High Gradient Experiments by the ATF

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High gradient experiment by using traveling wave structures at S-band frequencies is presented. Discussions are given about dark current depending on the structure length and also the effect of a dust-less and dielectric-less structure.

INTRODUCTION

The accelerating gradient is one of the important parameters for e^+e^- linear colliders in TeV energy region such as Japan Linear Collider (JLC). The optimum number of particles to be accelerated in main linacs is determined by the accelerating gradient. The attainable luminosity at the interaction point is limited not only by the beam-beam interaction but by the accelerating gradient. The higher accelerating gradient is preferable to obtain higher luminosity, while the higher peak power of rf sources should be fed into the accelerating structures.

The pioneer and systematic studies on maximum attainable accelerating gradients have been performed in standing-wave structures by several authors[1-2]. It was found that the maximum surface electric field E_{smax} is 330 MeV/m at 2.856 GHz. The maximum accelerating gradient E_{amax} at the rf breakdown limit is estimated to be 150 MV/m at 2.856 GHz for traveling structure, since the ratio of the surface and accelerating fields is 1.9 to 2.2. It was also found that the maximum surface field is proportional to square root of rf frequencies. The higher rf frequencies are preferable to obtain higher gradient and then the frequency of 11.424 GHz has been chosen for the main linacs of JLC.

In the experiments reported several authors, the standing wave structures of one or a few cavities were utilized since the extremely high power rf sources are unavailable[1-2]. The understanding of dark current phenomenon in long traveling structures similar to the structures for real linacs is necessary to determine the maximum gradient that can be obtained and used realistically. High gradient experiments carried out at KEK have being focused to the rf breakdown and dark current phenomena in traveling wave structures of long length[3]. For X-band high gradient experiment, a 0.2 m-long structure has been fabricated to generate the maximum gradient of 100 MeV/m by using 30 MW XB-50K klystron. The facility is being prepared in the TRISTAN Nikko experimental hall.

For S-band high gradient experiment, the high gradient experiments have been carried out using ATF phase-I linac. A 0.6 m-long constant gradient traveling type structure was utilized to generate the maximum accelerating gradient of 100 MeV/m at 200 MW of rf peak power. The maximum accelerating gradient of 93 MeV/m could be attained and the electron beam from the thermionic gun could be accelerated at 85 MeV/m of maximum accelerating gradient in March 1990. The recent experiments are focused to the dark current and rf breakdown phenomena.

EXPERIMENTAL SET-UP

Figure 1 shows the experimental set-up. A SLAC-5045 klystron and a Toshiba-E3712 klystron are connected with the accelerating structure with a 3 dB coupler. The peak power from each klystron can be increased to 100 MW if the drive voltage is increased to 450 kV and the pulse duration decreased to 1 μs. The maximum peak power of 200 MW can be fed into the structure.

The accelerating structures are traveling type constant gradient disk-loaded structures with 17 cells and 2 couplers. The diameter of disk aperture 2a is 19.0 mm at input cell and 15.9 mm at output cell to obtain constant gradient along the structure. The average shunt impedance is 61.2 MΩ/m and figure of merit Q is 11,600. The attenuation constant τ is 0.37 and the filling time t_f is 0.47 μs. The material of the structures is first class OFHC. The surface roughness of both the disks and cylinders are 0.02 μm except the rounded irises where the surface roughness is 0.2 μm. The result of the simulation using SUPERFISH shows that the peak surface electric field around the rounded iris is about 2 times higher than the average accelerating gradient.

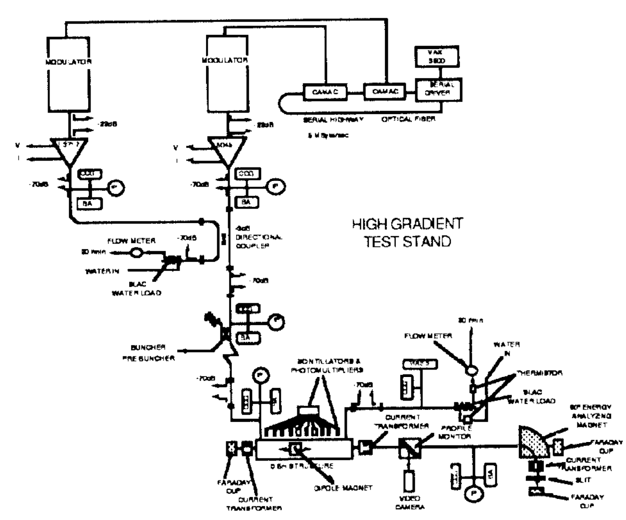

Figure 1. Diagram of the experimental set-up.

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The klystron modulators are operated at 50 Hz of repetition rate and the average power dissipation in the structure is estimated to be 5.2 kW. To intensify the cooling effect, cooling water is flowed through the channels pre-drilled in the cylindrical wall. The structures without water jacket give rise to the precise alignment of the structure. The axis of disk apertures can be estimated by measuring the position of the outer wall of the structures.

The current transformers and Faraday cups are used to measure the dark current at both the downstream and upstream of the structures. The energy spectrum of the dark current is measured by an analyzer magnet installed at the downstream of the structures. The X-ray bursts due to the dark current are detected by ten plastic scintillators set on the surface of the structures. The real-time waveform of the X-ray bursts are observed by a 8-channel oscilloscope[3].

A. *Clean Accelerating Structure*

One of the origins of the dark current is dielectric material such as dust and machine-oil remained on the copper surface. It is expected that a clean structure with low dust and low dielectric material will be a structure of low dark current. A clean structure has been fabricated by improving the manufacturing process to compare the normal accelerating structure.

B. *Application of HIP (Hot Isostatic Pressing)*

The micro-cavities in the grain boundaries of the copper are the origins of the dark current, since dielectric material such as machine oil remains in the micro-cavities of the copper surface. An accelerating structure is being developed by using thermomechanical process, HIP (Hot Isostatic Pressing). The first class OFHC is preprocessed by HIP at the temperature of 800 °C in the pressurized Ar gas of 1200 kg/cm². The grain boundaries are closely pressed and size of micro-cavities is remarkably reduced[4]. It is expected that the rf breakdown limit would be increased due to the reduction of dielectric materials[4].

RF Processing

The accelerating gradient could be increased by computer controlled rf processing. The rf processing was accompanied by the rf steady out-gassing The rf peak power to the structures was controlled to maintain vacuum pressure below 1 x 10^{-7} Torr. The burst of the out-gassing due to an rf breakdown within a pulse interrupted the next pulse.

As for the normal structure, the maximum attainable accelerating gradient was achieved to 35 MeV/m by the rf processing of 60 hours. It was achieved to 50 MeV/m by the rf processing of 200 hours. The field enhancement factor β estimated from modified Fowler-Nordheim plots decreases from 90 to 66 by the rf processing of 300 hours. The accelerating gradient of 90 MV/m could be obtained at 160 MW rf input after 800 hours of rf processing. The field enhancement factor β estimated from modified Fowler-Nordheim plots. For the total dark current, the field enhancement factor (β = 66) agrees with the measurement with the Faraday cup. The field enhancement factor in the structure except output coupler was evaluated to be 39.

As for the clean structure, the accelerating gradients could be achieved to 35 MeV/m by the rf processing of 26 hours. It could be achieved to 50 MeV/m by the rf processing of 45 hours. The field enhancement factor β is about 100 after 45 hours rf processing while the dark current is one order lower than the normal structure. The field enhancement factor of the clean structure would be decreased by continuing of the rf processing.

DARK CURRENT MEASUREMENT

The transient analysis of the dark current of normal structure has been reported[3]. The experimental result shows that the bursts of both the current waveform and X-ray are detected simultaneously with the rf front arrival to the output coupler. The multipactoring would be produced near the iris of the output coupler.

Figure 2 shows the energy spectrum of dark current of the normal structure and clean structure at 75 MeV/m of the accelerating gradient. It was also found that the dark current from a clean accelerating structure is one order lower than the normal structure fabricated by a standard fabrication process. The peak at low energy shows the field-emitted electrons generated by multi-puctoring around the iris of the output coupler.

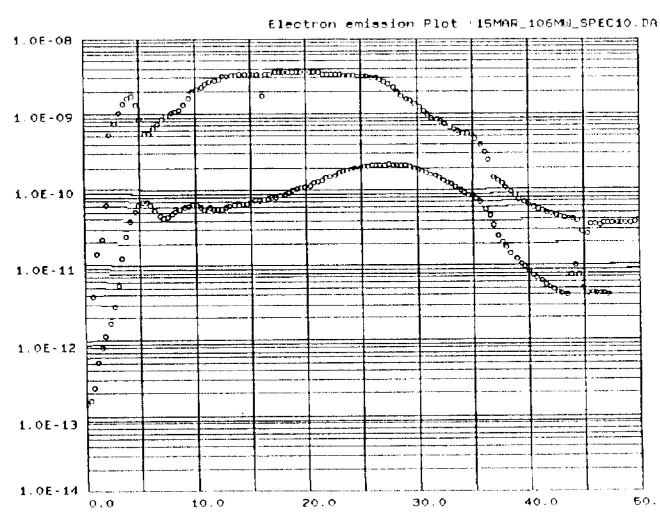

Figure 2. Energy spectrum of the dark current from the normal accelerating structure and the clean structure at 75 MeV/m of the accelerating gradient. (vertical axis: A, horizontal axis: MeV, upper curve: normal structure and lower curve: clean structure)

MULTIPLICATION FACTOR η OF DARK CURRENT

There has been an interest in the relations between the dark current and structure length[5]. However, it is not easy to fabricate several numbers of structures of same conditions for dark current experiments. The net length of the structure would be reduced by using the dipole magnets. If the dipole magnets are set on along the outside of the structure from the input coupler towards the output coupler, the field-emitted electrons from the upstream cells are bent by the magnetic field and they are collided to the disks. The source of the dark current measured at the downstream of the structure can be limited to the cells without the dipole magnet. The number of cells where the field-emitted electrons can pass through the structure can be decreased.

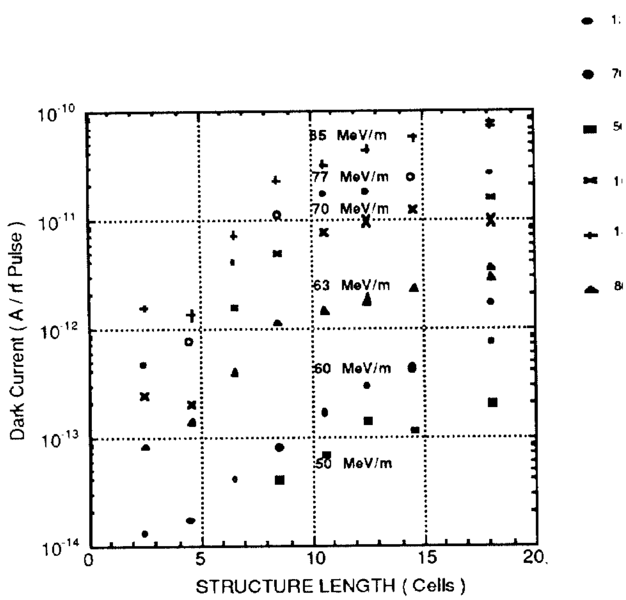

Figure 3. Dark current against the number of cells (structure length) for the accelerating gradient of 50-85 MeV/m.

The seven permanent dipole magnets have been prepared for the experiments. The magnetic field strength is 1 kG at the axis of the structure. The energy spectrum of the dark current measured by the analyzer magnet show that the highest energy component is decreased with decrease of the number of cells without magnets. The dark currents depend on the structure length were obtained by integrating the energy spectrum.

Figure 3 shows the logarithm of dark current against structure length. It shows that the dark current exponentially increases with structure length at relatively low accelerating gradient less than 60 MeV/m while the dark current linearly increases at high accelerating gradient higher than 63 MeV/m. At low accelerating gradient less than 60 MeV/m, the dark current Id would be increased as η^N, where N is the number of cells in the structure. It is reasonable to consider that the field emitted electrons from the upstream cells are multiplied in the successive cells in the down stream of the structure. The multiplication factor along the structure is constant ($\eta = 1.6$/ cell at 60 MeV/m and 70 MW input). It is predicted that dark current phenomena have two components: one is the multiplication in the successive cells and the other is the direct-acceleration toward the down stream of the structure. It is reasonable to consider that the multiplication components would be dominant at low accelerating gradient and the direct-acceleration components would be dominant at high accelerating gradient.

SUMMARY

The clean structure of low-dust and low-dielectric material would be suitable to decrease the dark current one order lower than the normal structure by standard fabrication process. It was shown that the dark current depends on the structure length.

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