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Title: Electromagnetic Enhancement of Detonation and Its Applications

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Electromagnetic Enhancement of Detonation and Its Applications

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April 4, 2011

Electromagnetic Enhancement covers any electromagnetic enhancement of an explosive system whereas *Energy Coupling* enhances the detonation of an explosive by the deposition of electrical energy into the reaction zone. We will discuss our work on Energy Coupling and its applications, but will touch on other aspects of Enhancement.

Unreacted explosives are good insulators, whereas the explosive reaction zone (*conduction* zone) is an effective conductor. Detonation conductivities range from 100 S/m to 10 kS/m, depending on the explosive, and the conduction zone is typically 0.1 to 1 mm wide. So if the explosive is detonated between electrodes, with an applied electric field between them, a current flows through the explosive just behind the detonation front. When the Joule energy density deposited is comparable to that due to chemical reaction, e.g., 100 TW/m^2, the explosive power can be enhanced. The maximum enhancement is limited by the dielectric breakdown strength of the explosive. For a typical explosive the maximum enhancement is a ten-fold increase in the detonation energy; TATB can be enhanced by a factor of ~100! We will summarize the theory and experimental successes (and a few failures).

Doug has been active in Detonics, Shock Wave Physics, and Pulsed Power Physics since 1972; he is presently employed as a Senior Scientist in the High Explosives Pulsed Power group at LANL where his primary interest is in magnetic Isentropic Compression Experiments (ICE). However, he has worked extensively on a broad range of electromagnetic phenomena associated with explosives and shock waves, both in the US (including BRL for a short time with Phil Howe and Bob Frey) and the UK. Doug obtained his bachelor's in Physics at the City University (London, UK) and his doctorate in Physics and Electrical Engineering at Loughborough University (UK). He has published in excess of ninety papers.

This has been reviewed and determined to be Unclassified; Cleared for Public Release *LA-UR 11-01933*.

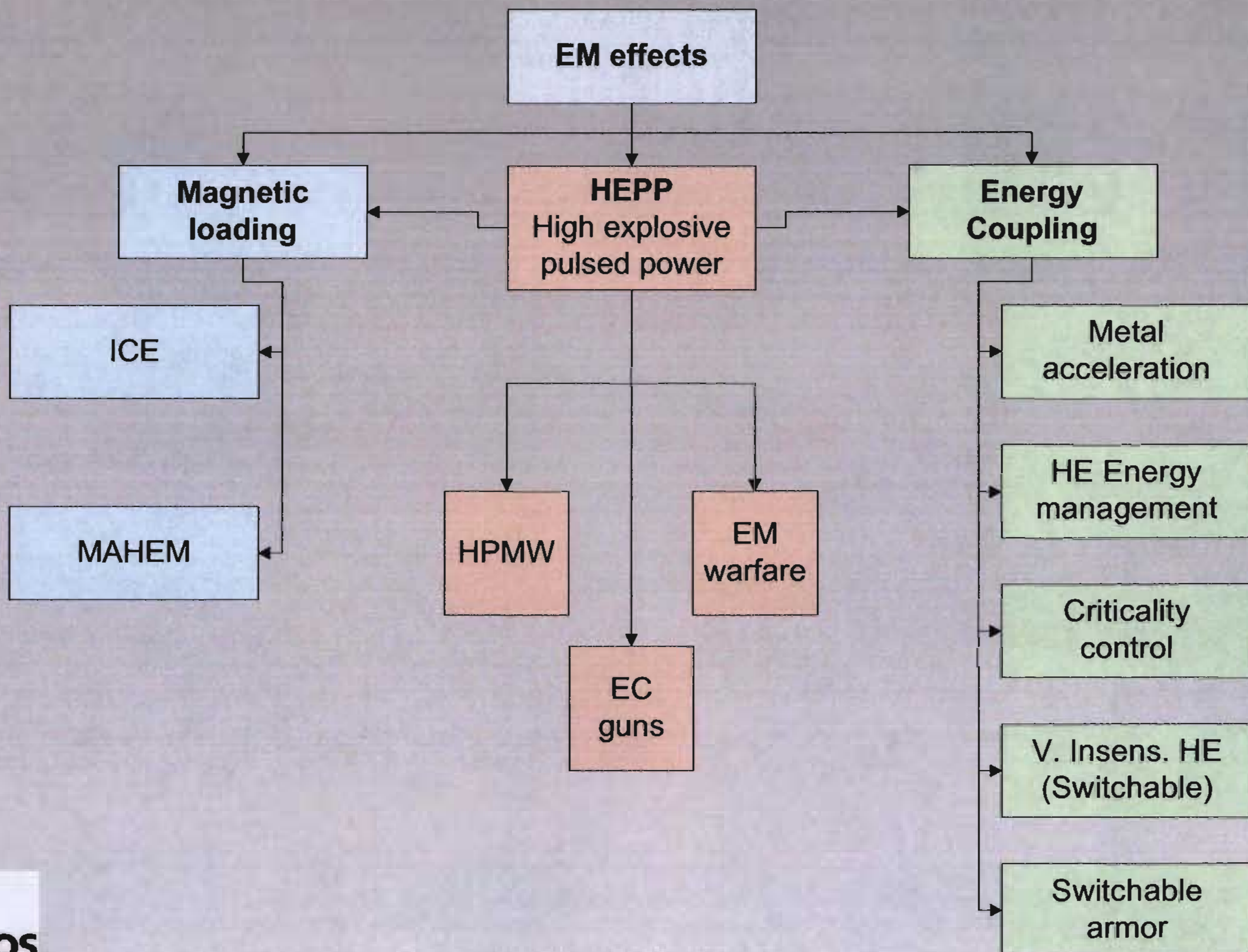
Electromagnetic Enhancement of Detonation and Its Applications

Douglas G. Tasker

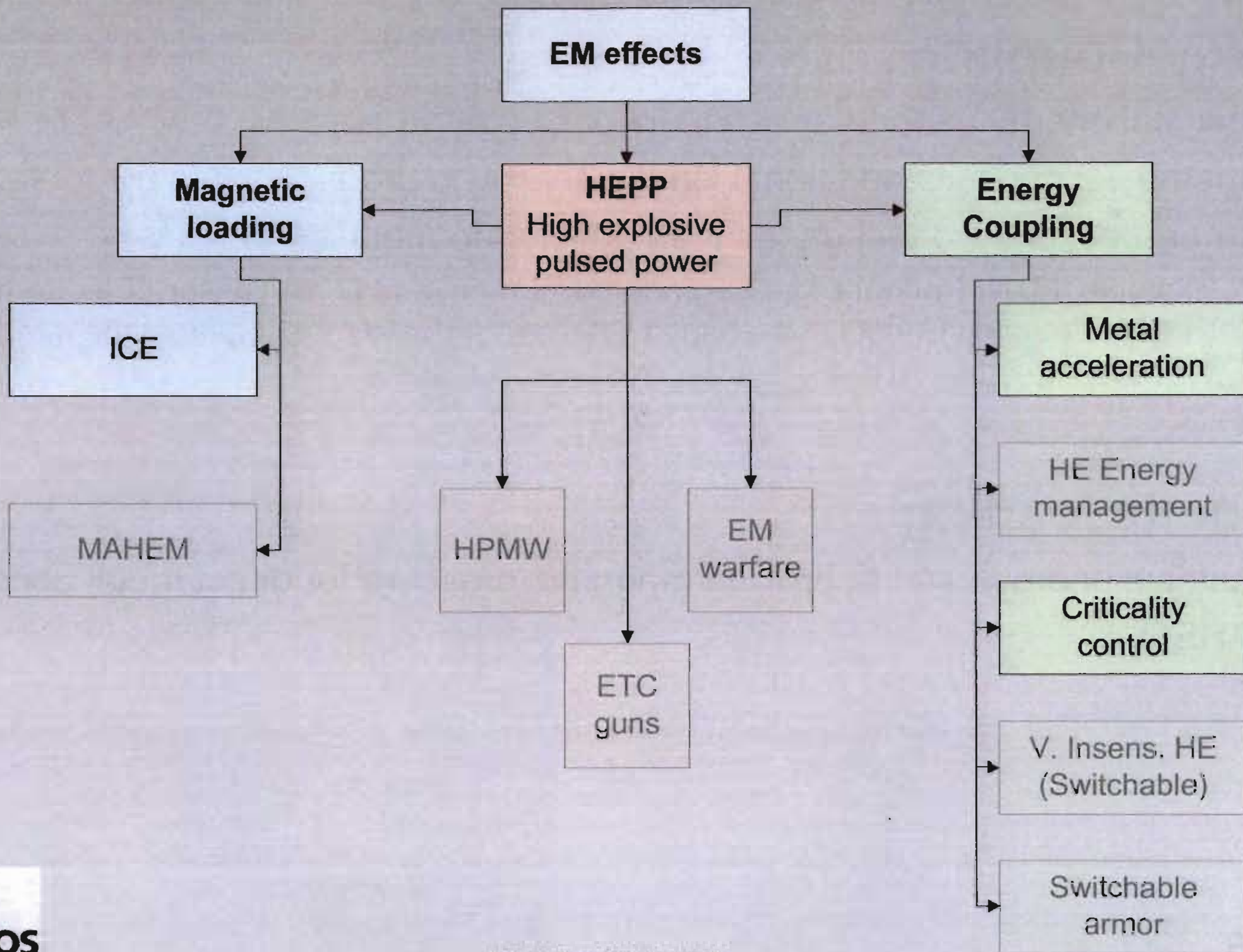
Los Alamos National Laboratory, Los Alamos, NM

April 14, 2011, ARL

Immediate family of electromagnetic effects



Today ...



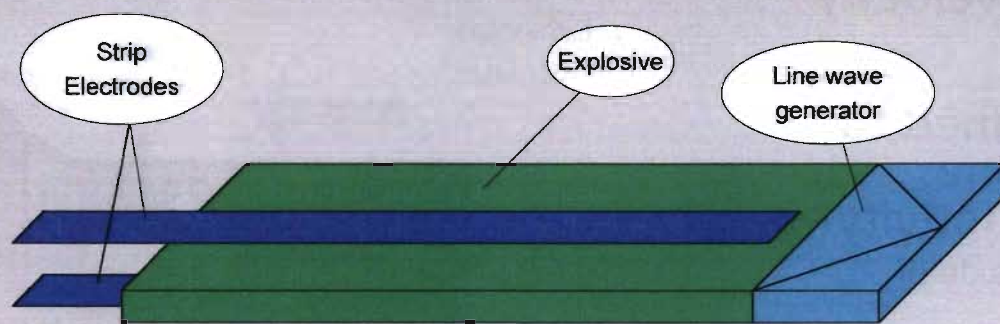
EM effects
Magnetic loading
HEPP
High explosive pulsed power
Energy Coupling
ICE
MAHEM
HPMW
EM warfare
ETC guns
Metal acceleration
HE Energy management
Criticality control
V. Insens. HE (Switchable)
Switchable armor

Electromagnetic Enhancement

- **Energy Coupling**
  - Electrical energy used to enhance explosive performance
  - Hypothesis: deposits additional kinetic energy in product gases by Joule heating
  - Higher pressure product gases then accelerate metal surfaces
    - Example, M. N. Raftenberg, G. Randers-Pehrson, and D. G. Tasker, "Electromagnetic Energy Coupling Effects in a Shaped Charge Warhead," presented at the 42nd Bomb and Warhead Meeting, ADPA, Picatinny Arsenal, NJ, 1992.

- **Magnetic loading**
  - Electrical energy used to provide magnetic pressure for direct metal acceleration
  - MAHEM
  - ICE

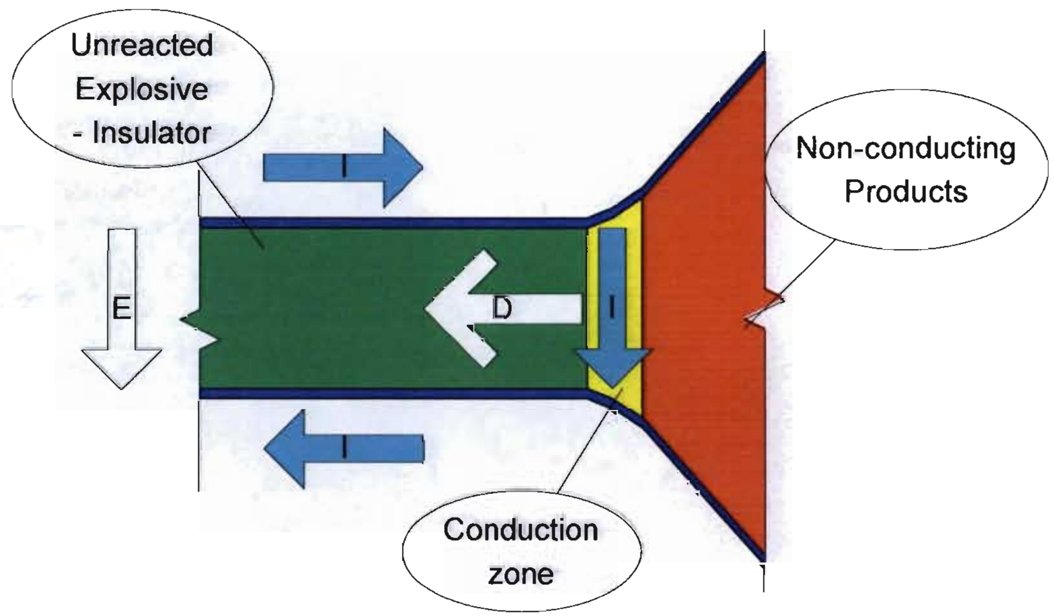
Energy Coupling



Energy Coupling

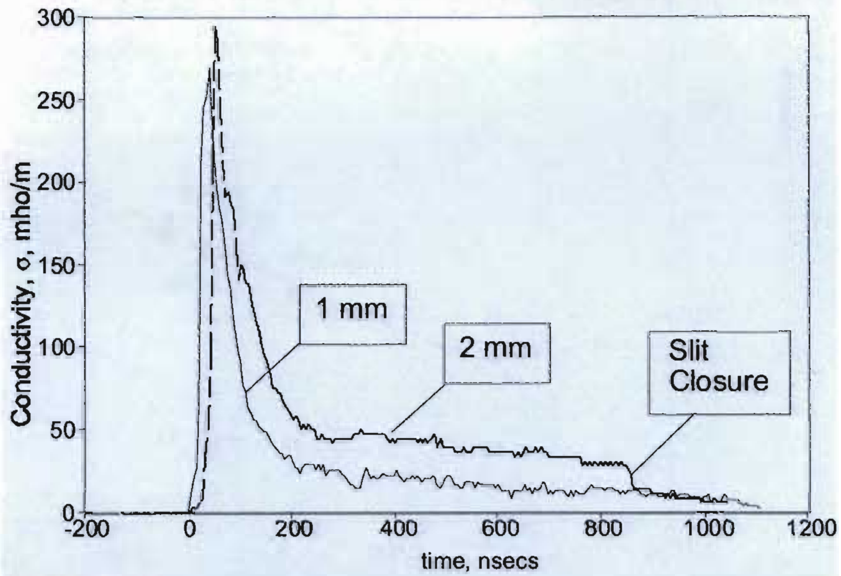
- **Concept - enhancement effects isolated between electrodes**
- **Applied <u>E</u> field normal to detonation velocity <u>D</u>**
- **Current I confined to conduction zone, width Δ, conductivity σ**
  - insulated either side of reaction zone
- **Goal: deposit sufficient <u>power</u> to enhance explosive performance**

Side view of sheet



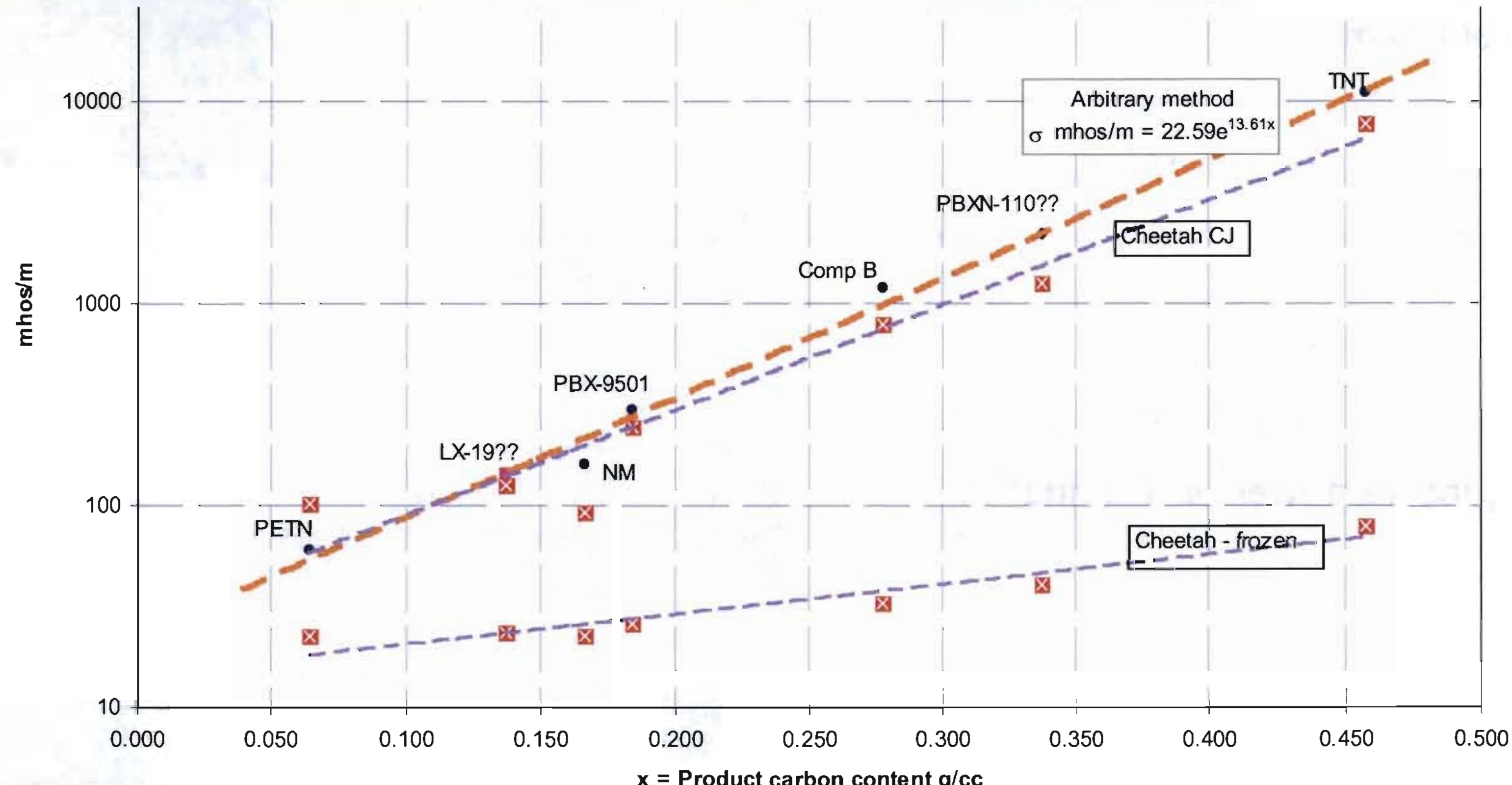
Conductivity profile of PBX-9501 – Ershov technique

- **PBX-9501 results for two sheet thicknesses (1 mm and 2 mm) σ ~ 200 to 300 S/m**
  - See Ninth Detonation Symposium, Tasker & Lee
- **Peak duration dt ~ 100 ns**
  - corresponds to conduction width Δ ~ 1 mm
  - I.e., Δ > reaction zone width (~0.1 mm) - supposedly
- **σ used to find ratio of electrical to explosive power, η. But first …**



Origins of conduction: Peak conductivity vs. carbon content

Bud Hayes (LANL) showed convincing correlation between carbon content of products and conductivity



Origins of conduction

- **We extended this work, carbon content estimated from:**
  - reaction "arbitrary" pathways

$$C_aH_bN_cO_d \Rightarrow \tfrac{c}{2}N_2 + \tfrac{b}{2}H_2O + \left(\tfrac{d}{2} - \tfrac{b}{4}\right)CO_2 + \left(a - \tfrac{d}{2} + \tfrac{b}{4}\right)C$$

    - gives carbon in vicinity of CJ plane
  - Cheetah calculations
    - give condensed carbon at CJ plane AND beyond in "frozen" state, when all reactions complete
    - show carbon is reduced by post-CJ reaction
      - as is conductivity!

- **We thus have the tools to design HEs with the right conductivity**

Enhancement, ratio of powers

- Ratio of electrical power deposited in explosive to chemical power liberated by reaction:

$$\eta = \sigma\Delta\, E^2 \Big/ \rho_0\, Q_{det} D$$

  - Denominator = Explosive power ~10^{14} W /m^2

- Conductivity - conduction width product $\sigma\Delta$ of explosive detonation products - or $\int \sigma(x).dx$

- E_{br} Dielectric strength of unreacted explosive, 17 - 40 kV/mm

  - measured in parallel plate configuration

Maximum enhancement and other limits

	ρ_0 kg/m^3	Q_{det} MJ/kg	D m/s	$\sigma\Delta$ max mhos	E_{br} MV/m	η
PBX-9404	1840	5.94	8800	2	19	7.51
PBX-9501	1840	6.03	8830	2	19	7.37
PBX-9502	1900	4.18	7710	10.2	40	**267**
PBXN-110	1680	5.68	8391	2.7	17	9.75

Limited by magnetic effects

- Large enhancement possible, η = 7 to 267
  - Maximum η ultimately limited by magnetic instabilities.
  - Above ~½ MA/cm, the duration of the current pulse must be limited to wave transit time in conductors
    - At 1 MA/cm, magnetic pressure $P_B = 2\pi$ GPa (63 kbar)
    - In HEPP-ICE we approach 20 MA/cm

$$P_B = B^2/2\mu_0 \quad \text{where } \mu_0 = 4\pi \times 10^{-7}$$

$$P_B = \tfrac{1}{2}\mu_0 \left(\frac{I}{w}\right)^2$$

Predicted performance enhancements

- **Several methods have been used**
  - e.g., see Cowperthwaite, Ninth Detonation Symposium
  - Assume Joule heat indistinguishable from heat of reaction
  - Detonation enhancement depends on position of conduction zone relative to CJ plane
- **Modified Kamlet method (Seventh Detonation Symposium) :**
  - Uses "arbitrary" to calculate gas product volume and mass
  - Obtain Φ, based on: number of gram moles of gas products, N; mean molecular wt., M; heat of detonation Q

$$\Phi = N M^{1/2} Q^{1/2}$$

$$D = 1.01 \Phi^{1/2} (1 + 1.30 \rho_0)$$

$$P_j = 15.58 \rho_0^2 \Phi$$

Performance predictions with Kamlet EOS

- Substitute enhanced $Q' = Q(1+\eta)$, then …

$$D' = D(1+\eta)^{1/4}$$

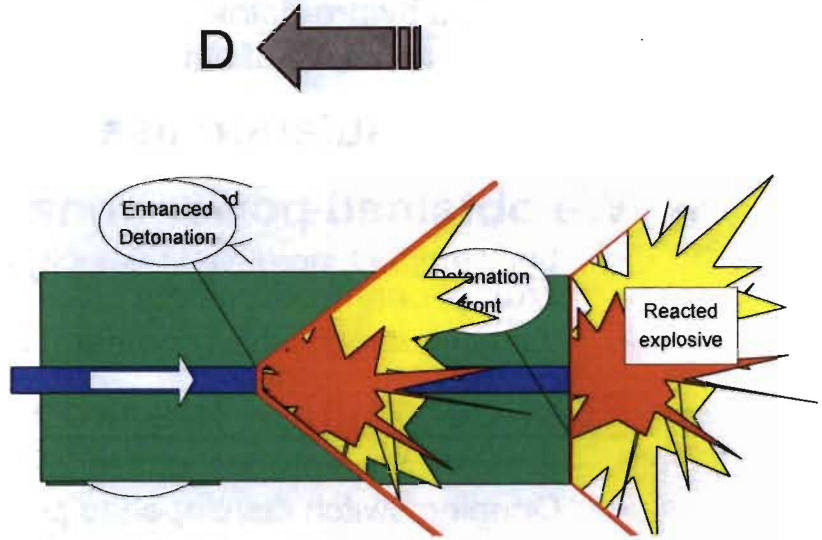
$$P_j' = P_j(1+\eta)^{1/2}$$

- For $\eta = 7$, $D'/D \sim 1.7$, $P_j'/P_j \sim 2.8$
  - *Velocity estimates may be too conservative*
- Note that if most of the electrical energy is deposited behind CJ (sonic) plane, then increase in D and P will be greatly reduced
- BUT by energy conservation, gas products in Taylor wave must be more energetic by a factor of $1+\eta$
- AND enhanced gas products will do more work!

Measurement of enhanced detonation velocity – transverse field

Experiment

- **Transverse experiments with streak camera**
  - Electric field E normal to velocity vector D
  - Capacitor bank energy source, 20 kV, 3 mF (not shown)
  - Explosive sheet 1 - 2 mm thick (thin to maximize E field)
  - Streak camera follows shock progress along electrode



E-field into paper

Measurement of enhanced detonation velocity, transverse field - 2

- **Breakdown limits power enhancement**
  - Caused by pre-detonation breakdown in explosives
  - Finite probability of obtaining small flaw in large area sheets of explosive
- **Kapton insulation used to correct problem**
- **We obtained power enhancement η ~15% in PBX-9501**
  - Only modest increase in velocity observed (~3%), close to predictions yet comparable with error of our measurement
  - Jaimin Lee published comparable enhancement … next slide
- **Post-detonation breakdown**
  - Breakdown in product gases 20 to 30 mm behind front
  - Opening switch developed to prevent breakdown
    - disconnected electrodes 20 mm behind front
  - Experiment became too complex
  - Results with streak camera and fiber optics
- **Method abandoned in favor of longitudinal field approach**

Other experimental enhancement studies suggest modified Kamlet equation too conservative

- Transverse enhancement study reported at APS SCCM, Snowbird, UT, June 1999
  - "Enhancement of Detonation Properties by Electrical Energy Input," Jaimin Lee, Jeong-Hyun Kuk, Chun-Ho Kim, and Eul-Ha Hwang
- D enhanced by 2.7 to 10.4% (η ~22% - my estimate) in sheet explosive
  - From Modified Kamlet equation we would expect D enhancement of 5%
  - From our work, sheet explosive (Detasheet C) conducts primarily behind CJ-plane
    - We did not expect such a significant change in D

Breakdown problems in transverse experiments

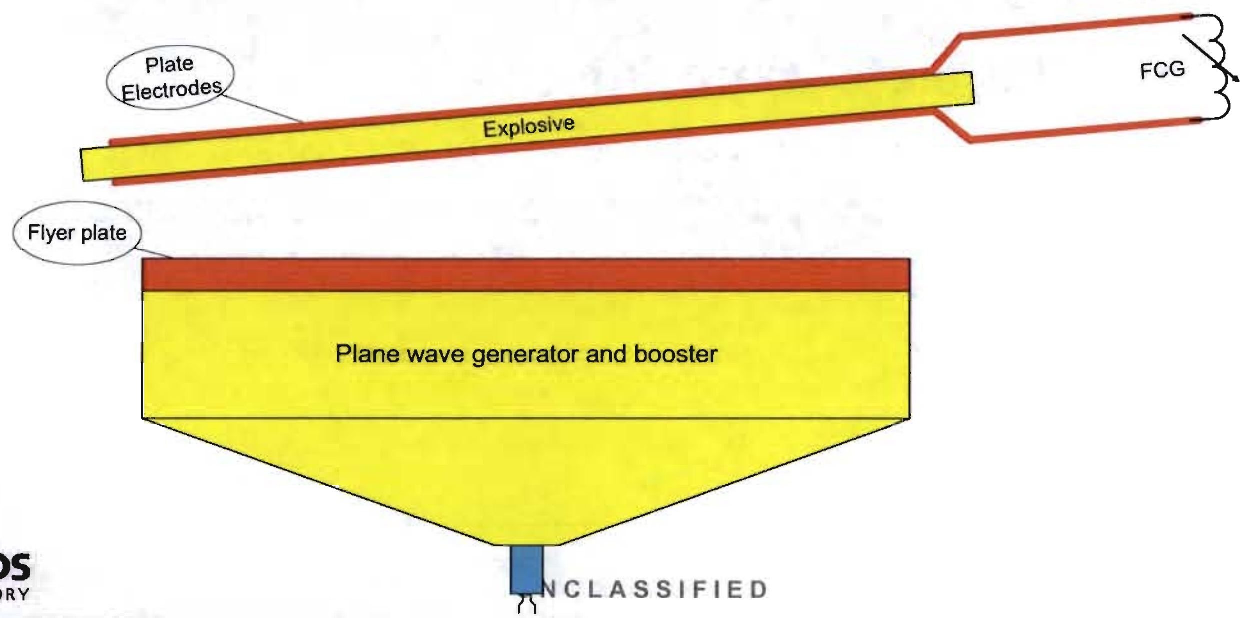
- **Pre-detonation breakdown**
  - Successfully corrected with Kapton
  - Useless after detonation
- **Post-detonation breakdown occurred 2 to 3 μs behind front**
  - Successfully corrected with plasma opening switches
  - Complexity of pulsed power system impeded measurement of detonation velocity
- **Parallel field experiments**
  - Can be performed in < 2 μs
  - Post-detonation breakdown avoided

Measurement of metal acceleration - parallel field

- **Avoids problems of post-detonation breakdown by limiting duration of experiment, < 2 μs**
- **Necessitates rapid transfer of electrical energy**
  - must transfer current within ~2 μs vs. ~20 μs for transverse method
  - hence FCG system used instead of capacitor bank and opening switch to enable rapid current transfer
- **Inclined parallel plate experiments**
  - angle of impact (3° to 4°) - facilitated electrical power transfer in ~2 μs
  - top plate velocity measured by flash X-ray technique with and without energy enhancement

Parallel plate flyer experiment

- **Flyer plate detonated explosive sheet on impact**
  - velocity ~1600 m/s
  - detonation phase velocity (left to right) ~20 to 30 mm/μs
  - electrodes 70 mm wide, explosive PBX-9501, 2 mm thick
- **Pulsed power system details (shown later) included:**
  - FCG, storage inductor, explosively formed fuse opening switch

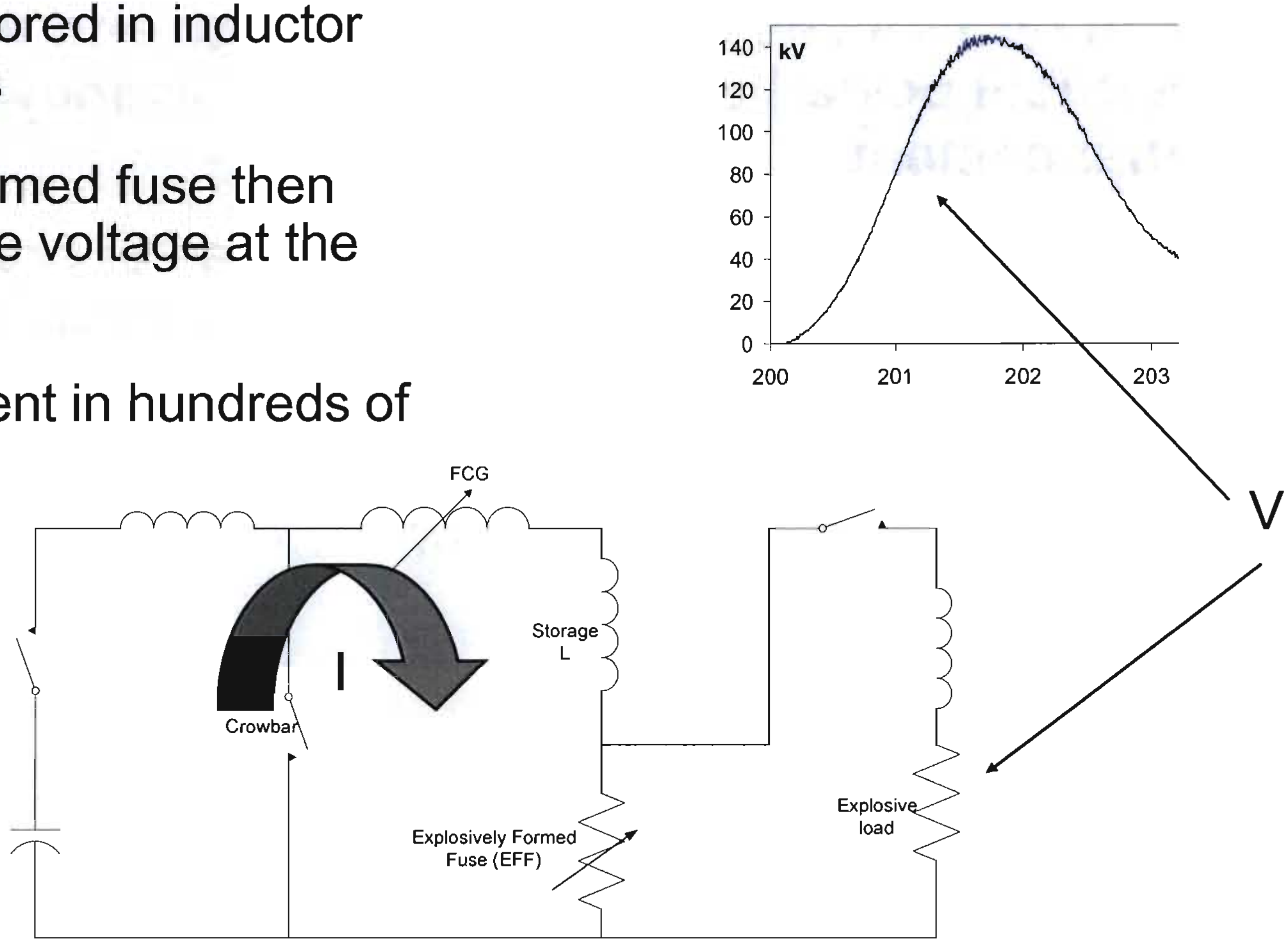


Parallel plate flyer experiment - results

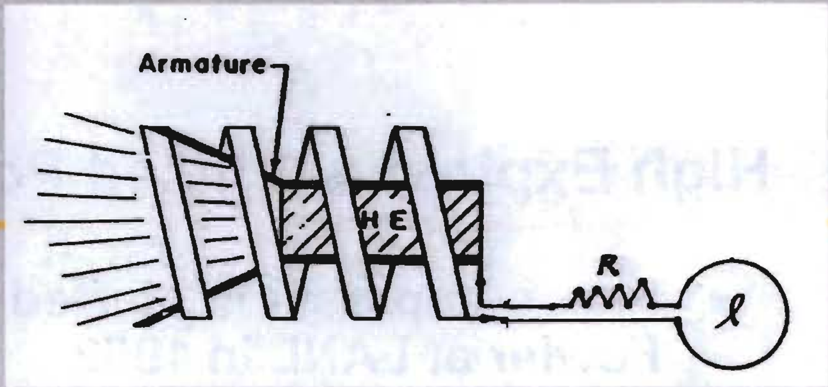
- **From differences in top plate KE (with and without electrical power) could determine efficiency of enhancement**
- **Assumed equipartition of product gas energy - up and down - i.e., 50 % of electrical energy enhances top plate**
- **Powers measured:**
  - Max change in plate KE / sec = 11.2 ± 0.5 GW
  - Electrical input at same time = 20.0 GW
- **Efficiency ~ 56%**
  - close to expected 50%
- **Results clearly demonstrated enhancement**
  - Energies consistent with expected performance

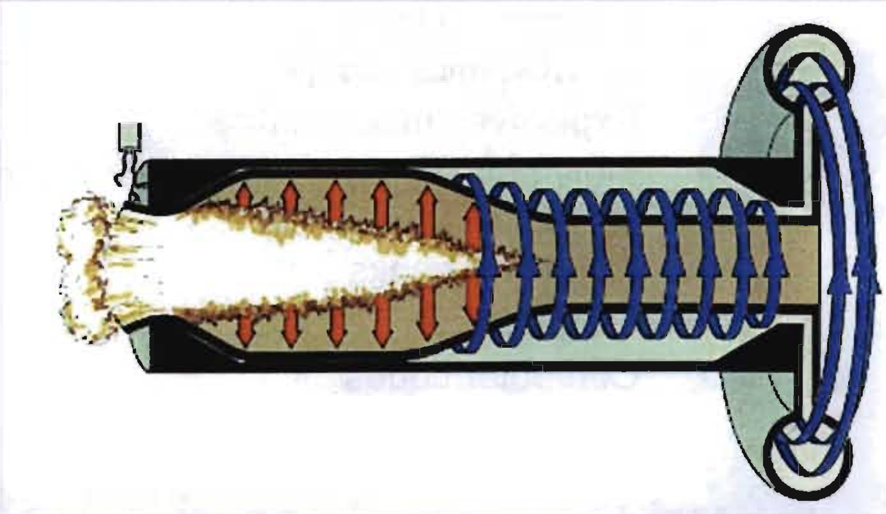
Typical High Explosive Pulsed Power (HEPP) circuit

- MA currents stored in inductor over tens of μs
- Explosively formed fuse then generates large voltage at the right time
- Transfers current in hundreds of ns to a few μs



Flux Compression Generators

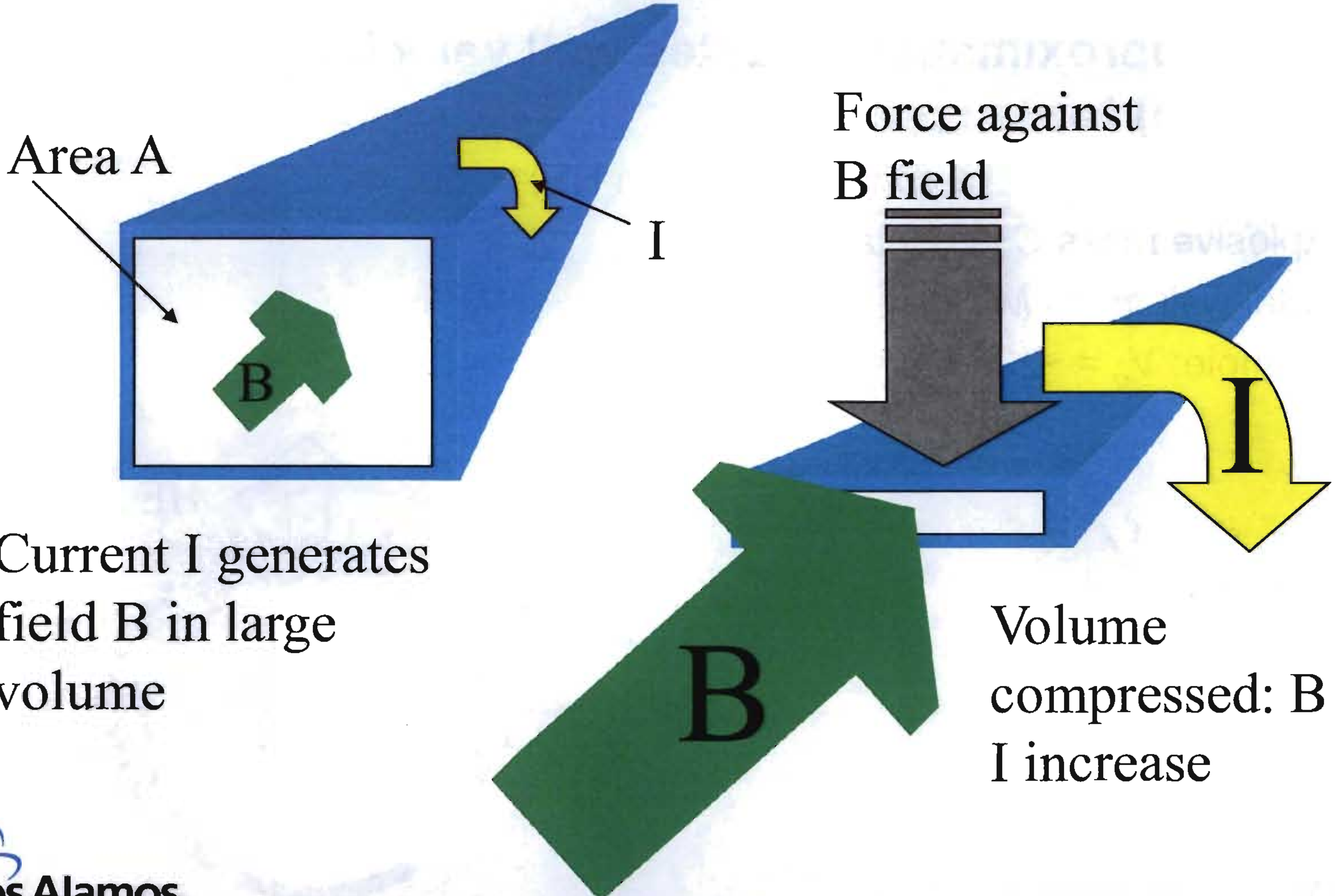




High Explosive Pulsed Power at LANL

- **Flux compression started by Max Fowler at LANL in 1952**
- **LANL has complete suite of capabilities**
  - Many generators from the small (100s kA) to the large (100s MA)
    - Risetimes ~50 μs to ms
  - Explosive opening switches for high voltage and fast current transfer
    - Risetimes ns to μs
  - Explosives manufacture
  - Multi-point slapper arrays for cylindrical or planar initiation
  - Capacitor banks
  - Diagnostics
  - Computer codes
  - ...

Basic flux compression generator (FCG)



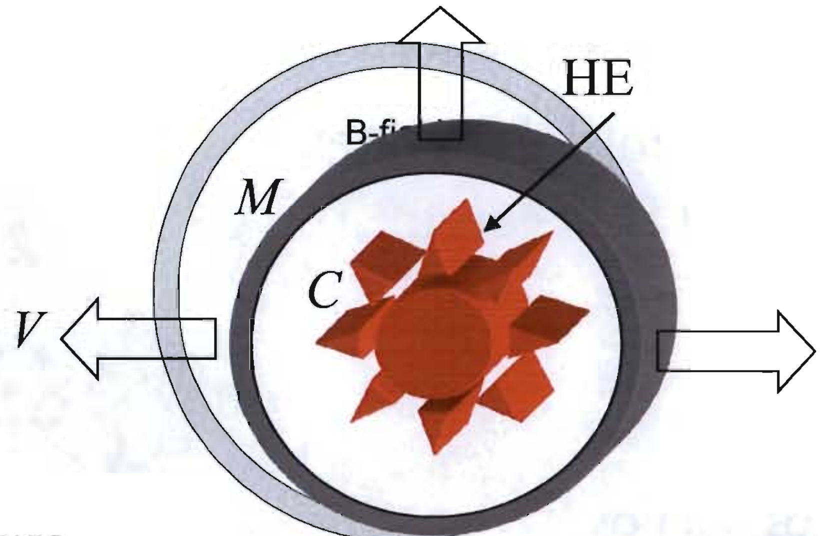
Current I generates field B in large volume

Volume compressed: B and I increase

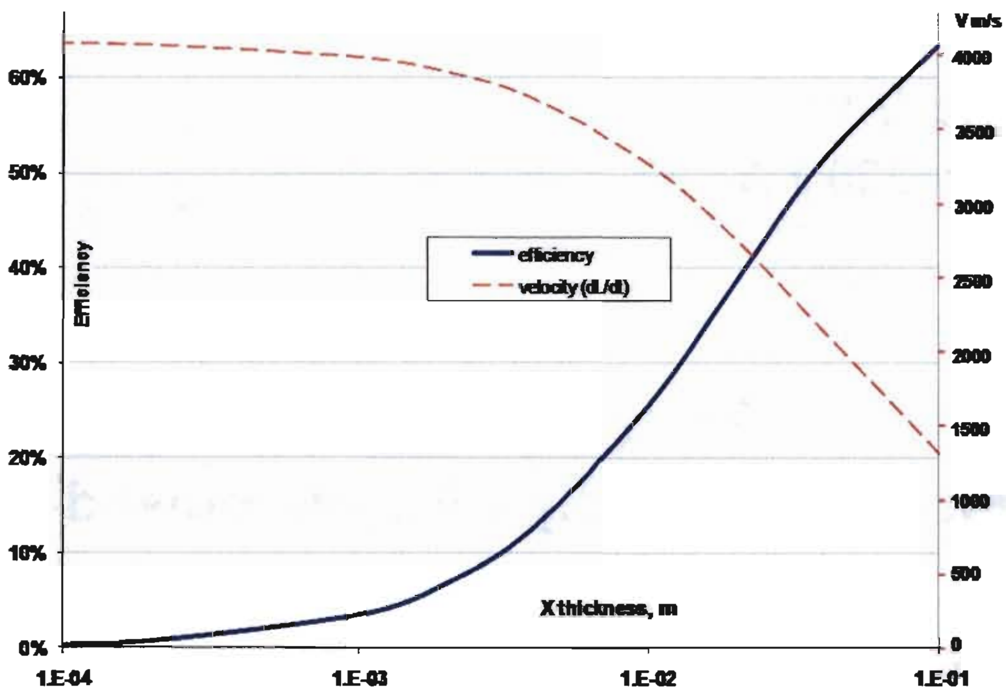
Velocity of HE-driven cylinder: Gurney equation for long cylinder

- **Gurney approximation equates wall velocity (@~2 times expansion) to:**
  - Gurney velocity V_g (a const. for a given HE)
  - explosive mass C in contact with wall
  - metal wall mass M
  - Example: V_g = ~2900 m/s - PBX-9501

$$V = \frac{V_g}{\sqrt{\frac{M}{C}+0.5}}$$



HE Energy efficiency vs. wall thickness

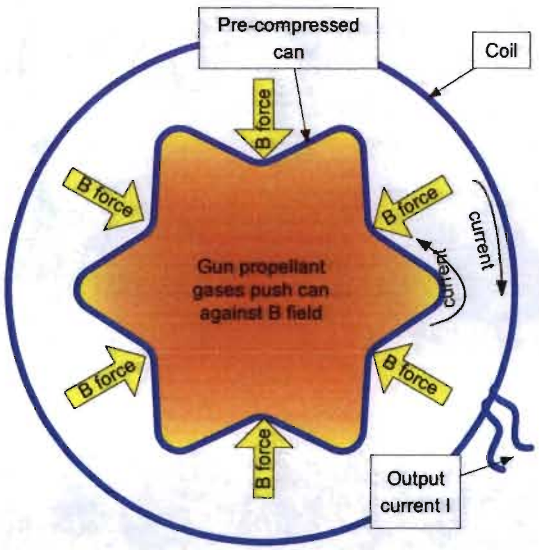


- Armature driven by PBX-9501 (95% HMX)
- *V* falls as *x* increases: 4100 m/s (*x*=0) → 0 (as *x* → ∞)
- **From plate velocity can obtain KE ...**
  - **Efficiency *rises* with x**
  - Range: 0 → 70% (as x → ∞)
    - 3.55% (4 km/s) @ 1 mm
    - **25% (3.28 km/s) @ 10 mm**
  - Trade-off: velocity (dL/dt) vs. efficiency
  - **High efficiency easily achieved**
    - **if that's important**
  - Energy per unit volume is key!!!!!
  - Explosives have very high energy densities
  - **Procyon generator - 18 MJ electrical energy from 100 lbs HE → 7% efficient**

FCGs = Compact, high energy density sources

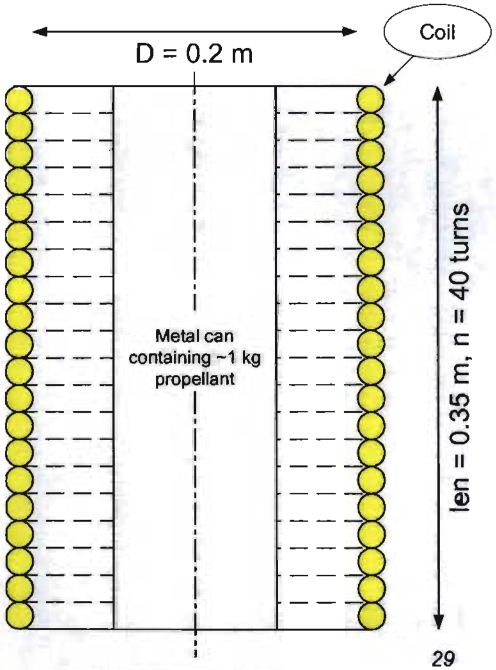
- **Explosive energy density =~11 GJ/m^3**
  - 5944 J/g, 1820 kg/m^3
- **FCG electrical energy ~ 1 GJ/m^3**
  - (Electrical power ~ $10^9/5\times10^{-6}$ = 200 TW/m^3)
- **Capacitor banks for comparison-**
  - Atlas - 24 MJ in ~5000 m^3 → ~ 5 kJ/m^3
  - Inflexible; experiments must be designed around bank
- **FCG cost ~$30K/shot compares favorably with any pulsed power system**
- **……. And what could be more fun?**

Propellant driven FCG (concept)



Drop in a mortar and fire

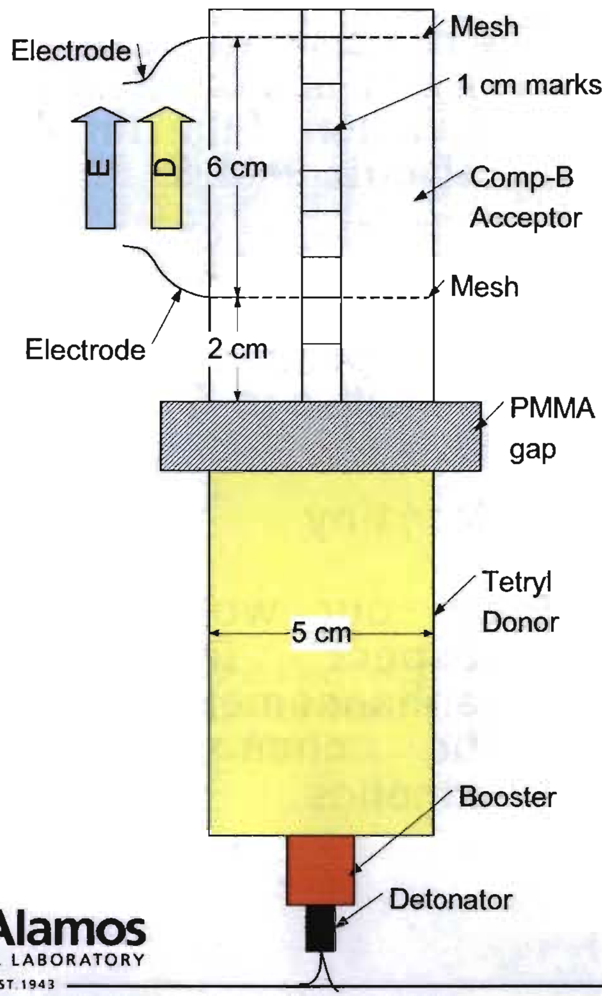
- Problem: Explosive FCG produces shrapnel
- Cannot be used in urban environments, e.g., for counter IED applications
- Solution: Reusable propellant driven system
- Other applications might include ETC gun



Criticality and reactivity control

- **Cook's experiments**
  - Applied E-field modifies run distance to detonation
- **Richard Lee's experiments**
  - Applied E-field controls extent of shock induced reaction
- **Salisbury's experiments**
  - Applied E-field controls failure thickness
  - We duplicated the effects at LANL

Mel Cook's electrical control of SDT*

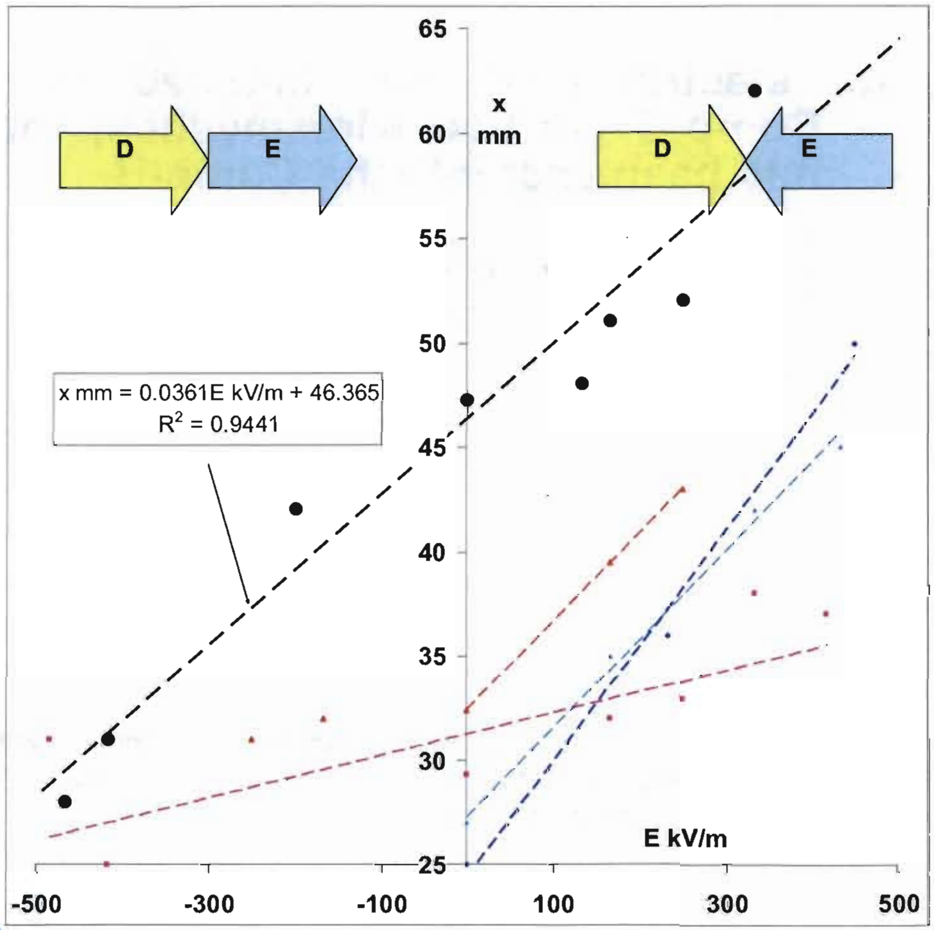


An electric field was induced in the Comp-B via two wire meshes; these had been cast into the Comp-B.

Run-distance to detonation observed as function of electric field E

*Melvin A. Cook and Tim Z. Gwyther, "Influence of electric fields on shock to detonation transition," Utah Univ. Salt Lake City, Utah, 28 Sept 1965, AD62923.

Cook's results



The run distance to detonation, x mm, is plotted as a function of the initial electric field, E

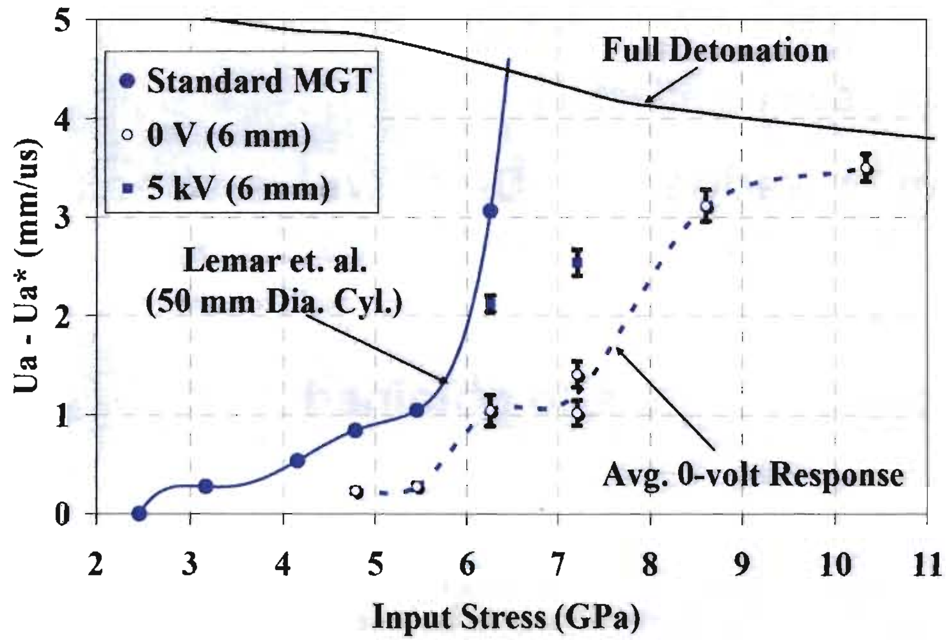
When initiation pressure is in the optimum range, x is sensitive to E.

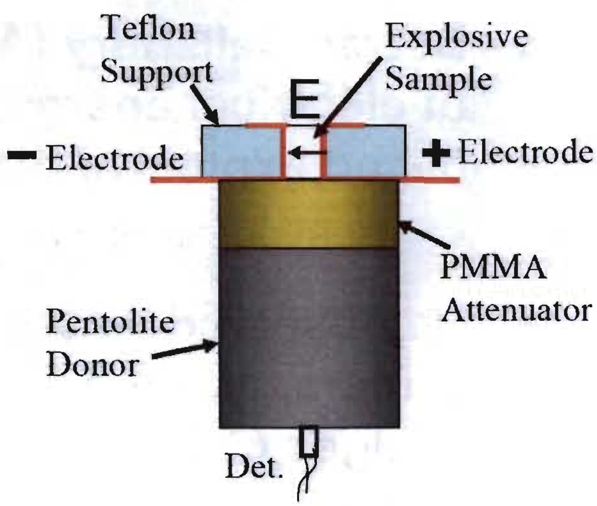
Note: η tiny

From our work would not expect to see an enhancement effect. Must be changing reaction kinetics.

E-field effects on modified gap test, Lee*

- **Transverse electric field effect on initiation and growth in HMX-**





- "…higher levels of reaction obtained with less input stress when voltages of 5 kV were applied across the 6 mm sample …" compared to zero field.

- * Lee, R.J., et al., "Effect of electric fields on sensitivity of an HMX based explosive," *SCCM- 2007*, pp. 963-966.

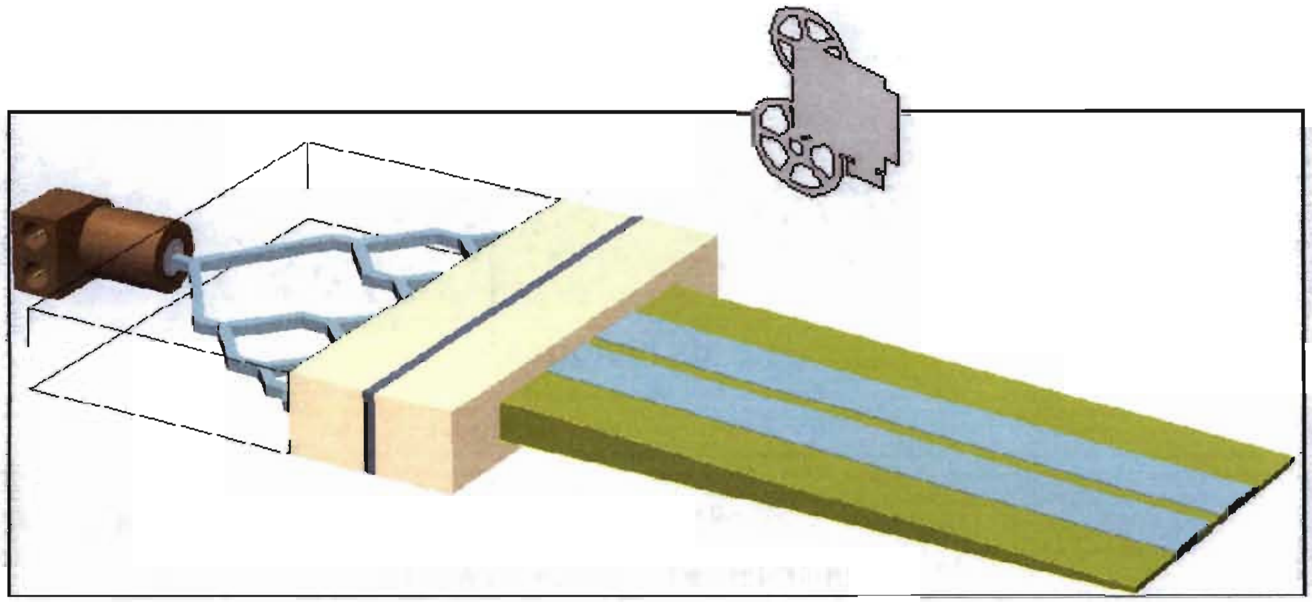
Salisbury – Electrical control of failure

- **Darren Salisbury (AWE, Aldermaston) presented work on the effect of electrical energy on detonation failure in wedges of the TATB-based explosive EDC35 [i]**
  - From our work, would not expect to see an effect [ii].
- **He observed wave propagation in wedges of EDC35 with a streak camera, and reported that they could reduce the failure thickness in wedges of EDC35 by applying an electric field.**
- **We (LANL) performed similar experiments and obtained comparable results**

[i] D. Salisbury, et al., "A study of the effect of electrical energy input on detonation failure in wedges of the TATB-based explosive EDC35," APS Shock Compression of Condensed Matter (SCCM) Conference, Baltimore, MD, USA, 2005.

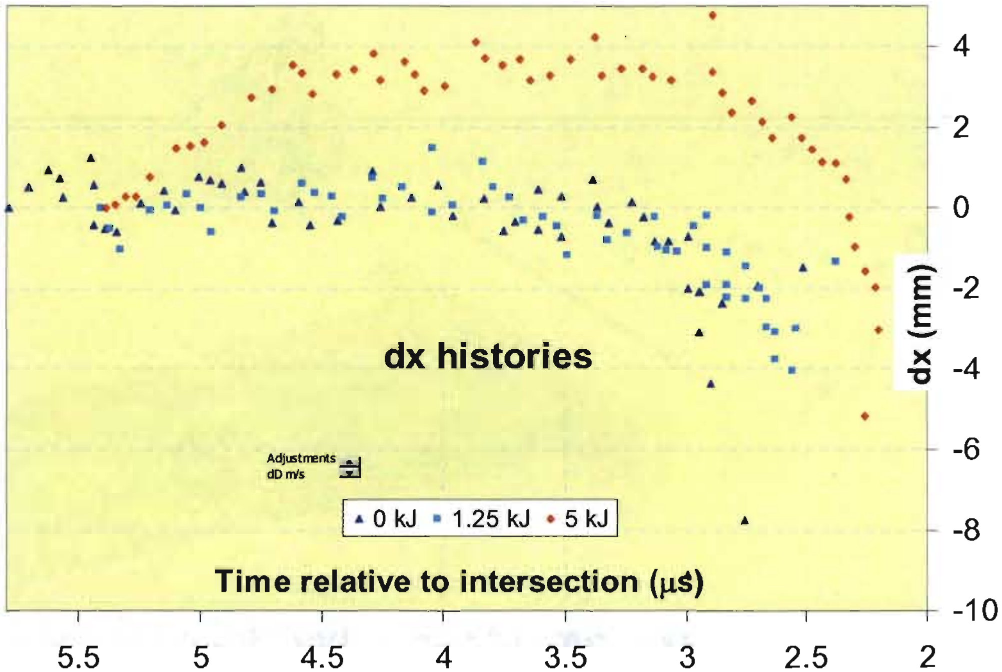
[ii] Tasker, D. G. and Lee, R. J., "The Measurement of Electrical Conductivity in Detonating Condensed Explosives." 9th International Detonation Symposium, 1989

AWE experiment



- Schematic of EED experiment assembly, 3mm slit for, streak view, Line initiator, Assembly, EBW detonator, 10-mil Al electrodes, Kapton insulation
- EDC35 – close match to PBX-9502. Wedge 6 mm to 1 mm over 100 mm; 50 mm wide; angle 3°
- Top & bottom electrodes connected to capacitor bank

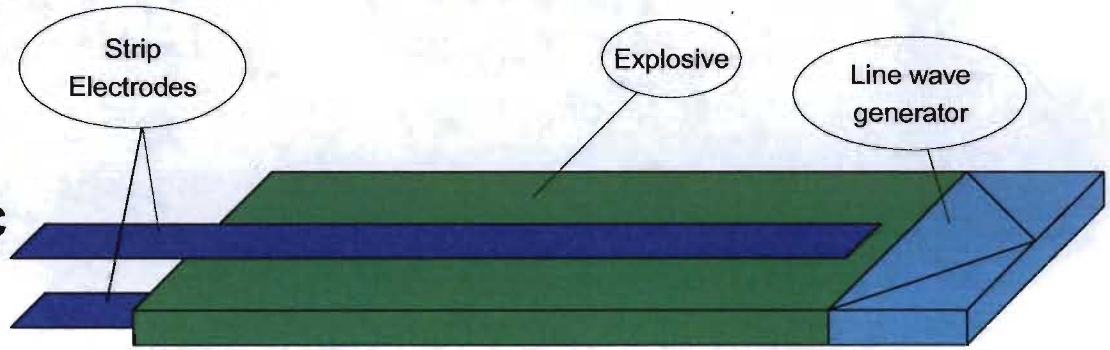
Analysis of AWE data

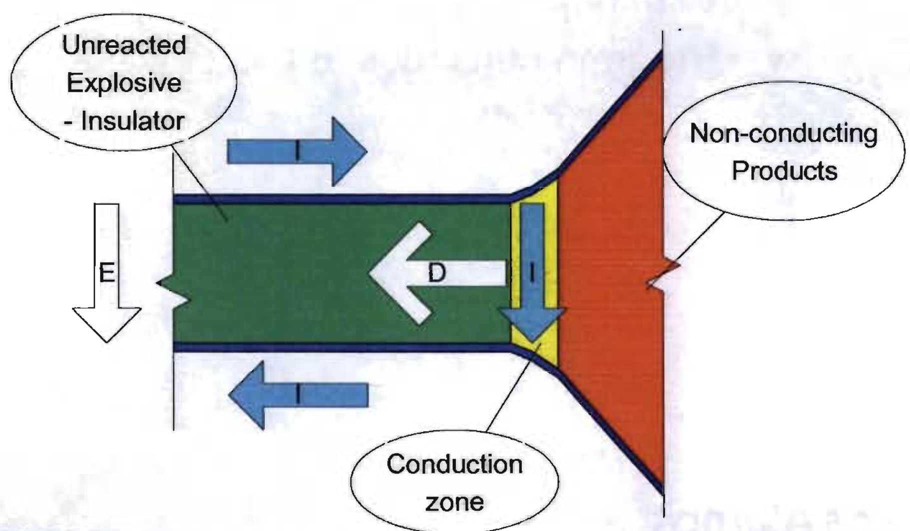


- Winter compared x-t plots with baseline (7415 m/s)
- 5 kJ line clearly failed later
- "… results of this experimental study suggest that the failure width of an explosive can indeed be reduced by adding external energy via electrical means."

Switchable explosive / Electric armor

- **Use explosive sheet armor that cannot detonate without the application of electric field - "switchable"**
- **Example: use TATB based explosive below its failure thickness**
- **Application of electric field allows it to detonate**





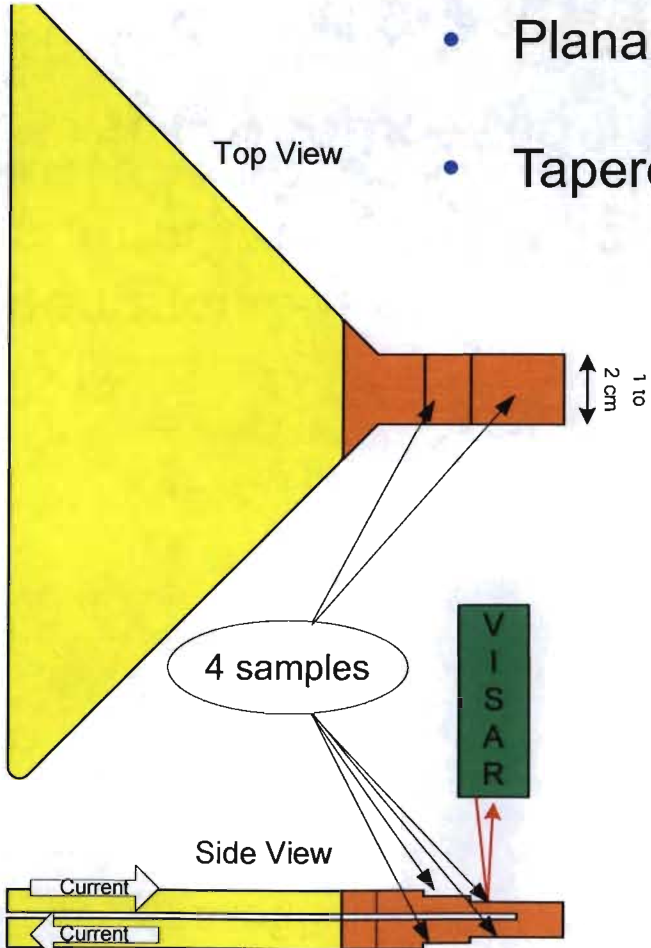
Direct magnetic loading

- **Isentropic Compression Experiments**
  - Explosive ICE first performed around 2000 at LANL
  - Magnetic loading theory
  - Limitations for weapon effects
- **MAHEM**
  - Started at NSWC White Oak by Jules Enig and Jay Pastine in early 80s
  - Experiments performed at White Oak and LANL in late 90s
  - Program continues to this day

HEPP-ICE

- **Must transfer current densities of >~5 MA/cm**
- **Transfer times ½ to 2 μs ideal, perfect for HEPP**
- **Experiment must be completed before rarefactions from back faces of conductors return to rip the conductors apart**

HEPP ICE load section



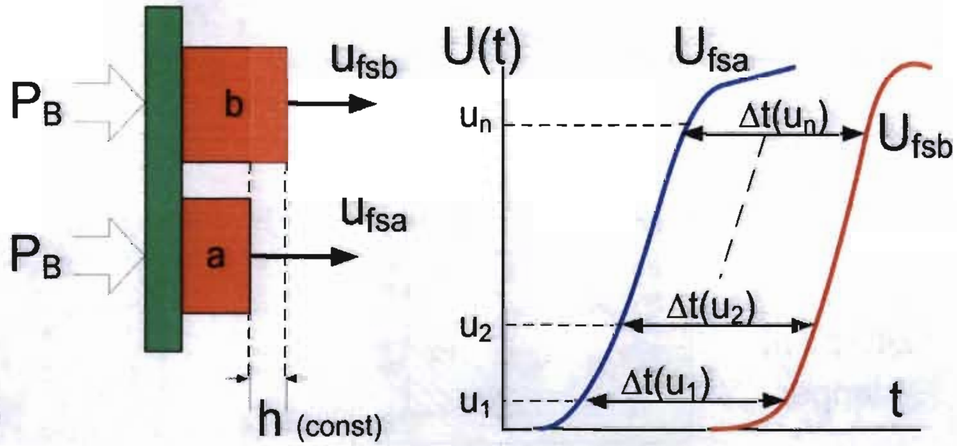
- Planar design (not coaxial)
- Tapered to minimize inductance

HEPP-ICE gap exaggerated, is ~ ½ mm

EOS data recovery – standard method

- **2 or more sample thickness compressed in each experiment**
  - Note: Magnetic pressures (P_B) must be equal so B-field(s) MUST be uniform
- **VISARs used to measure surface velocities at back faces**
  - with or without windows
- **Lagrangian analysis gives stress* etc., with *h* = constant**

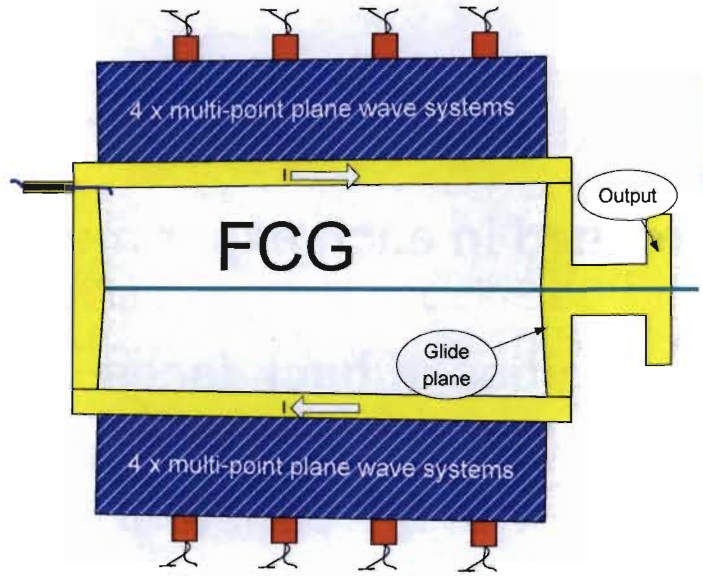
$$c_L(u) = \frac{h}{\Delta t(u)} \qquad d\sigma = \rho_0 c_L(u) du \qquad c_E = \left(\frac{\rho_0}{\rho}\right) c_L$$

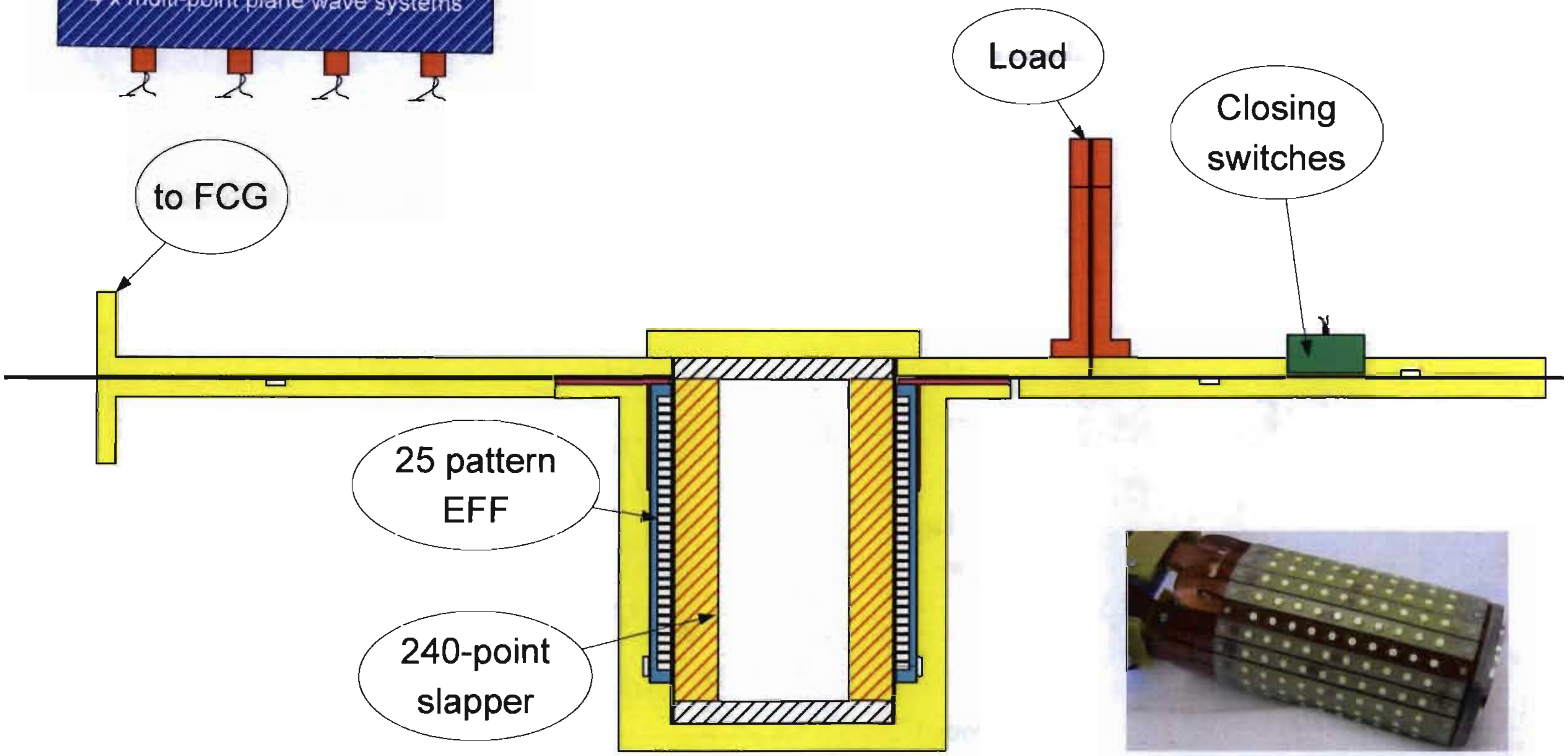


•*Pressure (P) is mean stress. $\sigma_x = P + 4/3\tau = P + 2/3\ Y_0$ above yield (τ - shear stress, Y_0 - yield strength)

HEPP-ICE schematic

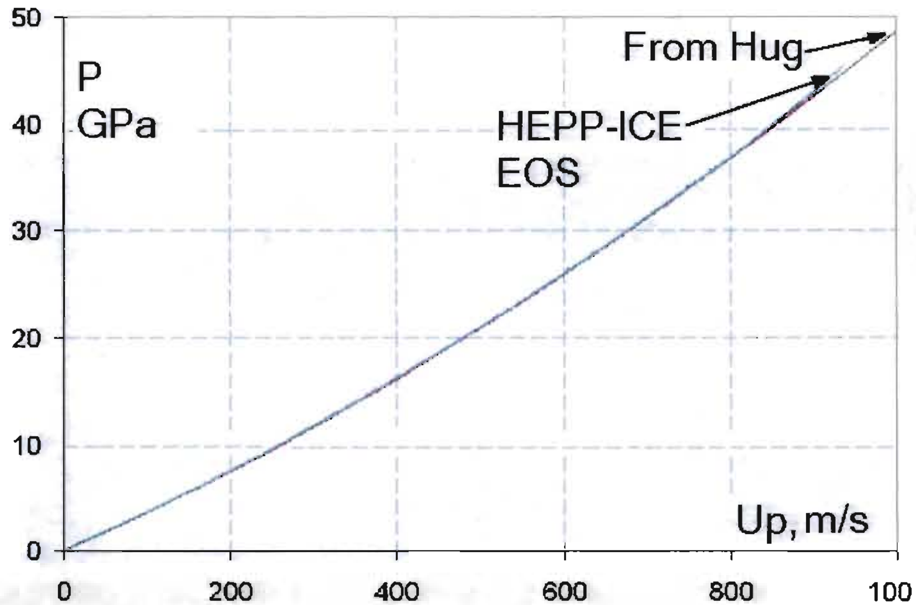
EFF explosive is a hollow tube instead of a solid cylinder



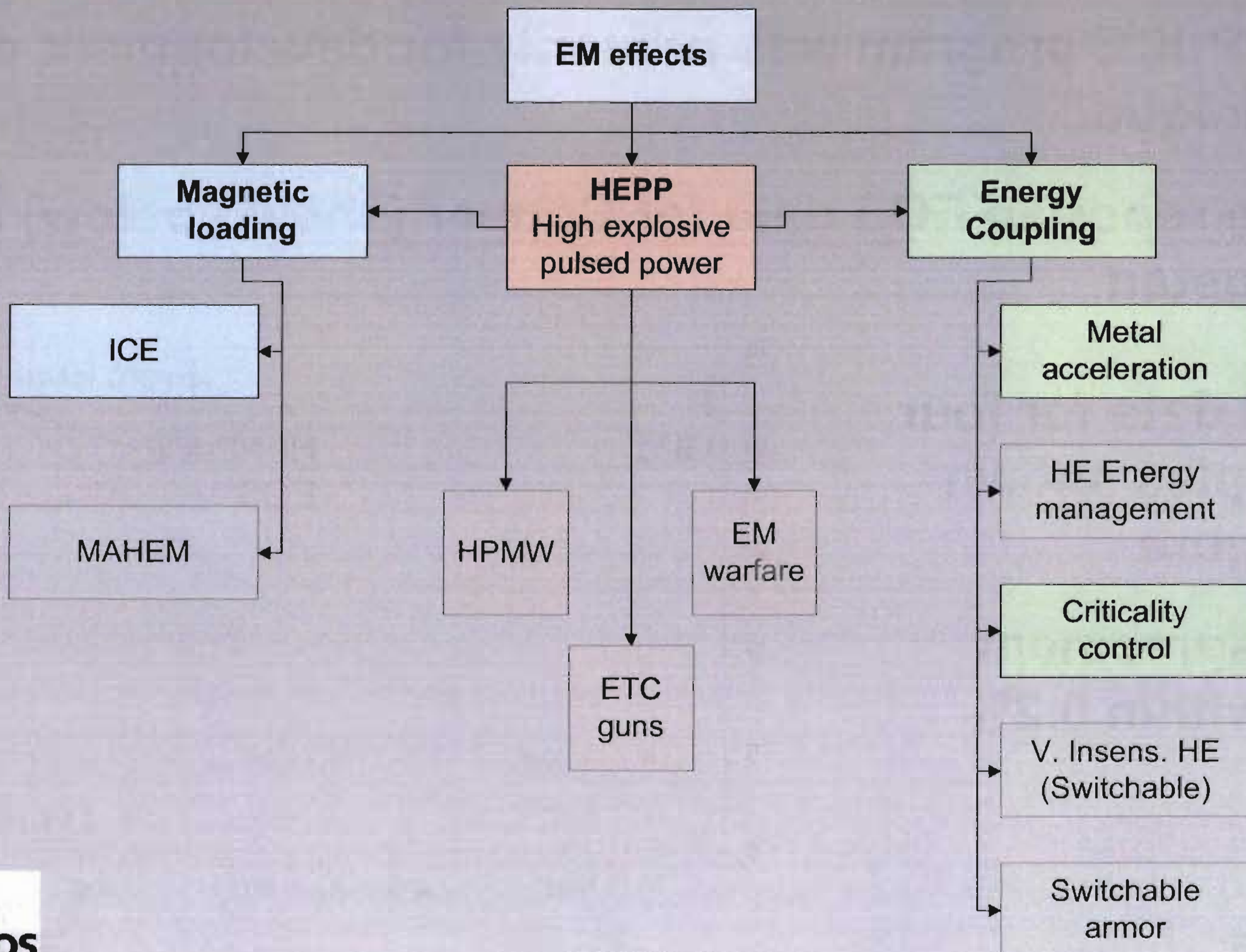


EOS Results

- **HEPP-ICE program was primarily for development of technique**
- **Have reported EOS data for Copper (shown below) and Tungsten**
- **EOS data for four samples shown in figure**
  - **Agreement within 0.2%**



Today we saw the following...

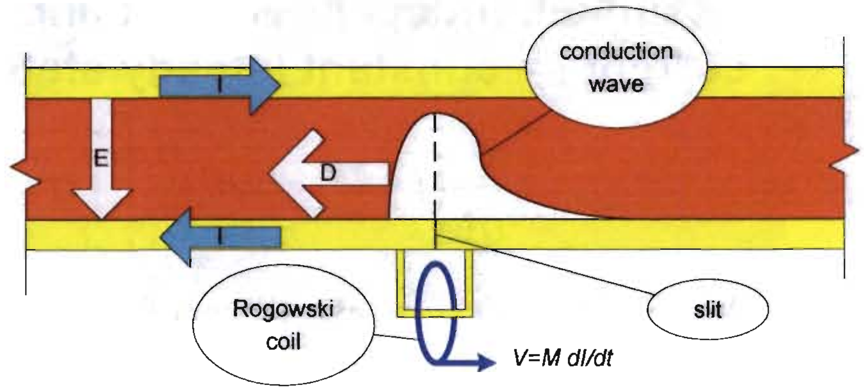


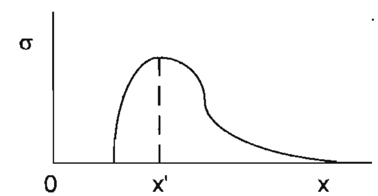
Summary

- **Work showed energy coupling to detonation zone viable but challenging**
  - large enhancements possible
- **Conductivity studies show interesting correlation with chemistry**
  - deserves further work
- **Whatever the application, flux compressors are adaptable, energy-dense, electrical sources**
- **Electrically controlled criticality experiments show feasibility of switchable HEs**
- **Magnetic drive techniques (ICE, MAHEM) can produce very high pressures (Mbar) but are limited in time duration**
  - HEPP-ICE experiments produce high quality, high pressure EOS data

Backup material

Ershov conductivity experiment





- **Current to left of slit (for width w)**

$$I_L = w\int_0^{x'} \sigma(x)\, E(x).dx$$

- **Can show**

$$\sigma(t) = \frac{V(t)}{wMDE}$$

Ershov theory

- **Assume E independent of x and t, narrow slit, and total current I = constant (steady state)**

$$\frac{d}{dt}(I - I_L) = wE\frac{d}{dt}\left[\int_{x'}^{\infty}\sigma\ (t).dx\right] = wE\sigma\ (t)\frac{dx}{dt}$$

- But *dx/dt* = *D* (constant), so Rogowski output becomes:

$$V(t) = M\,{d(I - I_L)}/{dt} = wMDE\sigma\,(t)$$

  - Here M is the mutual inductance between Rogowski coil and electrode

$$\sigma\,(t) = \frac{V(t)}{wMDE}$$

Denominator constant

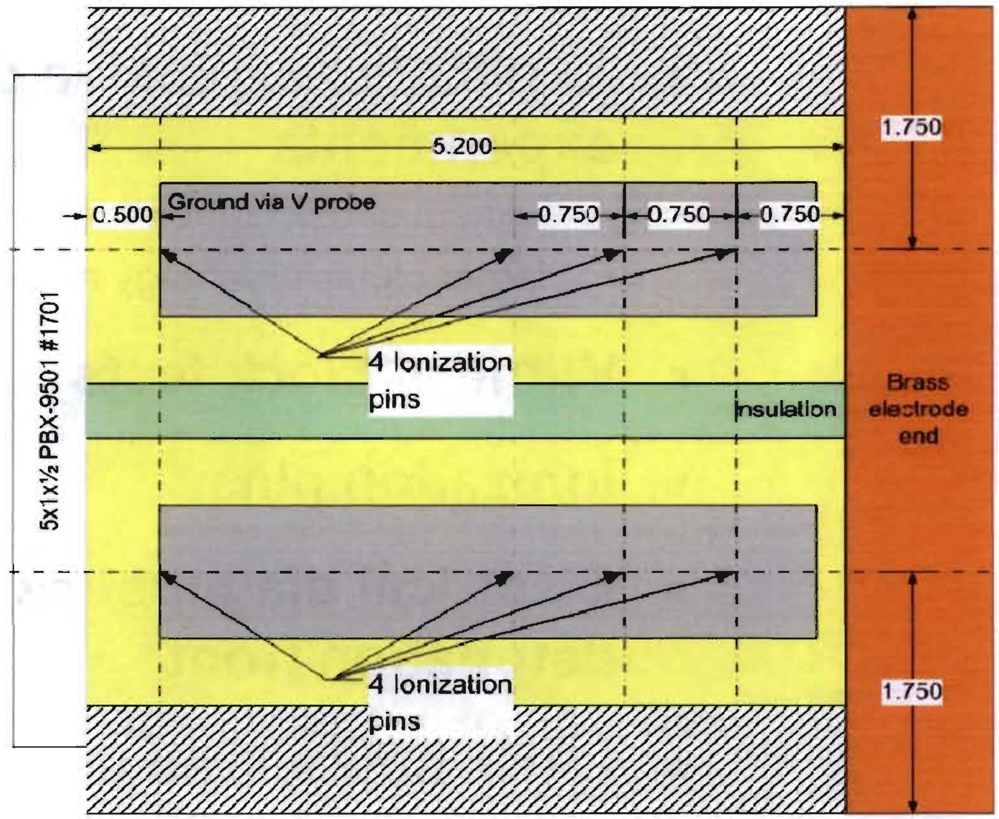
- Output from Rogowski coil directly proportional to conductivity
  - Can have <1 ns response time - if correctly designed

LANL design of AWE experiment

- **Replicates explosive dimensions of AWE experiments**
  - without streak camera
  - larger capacitor energy available (60 kJ vs 5 kJ)
- **Witness block tests**
- **Ionization pins**
- **Electrical diagnostics synchronized with position of detonation front**
- **LANL shots fired in June 06**

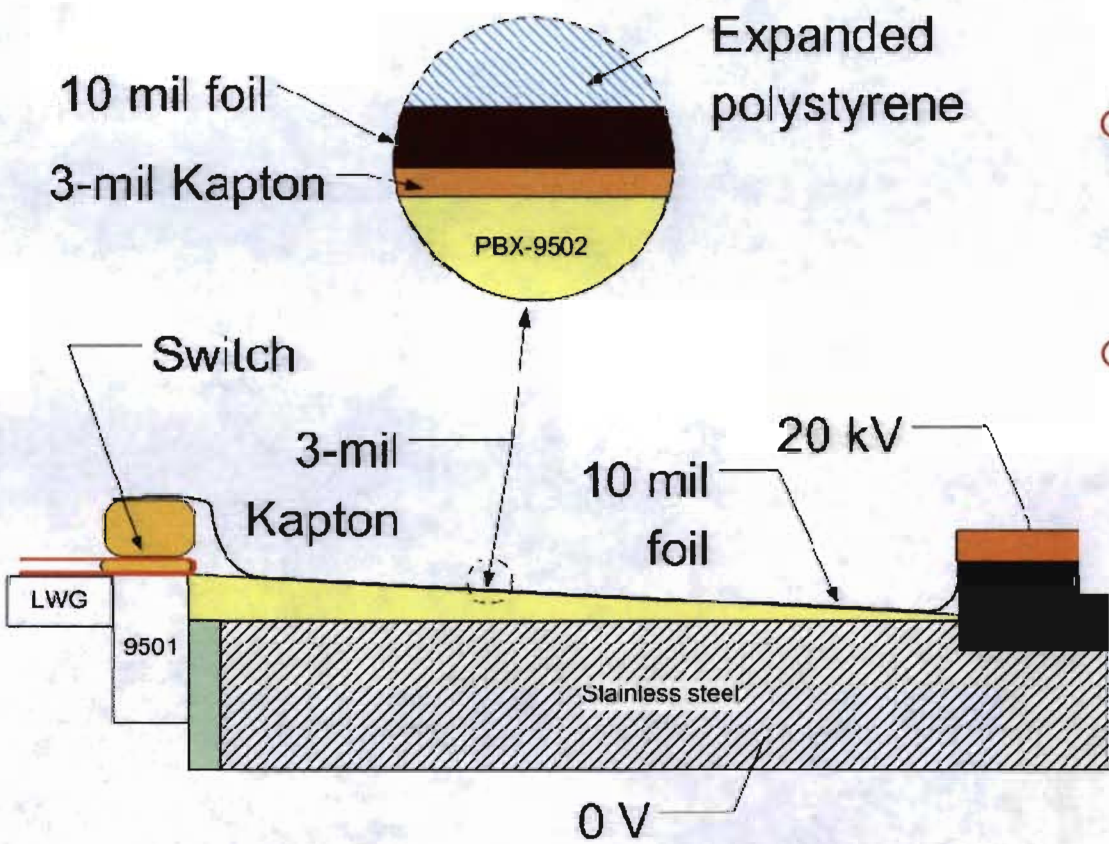
LANL experiment

- Pair of matched PBX-9502 wedges
- Wedges: 1 mm up to 7.92mm (angle 3°); 50 mm wide
- LWG initiation + PBX-9501 booster
- Top wedge had no electric (E) field applied
- Bottom wedge had E-field
- Confinement etc. identical
- Ionization pins underneath 9502 determined "start" of experiment and progress to end of run



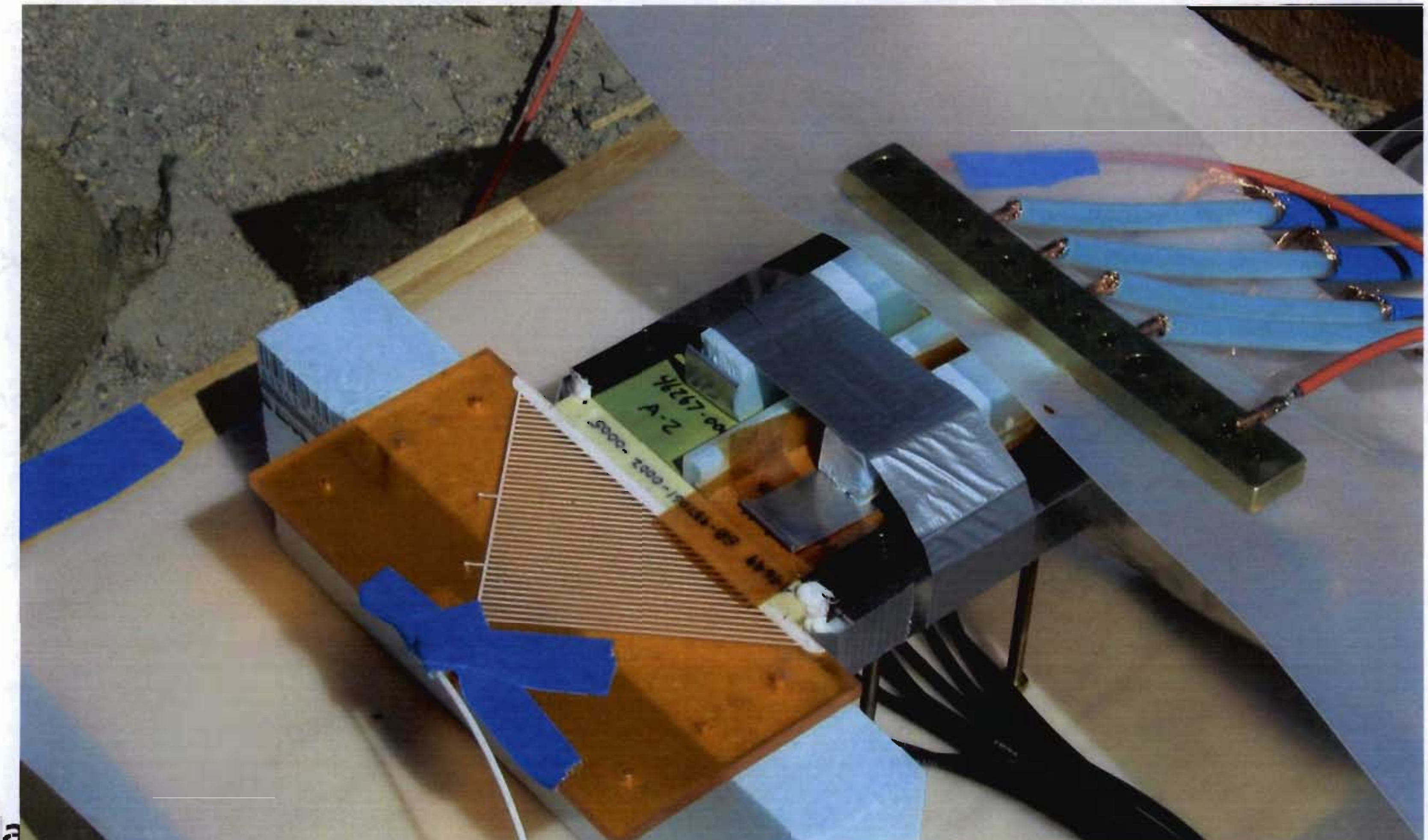
Dims: inches

LANL experiment – details of electrodes

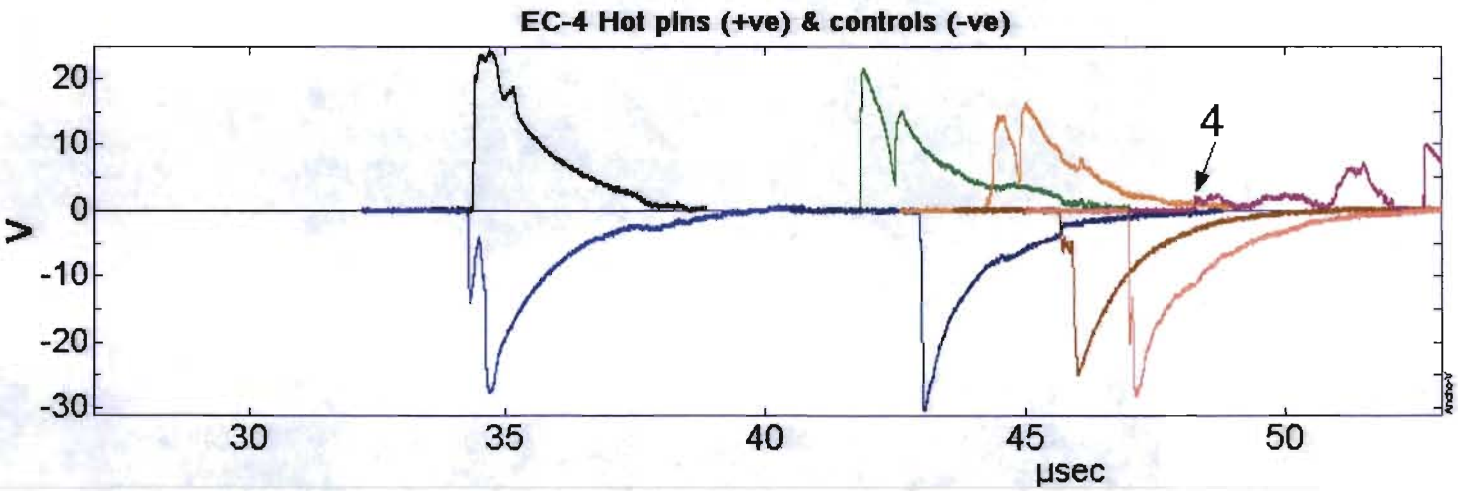


- 3-mil Kapton + 10-mil Al. + 25mm thick, 25 g/m^3, exp. polystyrene
- Shock switch protected voltage probes

Assembly on pad

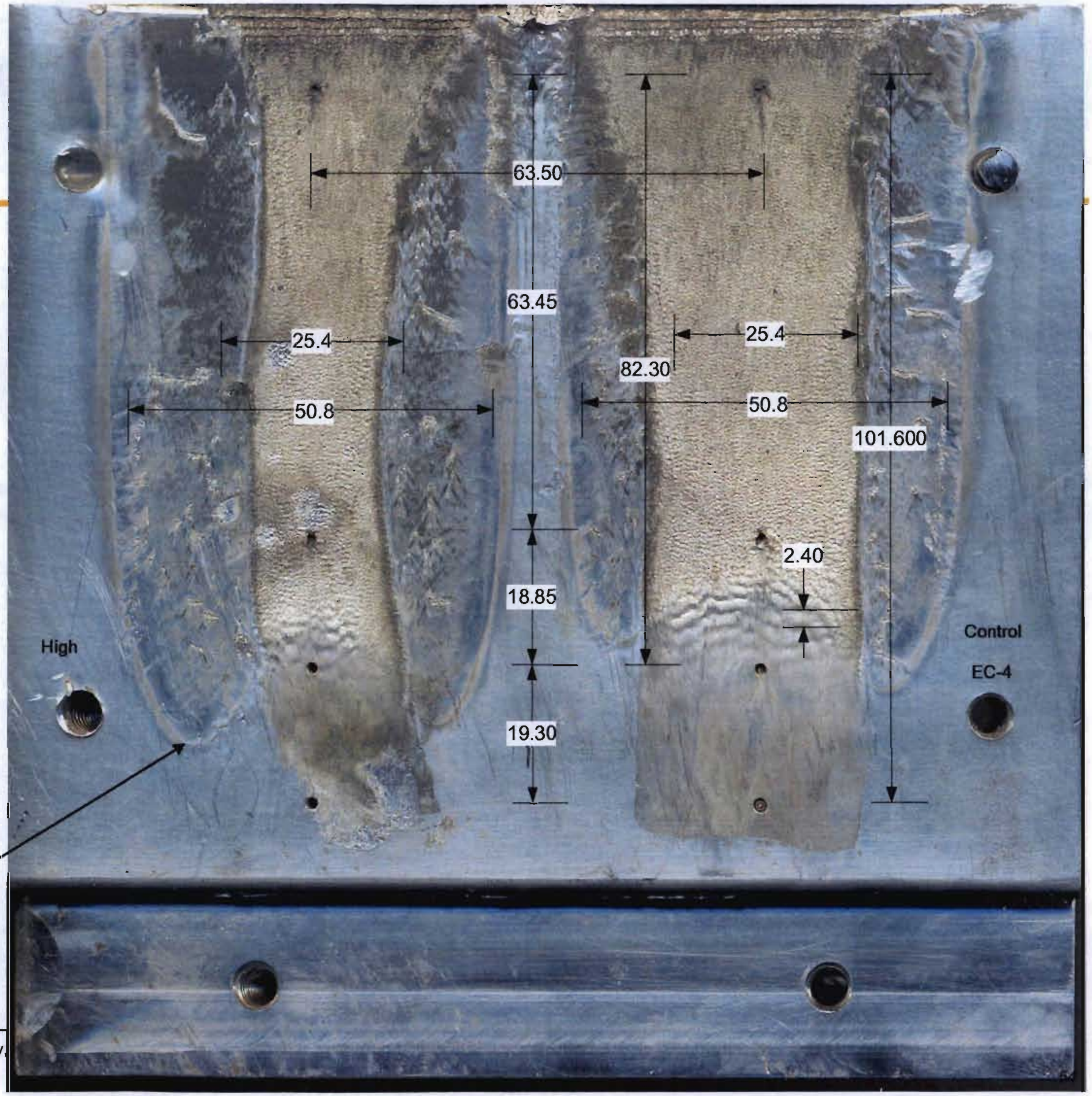


EC-4 "hot" electrode pin led ahead of control data (note precursors)



- **Hot" pins slightly *lagged* behind control pins, on EC-3 (15 kV)**
- ***Led* on EC-4 (18 kV)**

EC-4
18 kV



- Cause(s) of irregular sides to fine-structure regions not known
- "Hot" on the left
- "Hot" dent ran longer

Summary of LANL study

- **EC-4 (18 kV) showed a real extension of detonation into a thinner wedge when an electric field was applied**
  - Supported by pin data and dent ✓
- **Interesting fine structure at point of failure could provide a sensitive determination of failure thickness**
- **As detonation failed, a longer wavelength structure developed, λ = 1~2 mm**
- **Fine structure believed to be associated with "confinement" of electrode & insulation (Kelvin-Helmholtz instability?)**
- **Apparently confirmed AWE findings**