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PROPOSAL FOR TeV-SUPERCONDUCTING LINEAR COLLIDER

K.Saito*, M.Yoshioka, KEK Accelerator Lab, Tsukuba-shi, Ibaraki-ken, 305-0801, Japan

Abstract

L-band superconducting (SC) RF technology is an excellent choice for a sub-TeV e^+/e^- linear collider (LC), which is currently being considered by the world high-energy physics community. This technology has several advantages compared to X-band warm technology such as beam stability, high luminosity, and cost effective operation performance. However, the gradient is currently limited to 35MV/m, which is lower than that of the X-band (52MV/m with beam loading). In this paper, we will describe how to upgrade the gradient up to 50MV/m in the cold. In addition, applying a superstructure can improve the fill factor of RF structures. Thus, a way to 1 TeV SCLC will be developed in a 33km tunnel.

1. INTRODUCTION

Since the 1980s, linear collider (LC) R&D has been aggressively conducted worldwide. The energy reach of LC is noted in "the parameter for Linear Collider"[1], which says " the strong likelihood that there will be new physics in the 500-1000GeV range means that the upgradability of the LC to about 1 TeV is the highest priority step beyond the baseline". ITRP[1] (International Technical Recommendation Panel) will choose between the cold (L-band superconducting: TESLA) and the warm (X-band: GLC/NLC or C-band) technology by the end of this year. TESLA collaboration has already accomplished the ranking 1 R&D issues[1] (R1), which is required from the TRC (Technical Review Committee), for TESLA-500. On the other hand, the maximum energy of the original TESLA scheme is limited to 800GeV, which is lower than that of X-band warm scheme. The authors are convinced that TESLA-500 is feasible, but we feel that the energy upgradability should be more seriously considered. Thus, we seek the possibility of creating not 800GeV, but 1 TeV in a 33km long tunnel. One scenario to achieve >1TeV is to adopt a 46.8km long tunnel, which is being considered by the US study group for the US site. However, this long of a tunnel inflates the cost in early TESLA-500 construction. We propose to start TESLA-500 with a gradient of 35MV/m using the existing 9-cell cavity design in the 33km long tunnel. Then this tunnel should be filled with 2x8-cell superstructures that have a 45MV/m operational gradient in order to achieve 1 TeV (hereafter SCLC).

The aim of this paper is to demonstrate using experimental and theoretical viewpoints that a gradient of nearly 50MV/m is possible with a niobium (Nb) SC cavity. We will also show how to achieve 50MV/m and finally to propose a 1 TeV SCLC as the upgrade scenario in a 33km tunnel by applying 2x8-cell superstructure.

2. FIELD LIMITATION OF SRF CAVITY

At least a gradient of 45MV/m is needed in order to reach 1 TeV in a 33km long tunnel. At first, we will discuss the present high-gradient limitation with a Nb SC cavity. Figure 1 shows the last decade history of the high gradient with L-band single cell Nb cavities. In the early 1990s, it was steadily improved by the industrial high-purity Nb production, 1400°C titanium post purification, and so on. In 1995, a high-pressure ultra-pure water rinsing (HPR) became standard in cavity preparation, which resulted in a step-like improvement since the field emission problem was eliminated, but since then the gradient appears to be saturated around 40MV/m. Recently, the DESY group realized 40MV/m for a TESLA 9-cell cavity using their own electropolishing (EP) facility[1].

40MV/m corresponds to a surface peak magnetic field of Hp =1750Oe for a TESLA cavity shape. This magnetic field limitation is typical for different cavity shapes (e.g. Nb cavity with $\beta =$ 0.45 for proton LINAC [1]) or different cavity fabrications (Nb bulk seamless cavities, Nb/Cu clad seamless cavities [2]). These experimental facts suggest that the Nb SC cavity already meets the fundamental SRF critical magnetic field around 1750Oe.

The other interesting experimental results are the direct measurements of the SRF critical field (H_C^{rf}) at Cornell

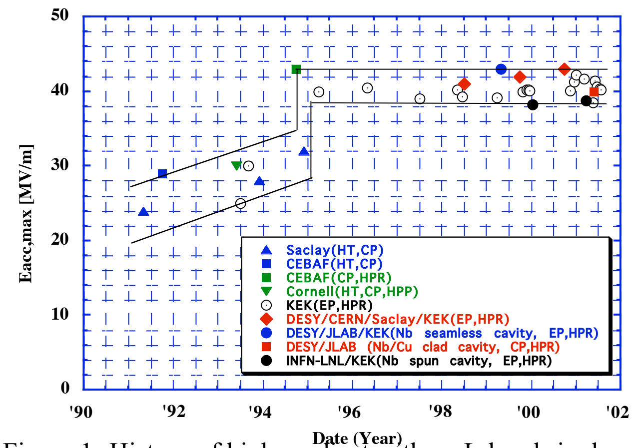

Figure 1: History of high gradient with an L-band single cell cavity.

University [3]. They measured it by a short pulse method on Nb, Nb_3Sn, and Pb cavities. This method can provide H_C^{rf} without the heating problem at temperatures above the λ-point (2.18K). In contrast, below the λ-point, CW measurement (KEK) can provide H_C^{rf} if the cavity does not have defects since the niobium cavity has a small surface resistance and He-II has a very high thermal conductivity.

*ksaito@post.kek.jp, 1 http://www.ligo.caltech.edu/~donna/ITRP_Home.htm, The classical superheating model does not fit the data [3]. The newly proposed formula [4] can fit the data quite nicely, which is obtained by a line vortex flux nucleation model.

$$\mathbf{H_c^{rf}(T) = \sqrt{2} \cdot \frac{\xi(T)}{\lambda(T)} \cdot H_c(T) = \sqrt{2} \cdot \frac{H_c(T)}{\kappa(T)}} \tag{1}$$

Here, H_C is the thermodynamical critical field, ξ coherence length, λ magnetic field penetration depth, and κ the Ginzburg-Landau kappa parameter. The factor $\sqrt{2}$ appears due to the effective magnetic field in the AC application. The temperature dependence of κ is obtained from Abrikosov theory and produces the explicit temperature dependence of $H_C{}^{rf}$ as:

$$\mathbf{H_c^{rf}(T) = \sqrt{2} \cdot \frac{H_c(0)}{\kappa(0)} \cdot \left[1 - \left(\frac{T}{T_c}\right)^4\right]} \tag{2}$$

here, T_C is the critical temperture of the superconductor. Figure 2 shows the fit for the Cornell data using formula (2) and the KEK results with L-band Nb cavities by CW measuements. This fit does not have free-parameters and all parameters like $H_C(0)$, $\kappa(0)$, and T_C are from experimental results for Nb cavities. The absolute value is consistent with the experimental results. This model shows that the $H_C{}^{rf}$ is 1750±50 Oe for the Nb cavity. The improvement in $H_C{}^{rf}(0)$ is only expected to be 5% for ultrapure Nb material (RRR=2000) [4]. The requirment, however, is 25% for 50MV/m, which is impossible to realize by just further improving the Nb material. For the other cavities (Nb_3Sn, Pb), the amplitudes are fitted as free-parameters. T_C is from experimental results. The fitting results are very nice. One will notice that there is

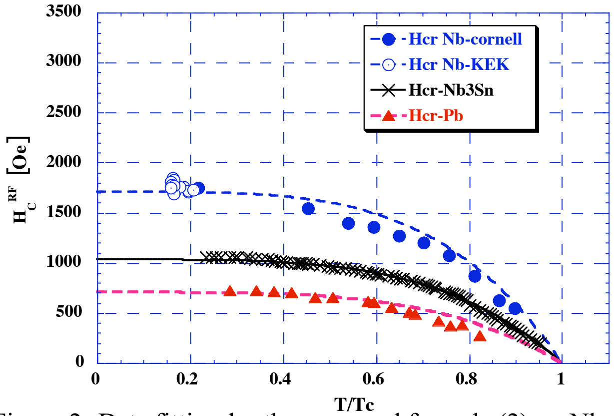

Figure 2: Data fitting by the proposed formula (2) on Nb, Nb_3Sn, and Pb cavities.

no hope for a high gradient in a higher T_C material like Nb_3Sn.

3. NEW CAVITY SHAPE

3.1 Cavity shape

The above analysis indicates that SRF technology meets the theoretical limitation and cannot be further improved. To achieve a 25% upgrade in the high gradient, a new cavity shape with a small Hp/Eacc ratio around 35Oe/(MV/m) must be designed. Here, Hp is a surface peak magnetic field and Eacc is an electric field gradient on the beam axis. For such a low field ratio, the volume occupied by magnetic field in the cell must be increased and the magnetic density must be reduced. In order to satisfy these requirements, the bore radius becomes smaller. A smaller bore radius creates three problems in: 1) poor HOM extraction, 2) weak cell-to-cell coupling, and 3) EP procedure. We must consider these trade offs in the new cavity shape design.

Fortunately, J. Sekutowicz *et al*. published a reference design at 1500MHz [5]. Their purpose was not for high gradient application, but a high Q for the CEBAF upgrades CW operation. Figure 3 is from their paper. They propose a LL (low loss) shape for CW operation. OC is the CEBAF original cavity shape and HG (high gradient) is for the TESLA shape. Table 1 summarizes the RF characteristics for each shape. These RF characteristics are frequency independent from each other. The LL shape has a lower Hp/Eacc ratio: 37.4 O/[MV/m], of which the gradient is expected Eacc = 47MV/m. Sekutowicz *et al*. already examined the HOM issue on a 7-cell superstructure and did not detect any problem with this shape.

3.2 Cell-to-cell coupling

The LL shape has a smaller cell-to-cell coupling κ_{CC} between each cell compared to that of TESLA: 1.72. Cell-to-cell coupling relates to the field error in each cell. The error is given by κ_{CC} as:

$$\mathbf{\Delta E_{acc} \propto \frac{N^2 \cdot \Delta \mathit{f}}{\kappa_{cc}}}$$

where, N is the number of cells in the cavity, and Δf error in the frequency among cells. If the same field error as the TESLA shape is required, the resultant number of cells is 8 as determined by:

$$\mathbf{N} = 9 \cdot \sqrt{\frac{1.49}{1.72}} = 7.99 \approx 8$$

3.3 Ep/Eacc ratio

The LL shape has a slightly larger Ep/Eacc ratio: 2.17 compared to the TESLA shape: 1.89. Here, Ep is the electric surface peak field, which relates to the field emission (FE) problem. HPR technology nearly suppresses the FE problem. KEK has experienced 1750Oe without field emission in a cavity with Ep/Eacc = 5.1, which is fabricated SC for a proton linac [1]. EP technology could reduce the high Ep/Eacc problem in the LL shape.

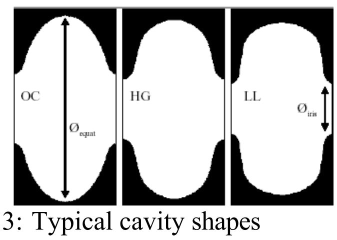

Figure 3: Typical cavity shapes

Table 1: RF parameters for the three shapes

Parameter	OC	HG	LL
Φequator [mm]	187.0	180.5	174.0
Φiris [mm]	70.0	61.4	53.0
κ_{cc}	3.29	1.72	1.49
Ep/Eacc	2.56	1.89	2.17
Hp/Eacc [Oe/(MV/m)]	45.6	42.6	37.4
R/Q [Ω]	96.5	111.9	128.8
Γ	273.8	265.5	280.3

3.4 Electropolishing

The smaller iris may cause a problem with EP. We need to place a cathode with a large enough diameter in the cavity beam hole in order to achieve optimum current density during EP. When scaled to 1.3GHz, the bore diameter of the LL shape is 61 mm. Usually, a diameter greater than 60mm is sufficient for 1.3GHz cavity. Therefore, there should not be a problem with EP.

4. 2_8-CELL SUPERSTRUCTURE

As mentioned above, an 8-cell structure is recommended for the LL shape. However, the lower cell number lowers the fill factor. Here the fill factor is defined as the ratio of the total effective accelerating length over the LINAC length. Using the superstructure, which was invented by J. Sekutowicz in DESY [6], solves this problem. Figure 4 illustrates the 2x9-cell superstructure for TESLA-800. In this case, two 9-cell cavities are welded through one beam pipe, which is half a wavelength long. If two 9-cell cavities are directly connected into an 18-cell structure, the field error seriously increases by a factor 4. This problem is relaxed by connecting the two cavities so that they are offset by a half of a wavelength. This structure has two advantages: 1) an increased fill factor due to the shortness by one beam pipe length and 2) the number of input couplers is cut in half, which can reduce the cost. We propose to use seven 2x8-cell superstructures in the TESLA-type 17m long cryomodule.

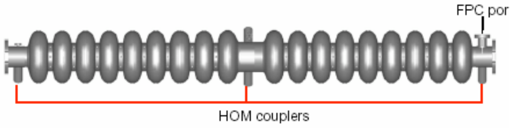

Figure 4: 2x9-cell superstructure for TESLA-800.

The total length of the seven structure-sets is 0.25m shorter than that of the TESLA-500 12x9-cell cavities scheme. In addition, a total of 112 cells can be installed in the module, which is 4 more cells than the TESLA-500 scheme (108 cells) and results in a 20MeV higher energy gain when the structure is operated at 45MV/m.

5. PROPOSED 1 TeV SCLC IN A 33KM TUNNEL

We propose to construct SCLC-500 in a 33km tunnel and to operate the cavities at 35MV/m. The 35MV/m operation will be realized in 2006 at DESY, which is what remains of R1 for the TESLA-800. The DESY group has already started to produce 40MV/m 9-cell structure and there will be less risk in engineering an upgraded structure. This high-gradient operation of 35MV/m will reduce the project cost for the SCLC-500. The 50MV/m cavity R&D can be carried out in parallel with SCLC-500 construction and operation. Thus, there is enough time for these developments. After successful developments, the 7x(2x8-cell) super-structure modules will be newly re-installed in the same tunnel. This scheme can reach 1020GeV at 45MV/m. Table 2 compares the current proposed SCLCs.

Table 2: Current proposed SCLCs

Energy Reach [GeV]	Gradient (MV/m)	LNAC Effective Length (km)	Fill factor (%)	LINAC Length (Km)	Tunnel Length (Km)
TESLA500	23.4	21.8	74.7	29.43	33
TESLA800	35.0 2x9-cell ss.	23.25	79.0	29.43	33
US SCLC500	28.0	17.58	74.7	23.53	46.8
US SCLC1000	35.0	28.30	74.7	37.88	46.8
SCLC500	35.0	14.07	74.7	18.84	33
SCLC1000	45.0 2x8-cell ss.	22.80	77.47	29.43	33

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