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ATF 1.54 GeV Linac for Linear Collider

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Abstract

The 1.54 GeV S-band linac for the ATF must be able to inject a multi-bunch beam of electrons into the damping ring. To meet the energy goal of 1.54 GeV given site constraints, an accelerating gradient of 33 MV/m has to be achieved under beam loading conditions. The ATF Linac is currently operating only the 80 MeV injector as a recognized beam accelerator. A 200 kV thermionic electron gun produces a 2.8 ns spaced 20 multi-bunched beam which is used for beam diagnostic equipment development, performance evaluations, and beam emittance and bunch length measurements. With $2x10^{10}$ electrons per bunch the measured normalized emittance and bunch length obtained were $<8x10^{-5}$ m·rad (1σ) and 11-14 ps (FWHM) respectively at a beam energy of 75 MeV. These data were obtained using a new method of bunch-by-bunch monitor system and optical transition radiation emitted from a 1 mm thick of stainless plate. The first beam commissioning of the linac will start at the end of September 1995.

Introduction

The Linear Collider-1 (LC-1) project [1], which is proposed for the next generation of high energy physics research, requires collision energies in the 300 to 500 GeV region (from experimental results of the 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 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.

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 a 1.54 GeV damping ring, followed by an extraction line with a bunch-compressor.

ATF researchers are working together with many collaborators at universities and industry groups in Japan as well as foreign institutes such as CERN, DESY, PAL, SEFT, and SLAC at this time.

As a first step, an 80 MeV injector part was established and 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 end of September 1995. The status of the experiments and the results achieved so for will be presented.

The 1.54 GeV injector linac

The main parameters of the linac are listed in Table 1. The 1.54 GeV injector linac comprises an 80 MeV pre-injector linac, eight units of regular accelerator sections, two units of energy-compensation accelerating structures, beam diagnostics and a positron target test stand [2]. The linac has to accelerate the multi-bunch beam with an energy spread of less than 1% (full width of 90%) at the end of linac. To achieve this, a new idea of an energy-compensation system (ECS) will be used. The system consists of two 3 m-long accelerator structures which are driven by two different frequencies at 2856+4.32727 MHz and 2856-4.32727 MHz. With the ECS both the bunches within the train obtain a different energy gain caused by the phase shifts during passage through the two structures. The ECS should reduce the energy spread from about 5% to 0.2% peak-to-peak with $2x10^{10}$ electrons per bunch.

Table 1 Main parameters of 1.54 GeV injector linac

<u>Beam parameters</u>		
Beam energy	1.54	GeV
Energy spread	< 1%	full width of 90% beam
Normalized emittance	$< 3x10^{-4}$	m·rad(1σ)
Number of bunches	20	
Bunch population	$2x10^{10}$	electrons
Bunch separation	2.8	ns
Bunch length	<10	ps (FWHM)
<u>Machine parameters</u>		
Total length	88	m
80 MeV pre-injector	18	m
Linac	70	m (active length=48 m)
<u>Regular accelerating sections</u>		
Operation frequency	2856	MHz
Phase shift/cell	2π/3	constant gradient, traveling wave
Structure length	3	m
Number of structures	16	
Accelerating field gradient	47.5 (33*)	MeV/m, * with beam loading
Klystron peak power	85	MW (maximum)
Klystron pulse width	4.5	μs
Number of klystrons	8	
RF pulse compression		Dual-iris SLED type
Power gain	5	at peak
Number of SLED cavities	8	
Number of modulators	8	200 MW of peak power
<u>Energy compensation system</u>		
Accelerating structures	f_0 + 4.32727 MHz	
f_0=2,856 MHz	f_0 - 4.32727 MHz	
Klystron peak power	50	MW (SLAC5045)
RF pulse width	1.0	μs
Number of klystrons	2	

80 MeV pre-injector linac

The pre-injector rf system consists of a 200 kV thermionic electron gun, a beam chopper, two 357 MHz standing wave Sub-Harmonic Bunchers (SHB), a 2856 MHz 7-cell traveling wave buncher and a 3 m long regular accelerator structure. The beam transport is composed of the 25 Helmholtz coils, a matching section of beam lattice, an energy analyzer magnet with a 45° bend angle and beam diagnostics.

<u>Thermionic electron gun</u> [2]

The gun uses a triode with a model EIMAC Y646-E or Y796 grid-cathode assembly. The energy of the beam is 200 kV in typical operation. The 20 bunches from the gun are extracted by applying an rf voltage to the grid, which is generated by a 2 kW rf amplifier with a 316 V peak-to-peak rf voltage at 50 Ω load impedance. It is synchronized with the 357 MHz of the SHBs. The main parameters of the gun are listed in table 2, and experimental results with multi-bunch generation are shown in Figure 1.

Table 2 Main parameters of the gun

Beam energy	200	kV
Number of pulses	20	
Bunch width	1	ns (FWHM)
Bunch separation	2.8	ns
Bunch population	$\geq 3 \times 10^{10}$	
Population tolerance	$\leq \pm 1.0$	%

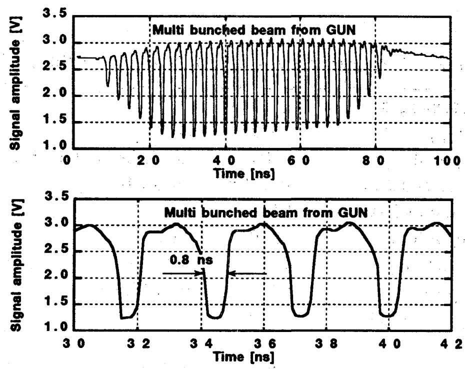


Figure 1 Multi-bunch beam from gun measured by a core current monitor

The 375 MHz SHB cavities [2]

The beam bunching cavities use two 357 MHz SHBs and a 2856 MHz traveling wave cavity. The 20 bunches from the gun have a 1 ns (FWHM) bunch length. Since each bunch contains more than 2×10^{10} electrons a cumulative loading voltage in the bunching cavities is produced. To reduce the phase shift of the cavity voltage due to beam loading, low R/Q SHBs have been developed as shown in Figure 2. Two low R/Q SHBs which have R/Q = 45 Ω were introduced to increase the beam tuning range. Two 5 kW, 30 μs pulse width, solid-state amplifiers are use to drive the SHBs.

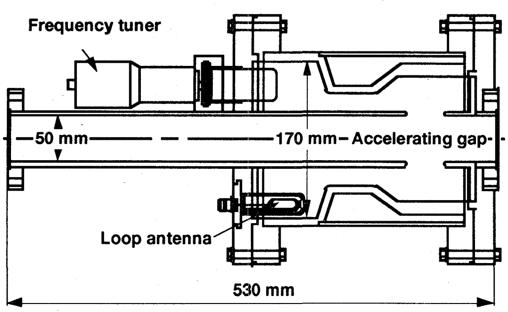


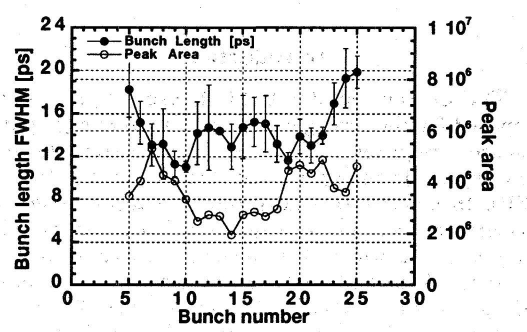
Figure 2 Low R/Q type SHB

Beam diagnostics

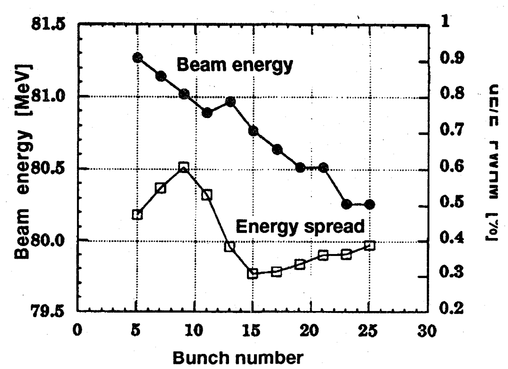
The 1.54 GeV injector linac will use conventional diagnostic monitors including core current monitors (CT), screen profile monitors, stripline type beam position monitors, a bunch length measurement system which detects Optical Transition Radiation (OTR) using a streak-camera, wire scanners and beam loss monitors. Further, to measure the bunch by bunch beam characteristics, a new monitor system with an 1 GHz bandwidth has been developed and has been used at the 80 MeV pre-injector since 1993. These new beam diagnostics confirmed that they are very useful to make precise machine tuning.

OTR monitor [2, 3, 4]

The OTR is generated by 1 mm thick of stainless plate mounted on a beam axis at a 45° angle. A gated-camera with a 3 ns gate width is used for beam profile measurements. A streak-camera which has 0.6 ps of time resolution is used for bunch length measurements. The measured bunch length has to be corrected for dispersion effects. Figure 3 shows the measured bunch length (a) and energy spread (b) of accelerated multi-bunch beam at the end of the 80 MeV pre-injector.



(a) Bunch length measurement using streak-camera with 2.8 ns bunch spacing



(b) Beam energy and energy spread with the 5×10^{9} electrons per bunch, and 2.8 ns bunch spacing

Figure 3 Measurement made with the OTR monitor system

Figure 3-a shows measured bunch lengths of 11-14 ps at the center of the bunch train. Each black circle and its error bar in Figure 3-a show the bunch length averaged from the five data measured at the same bunch, and the maximum fluctuation of data. From Figure 3-b, the beam energies reduce according to beam loading of the multi-bunch trains.

Multi-bunch emittance monitor [2, 3]

To measure the bunch-by-bunch beam emittance, a new measurement system has already been developed. A MCP-PMT with a gate function is used for detection of measured gamma rays produced by a scanning wire. The beam size of any single bunch can be by adjusting the timing of the 3 ns pulse. It takes about 5 minutes for an emittance measurement with 20 bunches as shown in Figure 4. The measured data show that the normalized emittance of each bunch is less than the 8×10^{-5} m·rad which is smaller than a specification of a 1.54 GeV linac

($3x10^{-4}$ m·rad). The emittance of each bunch does not strongly depend on the bunch order. Variations between bunches may be due to beam jitters during measurement.

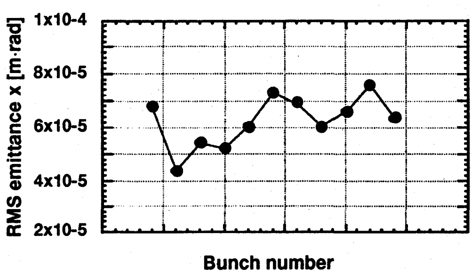


Figure 4 Beam emittance measurements using the gated wire scanner measurement system

The OTR system also can measure the emittance not only bunch-by-bunch but can also measure a single-shot profile. The normalized emittance is evaluated to be $2.5\text{-}2.8x10^{-5}$ m·rad which is smaller than that of wire scanners, because it does not excludes contributions from beam jitter.

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 the negative influences and factors shown in previous high gradient experiments. This principally involved the construction of the structure input and output couplers. To avoid the imperfections caused to the structure by rf tuning adjustments, and the accompanying contamination, direct precision machining of the coupler cavity was used. This was made possible by the use of a three-dimensional electromagnetic analysis code (MAFIA) for a very careful dimensional detail design [5]. Then Numerical Control (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) [6] processed, and care was taken to ensure that no machine oil remained in the material as it was fabricated. Table 2 shows the main parameters of the structure.

Table 2 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 cells	86	
Quality factor	13,000	
Shunt impedance (= $V^2/2P$)	60	MΩ/m
Attenuation parameter	0.57	
Group velocity / c	0.0204-0.0065	
Filling time	0.83	μs
E_p / E_a	1.9-2.1	

E_p : Peak surface electric field.
E_a : Axial electric field.

The 3m-long structure obtained 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 ß of 70 was obtained from Fowler-Nordheim plots [7]. Up to 200 hours of initial rf-processing time was required to condition an accelerator unit to operation with a 400 MW, 1μs SLED peak rf output. Figure 5 shows the first rf-processing of the regular accelerator unit. From this experiment, it was also found that once rf-processing had been completed, even after bringing the system up to atmospheric conditions, reestablishing vacuum, operation at 200 MW input was possible within a few hours.

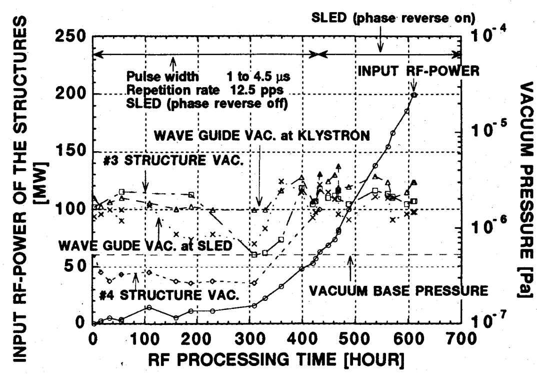


Figure 5. The first rf-processing of a regular accelerator unit.

Summary

The 80 MeV injector has been operating since August 1993 to efficiently conduct R&D on the multi-bunch and high current linac. The new idea of bunch-by-bunch beam monitors for size, emittance, energy spread and bunch length has been developed using the OTR system. It was confirmed that the new monitors are very useful for precise machine tuning. A new 3-m long structure confirmed that 33 MV/m beam acceleration would be no problem. The first beam commissioning of the 1.54 GeV injector linac will start at the end of September 1995.

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