X-BAND R&D AT KEK

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Abstract

We recently restarted the high gradient experiment on X-band accelerator structures at KEK. In this paper are highlighted some of the experimental high-gradient studies of the second structure, T18_VG2.4_Disk #2, made in collaboration among CERN-SLAC-KEK. This is being processed at Nextef, an X-band facility of KEK. The facility and some possible scenarios of its expansion are also presented. Then the on-going KEK fabrications of the structures dedicated for the high gradient study is reviewed.

INTRODUCTION

An X-band high power facility, GLCTA, and later renamed as XTF[1], which was dedicated for the developments for the linear collider based on X-band RF acceleration, was moved to settle down into the R&D area at KEKB injector[2]. This facility is now used fully for the basic research of X-band RF acceleration at a high gradient.

The frequency of CLIC main linac was optimized now at 12GHz[3] and it is close enough with our X-band frequency, 11.4GHz, to study the essential nature of the high gradient performance of the RF high power devices such as accelerator structures. Therefore, the collaborative study work was established since in 2007 between CERN and KEK[4]. In addition to this collaboration, KEK has been collaborating with SLAC on accelerator structures for many years. Especially in these years, various samples for high gradient tests and pulse heating tests have been sent to SLAC to test there[18].

The R&D works on accelerator structure development are now organized mainly among three laboratories, CERN, SLAC and KEK. Under this collaboration, various structures have been and are being made by KEK.

In the present paper, the above recent activities are reviewed, including high gradient test result and the technical status of the fabrication of structures.

HIGH-GRADIENT FACILITIES

There are two X-band facilities at KEK, Nextef[1] and KT-1. The former is two-klystron facility and extensively used for high gradient experiment of accelerator structure. The latter is driven by a single klystron and used for various tests, such as component tests or the evaluation of klystron itself.

Nextef

The schematic view is shown in Fig. 1. Power generated by the two klystrons were combined and delivered to the concrete vault via the low-loss circular wave guide. The accelerator structure sitting in the vault is fed by this power and the high-gradient processing and such studies as the evaluation of the breakdown rate or the study of the dark current are pursued.

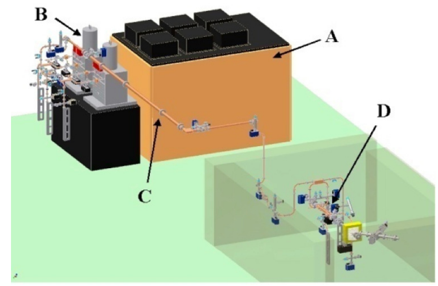

Figure 1: Nextef, X-band high power facility of KEK.

Typical specification of the system is listed in the Table 1. The klystron is periodic-permanent-magnet focus and can be operated at a higher power at shorter pulse length. For a longer pulse width, pulse shortening occurs at 50MW/klystron level, though they can be operated at 30MW or more in a longer pulse mode. In the present modulator, the pulse-forming-network makes it possible to produce the pulses with 800 nsec or more in length, though not the ideal square pulse shape.

Table 1: Nextef Specifications.

Item	Nominal
Combined power	100MW
Power at structure	75MW
Pulse length	400 nsec
Repetition rate	50 Hz

Nextef processing control system

A rough sketch of the Nextef control system[5] is shown in Fig. 2.

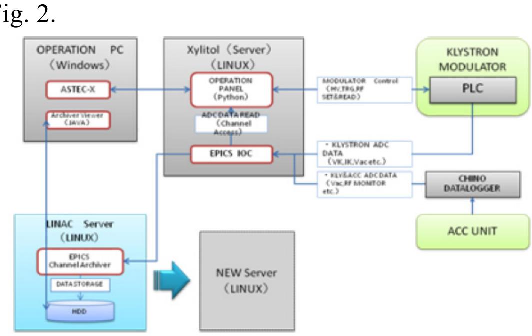

Figure 2: Nextef control system.

A Linux server located under the local area network of KEKB linac does the control and most of the data are archived through EPICS system. This system controls the PLC which operates the modulator. Various parameters are sampled through this PLC or a dedicated data logger.

Various pulse shapes are the most important for the analysis of the processing and most of the pulses taken by the oscilloscopes are recorded graphically and/or numerically.

Nextef observables

There are four main observables in Nextef[6]. 1; RF pulse shapes detected at various places in the wave guide system. The crystal detectors are used. 2; Current emission caught by the Faraday cups at upstream and downstream of the beam line. 3; Light emission seen through the optical window at various places. 4; Acoustic sound is measured by using Piezo device. 5; Vacuum levels are monitored by cold cathode gauges.

A view around the accelerator structure is shown in Fig. 3. Top-up device is the 3dB hybrid to sprit power into two arms to symmetrically feed the accelerator structure at the center of the figure. Beam line is from right-up to left-down. A schematic around this beam line is shown in Fig. 4. Downstream dark current can be energy analysed.

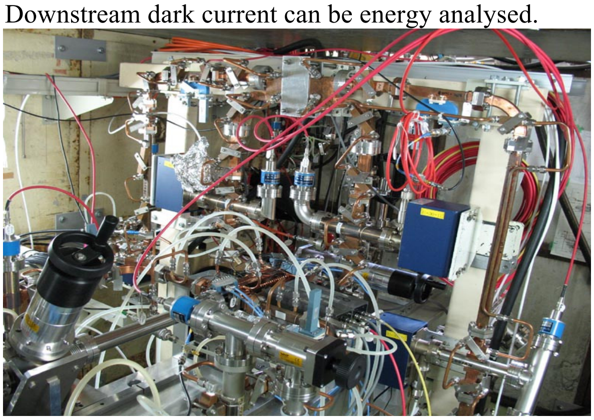

Figure 3: Accelerator structure and around it.

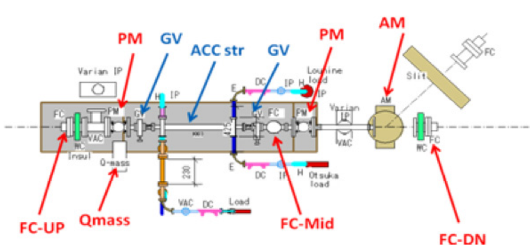

Figure 4: Setup around structure and beam line.

KT-1

This is a one-klystron setup and we have been pursuing a high gradient study using the rectangular wave guide with a reduced cross-section[7].

HIGH GRADIENT EXPERIMENT ON T18_VG2.4_DISK #2

The Nextef facility was firstly commissioned with feeding the power directly into RF loads. Then various system setups were established with installing our old structure, KX03[1]. Finally the new structure, T18_VG2.4_Disk[8] #2 was installed and the processing has started in October this year, 2008.

Processing protocol

The processing protocol is defined based on our usual custom; Firstly reach at a top power level in a short pulse length then increase pulse width by one level and reach to the top power. This is iterated until reaching the top power level at a specified pulse length. If numerous breakdowns happened below the fairly low power level, the program automatically reduce the pulse width by one step. This is illustrated in the Fig. 5.

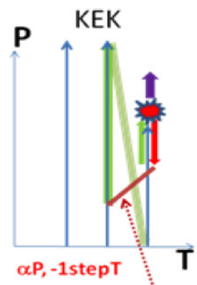

Figure 5: Processing protocol.

Processing history

In Fig. 6 is shown the initial history of the processing of T18_VG2.4_Disk #2. (It should be noted that the field in the figure is still to be calibrated for the precise value.) The first pulse width is 50ns, during which probably more time was elapsed until reaching to the goal of 90 MV/m. After reaching this level, a steady-state run at 80MV/m for more than several hours was conducted before increasing to the next pulse width. The pulse widths were 50, 112, 172, 213 before reaching to the last one, 252ns. After about 1000 breakdowns the processing reached to the final goal.

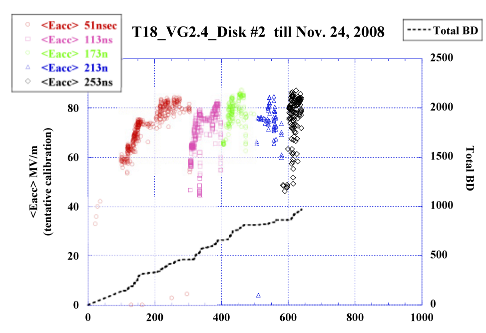

Figure 6: Initial history of processing.

Typical pulse shapes of breakdowns

All the RF pulses for the breakdown events[6] and some precedent pulses are recorded such as shown in Fig. 7. In the breakdown event, typically a big spike in the reflected RF appears with shortening of the transmitted pulse. The breakdown events are always accompanied by the current burst of 100mA and more to the Faraday cups along the beam line.

The actual criterion for the present system to identify the breakdowns is the current burst into the Faraday cups more than 100mV/50Ω.

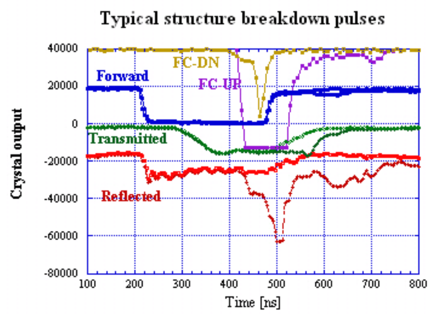

Figure 7: Typical breakdown pulses.

Breakdown rate measurement

Just after reaching to 90MV/m, the breakdown rate at a steady-state operation of 80MV/m was evaluated for each pulse width. Typical example is 13BD’s for 48hrs at 213ns. It is equivalent to 1.3 x 10^{-6} BD/pulse/structure. It is to be noted that this rate is that just after reaching to the level. The rate will be evaluated after further processing at higher power or longer pulse width.

Dark current

Steady state dark currents were evaluated at the Faraday cups (FC) at upstream and downstream of the beam line. These currents were plotted as a modified Fowler-Northeim formula[9] as shown in Fig. 8.

$$\frac{I}{E_p^{\;2.5}} \propto Exp(-\frac{6.5\times10^9\,\phi^{1.5}}{\beta E_p}) \qquad (1)$$

Here E_p is surface electric field at the relevant place of the structure and ϕ the work function of the copper material, which is assumed to be 5eV in this paper. If we assume E_p=2xE_{acc}, the field enhancement factor β can be estimated from the exponential slope. The deduced β values were about 50~60.

The peak currents estimated from the measured average current divided by the duty factor were about sevral to 10 μA toward upstream FC and a few 10 μA toward downstream FC.

EXTENSION OF FACILITY

The peak power level of the Nextef is limited by the peak power of the klystron. At a long pulse and a high power level, the RF pulses sometimes suffer from pulse shortening as shown in Fig. 9. For the pulse of 240ns needed for CLIC accelerator design, the 60MW power can be reached.

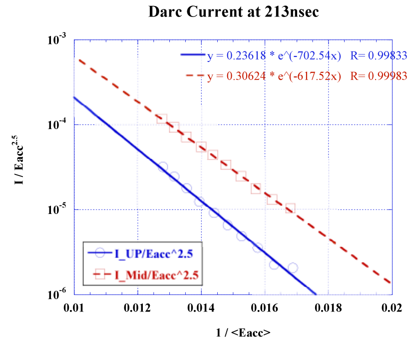

Figure 8: Dark current at 213ns operation.

However, if we want to proceed any experiment with much higher power, a pulse compression is a possible extension of the system. If the required peak power for the experiment can be as low as 30~40MW, we may divide the long pulse into two short pulses with delivering into two different experimental area. These two ideas are in consideration now.

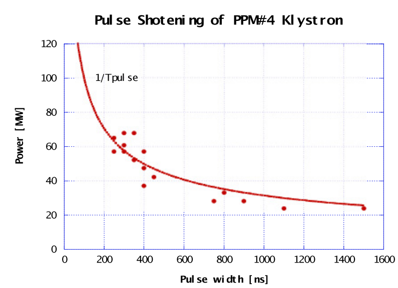

Figure 9: PPM klystron peak power versus pulse width.

Pulse compression

A 22m long round pipe is designed to be used as a pulse compression delay line for the Nextef[10]. It gives 150nsec pulse operated as TE_{11} delay line and this system will be established after summer 2009. In the next step, it can be extended to 300ns pulse by utilizing the double mode operation.

Another test stand

The two klystron powers are combined by a 3dB hybrid so that the combined power can be delivered into two different ports. We are making a small concrete vault now next to the present one so that the power can be delivered into these two vaults by dividing a pulse into two in time. The new vault is originally used for the high gradient experiment of C-band structure in next summer so that the X-band facility will be from next fall at the earliest.

ADDITIONAL ACTIVITIES

There are some activities related to the X-band study to be noted here.

GaN device

We have been using TWTA for many years to drive the klystron at a few 100 W. However, these are made in USA and suffer from the failures such as the high voltage supply and these are not repaired in a convenient manner. Nowadays, a GaN semiconductor device which amplified to the level of 50W CW at X-band regime was established[11]. KEK is now trying to evaluate the performance to study the possibility to replace the TWT's.

Waveguide valve

A wave guide value is an important device to isolate vacuum parts and sometimes plays an essential role in high-gradient experimental studies. A waveguide valve at X-band using TE_{0n} modes was proposed and evaluated to work at a high power level[12]. We have designed a similar valve but is operated at TE/TM_{11} modes. A prototype is now under fabrication. If it works, it can be more compact because the mode can easily be converted from rectangular TE_{10} to circular TE/TM_{11} mode.

Figure 10: Waveguide valve design.

Collaboration with the University of Tokyo

Many of the hardwares from the development of X-band linear collider, such as klystron, waveguide components and accelerator structures, were used for the R&D of a Compton-scattered X-ray source experimental setup[13]. We also collaborate on the development of NDT[14] utilizing the LC legacy.

STRUCTURE FABRICATION

KEK has been collaborating with SLAC for many years will 2004 under a formal collaboration for X-band linear collider development. KEK had an initiative on high precision machining, mostly using a turning with single-crystal diamond tools. Also a diffusion bonding technique was developed to make the bonding of constituent disks. Later years these technologies merged with SLAC development activities and established an assembly method[15] based on the SLAC surface cleaning technology and hydrogen furnace bonding.

For the development aiming at the structure developments targeting a CLIC-based accelerator structure, we decided to collaborate with SLAC based on the established framework between two laboratories in addition to the original demand from CLIC (CERN).

Disk-based structure

The four disk-based structures T18_VG2.4_Disk were made. Two of them were already assembled at SLAC. #1 was tested at SLAC and #2 are under testing at KEK. The fabrication is just the same way as the SLAC-KEK standard one before 2004.

Two more structures, TD18_vg2.4_Disk, dedicated for the high-gradient evaluation of damped structures are ongoing. The cell shape is shown in Fig. 11 which will be made in essentially the same manner as we did before 2004. We decided to maximally utilize the established fabrication method to test the effect of the opening of the damping wave guide. The milling is made by precision milling by the same vendor as that before 2004. The flat end surface is cut by a single-crystal diamond tool to make the burr-free final cutting in addition to keep the surface flatness to make the reliable diffusion bonding at SLAC.

Figure 11: Disk-damp cell.

Quadrant fabrication

The original CLIC structure design was based on the quadrant structure. It is good at higher mode damping but also may be good in mass production. KEK is new in this field and now tasting this in mechanical fabrication[16] followed by the high gradient evaluation at Nextef.

After asking five vendors for the trial cutting of short stacks, we nominated two vendors to make a full quadrant. Finally choosing one of the two vendors we made a set of full quadrant structure as shown in Fig. 12. We specified to use C150 (CuZr material) without any annealing. Due to the lack of experience and time, only carbide tools are used for the 3D ball point milling. A precision 5-axis milling machine, C30i, made by YASDA[17] was used. In this case, all the edges are rounded by 50 μm radius.

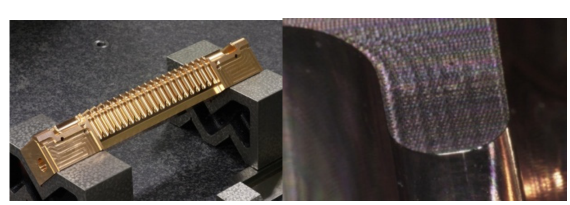

Figure 12: Top: Quadrant and Bottom: 50μm radius.

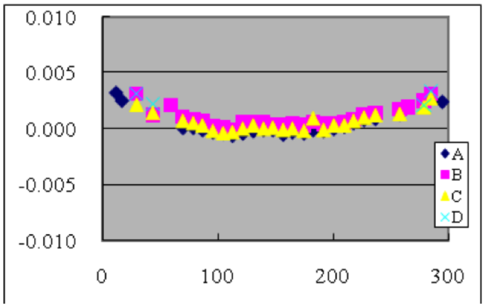

Figure 13: Flatness of reference surface of quadrant.

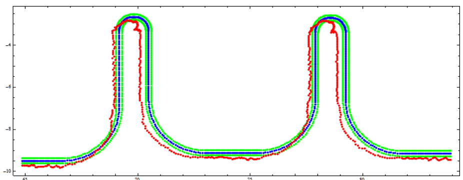
Figure 14: Typical profile of quadrant.

The surface flatness of the plane which meets with another quadrant surface is important to make a stable mechanical and electrical contact. In Fig. 13 are plotted the typical surface flatness of the products. As shown in the figure, the flatness of a few microns was established.

The position control of the tool in the beam axis direction over 200mm is about 5 microns. Though we admit that this error is twice the specified periphery tolerance of 5 microns, we assume the 3D surface formation will be OK because the cutting is designed to be proceeded along the beam axis direction in a monotonic manner from one end to the other. The typical profile shape measured from the reference surfaces, sitting at the outside of the quadrant bar, is shown in Fig. 14. Several micron error in beam axis direction is seen but the overall profile shape seems reasonably good for the frequency controllability within 5 MHz range.

Vacuum chamber for quadrant

The vacuum chamber to install the quadrant structure for high gradient test, shown in Fig. 15, is under fabrication now. The vacuum seal is made with copper gaskets. The quadrant structure is set under the top flange. Cooling water pipes are mounted on the quadrants by electron beam welding.

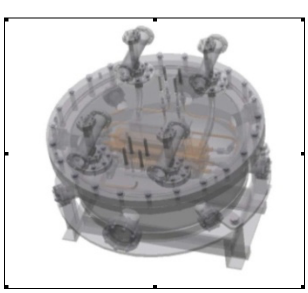
Figure 15: Vacuum chamber for quadrant test.

ACKNOWLEDGEMENTS

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Many of the works described here are the outcomes of the collaboration proceeded by of CERN and SLAC who have been studying the X-band accelerator structures. The author does not particularly acknowledge them but the collaboration plays an essential role to obtain the scientific understandings.

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