

SUPERCONDUCTING ACCELERATOR DEVELOPMENT AT STF FOR ILC

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Abstract

The superconducting RF test facility (STF) in KEK is the facility for developing technologies of the International Linear Collider (ILC) main linacs. The STF accelerator is a test linear accelerator using superconducting cavities (SC cavities) and cryomodules of ILC technologies. The injector of the STF accelerator consists of the L-band photocathode RF-gun (normal-conducting cavity), two superconducting 9-cell cavities for pre-acceleration of electron beam. The 12m-cryomodule (8 SC cavities and 1 SC quadrupole magnet with beam position monitor(BPM)) and 6m-cryomodule (4 SC cavities) are followed after the injector. They will be powered by 10MW multi-beam klystron and the distribution wave-guide system, and the accelerator field and phase are controlled precisely by the fast digital feedback at low-power level. For monitoring SC cavity alignment change during cool-down, the wire position monitors (WPM) are used inside of the cryomodules. Recent developments of the STF accelerator such as cryomodules, high power components, low-level controls, SC quadrupole magnet, BPM and WPM are discussed and summarized in this paper.

1 INTRODUCTION

The purpose of construction and operation of STF accelerator under the program STF-phase-2 is to demonstrate the ILC Main Linac accelerator technology and to experience operation of high current and high beam power superconducting accelerator. During STF accelerator construction and installation in the STF-phase-2 program starting from 2009, we conducted several experiments, such as S1-Global cryomodule experiment [1], and Quantum-beam experiment for a compact high-flux X-ray generation [2]. The Quantum Beam accelerator part is now used to the STF accelerator injector. The main accelerator by the long cryomodules were constructed from 2013, assembled in to the STF tunnel in 2014. The first cool-down test of these new cryomodules was performed from October 2014 to November 2014. The laser for the photocathode RF-gun was replaced from the one of the Quantum-beam experiment beam pattern to the one of ILC beam pattern.

The powering scheme of cryomodule is to use TDR (Technical Design Report [3]) system which is using multi-beam-klystron and Marx modulator, supplying the RF power to 39 cavities with flexible dividing ratio. The demonstration of the TDR RF scheme is one of milestone of the STF accelerator construction and operation. The newly installed cryomodule includes cavity beam position monitor and split-assembly superconducting quadrupole magnet, together with WPMs and stretched wires to check

alignment of cavities inside cryomodule during cooled state.

2 STF ACCELERATOR

The injector part of the STF accelerator consists of Cs-Te photo-cathode RF gun (1.3GHz DESY/FNAL design normal conducting gun cavity), and the capture cryomodule. Two 9-cell superconducting cavities in the capture cryomodule were tested and successfully reached its gradient up to 40MV/m and 32MV/m. They are powered by 800kW pulsed klystron (DLDS klystron). The downstream of the injector includes ILC-type cryomodule, CM-1, the half-size cryomodule, CM-2a, connecting beam lines and the beam dump. Overall view of the STF accelerator plan is illustrated in figure 1.

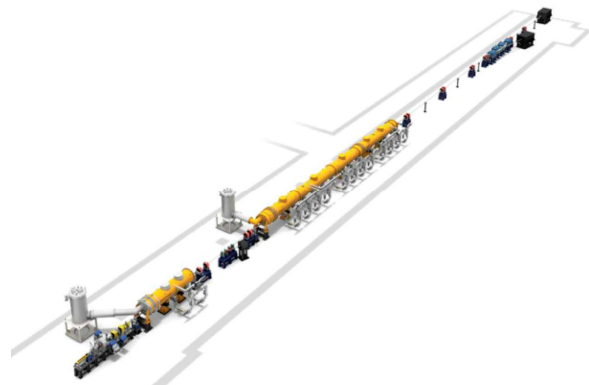


Figure 1: Planned view of the STF accelerator in 100m length of the STF tunnel. Left side is photo-cathode RF gun, followed by capture cryomodule, bunch compressor 1, CM-1, CM-2a, then bunch compressor 2 and the dump.

The accelerator will include two stage bunch compressor for future FEL application. The first stage bunch compressor is a chicane at the entrance of CM-1. The second stage compressor is a chicane in front of the beam dump. For undulators and user area of FEL need to be expanded more to the downstream. The connecting beam line is under design, not yet installed. The 2K cold-boxes for 2K liquid helium supply to CM-1 and CM-2a is installed at the front of CM-1, the wall-side.

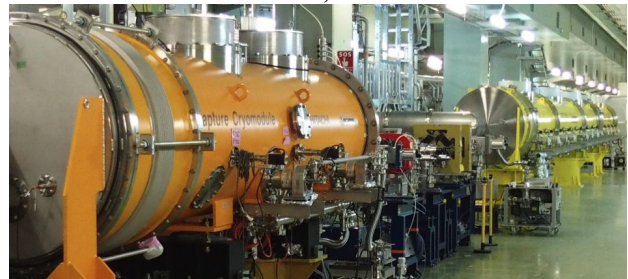


Figure 2: Current view of the STF accelerator.

The current installation picture of the STF accelerator is shown in figure 2. The accelerated beam energy will be 418MeV, assuming 31.5MV/m gradient for 12 cavities in CM-1 and CM-2a, and 40MeV energy at the exit of the capture cryomodule. The accelerating beam train length is 0.9ms with 5.7mA peak intensity and 2.7MHz bunch repetition in a train with 5Hz train repetition, which are met with ILC beam specification.

3 CRYOMODULE DEVELOPMENT

3.1 Superconducting Cavities

Total number of the cavities used for the STF accelerator was 14, while 15 cavities were fabricated. They are 2 for the capture cryomodule, 8 for CM-1, and 4 for CM-2a. The rest one is spare. In STF, the inner surface treatment and the field test were allowed maximum 4 treatment and field test. The summary of the field gradient performance in the first treatment, and the final gradient performance are shown in reference [4]. The average gradient in the final field test was 34.2MV/m. The maximum gradient was 41MV/m and the minimum gradient was 12MV/m. They will be tested their gradient performance in the cryomodule in October 2015.

3.2 Superconducting Quadrupole Magnet

The CM-1 is the ILC design cryomodule which contains eight 9-cell superconducting cavities and a conduction-cooled splittable superconducting quadrupole magnet together with a beam position monitor in the center position. The magnet uses conduction cooled, splittable structure, which are newly introduced concept in TDR (see figure 3 for the concept). The fabrication of the conduction-cooled quadrupole magnet by the collaboration with FNAL was completed in September 2013 [5].

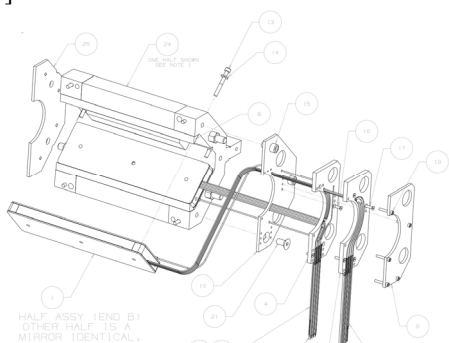


Figure 3: One half of the splittable quadrupole magnet. 4 coils are attached to inside of the steel body.

The installation of the splittable magnet into BPM chamber was successfully done as shown in figure 4, in normal cleanliness environment. This installation was done after the connection of BPM chamber with gate-valves on both end of cavity train by using local clean-room in the tunnel. The conduction strips attached on the coils and steel body, made by pure aluminium, were connected to 2K helium supply pipe, 5K shield and 80K shield.

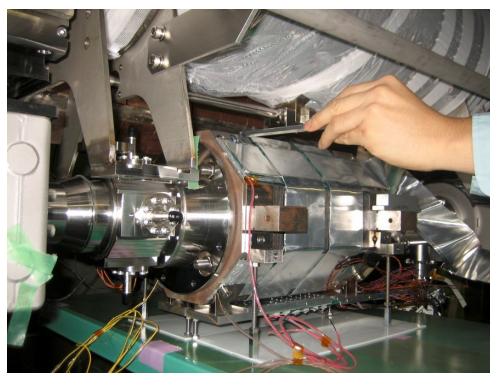


Figure 4: Picture of the splittable quadrupole magnet installation attached to the BPM chamber, under the cryomodule gas-return-pipe (GRP).

3.3 Cavity BPM

The beam position monitor using re-entrant cavity structure has been designed and developed since 2007 [6]. The resonant frequency of this cavity is 2.04GHz which is selected to avoid accelerating cavity HOM bands. The field pattern of the dipole mode of the re-entrant cavity is shown in figure 5. It has 4 coupling waveguide slots attached to the re-entrant cavity. 4 pick-up antennas are used in the coupling waveguide. This is to suppress common-mode leak to the pick-up antennas. In order to keep wide beam pipe acceptance, 80mm diameter beam pipe, which is the same as the accelerating cavity beam pipe diameter, is selected. The resolution was already demonstrated to 0.4 μm with 1×10^{10} electrons/bunch beam intensity during beam test at ATF beam line. Electrical center definition accuracy was also studied by using special BPM test stand. The results was around 25 to 50 μm accuracy relative to mechanical center.

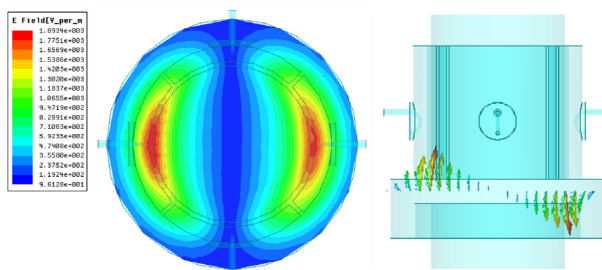


Figure 5: Electric field intensity pattern (dipole-mode) of the re-entrant cavity BPM.

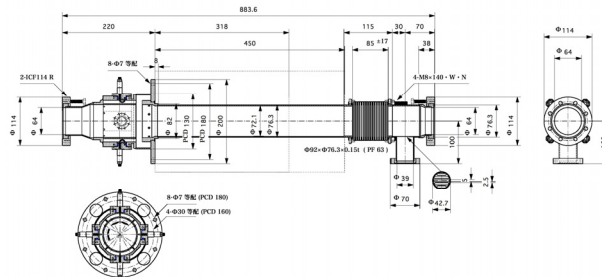


Figure 6: cryomodule-installation-type BPM chamber. It has long beam pipe for superconducting quadrupole magnet installation. Also pumping port is there.

As shown in figure 6, cryomodule-installation-type BPM chamber was fabricated for CM-1 installation. The chamber has been experienced liquid-nitrogen temperature thermal shock for leak-tight check, high-pressure-water rinsing, and baking in the clean room.

3.4 WPMs for alignment detection

In order to measure alignment of cavities during cooled state, the 70microns gold-plated-tungsten wires are stretched from the both end plates of the cryomodules, which is room temperature anytime. The total length of wires are 19.5m each. One end of the wire is connected to the N-type feed-through connector, and the other end is hang on the ceramics roller with 500g weigh for tension force. They are inside of the vacuum vessel of the cryomodule, so they are in vacuum. 5 WPMs are attached to the gas-return-pipe (GRP) and 16 of them are attached to the cavities in only CM-1, as shown in figure 7.

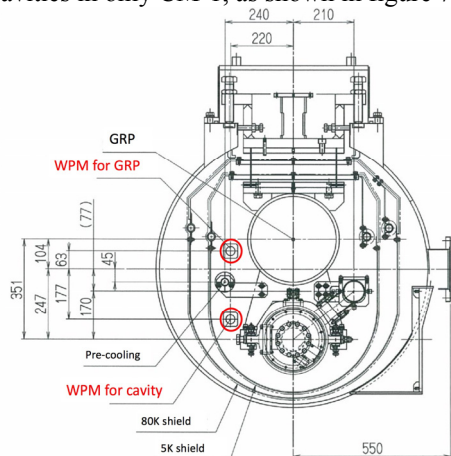


Figure 7: Positions of the WPMs (red circles) in the cross-section of the cryomodule. The upper one is attached to the GRP, the lower one is attached to the cavity jacket side-tubs.

They are 4 strip-line electrodes pickup, which detects burst 160MHz RF signal with 5 μ s width on the stretched wire (figure 8). The induced signals on the strip are digitized by the fast ADC of 1Gs/s 12 bits only for 512 points and FFT converted for 92ch multiplex. From the 4 peak amplitude of FFT 160MHz waveforms, the wire positions are calculated and recorded with 10 seconds interval.

The position measurement of GRP and cavities relative to the wires shows relative movement. Since the cavities are deep inside of cryomodule and thermally shielded by super-insulator, their position in a cooled state is hardly recognized. On the other hand, ILC requires their position to be kept within 300 μ m offset and 300 μ rad tilt. Confirmation of keeping alignment is important for the cryomodule assembly technology.

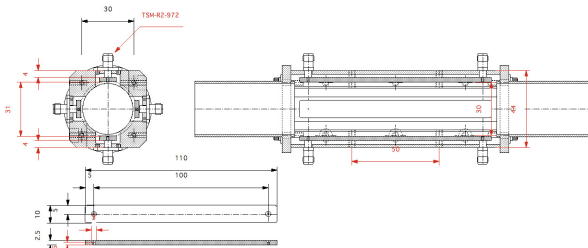


Figure 8: The WPM pickup. 4 strip-line electrodes are on the SMA feed-through connectors. The one end is terminated, the other is connected to the cable and out to outside of the cryomodule. The pickups are connected by aluminum pipes each other for the good signal transmission on the wire.

4 FIRST COOL-DOWN EXPERIMENT

The helium 2K cold-box for the cryomodules in the STF accelerator was installed in the STF tunnel and connected to the main helium refrigerator. They were cooled down to 2K and tested its low power performance in October 2014. The test has been performed to confirm cooling capability of the cryomodules and the cooling system, cavity low-power performance such as resonant frequency and Q-value, test of superconducting quadrupole magnet inside of the cryomodule, and GRP and cavities alignment check. The cavities were successfully cooled down to 2K. The low-power RF performance of them was expected one for every cavity.

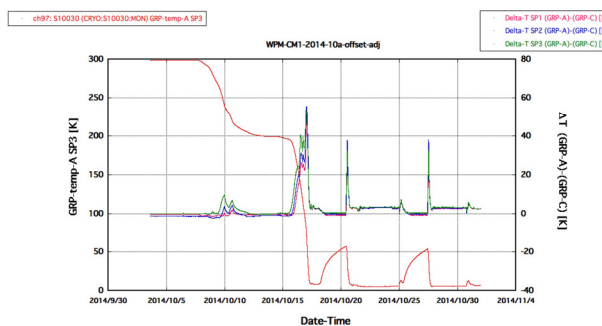


Figure 9: Temperature profile during cool-down. Red line shows GRP temperature. Three other lines are temperature difference between GRP top to bottom. Deviation of temperature difference happens on steep cool-down duration.

On the other hand, the conduction cooled splittable quadrupole magnet was cooled only at 9K, while the target temperature was 5K. The reason was analysed after warm-up, to be insufficient thermal anchor or thermal shield for incoming heat from current leads. It is now modified to improve thermal shield from current lead.

During the cool-down, alignment of the cavities hang on one long GRP of CM-1 is checked by the WPM. Relative movement of the wire by WPM on the GRP are plotted in

figure 10 for X direction (horizontal direction) and figure 11 for Y direction (vertical direction), during cool-down in one month. Big movements happened on steep cooling from 200K to 4K for Y direction, about 3.5mm on the both end of GRP. It seems to happen by temperature difference between GRP top and bottom. For X direction, the movement is not significant, however, very slow damping of vibration of wire was observed.

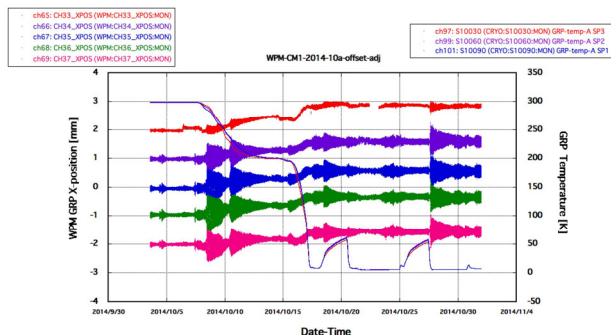


Figure 10: WPM trend plot for GRP X-direction, together with GRP temperature variation. Plots from top to bottom are for GRP upstream to downstream positions. Relatively big variation happens on the most upstream WPM(red).

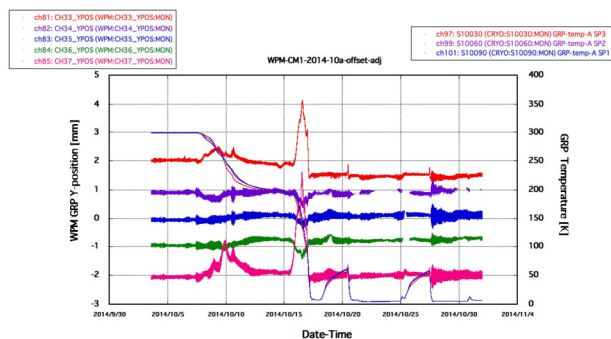


Figure 11: WPM trend plot for GRP Y-direction, together with GRP temperature variation. Plots from top to bottom are for GRP upstream to downstream positions. Fairly big variation happens on steep cool-down on both end of GRP (red and magenta).

2 set of WPMs for the cavities are attached to the both support tabs in CM-1. So we can measure the cavity offset movement and tilt movement, both. As an example of WPM data for the cavity, #1 cavity two set WPM trend data are plotted in figure 12, together with GRP temperature variation. They should be followed a movement of GRP upstream position, because the cavity#1 was hang on GRP upstream end part. Plot shows good traceability to GRP, however, reached positions by both upstream and downstream WPM in cooled state show tilts on X and Y, both direction.

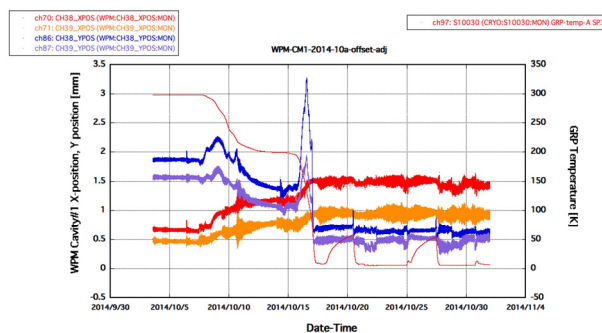


Figure 12: WPM trend plot for Cavity #1, the most upstream one, X-direction for red and orange, Y-direction for blue and purple, together with GRP temperature variation. Two set of plots are corresponding to cavity support tab upstream and downstream. Variations are follows from GRP movement.

5 BEAMLINE OPTICS PLAN

Considering future extension of the STF accelerator for possible FEL application, a design of beam energy 1GeV with two-stage bunch compressor have been done as shown in figure 13. After capture cryomodule, the first bunch compressor (BC1) has been designed with 45MeV beam energy. Then beam is accelerated by 3 cryomodules to 525MeV. The second bunch compressor (BC2) is placed at this energy. There is a plan for extension of three more cryomodules for 1GeV beam for undulators with new tunnel extension.

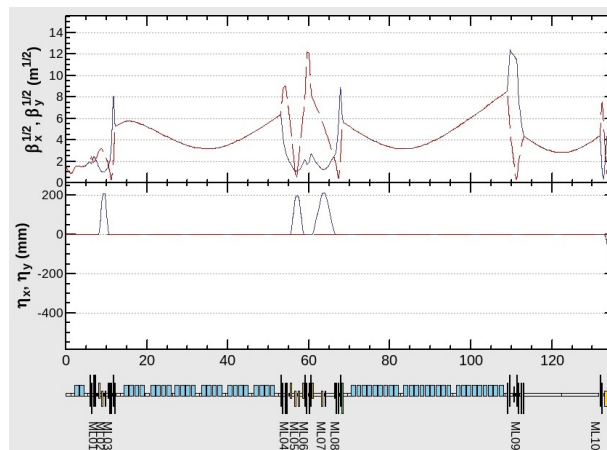


Figure 13: Planned beam line optics design for future STF accelerator. Total 6 cryomodules and 15m undulator section are assumed.

The BC1 compress the bunch length from 1.25mm to 0.3mm with 0.068% energy spread. And the BC2 compress the bunch length from 0.3mm to 0.05mm with the same energy spread.

6 RF POWER DISTRIBUTION AND CONTROL PLAN

The RF power scheme with control of power dividing ratio and phase is adopted as a cost effective baseline of TDR. The TDR RF power source consist of a 10MW multi-beam klystron (MBK) and a Marx modulator, and waveguide system which distributes 1.3GHz 1.6ms pulse RF power into 39 cavities with circulator in each input. In order to supply RF power effectively to 20% spread of gradient performance cavities, the power can be split with flexibility by a variable hybrid (Pk control). Also, a phase of RF input can be controlled by a phase shifter in each of cavity input line. A coupling of cavity (loaded-Q, QL) can be controlled by an input coupler insertion length. In order to control each cavity power input and loaded-Q of each cavity among vector-sum controlled cavities, the above variable adjustment (Pk-QL control) are controlled remotely. Figure 14 shows waveguide installation outside the cryomodule, CM-1 and CM-2a, to accommodate these functions. Figure 15 shows detail side view of this waveguide system for CM-1.



Figure 14: RF power distribution scheme of STF phase-2 cryomodule, according to TDR design.

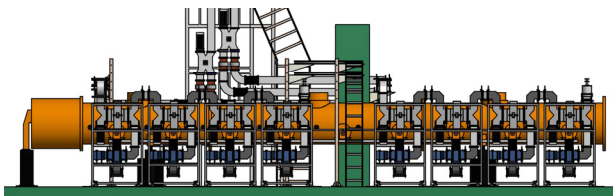


Figure 15: 2 set of RF power distribution for 4 cavities set. In STF, 3 set of this waveguide packages are used for 12 cavities.

To control RF pulse flat-top with very flat in amplitude and phase for beam acceleration, the fast digital feedback is used by utilizing FPGA controller element together with fast A/D and D/A. The software in the FPGA capture the every RF pulse waveform digitally, and calculate feedback value for amplitude and phase control, and also calculate loaded Q value (QL) for every pulse. Once QL has abnormal value, it can be predicted that cavity will quench in the next pulse or so. Then we can shut-down RF power to cavities beforehand, in order to avoid any over-loaded RF power in the cavities. So it is used for the QL interlock. Communications between other RF unit

during RF pulse interval of 200ms makes it possible to compensate acceleration voltage shortage by this interlock RF shutdown. So we can keep beam energy constant by this control logics and communications in any predictable events, in ILC.

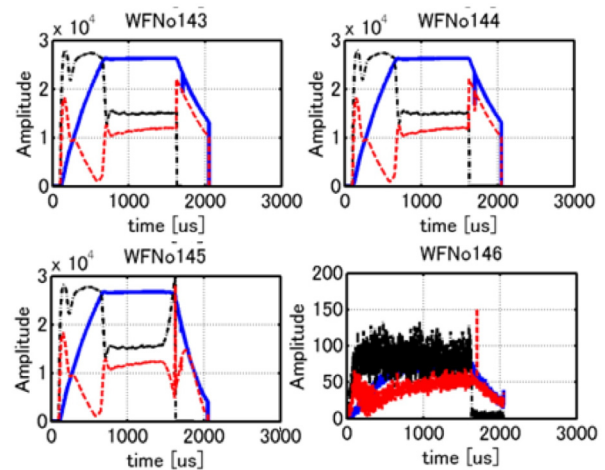


Figure 16: Example of a pulse-by-pulse RF waveform acquisition and analysis. There are sequence of RF waveforms from 143 to 146 pulse number. The loaded Q are calculated using tail slope for every pulse. We can know variation of QL at 145 pulse, then control logic shutdown the RF power supply. So, in 146 pulse, there is no RF power, just noise.

7 ACKNOWLEDGEMENT

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