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# Circuit model development to improve the predictability of shaped current pulses on Z*

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# Outline

- Background
- Z circuit topology and features
  - Cross coupling between adjacent modules
- Self-breaking water switch model
- Runtime optimizations
  - Graphical preprocessor for BERTHA
  - Parallel processing
- Benchmarks to Dynamic Material shots

# Abstract

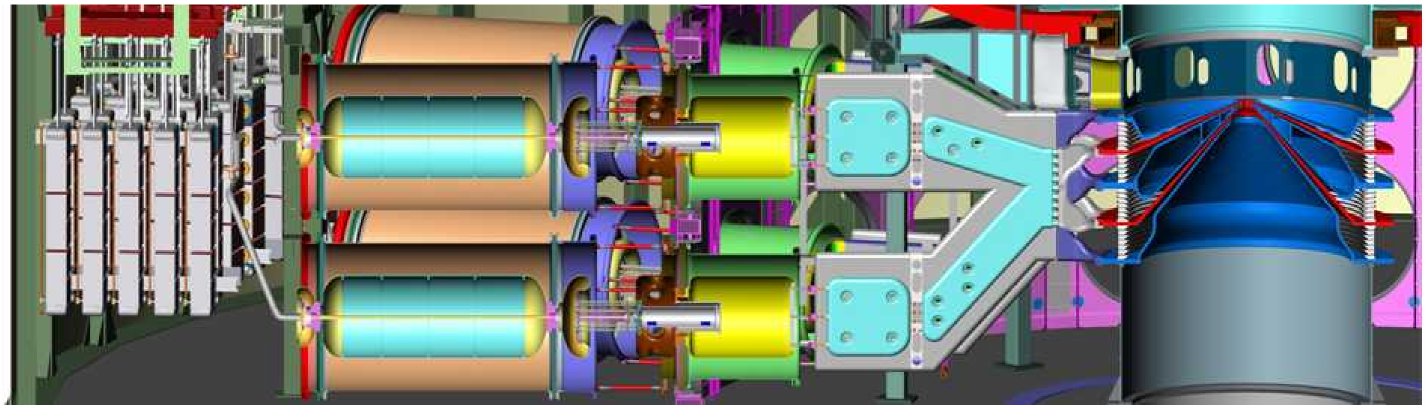
This paper describes a new electrical circuit model of the refurbished Z machine (ZR) at Sandia National Laboratories that accurately predicts shaped current pulses used for Dynamic Materials Program (DMP) experiments. Particular pulse shapes are obtained by individually configuring gas-switch trigger time and water-switch gaps in each of the 36 pulse lines. This mode of operation differs from standard Z-pinch operation where all 36 pulse lines are configured identically to deliver the same short pulse simultaneously to the load. Accurate model predictions are essential for determining how to configure the pulse lines prior to a shot to achieve the desired current-pulse shape.

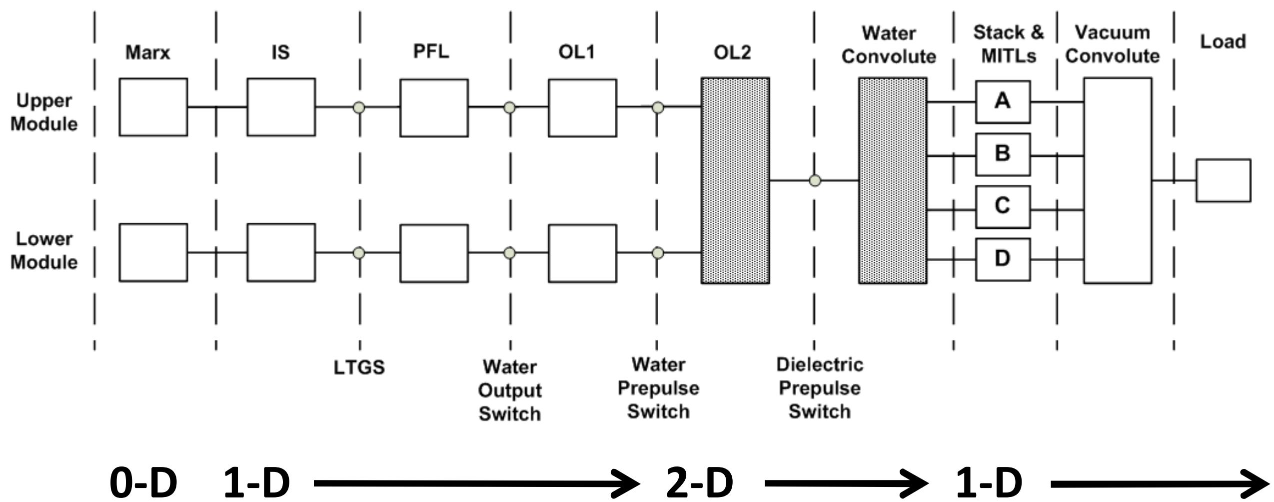
The new circuit model includes both 1-D and 2-D networks of transmission line elements and was based on prior models that had been benchmarked to measurements under Z-pinch mode operation. Recent model developments are described which include improved switch models, improved coupling between adjacent pulse lines, and runtime optimizations. These improvements have allowed better predictions in less time to determine how to configure the machine. The most important of the improvements is a self-breaking water switch model that predicts water switch closure given only the switch gap, even when the field in the gap initially reverses due to coupling between early-triggered and late-triggered pulse lines. The runtime optimizations include an extension to parallel processing and a custom user interface. Also described are benchmarks to DMP shots, to well defined test-load shots, and between circuit codes.

# Background

- Circuit model predictions are used to determine the pulse line configuration for Dynamic Material shots
  - Pulse line mode: long, medium, short, bussed out
  - Marx charge, IS switch time (laser-gas), PFL and OTL1 water switch gaps
- Circuit is based on Z circuit previously developed to model z-pinch mode operation

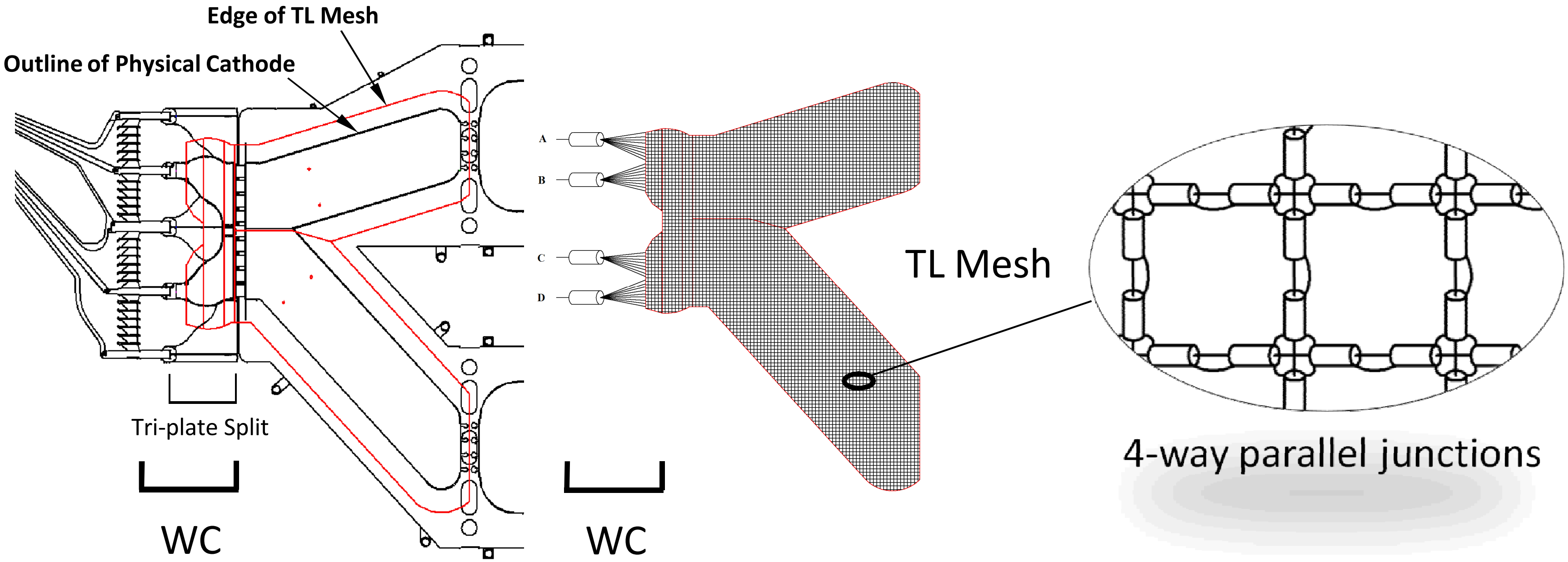
# ZR circuit topology

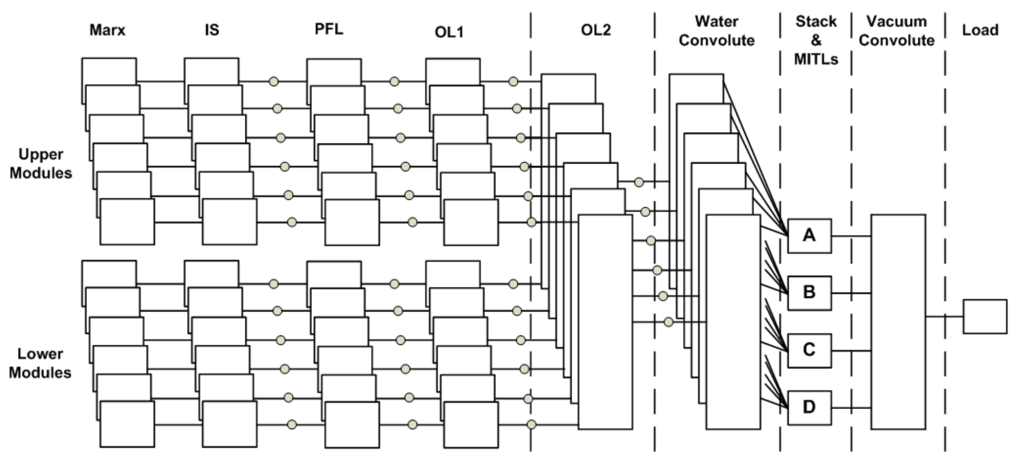





- Model probes placed at same location as physical probes in ZR
- Vacuum loss models for un-insulated flow, insulated flow lost in vacuum convolute, resistive wall losses, effect of cathode plasma closure (as for SATURN, Z)

# Circuit features




Full ZR Model (6 of 18 modules shown)

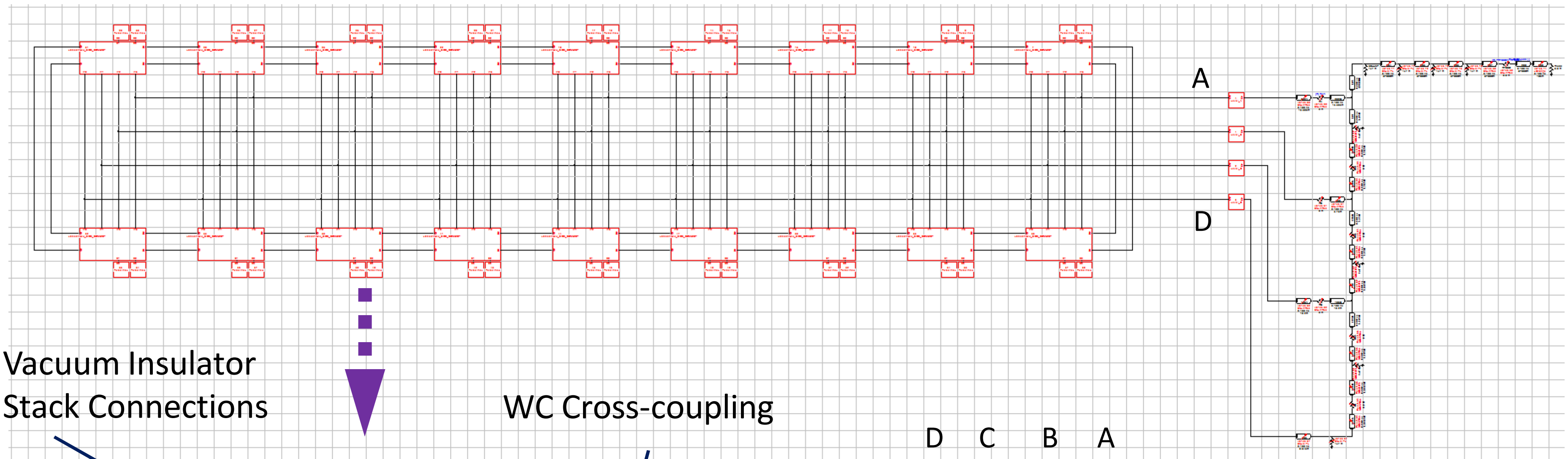
- 36 pulse line modules
- 18 2-D OTL2 and WC
- 61,000 TL elements
- 26,000 resistor elements
  - passive loss
  - active switches
  - active vacuum region loss

# ZR Bertha Model Implementation

**18 Module Pairs** : (upper and lower Marx, IS, PFL, OTL1, OTL2, WC)

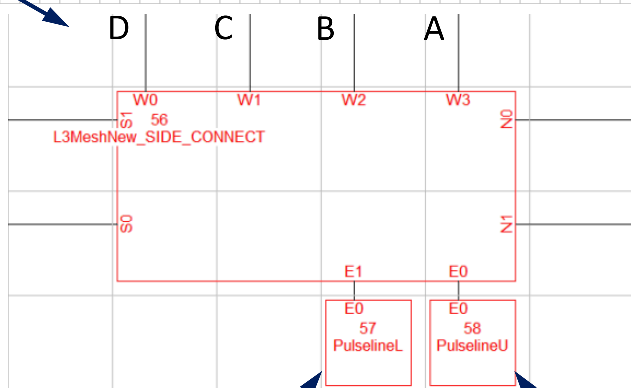
**Stack & MITLs**

**DPHC & Load**




Vacuum Insulator Stack Connections

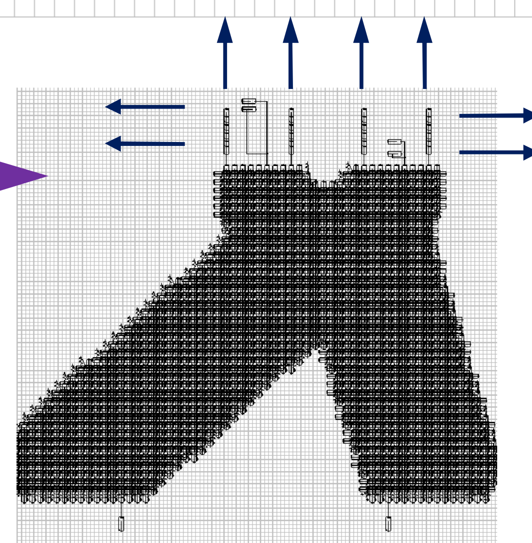
WC Cross-coupling

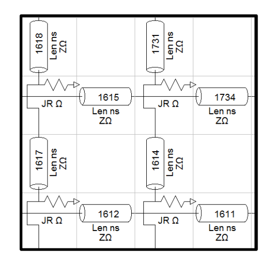



Lower Pulseline

Upper Pulseline

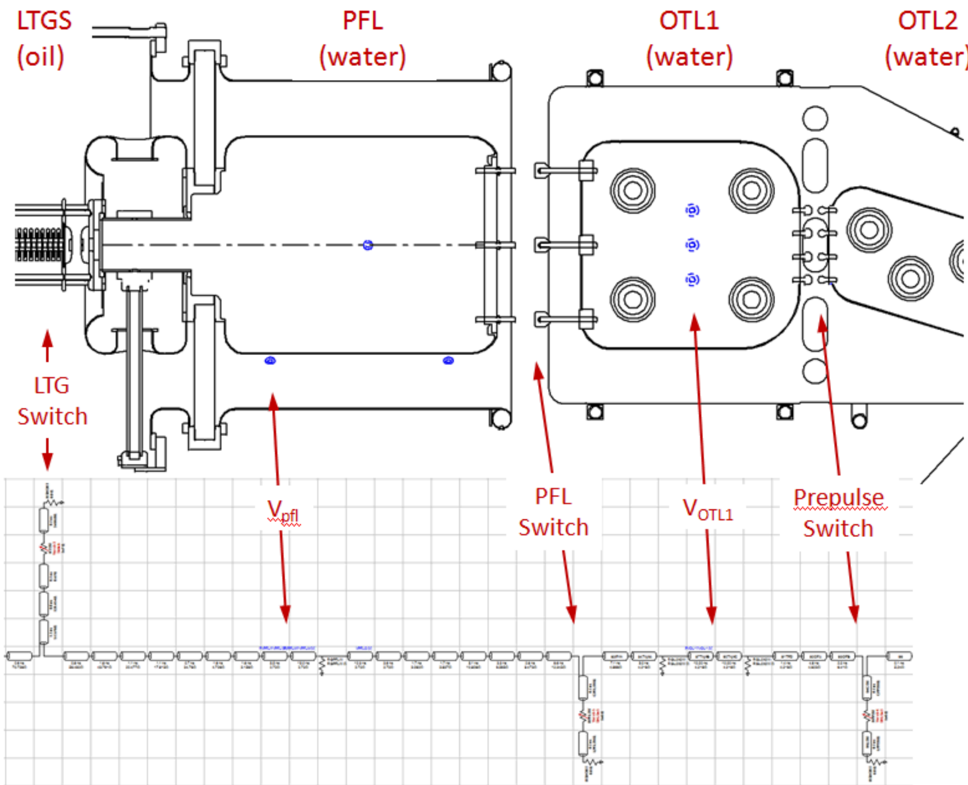
D C B A

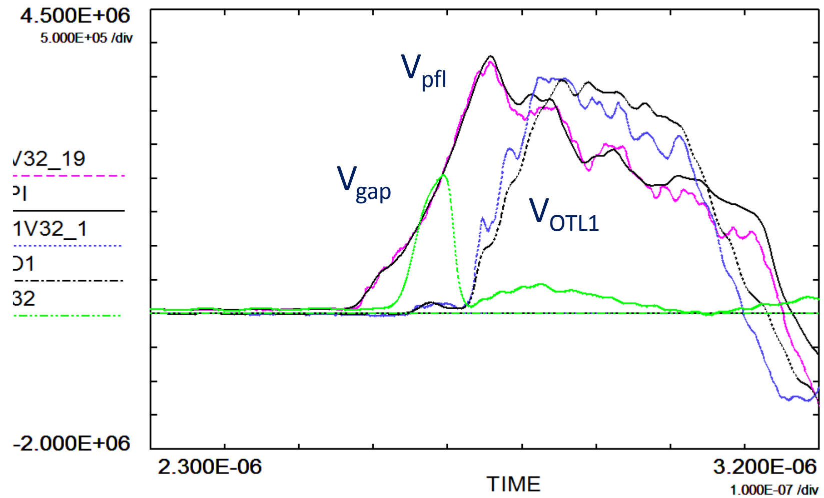





2-D Mesh OTL2 from TL - water conductivity shunt resistors shown

# ZR pulse line model, probes, and operation




Medium pulse operation (3.5cm gaps)

- PFL gaps closed on charge by IS
- Pulse line inner conductors charged negative
- Gaps have enhanced negative electrodes

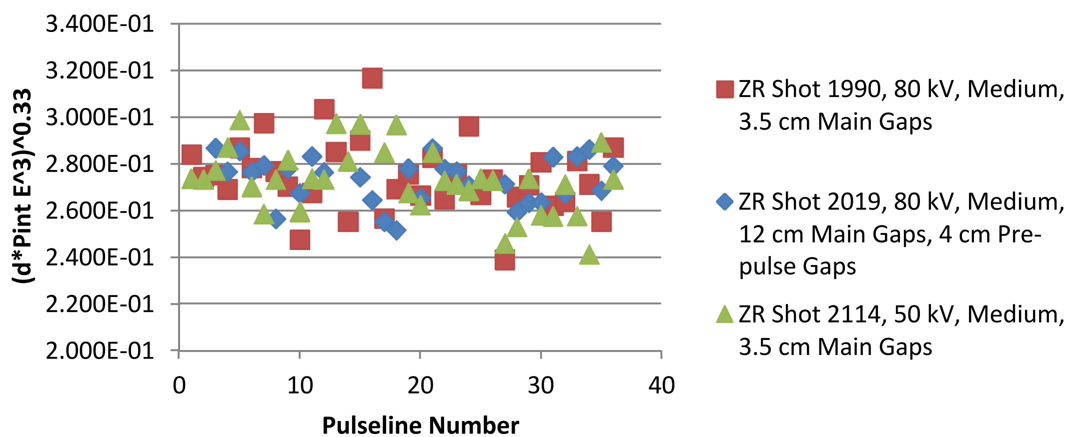
- Voltage probes located away from the water switch
- Circuit model switch closure times matched to up- and down-stream measurements
    - Pulse shapes match well on some lines, shots, some locations; others not
    - Measured PFL amplitudes are suspect (scatter, probes moved after calibration, damage to inner)
- Circuit model used to calculate voltage on gap

# Self Breaking Water Switch Model

- Model depends on initial switch gap, time history of voltage in gap (circuit model)
- Assumed general form of past fits to point plane data: $Ft^n = k$
  - $F = V/d$, (MV/cm); t in $\mu s$
  - n and k determined by fit to given shot data ( n range 1/2 to 1/3 in literature)
  - used integral form $(\int F^{1/n} dt)^n$ for running calculation in simulation
  - Fit to data on three shots (data for 30-36 pulse lines each)

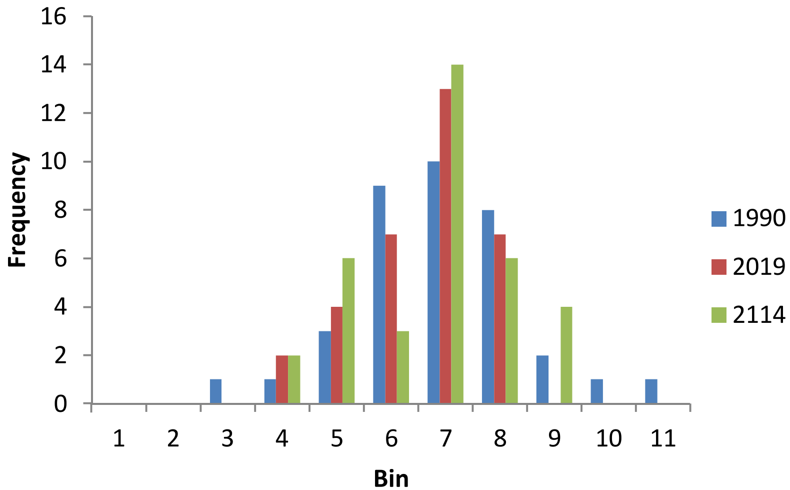
| Z Shot Number | 2114 | 1990 | 2019 |
|---|---|---|---|
| Marx charge (kV) | 50 | 80 | 80 |
| d (cm) | 3.5 | 12 | 3.5 |
| Average V (MV) | 1.9 | 4.1 | 2.1 |
| Average teff (ns) | 47/35 | 56/42 | 32/27 |
| **$Ft^{1/2}$** | **0.117** | **0.0814** | **0.109** |
| $\sigma$ (%) | 5.8 | 3.8 | 6.7 |
| **$Ft^{1/3}$** | **0.178** | **0.119** | **0.181** |
| $\sigma$ (%) | 5.2 | 3.6 | 5.6 |
| **$Ft^{1/3} d^{1/3}$** | **0.273** | **0.273** | **0.2745** |

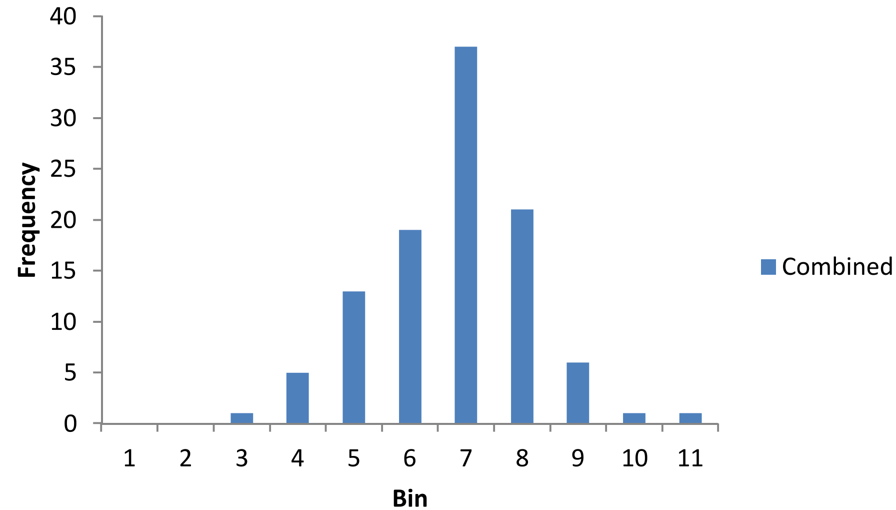
- Best fit for n was 0.35 (approximated by 1/3)
- Larger gap data fit best with addition of a gap term
  - best fit was $d^{1/3}$



# Unipolar Switch Model

- Switch threshold $k = (d\int F^3 dt)^{1/3}$ calculated at each time step of simulation
- Switch modeled by usual tanh function after threshold k is reached
    - R(t) for resistive phase set 300 ohms at threshold (same as model fit)
- Switch jitter modeled by assuming normal distribution of k, $\sigma = 0.02$
    - Actual distribution not symmetric (also cited by others)
    - Random number generator used to set up circuit parameters
    - Multiple simulations are used to assess effect of jitter on pulse shape

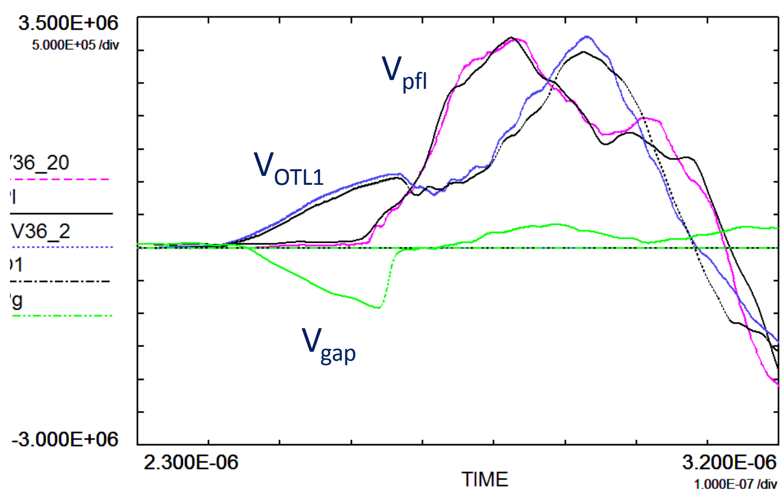


# Switch operation is complicated by large range of pulse line trigger times

- Pulse shaping requires mixed pulse line modes and firing times
  - Modes: long (water gaps shorted); medium (small main gap, PPSW shorted); short (nominal gaps)
  - Firing times: long pulse lines fired up to ~500 ns before shorter pulse lines
    - set by laser trigger times
- Earlier lines couple to later through water convolute (adjacent) and through vacuum region
  - "back-pulse" reverses field in open switch gaps
  - can lead to early closure if not anticipated

| Module Configuration | | Water Switch Configuration | | | Trigger |
|---|---|---|---|---|---|
| Mode | Module | Main Switch Gaps | Peaking Gaps | Pre-Pulse Boards | Timing Advance (ns) |
| Long Pulse | 1 | 0 | 0 | no | 500 |
| Long Pulse | 3 | 0 | 0 | no | 120 |
| Long Pulse | 5 | 0 | 0 | no | 360 |
| Medium Pulse | 7 | 3.5 | 0 | no | 90 |
| Medium Pulse | 9 | 3.5 | 0 | no | 60 |
| Medium Pulse | 11 | 3.5 | 0 | no | 0 |
| Long Pulse | 13 | 0 | 0 | no | 500 |
| Long Pulse | 15 | 0 | 0 | no | 60 |
| Long Pulse | 17 | 0 | 0 | no | 460 |
| Medium Pulse | 19 | 3.5 | 0 | no | 110 |
| Medium Pulse | 21 | 3.5 | 0 | no | 40 |
| Medium Pulse | 23 | 3.5 | 0 | no | 0 |
| Long Pulse | 25 | 0 | 0 | no | 500 |
| Long Pulse | 27 | 0 | 0 | no | 30 |
| Long Pulse | 29 | 0 | 0 | no | 480 |
| Medium Pulse | 31 | 3.5 | 0 | no | 130 |
| Medium Pulse | 33 | 3.5 | 0 | no | 20 |
| Medium Pulse | 35 | 3.5 | 0 | no | 0 |
| Long Pulse | 2 | 0 | 0 | no | 513 |
| Long Pulse | 4 | 0 | 0 | no | 133 |
| Long Pulse | 6 | 0 | 0 | no | 373 |
| Medium Pulse | 8 | 3.5 | 0 | no | 103 |
| Medium Pulse | 10 | 3.5 | 0 | no | 73 |
| Medium Pulse | 12 | 3.5 | 0 | no | 13 |
| Long Pulse | 14 | 0 | 0 | no | 513 |
| Long Pulse | 16 | 0 | 0 | no | 73 |
| Long Pulse | 18 | 0 | 0 | no | 473 |
| Medium Pulse | 20 | 3.5 | 0 | no | 123 |
| Medium Pulse | 22 | 3.5 | 0 | no | 53 |
| Medium Pulse | 24 | 3.5 | 0 | no | 13 |
| Long Pulse | 26 | 0 | 0 | no | 513 |
| Long Pulse | 28 | 0 | 0 | no | 43 |
| Long Pulse | 30 | 0 | 0 | no | 493 |
| Medium Pulse | 32 | 3.5 | 0 | no | 143 |
| Medium Pulse | 34 | 3.5 | 0 | no | 33 |
| Medium Pulse | 36 | 3.5 | 0 | no | 13 |



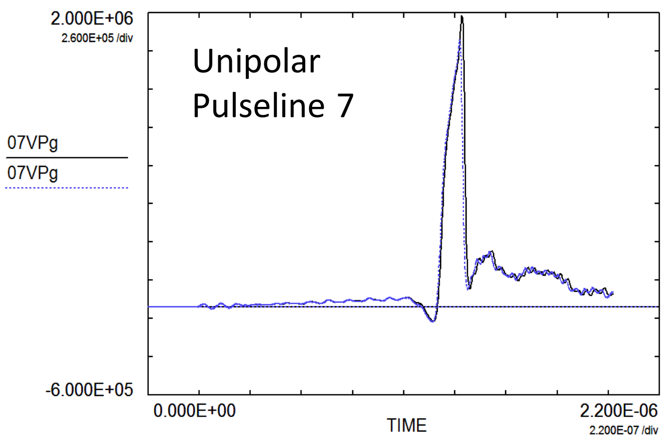

PFL gaps closed on "back-pulse" from adjacent lines fired ~500ns earlier

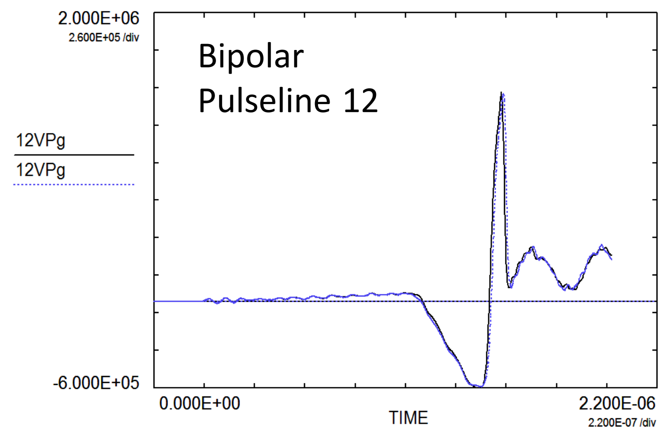
- line set for medium pulse delivered an earlier long pulse

# Reverse Polarity and Bipolar Switch Model

- Reverse polarity and bi-polar switching was observed on 18 pulse lines of shot 2095
  - 9 switched on reversal, 9 were bipolar
- Additional data from every other pulse line of shot 2137
- Limited data shows reverse polarity can be fits $F(dt)^{1/3} = 0.133$
  - Roughly half the opposite polarity threshold
  - Consistent with the difference between positive and negative breakdown formulas
- Bipolar data suggests that two opposite polarity stress can be combined in a single threshold
  - $k_{bp} = [\ (d\int F_-^3 dt)^{1/3} + 8(d\int F_+^3 dt)\ ]^{1/3}$

    where $F_-$ is the average field in the negative enhanced gap and $F_+$ is the positive




Shot 2181

- Bipolar model prediction – black
- Switch times matched to data postdiction - blue

# Circuit run time optimization

The iteration time for pulse shape design and analysis is critical

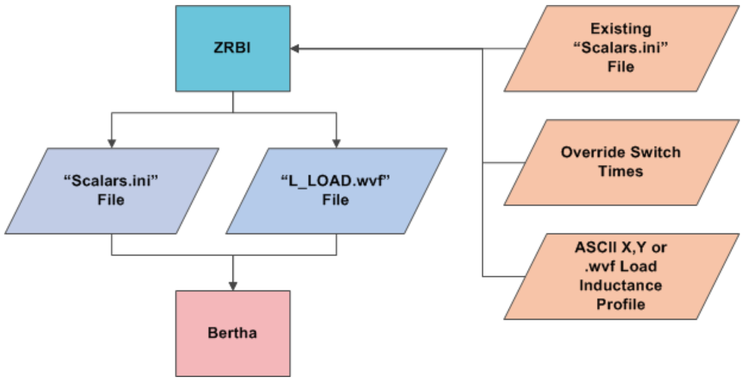
- Circuit run times ~ 1 minute are generally required
- Trial and error match circuit prediction to target pulse shape
  - new shapes or make adjustments between shots
  - many iterations are often needed in short time
- presently done manually
- future will try genetic optimization algorithm (may need many more iterations)
  - runtime < 1 minute may be needed

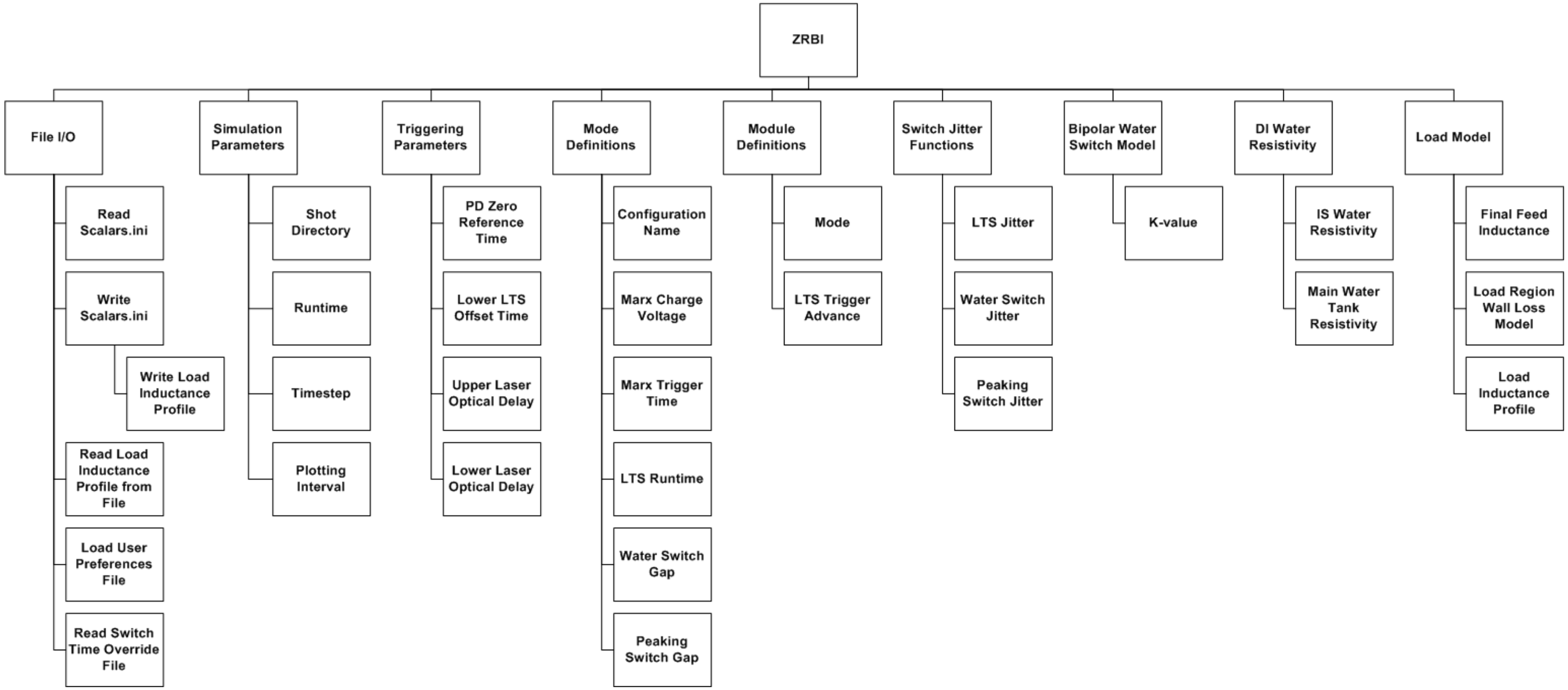
Two efforts have resulted in greatly reduced times

1. preprocessor for the BERTHA simulations
   - ZR Bertha Interface (ZRBI)
   - Graphical interface for manual pulse shaping
   - Fortran routines will be used for automated pulse shaping
2. Running a single circuit on multiple processors

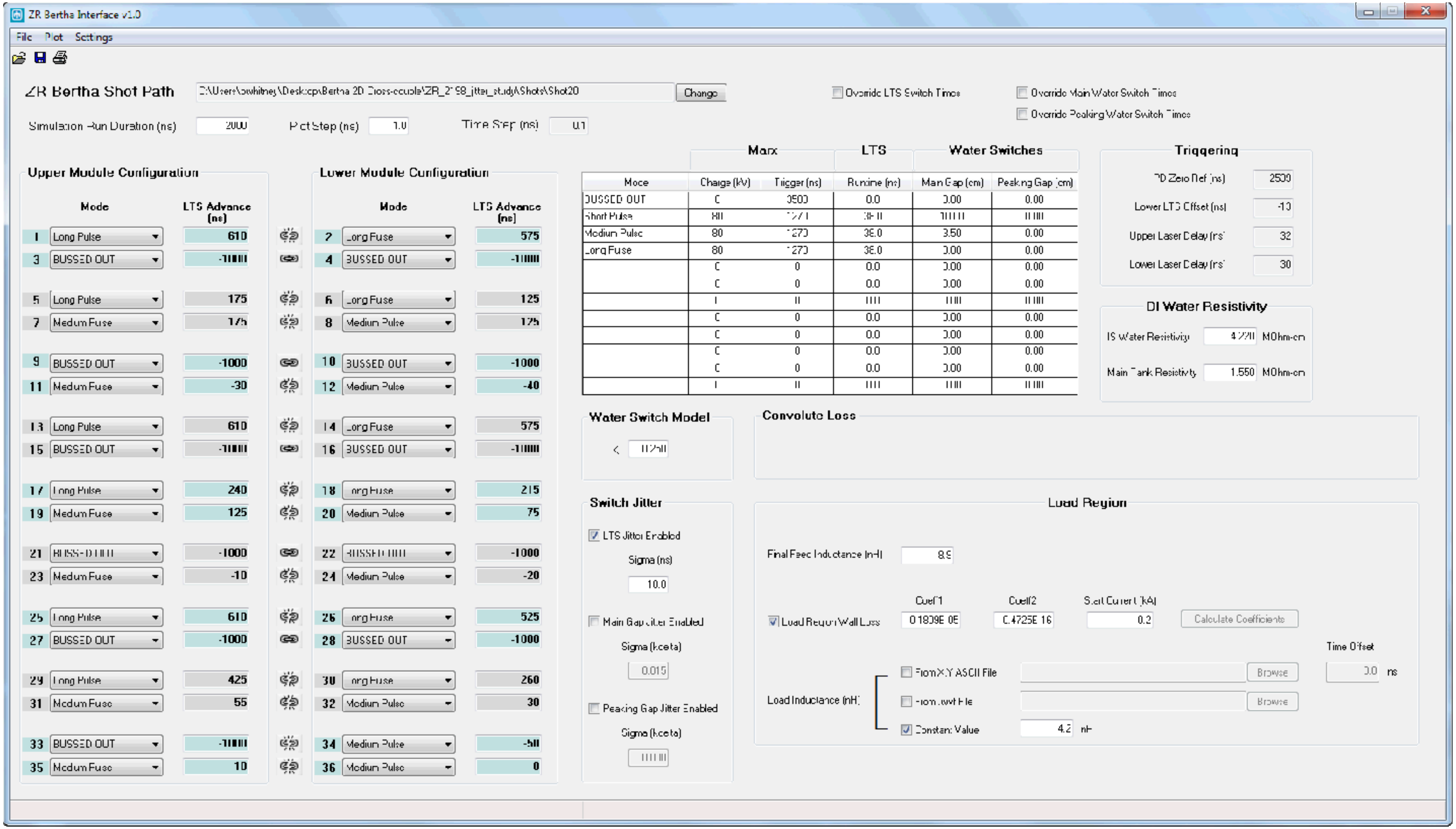
# ZR Bertha Interface (ZRBI)

- ❑ The ZR Bertha Interface (ZRBI) is a standalone application which allows users to easily manipulate model parameters such as switch timing, loss model parameters, etc. from shot to shot
- ❑ Shot configurations can be recalled and modified as needed
- ❑ ZRBI extends the functionality of the "Scalars.ini" file feature of Bertha
- ❑ Originally a Windows application, being ported to Linux as well
- ❑ Intended to eventually interface with the "genetic" switching algorithm



# ZR Bertha Interface (ZRBI)



# Runtime optimizations - Serial and Parallel processing

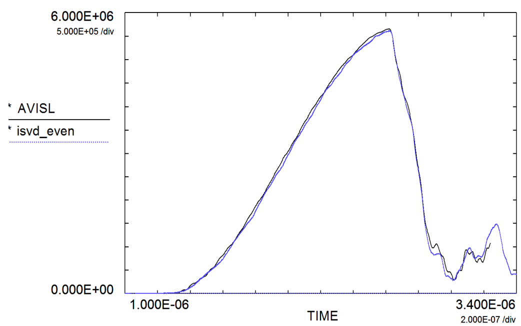
Wall clock benchmarks:

- TL run on 4 core Intel® Xeon ® CPU at 2.67GHz
  - 23,000 time step (2.3μs) simulation
    - One processor: 70 seconds
- BERTHA run under Open MPI running 8 core Xeon Linux 3.3GHz workstation
  - 20,000 time step (2.0μs) simulation
    - One Processor: 125 second
    - Seven processors: 30 seconds
  - Circuit grouped into 7 MPI modules
    - 6 MPI modules each containing 3 PFL pairs and WCs
    - 1 MPI module containing stack MITLs and load

# TL circuit model of ZR reproduces many of the measured waveform features

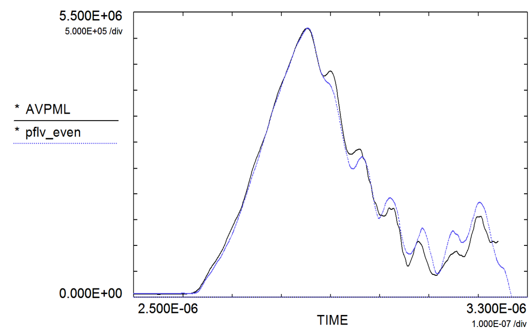
## Z-pinch Load – synchronous pulse lines

Intermediate Store Voltage



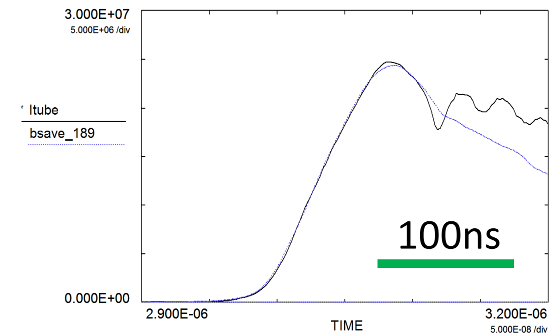

Shot 1896

PFL Voltage




Shot 1896

Total Stack Current

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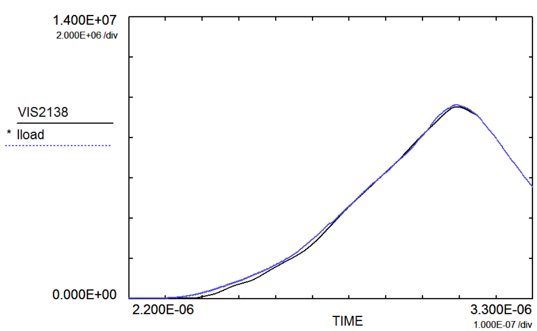
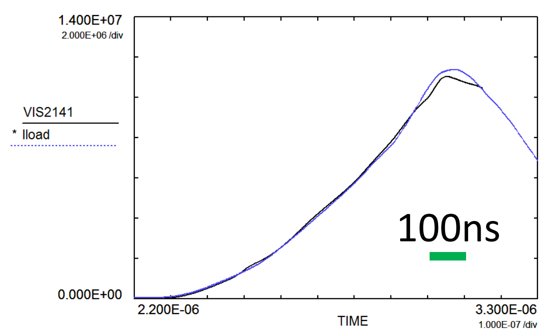
## Material Response Load – pulse lines staggered over ~500ns

Load Current




Shot 2138

Load Current

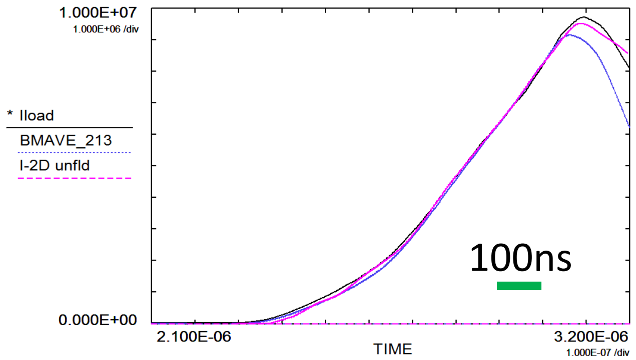



Shot 2141

- Simulated load current compared to unfold from VISAR data
  - L(t) unfolded from VISAR and 2-D MHD simulations
  - Matched switch times

**TL Simulation (black)**
**ZR Shot Data (blue)**

# Still more work to be done …




Conflicting data on peak currents:

- Postdiction load current - black
- Measured MITL current – blue
- Unfolded VISAR current – pink

Shot 2138