# CRITICAL FIELD LIMITATION OF THE NIOBIUM SUPERCONDUCTING RF CAVITY

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*Abstract*

The highest gradient with niobium sc rf cavities at beta = 1 was viewed historically. There is no progress from 40 MV/m since 1995. Is this due to no finding breakthrough technology, or does it mean a theoretical field limitation? In this paper, the best results are compared to the lower critical magnetic field ($H_{c1}$) or superheating field of niobium material measured in KEK, The highest 40 MV/m might be the upper limitation from Hc1 of niobium material.

## 1 INTRODUCTION

There is a hypothesis that rf field limitation in a superconducting cavity will be a so-called superheating field (Hsh), which is expected to exceed the thermodynamic critical field (Hc) of the superconductor by 10 – 20 % at lower temperature [1,2]. By the hypothesis, upper rf magnetic field ($H_{RF}$) will be a 2000 Gauss at 1.8 K in high pure niobium material with RRR=300, which corresponds to 46 MV/m in acceleration gradient (Eacc) with our 1300 MHz niobium cavities with Hp/Eacc = 43.8. However, it is still an open question with niobium cavities. To date material quality of niobium, cavity fabrication and surface treatment method have been upgraded so much in past one decade: high RRR (300~500) niobium material can be easily obtained by industrial productions, electron beam welding technology was improved, field emission is nearly solved by high pressure water rinsing technique so on. When the highest gradient is plotted historically in past 10 years as seen Fig.1, there is no progress. Is this no finding a breakthrough technology or does it mean a theoretical field limitation in niobium superconductor? It has therefore a meaning that one compares the highest gradients with magnetic properties of present niobium materials. In this paper the world recorded gradient, which was almost obtained by electropolishing at KEK, Jlab, DESY are compared with $H_{c1}$ measured at KEK. The field gradient of 40 MV/m might be the upper limit with niobium sc cavities.

## 2 $H_{C1}$, $H_{C2}$ MEASUREMENT

$H_{c1}$ and $H_{c2}$ measurements were done in KEK with recent high pure niobium material from Tokyo Denkai (RRR= 250 ~ 400). $H_{c1}$ or $H_{c2}$ of type-II superconductor is very easy. There are two ways: differential method and integrated method. We used the former. In this method, the induced voltage is directly observed. The latter integrates it over the excited external field. The former is much simpler than the latter and is very sensitive to $H_{c1}$. It can also observe pinning effects as presented latter. One weak point is not to measure Hc directly.

Our instrument is sketched in Fig 2. A niobium sample is set on the bottom copper block, to make thermal anchor to the liquid helium temperature. Two thermometers are attached on the sample at the upper and lower sides. The sample temperature is defined by the average value. On the top, radiation shields are mounted in order to intercept radiations through the vacuum tube. The sample is set in vacuum by pumping. A Nb-Ti superconducting magnet applies external magnetic field. The sample is a 2.5mm thick and 5 mm wide and 150 mm long (rectangle cross-section). A thin Kapton film is attached on the sample surface and the pickup coil (0.2 mm copper wire) was wound 250 turns on it. External magnetic fields were increased with a constant speed (10A/min corresponding to130Gauss/sec). Pickup signal was observed by a high sensitive recorder (highest sensitivity 0.1 μV range).

Two samples were prepared. Both samples are machined from a niobium sheet with RRR=246 from Tokyo Denkai. One is directly measured as received, then chemically polished by 100μm (CP). The other sample is annealed at 1400°C for 4 hours with titanium getter after a light chemical polishing (CP 10μm). The RRR value was improved to 400.

Figure 2 illustrates the output signal from the pickup coil: as received with RRR=246 (raw material), as removed by chemical polishing (CP) 100 μm, as annealed at 1400°C with RRR=400. Every measurement has a constant induced voltage due to a gap by Kapton film between pickup wire and sample surface. It is different in

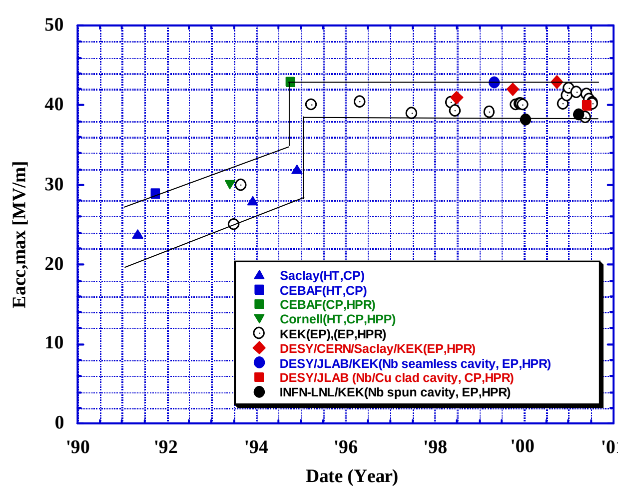


Figure 1: Progress in high gradient with niobium sc cavities in the last one-decade

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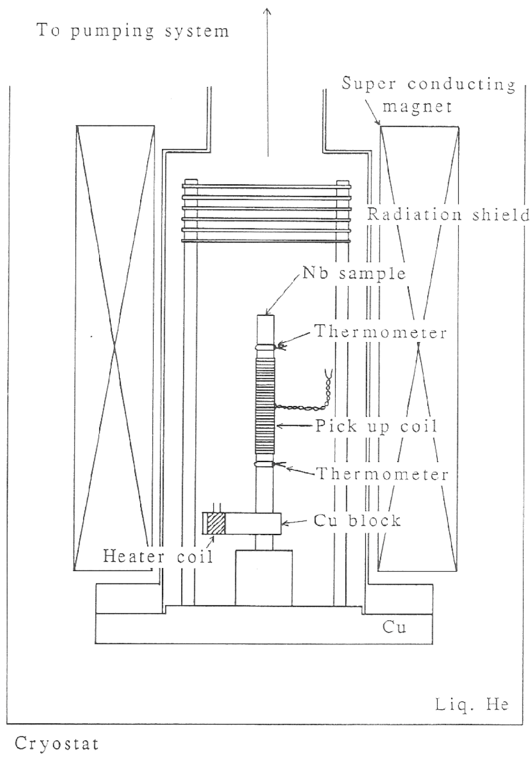


Figure 2: Measurement system of Hc1 or Hc2

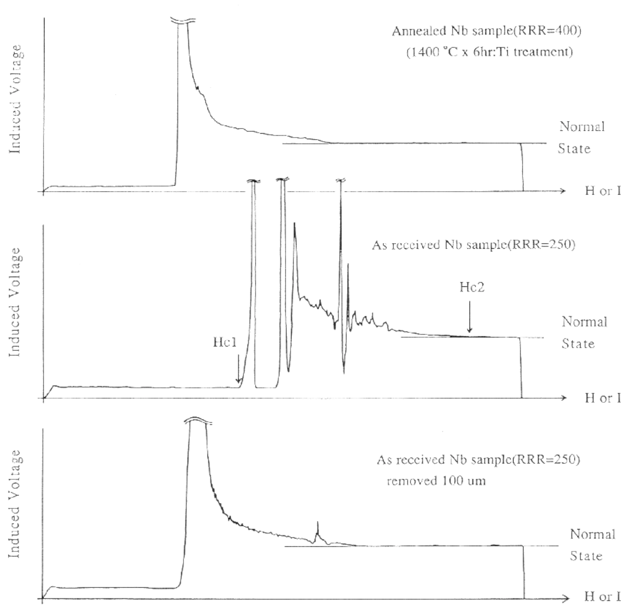


Figure 3: Output signal from the pickup coil

sample to sample because the gap is not same. When the external field exceeds Hc1, it starts to penetrate the material. Then a large induced voltage appears. One can see flux jumping with the raw material (middle of Fig.3). It happens by the following mechanism. The surface imperfections by sample machining act as a strong pinning centers. Even increasing the fields, fluxes are tightly trapped on the surface and cannot enter into the material, resulting in zero pickup signals. While the field becoming strong enough, the trapped fluxes moves into the material, then a large induce voltage appears (flux jump). Such a process continues in the surface defect layer. When a full annealing (1400°C) is done, or the surface imperfection is removed (by CP), flux jumps disappear (see the top and bottom graphs in Fig.3).

Our measurement method can obtain Hc1 and Hc2 only. Fig.4 is the temperature dependence of the Hc1 in this experiment. The results were compared with early measurements by A.R.French [3] to confirm the consistency. The results with fully annealed or material removed samples have a good agreement within 4% with his results. The larger values in both Hc1 and Hc2 with the row material may look to be doubtful but there is a physical meaning, which comes from the pinning effects in the surface defect layer. When removed enough surface (> 50 μm), they go down the normal value as shown in Fig.6. One can use itself to investigate surface defect layer [4].

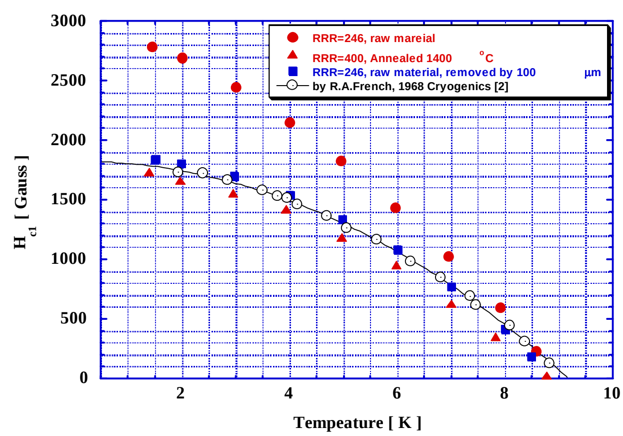


Figure 4: Temperature dependence of Hc1

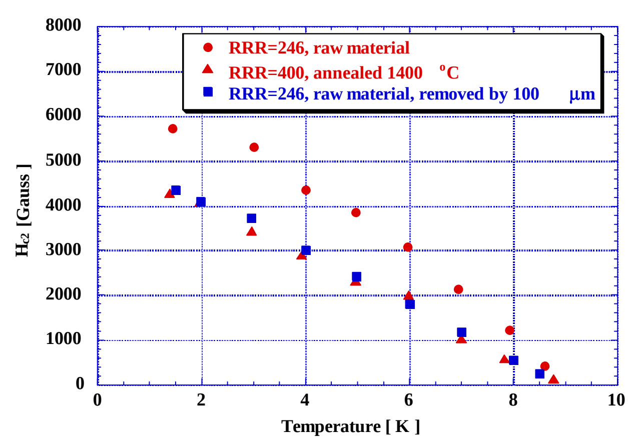


Figure 5: Temperature dependence of Hc2

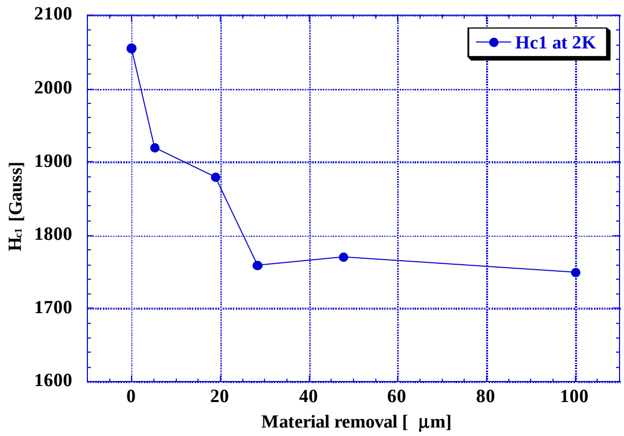


Figure 6: Enhancement in Hc1 due to flux trapping in surface defect layer

## 3 PRESENT ART OF HIGH GRADIENT WITH β=1 MONO-CELL NB CAVITIES

Figure 1 shows the highest gradient with β=1 1300 MHz mono-cell niobium cavities in last one decade. All the data were measured by CW rf measurement. A clear progress is seen until 1995 by new technologies: high temperature annealing (HT), high peak power processing (HPP) developed at Cornell University. In 1995 high pressure water rinsing (HPR), which was developed at CERN by D.Bolss [5], had been used routinely at TJNAF and KEK. This technology has solved field emission problem and made a jump as seen in Fig.1.After eliminated field emission, several new findings made about high gradient; superiority of electropolishing over chemical polishing with high gradient in 1996 [6] and finding of the baking effect in 1997 [7].

Thereafter, seamless niobium bulk cavities were developed in INFN-LNL (spun cavities) [8], DESY (hydro-formed cavities) [9], however, the highest achievable gradient in niobium cavities is not changed since 1995, Seamless cavity fabrication was expected a improvement because of no electron beam welding at equator: high surface current area. It is also not changed in the niobium copper clad cavities [9,10], which has no electron beam welding and high thermal conductivity backed by the copper wall. Here, it has to be emphasized that present worldwide data with high gradient seems to be saturated around Eacc = 40 MV/m even with upgraded fabrication technologies.

## 4 COMPARISON WITH $H_{C1}$ AND DISCUSSION

### *4.1 Comparison with Hc1*

To see such the saturated situation of the high gradient in niobium sc cavities is due to no finding a breakthrough technology or the upper field limitation from magnetic property of niobium superconductor, the highest rf magnetic fields calculated from the highest gradients (Hp/Eacc) are compared with our Hc1 measurement results. The ratio of Hp/Eacc is a 43.8 typically in our β=1 1300 MHz mono-cell cavities. The results are presented in Fig.7, three results of $H_{c1}$ are presented: 1) sample with high homogeneity by 1400°C annealing (—), 2) sample removed 100μm by CP (---) and 3) the measurement result by R.A French[2] (—). These are the fitted results from the measured data. The rf measurement errors are about 5~10 %. The results are well fitted by Hc1 within experimental errors. $H_{c1}$ will limit the $H_c^{rf}$ at the lower temperature.

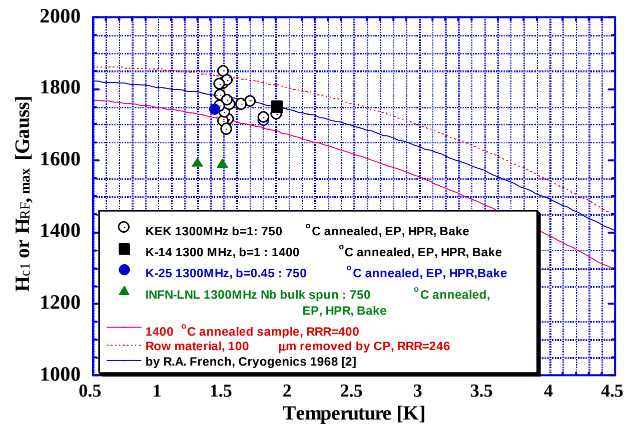


Figure 7: Comparison between present highest field and $H_{c1}$ of niobium superconductor

### *4.2 Superheating field*

There should be a critical opinion against that $H_c^{rf}$ is limited by $H_{c1}$ because $H_{rf}$ field is limited by not $H_{c1}$ but superheating field ($H_{sh}$) at higher temperatures [11]. The superheating field is determined by balancing the loss in condensation energy against the gain in diamagnetic energy which accompanies the formation of a phase boundary in a field H. Most calculations have been done in a one-dimensional limit for which this balance occurs at a plane boundary when the energies per unit area are equal or, when $\lambda_L H^2 \sim \xi H_c^2$. Thus, the dc superheating field is the following [12];

$$H_{sh} = (\lambda_L/\xi)^{-1/2} H_c \qquad (1),$$

where $\lambda_L$, ξ and $H_c$ are, the London penetration depth, the coherence length, and the thermodynamic critical field, respectively. For microwave, however, one should take the effective field, namely $H/2^{1/2}$, then equation (2) becomes;

$$H_{sh} = 2^{1/2} \cdot (\lambda_L/\xi)^{-1/2} H_c \qquad (2),$$

The concept of the superheating is valid for higher temperatures around Tc because it was derived by the Ginzburg-Landau theory [13], which is perturbation theory around Δ~ 0, namely T ~ $T_c$. However, here, we make an assumption that equation (2) is still valid for all the temperature rage, then we can calculate $H_{sh}(T)$ from $H_c(T)$ and $H_{c2}(T)$.

Hc is defined as following:

$$F_n(T) - F_s(T) = -\int_0^\infty M dH = H_c^2/(8\pi) \quad (2),$$

where $F_n$ and $F_s$ are the free energies per unit volume in the normal and the superconducting states, respectively. Magnetization curve measurement (integration method) gives Hc but our measurement gets only the temperature dependences of $H_{c1}$ and $H_{c2}$. However, there is given an expression between $H_{c1}$ and Hc in the reference [3] as following:

$$H_{c1}/H_c = 0.9[1+0.0925*(1-T/T_c)] \quad (3).$$

We calculate $H_c(T)$ using the equation (3) and our measured $H_{c1}(T)$. On the other hand, by G-L theory $H_{c2}$ and Hc are related to $\xi$ and $\lambda_L$ as followings [12]:

$$H_{c2} = \phi_0/(4\pi\xi^2) \quad (4),$$

$$H_c \cdot \xi\lambda_L = \phi_0/(4\pi) \quad (5),$$

where $\phi_0 = hc/2e = 2.067\times10^{-7}$ $Gcm^2$ is the fluxoid quantum. We can derive $\xi(T)$ and $\lambda_L(T)$ from these relations, the measured $H_{c2}$, and the calculated Hc from measured $H_{c1}$. The results are presented in Fig.8. We used results of the 1400°C annealed sample for the calculations. By the G-L theory, temperature dependence of $\lambda_L$ and $\xi$ is given as followings:

$$\lambda_L(T) = \lambda_{L0}/[1-(T/T_c)^4]^{1/2} \quad (6),$$

$$\xi(T) = \xi_0/[1-(T/T_c)]^{1/2} \quad (7).$$

As seen in Fig.8, data were fitted by three free parameters (A,B,C);

$$Y = A/[1-(T/B)^C]^{1/2} \quad (8).$$

A = 438.62Å for $\lambda_L$, 180.51 Å for $\xi$ are fitted respectively. On the other hand, C = 5.34 for $\lambda_L$, 1.14 for $\xi$ are obtained, respectively. B = $T_C$ = 8.60 was reasonably obtained in both fittings. The temperature dependence of $\lambda_L/\xi$ is presented in Fig.9. It changes linearly over the all temperature rang. The calculated $H_{sh}(T)$ by the equation (1) is shown in Fgi.10 with Cornell's and KEK's results. The results were nicely fitted all over the temperature range. However, around 2K, three kinds of fields ($H_{sh}$, Hc, $H_{c1}$) are very close each other within 5%. Therefore, it is not wrong to say $H_{c1}$ limits the $H_c^{rf}$. One will understand the maximum $H_c^{rf}$ is 1800 Gauss at T < 2K. If designing Hp/Eacc < 36, then one cane get Eacc = 50 MV/m but it will be not so easy. From this analysis one can notice that the fabrication technology has already come to the theoretical limit with niobium. If looking higher gradients Eacc = 40MV/m, we have to go to other material as $Nb_3Sn$, $B_2Mg$ high Tc materials, which is now undergoing [14,15]. However, in such developments, magnetization curve measurement will give us a very good prospect.

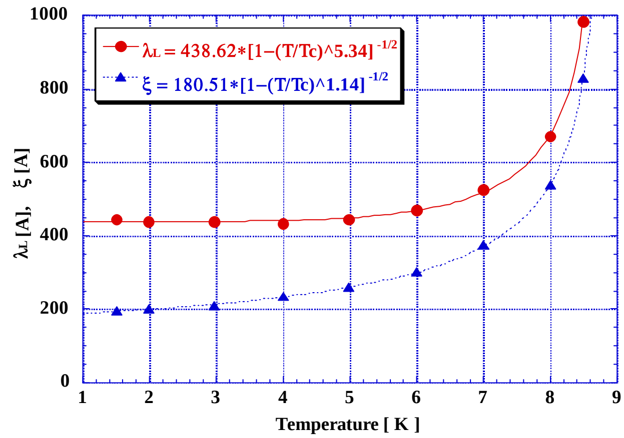


Figure 8 : Temperature dependence of $\lambda_L$ and $\xi$

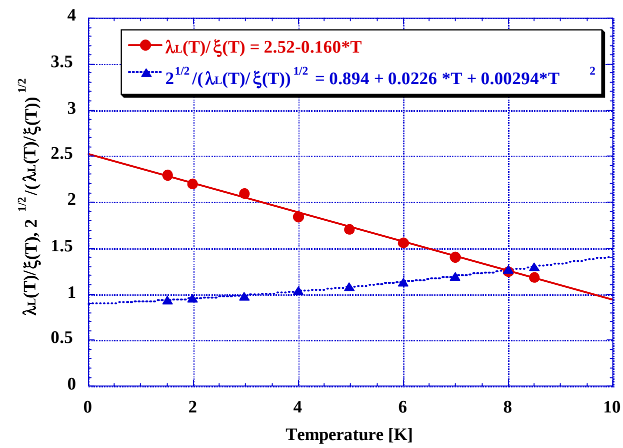


Figure 9 : Temperature dependence of $\lambda_L(T)/\xi(T)$ and $2^{1/2}/(\lambda_L(T)/\xi(T))^{1/2}$

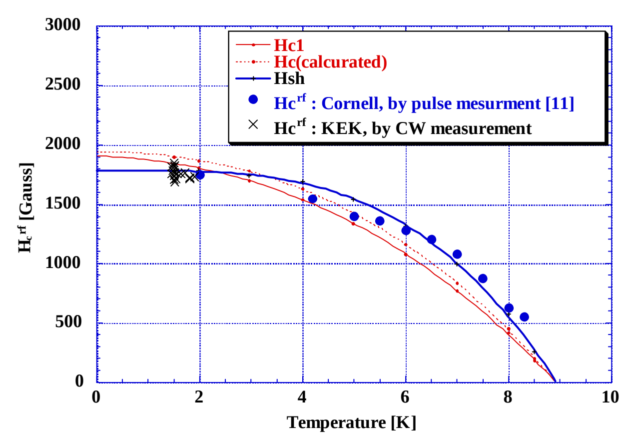


Figure 10 : Comparison $H_c^{rf}$ (T) data with $H_{sh}$ (T), Hc (T) and $H_{c1}$(T)

## 5 CONCLUSION

In this paper, the worldwide highest gradient of sc niobium rf cavities is viewed historically. It looks to be saturated since last 5 years. We measured the magnetic properties of present industrial produced niobium materials with RRR = 250. The results were compared with the high gradient. By a calculation superheating field from these material parameter, Hsh is really limiting the $H_c^{rf}$ is confirmed. Simply saying, $H_{c1}$ limits the $H_c^{rf}$ less than 2K.

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