ATF LINAC COMMISSIONING

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Abstract

Accelerator Test Facility (ATF) [1] is now under construction in the TRISTAN Assembly Hall in order to generate a extremely low emittance beam for linear collider studies. It consists of 1.54 GeV S-band Linac, beam transport line, damping ring and extraction line. The S-band Linac is an injector of the damping ring which supplies a multi-bunch train beam which is 20 bunches with 2×10^{10} electrons/bunch and 2.8 ns bunch spacing. The newly developed techniques which are high gradient accelerating unit, precise alignment system, beam energy compensation system, compact modulators, multi-bunch beam monitors are used in this linac. The commissioning of the linac was held on November 1995. The beam experiments on a high gradient acceleration and a beam energy compensation for the transient beam loading were performed. The results of these experiments are shown.

Introduction

The main purpose of ATF is to develop an extremely low emittance beam and to demonstrate that one of main key issue of a linear collider is solvable. ATF linac is not only a injector linac of the damping ring but also a test-stand of common key components to realize a linear collider such as multi-bunch beam generation, high gradient acceleration, beam loading compensation and instrumentation development. The construction was started since 1991 in the TRISTAN Assembly Hall in KEK which was a building of 120 m × 50 m width. The reinforcement of the floor driving many piles into the ground was done at first to support heavy concrete shield blocks of tunnels and to avoid floor vibration. The construction of linac was started on October 1992. The 80 MeV electron beam by the preinjector part of the linac [2] has been utilized to test structures and monitors since August 1993. The main part of the linac and the beam transport line to the damping ring has been constructed for about two years. The commissioning of the linac was then held on November 1995. The accelerated beam energy was 1.3 GeV for both single bunch and multibunch. In this stage, the damping ring and the extraction line are still under construction. The performance and development status of ATF linac are summarized in detail. The beam experiments of high gradient acceleration and beam loading compensation are also described.

ATF Linac Sub-system

The ATF linac summarized in Table 1 is consist of 80 MeV preinjector, 8 regular accelerating units, two unit of energy compensating structures. The special concern on the high gradient acceleration, beam loading compensation, active alignment system and fast and precise beam instrumentation are also paid.

Beam Energy for DR	1.54 GeV
Total Length	85 m (from Gun to linac end)
Accelerator Structure	2 π/3 mode constant gradient
Total length	3 m
Total number	16
Accelerating Field	
Maximum Peak Field	52 MV/m
Nominal with Beam	30 MV/m
RF Frequency	2.856 Ghz
Feed Peak Power	200 MW/structure
Klystron	
Klystron Peak Power	80 MW/structure
Klystron Pulse Length	4.5 µs
Number of Klystrons	8
Pulse Compression	Two-iris SLED
Power Gain	5.0 (average)
S-band Preinjector	
Beam Energy	80 MeV
Number of Bunches	20
Bunch Population	2×10^{10} electrons
Bunch Separation	2.8 ns

Table 1 1.54 GeV ATF Linac Parameters

80 MeV Preinjector of Linac [2]

The role of preinjector is to generate 20 multi-bunch of 2×10^{10} electrons/bunch with 2.8 ns bunch spacing and to inject it to 1.54GeV Linac. Since the bunch length less than 10ps(FWHM) is required to meet the energy acceptance of the damping ring, the buncher cavities are designed to have low R/Q values in order to reduce beam induced voltage which affects to bunching of successive bunches.

The extraction of multi-bunch from ordinary thermionic gun is done by applying RF wave of 357 MHz to the grid [3]. The extracted bunch has 1ns (FWHM) and 3A peak current with 200 kV energy. The bunch is shrunk to 15 ps (FWHM) by the two 357 MHz SHB cavities and the 7 cell traveling-wave 2856 MHz buncher cavity. After bunching, the bunches are accelerated up to 80MeV by a 3 m structure, then go into the Linac regular section. One klystron is used in the preinjector which is operated at 60 MW, 1 µs with no SLED. It supplies an rf power into the 3m structure together with the buncher cavity.

High gradient accelerating unit [4]

An 1.54 GeV beam energy is required within about 85 m of total Linac length including preinjector, quadrupole magnets and beam monitors, because of the limited length of the building. A high gradient of 30 MeV/m is necessary for the beam acceleration. The limit of accelerating gradient in the accelerating structure is determined by the break down of the electrical field and the intensity of the field emission current. Since the break down comes from the field emission current, to reduce the field emission current is a key point to get a high gradient field. From the conclusion of the high gradient experiment which we have done for several years, the effort for high gradient structure has done as listed below;

1. keep cleanness during fabrication and tuning in order to avoid dust and contamination on the surface of the structure.
2. the input and output coupler are carefully designed to avoid field enhancement like tuning dimple.
3. use HIP (Hot Isostatic Press) OFHC for the disks to reduce voids between crystal grains.

As a result, a maximum peak gradient of 52 MV/m was achieved with 200 MW peak rf power input in the one of regular unit.

Using these high gradient structures, the regular accelerating unit is composed by 80MW klystron, two-iris SLED and two 3 m structures. This system can generate 400 MW peak power rf from the SLED (200 MW peak power rf into 3 m structure) and 240 MeV energy gain (Fig. 1).

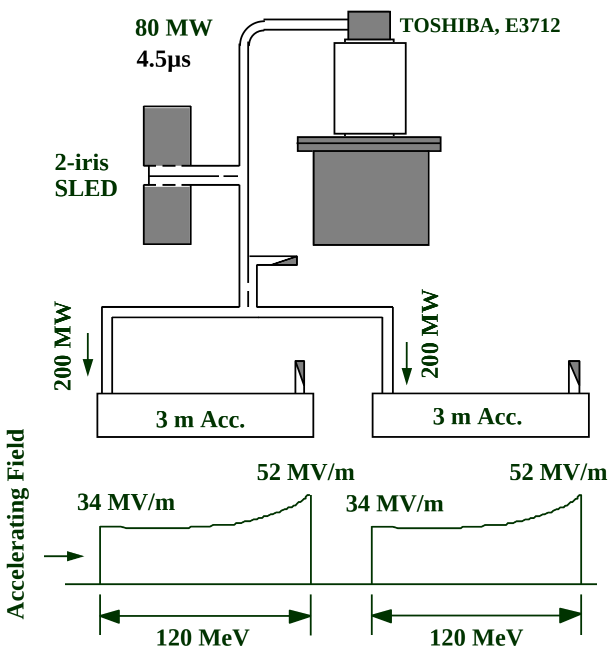

Fig. 1. Block diagram of the high gradient accelerating unit.

Energy Compensation System

In multi-bunch acceleration, a beam energy decreases from the front to the end gradually by a transient beam loading of the structures. Since the maximum energy acceptance of damping ring is ±1% and since a variation of bunch spacing is not acceptable, the new energy compensation scheme for the multi-bunch was developed. Using the accelerating structure which is operated in slightly higher frequency, the front bunches can get deceleration and the rear bunches can get acceleration. To cancel out an energy spread within a bunch, the other structure which is operated in lower frequency of the same amount with opposite slope is used. With this system the energy spread among bunches can be reduced from about 5% to 0.2% peak to peak. In order to simplify the timing system, the frequency deviation was chosen to 4.327 MHz which is just twice of damping ring revolution frequency [6]. Consequently all of the frequencies are fully synchronized. The system consist of two klystrons and 3 m structures which are operated in 2856+4.32 MHz and 2856-4.32 MHz each. The maximum output of klystron is 50 MW, 1 μs square wave which can compensate maximum 80 MeV beam energy in one unit.

200 MW compact modulators [7]

A 200 MW modulator development has been continued since 1987. In total eleven modulators, seven of them are supplied by the one common DC power supply. Four of them are independent type which are supplied by 200 V AC. The main effort of this development is focused on the total size, stability and efficiencies which will directly affect on the scale of the linear collider machine. The use of the compact self-healing type capacitors makes the PFN more compact. The packing of each device into the modulator box was re-checked to make high density packing. By discarding the electric standard for spacing of high voltage device in Japanese industry, 1.5 m × 2.5 m width and 2.2 m height modulator was realized for the three of them. To make a hold-on time of thyratron shorter, the charging into the PFN is initiated by the command from the controller (command charging). To avoid reverse voltage on the thyratron, a tail clipping diode circuit are added. By these method, the lifetime of the thyratron will be longer. The energy loss of the de-Qing circuit is collected by a simple circuit which makes 5% saving of wall plug power.

Wire Alignment System [4]

The stages of the linac have an active mover mechanism and wire position sensors. In order to monitor the stage position and to align the whole stages, two stretched wires are used with the length of about 85 m. The wires are stretched in both side from the preinjector stage to the end of the linac. The sag of wires are calculated in each sensor position as far as no kink on wires and assumption of uniform wires with no creep and no friction on the wheel. The center position of wire sensors mounted on the support stage are calibrated in its calculated position in the calibration stand. Each sensor mount is fixed to the reference surface of the stage which is machined with less than 10 μm in accuracy. In this way, when the stages are aligned so as to get the wire position into the center of the sensors, the reference surface of the stages are aligned to the wires in straight. The resolution of position sensor is 2.5 μm and the accuracy of center finding is ±30 μm. The wire position is detected by a synchronous detection of the signal from the differential coils using 60 kHz current on the wire.

Since the stretched wires had a big sag of a few cm greater than the calculated value at the initial alignment, the alignment of the stage has been done by using the telescope and the alignment target. The alignment sections are divided to five sections and connected them by partial superposition. As the first result of the telescope alignment, the stage reference edges were lied in the range of ±250 µm. The further study will be done on this alignment problem.

Beam Position Monitors

In order to measure the orbit in the linac and the beam transport line, the BPM system was installed and commissioned on February 1996. The pickup chambers are 6 button-type BPM for the pre-injector part and 24 stripline-type BPM for the linac and the beam transport line. The stripline type BPM which has 80 mm length of strip and 30 mm inner diameter has a resolution of 1 µm for 2×10^{10} beam charge together with the high precision track&hold electronics [9]. Figure 2 shows the cross-section of the stripline BPM chamber used in the linac. These BPM chamber are installed in the reference stage girder of the linac by the precision support.

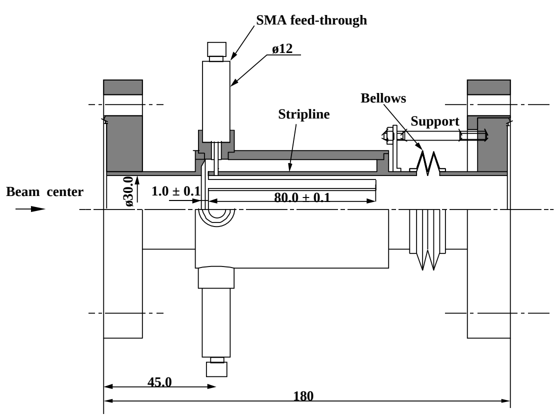

Fig. 2. Stripline BPM chamber.

The relay multiplexing is used for the detection electronics which consist of 5 set of the track&hold electronics of x and y position detection. The measurement of beam position is done by 6 pickups multiplexing for each set. The measured orbit of the beam is corrected by the program "SAD". The convergence of the correction into ±1 mm deviation is attained by around 4 iterations.

Multi-bunch Beam Monitors

In addition to ordinary monitors such as toroid current monitor, screen profile monitor, stripline beam position monitor and bunch length by streak-camera, we are developing bunch by bunch position, size and current monitors which measures each bunch in the 20 bunch train. The preliminary result of gated beam size measurement done by using a fast gated camera on OTR light and gated gamma detection in the wire scanner is reported in elsewhere [1, 7]. The fast current measurement using wall-current monitor and gated position measurement using fast sample-hold circuit are now under developing.

Control System

The control computers are VAX cluster which consists of one main control computer (alpha), one hardware interface computer (VAX4000) which is connected to the hardware device by the CAMAC serial highway, and four workstation terminals. V-system is adopted as a control software for the window system. In order to connect to the program 'SAD' running on the HP workstations in the different place, and to support the experiment data processing, the Macintosh computer is used together with the VAX station. As a real-time control information, the CATV (cable TV broadcasting) system is introduced for monitoring beam signals on the oscilloscope, screen profile, streak-camera image and so on.

RF Processing of Accelerating Unit

A high power test of the regular accelerating unit has been done using one of the accelerating unit from January 8 to February 13, 1994. The power was raised up to 80 MW, 4.5 µs at the output of the klystron. The input peak power of each 3m structure was about 200 MW with SLED cavity. The total processing time was about 600 hours with 200 hours system check and SLED tuning. The rest units were processed from September 29 to November 28 1995 during night only. The day time was spent for the wiring of magnet and monitors, alignment of the linac and construction of the beam transport line. The power level of the klystron output was reached to 44 MW average at the commissioning time. After few months operation, it was raised to 62 MW average. The main reason of this lower operation power level comes from the modulator over-current trip initiated by the electrical noise.

Beam Commissioning

The beam commissioning of ATF Linac was begun on November 22 with insufficient rf processing level. The emittance of 80 MeV injection beam was measured at first. Then the optics which was the matching calculation result from 'SAD' by using the measured emittance was set. The delay timings of rf pulse with beam were adjusted by measuring a difference between BPM signal and rf signal. The phase of rf then searched to get good transmission. The orbit was also adjusted by using screen profile monitors. Once the beam went through the linac, the rf phase and timing were adjusted precisely to get the highest beam energy. After few days above beam tuning, the single bunch of 1×10^{10} was accelerated up to 1.3 GeV by the average gradient of 25.5 MeV/m, and the multibunch of 6 bunches/pulse were also accelerated with the intensity 1×10^{9}/bunch. The energy spread of the single bunch was 1% FWHM and the normalized rms. emittance was 2×10^{-4}. The intensity was raised up to about 2 × 10^{10} during the operation for the several experiments. However, the transmission ratio of the beam current from the exit of preinjector to the end of the linac was about 60% at around 1 × 10^{10} or over. The reason of this low transmission was investigated, and found that it came from the low energy tail of the energy spread which slipped out from the acceptance of the optics. The energy of the beam which is still below the required. The reason comes from the modulator over-current trip problem which is caused by an interference with an electrical noise. This is now under fixing. On February 1996, the BPM system was installed and commissioned as mentioned above. The measured orbit of the beam is corrected by "SAD". The beam operation of linac became easy than before. The linac is now operating routinely for various beam experiments of linear collider R&D. To summarize the performance of this linac, the achievement are listed in Table 2.

Maximum Beam Energy	1.42 GeV
Maximum Gradient with beam	28.7 MV/m (average)
Maximum Klystron Power	62 MW (average)
Accelerated Intensity: single bunch	1.7 × 10^{10}
:20 multi-bunch	7.65 × 10^{10} (total)
Energy Spread : single bunch	0.4% (FWHM)
:20 multi-bunch with ECS	~ 0.3% (FWHM)
Emittance $\gamma\varepsilon_x$: single bunch	1.3 × 10^{-4} (1σ, at Inj.)
: 20 multi-bunch	not measured

Table. 2 Achievement of the Linac

Energy Compensation Test

In order to confirm the principle of this compensation scheme, the beam test was performed by using the 2856+4.32 MHz structure only at the beginning. Since the klystrons of the energy compensation system (ECS) were not ready at that time, the regular unit klystron was switched to the ECS structure. The frequency of the ECS is generated by the single side-band modulator which combines the signal of 4.32 MHz with the carrier of 2856 MHz. The measurement of beam energy for each bunch was done by using BPM after the bending magnet of the beam transport line. The multibunch signal from the BPM was measured by the digital oscilloscope of 1 GHz band width. After the adjustment of the beam timing with rf pulse, the phase of rf was set to an appropriate value to get a maximum deceleration for head bunches and a maximum acceleration for tail bunches. Then, the rf amplitude was set to get a flat energy distribution for all the bunches. The effect of the ECS is successfully demonstrated in the case of 10 bunches with 4 × 10^9 each bunch and 20 bunches with 7 × 10^9 each bunch intensity [1]. The calculated energy difference by the beam loading was 5% for 20 bunch case, the ECS by 2856+4.32 MHz frequency could compress it to 0.5% by 25 MW rf power.

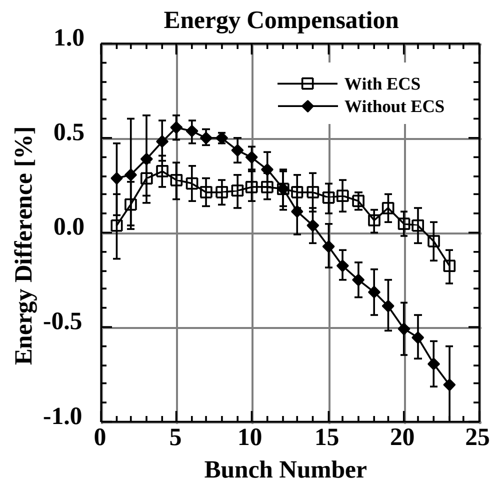

Fig. 3. Energy of each bunch with and without ECS.

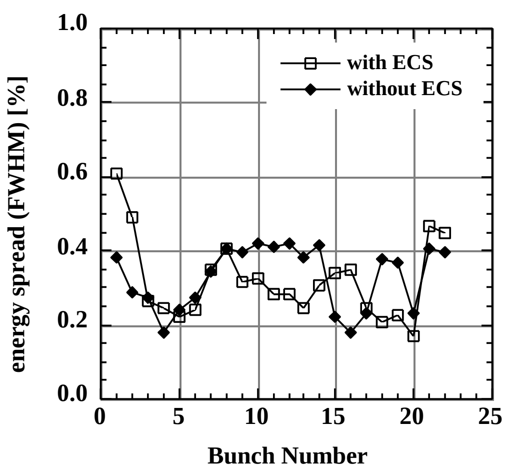

Fig. 4. Energy Spread of each bunch with and without ECS.

After the installation of two sets of ECS modulator and klystron, a beam test of this regular ECS system was held on July 1996 using both 2856+4.32 MHz and 2856-4.32 MHz frequencies [10]. The OTR monitor combined with a bending magnet was installed for the measurement of energy and energy spread of multibunch beam in order to confirm the ECS performance. The bunch charge was limited to 1.5 × 10^9 each by the radiation control alarm which was caused by an emitted radiation from the OTR monitor. The measured relative energy of each bunch by the BPM demonstrate the ECS compression performance shown in Fig. 3. The power level of the klystron was around 2 MW in this low charge compensation. The energy decrease at front of the bunches seems to come from the position shift caused from the side tail cut by the collimator.

The energy spread of each bunch, on the other hand, was measured by the OTR monitor with the 3ns gated camera [11].

Figure 4 shows the energy spread with ECS and without ECS in the case of 2.5×10^9 each bunch. Although the measured spreads are scattered around 0.3% FWHM, there is no big difference even with this ECS. The observed waveform of multi-bunch beam by the wall-current monitor is shown in Fig. 5 in the case of the same charge. The monitor is placed at the downstream of the linac in front of the first bending magnet of the beam transport line.

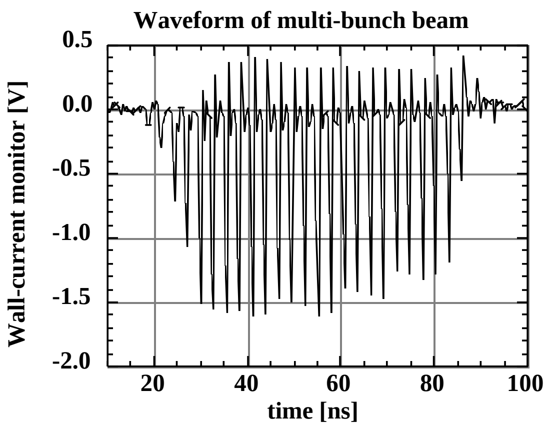

Fig. 5. Waveform of the multi-bunch beam.

Schedule toward Damping Ring commissioning

After the commissioning of the Linac in 1995, the installation of Damping Ring components was started in urgent. Almost all the magnets, chambers and active stages were ordered during 1995. The fabrication of these component are almost finished. The installation will be finished till November 1996. Then, we will have the beam commissioning of ATF Damping Ring on December 1996.

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