# THE KEK ACCELERATOR TEST FACILITY

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## *Abstract*

Accelerator Test Facility ( ATF ) is under construction in the TRISTAN Assembly Hall consists of 1.54GeV S-band Linac, beam transport line, damping ring and extraction line for linear collider R&D. The S-band Linac is an injector of the damping ring supplies a multi-bunch beam train which is 20 bunches with $2x10^{10}$ 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 introduced. The commissioning of the linac was held on November 1995. The beam experiment on a high gradient acceleration and a beam energy compensation for the transient beam loading are performed. The result of these experiments will be shown. Also the development and construction status of the damping ring is described as well.


## 1 INTRODUCTION

ATF is a test-stand of key components to realize a linear collider such as multi-bunch beam generation, high gradient acceleration, low emittance beam generation and its instrumentation development. The ATF consist of 1.54GeV S-band Linac and damping ring built in the TRISTAN Assembly Hall(Fig. 1) which is 120m x 50m. The ATF Linac is consist of 80MeV preinjector, 8 regular accelerating units, two unit of energy compensating structures. The 1.54 GeV damping ring whose circumference is 138.6m has a beam current of 600mA. The main purpose of the damping ring is to develop an extremely low emittance beam(30nm for vertical) and to demonstrate that one of main key issue of a linear collider is solvable. At this stage, whole tunnel construction, tunnel air conditioning, water cooling system and installation of Linac and Beam Transport Line components were completed. The first operation of the linac was held on November 1995. A beam acceleration of the single bunch and the multibunch were succeeded at 1.3GeV energy. The beam experiment of the energy compensation of multibunch beam was also succeeded. Damping Ring components are now under developing and fabricating. The installation of them will be completed on November 1996. The commissioning of the Damping Ring will be on December 1996. The performance and development status of the ATF together with the beam experiments of the linac are summarized in detail.

## 2 1.54GEV ATF LINAC

### *2.1 80 MeV Preinjector of LINAC* [1]

The preinjector is designed to generate 20 multi-bunch of $2x10^{10}$ electrons/bunch with 2.8 ns bunch spacing and to inject it to 1.54GeV S-band Linac. The buncher

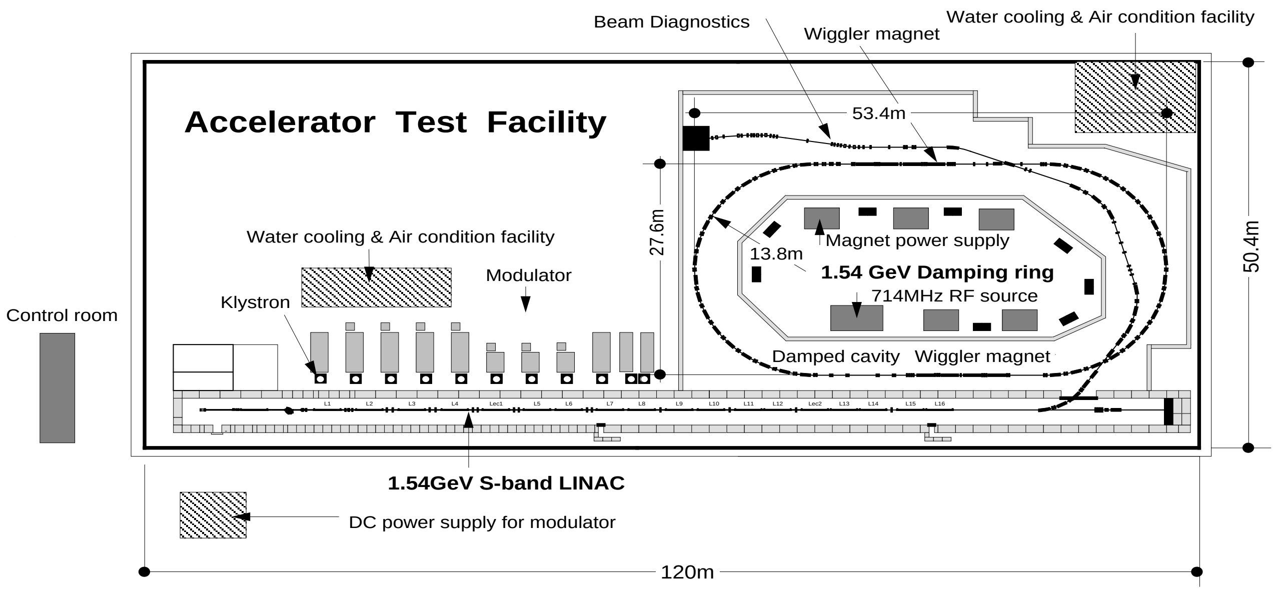


Figure 1 ATF overview

cavities are designed to have low R/Q values in order to reduce a beam induced voltage which affects to bunching of successive bunches. The extraction of multi-bunch from the thermionic gun is done by applying RF wave burst of 357MHz to the grid[2]. The extracted bunches have 1ns(FWHM) and 3A peak current with 170kV energy. The bunches are shrunk to 20ps(FW) by the two 357MHz subharmonic buncher(SHB) cavities and the 7 cell travelingwave(TW)-type 2856MHz buncher cavity. After bunching, the bunches are accelerated up to 80MeV by the one 3m structure without rf pulse compression, then go into the Linac regular section. The bunching by the TW and 80MeV acceleration is done by the one klystron with 60MW, 1μs rf pulse output.

## *2.2 High gradient accelerating unit* [3]

An 1.54GeV beam energy is required by the damping ring with the limited length of the building. The allowable length for the whole linac was about 80m including accelerating structures, quadrupole magnets and beam monitors. Therefore, the high gradient of 33MeV/m is used for the beam acceleration. The limit of accelerating gradient in the accelerating structure is determined by the break down of the electric field and the intensity of the field emission current. Since the break down comes from the intensity of the field emission current, to reduce the field emission current is necessary for the high gradient. From the conclusion of the high gradient experiment which we have done for several years, the effort for high gradient structure has been done are as follows; in order to avoid dust and contamination on the surface of the structure, cleanness during fabrication and tuning was kept. The input and output coupler are carefully designed to avoid field enhancement arising at a projection of tuning dimples. We used HIP(Hot Isostatic Press) OFHC for the disks to reduce voids between crystal grains. As a result, a maximum gradient of 52 MV/m was achieved with 200MW peak rf power input for the 3m structure.

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

## *2.3 Wire Alignment System [4]*

The stages of 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 80m. The sag of the wires are calculated in each sensor position assuming uniform wires with no kink, no creep. The center position of wire sensors mounted on the support stages are calibrated in its calculated position at the calibration stand. Each sensor mount is fixed to the reference surface of the stage which is machined with less than 10μm in accuracy. The resolution of position sensor is 2.5μm and the accuracy of center finding is ±30μm. The wire position is detected by a synchronous detection of the signal from the differential coils pickups using 60kHz current on the wire.

## *2.4 Energy Compensation System*

In multi-bunch acceleration, a beam energy decreases from the front to the end gradually by a beam loading of 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 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 same amount with opposite slope is introduced. 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[5]. The system consist of two klystrons and 3m structures which are operated in 2856+4.32MHz and 2856-4.32MHz each. The required maximum output of the klystron is 50MW, 1μs square wave which can compensate maximum energy difference of 80MeV.

## *2.5 200MW compact modulators* [6]

The main effort of the development of modulator 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 of Japanese industry for spacing of high voltage device, 1.5m x 2.5m width and 2.2m height modulator was realized. To make a hold-on time of thyratron shorter, the charging into the PFN is initiated by the command from the controller. By this 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.

## *2.6 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 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.

## 3 ATF LINAC COMMISSIONING

The completion of construction was done on October 1995 excluding the energy compensation system, beam position monitors and control software. During November, the rf processing of the structures and development of control software have been carried. The beam commissioning of ATF Linac was begun on November 22 with insufficient rf processing level. After few days beam tuning, the single bunch of $1\times10^{10}$ was accelerated up to 1.3GeV by the average gradient of 25.5MeV/m, and the multibunch of 6 bunches/pulse were also accelerated with the intensity $1\times10^{9}$/bunch. The energy spread of the single bunch was 1%FWHM and the normalized rms. emittance was $2\times10^{-4}$. The intensity was raised up to $2\times10^{10}$ during the operation for the several experiments. However, the transmission ratio of the beam current from the exit of preinjector to the exit of the linac was about 60% at around $1\times10^{10}$ or over. The reason of this low transmission is now investigating. The energy of the beam which is still at 1.3GeV is below the required. The reason comes from the modulator over-current trip problem. We are now also investigating the modulators. On February 1996, the BPM system was installed and commissioned. The pickup chambers are 6 button-type for pre-injector part and 24 stripline-type for linac and beam transport part. 5 set of the conversion electronics were installed. The measurement of beam position was done by 6 pickups multiplexing. The measured orbit of the beam was corrected by the program “SAD”. The convergence of the correction was around 4 iterations. The linac is now operating routinely for various beam experiments.

## 4 ENERGY COMPENSATION TEST

In order to confirm the principle of this compensation scheme, the beam test was performed by using the 2856+4.32MHz structure only. Since the klystrons of the energy compensation system(ECS) are not ready at this 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 4.32MHz with the carrier of 2856MHz. As the 4.32MHz signal which is generated by dividing the 2856MHz carrier is twice of the damping ring revolution frequency, this ECS frequency is fully synchronized with each other. The measurement of beam energy for each bunch was performed 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 1GHz band width. After the adjustment of the beam passing timing with rf pulse, the phase of rf was set to an appropriate value which was searched by a phase scan 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 on/off is demonstrated in Fig. 2 in the case of 10 bunches with $4\times10^{9}$ each bunch. As for 20 bunches, all the bunches could not transmit without ECS because of big energy difference at tail bunch. The ECS test was done for it by changing the rf amplitude in order to get a flat beam energy. The results are shown in Fig. 3 with $7\times10^{9}$ each bunch intensity in case of 18, 25, 28MW of rf power. Although the calculated energy difference by the beam loading was 5%, the ECS could compress it to 0.5% by 25MW rf power.

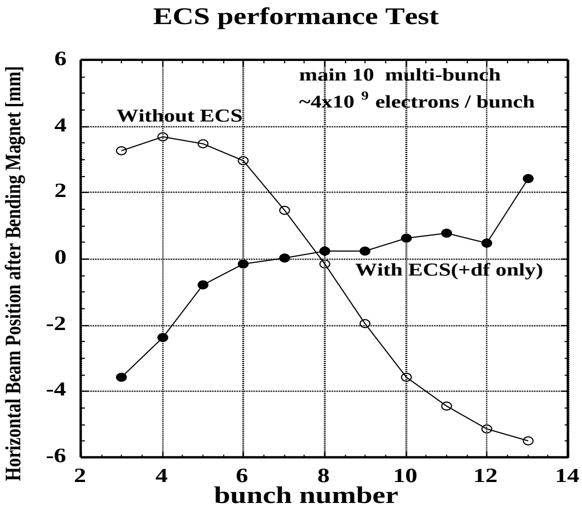


Figure 2 The effect of ECS for 10 bunches

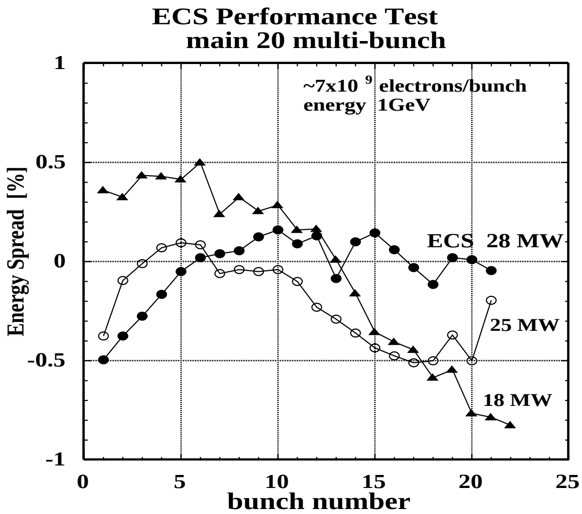


Figure 3 20 bunches Energy spread with ECS

## 5 DAMPING RING[8]

### *5.1 Lattice*

The basic magnet lattice of ATF damping ring is the normal cell with a combined-function bend. Placing each bend which radiates a synchrotron light at the minimum of the horizontal dispersion in each normal cell is to reduce the equilibrium emittance. Therefore the bending magnet must play a roll of a horizontal defocusing magnet. The defocusing of the bend also helps the horizontal emittance to be further reduced by changing the ratio of the damping rate between the horizontal and longitudinal planes. The value of the horizontal equilibrium emittance is basically determined by the structure by the unit cell. The wigglers are for reducing the damping time.

The vertical emittance is generated by both the vertical dispersion and betatron coupling, both of which strongly correlate to the alignment errors. The vertical dispersion is produced by any vertical misalignment of the quadrupoles, rotation of the horizontal bends and the vertical correction dipoles. The sensitivities of the emittance to random misalignments have been studied by an analytical approach and by a combination with simulations. The tolerances of misalignments at the 95% confidence level both with and without the bump tuning are 100µm, 60µm each for y direction. These tolerances seems to be feasible, and the bump-tuning gives a looser tolerance by roughly a factor of two.

## *5.2 Active Girder Stage*

The relative movement of the magnets due to a ground motion is the same order of the alignment tolerance. The correction of this movement will be done by an active support system for the magnets. The set of magnets of normal cell is installed on an active support table whose position can be controlled by stepping motors with 5 directions(x, y, z, rolling angle, pitching angle). The precision of the table positioning is measured for the prototype as 2µm. The angle precessions were 2.5µrad for pitching angle and 10 µrad for rolling angle. The installation of these magnets on the table; one bending magnet, two quadrupole magnets, two sextupole magnets and two corrector magnets, is done by using a laser tracker measurement system before the installation of the table into the tunnel.

## *5.3 BPM*

The precise measurement of the beam position with its less than 5 µm resolution is required by the measurement and correction of the dispersion in the wiggler section. The low longitudinal impedance less than 0.2Ω is also required to avoid a beam instability. To meet these requirement, button type electrode for the beam position monitor(BPM) were selected.

The pickup electrodes with SMA connector vacuum feed through are installed into a BPM block. The BPM block was machined from a mass of aluminum alloy, and four pickup electrode were welded onto the block. It has both horizontal and vertical reference planes with an accuracy within 50µm. Both planes become a reference for the calibration process to obtain an electrical center offset from the mechanical center of the BPM block.

## *5.4 Vacuum Chamber*

The vacuum chamber must be designed to have low impedance and to achieve a pressure which does not cause an unacceptable emittance growth through beam-gas scattering. The gas desorption in an electron storage ring is dominantly induced by the irradiation of synchrotron radiation (photodesorption). The aimed average pressure of the ring is below $6 \times 10^{-6}$ Pa. The required pumping speed, therefore, should be 140 and 70 l/s/m for the wiggler section and for the bending section where the photo-desorption is severe. The most part of the chamber is made by the extruded aluminum alloy. Copper is for the SR absorbers. Stainless steel is for the bellows. All the chamber will be baked to 150°C for 24 hours before assembly at the beam line. For the chamber connection, optimized clamp-chain flanges with no gap inside are used. The cross section of chamber is ø24mm for the arc section, a race-track shape 15mm high x 47mm wide for the wiggler section. The rf shield is inserted into the bellows and gate valves.

To avoid a single bunch instability in the longitudinal plane, the impedance of the vacuum chamber and components should be carefully evaluated. The impedance sources in the ring were estimated by the program 'TBCI' and 'ABCI' code. The threshold intensity are estimated to about $N=3.5 \times 10^{10}$ by solving the Vlasov equation and computing the growth rates of eigenmodes taking into account the potential-well distortion and the synchrotron radiation. This is above the design intensity $N=2.0 \times 10^{10}$.

## *5.5 Damped RF Cavity*

The longitudinal coupled-bunch instability excited by the tail of the accelerating mode impedance can be avoided by using a low rf frequency and high accelerating voltage with low-R/Q cavities. The design of rf system will achieve this condition. The low-R/Q cavity also suppress a bunch position shift because of small beam loading. The other method such as rf feedback for specific oscillation modes and beam loading compensation will be installed for cures of these instabilities. The longitudinal instabilities caused by the higher-order modes(HOM) can be suppressed by the damped cavity (cavity with low Q values of HOMs). The transverse instabilities can also be suppressed by a damped cavity and the bunch-to-bunch tune spread in each train.

In the damped rf cavity, the power from harmful HOMs is extracted through waveguides attached to the cavity. A cylindrical cavity with round corners and nose cones was chosen for the basic shape. The cavity shape was determined to obtain as high a shunt impedance as possible, while almost all harmful HOMs have strong magnetic fields at the outer corners of the cavity where the waveguide are attached. For damping HOMs, four waveguides are attached at the corners. The calculations of HOM damping by the waveguide loading were carried out using the program code 'MAFIA'.

A low power test of the HOMs damping shows that the loaded Q of HOMs are significantly lowered by these damping waveguides. A high power test of the cavity was carried out at the level of 50kW CW and at the frequency 714MHz. The rf processing time was about 50 hours to reach 50kW. We could find no problem for the high power operation. The power which is limited by the klystron will be upgraded.

### *5.6 Confirmation of Emittance*

In order to confirm the main performance of the damping ring, that is equilibrium emittance, we have to measure the beam size in the ring and in the extraction line. The vertical beam sizes at the maximum β-function of vertical direction is $\sigma y=7\mu m$ for the center of the combined bend in the ring, and $\sigma y=10\mu m$ for the center of the focusing quadrupole in the extraction line. The special beam size monitor are required for both small size beam measurement.

For beam size measurement in the ring, a visible synchrotron light monitor is now under development. A gated camera by using a multi-channel plate (MCP) gives synchrotron light measurement at any timing with sufficiently narrow gate (2.5ns). The development of this monitor using a gated camera is done by a fast and precise data taking system using workstation and precise timing circuit. However the resolution is limited by the diffraction of light to 30 ~ 40 μm, the size measurement of 7μm is very difficult by this monitor. The other method is now under planning and developing. They are synchrotron X-ray measurement, laser wire scanner measurement and laser compton monitor. In these measurement, we have to consider the large beam repetition( 2MHz ), access method to the beam through the limited space and small chamber, and a signal detection in the presence of large amount of synchrotron light and kicker electrical noise.

For beam size measurement in the extraction line, a 4μm carbon wire scanner is now under development. In the case of a carbon wire scanner and laser wire scanner, the key issue is to make a good S/N gamma detector in the presence of a background gamma-ray caused by the beam hallow hitting. The main effort to these monitor are done for the development of the gamma-ray monitor. However, in the extraction line, the beam size will be affect by the kicker magnets, the measurement in the ring is more important for the confirmation of equilibrium emittance.

### *5.7 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 will be finished till summer 1996. The installation will be finished till November 1996. Then, we will have the beam commissioning of ATF Damping Ring on December 1996. At that time, rf system will be installed half of them, then will be upgraded gradually. The performance of the ring, therefore, will not be the design value at the commissioning.

## 6 ACKNOWLEDGMENT

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