US-Japan cooperation program

JFY2009 Progress Report on the “Research of High-Gradient Acceleration Technology for Future Accelerators”

(Reported from Japanese side)

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Introduction

The mission of the program is to develop the normal conducting high gradient acceleration technology capable of demonstrating a stable high-gradient operation. The basic studies trying to unveil the physical mechanisms behind the performance limitation are also performed. Based on this, we would make design proposals toward a multi-TeV linear collider.

One year ago, the operation at 100MV/m was already proved in a Compact Linear Collider (CLIC) prototype structure. This experiment was made collaboratively between SLAC and KEK under US-Japan program. Under the same cooperation framework, we have been pursuing last year the high gradient tests on a wider range of CLIC prototype structures aiming at obtaining the feasibility in the travelling-wave design. Through these activities, we confirmed the high gradient performance of 100MV/m level but also observed relevant features which may prevent them from satisfying all the requirements. In order to understand the high gradient features and the origins governing various mechanisms, we have been conducting fundamental research into the causes of breakdown and a better understanding of the optimal structure design has allowed the gradient to be increased to over 100 MV/m. A gradient over 150 MV/m was also realized in short standing-wave structures. There is ongoing fundamental R&D into material limitations, the effect of the structure geometry, the impact of processing and cleaning, modeling of breakdown, and the design of the HOM damping. The goals for this program are to further understand the basic physics and then to demonstrate an optimized accelerator structure design.

The following presents some highlights of the research efforts and recent results, then briefly describe our plan for the next year. This includes both fundamental studies on high gradient and practical studies of accelerator structures to foresee more comprehensive R&D towards a fully-featured, optimized structure for the following years. The last point of this research program is to address system integration, with a global look at the system optimization as a whole. The high gradient research effort started with the accelerator structure, since it was a bottleneck, but will eventually need to expand to include RF sources to power those structures.

Current Efforts and Future Plans

High gradient research is a multifaceted discipline. Many individual aspects of the accelerator structure design are interrelated and must be developed and optimized together. This has influenced the development path and scheduling. Fig. 1 is a flow chart, the same as last year, which includes the natural extension of this work towards an optimized RF system and sources.

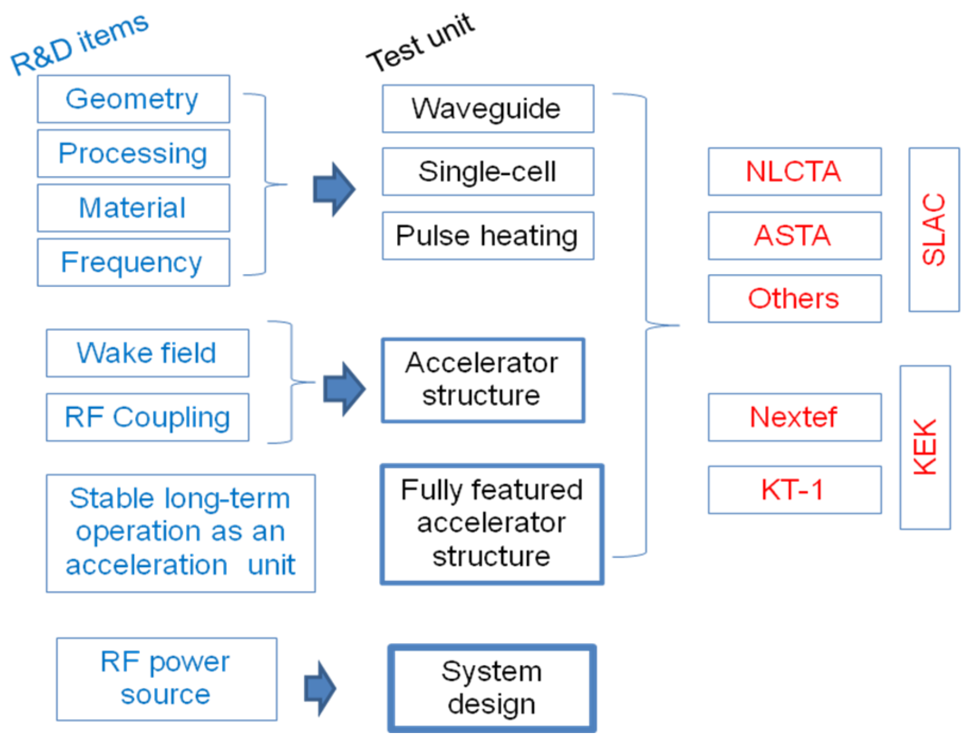


Figure 1. The development of high gradient accelerator structures

There are four main thrusts to the R&D:

1. Basic physics research:

Geometrical effects: the goal is to have a clear understanding of the effect of geometry on high gradient performance.

Materials: the goal is to understand the advantages of using alloys, in particular copper alloys, as building materials for accelerator structure.

Surface processing: the goal is to study the effect of surface preparation and crystal structures.

2. Advanced features:

Wakefield damping features: this is an ongoing effort that will continue.

Distributed Coupling: the goal is to design an advanced accelerator structure with high gradient and high efficiency performance.

Efficient fundamental mode couplers: this is linked to the distributed coupling effort

3. Fabrication of test units:

By the year of 2004, KEK and SLAC have established an optimized fabrication technology of the accelerator structures taking the advantage of the collaboration framework. Here KEK takes part in precision fabrication of parts, while SLAC takes part in surface cleaning, bonding and vacuum baking. We believe it best for us to start with this framework. The framework was reactivated under the present program in 2008 to initiate the essential experimental studies.

4. High power test facilities:

Both KEK and SLAC have the facilities that can produce ultra-high RF power at X-band for high gradient experiments. Both laboratories tuned their facilities for the present purpose. The collaboration has been developing the RF systems and components used in these facilities. This effort is essential for the experimental program and will continue. In the second year of this program, we have been conducting a series of high gradient tests of accelerator structures obtaining relevant properties for high gradient performance. A series of simple and basic studies have also been conducting by SLAC. At KEK, the similar basic test stand has been preparing and some of the key components were made by SLAC.

Design of liner collider

By the end of this three-year program, model accelerator structures with proper damping features are to be tested in high gradient and for a long period in order to confirm the feasibility of the high-gradient acceleration for the multi-TeV linear collider.

Finally, this program must extend beyond the accelerator structure and look at system components and integration for collider optimization. The plan for this work will be developed toward the end of the current program and be continued later guided by its success.

Review of recent efforts centered in JFY2009

Experimental Facilities

To explore the basic physics of breakdown phenomena, the program should include a large number of experiments addressing different aspects of geometry, material and treatment. Two X-band experimental facilities were established, capable of operating with high enough power and repetition rates and these have been fully utilized for basic studies and CLIC prototype structures. These are NLCTA of SLAC and Nextef of KEK, which are still now the only places in the world capable of doing this at X-band frequency. Between the two laboratories there are several experimental stations producing uncompressed pulses of 50-100 MW, and some with an associated pulse compressor for power up to 500 MW. These stations have varying capabilities and are suitable for different experiments.

SLAC facilities:

The experimental facilities at SLAC were established last year. The NLCTA and ASTA have been running in the two-Pack system capable of delivering 100-500MW scale. Efficient operation of NLCTA makes it possible to run the high gradient test on accelerator structures over a few thousand hours. The two-klystron ASTA and other single-klystron test stations at the klystron labs allowed 10s of experiments in 2009.

The programs/users that these stands have been serving are:

SLAC experiments on geometries and materials

Test structures manufactured by KEK

CERN structures

INFN, Frascati test samples

Etc.

KEK facilities:

By spring of the year 2009, the high gradient experiment at Nextef, a new facility of KEK, was established based on the combined power from two klystrons, through the re-processing of the prototype structure for Global Linear Collider (GLC). Then in JFY2009, a structure out of a pair of T18 structures was tested by running for 4000 hours over 9 months' period. One of the main issues of the program is to compare the high gradient test results between different laboratories. From this experiment, the facility was proved to serve for the critical comparison. Then after, a structure called "Quadrant #5" was tested. Finally one of paired damped structures, TD18, has been testing to date.

In another test stand KT-1, the research program was conducted for test the high gradient performance with reduced-cross section waveguide. This stand was used also for the high power evaluation of waveguide components such as RF loads, which are critical for the test at Nextef.

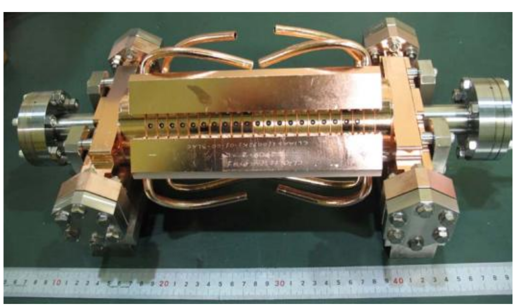
Hardware developments:

SLAC has completed a pair of mode launchers for KEK to start the basic studied based on the single-cell or 10-cell setup. Also for KEK, SLAC made the electrical design of a precision directional coupler with directivity better than 35 dB and the mechanical drawing is now being drawn.

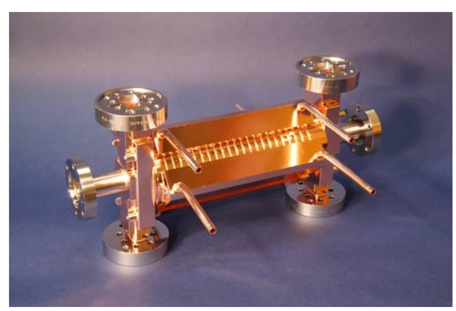
Fabrication and test of accelerator structures:

The idea that a pair of structures should be made as a pair has been kept since the beginning of the present US-Japan collaboration. This idea realizes the better comparison of the structures in the more quantitative manner. The philosophy that KEK should make all the parts based on his talent in high precision machining and SLAC should make the cleaning, bonding and baking has also been kept to standardize all the processes to make structures. It is to make the test as the basic starting point of the developments with best technology we have to date.

In the year 2009, SLAC completed the second pair of the test structures (#3 & #4) of T18 type based on the parts made by KEK. KEK made the high gradient test on #2 of the first pair and SLAC made on #3 of the second pair.



(a) #2 being tested by KEK



(b) 2 being tested by SLAC

Fig. 2 A pair of 18-cell damped structures made and tested by KEK and SLAC.

KEK and SLAC made also a pair of 18-cell damped structures, TD18. Here again, KEK made all of the parts and SLAC made bonding and vacuum baking by treating the pair in the same manner as much as possible. This pair is now being tested at both laboratories. These two structures are shown in the Fig. 2. As seen in the figure, the two structures were designed in exactly the same manner, except for the waveguide flanges which are defined as the demand from the test facilities.

Based on the further optimization of the structure, CERN made a better design of accelerator structures, called T24 (un-damped version) and TD24 (damped version). The structure consists of 24 acceleration cells with not only the magnetic field variation along the structure almost constant but also the efficiency from RF energy to beam is higher. In the year 2009, KEK made both pairs of T24 and TD24. SLAC is preparing the cleaning and bonding in March 2010.

In addition to the fabrication of these prototype structures, two pairs of ten-identical cells, C10 and CD10, were made by KEK. These are to be used for the basic research on high gradient in a simpler setup and in a quicker turn around.

Various test samples were made by KEK with carefully prepared with their crystal structures and added elements in mind. Today, we can obtain 6N or 7N copper with sometimes in a large grain size. KEK made a single-cell high gradient test setup with these materials. KEK prepared also the test setup with silver-doped and zirconium-doped copper materials. Furthermore, KEK made a few choke-mode single-cell setups and these have been being tested at SLAC.

Highlights from some recent results:

i) Standing-Wave Accelerator Structures

Standing wave accelerator structures have been thought to self-protect during the breakdown process. A variety of single and multiple cell standing wave structures have been built which do indeed self-protect and have short processing time. Generally these have been run without the benefit of a control program to limit the breakdown frequency, which is typically needed for traveling wave structures to limit the damage.

In JFY2009, KEK made a few setups with the copper purity in mind. An experiment with 6N-copper was tested at NLCTA of SLAC. The result gives the similar breakdown rate as those tested in single-cell test setups done at the klystron test lab of SLAC as shown in Fig. 3. The data points connected by lines are those measured at NLCTA.

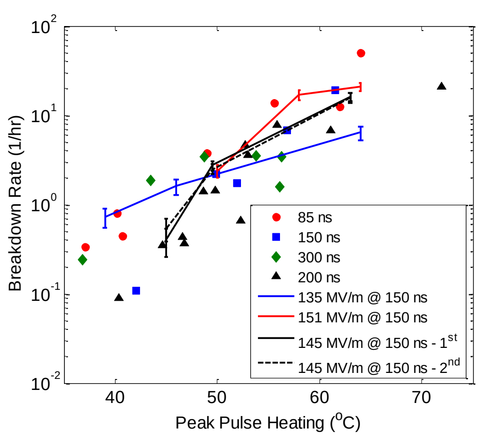
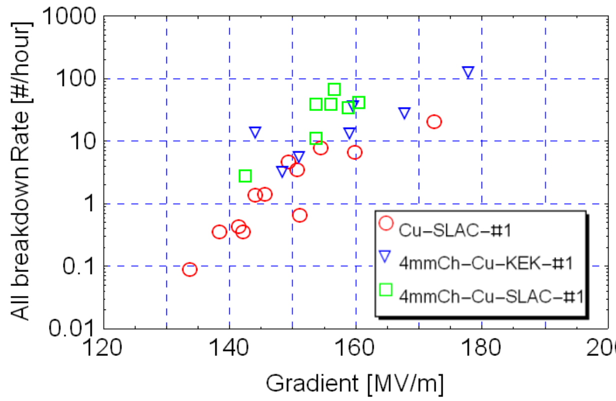


Figure 3. Breakdown rate of a standing-wave single-cell setup tested at klystron lab and NLCTA. The test sample for NLCTA run was prepared by KEK with 6N-purity copper.

One of the concern against the operation at more than an acceleration gradient of 100MV/m is the magnetic field. There was found through the experiment of last year that the breakdown rate in a single-cell setup was well reproduced by its pulse heating temperature rise, equivalent to the magnetic field squared. In JFY2009, SLAC designed a few choke-mode single-cell setups and KEK and SLAC actually made them. It seems the choke cavity behaves the same as that without as shown in Fig. 4(a). It means that the choke structure behaves well even with the heavy damping of the higher modes. One of them was cut and found frequent discharges at the choke small gap area as shown in Fig. 4(b). The choke cavity is still to be studied carefully.

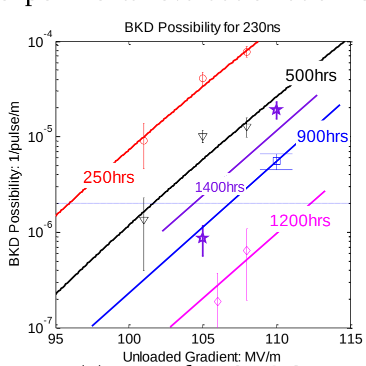


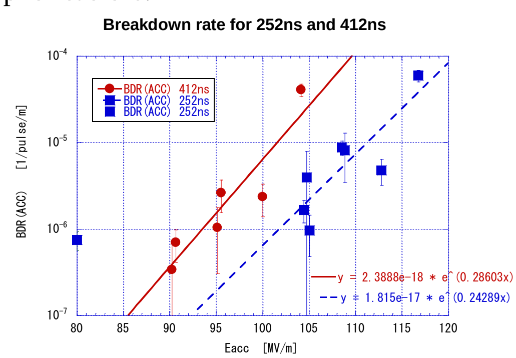
(a) Breakdown rate (b) Surface after test.

Figure 4. Performance of a standing-wave accelerator structure with choke.

ii) Traveling-Wave Accelerator Structures

The tests of the un-damped structures, T18, were done at SLAC and KEK. The measured breakdown rates are shown in Figure 5. From this figure, we confirmed that the operation of a travelling structure of this long at 230-250 nsec at more than 100MV/m with satisfying the requirement of the tolerable rate for the linear collider. It is noted that the processing made the breakdown rate smaller and smaller as shown in (a). It is also noted that something happened after 1200 hours so that the rate jumped up. This sort of problem should be considered. The points are at 80MV/m in (b) were evaluated also at the initial stage of the processing. For the wider pulse, the rate increased much as shown in (b) where it increased from 250ns (blue) to 400ns (red). We conclude from this experiment that the two structures behave in the same manner and the experimental evaluation at different setup is feasible.

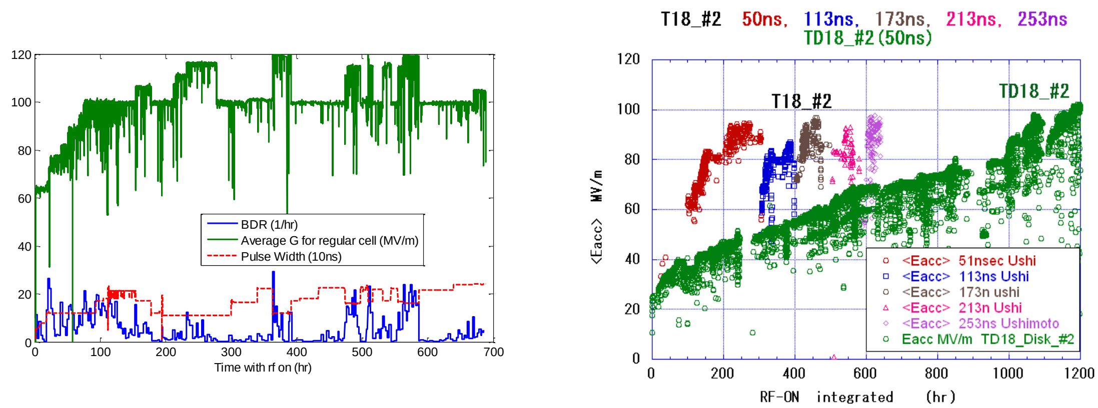




(a) Tested at SLAC (b) Tested at KEK

Figure 5 Performance of the pair of T18 traveling-wave accelerator structures.

Both SLAC and KEK have been conducting a pair of damped structures, TD18, as shown in Fig. 6. The processing trends are shown in green dots in (a) SLAC test and green lines in (b) KEK test. The considerable difference is seen between them, where that of (a) is up to full pulse width of 230 nsec while that of (b) still at the initial width of 50 nsec even after 1200 hours operation. The breakdown rate was evaluated to be higher than that of the un-damped case observed in SLAC case. The effect of the larger magnetic field than that of un-damped structure may be the relevant cause and it should be carefully studied taking these examples. The experiment to this end is on going now.



(a) Being tested at SLAC (b) Being tested at KEK

Figure 6 Processing of the pair of TD18 traveling-wave accelerator structures.

Material studies:

Hardness of the material is thought to be one of the important material properties related to the high gradient breakdowns. To study the hardness and hardening or change of the material surface due to the repetition of many RF pulses, the pulse heating experiment was conducted at SLAC using the TE01 mode. Materials such as CuZr, CuAg showed resistance against it. The single-crystal surface was also interested in the change of hardness because some of the crystal orientation should be better resistive against fatigue due to cyclic stress. The hardness was measured as shown in Fig. 7 showing the pattern of magnetic field of TE01 mode. The actual quantitative judgment for the resistivity to RF breakdown is to be foreseen in future.

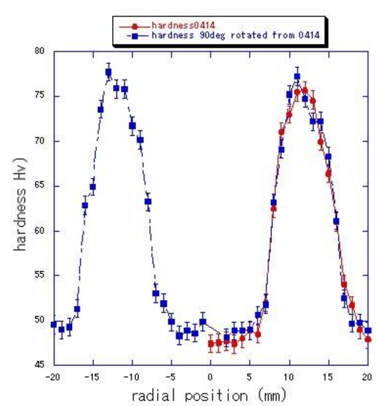


Figure 7. Hardness of the single-crystal test sample from the pulsed heating experiments, showing the magnetic field pattern of the excited TE01 mode.

Research Plans for Near Future:

Baseline activities on high gradient:

In the near future, our research efforts will continue along the same directions, namely improving test facilities and basic research on the fundamentals of the breakdown phenomenon and estimating the high gradient performance of the accelerator structures to estimate their feasibility in their accelerator gradient. For this program, the US/Japan collaboration is being very important because it allows the activities to be most effectively prepared and studied with the best integrated effort in our hands. In addition to these activities, our research activity begins staring to expand and to include advanced features as described below.

The basic study stand of KEK:

In the JFY2009, SLAC reached the final stage of the fabrication of a pair of mode launchers shown in Fig. 8. These will be used next fiscal year at KEK with the simpler experimental setup such as used for the C10 and CD10 cells which were made by KEK. These are the critical elements for the simple and basic experiments to be fast and effective for serving to the other parallel-going baseline programs stated above.

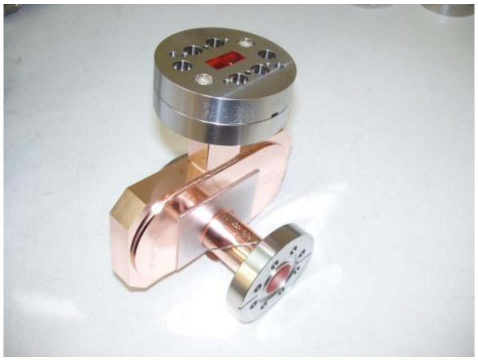


Figure 8. Mode launcher to be prepared for the KEK basic study setup.

The Development of Wakefield Damping Features:

The global community is currently developing ideas, simulations and designs for wake field damping in both traveling and standing-wave accelerator structures. The work is being optimized internationally, with KEK/CERN investigating magnetically-coupled heavy damped or damped-detuned traveling wave structures, and also choke-mode damped structure initiated by the SLAC investigating in the single-cell studies.

Structures Integration:

All structures currently studied are short in their length from 1 to 20 cells. This includes both standing and traveling wave accelerator structures. These structures must be integrated into a superset that can be handled as a group by an appropriate RF system. This is a critical step towards a true engineering design of an accelerator structure. This also has the potential to improve the overall efficiency of the structure, especially for standing-wave structures. Design of such an RF unit was started at SLAC in parallel to the R&D on high gradient, wakefield damping and coupler designs. A schematic view is shown in the Fig. 9.

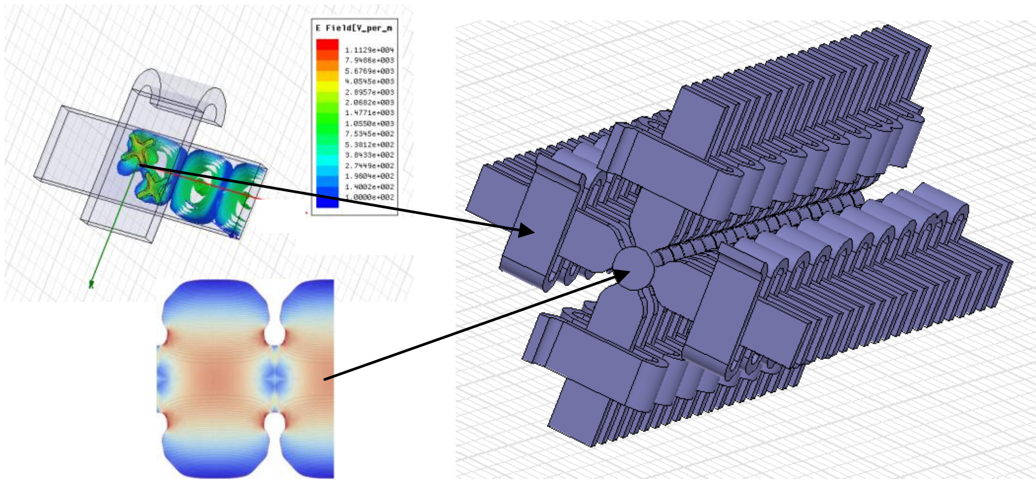


Figure 9. Schematic of standing-wave, mechanically multi-cell structure being designed by SLAC.

Finally it is to be noted that SLAC and KEK will continue the theoretical and experimental studies in the framework the same as that to date. This framework is essential for the efficient and essential outcome from the studies. In the next fiscal year as the final year of the present US-Japan program, we take the experimental results into consideration to propose a possible RF system for a multi-TeV linear collider.