SUMMARY OF THE ARGONNE WORKSHOP ON HIGH GRADIENT RF

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Abstract

The Workshop on High Gradient rf was held at Argonne, Oct. 7-9, 2003. This workshop reviewed the progress in a number of accelerator technologies approaching high gradient limits. In addition to progress reports, one aim of the workshop was to involve materials scientists and look at trigger mechanisms and surface interactions. Talks were presented on superconducting rf, progress with high and low frequency copper cavities, and dielectrics. The focus was on both experimental and theoretical aspects of the problem. The overall picture presented at the workshop will be summarized.

INTRODUCTION

This paper will attempt to review the highlights presented at the workshop, summarize in a little more detail ongoing work not otherwise mentioned at this conference, and discuss some of the open questions in the field of high gradient rf. Since many of the participants in this workshop are also presenting more recent results at LINAC 2004, and it is desirable to avoid repetition and discussion of older data, the emphasis will be on topics not covered in this conference, and on general conclusions that could be extracted from the workshop.

Effort on the Workshop was begun as an attempt by members of the Muon Collaboration to explore how much overlap there was between the problems of building muon cooling linacs, with very low frequencies (200 MHz) but comparatively high gradients, and the better understood problems of high frequency electron linacs. There was also a strong feeling that the material dependence of rf breakdown was an important and not well understood aspect of this problem, and it might be possible to productively involve materials scientists in a study of this problem. There was an organizational meeting at PAC03, in Portland Oregon and the workshop was held at Argonne, Oct. 7-9, 2003. A short summary of the workshop was published in the CERN Courier [1].

The website, with copies of all talks given at the workshop, is located at http://www.hep.anl.gov/rf/ [2]. In order to simplify this paper, contributions will be identified by name and not referenced individually.

LINAC DEVELOPMENTS

The majority of the effort on high gradient rf has been done as part of the NLC, CLIC and TESLA effort to produce TeV scale electron linacs for the next generation of particle accelerators. This work has been done by an international group centered at SLAC, FNAL, KEK, DESY and CERN, with important contributions from many other laboratories and individuals.

Linear Collider Work

Although the emphasis of the workshop was on normal conducting rf, two talks were given on superconducting rf A. Matheisen described SRF surface technology. preparation techniques, and K. Saito discussed recent results with high field SC cavities. The techniques used in this technology involve enormous effort to insure that the metals and surfaces are as free of defects and contamination as possible, the manufacturing process are clean, and assembly and testing do not further contaminate the structures. In many cases this has been done to the point where there is no field emission even at the highest fields. While these methods are widely respected, there is some doubt if they are applicable to high frequency cavities, which are somewhat harder to clean and seem prone to produce damage sites when first exposed to high powers.

The majority of the effort devoted to the linear collider has been adequately summarized elsewhere in this conference. At the workshop C. Adolphsen gave an overview the NLC structure tests done by KEK, SLAC and others, showing that the specifications of the NLC design were being met by prototypes. This was followed by S. Tantawi, who talked about breakdown experiments in waveguides of different dimensions (local B/E ratios) and single cell traveling wave structures. V. Dolgashev described the effects of magnetic fields and input power levels on test cells in the NLCTA and simulations of breakdown. S Doebert looked at gradient limitations on high frequency accelerators showing how breakdown depended on a number of variables (pulse length, power, electric field etc.), but ultimately seemed to occur when the product $\beta E_s \sim 7$ GV/m. S. Harvey presented results of autopsies on structures following high power processing, which showed cracks, craters, and a variety of inclusions and sparking sites, extending the description of surface defects from that published recently by Pritzkau and Siemann [3]. T Higo, showed some preliminary data on the effects of high pressure rinsing of cavities and other treatments. Some of these resulets are shown in Figs. 1-4.

The CLIC effort was summarized by W. Wuensch, who described the work done at the CLIC test facility, which produces high power rf from structures exposed to high energy bunched beams, and uses this power to drive accelerating structures. Results were presented which showed that the breakdown rates seemed to be essentially independent of frequency and initial temperature.

Other Structures

High gradient structures are under construction at other facilities. S. Yamaguchi described a very thorough construction, cleaning and conditioning program for a high gradient test of a new S band structure at KEK.

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Among other things, the data showed that during conditioning, the enhancement factor, β , decreased as the surface field, *E*, increased with almost the same exponential time constant, During this time the product remained constant, and equal to 6 - 7 GV/m, see Fig 5. This value is significant since it is roughly equal to the surface field at breakdown measured in a number of rf and DC experiments over the years, and is close the field where *tensile stress* = *tensile strength* for copper. They found that high pressure rinsing of the structure cut the conditioning time of the structure by about half and also cut the flux of dark current electrons to one third of the untreated case.

S. Fukuda described a high gradient test of a C band structure built for the SuperKEKB built to increase the positron beam energy to 8 GeV, and showed how the cavity conditioned to the 42 MV/m design field in less than two months.

H. Haseroth described the history of the ion source at CERN, showing the importance of eliminating contamination, particularly pump oils, from the vacuum system.

M. Shapiro showed results from a new photoelectric gun that operates at peak surface fields of 200 MV/m at 17 GHz.

Muon Cooling

The Muon Collaboration effort has been aimed at developing 200 MHz cavities that can operate at gradients of 10 – 20 MV/m, the initial goal for this program is to build cavities for the Muon Ionization Cooling Experiment (MICE), and eventually neutrino sources or muon colliders. The development of the 201 MHz test cavity was described by D. Li, and the Muon Test Area (MTA) built near the linac at Fermilab, which has high power available at 201 and 805 MHz, was described by M. Popovic. Some results of 805 MHz cavity tests, done in Lab G, were described by J. Norem, Fig 6, and A. Moretti, who reported new data on the magnetic field dependence of the maximum useful electric field and new results using Be windows.

HIGH GRADIENT DEVELOPMENT

While much of the work presented directly described linac developments, there were other topics that were covered which were relevant to high gradient rf.

High Pressure Cavities

An effort by Muons Inc. looking into the breakdown properties of cavities with high-pressure hydrogen, which would satisfy both the acceleration and absorber requirements of a muon cooling system, was reported by R. Johnson.

Dielectric Accelerators

The status of high gradient dielectric cavities was covered in three talks. Y. Y. Lau described the theory of multipactor in dielectrics. A. Neuber discussed an

DC Studies

Although the subject of the workshop was high gradient rf, one of the basic questions of the field is how rf phenomena compare with DC processes and systems. G. Werner, described DC studies motivated by the high gradient rf program, and described similarities between the starbursts seen in DC and SCRF systems.

Gas Cluster Ion Beams (GCIB)

Z Insepov described how Gas Cluster Ion Beams (GCIB) which consist of charged clusters of argon atoms accelerated to a few kV/atom can be used to alter the surface of a metal Fig 8. This technique is now used in the semiconductor industry to achieve the highest level of local smoothing, down to 1.7 Angstroms rms. The technique has a possible application to smooth and clean rf cavity surfaces such as the NLC cavity sections or TESLA structures. This technology was developed by Epion Corp [4], and is in wide use in the semiconductor industry.

MODELING AND ANALYSIS

Although the problems of high gradients in vacuum have been studied for 100 years, there seems to be no agreement on the cause of breakdown, and no unambiguous recipe for minimizing the frequency or damage it produces. The situation was summed up by S. Tantawi:

- Breakdown seems to be a mysterious process, with no clear theory that enables understanding of the phenomenon.
- Most of the experimental work is done with complicated structures that make interpretation of the data very hard.

In spite of this, there are a number of modeling efforts underway, with a variety of goals and approaches. Historically there have been two efforts at SLAC and Cornell.

Modeling

At Cornell simulations of breakdown is continuing from an effort begun with Padamsee and Knobloch [5]. Particle in cell models showing the development of electron and ion clouds around a potential breakdown site implied that the breakdown events began in a few rf cycles with back-bombardment of the wall, Fig 9. G. Werner described how the process would work once some trigger produced an initial concentration of electrons and ions.

A somewhat similar model was presented by V Dolgashev, at SLAC, who looked at the development of breakdown in a rectangular waveguide. Modeling the

development of an event from an initial low concentration of ions to complete absorption of all stored energy in the cavity in a few cycles, he showed how the model agreed with measurements of transmitted and reflected power on recent NLC prototype cavities.

An effort at Argonne, aimed at understanding the trigger mechanisms has also involved some theoretical and experimental work. J. Norem summarized a model in which breakdown seems to be triggered at the local fields where tensile stresses in the field are comparable to the tensile strength of the material. Z. Insepov showed simulations of a molecular dynamics code displaying individual atoms being torn off an asperity by electric fields, Fig 10. I. Konkashbaev showed calculations of field evaporation and field emission and discussed their consequences. Data was presented that showed that high current densities can produce high electric fields at grain boundaries and defects of the sort seen by Pritzkau and Siemann [3] and Harvey.

Calculations of field emitted electrons were presented by V. Ivanov, who showed the trajectories these electrons would follow and the secondary electrons they would produce when they hit the walls.

Y. Iwashita showed how the surface current density could be calculated with high precision with variable mesh sizes.

Open Questions

There are a number of questions that may be worth wider discussion. There was no agreement on the nature of the enhancement factor β , this quantity is used to relate the field at an emitter to the average surface field, but there is some doubt if these geometrical enhancements actually exist. It seems that all cavities see field emitted electrons, which the Fowler-Nordheim formalism says are only produced above 5 GV/m, and this may imply the enhancements are real.

The "Fowler-Nordheim Plot" seems to be the most common way of plotting field emitted currents as a function of surface field. Unfortunately, this method seems to be unnecessarily complex, somewhat unintuitive and difficult to associate with experimental or fitting errors. Simply plotting the current as a function of the field may have a number of advantages. The primary variables are the emitter area and enhancement factor, and this method clearly expresses these quantities in perhaps more intuitive way. The effects of experimental uncertainties such as saturation and noise can also be understood more directly.

CONCLUSIONS

Although the meeting itself did not have time for long discussion periods, a number of conclusions that seem to present themselves.

Although the linear collider effort has been pursuing high gradients more aggressively than is done at lower frequencies, the problems they are finding seem similar to those seen at lower frequencies and even DC systems. The local fields of 6 - 10 GV./m are almost always associated with breakdown events or unstable operation, and lowering the fields by a small amount reduces the sparking rates considerably.

It seems possible to find engineering solutions without a good physical understanding. Experiments are difficult, and comparisons between the results are even more difficult, primarily because the hardware is complex. The NLC/GLC effort has found and cured the primary source of breakdown in their structures with very minor modifications.

A wide, and increasing, range of instrumentation is being used to attack the problems of breakdown.

Breakdown fields are a function of a number of variables and there were no clear understanding the majority of problems faced at high gradients. There may be more than one mechanism responsible for breakdown and these have not been well documented. There could be more effort on the physics of high gradients.

ACKNOWLEDGEMENTS

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- [1] J. Norem, CERN Courier, Jan/Feb 2004, p21.
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- [4] Epion Corp. Billerica, Ma.
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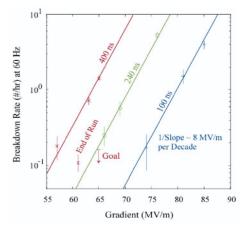


Figure 1: Breakdown rate vs. Gradient for NLC prototype structures (Adolphsen).

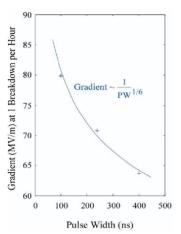


Figure 2: Maximum gradient vs. pulse length for NLC/GLC structures (Adolphsen).

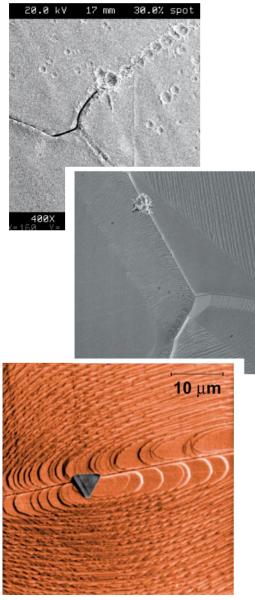


Figure 3: Various SEM pictures from autopsies, with false color (Harvey).

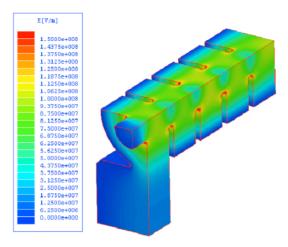


Figure 4: Electric fields in a NLC/GLC structure (Dolgashev).

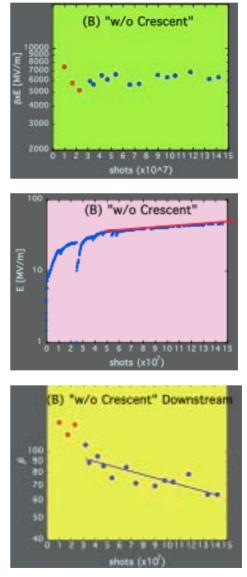


Figure 5: Enhancement factor, surface field and the local surface field during condidtioning of structures. (Yamaguchi).

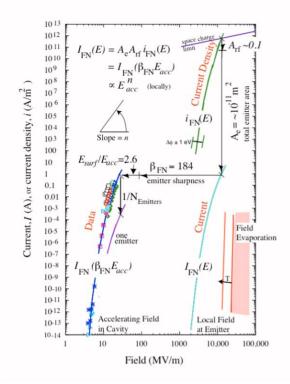


Figure 6: 805 MHz data with FN model and other processes (Norem).

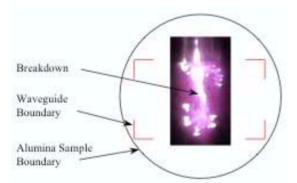


Figure 7: Breakdown in a dielectric window (Neuber).

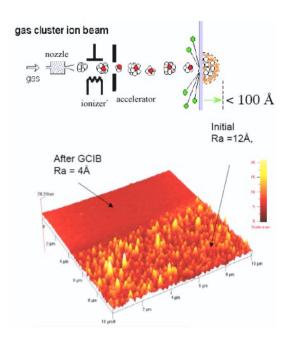


Figure 8: Gas Cluster Ion Beams (Insepov).

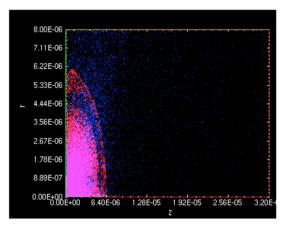


Figure 9: Simuations of the first few cycles of rf breakdown (Werner).

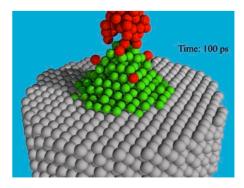


Figure 10: Modeling of cluster emission (Insepov).