Transmission-line-circuit simulations of Z with an ion-diode current-loss mechanism

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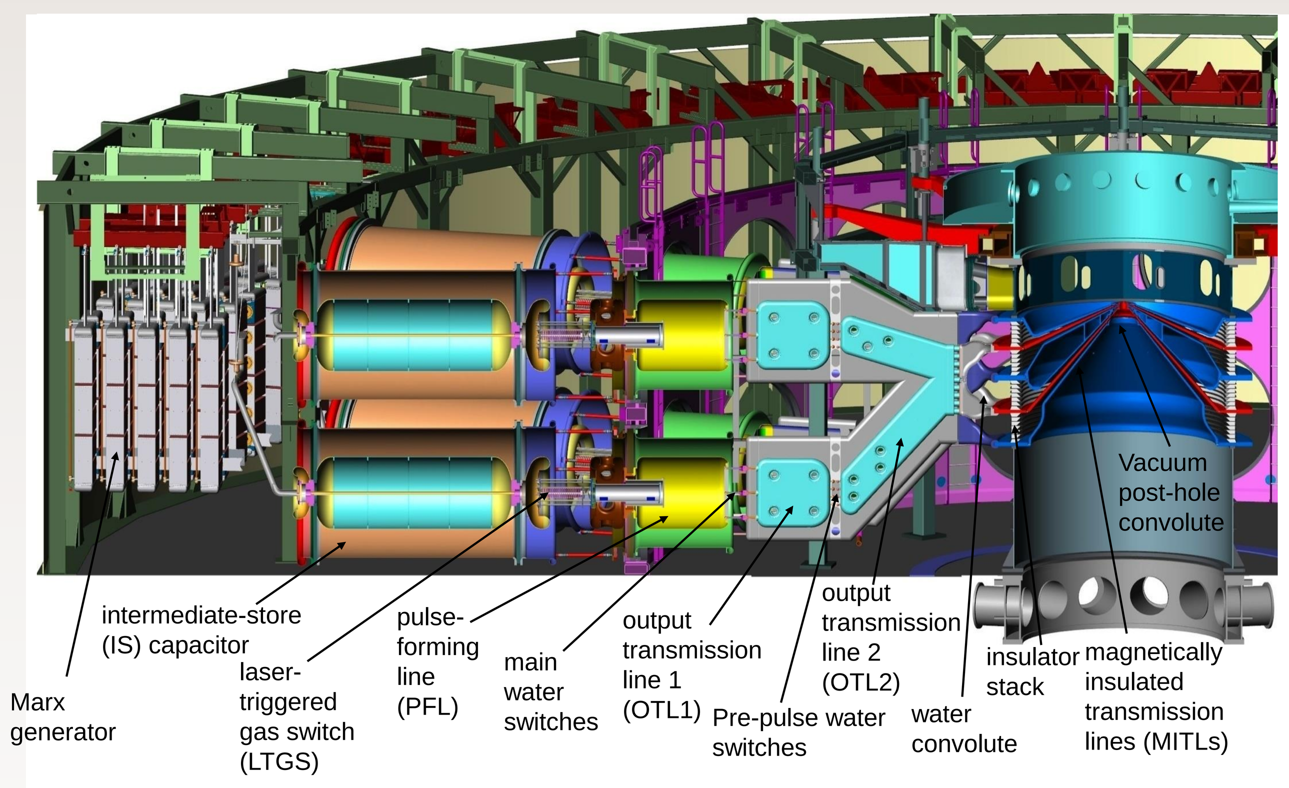
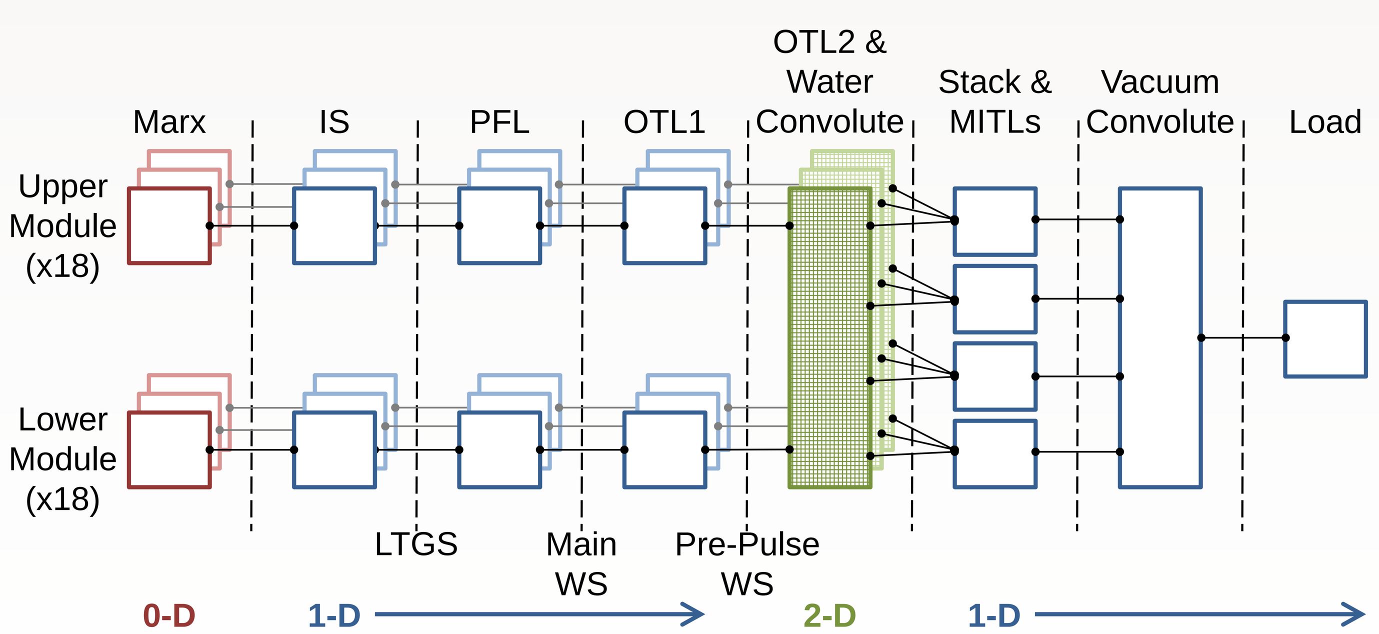
A transmission-line-circuit model of the Z accelerator has been developed.

- The circuit uses 0D, 1D, and 2D transmission line elements to model the entire accelerator from Z's 36 Marxes to the insulator stack, MITL system, vacuum-post-hole convolute, and load.
- The model was implemented using the Bertha transmission line circuit code.
- Simulations run in less than 30 seconds on a desktop computer.
- The model is used for pre-shot analysis to design experiments and provide a prediction for the load-current time history, and post-shot analysis to provide a load-current measurement.
- We are presently developing a physics-based model of current loss within the Z vacuum section, to allow us to design loads with improved current delivery.
- The current loss model simulates electron emission from cathode surfaces, ion emission from anode surfaces, and the formation and evolution of electrode plasmas.

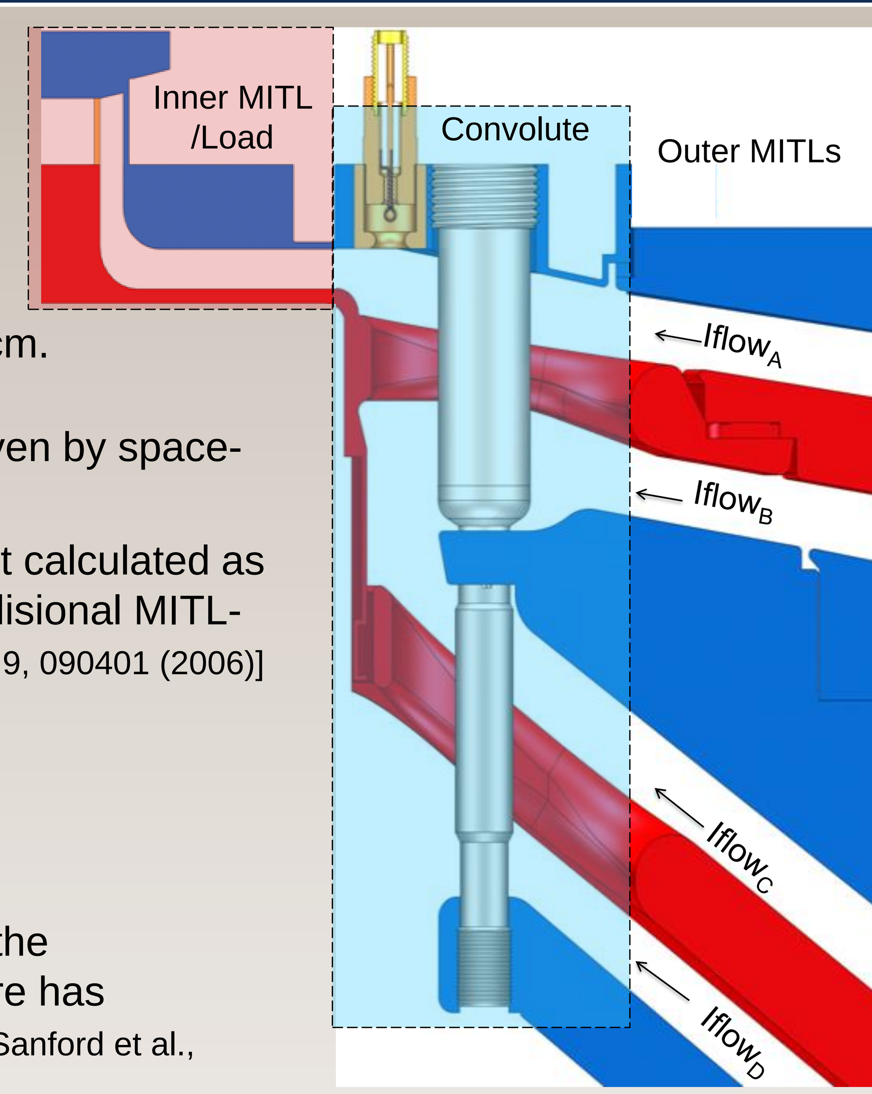


Cross section of the Z accelerator



Block diagram of the Z circuit model

The model includes the following sources of current loss within the vacuum region of Z.



- Electron emission from cathode surfaces:
  - Turns on when electric field exceeds 240 kV/cm. [Di Capua and Pellinen, J. Appl. Phys. 50, 3713 (1979)]
  - Prior to magnetic insulation, loss current is given by space-charge limited emission.
  - After magnetic insulation, electron flow current calculated as the average between the collisionless and collisional MITL-electron-flow models. [Phys. Rev. ST Accel. Beams 9, 090401 (2006)]

$$I_{\text{flow}} = \frac{13}{16}\frac{V^2}{I_{\text{anode}} Z_{\text{MITL}}^2}$$

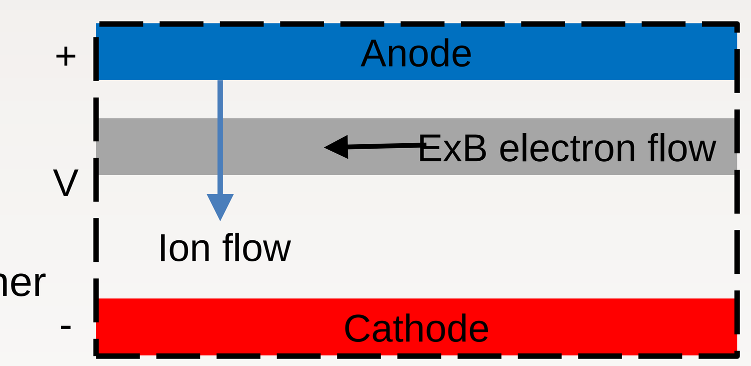
- Ion emission from anode surfaces:
  - Ions emission from an anode surfaces within the convolute and inner MITL after the temperature has increased by 400 K. [Cuneo, Ph.D. thesis, (1989); Sanford et al., J. Appl. Phys. 66, 10 (1989)]
  - The anode-surface temperature increases due to ohmic heating and energy deposition by MITL-flow electrons that impact the anode. [Knoepfel (2000); NIST ESTAR data]
  - Ion-current loss is assumed to be space-charge-limited, and is estimated using the non-relativistic Child-Langmuir expression. [Child, Phys. Rev. (1911); Langmuir, Phys. Rev. (1913)]
  - The space charge limited ion current can be enhanced due to electron-flow charge that accumulates within the convolute and inner MITL. [Langmuir, Phys. Rev. (1929); Desjarlais, Phys. Rev. Lett. (1987)]

$$\Delta T = \frac{\partial B^2(t)}{2\mu_0 c_v} + c_v \int \frac{E_{\text{flowloss}}}{\frac{AV}{S}\cos\theta}\,dt$$

$$I_{\text{ionloss}} = \frac{4\epsilon_0}{9}\eta A\sqrt{\frac{2q}{m}}\frac{V^{3/2}}{d^2}$$

$$\eta(t) = \frac{3}{4}k_{vi}\int I_{\text{flow}}\,dt\,\frac{d}{\epsilon_0 A V}$$

- Formation and evolution of electrode plasmas:
  - Cathode plasma expansion rate of 1.1 cm/μs. [Hutsel et al., SAND2014-17769 (2014)]
  - Anode plasma expansion within the convolute and inner MITL.



Several ion diode model parameters were optimized using a particle swarm optimization technique

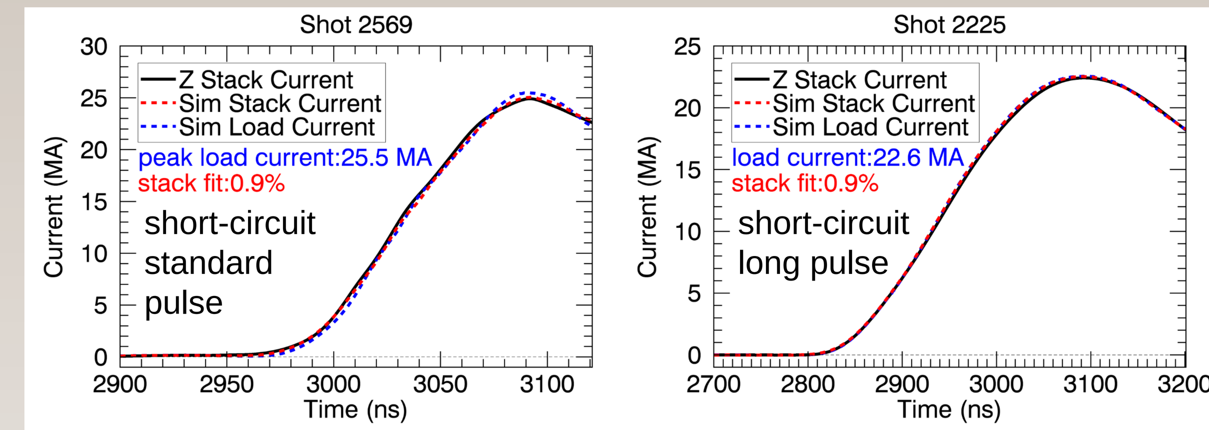
- The optimization was used to determine several model parameters that were not constrained based on published data.
- The optimized parameters determined the distribution of outer MITL electron flow current within the convolute and inner MITL, anode plasma velocities, and ion current enhancement.
- The parameters were optimized to the overall stack current fit, stack current at stagnation, and stagnation timing from six Z shots.
- The results of the optimization are applied to all of the simulated Z shots.

circuit-model parameter	optimization result
outer-MITL flow charge lost in the convolute	85%
outer-MITL flow charge accumulated in the convolute	4%
outer-MITL flow charge lost in the feed	10%
outer-MITL flow charge accumulated in the feed	1%
electron-impact angle (from anode normal)	82 degrees
anode-plasma-expansion velocity (feed)	3.7 cm/μs
anode-plasma-expansion velocity (convolute)	17 cm/μs
ion-charge enhancement constant	1.3

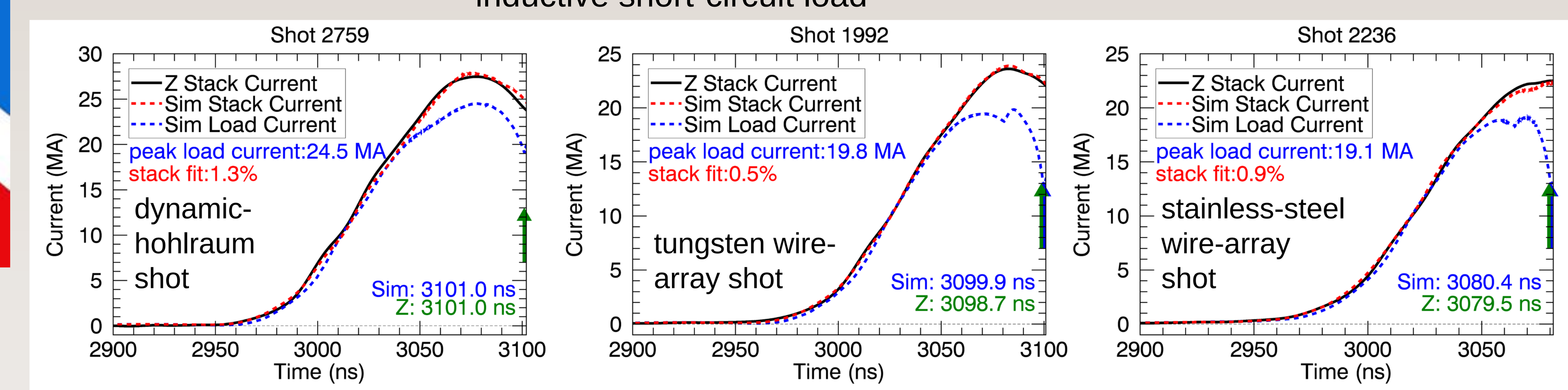
The Z circuit model is consistent with experiments using a variety of inner MITL and load configurations.

- Measured and simulated insulator-stack currents agree to within 2%.
- Measured and simulated load-implosion times agree to within 2 ns.

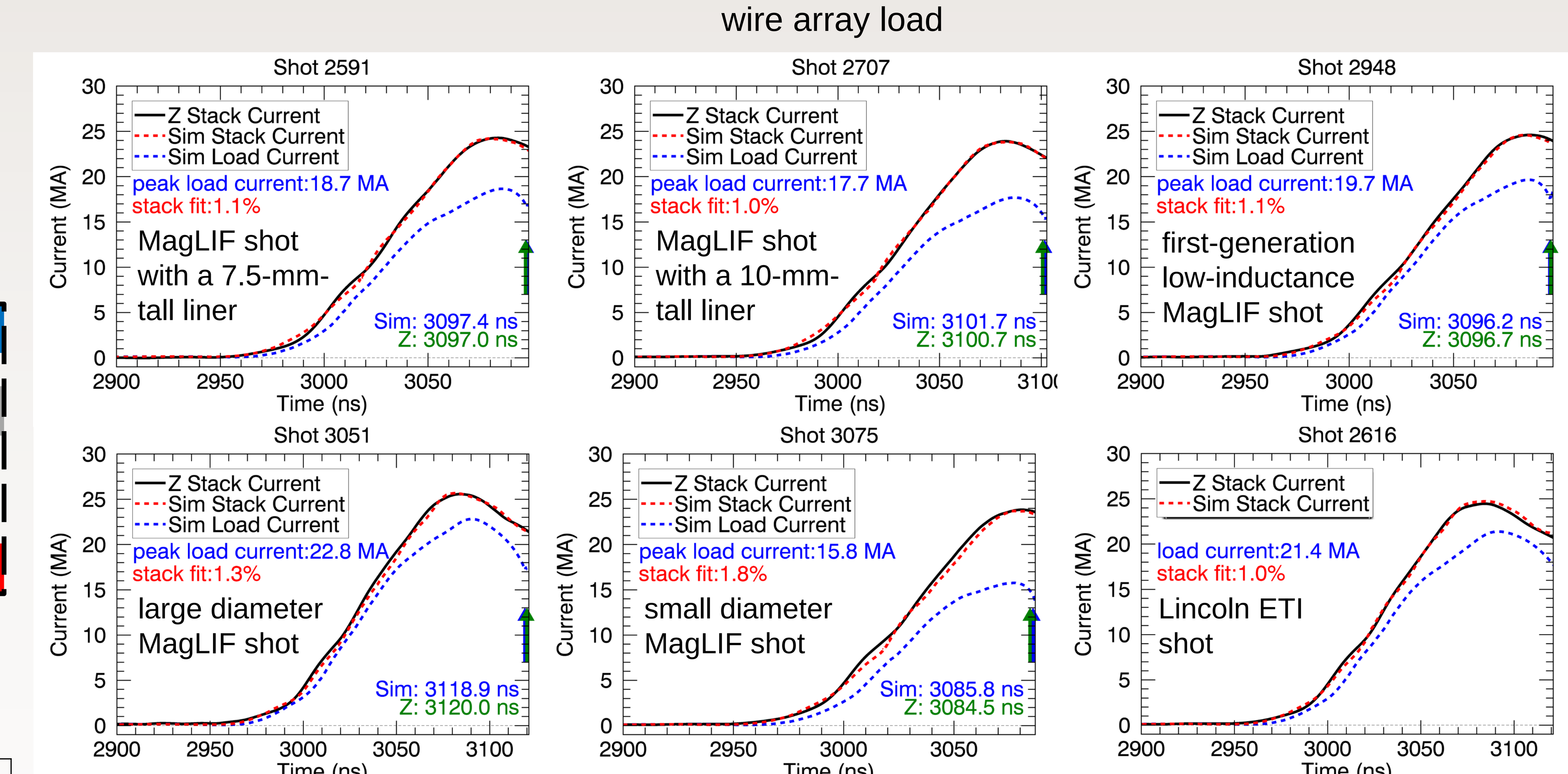
Load configuration	L_0	min A-K gap
MagLIF – 10-mm-tall liner	7.2 nH	3 mm
MagLIF – 7.5-mm-tall liner	6.4 nH	3 mm
Washington - MagLIF feed with a large-diameter heavy liner	5.4 nH	3 mm
Lincoln ETI	5.3 nH	4 mm
Low-inductance MagLIF	~5 nH	3-4 mm
Dynamic hohlraum	2.8 nH	6 mm
65-mm-diameter tungsten-wire array	2.7 nH	7 mm
70-mm-diameter stainless-steel-wire array	1.7 nH	6 mm
Inductive short-circuit load	1.5 nH	6 mm



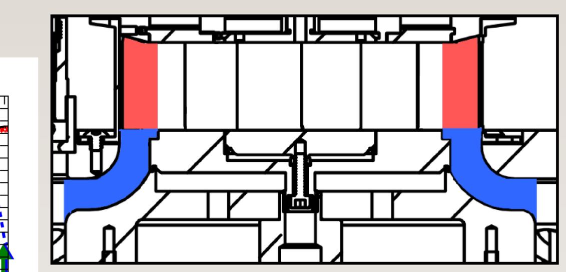
inductive short-circuit load



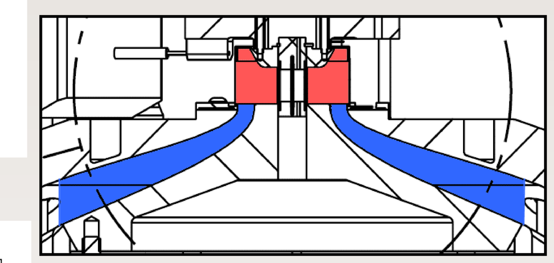
wire array load



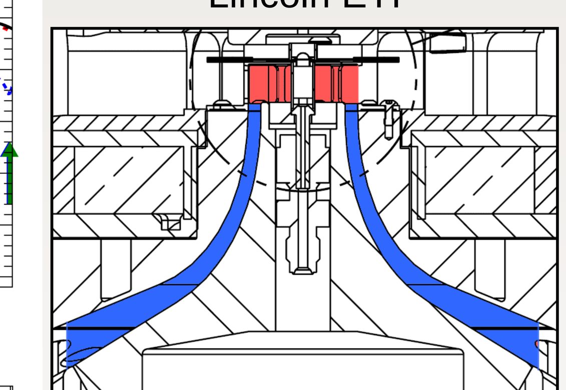
cylindrical liner load



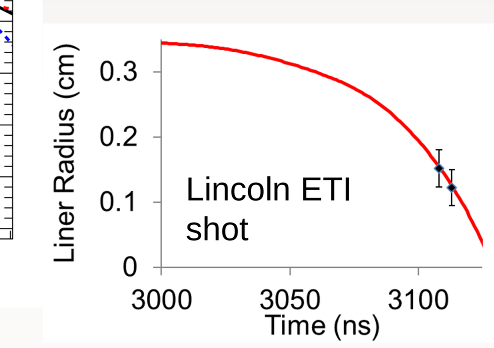
70-mm stainless wire array



Lincoln ETI

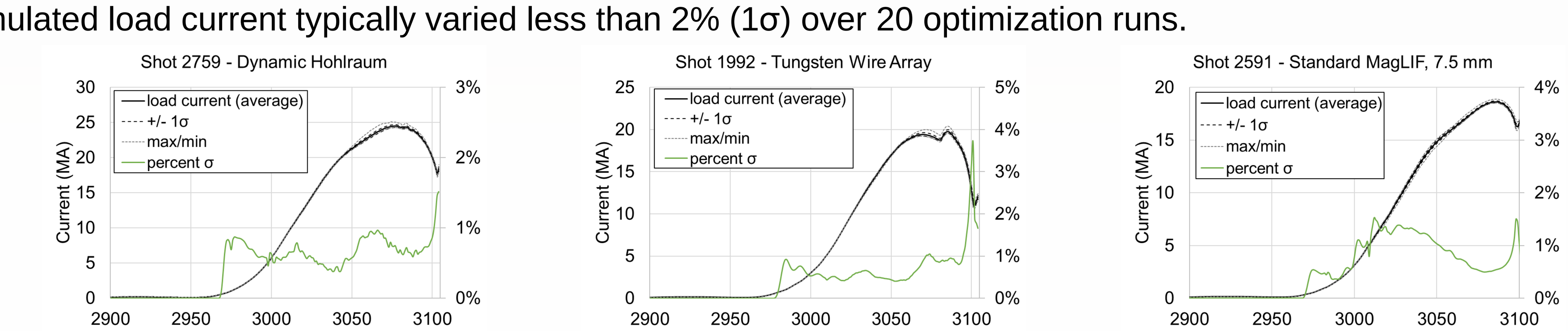


MagLIF inner MITL



The simulation results are insensitive to random error in the ion-diode model parameter optimization.

- Random error in the simulated load current and simulated implosion time was determined from simulations using parameters from multiple optimization runs.
- Simulated load current typically varied less than 2% (1σ) over 20 optimization runs.



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