KEK PLANS FOR A LINEAR COLLIDER R&D

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Abstract

An overall R&D activities of Japanese Linear Collider (JLC) is surveyed. The JLC is a conceptual plan of post TRISTAN projects in KEK. This is a large linear collider consisting of a pair of linear accelerators of 0.5 TeV each (for electron and positron), and a pair of damping rings. As a preliminary work, an R&D group is promoting the Test Accelerator Facility (TAF) as a pilot plan. The TAF consists of a linear accelerator with an energy of 1.5 GeV and a damping ring, and will be used for the beam acceleration test with a high gradient of 100 MV/m. An R&D on the high Tc superconducting thin film is also underway to investigate possible application to the RF accelerating structure for the superconducting linear collider.

Introduction

What kind of accelerator will be the main one in the field of high energy physics in Japan after TRISTAN ? This subject has been the most serious topics among the high energy accelerator scientists and high energy physicists in Japan in the last five years. It is natural for a high energy accelerator that it debuts as the largest accelerator in the world and, after a rather short time, it gives the honarable position to a new accelerator and retires. This is not an exception, of course, for TRISTAN. If we limit our consideration only to high energy electron (or positron) rings, the maximum energy is limited almost only by the synchrotron radiation power. If the total accelerating voltage per turn is proportional to the circumference L, the size of the electron (or positron) ring will increase with E^2. In Fig. 1, we can see a rough relation between beam energy E and ring circumference L of existing or ever existed electron rings. According to the above consideration, the LEP which is a collider ring of 9 km in average diameter and of 80 GeV in beam energy would be the last largest electron-positron collider ring with a reasonable size. In order to realize collision with a center of mass energy of 1 TeV in a collider ring, the size of the collider ring would be about 350 km in diameter provided that the field gradient of accelerating cavity is nearly the same as that in LEP. For electron-positron collision experiments at energies beyond 100 GeV, the idea of linear collider looks like to be more promising than the collider ring, although many difficulties still remain to be solved in the future.

In 1986, the High Energy Committee, high energy scientist organization in Japan, showed the directions in the fields of accelerator science and high energy physics. One of them being addressed to the accelerator group was to initiate R&D efforts to investigate a possible construction of an electron-positron linear collider with beam energy of 0.5 to 1 TeV as a home-based facility. Responding to this proposal, KEK has organized the JLC (Japanese Linear Collider) study group in 1986 to promote a coherent R&D work on the linear collider.[1]

In 1984, two years before the proposal of the High Energy Committee, a group began an R&D work on lasertron as a new high power RF source. As high power RF sources are also very important in linear collider, the lasertron group has been merged into the JLC group since 1986. Since 1986, main efforts of the JLC group have been concentrated on R&D of high power pulsed X-band klystron and high field gradient test accelerating structures, and design study of Test Accelerator Facility (TAF), together with theoretical study of the linear collider. Recently, an R&D of high T_c superconducting cavity has also been started.

In this report, we survey all activities of the JLC study group, including future perspectives of the JLC plan.

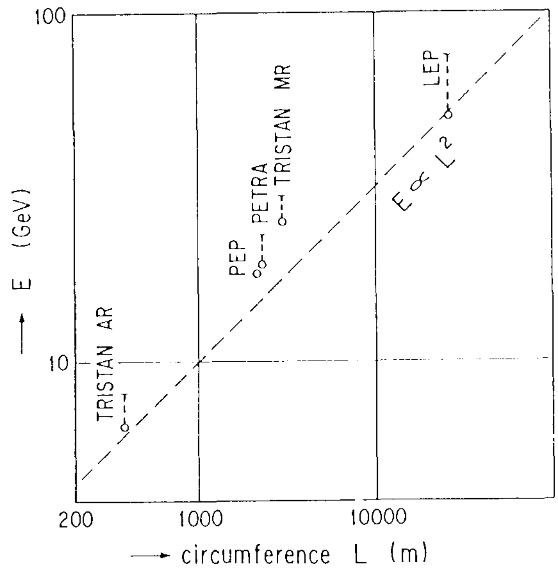


Fig. 1 Relation between beam energy E and ring circumference L of high energy electron rings.

Lasertron

An R&D of lasertron was started in 1984 two years prior to the organization of the linear collider group[2]. The final target of the R&D was to certify fundamental principle of lasertron and to accomplish an S-band RF source of about 1 MW by the lasertron. Intensive efforts have been continued and many good results were botained.

First, a mode-locked YAG laser with a multi-mirror system was built. It emits light in a pulse train of very short width. The pulse width of the light of less than 70 ps was accomplished and by means of the multi-reflection system the pulse interval is reduced down to 350 ps which corresponds to 2856 MHz. In Fig. 2, typical light pulses with a pulse width (FWHM) of 70 ps and a pulse to pulse interval of 350 ps are shown. On the other hand, a photocathode of GaAs with a diameter of 40 mm was tested and verified to have a good quantum efficiency of about 10 % for the light of 532 nm. A problem as to the life of the photocathode is important. We made a life test of the GaAs photocathode under a condition of low cathode voltage and obtained a life time of more than 500 hours. But under a practical operating condition in which a high voltage will be applied to the cathode, the cathode has to suffer a severe damage due to ion bombardment which depends largely upon the surface condition of the electrodes even if the vacuum is kept 1~3 x 10^{-10} Torr. Materials for the photocathode such as Cs_3Sb or Cs_3Sb-K are reported to be promising.

In the RF test of the lasertron, we applied a cathode voltage of 150 kV and obtained a microwave power of 80 kW at 2856 MHz with a duration of 1 μs[3]. In this case, the photo-emitted current was 21 A and the conversion efficiency was about 2.5 % which is much smaller than the typical efficiency of 40 % of a conventional pulsed klystron. According to the numerical simulations,[4] it is considered that the main reason of the low efficiency is due to debunching of electron beams by a space charge effect before reaching the output cavity. This debunching effect becomes severer when the frequency is increased up to 11.4 GHz. To avoid this effect, we have to operate the system at a higher cathode voltage where the debunching is less prominent. Another possible reason of the low efficiency is the time-response characteristics of the GaAs cathode surface. To confirm this

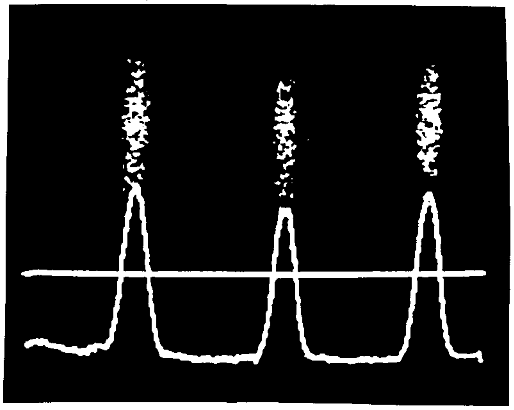


Fig. 2 Light pulse train produced by a mode-locked YAG laser and a multi-reflection system.
pulse width : 70 ps, interval of pulses : 350 ps.

speculation, we are preparing an experiment to investigate the time response characteristics of the photocathode.

It seems that the lasertron is only in an initial stage of development and far from the practical use as an accelerator component. But the photocathode itself is very promising as an electron source of the JLC with a very short pulse width and a very small emittance.

High Field Gradient Experiment

Since the high field acceleration is essential in a linear accelerator of high energy, the performance test of accelerating structure under a high electric field is very important. For the purpose of this test, we

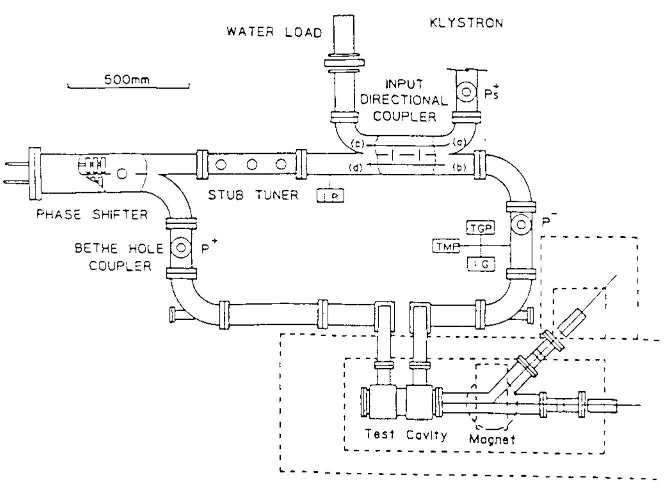


Fig. 3 Schematics diagram of resonant ring system.

constructed a resonant ring system in which a circulating RF power of more than 100 MW was accomplished with an RF source of 30 MW (Fig. 3). This resonant ring is also being used for a high field test of high power RF windows.

In the preliminary design of the linear collider, we set a field gradient of 100 MV/m which is about one order of magnitude larger than the existing S-band linac (KEK 2.5 GeV linac for example). Although the field strength of 100 MV/m has been realized already in SLAC with a test structure, we also made a test to confirm the attainability of such a high field in a accelerating structure.[5] Instead of a standing wave mode which has already been tested in other institutes, we chose a traveling wave mode for the test. The structure tested was of the same type as one in the SLAC linear accelerator, i.e., a disk loaded structure operated at the $2\pi/3$ mode. It is composed of 5 cells, two of which at the both ends are for coupling to the external wave guides. We reduced the aperture diameter of the disk to 16 mm so as to obtain as high field as possible. The relative group velocity of the wave in the structure is only 0.32 %. According to an estimation by a SUPERFISH calculation, the peak traveling wave power of 115 MW will correspond to an accelerating field gradient of 100 MV/m and the maximum field gradient on the disk surface is 2.1 times the accelerating field.

The test structure was fabricated in the same way as that for the Photon Factory linear accelerator. Disks and cylinders of OFHC

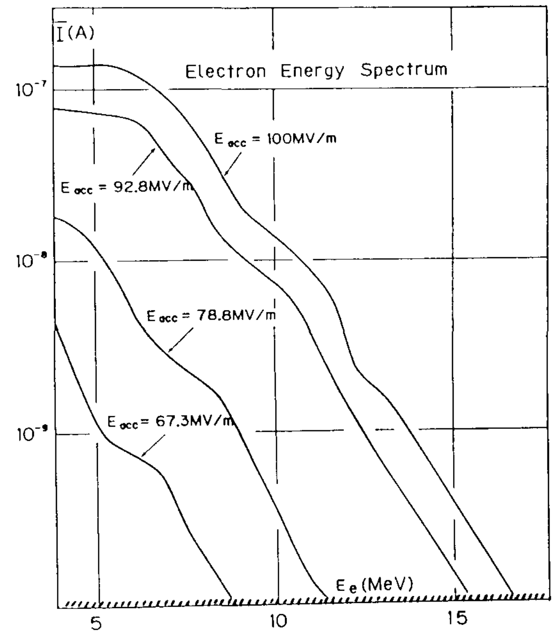


Fig. 4 Energy distribution of dark current electrons running out of the high gradient test structure.

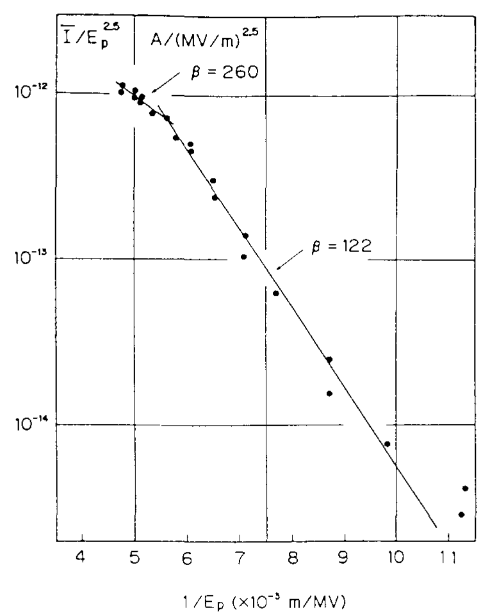


Fig. 5 A Fowler-Nordheim plot of dark current electrons.

copper are super-finished by a well selected diamond tool. The surface roughness of these components is less than 0.6 μm. These components are stacked, compressed by well controlled forces on both sides and electroplated on the outside surface to form a final accelerating structure. The thickness of the electroplated copper layer is about 5 mm.

After about 500 hour conditioning in the resonant ring wave guide system with an RF power of 2 μs in pulse width and repetition rate of 20 Hz, the traveling wave power in the resonant ring reached 123 MW, which corresponds to an accelerating gradient of 105 MV/m. The energy distribution of the dark current electrons running out of the structure, which is shown in Fig. 4, is consistent with the above estimation of the gradient, and the Fowler-Nordheim plot (Fig. 5) shows the microscopic field-enhancement factor β of about 122 which is nearly the same value as that obtained in a similar experiment at SLAC.

We are constructing another resonant ring system to extend the high gradient experiment further. We will use a SLAC 5045 klystron at an RF output rate of 67 MW and thereby aim at a field gradient of 150 MV/m.

We are now preparing some structures with different surface finishes to know their effects on the aging time and β. Structures made by a brazing process are also to be evaluated. Physical understanding of the microscopic mechanism of so high β value is also an important problem which must be investigated from a view-point of surface physics.

For the test at 11.4 GHz, which is assumed to be the accelerating RF frequency of the JLC, we have to wait until klystrons of an output power of at least 20 MW are fully developed.

Development of X-band Klystron

The final target of the JLC conception is to realize a TeV class linear accelerator. The high power RF source is one of the most important components to be developed. Recently, many new types of RF sources including the lasertron are proposed, but most of them are too ambitious and too sophisticated to be realized. We will, therefore, take a rather conservative way to employ conventional klystrons which is, at present, well established and is the most reliable RF tube, as the first step. It is clear that the necessary peak RF power for the linac is inversely proportional to the square of RF frequency. However, for too high a frequency the accelerating structure becomes too small for easy fabrication, we finally chose 11.424 GHz as the main RF frequency of the accelerating structure. The frequency 11.424 GHz is 4 times 2856 MHz, which also we are going to use in the pre-acceleration stage of the linac.

If we scale down the present 2856 MHz 3 m accelerating structure with a disk aperture of 23 mm in diameter to that of 11.4 GHz, the length of a unit would be about 40 cm and the necessary input power for an accelerating gradient of 100 MV/m be 57 MW. This output power level is very large for a conventional X-band klystron. As a first step for this, we tentatively designed a 30 MW X-band klystron as a model tube. The designed beam voltage and current are 450 kV and 170 A, respectively, hence the perveance is 0.57×10^{-6} A·V$^{-3/2}$. Assuming a resonable conversion efficiency of 40 %, we can expect a peak power of 30.6 MW. The cathode will be a barium impregnated tungsten cathode coated with a metal like iridium. To keep the emission current density less than 10 A/cm^2 for a long cathode life time, the cathode diameter would be 50 mm. The klystron of this type is called XB50.

If we assume the same emission density, conversion efficiency and perveance as those of XB50, we can design a larger X-band klystron with an output of 58 MW. The beam power has to be 145 MW, and the beam current and voltage are 580 kV and 250 A respectively. If we keep the same current density at the cathode 10 A/cm^2, the diameter of the cathode would be 65 mm. Therefore, the tube is called XB65.

The above estimation as to the necessary RF power is rather optimistic. The accelerating structure which is proportionally scaled down from the S-band accelerating structure is not so safe against the beam break up (BBU) instability. The disk aperture which is 22 % of the RF wave length is rather small and may have some chance to excite BBU. Therefore we must increase the disk aperture and, as a result, a larger peak RF power will be necessary to obtain the same gradient. If the disk aperture diameter is increased up to 29 % of the wavelength, for instance, as was done at SLAC for a test structure in combination with the RK (relativistic klystron) experiment[6], the necessary peak RF power for a field gradient of 100 MV/m will be about 165 MW. This power level would be very difficult to realize with a single conventional klystron. If the XB65 tube can be operated at a slightly higher voltage of 675 kV with a beam current of 315 A, a pair of the tubes for every 40 cm section would suffice for the required gradient.

To realize a high power X-band klystron, not only computational simulations but also experimental works are very important. As a first step of the X-band high power klystron R&D, we are planning to make a test diode for the beam study and then a prototype X-band tube in KEK in collaboration with external companies. In FY 1987, a large vacuum furnace of the double pumping type was prepared. The size of the effective working volume in the vacuum chamber of the furnace is 1.4 m in diameter and 2.5 m high which is large enough to carry out a thermal treatment of high power pulsed S-band klystrons also. The nominal temperature of the furnace is 550°C with a spatial uniformity of less than ± 10°C within the available volume, while the maximum tem-perature is 700°C.

A Conceptual Design of the Japanese Linear Collider

The Japanese linear collider (JLC) is a high energy accelerator complex for high energy e^+e^- collision experiments and consists of a couple of linear accelerators for electrons and positrons with an energy of 0.5 TeV and a couple of damping rings[7]. Beams of electrons and positrons with an energy of 0.5 TeV each are brought into collision. The design value of the luminosity is in the range of 10^{33} cm^{-2}·sec^{-1}. In Table 1, principal parameters for the JLC being conceived at present are shown. The RF frequency is, as stated above, chosen to be 11.424 GHz. This is 4 times of the frequency 2856 MHz which is being employed in the Photon Factory linear accelerator in KEK.

Table 1 Parameters of the linear collider tentatively designed at KEK

Energy	0.5 TeV + 0.5 TeV	
Luminosity	$>1 \times 10^{33}$ cm^{-2}·sec^{-1}	
Linac length	5 km + 5 km	
RF frequency	11.4 GHz	
Accelerating gradient	100 MV/m	
Beam power	2.5 MW	
Disruption parameter	2	
Aspect ratio	1	100
Number of particles per bunch	1.9×10^{10}	4×10^9
Bunch frequency	1.6×10^3	7.8×10^3
Bunch height at collision point	0.17 μm	0.003 μm
Bunch length	1 mm	0.08 mm

The beam efficiency is set at 0.1. This is the ratio of the energy gained by the beam to the RF stored energy in the accelerating structure without beam and it would be of the same order as the relative energy spread of the accelerated beam. If the conversion efficiency from plug power to RF power is about 35 %, the average beam power of 2.5 MW per beam means that the total necessary plug power for the facility would be less than 150 MW which is well below the maximum available power of KEK.

For the beam aspect at the collision point, we consider two extreme cases, i.e., a round beam with an aspect ratio R = 1 and flat one with R = 100. The disruption parameter D is the ratio of the longitudinal bunch length to the focal length due to the electro-magnetic field of the countering bunch. It is a measure representing luminosity enhancement due to the pinch effect and is assumed to be a moderate value of 2. With these parameters being given above, the other parameters are deduced straightforwardly by use of the standard linear collider formulae. Although the flat beam has some merits, the size of the beam is too small to be realized. Furthermore, the flat beam requires a large number of bunches per RF pulse to compensate small particle number per bunch. Energy spread among bunches and multi-bunch BBU would be troublesome, too. Thus we consider that the round beam would be of a first priority at the initial stage of the JLC.

Test Accelerator Facility (TAF)

To bring the above conceptual design into a practical one, there still exist many problems to be solved, but the most fundamental problem is to survey the best way to realize a high energy linac with a minimum cost. Although the whole time schedule of the JLC is not clear, a pilot project, TAF, has started as the first step of the JLC. The main purpose of the TAF is the overall test of high gradient acceleration. At the same time, the TAF will supply electron or positron beams for the studies of beam instability and of final focussing. The construction of the TAF is divided into three phases.

In Fig. 6, a conceptual constitution of TAF is shown. In phase I, we construct the injection system comprising a 200 kV hot cathode gun, prebunching cavities operating at several subharmonics of 2856 MHz and a short regular section 0.6 m long of a 2856 MHz, $2\pi/3$ mode constant-gradient structure. For the RF power source, we will use two SLAC 5045 klystrons which were transported from SLAC to KEK last year. Although the nominal output power of the klystron is 67 MW, we will try to push it up to 100 MW and, by combining the output power of the two tubes, obtain an average gradient of 100 MV/m in the 0.6 m section. Modulators compatible with the 100 MW operation were also constructed in FY 1987.

In phase II, the above injection system will be followed by three 3m sections of the same structure as the 0.6 m section. Each 3 m section, excited by a pair of 5045 klystrons operating at a rate of 67 MW peak power, sets up an average accelerating gradient of 41 MV/m or a total beam acceleration of 123 MeV. An X-band linear accelerator of the frequency 11.4 GHz will also be constructed in parallel and the accelerated beam will be transported into the X-band structure in order to test acceleration at the field gradient 100 MV/m therein.

In the final phase, phase III, we will increase the number of the 3 m 2856 MHz sections from 3 to 12, and excite each section at an average gradient of 41 MV/m by a pair of the 67 MW klystrons in the same way as in phase II. With this configuration, we will get a 1.5 GeV beam at a repetition rate of about 50 Hz. The injection system will be able to deliver a train of up to 10 bunches of 5×10^{10} electrons within an RF pulse of 4 µs duration. The 1.5 GeV beam will then be used to study both a high intensity positron source and a damping ring to get a very low emittance beam.

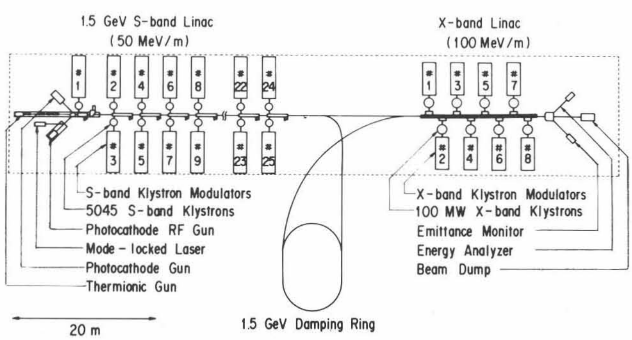
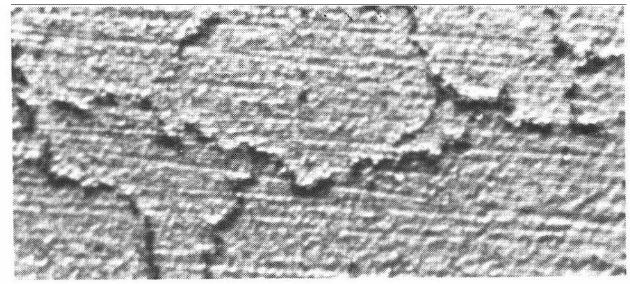


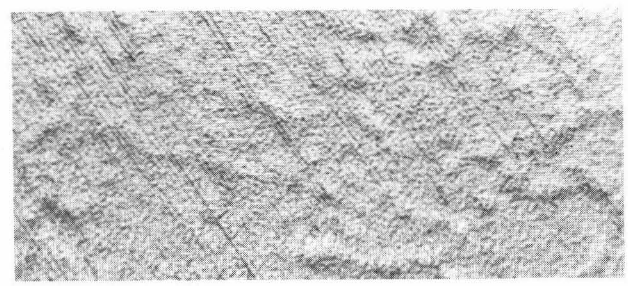
Fig. 6 Conceptual construction of the TAF.

R&D of High T_c Superconducting Cavity

The art of designing linear colliders is in its infancy and many questions are yet to be answered. It becomes more comprehensible during these years what will be the problem to be solved by engineering and technical R&D for the accelerator complex, considering beam-beam effects, beam optics, beam-cavity interactions, and other beam dynamical problems. A straightforward solution for those problems is to obtain a high duty factor, stable electron and positron beams with low emittance and small energy spread by reducing the peak beam intensity and the beam strahlung. This would be realized only by superconducting linacs instead of conventional linacs, provided that the accelerating gradient attained presently in the former will be improved and become comparable to that obtainable in the latter.[8] Then we have started experimental studies of the high T_c superconducting thin film to investigate possible application to the high gradient accelerating structure for the superconducting linear collider. Recently Padamsee also pointed out[9] that the high T_c superconducting material has a potential to be a good material for a high gradient accelerating structure.



(a) Before annealing.



(b) After annealing.

Fig. 7 YBaCuO thin films on Cu substrates before (a) and after annealing (b).

As a candidate for the high T_c superconductor, we are investigating YBaCuO type thin films on metal substrates. We introduced a Pt intermediate layer, a barrier to prevent the interface diffusion between the superconducting film and the underlying Cu substrate[10]. The effects of the Pt buffer layer on the superconducting properties have been studied. We expect the high quality films on metal substrates are obtained by optimizing the sputtering parameters and the annealing conditions. We can see in Fig. 7 the annealing effect of the YBaCuO type thin films deposited on Cu substrates. As a new method for depositing high T_c superconducting films onto metal substrates, we tried a low-pressure plasma spraying method[11]. This method has a great advantage of a large deposition rate, and is characterized by a high density of deposits and a controllable spraying atmosphere. We will measure the temperature dependence of the RF surface resistivity for plasma sprayed YBaCuO type films on end plates of TE_{011} mode niobium superconducting cavity at 6.5 GHz. For ideal YBaCuO type surfaces, one expect to reach very high accelerating fields of 400 MV/m, compared with 50 MV/m for ideal Nb surfaces. We have already achieved almost 10 MV/m accelerating fields for 5-cell niobium cavities. Hence, by using high quality superconducting YBaCuO type surfaces for RF cavities, about 80 MV/m which is one-fifth of ultimate accelerating fields may be realized. At the same time, a new material of BiSrCaCuO type is also under the investigation.

Acknowledgement

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References

1) Y. Kimura, K. Takata and M. Yoshioka, Proc. of the 1987 ICFA Seminar on Future Perspectives in High Energy Physics, 232 (1987).
2) Y. Fukushima et al., Nuclear Instr. and Method in Physical Research A238, 215 (1985).
3) M. Yoshioka et al., Proc. 12th Linear Accelerator Meeting in Japan (1987), 195 (in Japanese).
4) T. Shintake, Linear Collider Study Note, LC-87-8 (1978, unpublished).
5) H. Matsumoto et al., Proc. of the 1987 IEEE Particle Accelerator Conference (Washington DC) 1654 (1987).
6) M. A. Allen et al., SLAC-PUB-4650 (1988).
7) Y. Kimura, proc. European Particle Accelerator Conference (Rome 1988).
8) T. Nishikawa, Proc. of the 1987 ICFA Seminar on Future Perspectives in High Energy Physics, 281 (1987).
9) H. Padamsee, Work Shop on Novel Application of High Temperature Superconductors, Salem, Mass., June 22-24, 1988.
10) K. Asano, private communication.
11) K. Tachikawa et al., Appl. Phys. Lett. 52 (12), 21, (1988).