DARK CURRENT SIMULATION FOR THE CLIC T18 HIGH GRADIENT STRUCTURE*

Z. Li[1], A. Candel, L. Ge, C. Ng, G. Schussman, K. Ko, SLAC, Menlo Park, CA 94025, USA
Steffen Doebert, Mathias Gerbaux, Alexej Grudiev, Walter Wuensch, CERN, Geneva
Toshiyasu Higo, Shuji Matsumoto, Kazue Yokoyama, KEK, Japan

Abstract

Normal conducting accelerator structures such as the X-Band NLC structures and the CLIC structures have been found to suffer damage due to RF breakdown and/or dark current when processed to high gradients. Quantitative understanding of these effects is crucial to the development of improved structure designs and processing techniques. While a vigorous program of high power tests is in progress to explore the gradient parameter space, detailed numerical simulations are beneficial to the study of multipacting and dark current issues at high gradients. In this paper, we present the simulation analysis of dark current and the associated surface heating in the CLIC T18 structure using the parallel finite element simulation code Track3P and compare the results with high power measurements.

INTRODUCTION

Normal conducting X-band structure has been adopted for the main accelerator linacs of the proposed Compact Linear Collider (CLIC) [1]. Past and ongoing high gradient testing of the NLC and CLIC X-Band prototype structures have found structures suffer damage due to RF breakdowns when processed to high gradients. For a large scale accelerator such as the CLIC, reliable operation of its accelerator components is crucial. The breakdown trip rate for the CLIC, for example, has to be below one in a million pulses. The limitations of the breakdown gradient strongly influence the design and operation of the collider. Improved understanding of the breakdown and dark current issues has become a high priority in the accelerator structure development. Vigorous experimental efforts have been put forward to explore optimal parameter space, structure materials and processing procedures to achieve high gradient. At the same time, there are growing interests in understanding the measurement data using simulation in order to gain insight into high power behavior. Numerical modeling capabilities enable effective means to "measure" and analyze RF quantities inside the structure which otherwise would be difficult with experimental measurement. Comprehensive numerical analysis of dark current and multipacting in high gradient structures could provide interesting clues to the pre-breakdown RF process. Such simulations would require modeling the full accelerator structure geometry, and in turn require large amount of computing resources to perform the calculations. Over the past years SLAC has developed a suite of parallel simulation tools to meet such simulation needs. Numeric simulations of multipacting and dark current are being carried out using the SLAC parallel particle tracking code Track3P [2,3] as part of the concerted effort to understand the effects of dark current and multipacting in high gradient structures. Experimental data on high power processing of X-band structures are becoming readily available for comparison with numerical simulations. Most recently, the prototypes of the CLIC T18 [4] design were high power tested at KEK [5] and SLAC [6,7]. In this paper, we present the progress in the modeling of the CLIC T18 structure and the comparison with the measurement data.

CLIC T18VG2.6 STRUCTURE

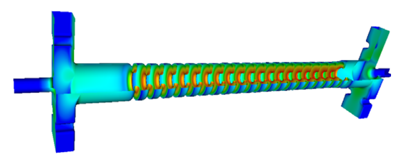

Figure 1: The CLIC T18 detuned structure.

The CLIC T18 structure consists of 18 regular cells and two coupling cells that match the structure to the wave guide input and output couplers. The structure is tapered with a group velocity ranging from 2.6% to 1.0%. For the Track3P dark current simulation, the travelling wave RF fields were obtained using the parallel program S3P [6,7]. The surface impedance of copper is included in the S3P simulation such that correct power attenuation due to the wall loss is taken into account. The S-parameters obtained using S3P are S11=0.014, S22=0.032 and S12=0.82, which corresponds to an attenuation factor of τ=0.40. The surface field profiles in the T18 structure are shown in Figure 2. The Es at the output end is about 55% higher than the input end due to heavy tapering.

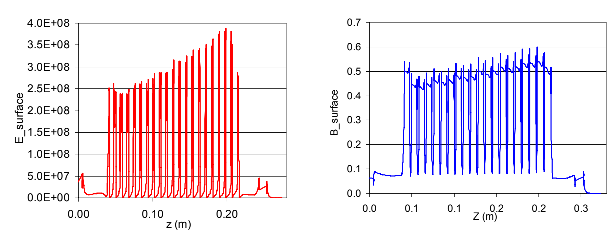

Figure 2: The accelerating field profile along the structure obtained from S3P simulation.

*Work supported by the U.S. DOE ASCR, BES, and HEP Divisions under contract No. DE-AC02-76SF00515. The work used the resources of NCCS at ORNL which is supported by the Office of Science of the U.S. DOE under Contract No. DE-AC05-00OR22725, and the resources of NERSC at LBNL which is supported by the Office of Science of the U.S. DOE under Contract No. DE- AC03-76SF00098.
[1]lizh@slac.stanford.edu

DARK CURENT SIMULATION USING TRACK3P

Track3P is a 3D particle tracking code on the finite element grid. Curved elements fitted to the curvature of the boundary allow high-fidelity modeling of the geometry which is important for accurate surface field calculation and current emission. The parallel implementation enables to handle large problem size and to speed up simulation time. The RF fields for the particle tracking are imported from SLAC's finite element field solvers [8,9] - Omega3P for resonant mode, S3P for traveling wave, and T3P for transient RF excitation. All of these codes share the same finite element mesh and data structures. Track3P has been extensively benchmarked against measurements for dark current and multipacting [2, 3]. It was used to predict correctly the multipacting barriers in the ILC ICHIRO cavity [10].

Track3P simulates the evolution of the field and secondary emitted electrons, and calculates the dark current capture and the surface heating due to the bombardment of the dark current electrons on the cavity wall. Field emitted or primary emissions are treated according to the standard Fowler-Nordheim formula [11] where the emission current is determined by the strength of the surface electric field:

$$J(r,t) = 1.54\times10^{\left(-6+\frac{4.52}{\sqrt{\varphi}}\right)} \frac{(\beta E)^2}{\varphi} e^{\left(\frac{-6.53\times10^9 \varphi^{1.5}}{\beta E}\right)}$$

where φ is the work-function of the material and β is the local field enhancement factor. The primary field emitted particles are generated during the whole duration of simulation whenever the electric field exceeds the emission threshold. Secondary particles are emitted when a particle hits the material surface based on the value of secondary electron yield (SEY). The SEY curve used for copper is shown in Figure 3. Power monitors are implemented to record the dark current power intercepted by the cavity wall. Current monitors are placed at the end of the beam pipe to record the captured current.

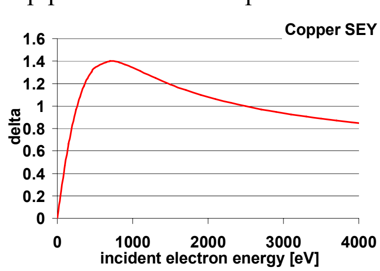

Figure 3: SEY distribution for copper. The SEY peaks at around 800 eV.

Dark Current Heating

It is generally believed that the RF heating plays an important role in the RF breakdown in high gradient structures. In addition there is evidence of breakdown triggering and surface damage caused by field emitted dark current bombardment in the high power testing of normal conducting cavities under strong magnetic fields [12]. In the high gradient structures, a large fraction of the dark current generated by field and secondary emissions is intercepted by the structure disks. The energy of the intercepted electrons could reach up to a few MeV, which may produce significant heating to the structure surface.

The T18 structure was simulated using Track3P. The run time covers 20 RF cycles. It takes a few cycles for the dark current to reach steady state in the simulation (for electrons to travel through the structure). Then the energy deposition of the electrons to the structure wall is accumulated when they impact the surface. A contour plot of the accumulated dark current energy distribution at a gradient of 97-MV/m is shown in Figure 4.

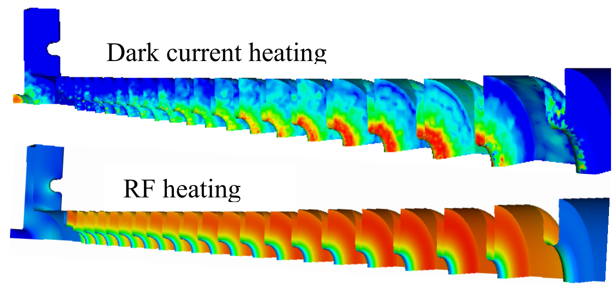

Figure 4: Top: dark current heating distribution. Bottom: RF heating distribution for comparison.

Most of the high energy electrons are intercepted by the tips of the irises, producing heating in this high electric field region as shown in Figure 4. As a comparison, the RF heating is maximized on the outer wall. Simulation results presented here assumed that all copper surfaces were emitters with a field enhancement factor beta of 50, which produced azimuthally symmetric heating profile. In reality, the high beta value emitters are most likely clusters on the surface which would produce localized hot spots instead.

Because the emitter density and surface cleanness are structure dependent, simulation alone will not be able to determine the absolute amplitude of the dark current. What can be obtained from the simulation is the ratio of the intercepted and captured dark current. The later can be compared with measurement to obtain a realistic scaling of the amplitude of the intercepted current inside the structure.

Captured Dark Current Energy

Electrons emitted at different locations along the structure get different amount of acceleration and thus obtain different energy. The amount of current that can reach the current monitor downstream also depends on the location of emission as the electrons experience different capture and collimation effects by the irises. The tapering of the surface electric field along the structure adds additional dependence on location. Figure 5 shows the dark current amplitude (a.u.) and energy, at 97MV/m gradient, vs. the cell number, with higher numbers indicating downstream locations.

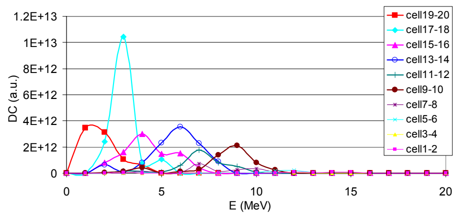

Figure 5: Dark current amplitude and energy v.s. emission location at 97 MV/m gradient. Cell 19-20 are the cells at the output end.

COMPARISON WITH MEASUREMENT

Prototype T18 structures are being high power tested at KEK and SLAC. The schematic of the KEK high power test stand is shown in Figure 6. Faraday cups and a spectrometer are instrumented to measure the dark current. The spectrometer is located about 1.9 meters down stream.

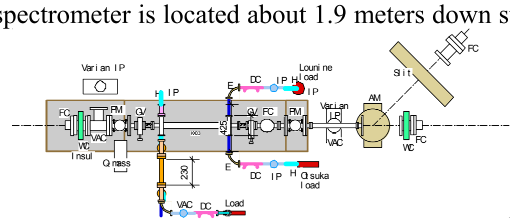

Figure 6: Schematic of high power test setup at KEK.

Both high power tests at SLAC and KEK have shown significantly higher breakdown rate at the output end as shown in Figure 7 (KEK data). It is interesting to note that the distribution is well correlated with the distribution of the dark current heating. The RF heating is another factor that contributes to the breakdown, but the field enhancement at the output end is not as drastic as that of the dark current. The dark current heating (as well as the RF heating) in the high surface electric field region may have produced undesirable conditions for high power processing in the output end.

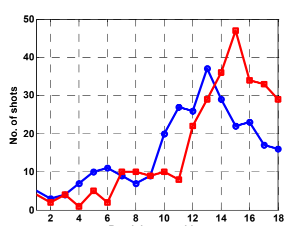

Figure 7: Breakdown rate significantly higher at the output end (Red real cell timing, blue linear cell timing).

The measured and simulated dark current spectra are shown in Figure 8 for comparison. The red curve in the simulation included contributions of all the disks, the blue one only includes cells 1-14. Both the measured and simulated showed similar feature of current amplitude modulation. Some discrepancies between the simulation and measurement were observed: a) the simulation spectrum is shifted toward lower energy; b) the simulation shows a high dark current peak around 3 MeV while in the measurement there is very low dark current below 5 MeV. More analyses are under way to understand these discrepancies.

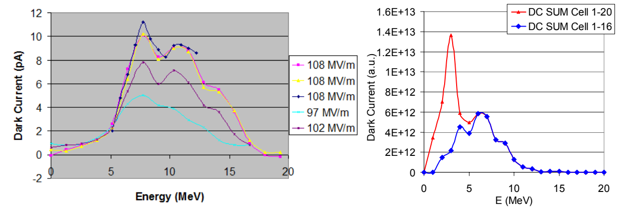

Figure 8: Dark current spectrum. Left) measured; Right) simulation – red includes all cells, blue has a similar shape as measurement but includes cells 1-14 only.

SUMMARY

Mutipacting and dark current simulations are effective tools, a complement to experimental measurement, help to gain insight of RF processes in accelerator structures. Progress are being made in simulating the CLIC T18 using the parallel code Track3P. Preliminary comparison between measurement and simulation is presented. More detailed studies of dark current effects are under way.

ACKNOWLEDGEMENTS

The simulation codes used for the work were developed under the support of the US DOE SciDAC [13] program. The work used the computing resources of NCCS [14] at ORNL and NERSC [15] at LBNL.

REFERENCES

[1] http://clic-study.web.cern.ch/clic-study
[2] C.-K. Ng et al, "Simulating Dark Current in NLC Structures", Nucl. Instru. Meth. A558, 192 (2006).
[3] L. Ge, et al, "Multipacting simulations of TTF-III Power Coupler Components," Proc. PAC07, Albuquerque, New Mexico, 2007.
[4] W. Wuensch, "CLIC Accelerating Structure Development," Proc. of EPAC08, Genoa, Italy, 2008.
[5] S. Matsumoto, et al, "NEXTEF : 100MW X-Band Test Facility in KEK", Proc. EPAC08, Genoa, Italy.
[6] S. Döbert, et al, "High Power Test of a Low Group Velocity X-band Accelerator Structure for CLIC", CERN-AB-2008-069 or CLIC- Note-767.
[7] Chris Adolphsen, et al, "Results from the CLIC X-Band Structure Test Program at NLCTA," this proceedings.
[8] K. Ko et al, SciDAC and the International Linear Collider: Petascale Computing for Terascale Accelerator, Proc. SciDAC 2006 Conference, Denver, Colorado, June 25-29, 2006.
[9] L.-Q. Lee et al, "Enabling Technologies for Petascale Electromagnetic Simulations", Proc. SciDAC 2007, Boston, Massachusetts.
[10] C.-K. Ng et al, "State of the Art in EM Field Computation", Proc. EPAC06, Edinburgh, Scotland.
[11] R.H. Fowler and L. Nordheim, Proc. Roy. Soc. A119, 173 (1928).
[12] D. Li and R. Palmer, private communications.
[13] http://www.scidac.gov.
[14] http://nccs.gov.
[15] http://www.nersc.gov.