Modeling acoustic signatures of rf cavity breakdown

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LCRD 2.15

George Gollin, LCRD 2004
Can we learn more about NLC rf cavity breakdown through acoustic signatures of breakdown events?

1. Who is participating
2. Studying the acoustic properties of Copper + transducer system
   • transducer response
   • speed of sound in Copper
   • scattering vs. attenuation at 1.8 MHz in Copper
3. Modeling of acoustic systems
4. Conclusions
Who is participating at UIUC

Joe Calvey (undergraduate)
Michael Davidsaver (undergraduate)
George Gollin (professor, physics)
Mike Haney (engineer, runs HEP electronics group)
Justin Phillips (undergraduate)
Bill O’Brien (professor, EE)

Haney’s PhD is in ultrasound imaging techniques; O’Brien’s group pursues a broad range of acoustic sensing/imaging projects in biological, mechanical,… systems

We discuss progress and plans from time to time with Marc Ross at SLAC.
This is what we’re going to be studying

Ross sent us a short piece of NLC and some engineering drawings specifying the geometry.

We need to understand its acoustic properties.

Start by pinging copper dowels with ultrasound transducers in order to learn the basics.
Long range plan

1. Use ultrasound transducers to “ping” copper cylinders.
2. Learn about the acoustic properties of transducer + copper system
3. See how well we can model acoustic properties using MatLab and home-grown code, including incorporation of grains into copper
4. Develop an acoustic model for the NLC structure we have on hand
5. Ping the NLC structure and determine how well our model describes our measurements
6. Predict characteristics of the acoustic signature for various electrical catastrophes inside an NLC structure
7. Generate sparks inside cavity, measure what we can, then see how much information we can extract from the acoustic information.

So far we’ve been working on items 1-3.
Copper dowels from Fermilab NLC Structure Factory

Harry Carter sent us a pair of copper dowels from their structure manufacturing stock: one was heat-treated, one is untreated.

NLC structures are heat-brazed together; heating creates crystal grains (domains) which modify the acoustic properties of copper.

Ross also sent us a (small) single crystal copper dowel.

We cut each dowel into three different lengths.
We can listen for echoes returning to the transducer which fires pings into the copper, or listen to the signal received by a second transducer.
Modeling the Copper + transducer system

We want to understand this “simple” system in detail.

If we can model it accurately (using MatLab), we might be able to interpret acoustic information from the more complicated NLC structures.

HV pulses used to zap the transducer are short: ~10 nsec, ~1 kV, but there are reflections and other complicated effects which play a significant role in determining the actual excitation of the transducer.

NI PCI-5112: 50 ppm accuracy. TDS 224: 100 ppm accuracy. (Systematics dominate!)
Pinging the shortest heat-treated dowel

Two transducers: fire a ping, then listen for signals in both transducers. The initial excitation is complicated (note the protection diodes).
Modeling the transducer

Model the Panametrics piezoelectric transducer as a (linear) damped oscillator

- response to a $\delta$ function: $x(t) \sim \frac{F_0 e^{-bt}}{\omega_1} \sin(\omega_1 t)$

- response to $F(t)$: $x(t) \sim \int_0^t \frac{F(t-t')e^{-b(t-t')}}{\omega_1} \sin(\omega_1 (t-t')) dt'$

- pressure generated by transducer $\sim a(t) = \frac{d^2 x(t)}{dt^2}$
Transducer phenomenology

Try describing the excitation in terms of four $\delta$ functions applied to the piezoelectric crystal; adjust delays and amplitudes so that prediction for first echo signal looks reasonably good.

Accuracy of prediction for second echo’s signal is a check of sorts.

Looks pretty good, but not perfect (see plots on next slide).

Our transducer: $\omega_1 = 2\pi \times 1.8 \text{ MHz}$; $b = 1.70 \times 10^6 \text{ sec}^{-1}$.

Recall that response to $F(t) = F_0\delta(t)$ is $x(t) \sim \frac{F_0 e^{-bt}}{\omega_1} \sin(\omega_1 t)$
Transducer phenomenology

“sum of 1-4” is our four-δ model after hand-tuning its parameters using the first echo.
Transducer phenomenology

The behavior of the transducer is influenced by how well it is coupled to the copper (acoustic loading, acoustic impedance $[Z]$ mismatches, etc. etc.). We use a glycerin film to make transducer-copper contact.

It’s a little tricky figuring out exactly what the transducer is pumping into the copper, and we may need to work up a different parameterization for each of the dowel/transducer combinations.

Reflection coefficient:  

$$R \equiv \left( \frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2; \quad E_{\text{reflected}} = R \cdot E_{\text{incident}}$$

Pulse shapes are very reproducible from shot to shot, but care is necessary in how the transducer is coupled to the copper.
Speed of sound at 1.8 MHz in copper

We have three different lengths of dowels and can make speed-of-sound measurements by timing the arrival of various reflections.

This way, effects related to transducer geometry cancel.

<table>
<thead>
<tr>
<th>Dowel lengths</th>
<th>Dowel 1: not heat-treated</th>
<th>Dowel 2: heat-treated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>diameter: 6.907 cm</td>
<td>diameter: 6.908 cm</td>
</tr>
<tr>
<td>2.52 cm</td>
<td>2.56 cm</td>
<td></td>
</tr>
<tr>
<td>5.09 cm</td>
<td>5.09 cm</td>
<td></td>
</tr>
<tr>
<td>17.6 cm</td>
<td>17.6 cm</td>
<td></td>
</tr>
</tbody>
</table>
Speed of sound and grain structure...

Closeup of one of the (heat-treated) dowel #2 sections.

Note that grain patterns visible at the copper’s surface.

Grain structure is not visible on the surface of dowel #1.
Speed of sound at 1.8 MHz in copper

The speed of sound is different in the two kinds of copper dowels. It’s 5.2% faster in the grainy (heat treated) copper. (You can hear it!)

Blue points: dowel #2 (heat treated)
\[ \nu_s = 4985 \text{ m/sec} \]

…so \( \lambda \approx 2.8 \text{ mm} \)

Red points: dowel #1 (not heat treated)
\[ \nu_s = 4737 \text{ m/sec} \]

Single crystal:
\[ \nu_s = 4973 \text{ m/sec} \]
(4.973 mm/μsec)
Scattering/attenuation at 1.8 MHz in copper

A “ping” launched into a copper dowel will bounce back and forth, losing energy through

- absorption in the transducer (large acoustic impedance mismatch between the transducer and the copper: not much energy crosses the copper/transducer boundary)
- scattering of acoustic energy out of the ping
- absorption of acoustic energy by the copper.
Scattering/attenuation at 1.8 MHz in copper

Loss of signal (scattering, absorption) will make interpretation of the acoustic signature of cavity breakdown more difficult.

We would like to understand the relative importance of absorption and scattering.

Perhaps there is still information to be extracted from the acoustic signal if the primary mechanism for loss of energy from the acoustic beam is scattering.

If so, perhaps we can model scattering (with MatLab, also our own code) and learn how to extract information in spite of all that scattering.
Scattering vs. attenuation

Attenuation: energy is lost and copper is quiet except during pulse

Scattering: there’s an acoustic “glow,” pumped by energy from the acoustic pulse.

Measure rate of decrease in size of successive echoes seen by one transducer (caused by a combination of scattering and absorption)

Look at RMS acoustic signal between pulses/echoes to see if it builds up, then decays (due to scattering of energy out of the beam and subsequent absorption by copper)
Scope shots

Single transducer: ping, then listen for echoes. Adjust ping energies so that first echoes are approximately equal in amplitude.

Note the difference in sizes of the second echoes as well as the different amounts of baseline activity between the echoes.
RMS baseline activity in scope shots

Single transducer: ping, then listen to baseline “noise” as pulse travels into copper, pumping energy into acoustic baseline “glow.”

Here’s the baseline glow, 5 mV and 100 \( \mu \text{sec} \) per division. Scope shot from heat-treated (grainy) long dowel.
RMS baseline activity in scope shots

Two transducers: ping using #1, then listen to baseline “noise” using #2. Data from heat-treated (grainy) long dowel.

Look at RMS acoustic signal in a sliding 20 μsec window.

We see glow beginning to arrive at second transducer after the direct signal (not surprising!); it builds for a short while, then begins to decay (also not surprising!). There’s a lot of structure too, which is surprising to us.
Beam spread

Two transducers: ping using #1 (centered), then listen using #2. Move #2 off center and measure signal size in different length dowels: we see very little beam spread in non-heat-treated dowels.

Relative signals at far ends of dowels vs. off-axis distance of receiver

- 17.6 cm length dowel
- 5.1 cm length dowel
- 2.5 cm length dowel

Displacement from center (mm):
0 5 10 15 20 25

Signal amplitude:
0.0 0.2 0.4 0.6 0.8 1.0 1.2
Measurements and modeling

It feels like we’ve made about as many measurements as we need to of copper’s acoustic properties at this frequency.

So far we have been using 2.25 MHz unloaded (1.7 MHz loaded) transducers.

We bought a pair of 500 kHz (unloaded?) transducers. No results with them yet.

We can measure acoustic signatures with good reproducibility, though coupling of transducers to copper is a little fussy.

We are using WaveStar and LabVIEW to acquire (and process) oscilloscope information.
Measurements and modeling

Ongoing (parallel) efforts:

• develop MatLab acoustic model for transducer + Copper system.

• develop our own code to do the same thing

MatLab: exact solutions to differential equations which describe elastic interactions among mass points connected by springs

UIUC local code: 4th order Runge-Kutta numerical integration of force equations for elastic interactions (just use MatLab as a display driver)

For simple systems the results are identical. For complex systems MatLab chokes, but UIUC code works fine.
Measurements and modeling

We could take a bulk-properties approach, working directly with the wave equation. Here it is:

\[ \rho \frac{\partial^2 \mathbf{u}(\mathbf{x}, t)}{\partial t^2} = \left( K + \frac{4}{3} \mu \right) \nabla \left( \nabla \cdot \mathbf{u}(\mathbf{x}, t) \right) - \mu \nabla \times \left( \nabla \times \mathbf{u}(\mathbf{x}, t) \right) \]

But we’re “newbies” and a microscopic approach might let us better understand how to handle grains and other irregularities…
Measurements and modeling

The plan: work up a simple phenomenological model (based on sensible physics) which includes scattering off grain (and other) boundaries and includes attenuation.

If we can model the copper cylinders adequately, perhaps we will be able to describe the NLC structure’s acoustic properties.

Technical language: we would like to be able to understand how to describe the (acoustic) Green’s function for our Copper structures.
Condensed matter, as done by folks in HEP

Initial models: regular (rectangular, 2D) grids of mass points connected by springs.

Speeds of propagation for pressure and shear waves are determined by $k_1$, $k_2$, and $k_1/k_2$.

It is straightforward to generalize to 3D, to vary spring constants arbitrarily, to introduce dislocations and changes in crystal orientation.
Propagation of a pressure wave in a homogeneous grid
Pressure wave propagation: stills from the movie…
More stills from the movie…
More stills from the movie…
More stills from the movie…
More stills from the movie…
Simulated transducer response
Propagation of a pressure wave through one “grain”

Change the spring constants inside a parallelogram-shaped region to see effects on pulse propagation.
Some stills from the animation
Animation
More stills from the movie
What we are/will be working on

• More realistic modeling of grains: multiple grains, disruption of coupling between mass points at boundaries,…

• Refinement of description of transducer-copper coupling. (Transducer absorbs some of the energy which arrives at its point-of-coupling.)

• Modeling of more complicated (2-D) shapes (not yet).

• Modeling in 3-D, with investigation of the NLC structure’s acoustic properties.
Comments on doing this at a university

• Participation by talented undergraduate students makes LCRD 2.15 work as well as it does. The project is well-suited to undergraduate involvement.

• We get most of our work done during the summer: we’re all free of academic constraints (teaching/taking courses). The schedule for evaluating our progress must take this into account.

• Most support for students comes from our DOE base grant. We have borrowed PC’s from the UIUC Physics Department instructional resources pool for them this summer.

• LCRD 2.15 requested $9k in support from DOE, which has decided to support us at the requested level. We need more.
Budget items

1. three undergraduates: full time during the summer, ~5-10 hours per week per student during the academic year, indirect costs.
   • ~ $21k per year
2. transducers and National Instruments DAQ instrumentation
   • ~ $13k per year as system expands
3. small amount of travel
Conclusions, etc.

• We are able to make acoustic measurements of our Copper cylinders which are very reproducible from shot to shot.
• We observe significant differences in the acoustic properties of Copper which is, and is not, heat-annealed.
• We are working at refining our models in order to develop a phenomenological description of Copper which can be used to predict/interpret acoustic signals in NLC structures. We don’t yet know how well this will work: the complications of scattering and absorption may make this difficult.
• This is a lot of fun.