

# Dynamic Characterization of Materials

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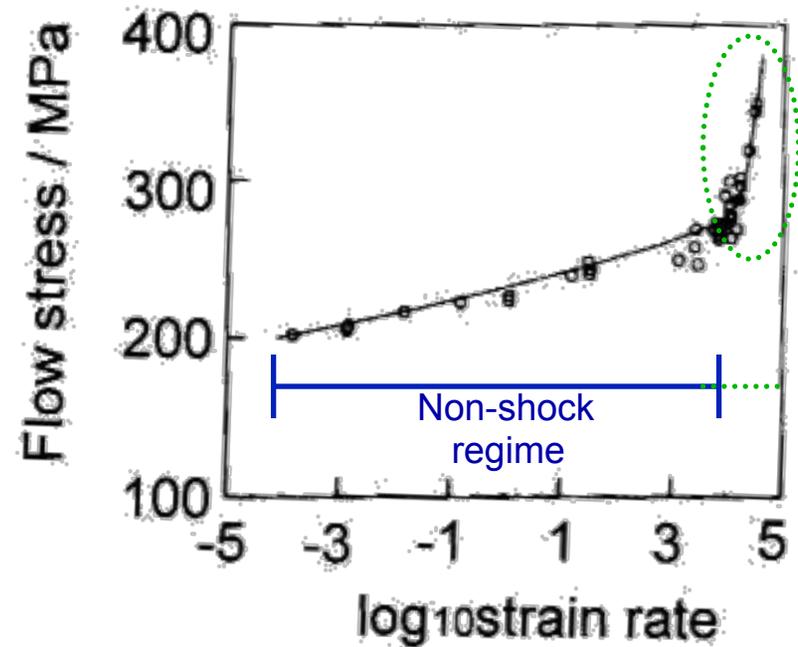
# Outline

- Motivations
- History
- The Photon Doppler Velocimeter (PDV)
- Obtaining Dynamic Stress-Strain Data
  - Some thoughts...
- Compaction Testing for P- $\lambda$  EOS validation

# Why?

do we study High Strain Rate Mechanical properties!

- Armor & Anti-Armor
- Crash & Impact
- Machining
- Metal Forming
- Validation of models
- Scientific understanding...



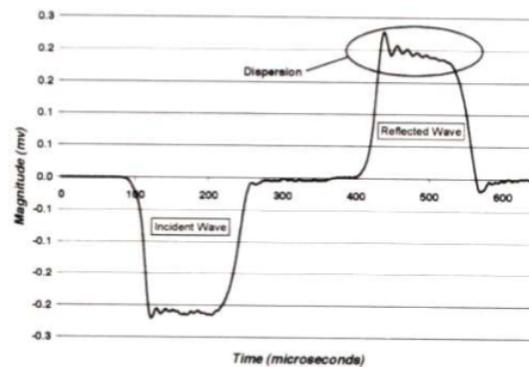
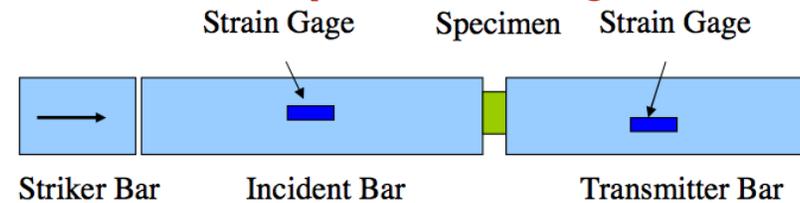
From Follansbee and Kocks (1988):  
Copper deformation

# Split Hopkinson Bar (Kolsky Bar)

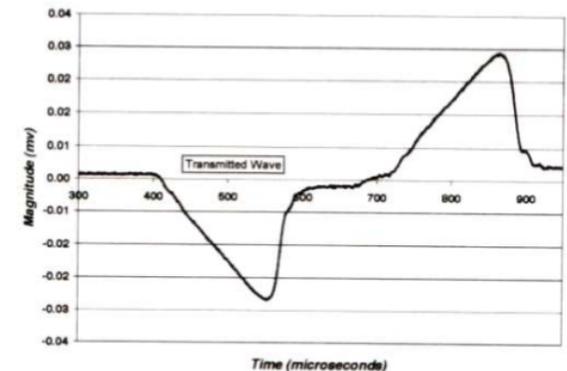
**THE STANDARD test for high strain rates**

Problems exist though:

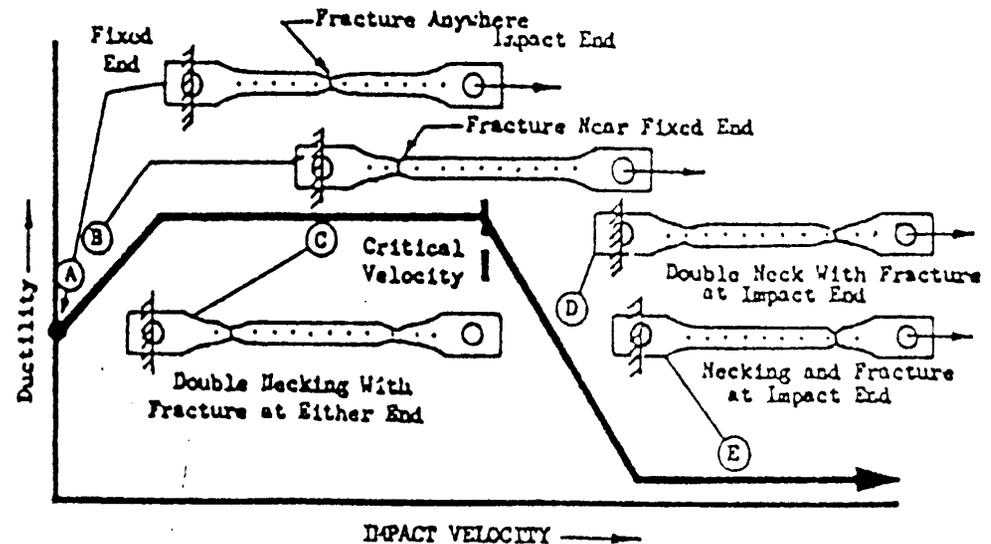
- Tension is difficult to implement and requires carefully chosen sample dimensions
- High temperature is possible, but difficult and heating is slow
- Test and analysis is time consuming
- Tensile ductility is more affected by test conditions than intrinsic behavior. (see Wood, 1967, lower right)



Incident bar strain gage signal



Transmitted bar strain gage signal

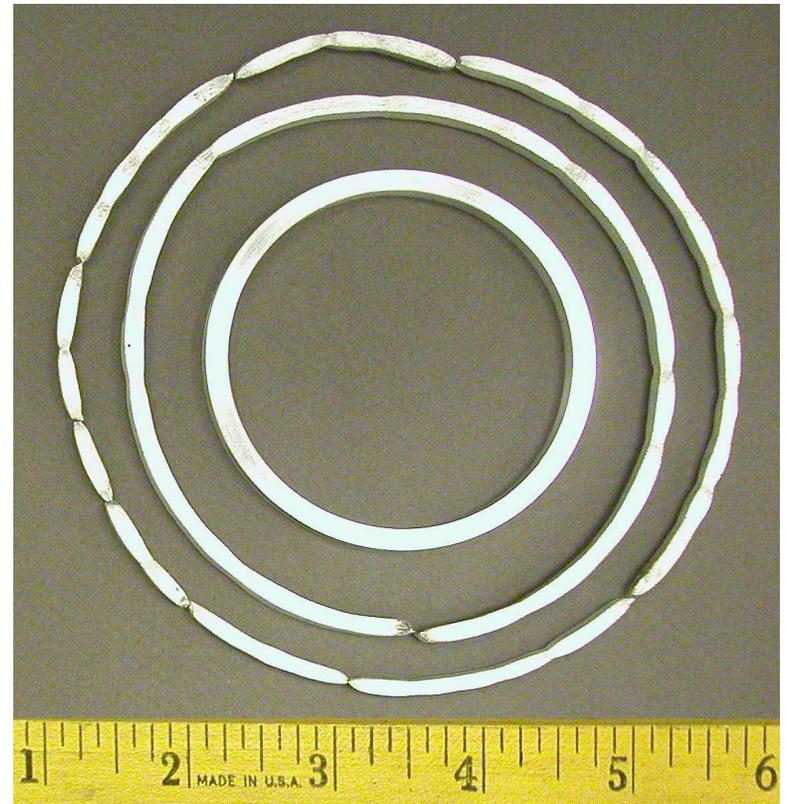


# Characteristics of the EM Ring Expansion Test

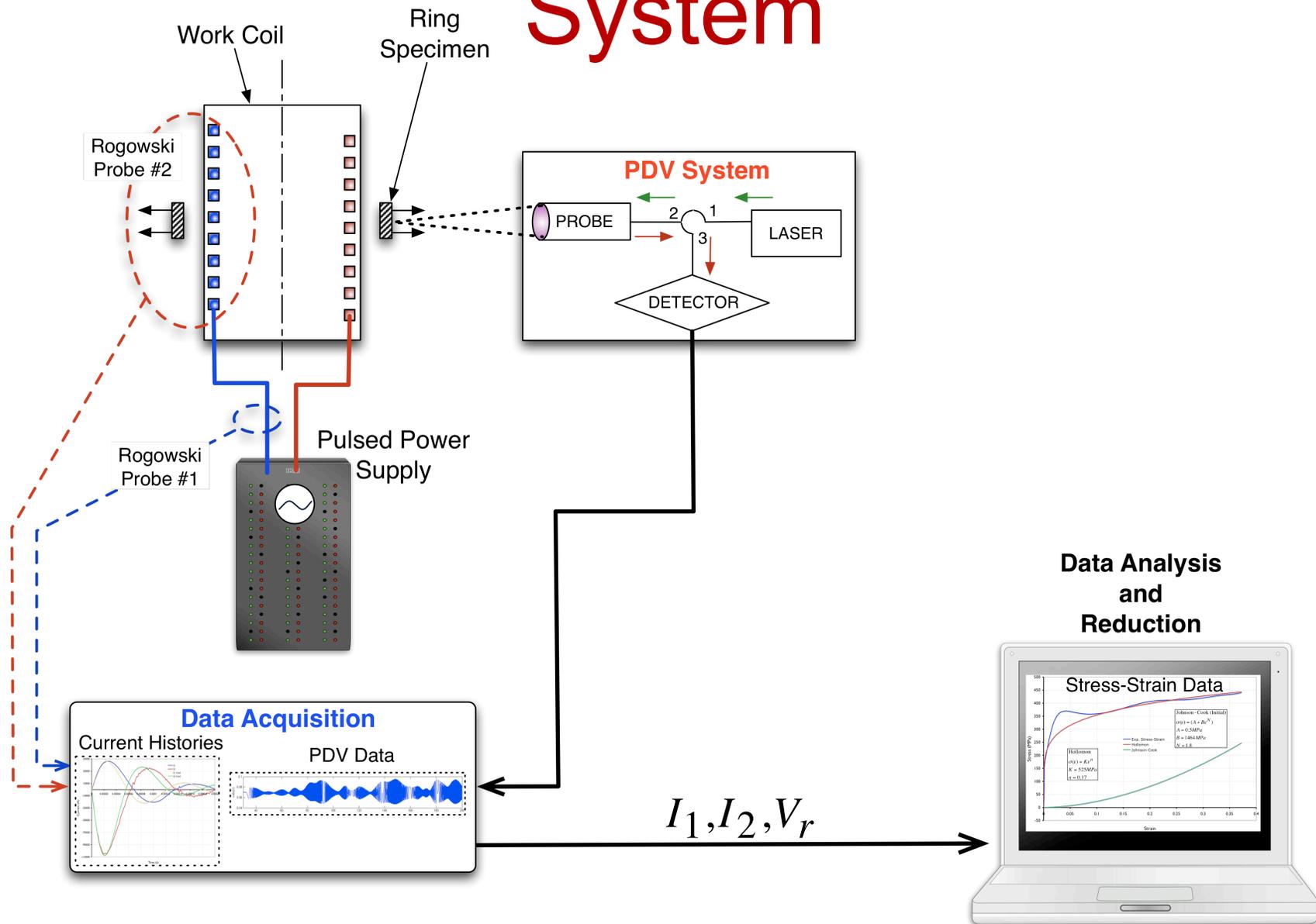
- Opposed primary and induced currents provide a uniform tension in the ring by accelerating the ring to velocities  $> 500$  m/s.
- Plastic work dissipates kinetic energy in ring
- In comparison to the Hopkinson Tensile bar:
  - You get uniform tension in ring, to a point!
  - You can study ductility and fragmentation in a uniform stress/strain state

# Electromagnetic Ring Expansion

- Has no wave propagation along direction of principal stress. Gives spatially uniform state of very nearly uniaxial stress for un-necked ring.
- Introduced by F. L. Niordson, 1965.
- Further developed by Grady and Benson, 1983.
- Quite refined by W. H. Gourdin and collaborators, 1988 and 1989.



# Experimental Measurement System

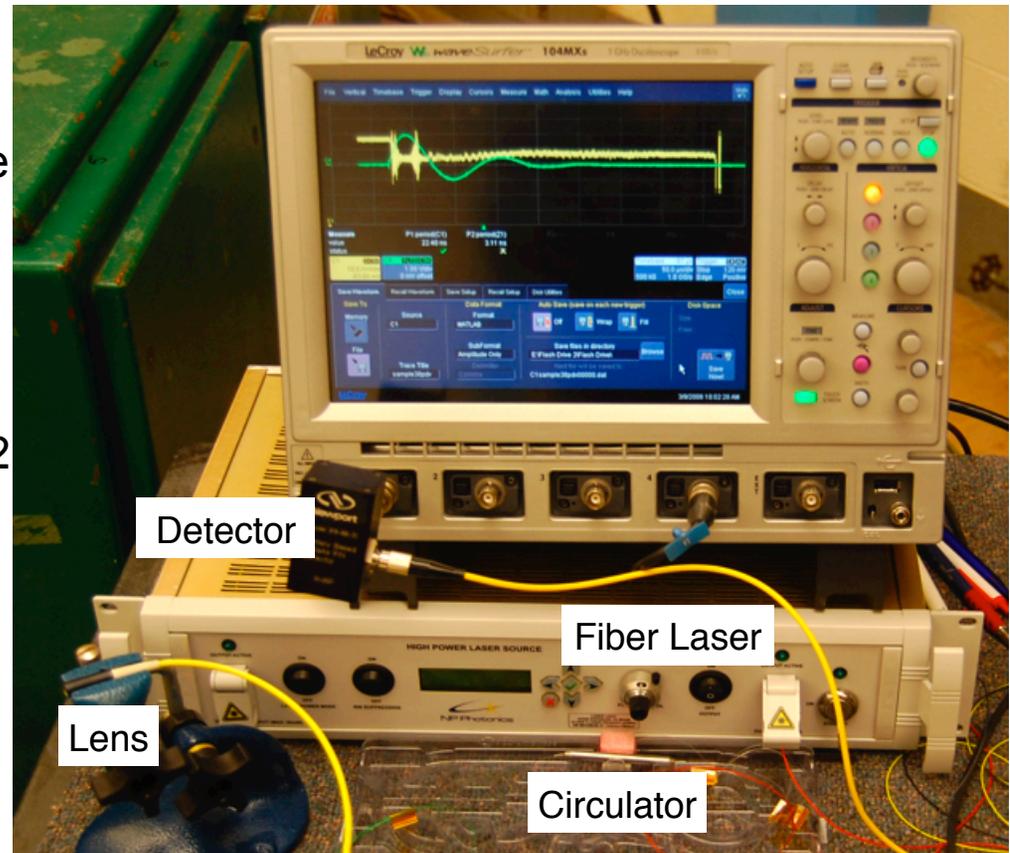


# The PDV Sub-System

Based on a 1 W 1550 nm erbium fiber laser and a 5 Gs/s oscilloscope with 10 Mpts of storage on 4 channels

Allows 4 channels of velocity measurement up to  $\sim 800$  m/s over 2 ms at full time resolution

Distances over 1m can be recorded



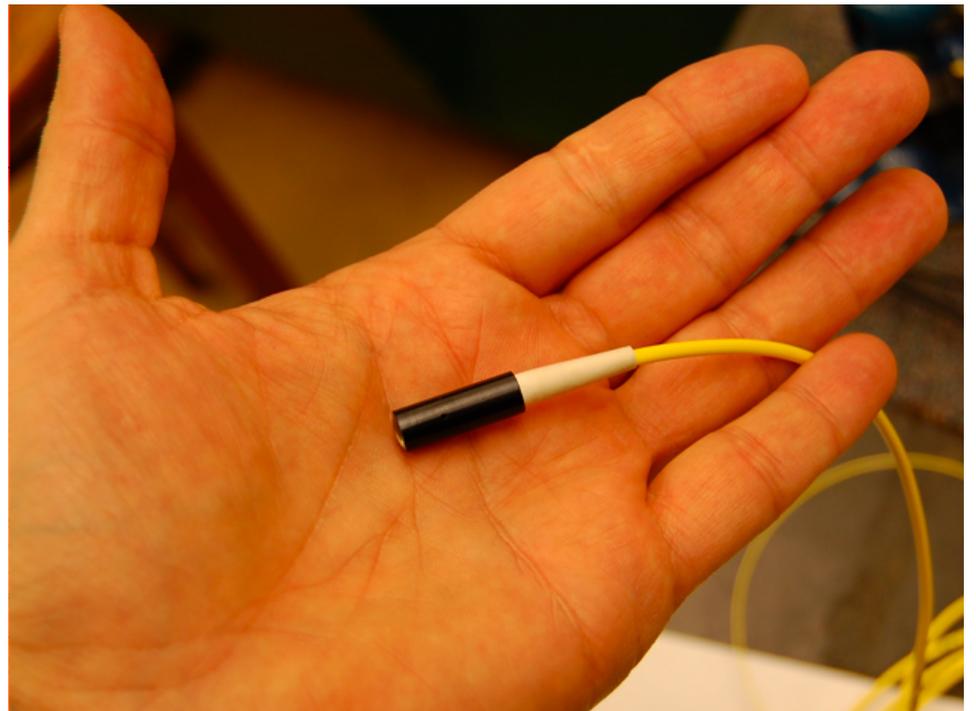
# The Real Beauty of PDV

No optical bench...  
Just Fiber Optics!

No need to align, very compact,  
and relatively safe

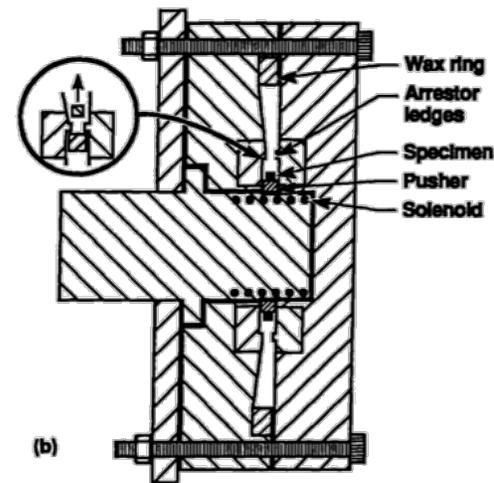
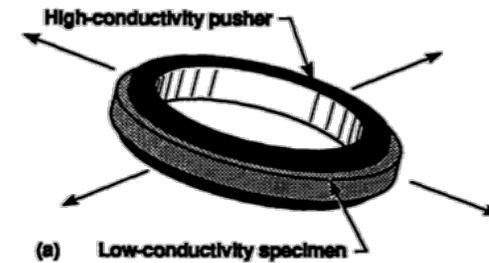
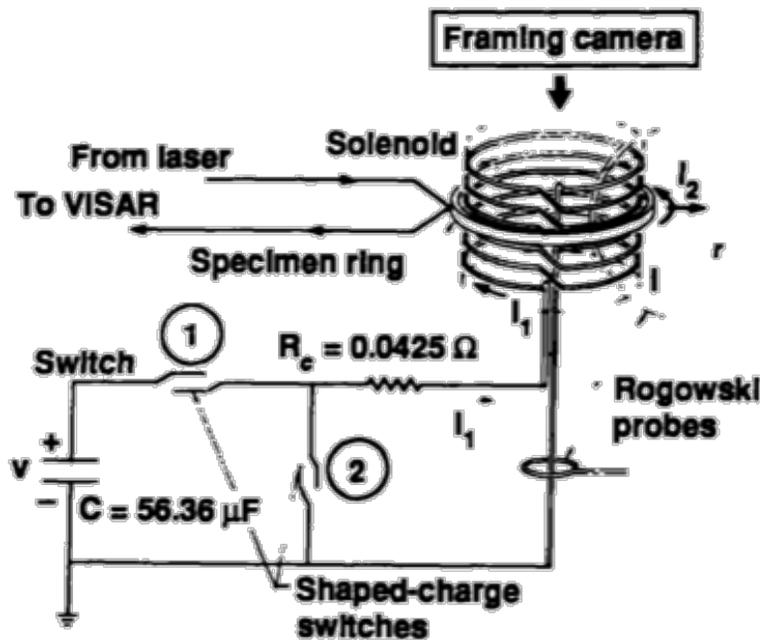
Diffuse reflection gives sufficient  
signal strength

Varied focal lengths available on  
probe lenses



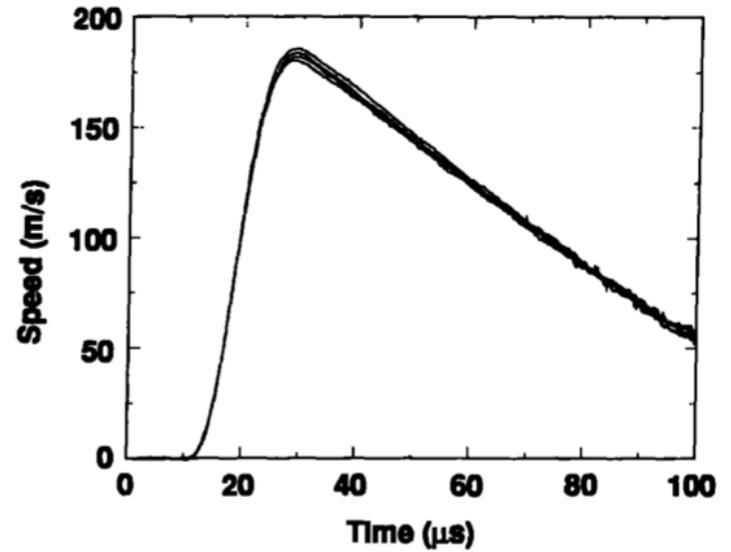
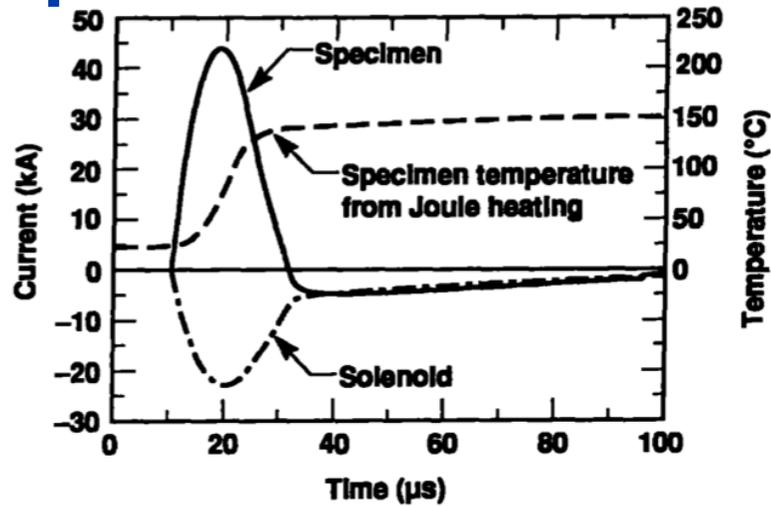
# Using Gourdin's Accomplishments

- Two key papers...
  - *J. Appl. Phys.* ('88)
  - *Rev. Sci. Instrum.* ('89), with Weinland and Bolling

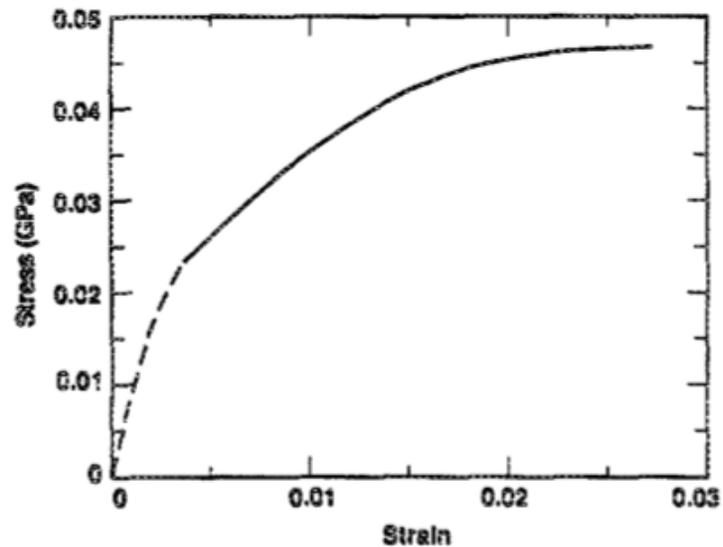


# Gourdin's Data

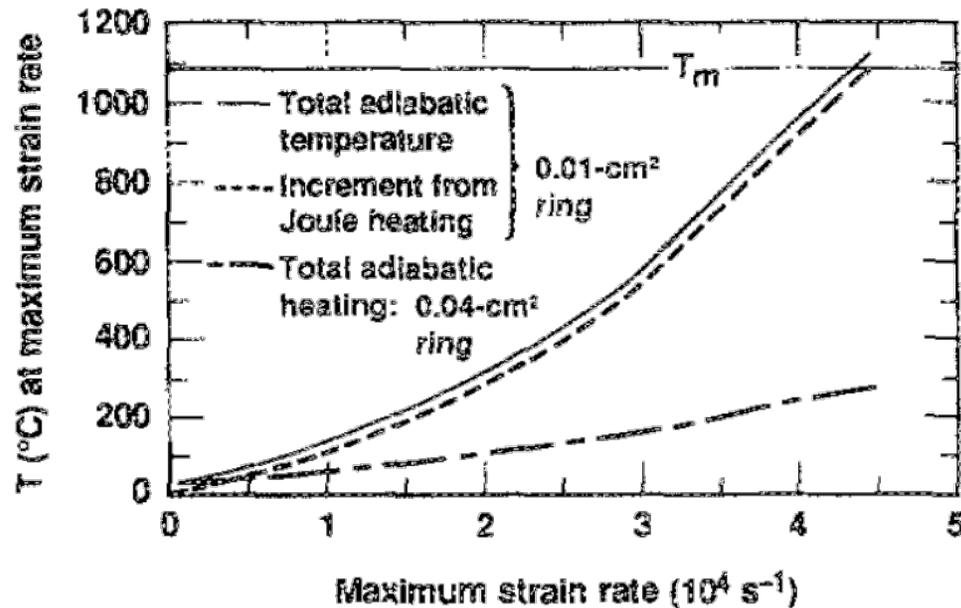
Inputs...



Output...



# Limitations In Gourdin's Work



Gourdin used slender rings to keep the mechanics *clean*, for a copper ring with a 1mm square cross-section the ring reaches melting temperature if driven to a strain rate beyond  $4 \times 10^4 \text{ s}^{-1}$ . There is *much less* joule heating as ring cross sections increase.

Challenge: Poses limits on available strain rates. At the time, very costly testing!

Opportunity: Ring cross section can be chosen to provide a designed heating rate. However, mechanics are *not as clean*.

# 1988 → 2008, What's New?

EM Ring Expansion still offers a very clean way to study high strain rate properties. What can we do now?

## Equipment (less expensive test)

PDV can replace VISAR (easier, cheaper, more versatile)

Coils can be more robust

$I_2$  can be measured directly and quite easily

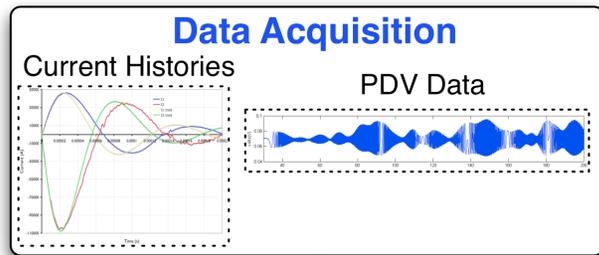
## Analysis (tolerance of messy mechanics)

Tools like the electromagnetics module in LS-DYNA and tools like LS-OPT allow analysis of almost any arbitrary geometry

Automated data reduction makes 1-D analysis very fast

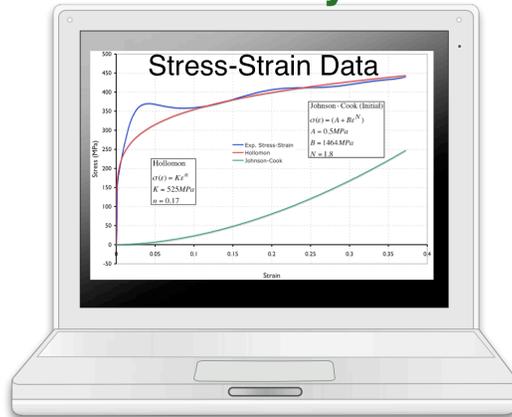
Tests may be much cheaper and more accurate than in the 1980's, and a good complement to Hopkinson bars.

# Obtaining the Stress-Strain Curve



$I_1$  &  $I_2$  signals  
PDV signal

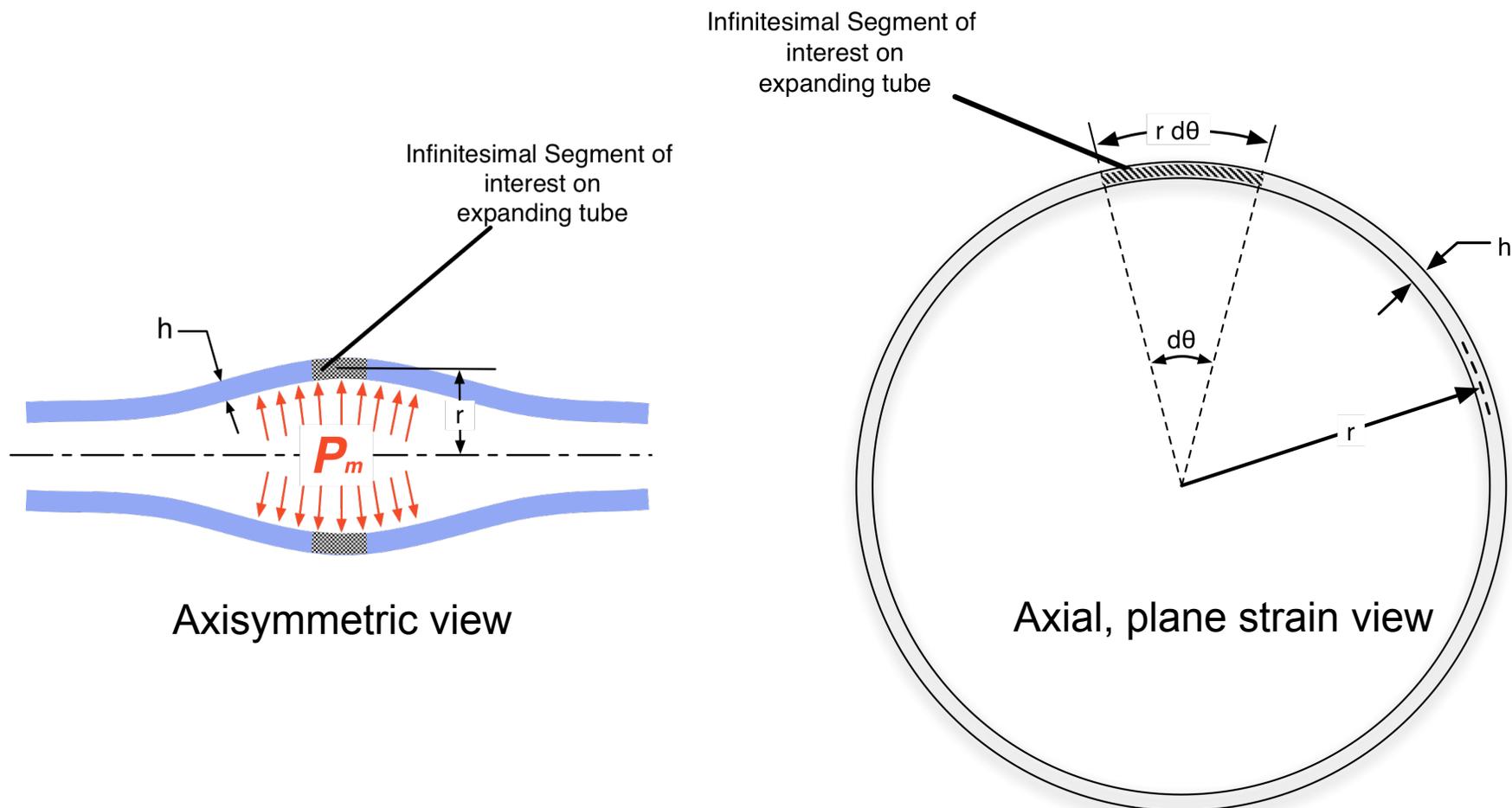
Data Analysis



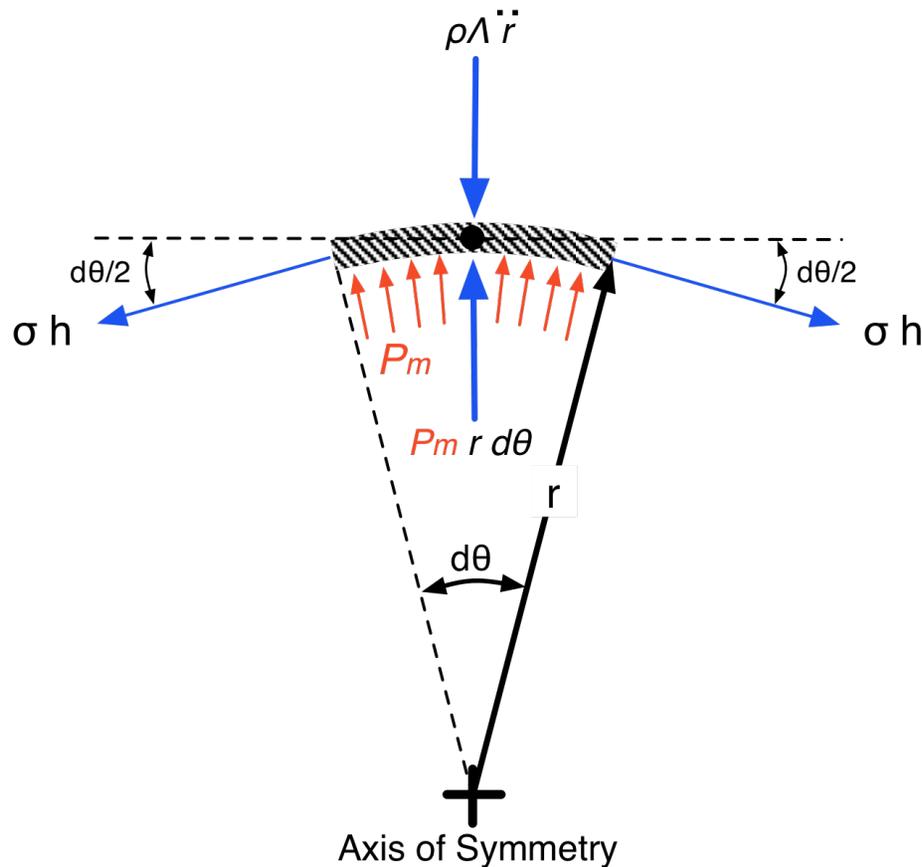
1. Reduce raw PDV signal into  $V(t)$  form.
2. Filter  $I_1$  &  $I_2$  signals using a Digital Smoothing Polynomial (DISPO) filter.
3. Pass filtered data into 1D analysis software (DSS code).
4. Obtain stress-strain curve,  $\sigma(\epsilon)$ .

# Data Analysis Assumptions

Start with pressurized expanding tube/ring concept...  
Utilize 1D Hoop Stress Approximation



# 1D Analysis - Hoop approximation



Sum these forces to get radial equation of motion

$$\rho \ddot{r} \equiv \rho \frac{dV_r}{dt} = \frac{F_r^m}{\Lambda} - \frac{\sigma}{r}$$

Where  $F_r^m$  is the radial component of magnetic force, i.e., the radial Lorentz force on the ring

$$F_r^m = \frac{1}{2} \frac{dL_2}{dr} I_2^2 + \frac{dM_{12}}{dr} I_1 I_2$$

Solving for  $\sigma$ ...

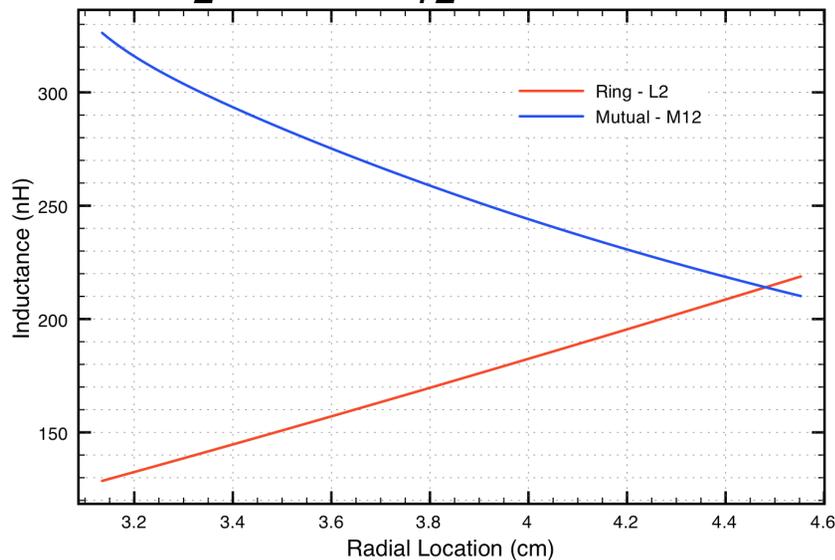
$$\sigma = \frac{F_r^m r}{\Lambda} - r \rho \ddot{r}$$

$\Lambda$  is the volume of the ring

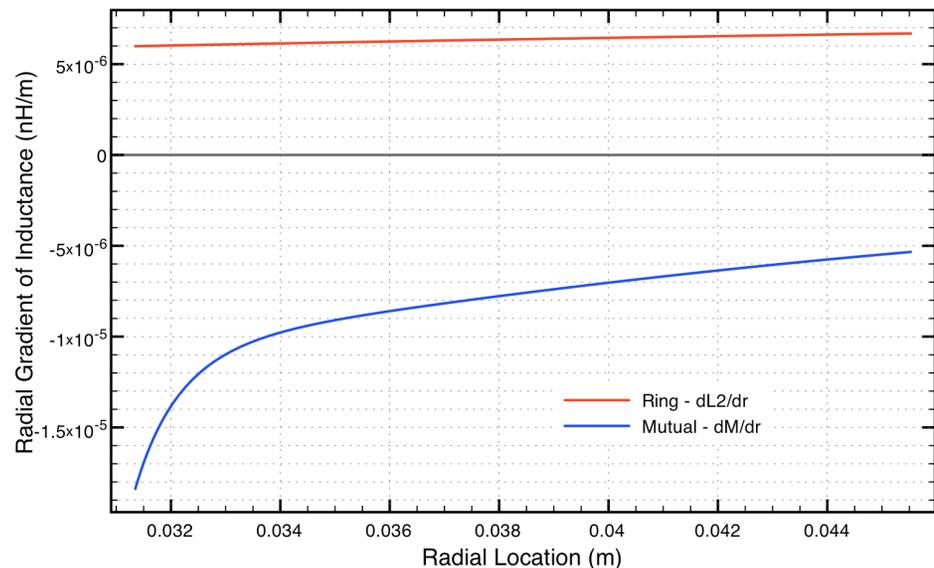
# Data Analysis

Inductances relate to the tube-coil geometry and the respective gradients of inductance are straight forward smooth functions of geometry, so they are easily obtained... **But**, care must be taken to accurately measure the tube and coil geometry for this to work!!!

$L_2$  and  $M_{12}$  vs. radius



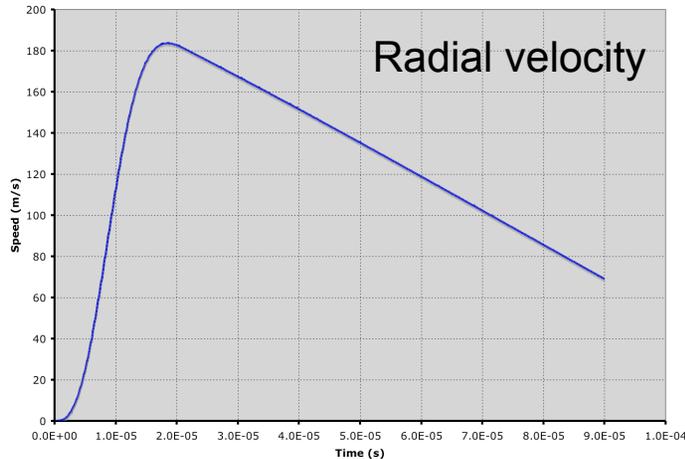
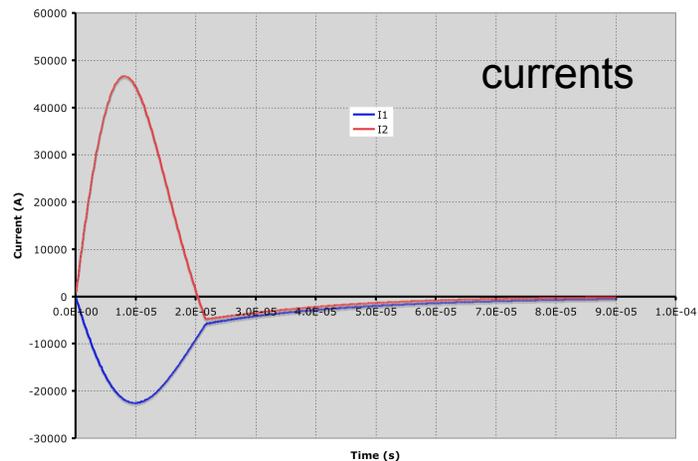
$\frac{dL_2}{dr}$  and  $\frac{dM_{12}}{dr}$  vs. radius



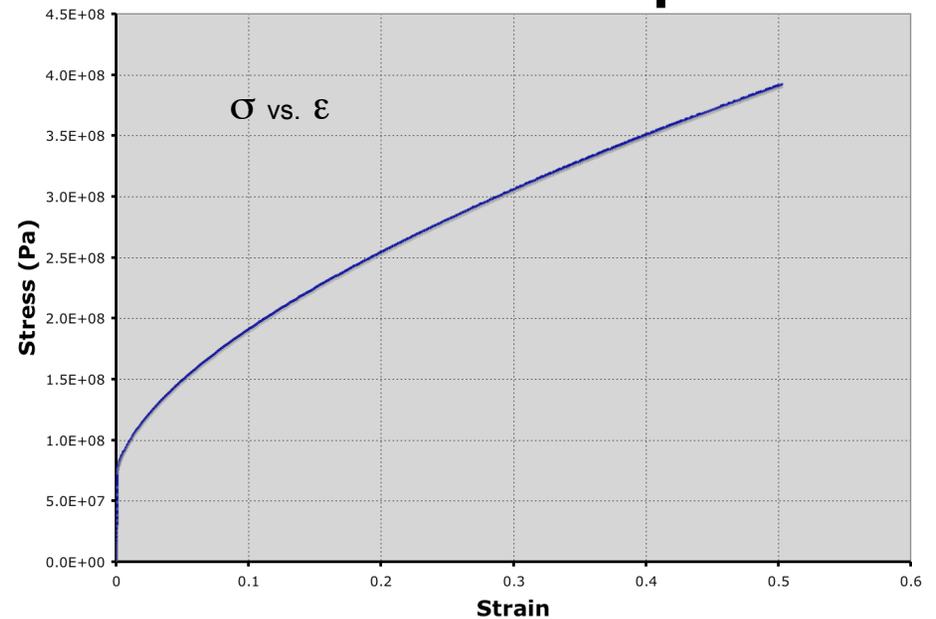
# Analysis - Step 1

Test the Dynamic Stress-Strain (DSS) software on a ring expansion test, using a known data set (The Gourdin data)

## Known "Inputs"

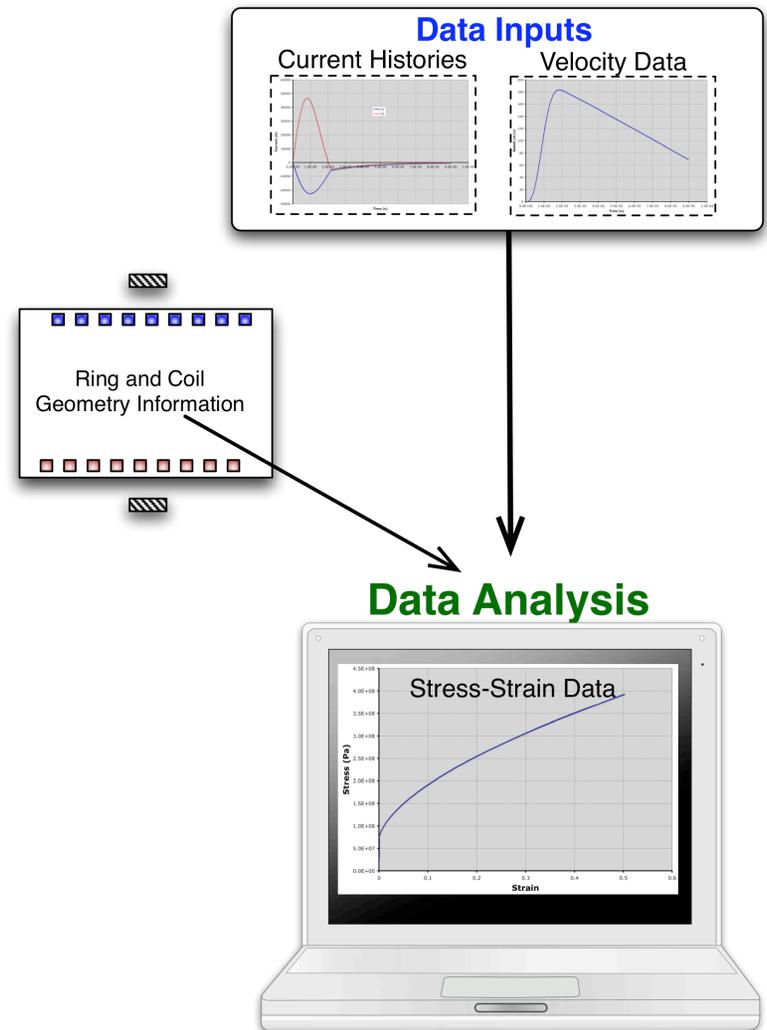


## Known "Output"



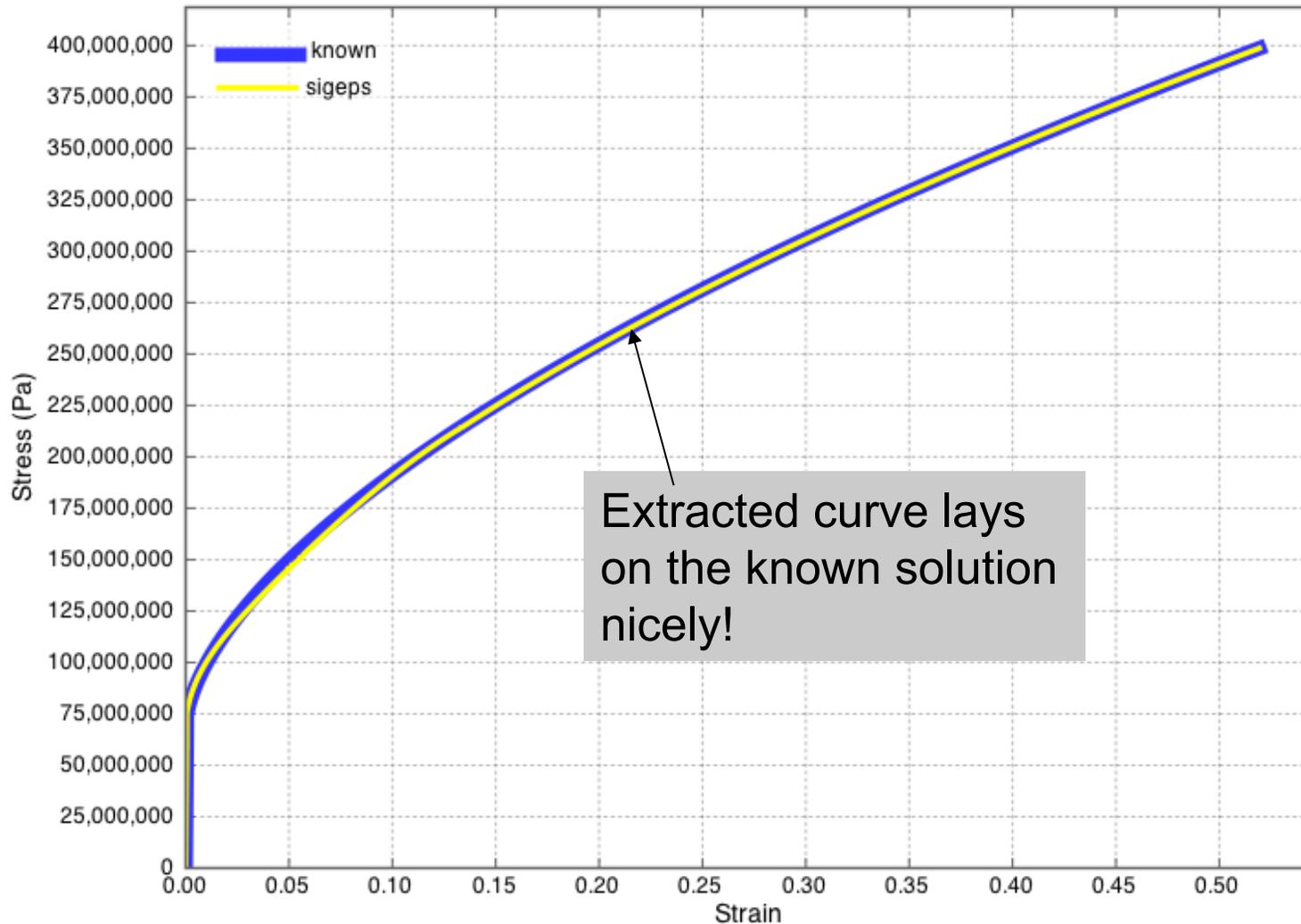
# Analysis - Step 2

Taking the known input data and other experimental information, then pass it into the Data Analysis code (DSS) to extract a ( $\sigma$  vs.  $\epsilon$ ) curve...



# Analysis - Step 3

Success - the DSS software works!



# Analysis - Step 4

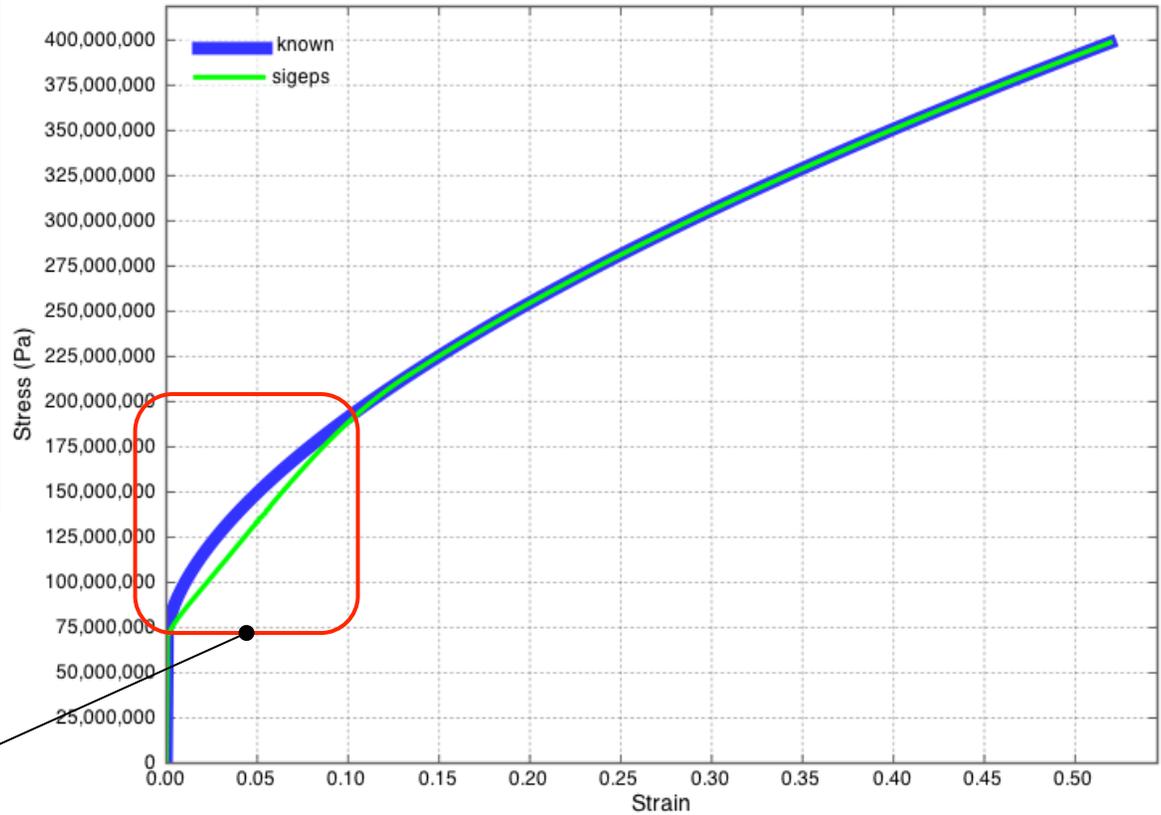
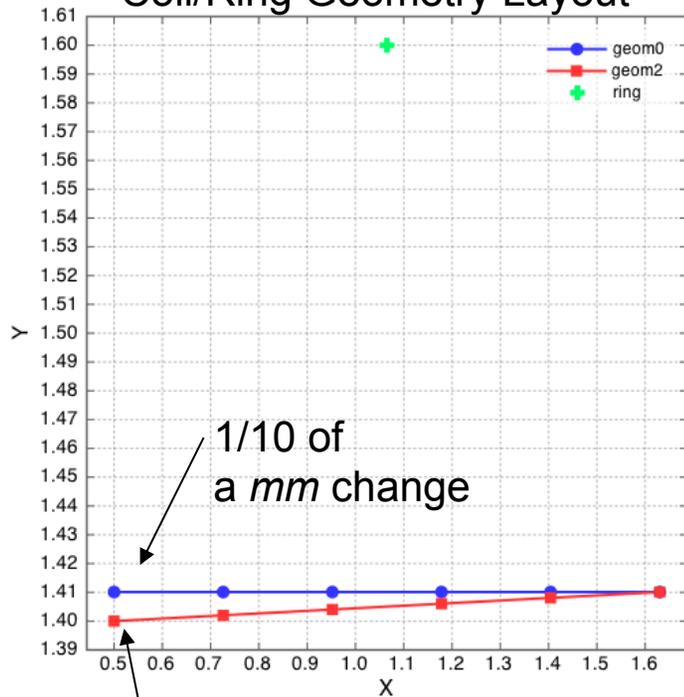
Sensitivity Study - vary coil/ring geometry

- Observe the influence of the coil/ring geometry on stress-strain curve
  - This reflects the influence of the inductances on the process ( $L_2$  and  $M_{12}$ )
- Illustrate that accurate geometry measurements are a vital necessity!

# Analysis - Step 4

## Small changes in coil layout

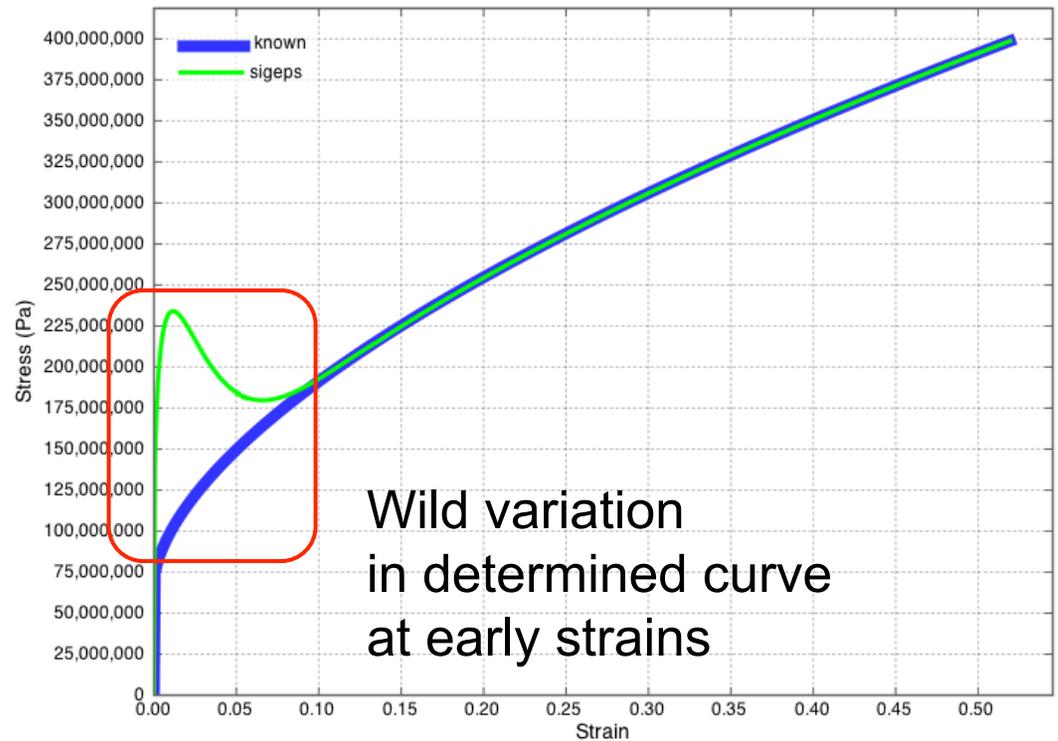
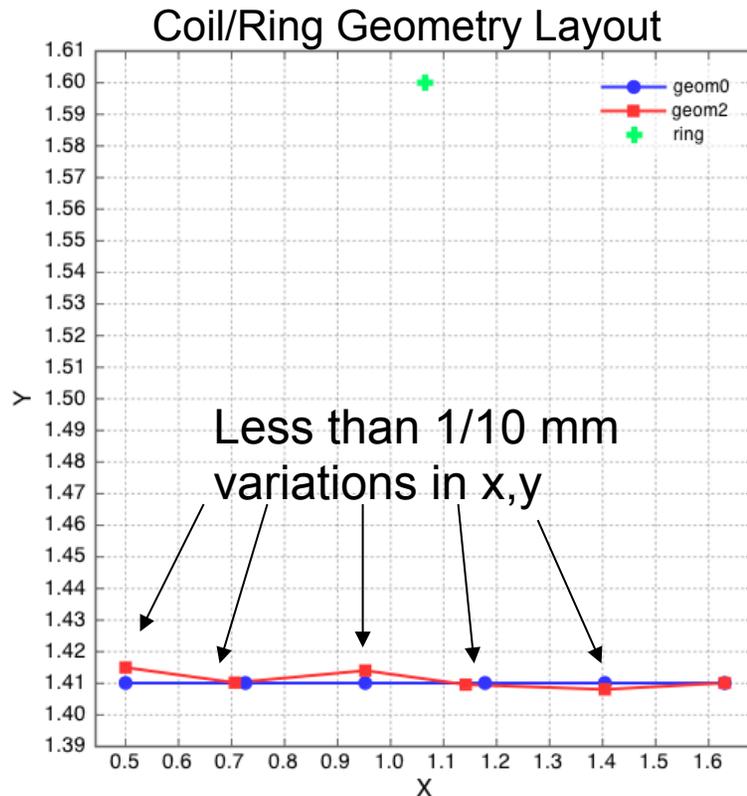
Coil/Ring Geometry Layout



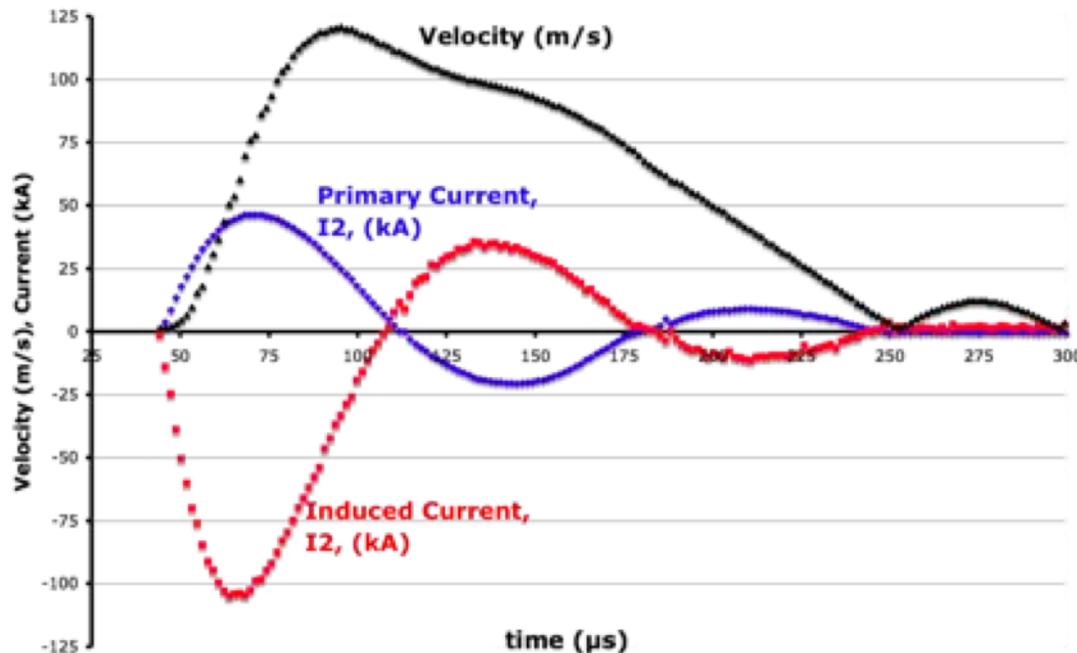
-0.7% decrease in coil cross section from original coil geometry at the left of the coil curve at early deformation

# Analysis - Step 5

Small changes in each coil turn locations  
< 1/10 mm variation in coil (x,y) locations



# A Real Data Set (Annealed Cu 122)



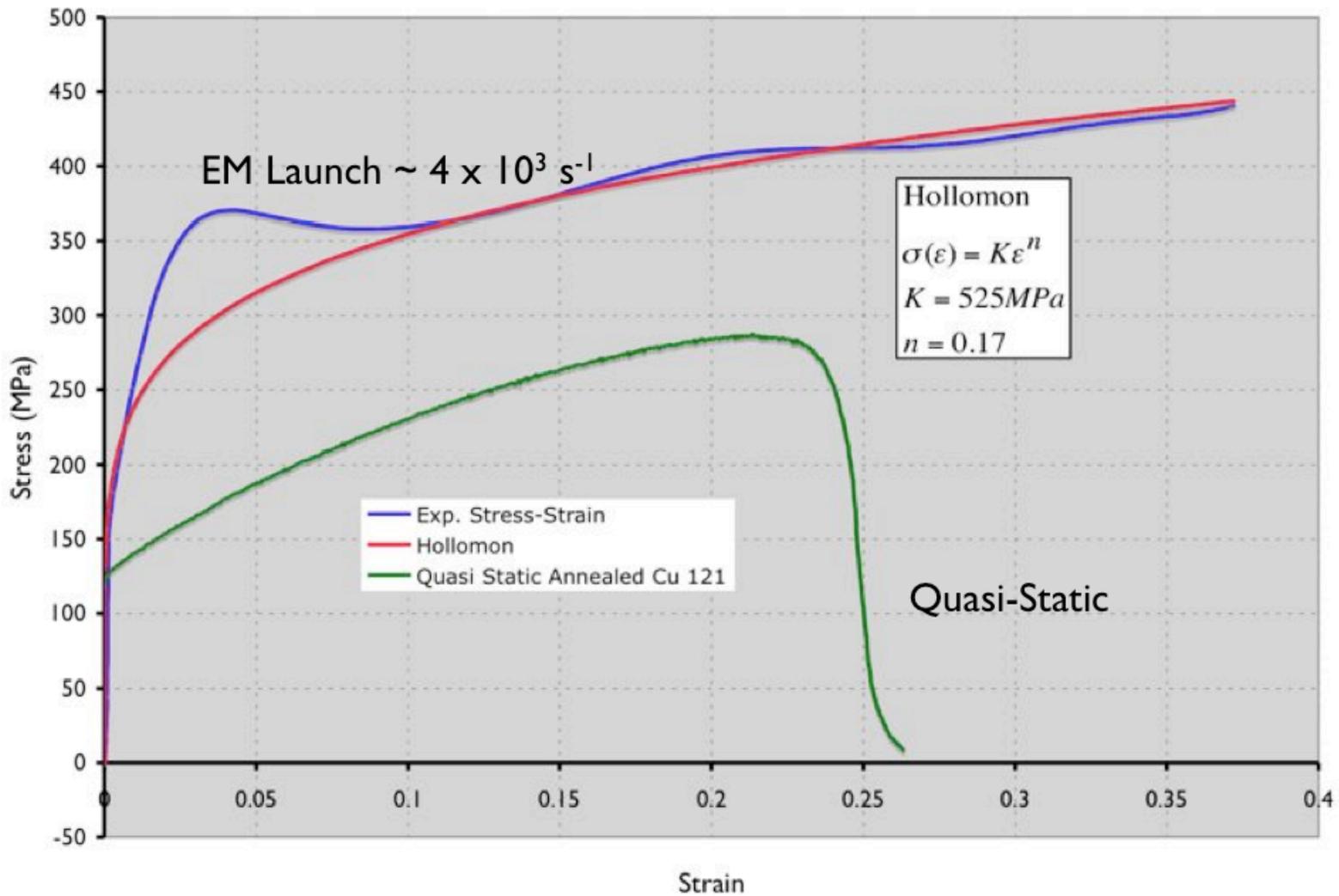
Annealed Cu 122 rings launched with 1.28kJ impulse with 5-turn brass coil with square x-section.

Ring has initial ID of 62mm, .9mm wall thickness and height of 9mm.

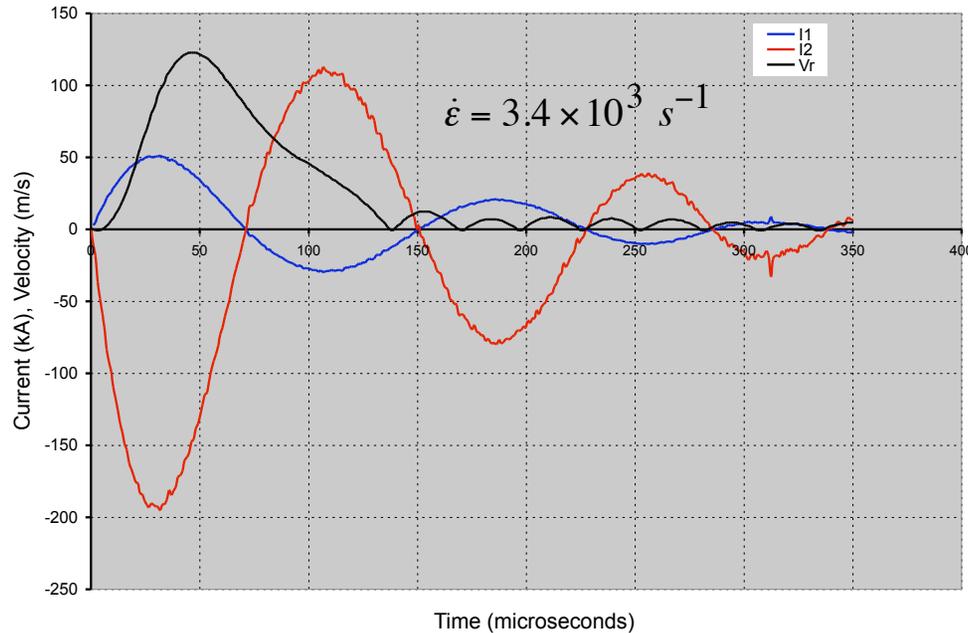
Ring has 45% hoop elongation, unbroken and 27% reduction in height after the experiment.



# Real Data Results (Annealed Cu 122)

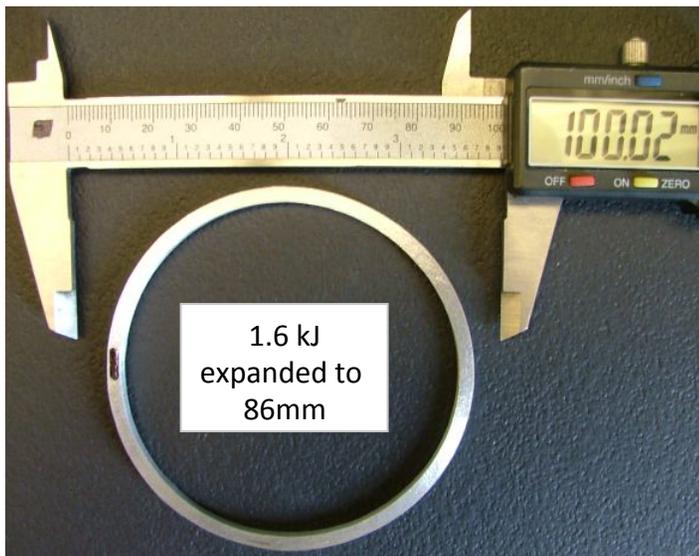


# Real Data Set (Annealed 5754 Al Ring 1)



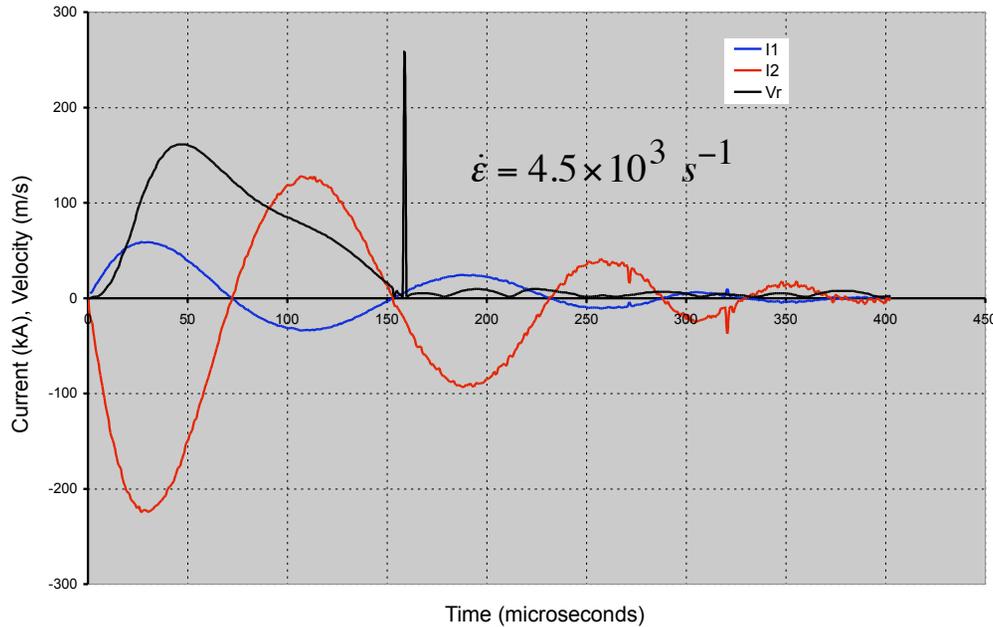
Annealed 5754 Al ring  
Launched with 1.6 kJ impulse  
with a 5 turn square x-section  
brass coil

Ring has initial OD of 70.1mm,  
4mm thickness, and 4mm  
height.



Ring has 23% radial elongation  
(8mm), un-broken, no necking, and  
18.5% reduction in x-section area.

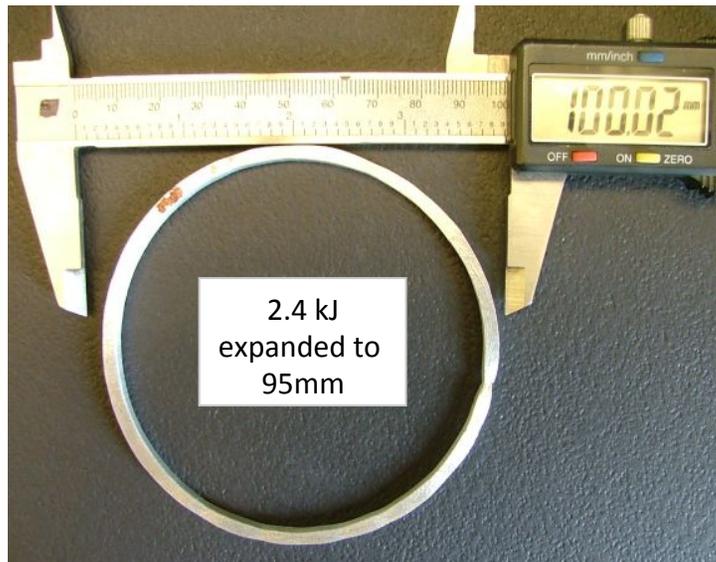
# Real Data Set (Annealed 5754 Al Ring 2)



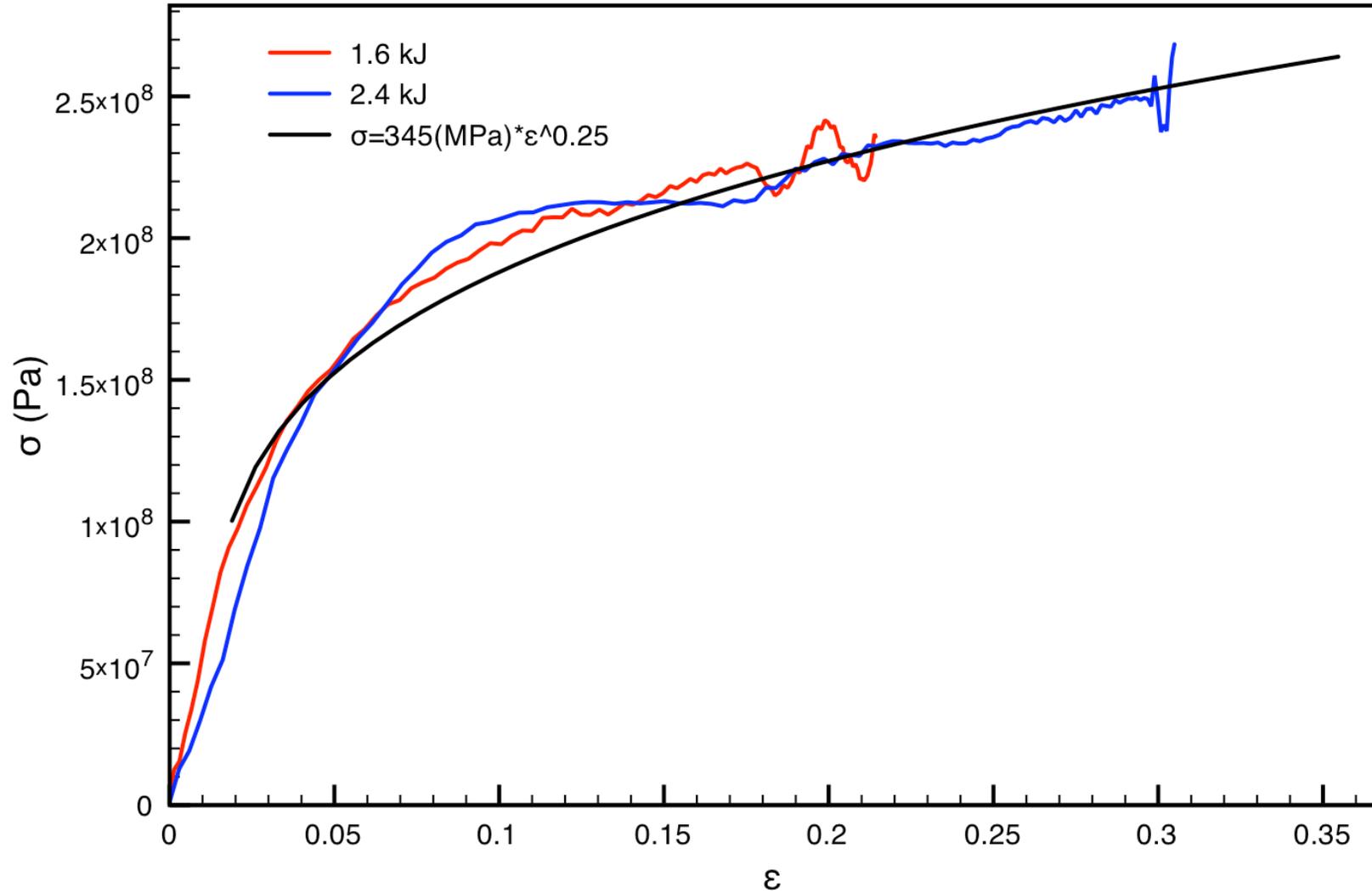
Annealed 5754 Al ring  
Launched with 2.4kJ impulse  
with a 5 turn square x-section  
brass coil

Ring has initial OD of 70.75mm,  
4mm thickness, and 4mm  
height.

Ring has 34% radial elongation  
(12mm), un-broken, 1 neck, and 45%  
reduction in x-section area.



# 5754 Al Rings ( $\sigma$ vs. $\epsilon$ )



# Initial Conclusions on Ring Expansion

- Accurate mutual Inductance is strongly influenced by geometry measurements of ring-coil
- Accurate measurement of coil geometry is paramount! (accurate initial placement of ring)
  - Good geometry measurements allow measured  $I_1$ ,  $I_2$ , and  $V_r$  data to provide a reasonable stress-strain relation
- Geometric discrepancies seems to have a weaker influence as deformation increases

# Thoughts on Ring Expansion...

- Precision coils may be needed to make this process work more easily!
- Coils need to be robust (non-deforming) during the forming event.
- Perhaps more coil windings and a larger ring diameter will mitigate some of the coil geometry variability for a given ring cross section at early strains.

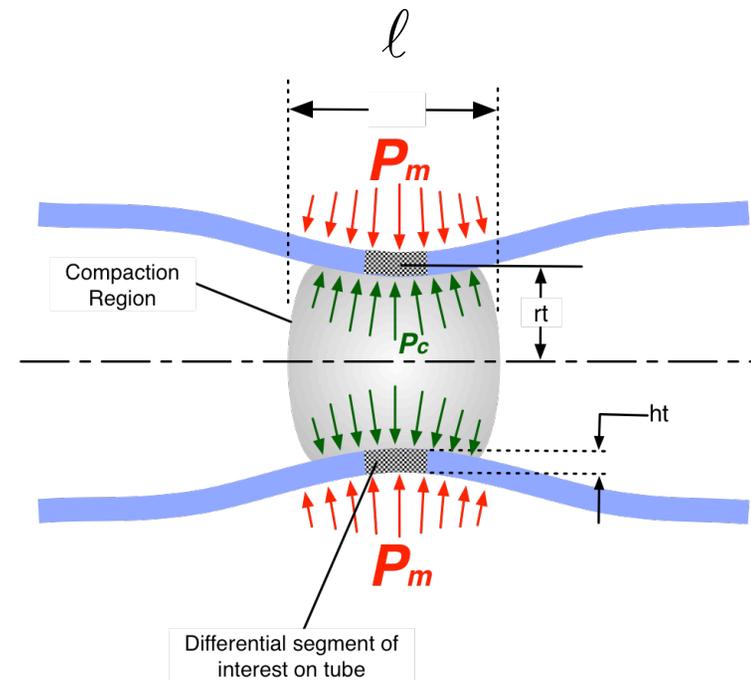
# Walk Away Thoughts...

- Cheap and easy experiments!
- Should use multi-test protocol on a given material (2 stage approach)
  - Multiple tests at low energy ( $\varepsilon < 10\%$ )
  - Multiple tests at high energy ( $\varepsilon > 10\%$ )

# Preliminary EM Compaction Testing

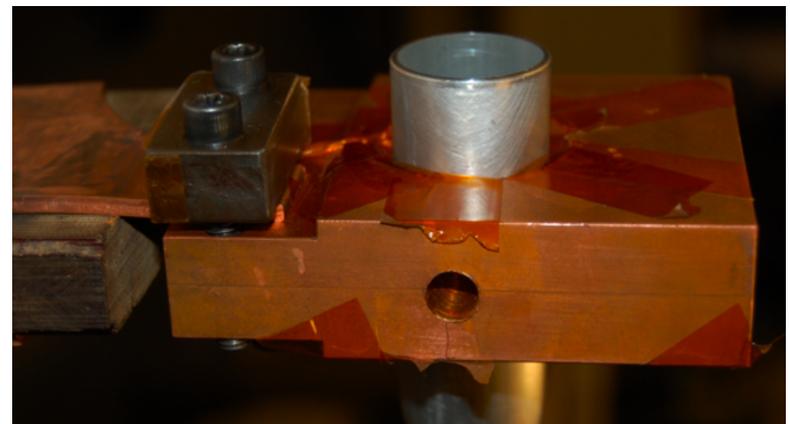
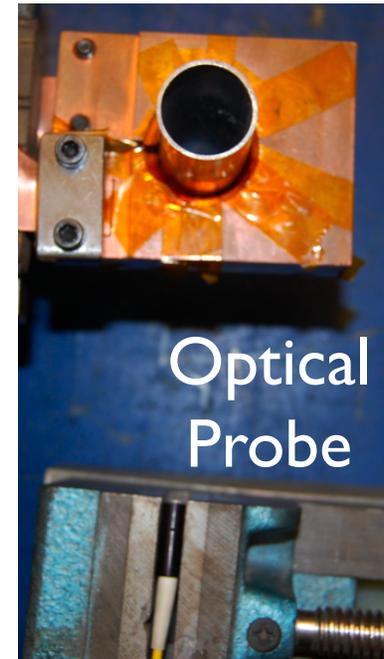
Work in support of  $P$ - $\lambda$  EOS validation

- Concept: a primary current pulse through a surrounding coil develops eddy currents in a containment tube.
- Electromagnetic force between the coil and tube provides a radial EM pressure on the tube.
- Velocity is measured, and EM pressure,  $P_M$  can be accurately calculated, allowing precise estimates of media pressure-volume relationships at the mixture-tube interface.



# Procedures (Initial EM Compression Testing)

- Tubes of 6061-T4 aluminum with a 31.75 mm OD and 1.5 mm wall thickness were studied empty and filled with hand-compacted foundry sand (sand with size range and some binder, etc.) Properly sized rubber-stoppers held the sand in the tube.
- Compaction was carried out with a very simple (low efficiency and poor uniformity) single turn copper work coil with a high-pressure region that acts over 15 mm of the tube. (total nominal coil thickness was 25 mm).
- A 9mm diameter hole in the coil accommodated the laser reflection for the PDV, which measured tube velocity w.r.t time. A probe with a 100 mm focal length was used in this exercise.
- A calibrated Rogowski Coil was used to measure the primary current with time. A second coil could be used to measure the induced current, or it can be calculated.



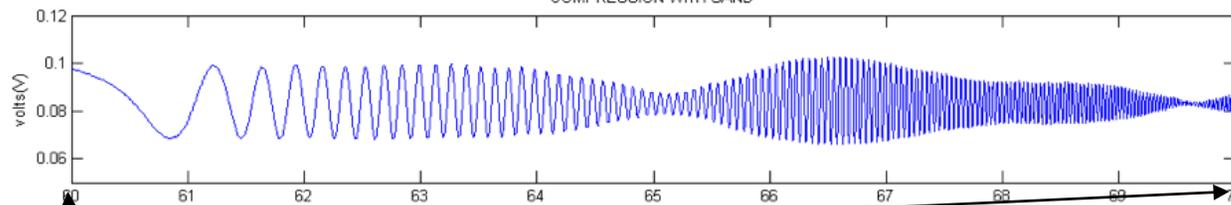
# Results (Preliminary EM Compression Testing)

- Tubes compacted with and w/o silica sand with a 6.4 kJ discharge (low energy).
- Both tubes show significant compaction and had a 'bubble' near the location of the hole in the coil. Despite this there was about 1mm of deformation near where the PDV signal was taken. Its also likely there was some motion of the tube axis off center because forces were not balanced.
- Good PDV data was obtained in the filled tube test. The more extensive deformation and convex surface of the unfilled tube gave low reflected intensity over part of the unfilled test.

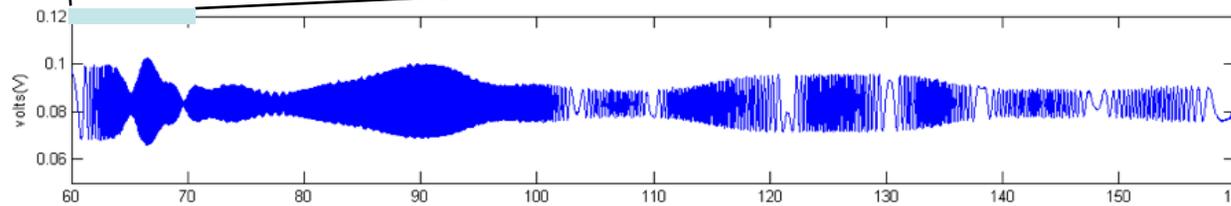


profile of bump

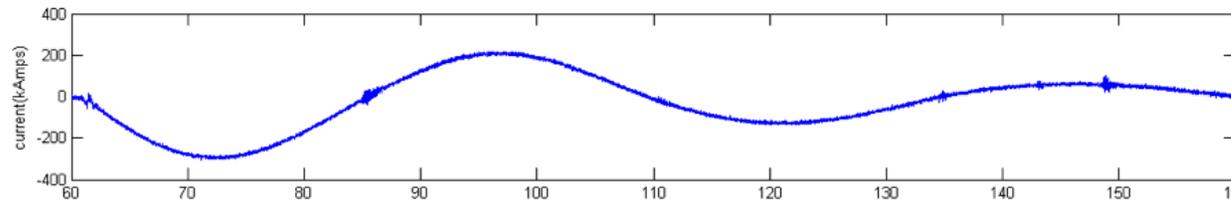
# Data (Preliminary EM Compression Testing)



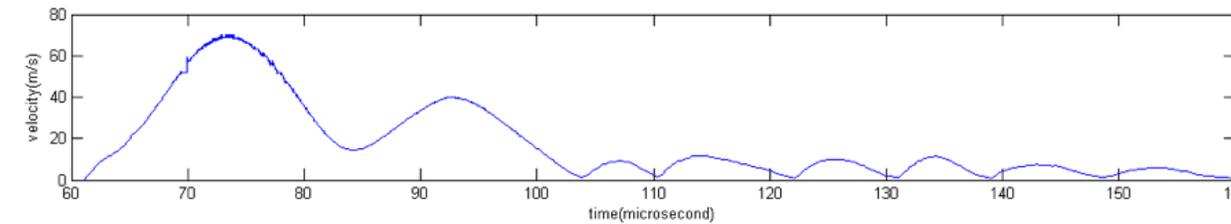
Raw PDV signal for first 10 $\mu$ s



Raw PDV signal over expt.

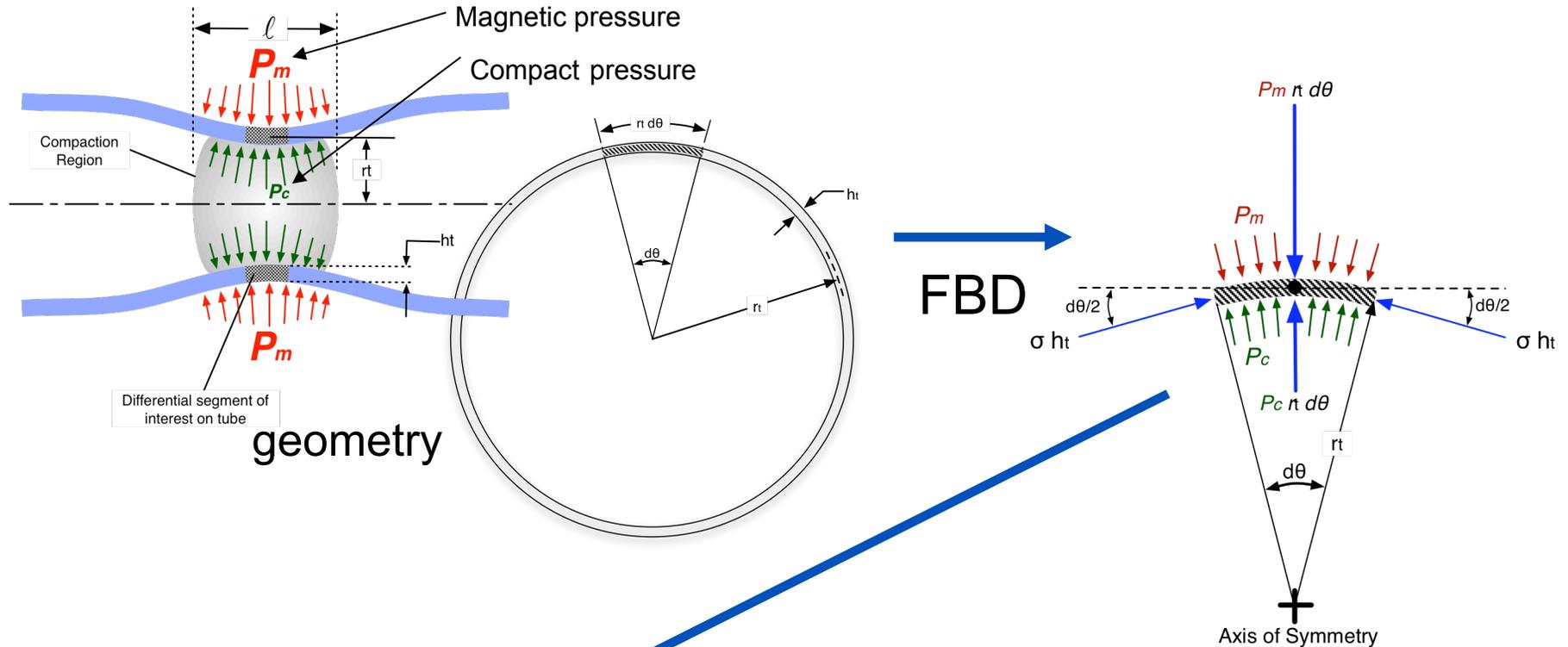


I(t) over entire expt.



Tube velocity over entire expt.

# Compaction Analysis



$$\frac{dV_{r_t}}{dt} = \frac{(P_m - P_c)r_t}{\rho_t h_{t_0} r_{t_0}} - \frac{\sigma_t}{\rho_t r_t}$$

$$P_m = \frac{\frac{1}{2} \frac{\partial L_2}{\partial r} I_2^2 + \frac{\partial M}{\partial r} I_1 I_2}{2\pi r_t \cdot l}$$

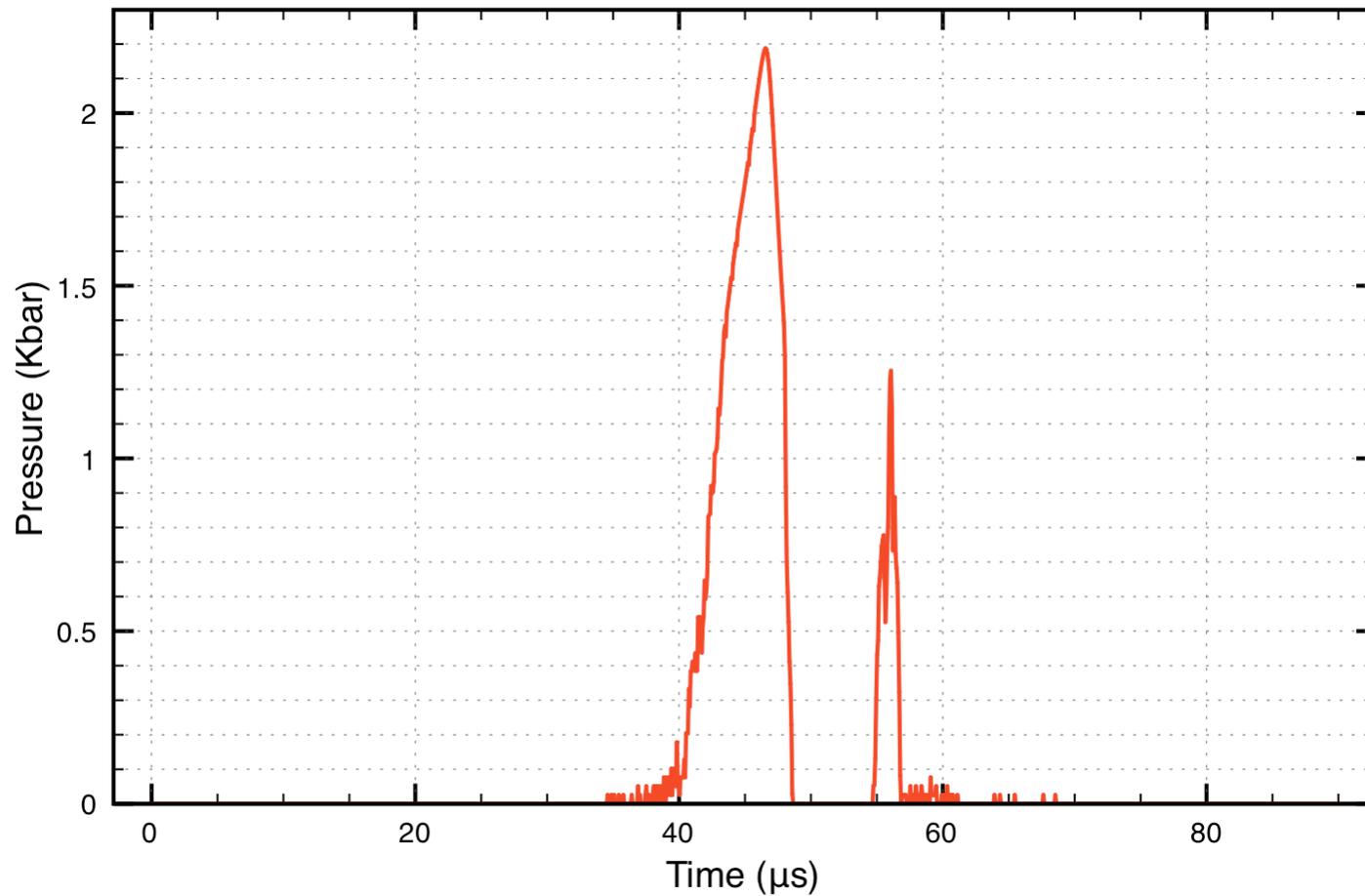
$$\sigma_t = f(r(t))$$

Experimentally Determine:  
 $\dot{r}(t), I_1, I_2$

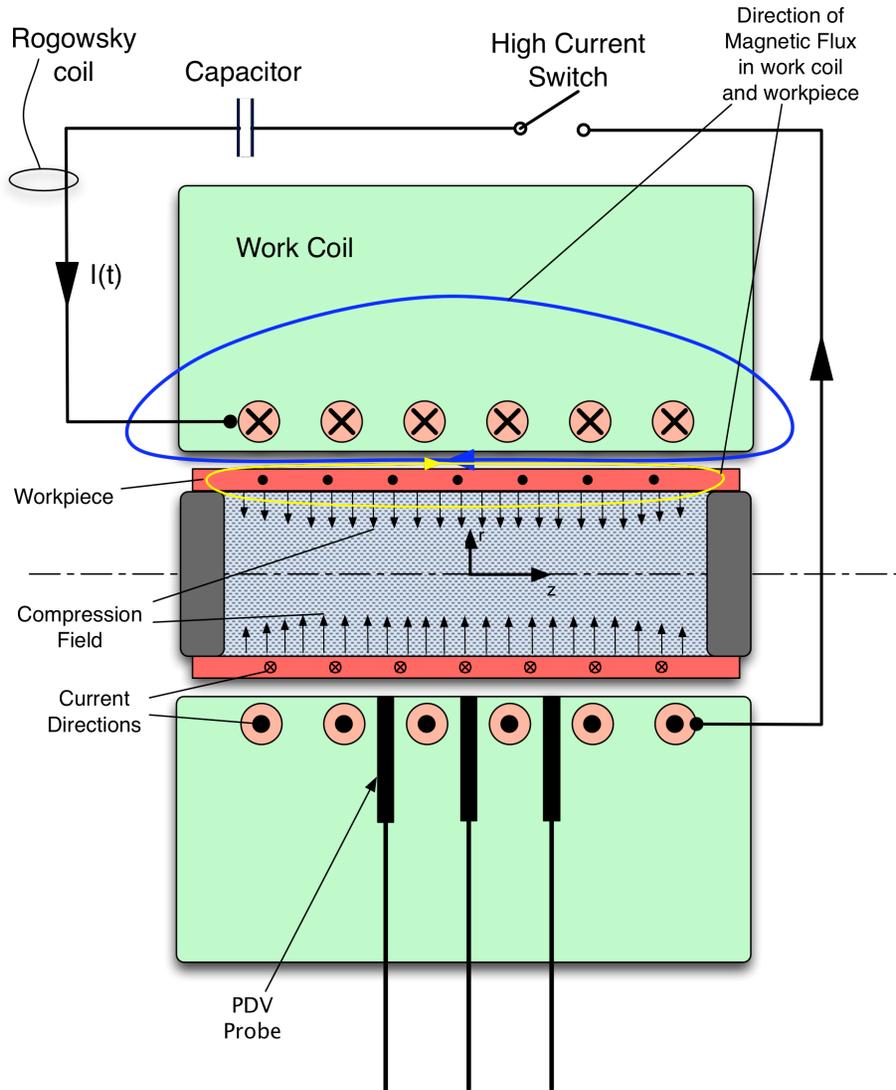
$$P_c = P_m - \frac{\rho_t h_{t_0} r_{t_0}}{r_t} \left( \ddot{r}(t) + \frac{\sigma_t}{\rho_t r_t} \right)$$

# Compaction Analysis Provides...

After some data analysis you can find the compaction pressure at the inside of the compressed tube... It may look something like this...



# Actual EM Compaction Setup



More work to come on the compaction testing...