HIGH POWER TEST OF A HIGH GRADIENT S-BAND ACCELERATOR UNIT FOR THE ACCELERATOR TEST FACILITY

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Abstract

The 1.54 GeV S-band linac for the Accelerator Test Facility (ATF) has to be able to inject a multi-bunch beam of electrons into a damping ring. To meet the energy goal of 1.54 GeV under the given site constraints an accelerating gradient of 33 MV/m has to be achieved under beam loading conditions. The 3m-long structure attained a maximum accelerating gradient of 52 MV/m at an input peak rf-pulse power of 200 MW without any problem. At that point the average field emission current from the structure was 0.34 nA per rf-pulse. A microscopic field enhancement factor β of 70 was obtained from Fowler-Nordheim plots. Up to 200 hours of initial RF processing time was required to condition an accelerator unit to operating with a 400 MW, 1μs SLED peak RF output.

Introduction

The Japan Linear Collider phase-1 (JLC-1) project[1] proposed for the next generation of high energy physics research, where collision energies in the 300 to 500 GeV region are required from experimental results of SLC and LEP. In order to actually realize such a large scale accelerator in a realistic length, a high gradient type linac is necessary to provide high beam energy gains in a shorter distances. A further very important design consideration is improving the overall reliability of such a large scale accelerator system by minimizing the number of active elements, such as klystrons and their pulse modulators etc. This can be achieved by using RF sources of the maximum possible peak an combination with a passive pulse compressor system, providing drive for multiple accelerating structures. To this end, the development of high output power klystrons is obviously necessary, but further R&D on high gradient accelerating structures, RF pulse compression technology[2] and so forth is essential.

The ATF has been started at KEK to efficiently conduct research on high gradient linac related matters. It consists of a 1.54 GeV S-band linac (including a positron test stand) and 1.54 GeV damping ring, followed by an extraction line with a bunch-compressor. As a first step, a 80 MeV injector part has already been established and it has been operating since August 1993. The other main linac components are installed within 90% at this time. The first beam commissioning of the 1.54 GeV S-band linac will start at middle of August 1995. ATF is working together with many collaborators at universities and industry groups in Japan as well as international institutes such as DESY (Germany), POSTECH (South Korea), SEFT (Finland) and SLAC (America) at this time.

High gradient experiments on S, C and X-band structures have already been carried out by research laboratories in other countries such as Varian[3] and SLAC[4], but in all cases they were studied with relatively few cavities in a standing wave structure. The first high gradient experiments were started on a small scale (five cavities) traveling wave structure in Japan in 1987 by the JLC. Since then we at ATF have been working with 0.6m S-band traveling wave type structures, operating as close as possible to realistic conditions with up to 100 MV/m axial electric field gradient (at 200 MW microwave input power). Investigation has been primarily pointed at elucidating the causal relationships between the internally generated field emission currents and breakdown electric fields in high gradient accelerator structures. From this work we can conclude

(1) The magnitude of field emission currents depends on the cleanliness of the inside of the structure.
(2) Shown conclusively that the maximum electric field gradient is determined by the geometry of the structure[5] especially that of the coupler cavity.
(3) Further we have shown the existence of microscopic voids between the crystal grains even in very pure OFHC copper, and that the voids are the cause of field emission currents[5].

In the following we will report the overall results of high gradient experiments on a 3m-long S-band structure, such as it is being planned for use by the S-band linac pre-accelerator section for JLC-1. This work was part of the total research and development program using a 100 MW class klystron and a 400 MW peak power class SLED type pulse compression.

High gradient 3-m long structure

A new 3m-long structure was fabricated in such a way as to eliminate or at least improve all of the negative influences and factors shown in previous high gradient experiments. This principally involved the construction of the structure input and output couplers. In order to avoid the imperfections caused to the structure by rf tuning adjustments process, and the accompanying contamination, direct precision machining of the coupler cavity was made possible by the use of a three-dimensional electromagnetic analysis code (MAFIA) for a very careful dimensional detail design[6], and then NC machines were employed for the precision machining. Further, in order to reduce the field emission currents, the material for the disk section was all HIP (Hot Isostatic Press) [7] processed, and care was taken to make sure that no machine oil remained in the material as it was fabricated. Table 1 shows the main parameters of the structure.

TABLE 1
Main acceleration structure parameters.

Operation frequency	2856	MHz
Phase shift/cell	$2\pi/3$	
Electric field distribution	Constant gradient	
Structure length	3	m
Number of cell	86	
Quality factor	13,000	
Shunt impedance	60	MΩ/m
Attenuation parameter	0.57	
Group velocity	0.0204-0.0065	vg/c
Filling time	0.83	μs
Peak surface electric field (E_p)/Axial electric field (E_a)	1.9-2.1	

Using the parameters from Table 1 and $E_p/E_a \approx 2$ from a SUPERFISH calculation. The maximum peak electric field at the surface is expressed as:

$$E_p\ [\mathrm{MV/m}] = 7.38 \times \sqrt{P_{in}\ [\mathrm{MW}]}, \qquad (1)$$

where E_p is the maximum surface electric field in MV/m and P_{in} is the input rf-power in MW of the structure. The relationship between the perpendicular electric field gradient E_p at the OFHC copper surface and the resulting field emission current is given by a Fowler-Nordheim Plot (F-N Plot) as:

$$\frac{I_e}{E_p^{2.5}} = \exp\left(\frac{-6.53 \times 10^9 \times \phi^{1.5}}{\beta \times E_p}\right), \qquad (2)$$

where I_e is the field-emission current from the structure, ϕ is the work function of the copper and β is the microscopic field enhancement factor in I_e over that expected for an ideal metal surface.

Accelerator unit high power test

Experimental procedure

Figure 1 shows a regular accelerator unit from the ATF linac as used in the high gradient experimental tests. The accelerator unit is composed of an 85 MW, 4.5 μs klystron[8], a 400 MW class SLED type rf pulse compressor[9], and two 3m-long traveling wave type structures.

The wave guide system, the SLED cavity and structures are pumped down to 5×10^{-7} Pa by two 80 ℓ/s and four 200 ℓ/s ion pumps. The vacuum pressure is monitored by the cold cathode gauges and the ion gauges.

The klystron and 3m-long structures rf-powers of both the forward and reflected waves were monitored by Bethe-hole type directional couplers with coupling ratio of -70 dB. The transmitted rf-powers through the 3m-long structures was also monitored by the same device.

The values for the structure electric field gradients (E_p and E_a) were calculated from the measured input rf-power (P_{in}) using equation (1). The field-emission current I_e from the structures were dumped in a Faraday cup type beam stopper which was located just downstream of each structure. The emission current I_e for both structures was measured by the pico-ammeter as a function of E_p.

RF processing

All of the components used in the experimental setup were new, none of them had been previously exposed to the passage of rf-power, and the RF processing was carried out carefully. Initial RF processing was done with the SLED tune and no phase reveres mode. The klystron pulse width was 1 μs and the repetition rate was 12.5 Hz. During conditioning, the klystron rf-power was controlled by a computer program to keep the vacuum pressure below 5×10^{-5} Pa. Normally the vacuum pressure of the whole system was below the 5×10^{-6} Pa at any rf-power level.

At beginning of RF processing, it occasionally rose up to 2×10^{-4} Pa at rf-power range of a few 100 kW to 6 MW due to multipactoring inside the wave guide components. After this, the peak and average rf-power were alternately increased up

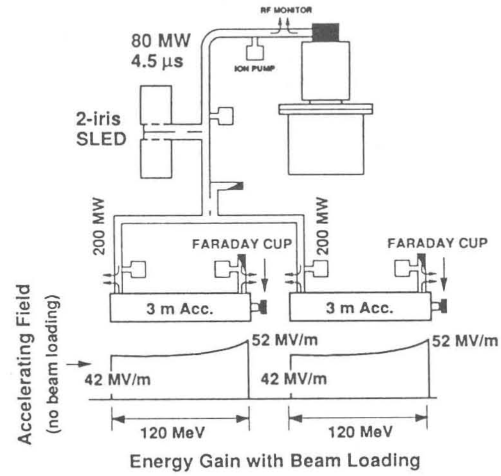

Figure 1. Regular accelerator unit for the ATF linac.

to 70 MW and 4.5 μs of klystron rf-power. It required the RF process time of 400 hours.

After passed the intermediate level of RF processing, the SLED operates in phase reverse mode with power multiplication factor of 5. After about 200 hours of computer controlled automatic RF processing, it was possible to input a peak power of 200 MW, at which time a maximum axial acceleration electric gradient of 52 MV/m was achieved. Figure 2 shows the rf-power monitor signal output waveforms.

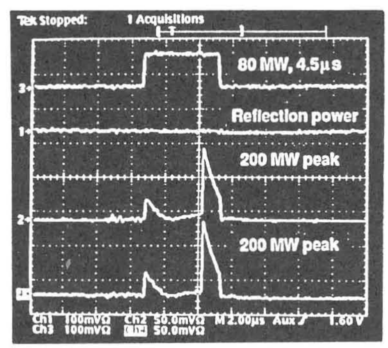

Figure 2. Waveforms from the rf-power monitors.

The top trace in Figure 2 shows the klystron output power (80 MW and 4.5 μs). The second trace is the power reflected from the SLED and the two 3m-long structures; it is extremely small being only about 100 kW or less at the point were the SLED cavity has its peak power. The third and fourth traces shows the input power (200 MW peak) to each of the respective structures.

It was then verified that operation after that was stable. Figure 3 shows the first rf-processing of the regular accelerator unit. Further it was also found that once RF processing had been completed, even after bringing the system up to atmospheric conditions, once the vacuum had be reestablished within a few hours or so operation at 200 MW input was possible as shown in Figure 4.

Since the SLED output power drops exponentially with time, the acceleration electric field distribution becomes 42 to 52 MV/m as shown in Figure 1. Thus in this case, we see that even taking into account the energy decrease that occurs with beam loading in the linac, we can expect a 120

MeV beam acceleration from each 3-m long structure, and a 240 MeV energy gain from each klystron.

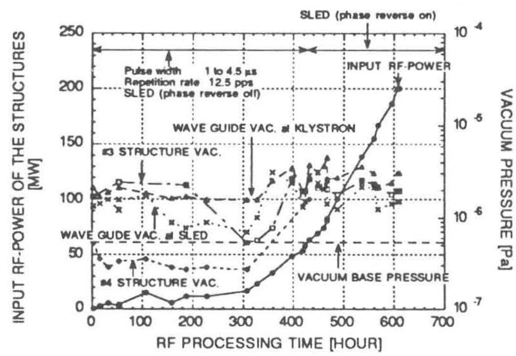

Figure 3. The first RF processing of the a regular accelerator unit.

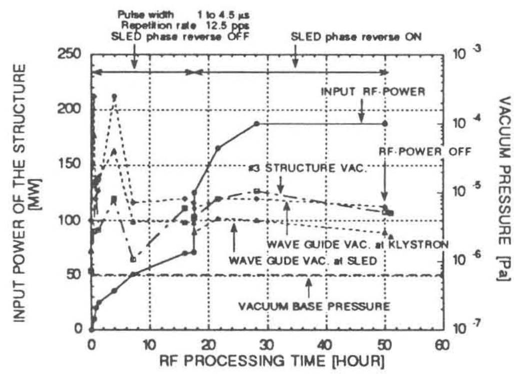

Figure 4. The second RF processing of the regular accelerator unit.

Experimental Results

A Faraday cup type current monitor was installed just downstream of each of the structures, and the field emission current I_e was measured as parameterized by the E_p. as shown in Figure 5.

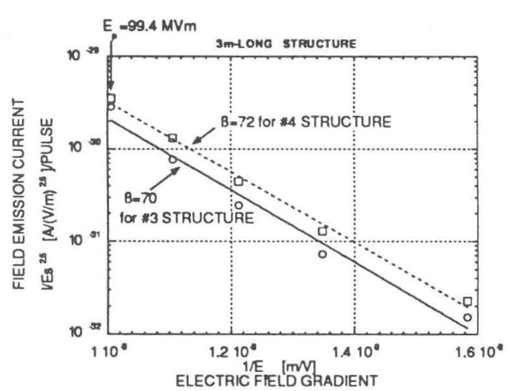

Figure 5. Fowler-Nordheim Plot for the two regular accelerator units.

Figure 5 showed that an almost identical β of about 70 was found for both of the two structures. From this we can conclude that there are no defective places inside either accelerator structure where the electric field is concentrated, and that there is only a little variation in their performance. We can also see that since the two I_e are only slightly different that the inner surfaces are also equally clean. The values of the I_e and β should reduce by spending more RF processing time.

This I_e is an average value, but when converted to the peak value from an equivalent 1 μs long rectangular pulse, we find that a maximum current of only 0.3 mA is produced even at E_p=104 MV/m. The corresponding on-axis electric field gradient E_a at this time would be 52 MV/m. From this we can conclude that a 33 MV/m beam acceleration would be no problem at all.

Conclusions

In order to reduce the field emission current in the structure and to make high gradient stable operation possible, the coupler dimensional design choices were made with a 3-dim. electromagnetic field analysis code (MAFIA) and a high gradient structure fabrication flow was established using HIP processed OFHC-copper materials, assembled in a clean room environment[10]. As a result, we were successful in realizing stable high gradient operation while at the same time drastically reducing field emission currents. The 400 MW class RF power source used was made completely of components successfully developed as part of the JLC research program: a 100 MW class klystron, a 400 MW class SLED type pulse compressor, a peak 200 MW class pulse modulator[11], and also 400 MW class high power wave guide components.

Currently the ATF Linac is operating only the 80 MeV injector as a recognized beam accelerator. Usually a 200 kV thermionic electron gun has its output divided into a 2.8 ns spaced 20 multi-bunched beam which is used for beam diagnostic equipment development and performance evaluations along with beam emittance measurements.

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References

[1] JLC group, KEK report 92-16, A/H/M, National Laboratory for High Energy Physics, Japan, December 1992.
[2] Z. D. Farkas, H. A. Hogg, G. A. Loew and P. B. Wilson, Proc. 9th Int. Conf. on High Energy Accelerators, SLAC (1974) p. 576
[3] Eiji Tanabe, IEEE Trans. NS-30, No. 4, (1983) 3551
[4] G. A. Loew and J. W. Wang, SLAC-PUB-4845, January 1989
[5] H. Matsumoto, M. Akemoto, H. Hayano, T. Naito, S. Takeda and S. Yamaguchi, KEK Preprint 92-84, August 1992, XVth Int. Conf. on High Energy Accelerators, Hamburg, Germany
[6] S. Yamaguchi, Proceedings of III Workshop on JLC, KEK, February 18-29, 1992
[7] H. Matsumoto, M. Akemoto, H. Hayano, T. Naito and S. Takeda, Proc. of Particle Accelerator Conference, May 1991, IEEE, New York, p. 1008
[8] H. Yonezawa, S. Miyake, K. Gonpei, K. Ohya and T. Okamoto, Proc. 14th Int. Conf. on High Energy Accelerators, Tuskuba, JAPAN, 1989, p. [1177]/219-224.
[9] H. Matsumoto, H. Baba, A. Miura and S. Yamaguchi, NIM A330 (1993) 1-11
[10] H. Matsumoto, S. Takeda and S. Yamaguchi, KEK Proc. 93-10, August 1993, p270-274
[11] M. Akemoto and S. Takeda, Proc. of the Linear Accelerator Conference, Albuquerque, USA, 1990