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Diagnosing Pulsed Power Flow Through Velocimetry

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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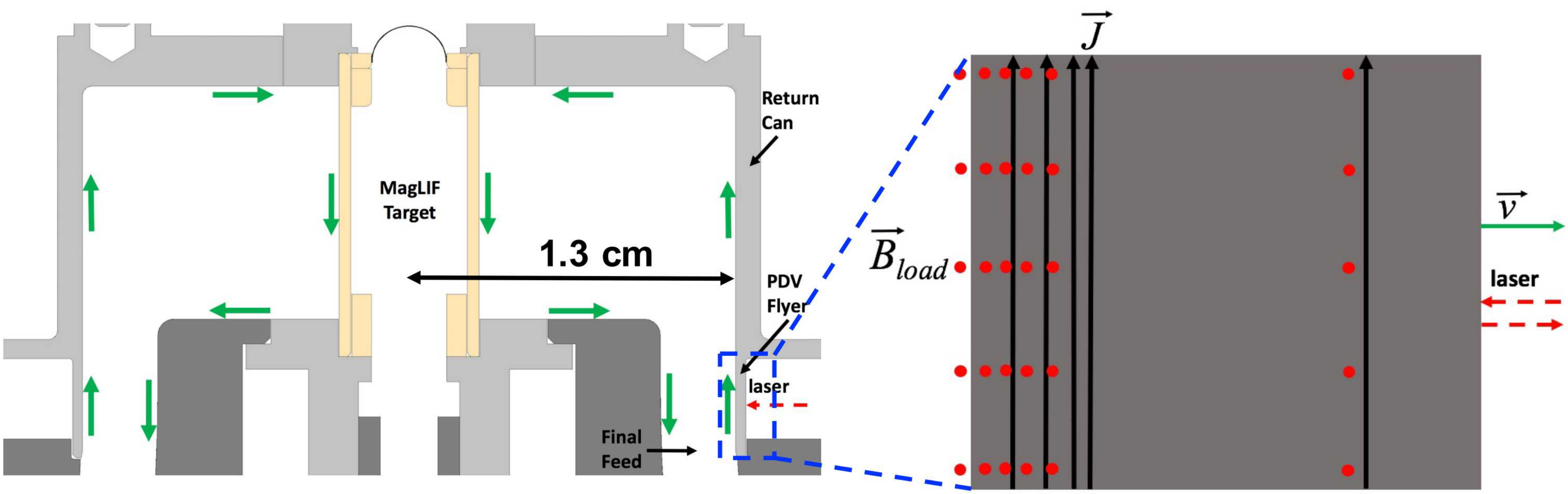
Outline

- **Why do we use velocimetry, such as PDV (Photonic Doppler Velocimetry)/VISAR (Velocity Interferometer System for Any Reflector) for diagnosing pulsed power?**
- **How do we simulate velocimetry?**
- **Application 1: Inferring Current Near a Load**
- **Application 2: Assessing Uncertainty on a Peak Load Current**
- **Application 3: Detecting the Presence of Charged Particles in inner MITLs**

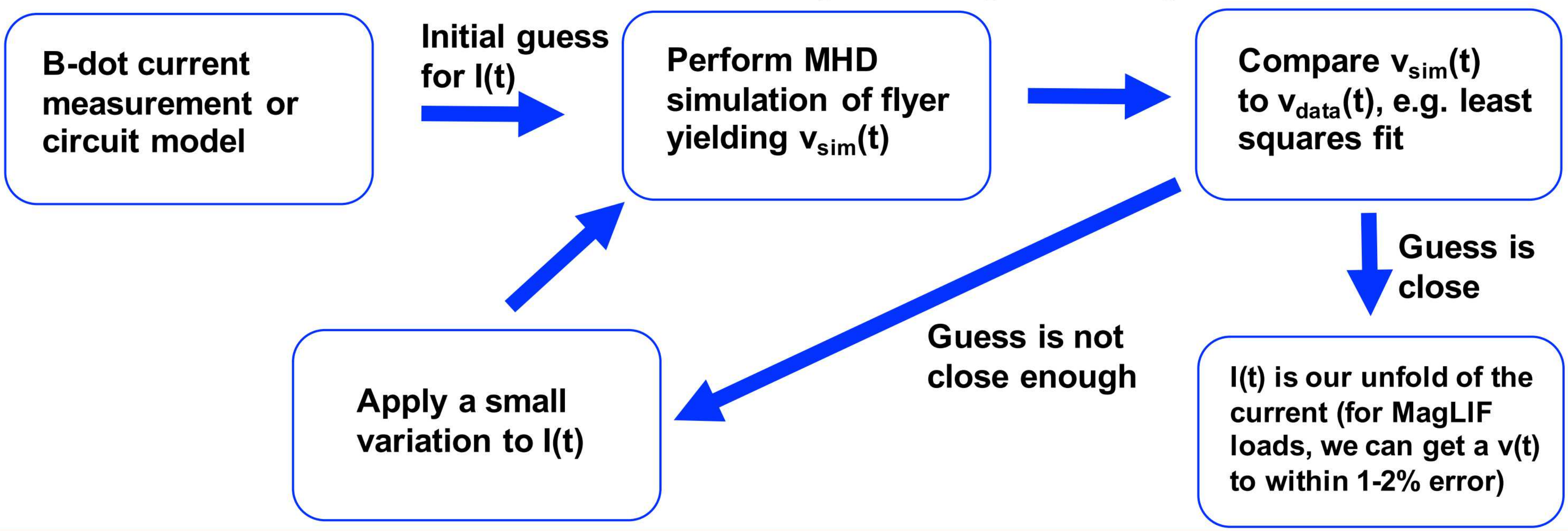
Velocimetry Diagnostics for Pulsed Power

- **For pulsed power systems, such as Sandia's Z machine, we would like to measure the current as close to the load region as possible.**
- **B-dot probes are always used for measuring current, but can be noisy and are known to fail sufficiently close to the load.**
  - **The closest B-dots on Z machine are at r = 6 cm, near the convolute posts.**
- **Our experiments, such as MagLIF, regularly infer that significant current loss is occurring in the inner MITL/return can region for r < 6 cm.**
- **Velocimetry techniques, such as PDV/VISAR, offer a non-invasive method for inferring magnetic pressure, and hence, current near the load by measuring the motion of a metal flyer region of the inner MITL/return can.**



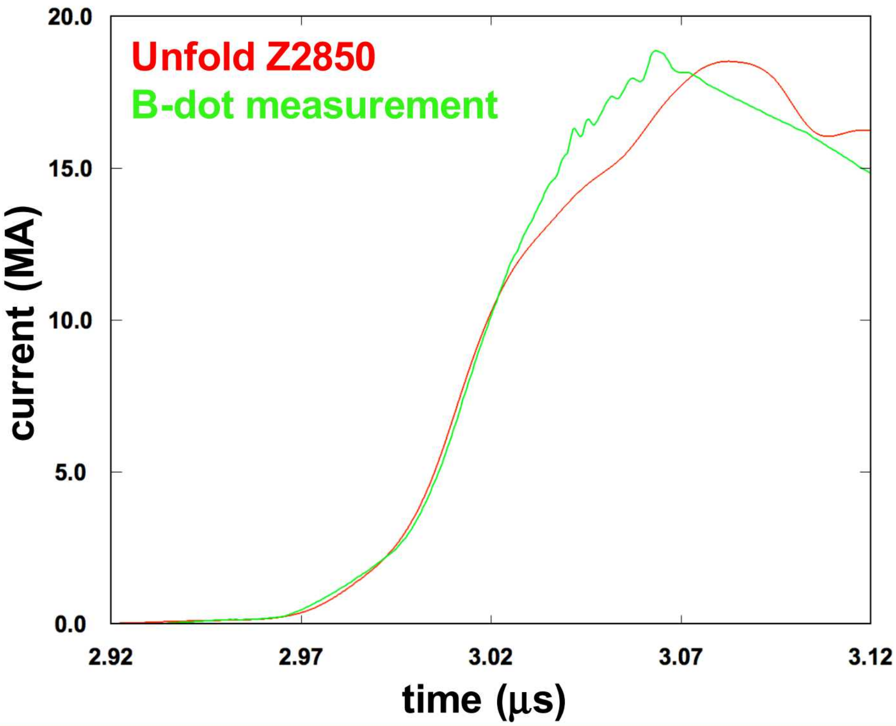
Simulating Velocimetry

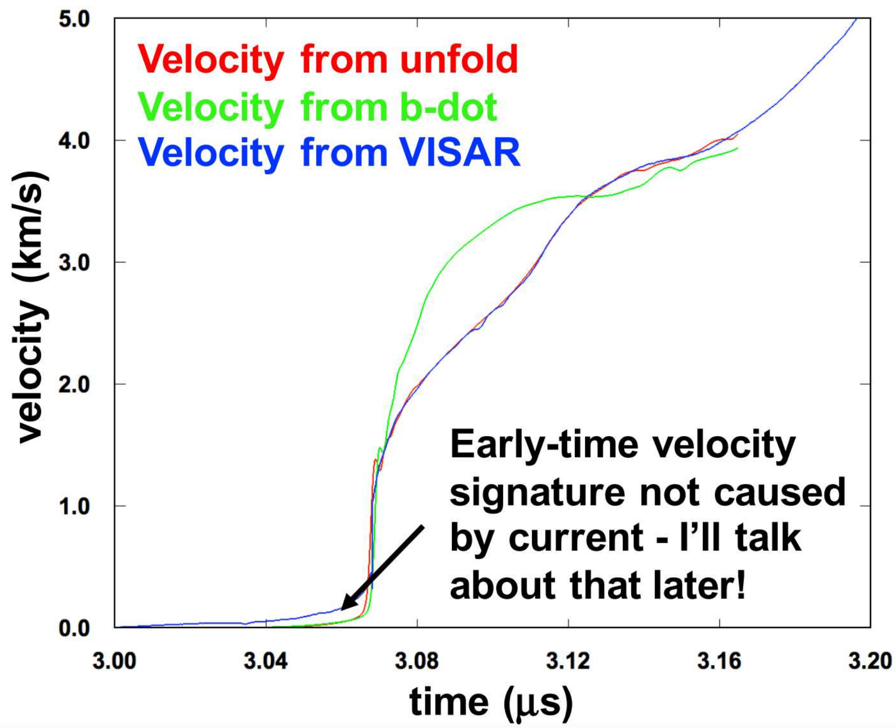
- **Since typically pulsed power velocimetry is measuring the motion of a flyer in response to a magnetic pressure, three elements are needed for simulations:**
  - **1) MHD code, e.g. ALEGRA[1] (SNL), HYDRA[2] (LLNL), GORGON[3] (SNL / Imperial College)**
  - **2) accurate EOS/conductivity models of the flyer material, e.g. SESAME[4] (LANL) / Lee-More-Desjarlais[5] conductivity**
  - **3) additional current measurement (e.g. B-dot) or an accurate circuit model of the pulsed power system**



Inferring Current Near A Load

- **The combination of a high-quality flyer velocimetry measurement (small velocity uncertainty), accurate MHD code, and high-quality EOS/conductivity tables for the flyer material yields an excellent inferrence of the current at the flyer location.**
- **Using a B-dot measurement or circuit model, as a starting point, a load current I(t) is varied over hundreds, possibly thousands, of individual simulations until the simulated flyer velocity is sufficiently close to the measured flyer velocity.**
- **Normally, our codes can find a current which produces a simulated velocity within 1-2% of the measured velocity for most of the pulse.**





Load current unfold courtesy of C. A. Jennings

Sources of Uncertainty

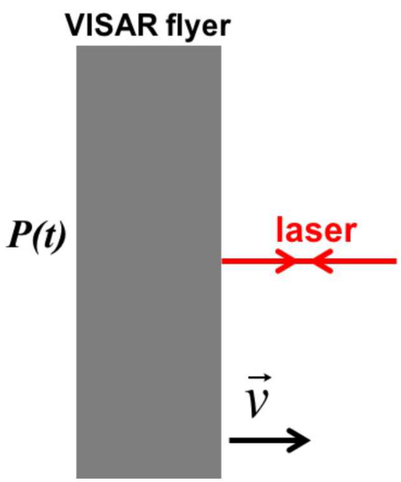
- **In general, it can be challenging to assess an uncertainty on the current unfold since the response of a flyer to a given current is highly nonlinear and there are a number of sources of uncertainty**
  - **Uncertainty in measured velocity (typically small)**
  - **Uncertainties in 3-D field asymmetries (may or not be small)**
  - **Uncertainties in MHD simulations**
    - **Numerical errors in code (typically small effect)**
    - **EOS uncertainty (may not be small)**
    - **Conductivity uncertainty (may not be small)**

- **As of yet, we do not have an accurate assessment of the uncertainty for a full MagLIF time-dependent current unfold, which incorporates uncertainties in the EOS/conductivity.**

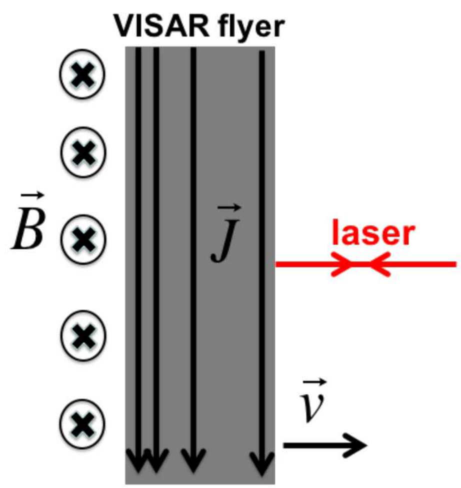
- **However, we can make an assessment of the uncertainty for the peak current of a MagLIF load.**

Measuring Peak Load Current

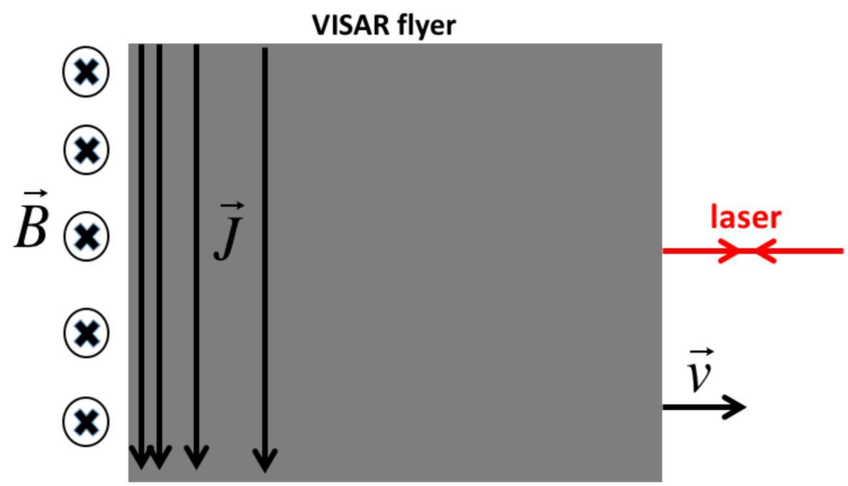
- Previous work on mechanical pressure driven velocimetry[6] showed that the magnitude of the flyer velocity had a one-to-one relation to the mechanical pressure applied at an earlier time on the opposite surface. From this relation, we can derive an expression for a peak velocity in terms of a peak mechanical pressure.
- In general, magnetic pressure in a flyer has nonlinear distributed JxB forces, so the flyer velocity at any time is not directly related to the magnetic pressure at an earlier time.
- However, by increasing the flyer thickness, the JxB forces are "more localized" to the flyer surface[7]. The system then resembles mechanical pressure PDV/VISAR.
- Our derived peak velocity for a given peak magnetic pressure yields an estimate of the load current uncertainty.



Mechanical Pressure PDV/VISAR



Magnetic Pressure PDV/VISAR

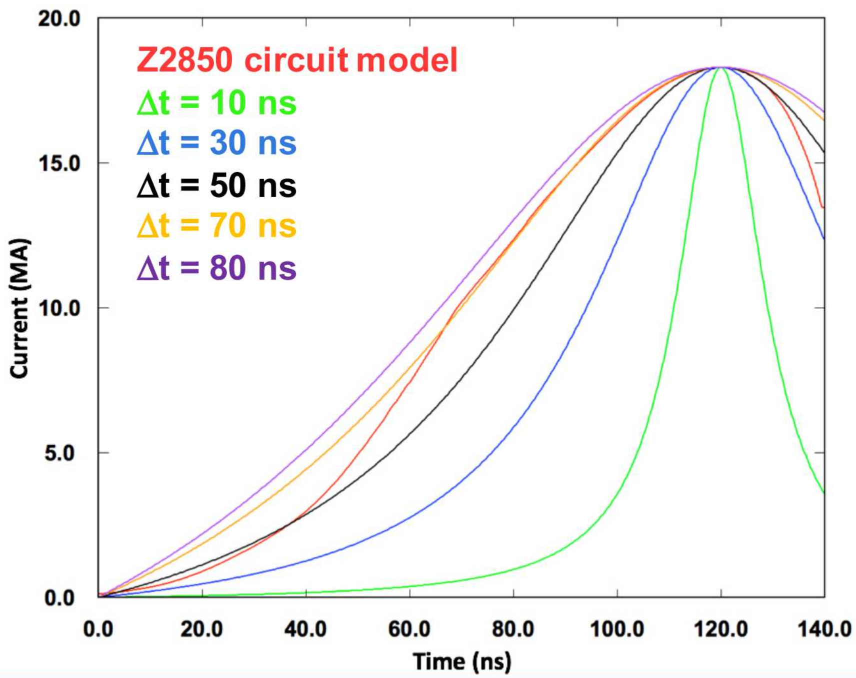


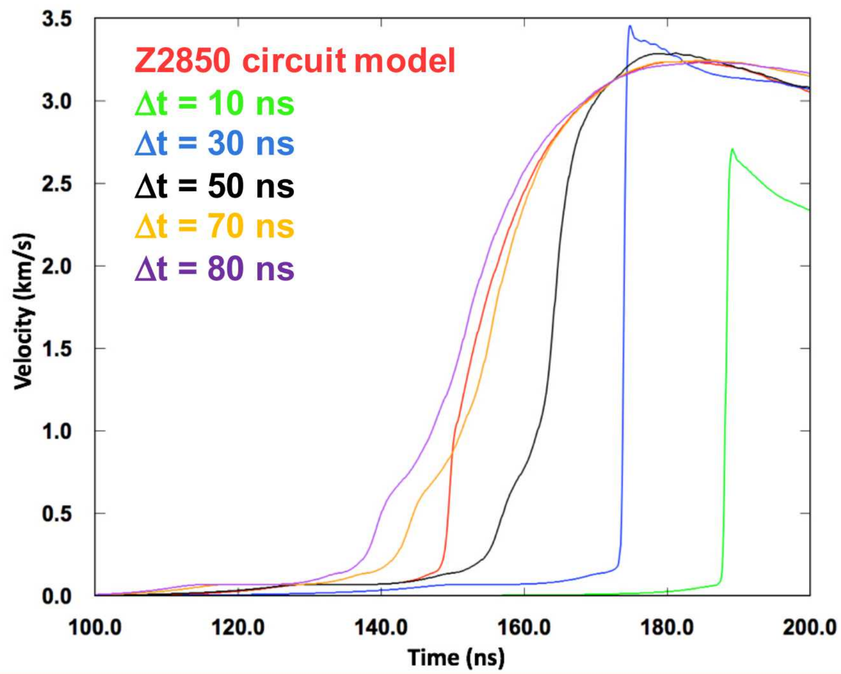
Larger Thickness - Magnetic Pressure PDV/VISAR for Peak Current Measurements

Peak Current and Peak Velocity

- **MagLIF current profiles are typically ~120 ns in length, monotonically increase to a peak current, and then have an inductive dip.**
- **We compare the simulated flyer velocities for a 600 μm thick aluminum flyer using a MagLIF circuit model[8] load current with Lorentzian shaped current pulses that have the same peak load current (18.3 MA) at the same peak time of 120 ns.**

$$I(t) = \frac{I_{peak}}{1 - f(t_{peak})}\left(f(t - t_{peak}) - f(t_{peak})\right) \qquad f(t) = \frac{1}{1 + t^2/\Delta t^2}$$





Flyer Thickness Design for a Reliable Peak Current Measurement

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- **From the table below, we expect that differences in current shape would cause a 1.5% variation in the peak flyer velocity for a 600 μm aluminum flyer.**

	Current Model	Peak Velocity (km/s)
	Z2850 Circuit	3.236
Outside of MagLIF range	$\Delta t = 10$ ns	2.710
	$\Delta t = 30$ ns	3.456
Within MagLIF range	$\Delta t = 50$ ns	3.286
	$\Delta t = 70$ ns	3.242
	$\Delta t = 80$ ns	3.234

- **Flyer thickness design for measuring a peak current on an arbitrary pulsed power machine:**

$$L > 10(\tau_{pulse}\eta/\mu_0)^{1/2}$$

Flyer needs to be "thick enough" to prevent magnetic diffusion (L > 490 μm).

$$L < \Delta t/(\frac{\rho_0}{\rho_{hp}c_{hp}} - \frac{\rho_0}{\rho_p c_p})$$

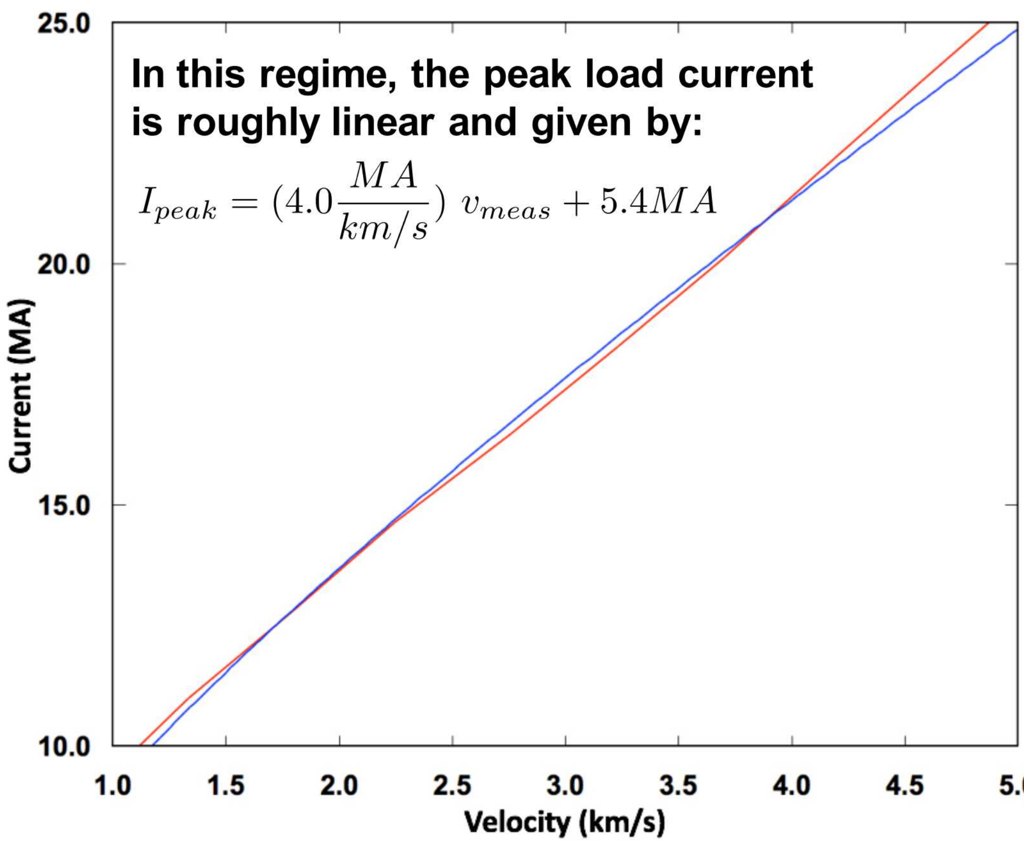
Flyer needs to be "thin enough" to prevent pressure waves at peak pressure from overtaking waves at half-peak causing a shock at the flyer (L < 1.0 mm)

Inferring the Peak Current from the Peak Flyer Velocity

- **By performing a series of forward simulations with ALEGRA[1], we can produce a curve (red) which relates the peak load current and peak velocity for a 600 μm aluminum flyer at a radius of 1.3 cm.**
- **The blue curve shows a 1-D model of the flyer velocity using the following peak mechanical pressure/peak velocity formula from the T = 298 K Al 3700 SESAME[4] table.**

$$v = 2\int_0^P \frac{dP}{\rho(P)c(P)}$$

- **The 1-D model yields the sensitivity of the inferred current for a given uncertainty in the EOS table.**



EOS/Conductivity Uncertainty

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- **Suppose that we apply a uniform uncertainty to the SESAME[4] Al 3700 EOS pressure function:**

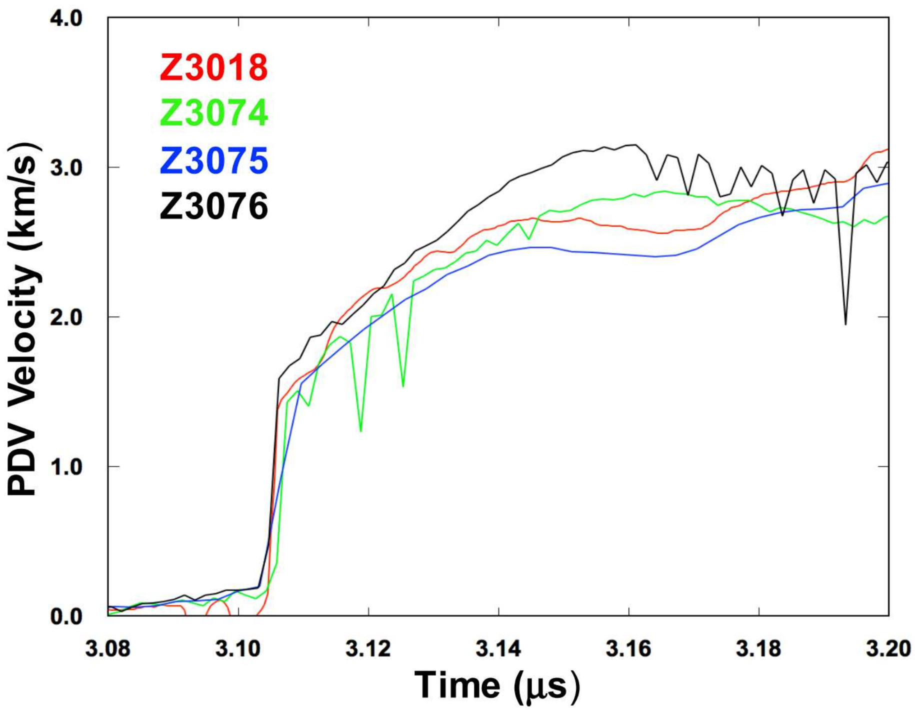
$$P(\rho) = P_{true}(\rho)(1+\epsilon)$$

- **The uncertainty causes a shift in the peak velocity vs. peak current curve yielding an uncertainty in the simulated peak current.**
- **In ALEGRA[1], we can apply a uniform uncertainty factor to the LMD[5] conductivity over all density and temperature space to test the velocity uncertainty.**

$$\sigma(\rho, T) = \sigma_{true}(\rho, T)(1+\epsilon)$$

Peak Velocity (km/s)	$\delta v_{EOS}/v$ (ϵ = **5% ,10%**)	$\delta v_{cond}/v$ (ϵ = **5% ,10%**)
2.0	1.8%, 3.4%	0.2%, 0.5%
3.0	1.5%, 2.8%	0.2%, 0.4%
4.0	1.3%, 2.3%	0.4%, 0.7%

Measured MagLIF Peak Currents and Uncertainties



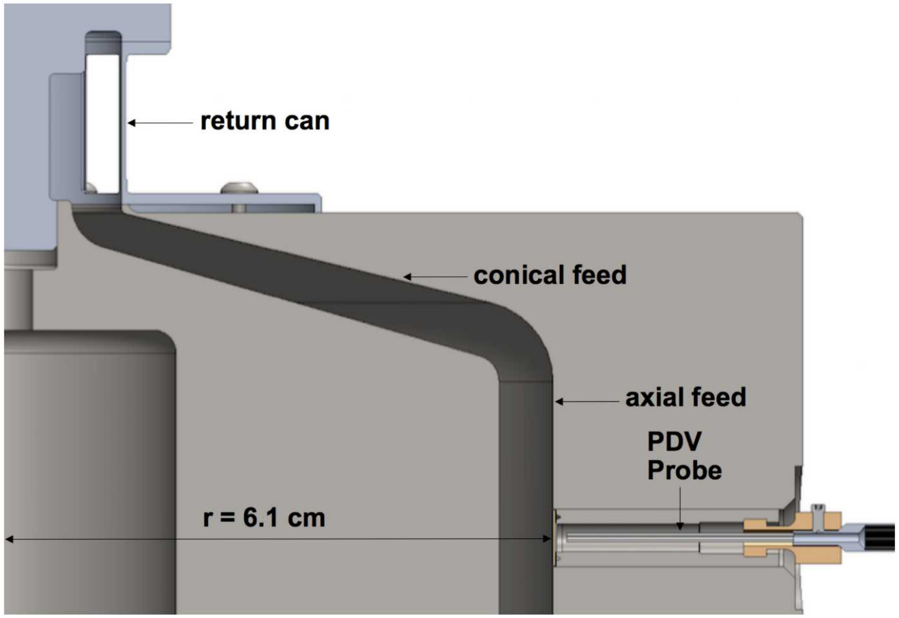
- **By finding the peak measured flyer velocity from each MagLIF shot and assuming a 5% uniform EOS uncertainty and up to 10% uniform conductivity uncertainty for aluminum, we can provide an uncertainty estimate in our peak load current.**
- **The measured peak load currents and predicted circuit model currents are in agreement to within the combined uncertainty bounds of the measurement and circuit model.**

Shot	Velocity (m/s)	I_{meas} (MA)	I_{circ} (MA)
Z3018	2638 ± 15	16.0 ± 0.3	15.2 ± 0.8
Z3074	2822 ± 14	16.7 ± 0.3	17.9 ± 0.9
Z3075	2435 ± 15	15.2 ± 0.3	15.2 ± 0.8
Z3076	3080 ± 98	17.7 ± 0.5	18.5 ± 0.9

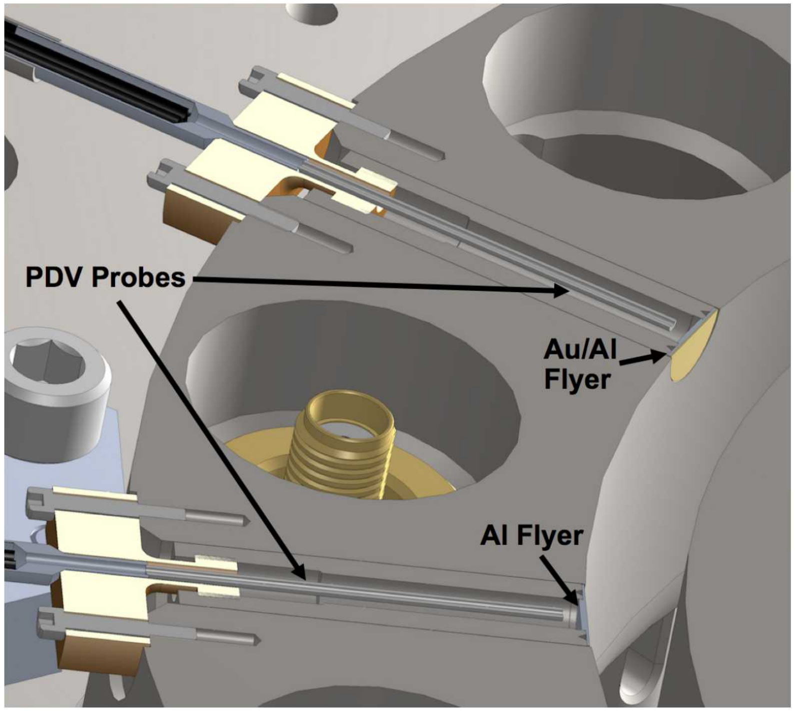
Detecting Charged Particles with Velocimetry

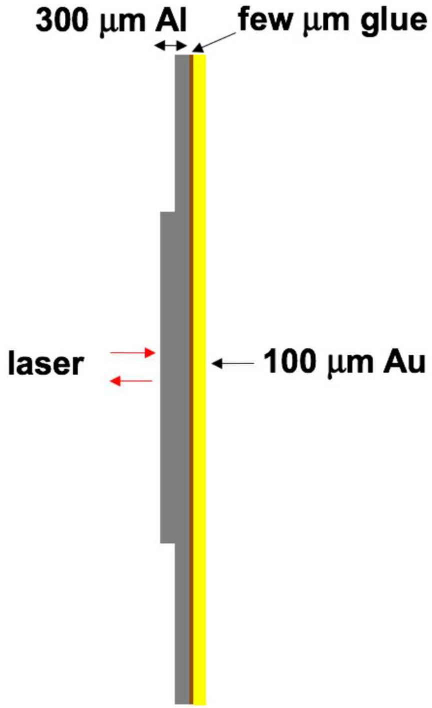
- Starting in 2015, we noticed that a number of MagLIF shots with flyers near the top of the final feed on the anode side had early-time velocity signatures that could not be explained with current [9]. Velocimetry can measure other "pressures" besides magnetic pressure in our inner MITLs/return can!
- PIC simulations, as well as, magnetic insulation calculations suggested that either electrons or negative ions impacting the flyer could be the explanation.
- In recent Z shots dedicated to studying power flow, we fielded a novel PDV diagnostic which has been developed for detecting particle loss in the axial power feed on the anode side.
- The novelty of this diagnostic is that the flyer can be comprised of different metals, e.g. Al and Au, having different sound speeds and charged particle stopping powers to determine whether electrons or negative ions are impacting the PDV flyer, and the power deposition from those charged particles.

Hardware for recent Z experiments investigating power flow showing the location of our PDV probe for detecting particle loss



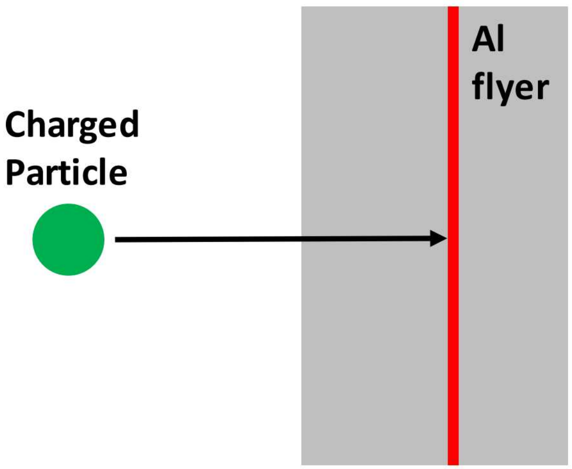
PDV Diagnostic



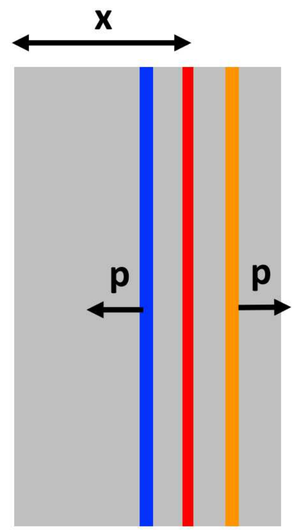


- There were three experiments in a recent series that fielded the probes in pairs at the same axial height and radius, but using different flyers.
- Au and Al composite flyers were glued together.
- Three Z experiments
  - Z3184: 400 μm Al and 100 μm Au / 300 μm Al
  - Z3185: 400 μm Al and 200 μm Au / 200 μm Al
  - Z3186: 100 μm Au / 300 μm Al and 200 μm Au / 200 μm Al

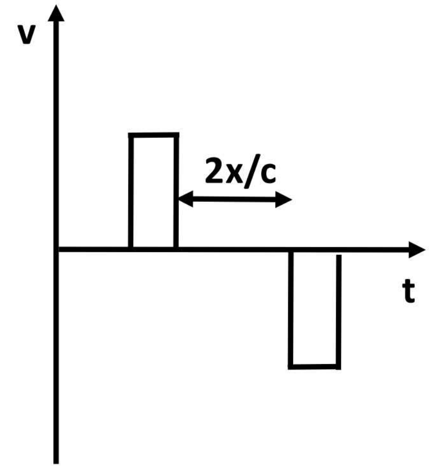
How the PDV Particle Detectors Work



particles deposit their energy into the flyer



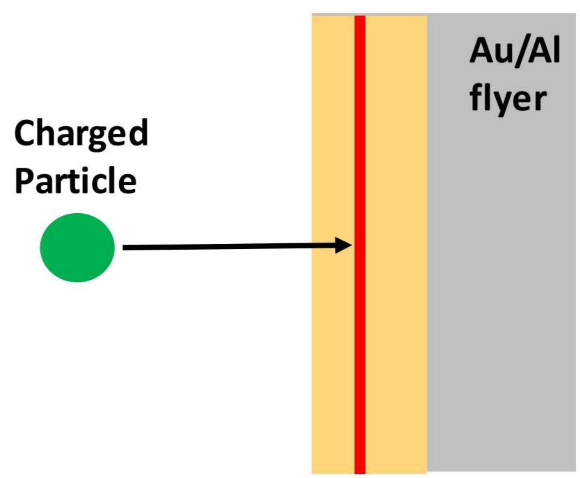
local energy deposition results in two propagating pressure waves carrying opposite momenta

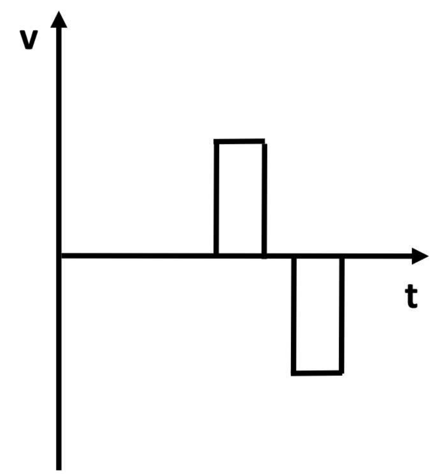


PDV probe measures velocity signals that depend on where the energy was deposited and the flyer sound speed

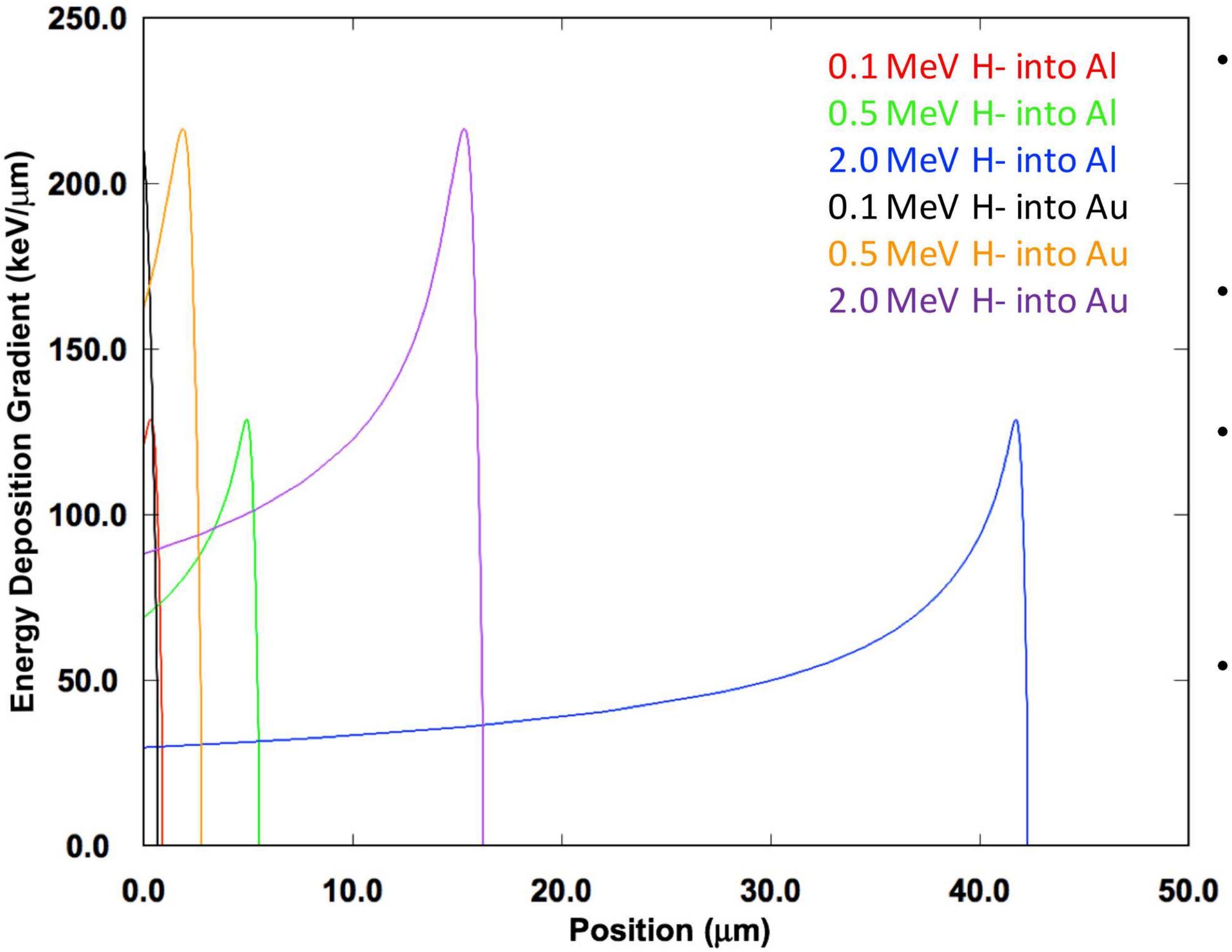
Flyers made of a Au/Al substrate will have a different location of the energy deposition compared to Al flyers since the two metals have different charged particle stopping powers.

This results in measurable differences in PDV flyer velocities between different flyers.





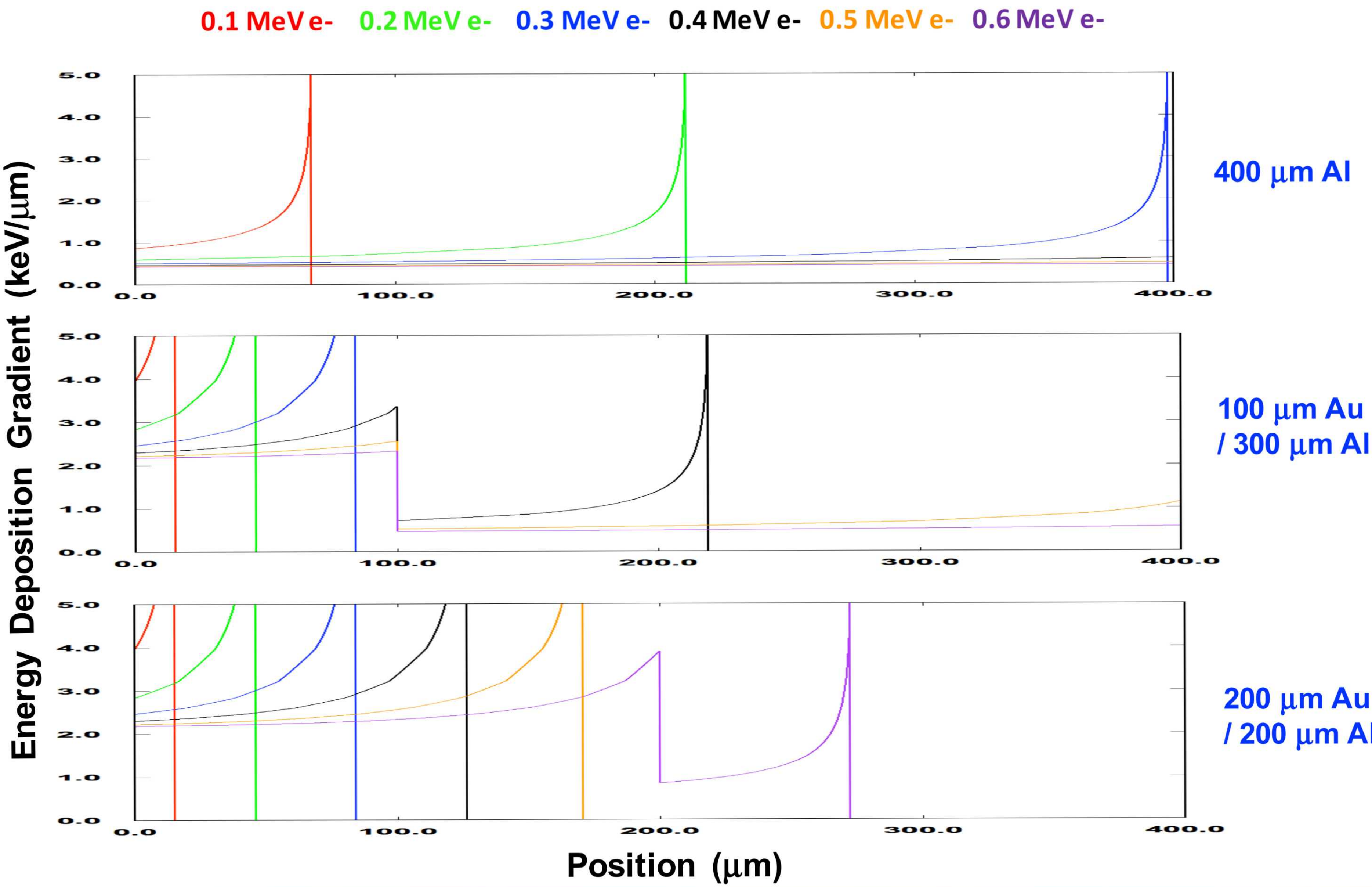
Comparative Ion Energy Deposition



- **Using well-known stopping power tables[10], we can calculate the energy deposition for ions into Al and Au.**
- **In general, Au has a higher stopping power than Al.**
- **Even for 2 MeV H- at normal incidence Al, the ion will only penetrate at around 40 mm into the flyer.**
- **Since the flyer thicknesses are 400 mm thick, ions will mainly deposit their energy near the surface <10% of the flyer bulk mass.**

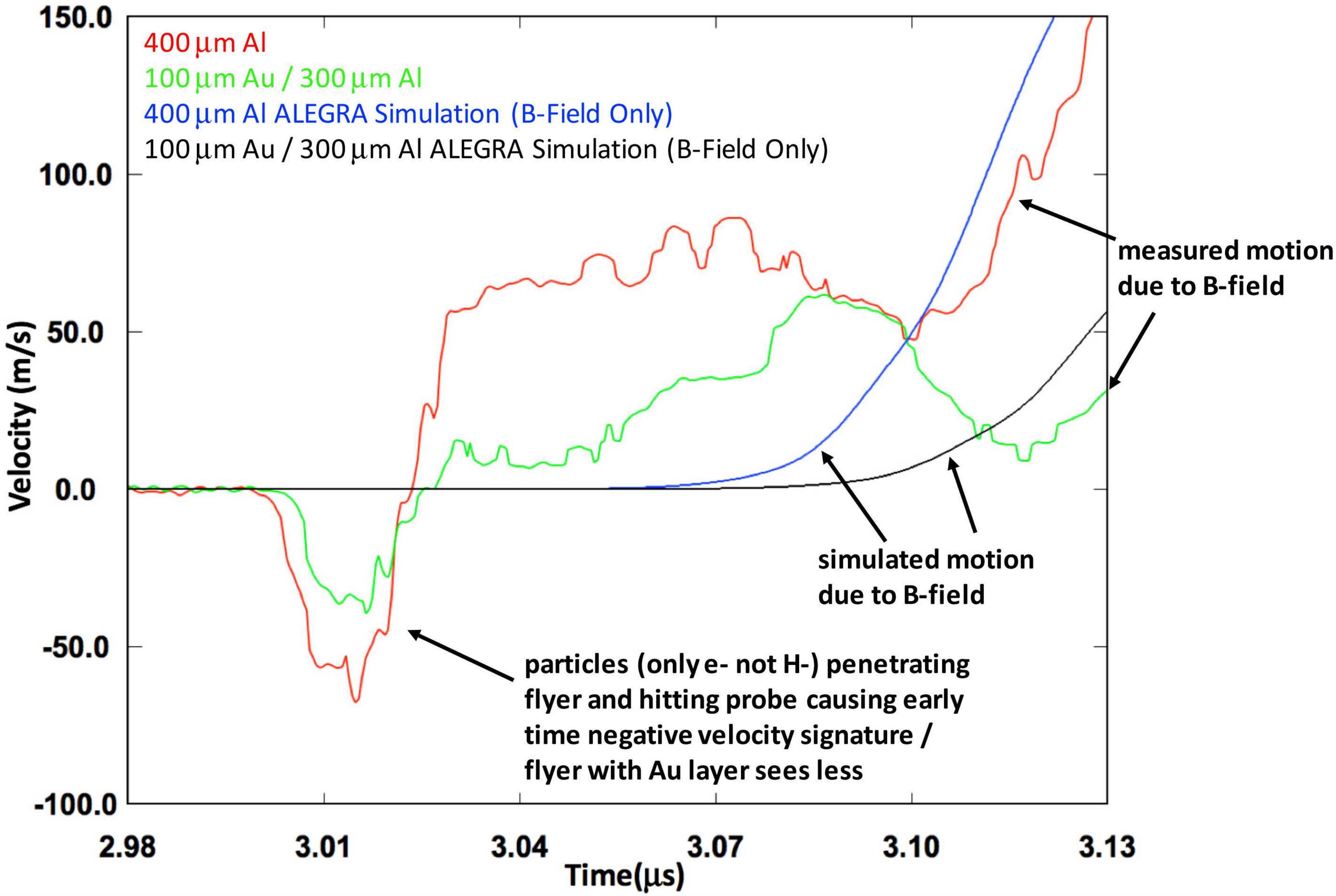
[10]M. J. Berger, J. S. Coursey, and M. A. Zucker, NIST Physical Reference Data

Comparative e- Energy Deposition[10]



[10]M. J. Berger, J. S. Coursey, and M. A. Zucker, NIST Physical Reference Data

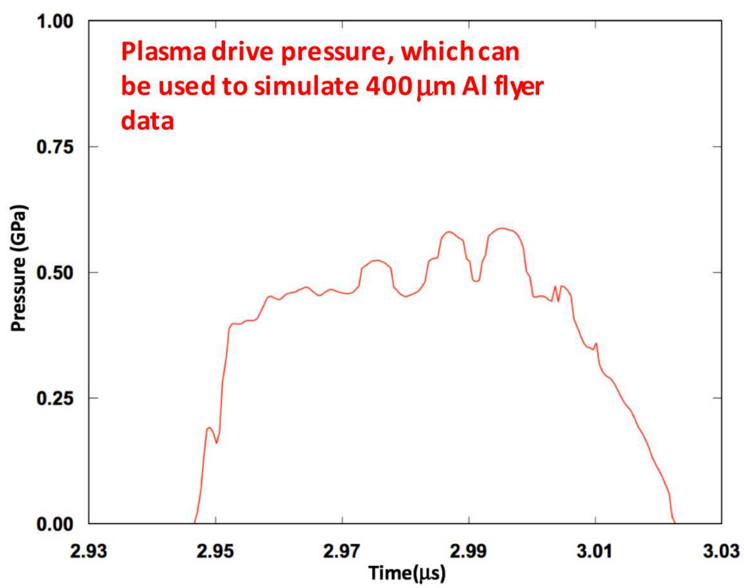
Z3184 Data

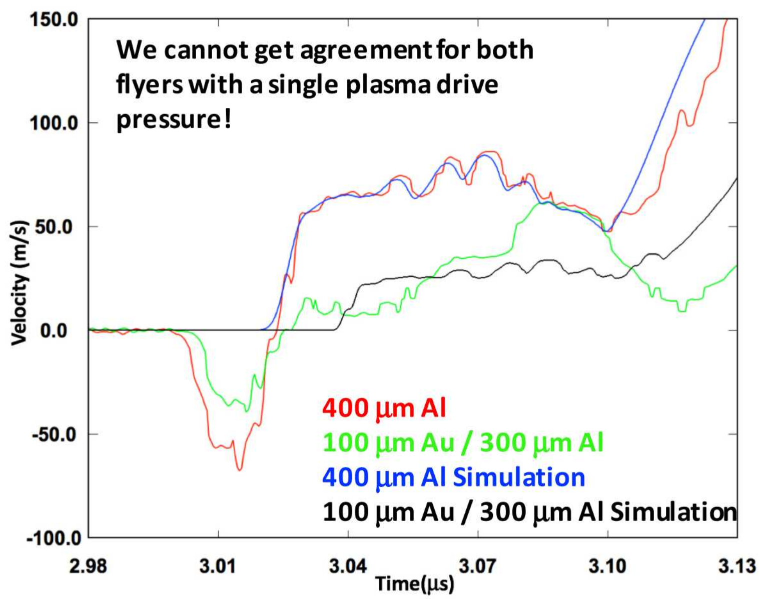


400 μm Al
100 μm Au / 300 μm Al
400 μm Al ALEGRA Simulation (B-Field Only)
100 μm Au / 300 μm Al ALEGRA Simulation (B-Field Only)
150.0
100.0
50.0
0.0
-50.0
-100.0
Velocity (m/s)
2.98
3.01
3.04
3.07
3.10
3.13
Time(μs)
measured motion due to B-field
simulated motion due to B-field
particles (only e- not H-) penetrating flyer and hitting probe causing early time negative velocity signature / flyer with Au layer sees less

Discussion

- We think that the negative velocity signature of energy hitting the PDV probe is probably not due to
  - ions since ions can only penetrate 40 mm into Al and even less into Au.
  - photons since we would need energies in excess of 30 keV and the simulated inner MITL temperatures do not exceed 10 eV.
- Moreover, we know that the measured positive velocity cannot be due to a neutral plasma hitting the flyers since a given plasma pressure cannot be used to simulate both flyer velocities.





- Our best conclusion: the PDV flyers for the recent power flow series are detecting electrons in the axial portion of the inner MITL.

Present Simulations

- **ALEGRA[1] simulations, in which energy is deposited into the flyer as a function of time, suggest that the measured velocities can be roughly explained by a 23 ns power deposition (time-scale of negative velocity signature) by the electrons within the bulk of the flyers having a deposition rate of 18 GW/cm^3 for the 400 mm Al flyer.**

- **However, matching the velocity data for both flyers is an ongoing project.**

- **This problem may not be solved using a fluid MHD code alone.**
  - **Since the theory of the flyer motion relies on understanding kinetic energy deposition of particles into the flyer, a hybrid fluid/kinetic method may be needed.**

Summary

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- At Sandia, velocimetry based diagnostics offer a rich and active area for studying pulsed power on Z machine.

- Our understanding of data from these diagnostics ultimately depends on how well we can model them using MHD codes / hybrid codes (in the future).

    - This also depends on the accuracy of our EOS/conductivity models.

- Velocimetry diagnostics provide a measure of the load current, as well as a glimpse into the local time-dependent conditions, such as energy deposited into the inner MITL wall by particles.

- We are actively looking for new applications of velocimetry diagnostics for investigating pulsed power!

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