SAND2017-11317C

A Novel Peak Load Current Measurement for Magneto-Inertial-Fusion Targets

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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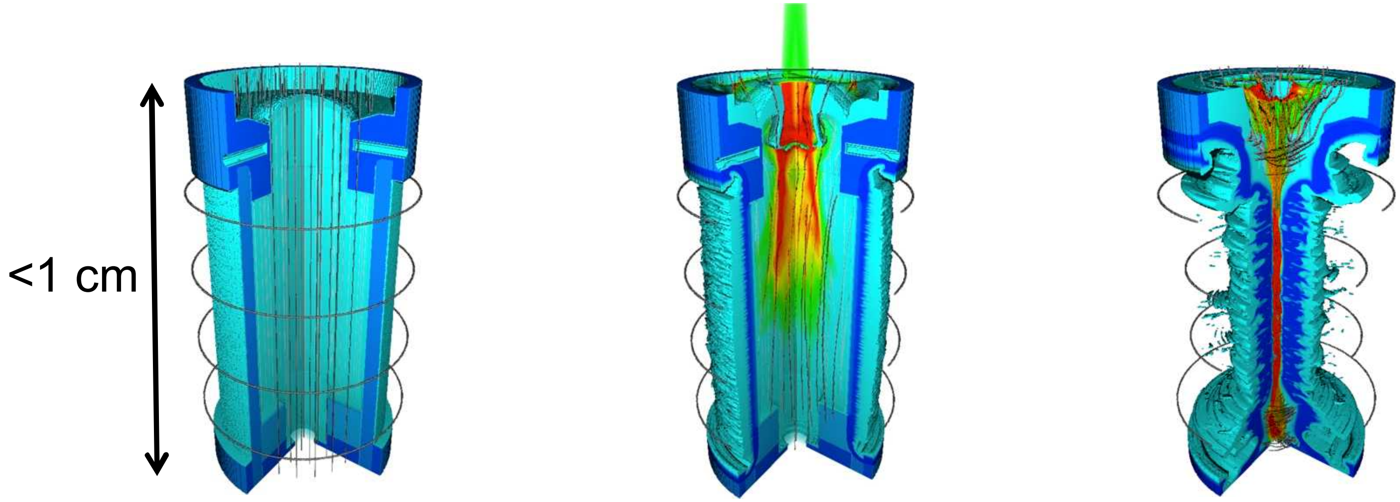
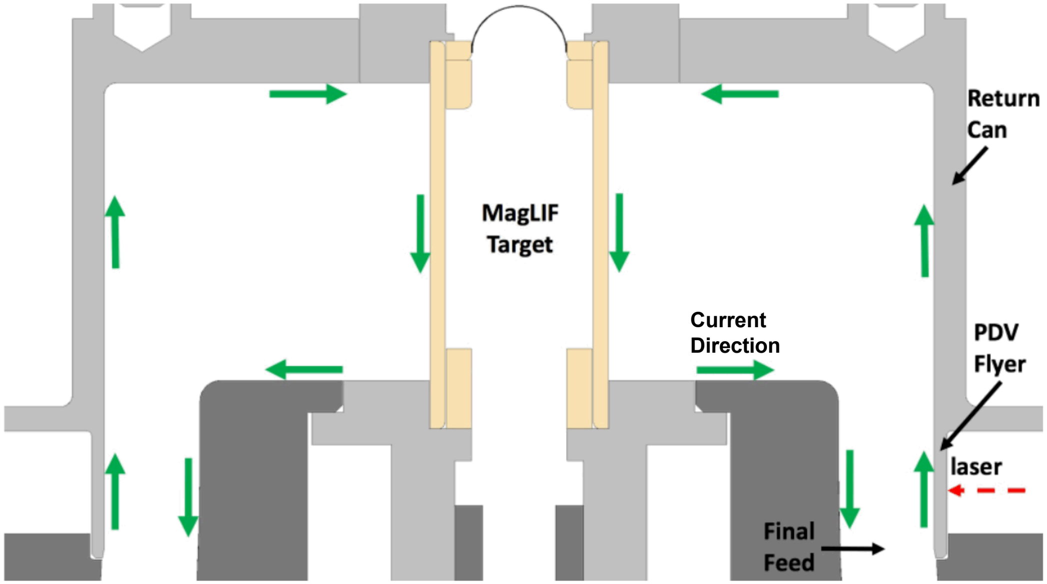
Motivation

- A novel fusion concept called MagLIF[1] (Magnetized Liner Inertial Fusion) is currently under development at Sandia.
  - A cylindrical metal liner, e.g. Al or Be, that contains a fuel is initially axially magnetized.
  - The fuel is preheated with a laser.
  - The liner, fuel, and magnetic field are all compressed with a high-current magnetic drive, e.g. Z machine, which can lead to fusion relevant conditions in the fuel.
  - The compressed axial magnetic field gives reduced electron thermal heat conduction losses and increased ion confinement.



PDV/VISAR Load Current Diagnostic



- Our PDV/VISAR system uses laser interferometry to measure the velocity of the metal flyer which is a few millimeters below the return can in the final power feed.
- The flyer velocity is due to the magnetic pressure from the MagLIF load current.
- Using an MHD code such as, ALEGRA[2], one can perform forward calculations to unfold the approximate time-dependent load current, which yields the measured flyer velocity.

Peak Load Current Diagnostic

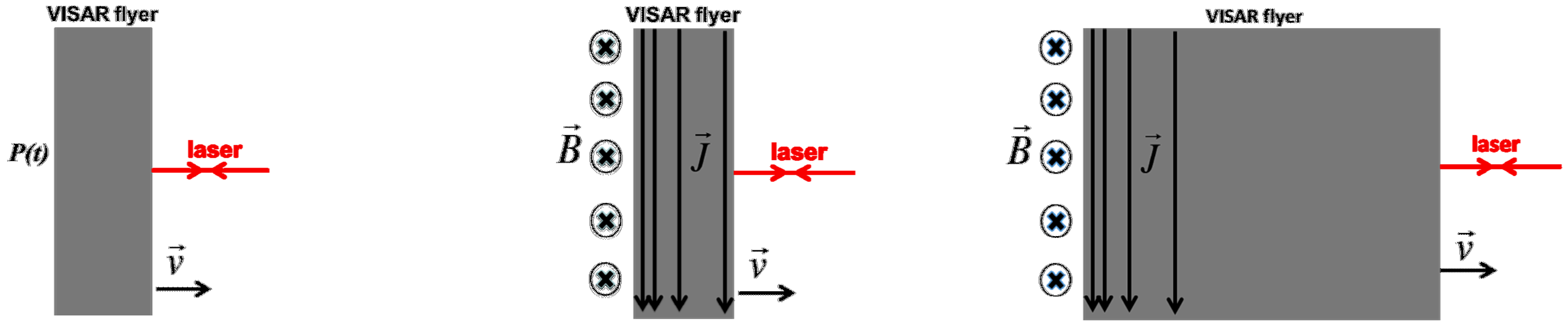
- Although measuring the entire time-dependent load current is desirable, the unfold process can be time consuming, i.e. it requires hundreds or even thousands of simulations. Moreover, it is difficult to assess the uncertainty associated with the unfold current, since the unfold can have non-unique solutions, i.e. different currents may produce very similar flyer velocities.

- However, for MagLIF loads, it is possible to perform a quick (< 1 hour) and accurate (< %5 uncertainty) analysis of the PDV/VISAR diagnostic to measure the peak load current.

- This measurement is relatively insensitive to the shape of the load current, which implies that we do not need to go through a time consuming process as was done in full current unfolds.

Increasing the Flyer Thickness

- Previous work on mechanical pressure driven VISAR[3] showed that the magnitude of the flyer velocity at some time depended on the pressure at an earlier time on the opposite surface, but did not explicitly depend on the flyer thickness. Therefore, the magnitude of a local velocity maxima only depends on the local maximum pressure applied at an earlier time.
- In general, magnetic pressure PDV/VISAR has nonlinear distributed JxB forces, so the flyer velocity magnitude will depend on the thickness. By increasing the flyer thickness however, the JxB forces are "more localized" to the flyer surface and take longer to diffuse. The system then resembles a mechanical pressure driven PDV/VISAR.
- For a 120 ns MagLIF load current, a 600 μm thick flyer is sufficiently thick to reduce the effect of the distributed JxB forces.



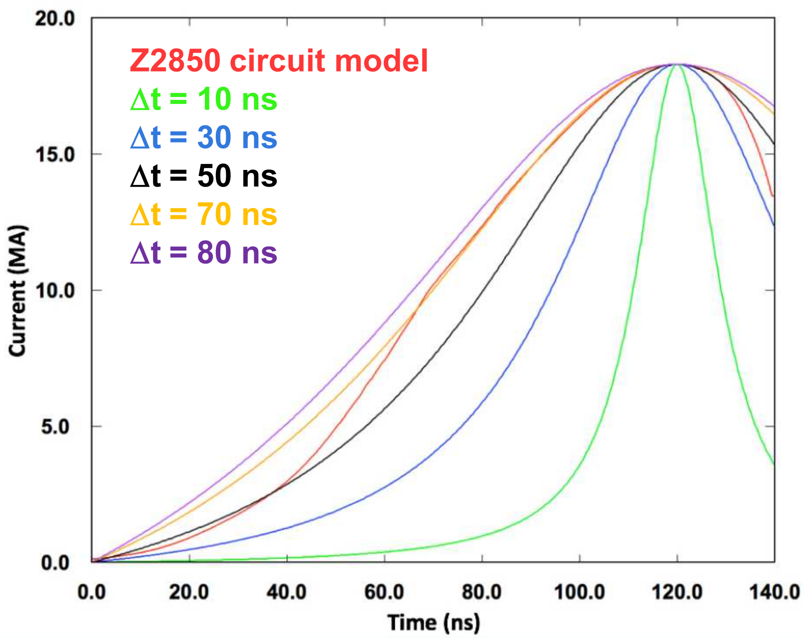
Mechanical Pressure PDV/VISAR | Magnetic Pressure PDV/VISAR | Larger Thickness PDV/VISAR

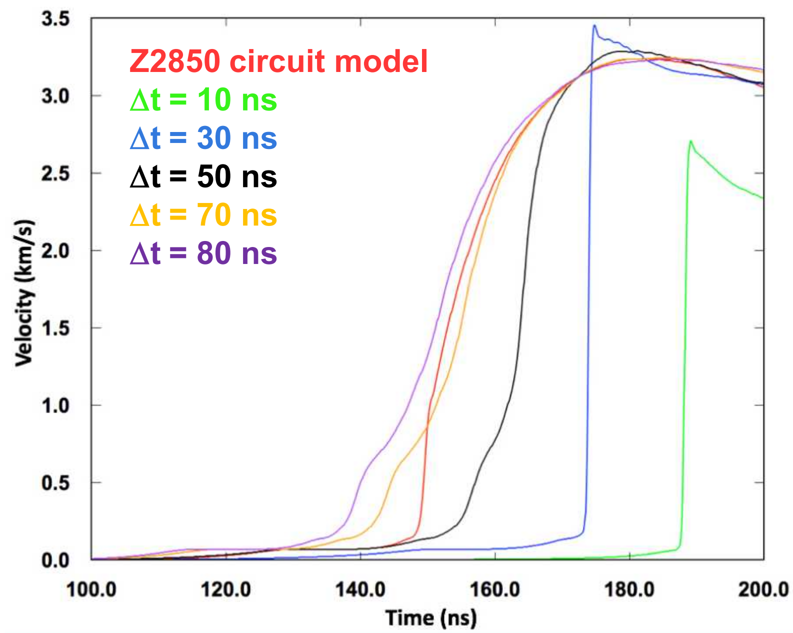
Peak Current and Peak Velocity

- 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 velocity using a MagLIF circuit model 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.

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





Comparing Peak Velocities

- We find that wider current peaks produce less variation in the peak velocity because
  - wider current peaks cause less shocking of the flyer
  - wider current peaks delay the time of the pressure release wave to erode the pressure peak

- The MagLIF circuit model produces load currents with shapes bounded by the Lorentzian model of 50 ns < Δt < 80 ns.

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

	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

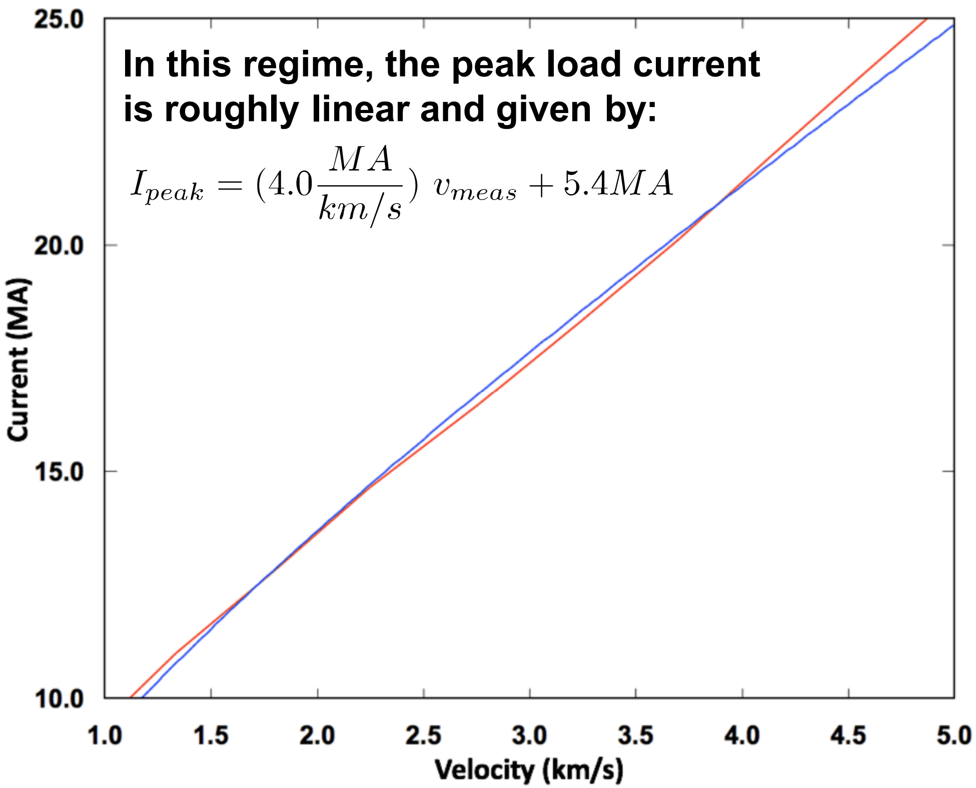
Inferring the Peak Current from the Peak Flyer Velocity

- By performing a series of forward simulations with ALEGRA, 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 Ref. 3 and the T = 298 K Al 3700 SESAME table.

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

- The blue curve demonstrates the similarity of the larger thickness PDV/VISAR concept to the mechanical driven concept. It can also be used to estimate the uncertainty of the inferred peak load current for a given EOS uncertainty.



Measurement of the Peak Velocity

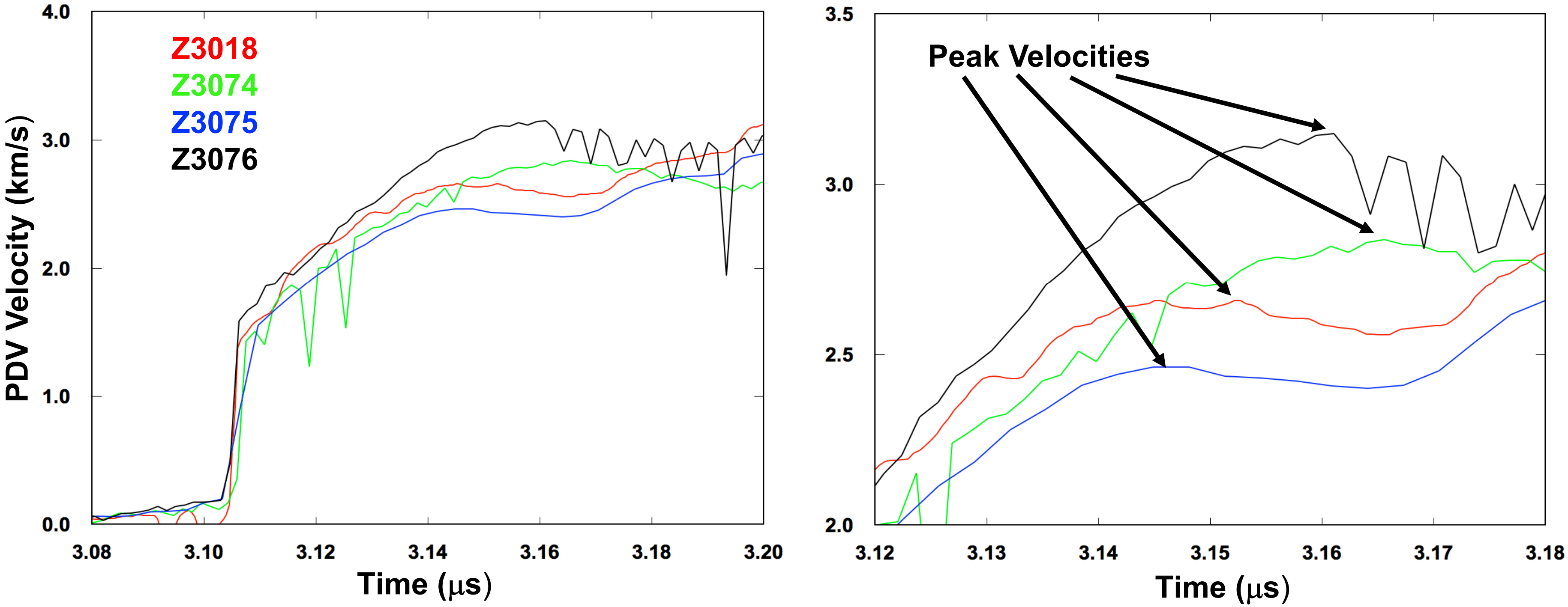
- As shown previously, the peak current at roughly 120 ns into the current rise should produce a peak velocity at approximately 180 ns into the rise.

- The best PDV measurements will have variations of +/- 10 m/s in the velocity signal.

- Typically, we see variations about the peak velocity on the order of 10’s m/s.

- Our measured peak velocity is found by first searching the data set for the local peak, and then performing a time window average of +/- 3 ns about that peak velocity.
  - The average velocity in the window is the measured peak velocity.
  - The standard deviation of the velocity distribution in the window is the measured peak velocity uncertainty.

MagLIF PDV Data



Z3018: AR 9, OR = 2.616 mm (Be), v_{meas} = 2.638 +/- 0.015 km/s

Z3074: AR 11, OR = 3.400 mm (Be) + 70 µm coating, v_{meas} = 2.822 +/- 0.014 km/s

Z3075: AR 9, OR = 2.567 mm (Be) + 75 µm coating, v_{meas} = 2.435 +/- 0.015 km/s

Z3076: AR 11, OR = 3.400 mm (Be) + 70 µm coating, v_{meas} = 3.080 +/- 0.098 km/s

Uncertainty of Peak Current

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- **The peak load current uncertainty can be estimated from the total velocity uncertainty as**

$$\delta I_{peak} = (4.0 \frac{MA}{km/s})\ \delta v_{tot}$$

- **We consider five possible contributions to the total velocity uncertainty:**
  - **Measurement uncertainty: we use the standard deviation within the measured peak velocity window**
  - **Fluctuations of peak velocity in simulations (assumed +/- 3 m/s)**
  - **Variations in the peak velocity due to shape variation (assumed +/- 50 m/s – from previous table)**
  - **Uncertainty in the EOS of aluminum (assumed uniform uncertainty in pressure space as a function of density)**
  - **Uncertainty in the LMD conductivity model of aluminum (assumed uniform factor applied to computed conductivity in all density and temperature space)**

- **The total uncertainty accounts for all five contributions in quadrature**

$$\delta v_{tot} = \sqrt{\delta v_{meas}^2 + \delta v_{fluc}^2 + \delta v_{shape}^2 + \delta v_{EOS}^2 + \delta v_{cond}^2}$$

EOS Uncertainty

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

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

- The uncertainty causes a shift in the peak velocity vs. peak pressure curve.

- This sensitivity study allows us to estimate the uncertainty in our inferred peak velocity due to a uniform uncertainty in the EOS.

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

LMD Conductivity Uncertainty

- In ALEGRA, we apply a uniform uncertainty factor to the conductivity over all density and temperature space.

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

- This sensitivity study allows us to estimate the uncertainty in our inferred peak velocity due to a uniform uncertainty in the EOS.

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

- One should note that in the strictest sense, EOS and conductivity uncertainties are not completely unrelated as we are assuming here. For example, the melt transition causes a significant drop in the conductivity for aluminum. Hence, uncertainty in the melt curve would cause uncertainty in the conductivity.

Uncertainty Estimate in Peak Load Current

- Below is our estimate for the total uncertainty in the peak current, which is based on the five uncertainties that we considered and assuming 5% uncertainties for both the EOS and conductivity.
- As a comparison, we provide the peak current predicted by a Sandia BERTHA circuit model[5], assuming 5% uncertainty.

MagLIF Shot	$v_{meas} \pm \delta v_{tot}$ **(km/s)**	$I_{peak} \pm \delta I_{peak}$ **(MA)**	$I_{Hutsel} \pm \delta I_{Hutsel}$ **(MA)**
Z3018	2.638 ± 0.07	16.0 ± 0.3	15.2 ± 0.8
Z3074	2.822 ± 0.07	16.7 ± 0.3	17.9 ± 0.9
Z3075	2.435 ± 0.07	15.2 ± 0.3	15.2 ± 0.8
Z3076	3.080 ± 0.12	17.7 ± 0.5	18.5 ± 0.9

Summary/Future Work

- We have developed a novel PDV/VISAR diagnostic which provides a quick and accurate measurement of the MagLIF peak load current.
- We have estimated the uncertainty in the peak load current measurement based on uncertainties from: measured peak flyer velocity, the flyer equation of state and conductivity, and current pulse shape.
- At present, we find good agreement between the peak load current measurement obtained from this diagnostic and the predicted peak load current of a Z machine circuit model developed at Sandia.

References

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