLA R&D.



	TESLA	LL	RE	IS
Diameter [mm]	**70**	**60**	**66**	**61**
Ep/Eacc	**2.0**	**2.36**	**2.21**	**2.02**
Hp/Eacc [Oe/MV/m]	**42.6**	**36.1**	**37.6**	**35.6**
R/Q [W]	**113.8**	**133.7**	**126.8**	**138**
G[W]	**271**	**284**	**277**	**285**
Eacc max	**41.1**	**48.5**	**46.5**	**49.2**

Figure 9: High gradient cavity shape for ILC. Courtesy of J. Sekutowicz.

High Gradient Cavity Shapes meantime, a thought of limit around 40MV/m in Fig. 8 came to the fundamental filed limitation on niobium cavity, which resulted in the high gradient cavity shape (Fig. 9); Low loss shape [10] and Re-entrant shape [11]. These shape have a ~20% lower Hp/Eacc ratio and expected to push up the gradient over 50MV/m. R&D of such high gradient shape was approved as an ILC R&D in the ILC R&D program in 2005. It have made the 2nd breakthrough in 2006 as seen in Fig. 8 [12].

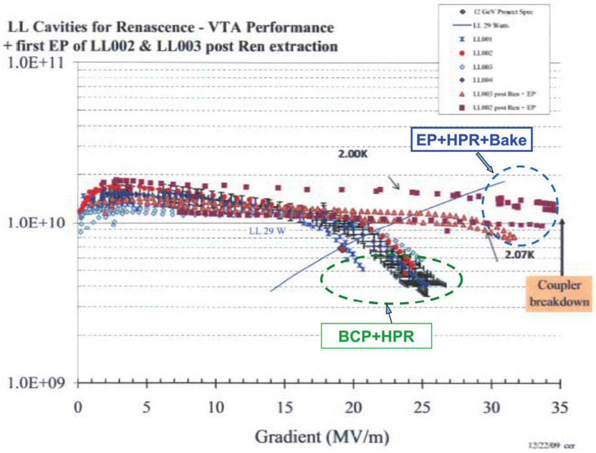


Figure 10: Cavity performance compared with the old and the state of art in Jlab CEBAF 12GeV upgrade project. Courtesy of C. Reece.

The State-of-the-Art Technology impressive improved SRF cavity performance is seen in two cases; Jlab 12GeV CEBAF upgrade and recent USA ILC activities. Fig. 10 shows for 12GeV CEBAF upgrade [13]. The original CEBAF cavity is elliptical 5-cell structure with rather a large Hp/Eacc = 47 Oe/(MV/m) and processed by just BCP. Those days HPR was not available for production yet. The typical performance is seen at the left bottom in Fig. 10. The 12GeV upgrade has applied LL shape 7-cell structure at 1.5GHz. Combination of BCP and HPR on LL shape cavities improves rather in not only the gradient but also Qo value, however, the gradient is still limited around 25MV/m by the Q-slope. The combination of LL shape, EP, HPR and Bake improves the gradient over 30MV/m with flat Q.

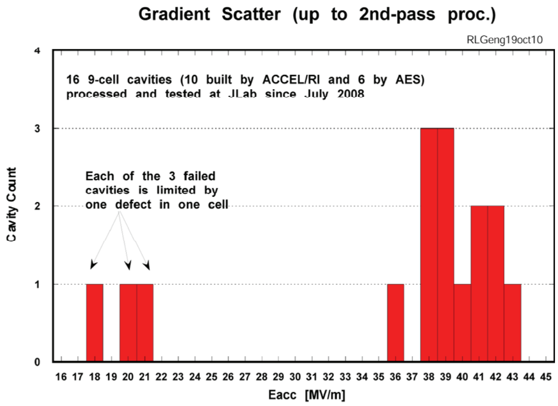


Figure 11: Statics with ILC cavities by the state of art technology in ILC activities USA. Courtesy of R. Gen.

Figure 11 shows the current ILC R&D status in USA [14]. The statics shows the result of sixteen ILC 1.3GHz 9-cell cavities by baseline preparation; EP, HPR and 120°C bake. Thirteen cavities of them have reached the ILC specification; 35MV/m, Qo $=0.8\text{x}10^{10}$. The other three cavities were limited around 20MV/m by defects near EBW seams. The centrifugal barrel polishing which is a kind of mechanical grinding developed at KEK should work to improve the gradient. It has been demonstrated in FNAL in 2011. kind of mechanical polishing method developed at KEK should work to improve the performance. It has been demonstrated in FNAL in an ILC 9-cell cavity in 2010 [15].

FUTURE PROSPECTS

Niobium Bulk Cavity

As already mentioned above, niobium bulk SRF cavity is getting reach to the fundamental critical field by Hc(2000Oe). Around 60MV/m might be the limit, even using large grain/single crystal material. The only one remained improvement is to increase the space factor efficiency like superstructure. This will push the gradient effectively by 8% but not so much. Niobium cavity has no hope the gradient over 100MV/m.

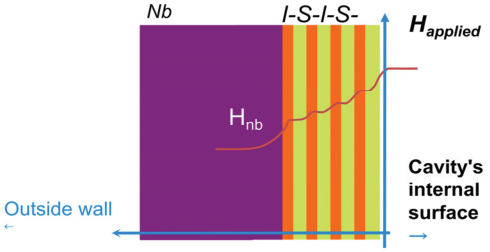
Classic HTS

Now new material is being explored in the SRF field for over 100MV/m gradient. In such an extremely high gradient application, gradient and Qo both have to be improved, otherwise cryogenic load limits the application. New material has to have higher Tc and Hc than niobium. Nb_3Sn was extensively studied with vaporization method at Wüppertal University in 80'-90' but high performance expected was not obtained. Vortex penetration mechanism might limit the performance. High temperature superconductors (HTS) discovered since '80 like YBCO is unusable for SRF application because of the d-wave superconducting phase. The candidates could be classical BCS HTS like Nb_3Sn (thin film), NbN or MgB_2, of which surface resistance increases with $\exp(-\Delta/k_BT)$.

Thin Film Multi-Layer Cavity

The materials above are brittle and have to be coated on a substrate cavity. An idea based most based on vortex penetration theory is proposed with the thin film multi-layers (TFML) on niobium cavity by A.Gurevich in 2006 [16]. As shown in Fig. 12, superconductor and insulator films are coated alternately on niobium surface by 4~6 layers. The points of this idea are; enhance the H_{C1} by making the HTS film with $d < \lambda$ and mitigate the weak like mechanism, and shield niobium surface from RF field to prevent vortex penetration. Niobium substrate can prevent the SRF surface from the perpendicular flux penetration of the residual magnetic fields.

Sputtering technology is a kye for TFML. Nb sputtering technology was well established for LEP-II cavity at the gradient of 5-10MV/m operation, however, its high gradient application is very hard because of Q-slope by weak link mechanism at fine grain boundaries. The effort is continuing over 20 years on this issue. Recently single crystal Nb film has been successfully developed in several cm^2 scale surface and the importance of preparation of substrate is also understood. Film coated cavity has own issue, so the TFML could be not straightaway and will take a time to reach the expected performance.



$$H_{Nb} = H_{appl}\exp(-\mathrm{Nd}/\lambda)$$

Figure 12: Concept of the thin film multi-layer cavity. Courtesy of A. Gurevich.

Material Evaluation

High peak short pulsing measurement method is very suitable for new material hunting. SLAC and Cornell University are investigating new materials by this method. Recently SLAC has investigated one S-I layer of $100nmMgB_2/20nmAl_2O_3$ coated on a niobium X-band cavity [17]. Q degradation is observed from 400Oe surface magnetic peak, which is a double of the intrinsic H_{C1} of MgB_2. TFML expects the enhancement of H_{C1} about a factor 200. The optimization of the film thickness is a further issue. However, MgB_2 has two phase consisted of s-wave and d-wave. D-wave is unusable due to the dominated surface resistance proportional to T^2. The band gap of s-wave is 2.3meV with MgB_2, which is rather small compared to 2.6meV of NbN and 3.1meV of Nb3Sn. Theoretically MgB_2 is not expected the performance as good as NbN or Nb_3Sn.

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