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Title: Rogowski coils for studies of detonator initiation and other diagnostics

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Rogowski coils for studies of detonator initiation

And other diagnostics

Doug Tasker, Pat Bowden, Elizabeth Francois, John Gibson, Teagan Nakamoto, Dalton Smith, Chris Trujillo and Zak Wilde

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Rogowski coils for studies of detonator initiation and other diagnostics

Doug Tasker, Pat Bowden, Elizabeth Francois, John Gibson, Teagan Nakamoto, Dalton Smith, Chris Trujillo and Zak Wilde

The Rogowski coil dates back to 1887 and it has commonly been employed to measure rapid changes of electrical currents without direct contact with the circuits, especially in high energy density applications. Recently, it has been used to measure currents in relatively low energy devices such as semiconductor circuits; here we report its utility in the analysis of detonator initiation.

From an electrical perspective, the coil is essentially an air-cored transformer and measures the temporal rate of change of current *dI/dt*. Following a careful characterization of the circuit, an accurate measurement of this derivative is shown to provide a complete solution of the detonator circuit, including current, voltage, power and energy delivered to the detonator. The dependence of the electrical sensitivity, accuracy and bandwidth on coil design will be discussed and a new printed circuit design will be presented.

Interesting features in the initiation of exploding bridgewire detonators have been observed with this coil and the results of various experiments will be discussed.

Diagnostics for detonators

- Detonators are fundamental to most explosive systems, yet the detonators themselves are rarely diagnosed to determine how well they function or why they fail
  - As a collective student project we sought to explore the application of various novel electrical diagnostics to remedy this:

Rogowski coils

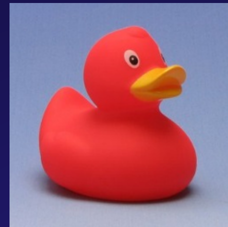
PVDF stress sensors in unconventional orientations

RF antennae

- **Initially we focused on Rogowski coils but have recently discovered some interesting phenomena with RF antennae**

If you haven't already, please see the posters by John Gibson, Teagan Nakamoto, Dalton Smith, Chris Trujillo and Zak Wilde for more details

Rogowski redux



1912

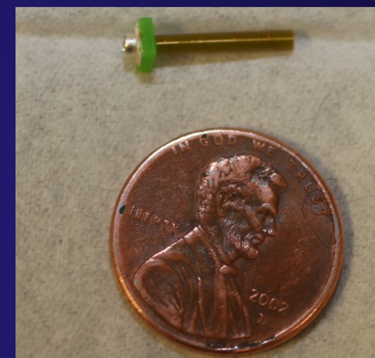
- **Rogowski coils date back more than a century**
  - (Rogowski and Steinhaus-Germany, 1912, Chattock-England, 1887)
- **Measures change of electrical current (*dI/dt*) without direct contact with the circuits**
  - Especially useful in high energy density applications (explosive pulsed power)

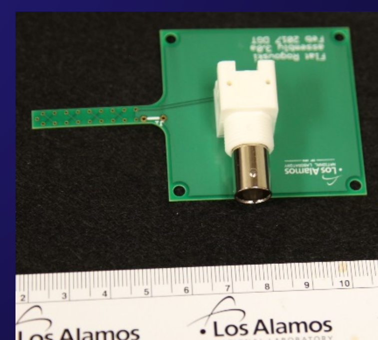
…

2017

- **Commercial company (PEM) uses electronic integration to measure currents (*I(t)* -not *dI/dt)* in low energy devices**
  - E.g., semiconductor circuits
    - Not suitable for *dI/dt* measurement

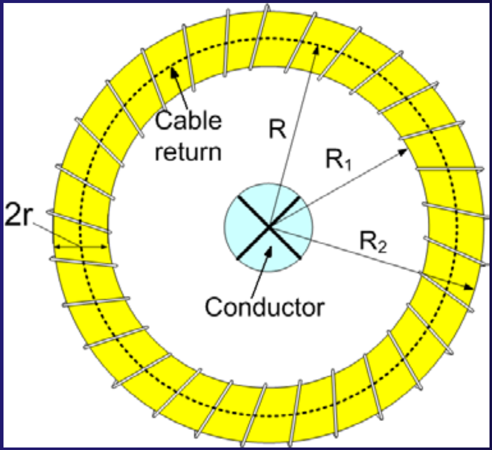
- **Here, we use LANL Rogowski coils, to measure *dI/dt*, for our detonator initiation study**

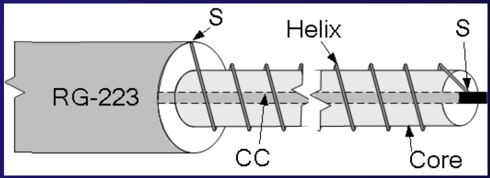




Rogowskis – how they work

- **High fidelity, high speed, dielectric-cored transformer**
  - Measures *dI/dt*
  - Based on Ampere's law $\oint \mathbf{B.dl} = \mu_0 \int \mathbf{J.da} = \mu_0 I$
  - Magnetic field B induces a voltage across the helix, $V = nA \times dB / dt \propto dI / dt$
  - Measures the current enclosed by the Rogowski OVER ANY PATH
    - Includes compensating loop (cable return) for external field rejection





Low frequency effects – skin effect

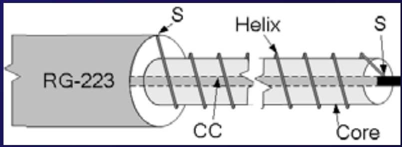
- **The area A is not really πr² all the time – or all the frequencies!!**

- **Area A includes the return conductor (hopefully copper*)**
  - At modest frequencies the magnetic field is pushed out of the central core by the skin effect – this reduces A and therefore reduces the sensitivity M

$$M = \mu_0 A p$$

- **Examples:**
  - M falls to 92% of its original value above ~28 kHz for RG223, above ~106 kHz for RG174.
  - This means that the Rogowski is more sensitive at low frequencies and can distort the data. BUT here's the good news…

- **…For a typical fireset signal the lowest frequency of interest is ~250 kHz, so RG174 and RG223 are great <u>for all our work</u>**
  - WARNING, some commercial probes (e.g., PEM CWT Ultra Mini) have high transition frequencies which causes problems when integrated
    - The <u>numerically</u> integrated PEM-dI/dt data will NOT match the <u>electronically</u> integrated data



- ***PS. Ask Doug about the copper and RG174**

High frequency effects: self-integration

- **Self-integration**
  - When the high frequency reactance of the coil's inductance exceeds the load resistance (e.g., 50 ohm scope termination)

$$\omega L = 2\pi f L \geq R$$

  - Examples
    - For an RG-223 cable with 1 turn/cm and 300 mm long (L = 23.6 nH)
      - HF limit = 337 MHz into 50 ohm ✓
        - HF limits into 1 Mohm are always too large to be meaningful (THz)
    - For an RG-223 cable with 1 turn/cm and 20 mm long (L = 1.5 nH)
      - HF limit = 5.3 GHz into 50 ohm ✓
    - For an RG-174 cable with 4 turn/cm and 300 mm long (L = 101.1 nH)
      - HF limit = 78.7 MHz into 50 ohm X
    - For an RG-174 cable with 4 turn/cm and 20 mm long (L = 6.5 nH)
      - HF limit = 1.22 GHz into 50 ohm ✓
- **Take away – for high frequencies keep the Rogowski short (could terminate with 1 Mohm)**
- **Highest frequency of interest: probably < 100 MHz, which corresponds to a risetime of 3.5 ns**
    - Typical 10-90% risetime of *dI/dt* at burst of a bridgewire is 10 ns (~35 MHz)

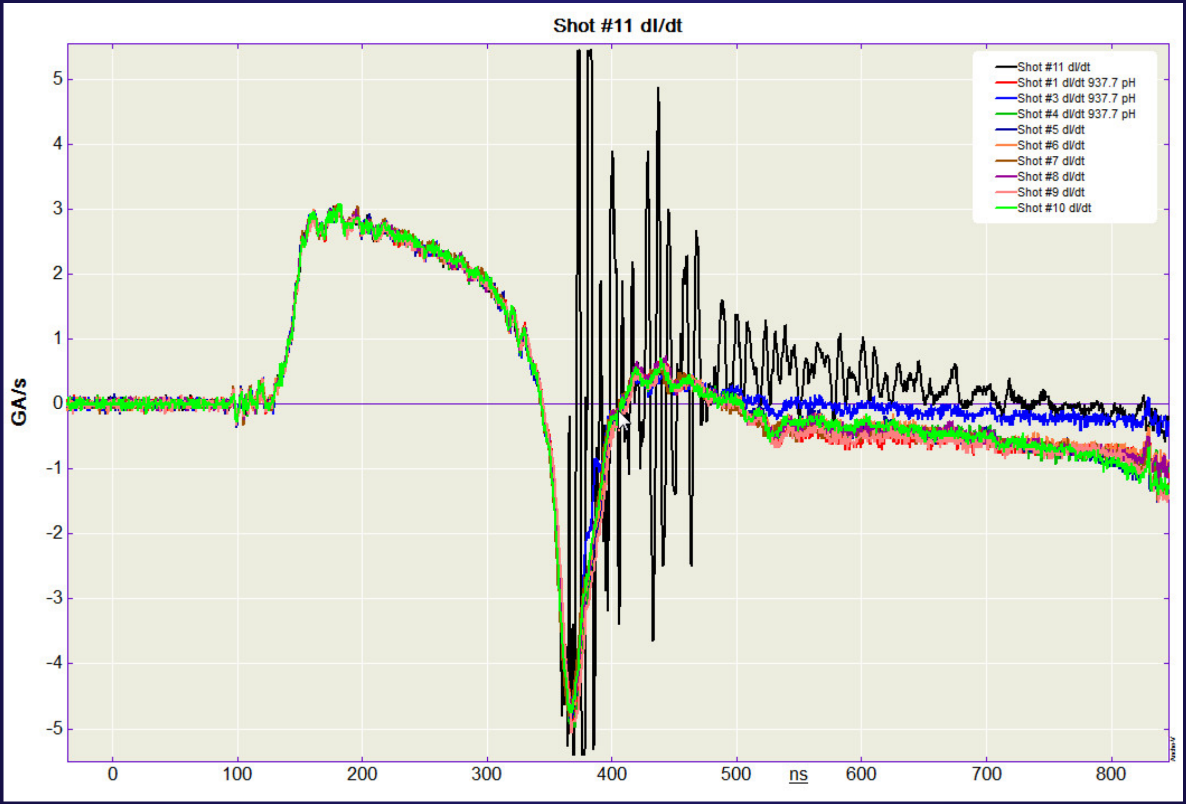
Tests to determine how burst signature changes with detonator filling

- **Standard detonator headers used with 1 x 10-mil Au bridgewires**
- ***dI/dt* signatures were obtained for bare bridgewire bursts and compared to bursts with various "fillings:"**
  - Air
  - Sugar mock
  - Plastic putty
  - Powdered creamer!
  - PETN

  - What we found was that if the bridgewire was fired in air, OR was separated from the powder filling, the signature was markedly different …

… Rogowski data for a series of detonators, one with poor solids loading.

Shows reproducibility of data and one failure



dI/dt analysis as an initiation diagnostic

- **Can clearly distinguish between bare wire and powders in contact with wires**
- **Can easily detect electrical failures (not shown)**
- **Not surprisingly , could not distinguish between goes and no-goes unless there was an electrical failure**
  - As to be expected, DDT processes not captured by *dI/dt* data

Rogowski: as a complete circuit diagnostic

Voltage across bridgewire & switch derived from *dI/dt*

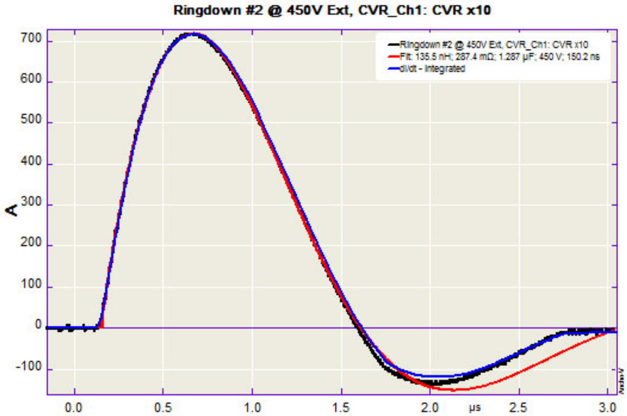
- **With good *dI/dt* data can calculate voltage across bridgewire and switch**
  - Accurate voltage measurement difficult because of impedances of connections and mutual L between det circuit and measurement circuit
    - Can detect a "voltage" with shorted leads
- **Math:**
  - From Rogowski *dI/dt*, integrate to get *I* and $\int I.dt$
    - Voltages across R, L and C found:

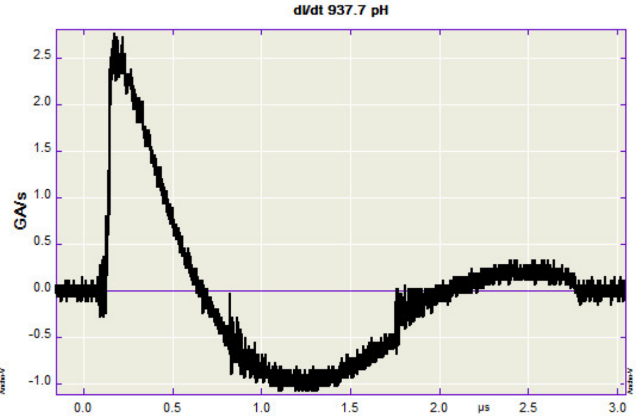
$$V_C = 450 - \frac{1}{C}\int_0^t I.dt;\ V_R = IR;\ V_L = L\frac{dI}{dt}$$

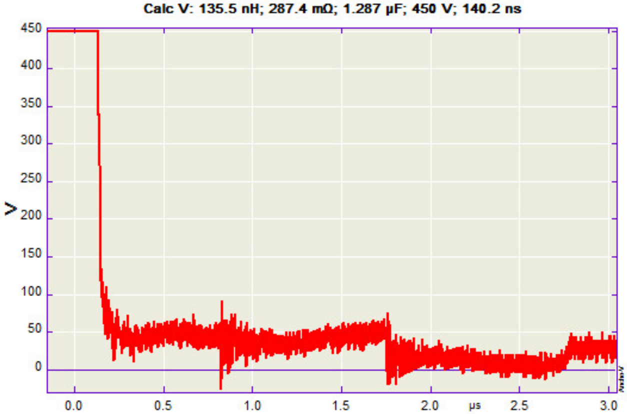
$$V_{wire} + V_{sw} = V_C - V_R - V_L;\ V_C(\mathrm{t}=0) = 450\mathrm{V}$$

- **Process:**
  - For a short-circuited load, calculated R, L and C for circuit from ringdown
  - Then fired circuit with 1 x 10-mil Au bridgewire

Ringdown data & switch performance

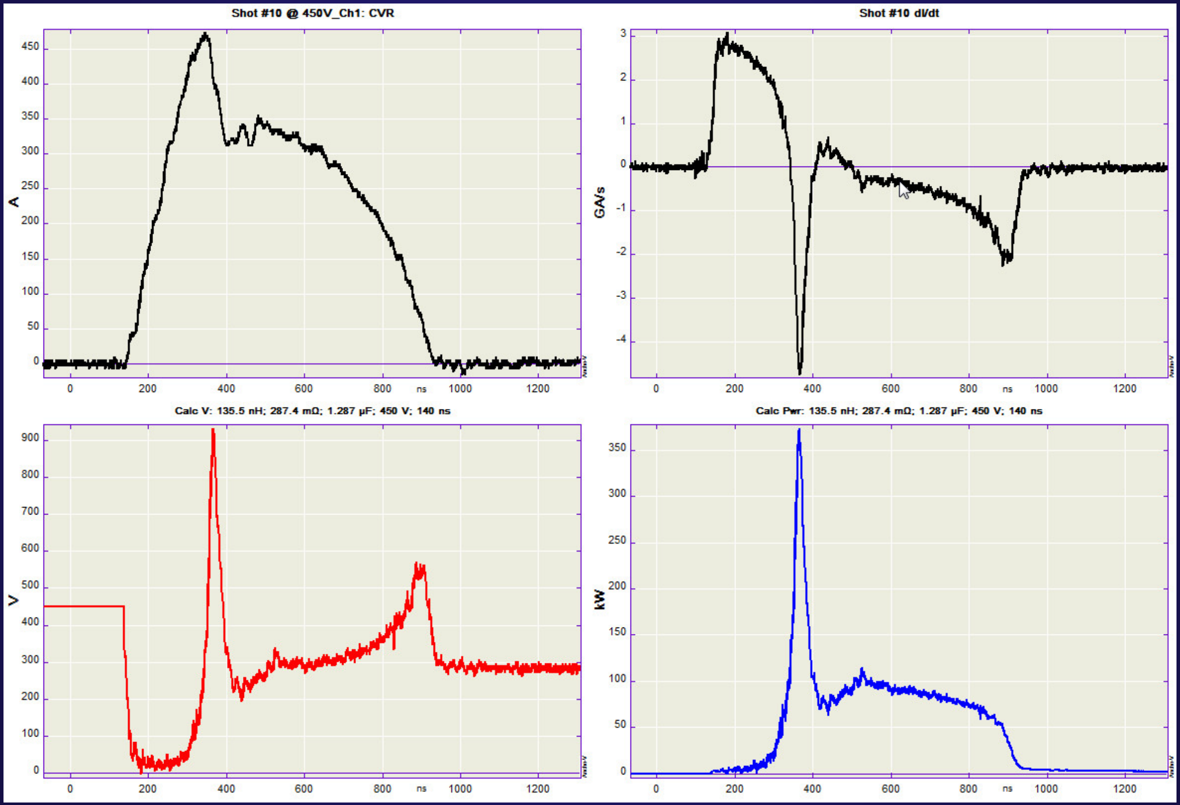






- **TL: CVR trace, integrated Rogowski trace, fit (red) (SD 3.4 A, SD signal noise 2.5 A)**
- **TR: Rogowski trace**
- **BL: Calculated solid state switch voltage**
  - On: 50 V typical (typical switch resistance ~1/10th ohm)
  - Calculated power and energy omitted

V calculation, switch and load



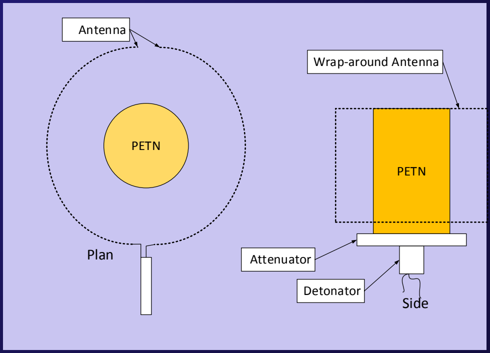
Rogowski diagnostics summary

- **Provides more information than conventional current viewing resistor (CVR)**
- **Can clearly detect electrical failures (not shown)**
- **Can clearly detect separation of bridgewire from explosive fill**
  - Will be testing the dependence of waveform on actual separation distances
- **As to be expected, differences in reaction buildup are not seen**
- **Can calculate voltage across load and switch**
  - Obviously works best for low impedance switch
- **Have high electrical bandwidths (~1 GHz), small, unobtrusive, isolated from circuit**

Radio frequency (RF) generation by shocked and detonating PETN

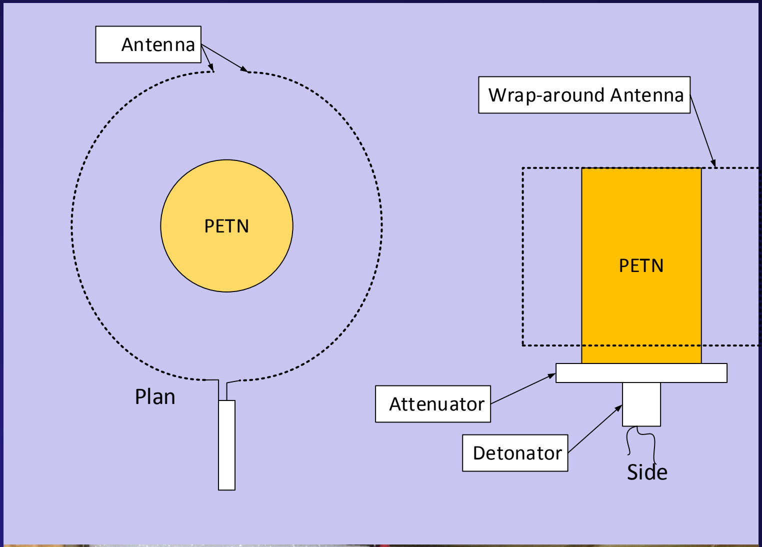
- **Can we detect the electric fields generated by collapsing PETN crystals and use them as a diagnostic?**
  - PETN crystals, like many explosives, are piezoelectric
  - Ultimate goal is to diagnose detonators, but for simplicity bare PETN pellets were studied

- **Work inspired by Bud Hayes: HAYES, B. 1967. The Detonation Electric Effect. *Journal of Applied Physics,* 38,** 507-511.



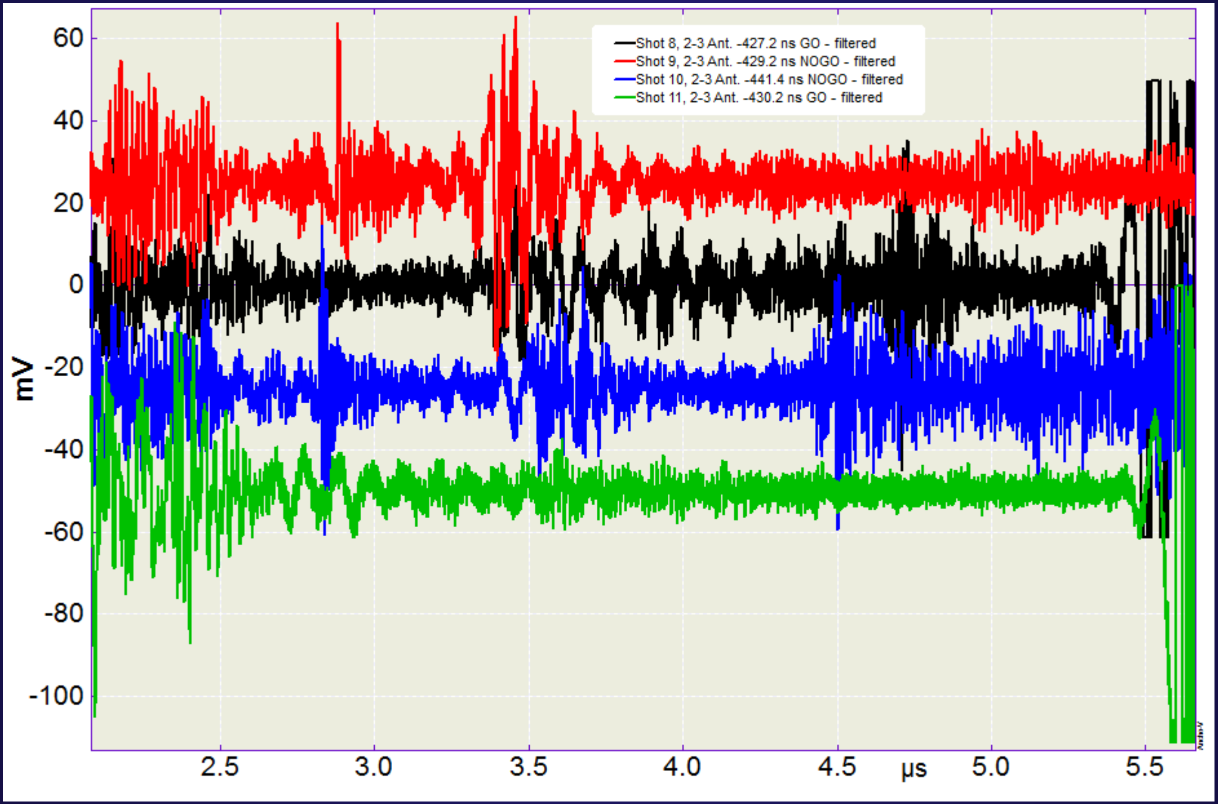
Experiment

- **1.30 g/cc PETN initiated by RP-2 detonator via PVC attenuators**
  - TMD 1.78 g/cc, i.e., 27% porosity
- **Attenuators (gaps) adjusted to find 50% GO / NOGO point**
- **Wrap-around copper-foil antenna used to detect piezoelectric RF signature (if any) from reacting PETN**
- **RF data examined for gaps close to the 50% point**



Temporal data from PETN pellets around 50%-point (200 ps resolution)

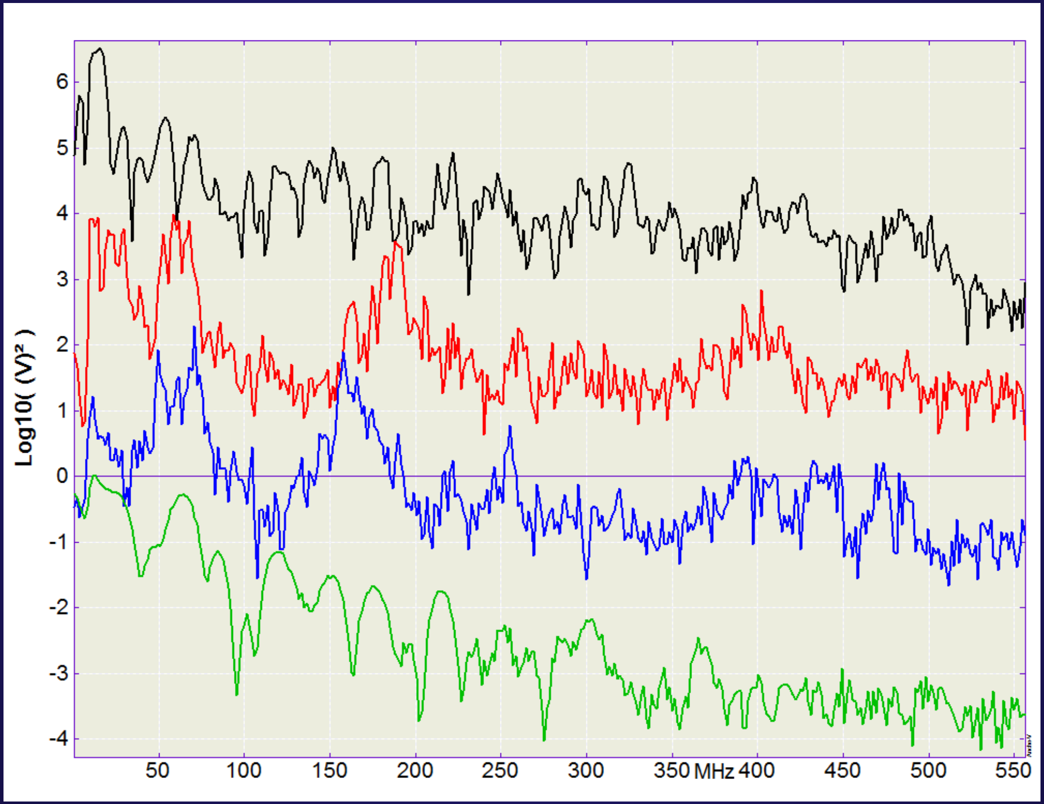
Attenuated below 10 MHz



Shot
9
8
10
11

- **Temporal data difficult to interpret**

Spectra from PETN pellets around 50%-point



Spectra below 10 MHz attenuated

Shot

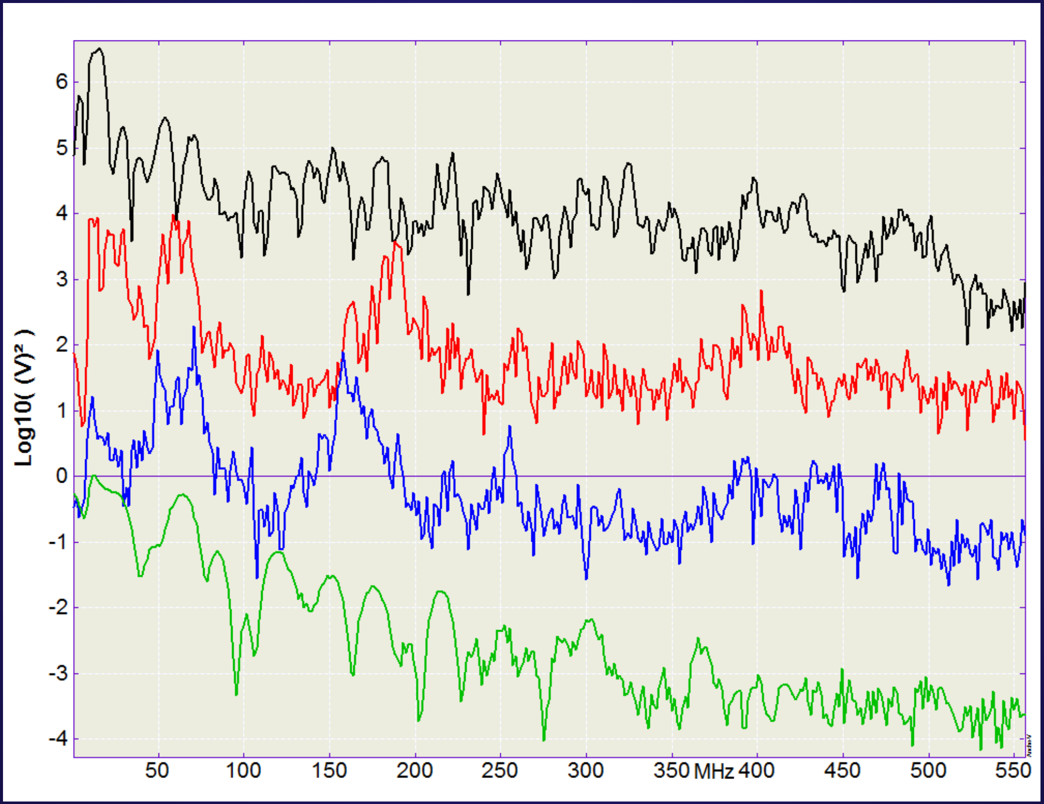
8

9

10

11

Spectra from PETN pellets around 50%-point



Spectra below 10 MHz attenuated

Shot

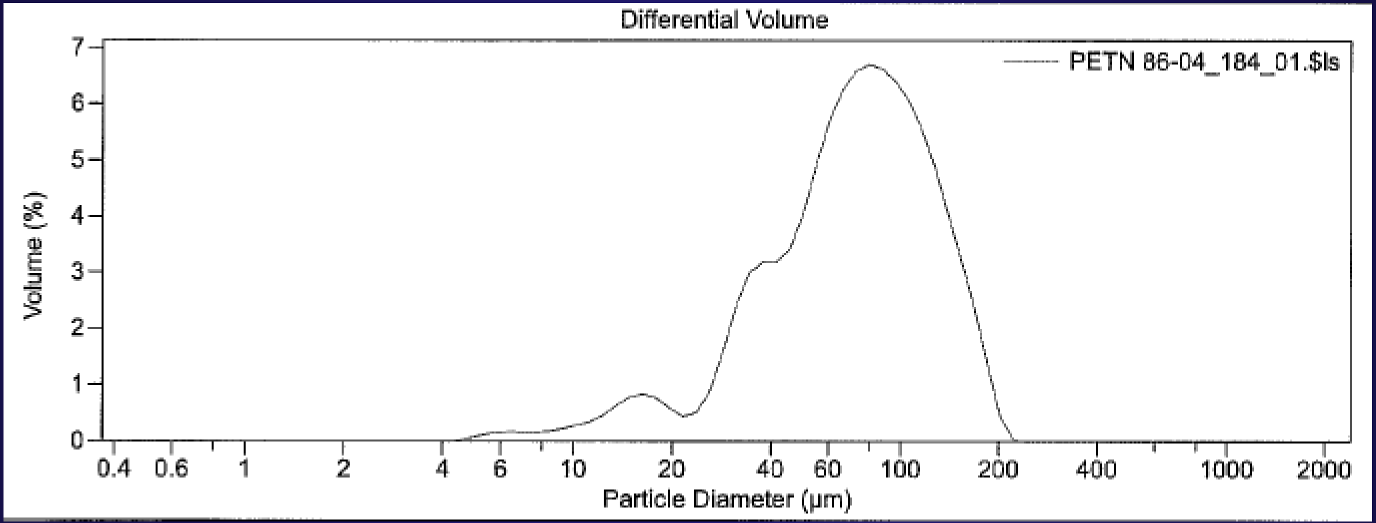
8 GO

9 NOGO

10 NOGO

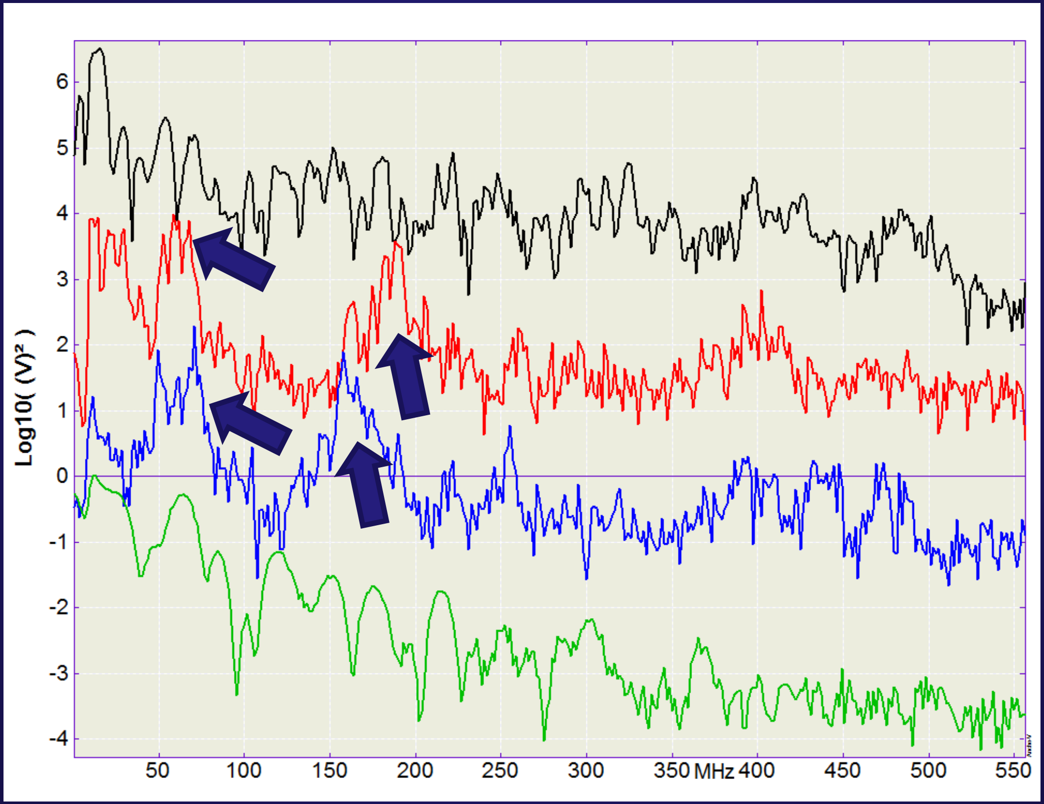
11 GO

Particle diameters predominantly 30~150 µm, what frequencies might we expect?



- Electric field generation not fully understood
- We expect crushed piezoelectric PETN particles to generate large local electric fields that discharge along crystal fracture planes
- Estimate pore collapse time dt ~0.37d / Up (Up: particle velocity*)
  - For Up = ~3 km/s (guess), dt = 4~19 ns; 1/dt = 50~250 MHz
    - *For perfect spheres gap = ($\sqrt{3}$ – 1)d/2

Spectra from PETN pellets around 50%-point
Additional peaks only seen in NOGOs



Spectra below 10 MHz attenuated

8 GO

9 NOGO

10 NOGO

11 GO

- **Resonant peaks consistent with estimated pore collapse times**

Why do the spectral resonances disappear for detonation?

- **We don’t know yet, but …**
- **… We do know detonating explosives are electrically conductive**
  - i.e., reaction zones are conductive
- We recovered most of the pellet as pulverized powder when there was a NOGO
  - Therefore little or no reaction

- **Hypothesis:**
  - Assuming the electrical noise is generated by the collapsing piezoelectric crystals, the conducting plasma may suppress or shield piezoelectric field generation

RF diagnostics summary

- **Have observed RF spectral structure from pulverized PETN pellets that is not present in detonating PETN**
  - We speculate that:
    - The emissions are due to the piezoelectric effect causing electrical discharges along fractured PETN surfaces
    - Conducting plasma within the detonation zone suppress or shield these electric fields
- **Much work to be done**
  - Other explosives, particle sizes, …
  - Determine electric field polarization with various antennae designs
  - Gas gun compression
  - Optical initiation
  - Use magnetic antenna, …

Acknowledgements