# Investigation of acoustic localization of rf coupler breakdown

### Classification (subsystem)

Rf couplers

### Personnel and Institution(s) requesting funding

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### Collaborators

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### Project Overview

Electrical breakdown in accelerating structures produces electromagnetic and acoustic signals that may be used to localize (in a non-invasive fashion) the breakdown site inside a cavity. Other indications of breakdown (microwave, X-ray, and dark current measurements) have proven insufficient to elucidate the basic physics of cavity breakdown. During tests of the ILC design it will be important to record information describing electrical breakdown in order to understand why cavities break down, and how cavity design and operating conditions influence accelerator reliability.

The goal of this project is to understand the acoustic properties of coupling structures with a substantial (over 300K) temperature gradient, in order to relate the acoustic signatures of breakdown events to the underlying electromagnetic catastrophes taking place inside the structures. We would do this by deriving (whether explicitly or implicitly) a time-dependant, invertible, acoustic Green's function for an individual structure. This Green's function could be used to predict the signals arriving at various sensors as functions of the acoustic excitation caused by a cavity breaking down. The inverse function, derived from data from a sufficiently large number of sensors, can be used to localize and classify breakdown modes in TESLA rf couplers.

Two years of investigation have so far been conducted at UIUC. The first year of investigation concentrated on building software tools and developing a small amount of laboratory infrastructure so that we could begin learning about the problems we are confronting. Our second year of investigation continued these developments, increasing the sophistication of the simulation and testing the simulation's fidelity to the underlying physical system.

We have developed an understanding of acoustic events propagating forward in time. In addition to deepening this understanding, our purpose now is to trace backward from effects to causes. We have three methods that may be able to identify the source of an event from signals received at sensors. Each method still needs testing – both simulated and actual – before we can use it to understand electrical breakdown.

### Broader Impact

Williams is currently involved in a search for a faculty position at an undergraduate institution. This proposal will be updated when the results of that search are known. Undergraduate institutions are underrepresented for purposes of high-energy physics (HEP) research; most have no active HEP programs. Because the effects of breakdown events are well described by classical mechanics, the research has proved ideal for participation by undergraduates – even undergraduates in the early stages of their higher education. The UIUC students involved have been remarkably productive and insightful; they are continuing LCRD involvement, but shifting their emphasis to a different project. Williams plans to recruit students to continue this project.

### Results of Prior Research

Our investigation has begun with examining NLC rf accelerating cavities. Although these cavities are simpler in structure, they have electromagnetic breakdown problems similar to those of TESLA rf couplers; they were a good place to begin investigations prior to the decision on an accelerating technology. Since the NLC structures are held at high temperature when they are assembled by brazing, the copper's grain size grows so that sound waves must propagate through a crystalline medium with randomly oriented, irregularly shaped grains a few millimeters in size. We have worked with two sets of copper dowels on loan from the Fermilab NLC structure factory. The copper stock is from a shipment of material used to construct actual NLC test structures. One set of dowels has been heat-annealed to bring up its grain size; the other has not and consequently has microscopic grains.

We have borrowed several 1.8MHz transducers and associated signal conditioning electronics from Bill O'Brien's lab as well as purchasing a pair of 500kHz Panametrics transducers. A variety of measurements (including speed of sound, attenuation length, and beam spread) for dowels of different lengths provide us with a nice set of experimental inputs with which to confront our acoustic models. Instead of a transducer, we can also use a mechanical tapper to produce acoustic waves in the dowels; this avoids cross-talk between transmitting and receiving transducer channels, although at the cost of not knowing the exact timing of the initial impulse.

We have developed a model for the propagation and detection of acoustic waves in copper. The model describes copper as a (possibly irregular) grid of mass points connected by springs.

We can vary the individual spring constants and the arrangement of interconnections to introduce irregularities representing grains in our simulated material. We can alter the spring constants over larger regions to model varying materials with different speeds of sound. This model, although it may seem simplistic, is able to support a variety of complex phenomena; we are able to tune various physical properties (such as the speeds of sound for compression- and shear-acoustic waves through adjustments of the model's parameters.

Our model, written by two students, performs a fourth-order Runge-Kutta numerical integration to compute the response of mass points to acoustic perturbations. Our early model systems were two-dimensional grids of roughly $10^5$ points. We "drive" signals into them using a transducer model in which the piezoelectric device is described as a damped oscillator excited by shocks of short duration. Because of reflections at the ends of the cable used to drive the real transducers, the actual drive signal is complicated; we find we can model it adequately as a series of four closely-spaced impulses. We have used the first echo to guide our selection of drive parameters; the shape of the second echo is well reproduced. We can simulate the transducer signal as a function of time by summing the amplitudes at the "face" of a transducer as it experiences the effects of the acoustic pulse. Figure 1 shows propagation of a simulated acoustic wave in a homogeneous $250 \times 650$ point grid. Figure 2 compares a real oscilloscope record of transducer signal vs. time to the results of this two-dimensional simulation. These results are promising but need a considerable amount of refinement.

Scattering off grains produces very complicated effects and it is important to confirm that our calculations are accurate. We have used *MatLab* as a computational engine to generate an analytic solution to the coupled equations describing the forces acting on each mass point. The numerical integration model is able to handle considerably larger systems than is possible with *MatLab*. However, when applied to smaller systems (with a few hundred mass points), the analytical calculation agrees with our model to an accuracy consistent with integration step size and machine precision.

The effect of inhomogeneities on an acoustic wave is dramatic. The disruption suffered by a pulse in an inhomogeneous crystal dumps a significant amount of acoustic energy into the bulk of the copper. This produces an acoustic glow that washes over the transducer site. Figure 3 shows this effect in the (real) heat-treated dowels when we drive them with our 1.8MHz transducers. The existence of the glow implies that transducers monitoring rf couplers are not limited to detecting acoustical breakdown in select regions, but can sense breakdown wherever it occurs.

There are two limitations on transducer placement for our investigations. One limitation is the cost of transducers, making it desirable to choose a method that requires fewer transducers to isolate a breakdown event. The second limitation is the geometry of the systems we are

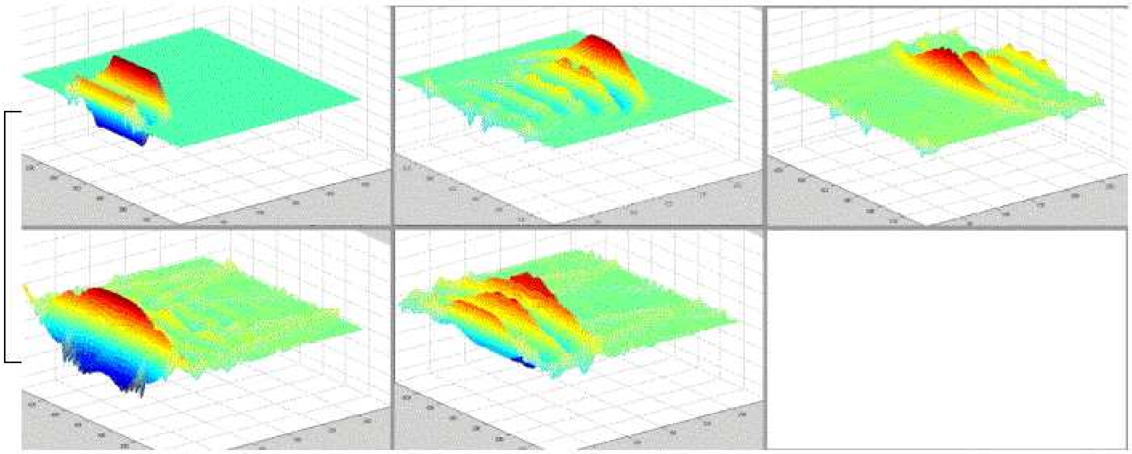

Figure 1: Acoustic wave propagating in a homogenous 250x650 point grid.

studying; even if cost were not a barrier to tiling the outside of NLC cavities or rf couplers with transducers, cooling pipes and power connections still would be.

We are investigating three methods of isolating the source of an acoustic event. One method uses the time-dependent transducer outputs of a simulation as inputs and runs the simulation backward in time. The waves detected by multiple transducers can then be used to isolate the place and time of the original impulse. A small number of transducers (three or four) is capable of isolating the source of an event if they have complete information about the behavior of the small area of the copper surface with which they are in contact. However, because the real transducers we use only receive information about the component of acoustic waves perpendicular to their surface, directional information is lost. Additional information is lost compared to the simulation because, unlike the mathematical points in the simulation, real transducers are extended objects that average over their surface. Better reconstruction may be possible with a large number of transducers. Also, transducers capable of measuring all three directional components of acoustical waves exist, but are custom-made and considerably more expensive than the transducers we use. In order to test the usefulness of transducers capable of sensing motion in three dimensions for isolating acoustic events, it may be possible to rent or borrow such transducers built for another purpose.

A second method is to triangulate the source of an event based on relative arrival times of glow at various transducers. Because arrival time is susceptible to analytic treatment, it is possible to pursue source triangulation both in conjuntion with and independently of our

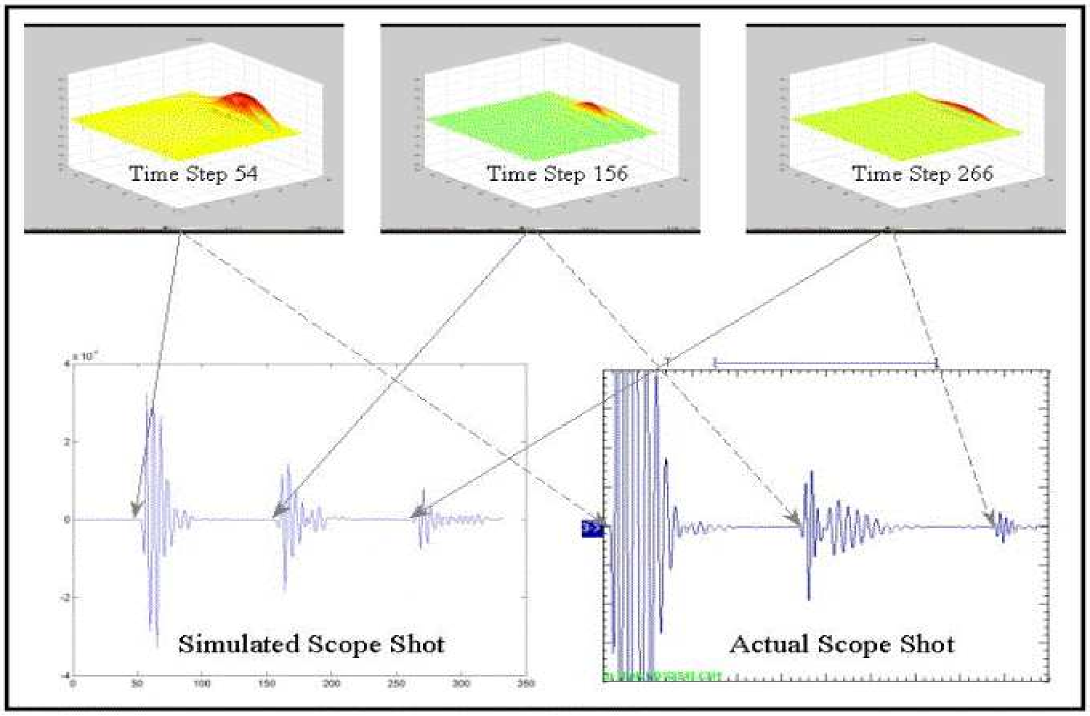

Figure 2: Real transducer output compared to a simulation.

simulations. Without *a priori* knowledge of the absolute time of the event, a minimum of four transducers is necessary to define a point source uniquely by this method. If the source is not pointlike, additional transducers are necessary to determine its location and extent. Propagation of direct signals precedes that of the glow; the process of triangulation could be disrupted by early responses by transducers in the direct path of an event. The geometry of the material in which the acoustic waves propagate can create discrete ambiguities in signal source. So far, we have only considered triangulation in a simplified model of an NLC accelerating cavity; we do not yet know how well this method will work in systems of more complicated geometry (such as TESLA rf couplers).

Our third method uses not only the leading edge of the acoustic glow but also its time-evolution. Figure 4 shows simulated responses for four transducers staggered in both axial ($z$) and azimuthal ($\phi$) directions along an NLC cavity. Shown for each transducer are responses to signals from five sources at the same $\phi$ but separated in $z$ by intervals of 2 cm. This method requires us to build a library of transducer responses to various breakdown modes, and then use a fitting program such as MINUIT to distinguish among the modes. By using the complete time-dependent record (rather than just the arrival time) from each transducer, we can treat the transducer responses as linear combinations of breakdown modes, and thus distinguish point sources from extended sources without requiring additional transducers.

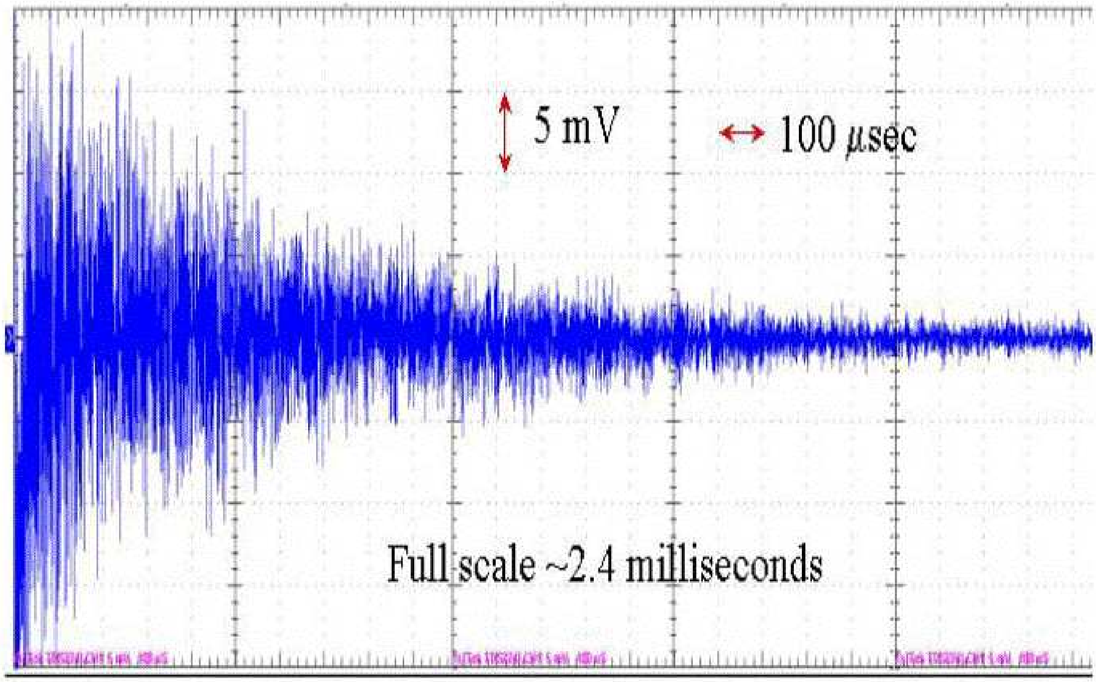

Figure 3: Acoustic glow at long times observed in a heat-treated, long, copper dowel. Note that the scope trace is not showing noise; the fine structure is reproducible from shot to shot.

We have solved several of the immediate challenges that faced us one year ago. We have made improvements in the efficiency of the simulation code, allowing us feasibly to simulate systems with a larger number of mass points, including three-dimensional systems. We have moved from simulation of simple geometrical regions to models of accelerating structures. The simulation is now able to handle multiple grains in the simulated medium (a year ago, at most one grain was possible). We have added a mechanical tapper as an alternate source of signals for the laboratory setup. We have improved our simulation of the transducers.

We will continue to pursue this investigation on several levels. Our models of accelerating structures still have room for additional refinements, modeling both temperature dependence and the more complex makeup of the TESLA rf coupler (the latter is shown in Fig. 5). We need a more quantitative understanding of grain structure and its effect on signal transmission. All three methods of source localization appear promising, and it is not yet clear which will yield the best resolution; each has its own particular challenges. The test of our methods is not merely internal self-consistency nor simulation benchmarks, but external validation by testing with real systems including the couplers.

### Facilities and Resources

The University of Illinois High Energy Physics group has excellent computing, networking, and electronics design infrastructure. Our group includes three electrical engineers and two technicians; Haney heads this electronics group. Another member of the group's technical staff manages the group's computing, which comprises a mixture of unix, linux, and Windows machines as well as file and print serving resources. Some of our laboratory instrumentation is managed by realtime systems such as VxWorks running in VME processors; a number of groups use PCI bus modules installed in lab Windows machines which run LabVIEW to control devices.

### FY2005 Project Activities and Deliverables

The collaborators' work on this project is already funded as part of LCRD. Williams, a UIUC postdoc, is currently seeking a faculty position; this proposal will be updated when the results of this search are known. A principal activity of the first year of this proposal, therefore, will be transplanting the project to a different institution and recruiting new students to participate. During the first year, we also plan to:

- Develop a geometrical description of TESLA rf couplers suitable for use in our simulations.
- Ensure the isotropy of signal propagation in three-dimensional simulations.
- Determine the precision with which the source of a breakdown event can be located in rf couplers by profile matching.
- Develop a quantitative description of how wave behavior (e.g. propagation speed, dispersion, attenuation) varies in the simulation with grain size.
- Determine the minimum number of transducers needed for the location of a point source in a rf coupler to be unambiguously determined by signal arrival time.

### FY2006 Project Activities and Deliverables

For the second year, we plan to:

- Adapt our simulations to include the temperature dependence of ultrasound propagation.
- Develop a method to measure ultrasound in materials at temperatures below the operating range of the transducers, perhaps by coupling acoustically without thermal coupling.
- Expand our model of rf couplers to include material and temperature variations.
- Acquire (preferably by renting or borrowing) transducer(s) capable of two- or three-dimensional measurements to test their use with our back-propagation technique.
- Match wave attenuation between simulation and bench tests.
- Investigate the possibility of field-testing our methods in conjunction with tests of rf couplers at ANL and FNAL.
- Complete such other studies as are suggested by our first-year objectives.

### FY2007 Project Activities and Deliverables

By the third year, we plan to have at least one functioning method (and preferably more) to localize breakdown in rf couplers and determine optimum placement of transducers.

### Budget justification: Unidentified Institution

The largest component of budget is student wages. This figure is based on two students each working 750 hours/year at a rate of $ 6.50 / hour. Because new students have not yet been recruited, we halve the number of hours for FY2005.

Equipment is a second large component of the budget. In FY2005, this includes two PCs on which to run simulations. In later years, we require transducers for bench tests. Conventional 500 kHz transducers cost $ 500 each; to locate an acoustic event requires at least four. Conventional transducers are sensitive to one component of an acoustic wave; one of our methods requires transducers sensitive in two or three dimensions. Such sensors are custom-built at a price of about $ 1500 each.

We include travel funds sufficient for one trip to a national laboratory in the first year and two trips per year thereafter.

### Three-year budget, in then-year K$

**Institution:** [University of Illinois at Urbana-Champaign]

| Item | FY2005 | FY2006 | FY2007 | Total |
|---|---|---|---|---|
| Other Professionals | 0 | 0 | 0 | 0 |
| Graduate Students | 0 | 0 | 0 | 0 |
| Undergraduate Students | 4.9 | 9.8 | 10.1 | |
| Total Salaries and Wages | 4.9 | 9.8 | 10.1 | |
| Fringe Benefits | 0.1 | 0.2 | 0.2 | 0.5 |
| Total Salaries, Wages and Fringe Benefits | 5.0 | 10.0 | 10.3 | |
| Equipment | 6.0 | 7.0 | 7.0 | 20.0 |
| Travel | 0.7 | 1.4 | 1.4 | 3.5 |
| Materials and Supplies | 0 | 0 | 0 | 0 |
| Other direct costs | 0 | 0 | 0 | 0 |
| Total direct costs | 11.7 | 18.4 | 18.7 | 48.8 |
| Indirect costs | 2.9 | 5.9 | 6.0 | 14.8 |
| Total direct and indirect costs | 14.6 | 24.3 | 24.7 | 63.6 |

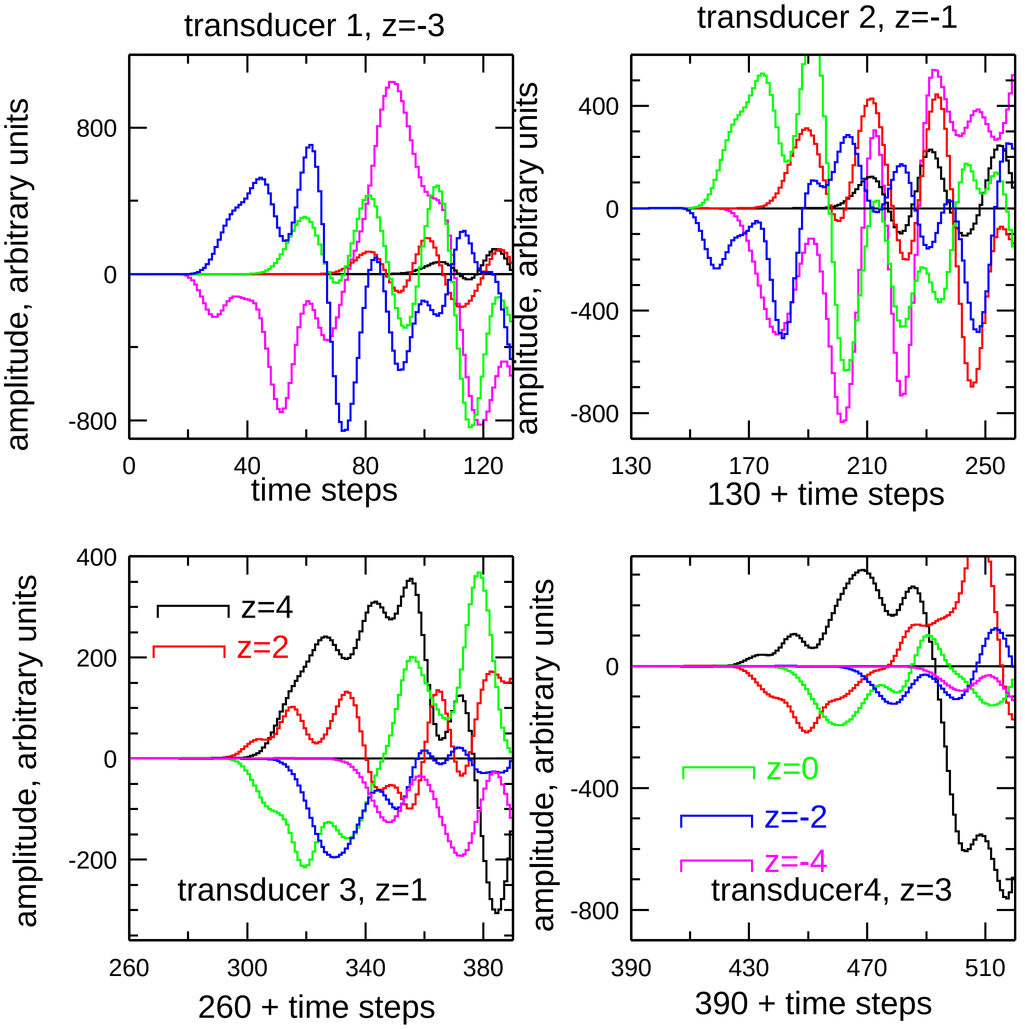

Figure 4: Amplitude vs. time for four simulated transducers staggered in both $\phi$ and $z$ about a cylinder. The time range is the same for each of the four transducers. For each of the transducers, response to signals from five different z positions (colors) is shown.