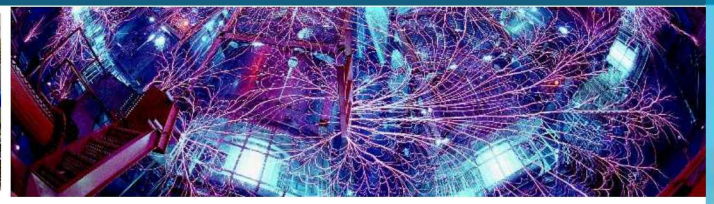
SAND2019-7021C

Experimental results from the 1.2 MA, 2.2 m diameter linear transformer driver cavity at Sandia National Labs



PRESENTED BY

Jon Douglass

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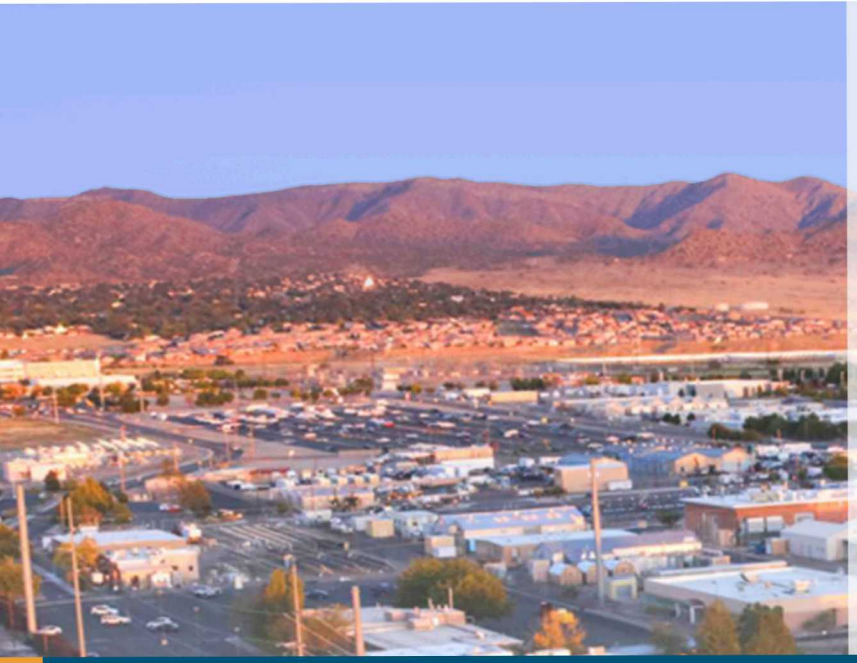
Outline

- Background on the "Z-Next", 6th generation high current LTD at Sandia
  - Motivation for a new LTD
  - Early development with 20 bricks
  - Performance and reliability with 20 bricks
- Results from the 6th generation LTD running with 24 bricks
  - Goals for 24-brick operation
  - Lessons learned
- Future plans for high current LTD development at Sandia



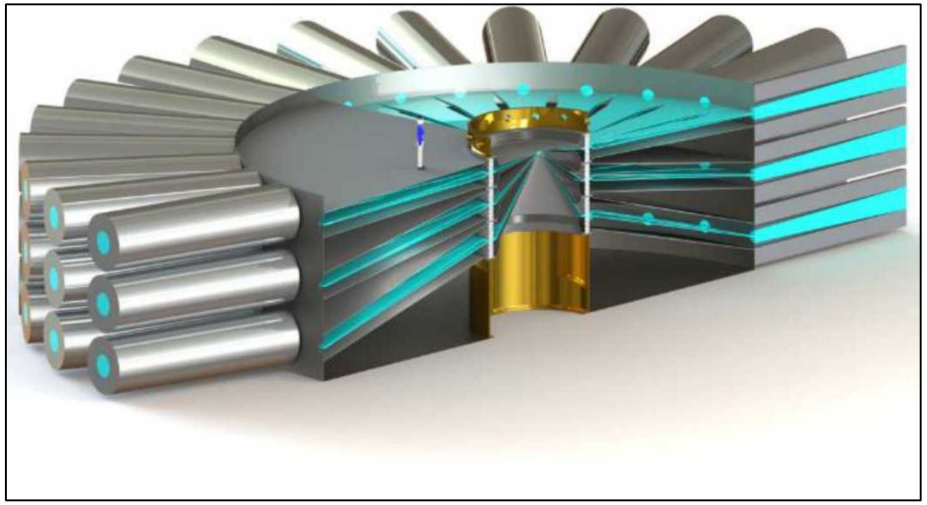
The "Z-Next" 6th Generation High Current LTD at Sandia

A compact, 100 kV, 20-brick LTD producing 1 MA in 100 ns

The "Z-Next" 6th generation high current LTD at Sandia

Motivation for the latest high current LTD at Sandia

- LTD-I through LTD-III greatly refined high current LTD design and operation
- High current LTDs are still considered experimental technology
  - They generally do not work "out-of-the-box"
- Maturity level required to justify an LTD-based Z-Next like "Z 300" (50 MA) or "Z 800" (70 MA) needed to be demonstrated
  - With 3,000 to 5,400 cavities the pre-fire rate needs to be very low (1 in 1,000)
  - Catastrophic component failures (inside cavities) must be very rare
- Need to demonstrate the compact (2 m) technology operating in a multi-cavity module



"Z 300" from W. Stygar et al., PRSTAB 2015

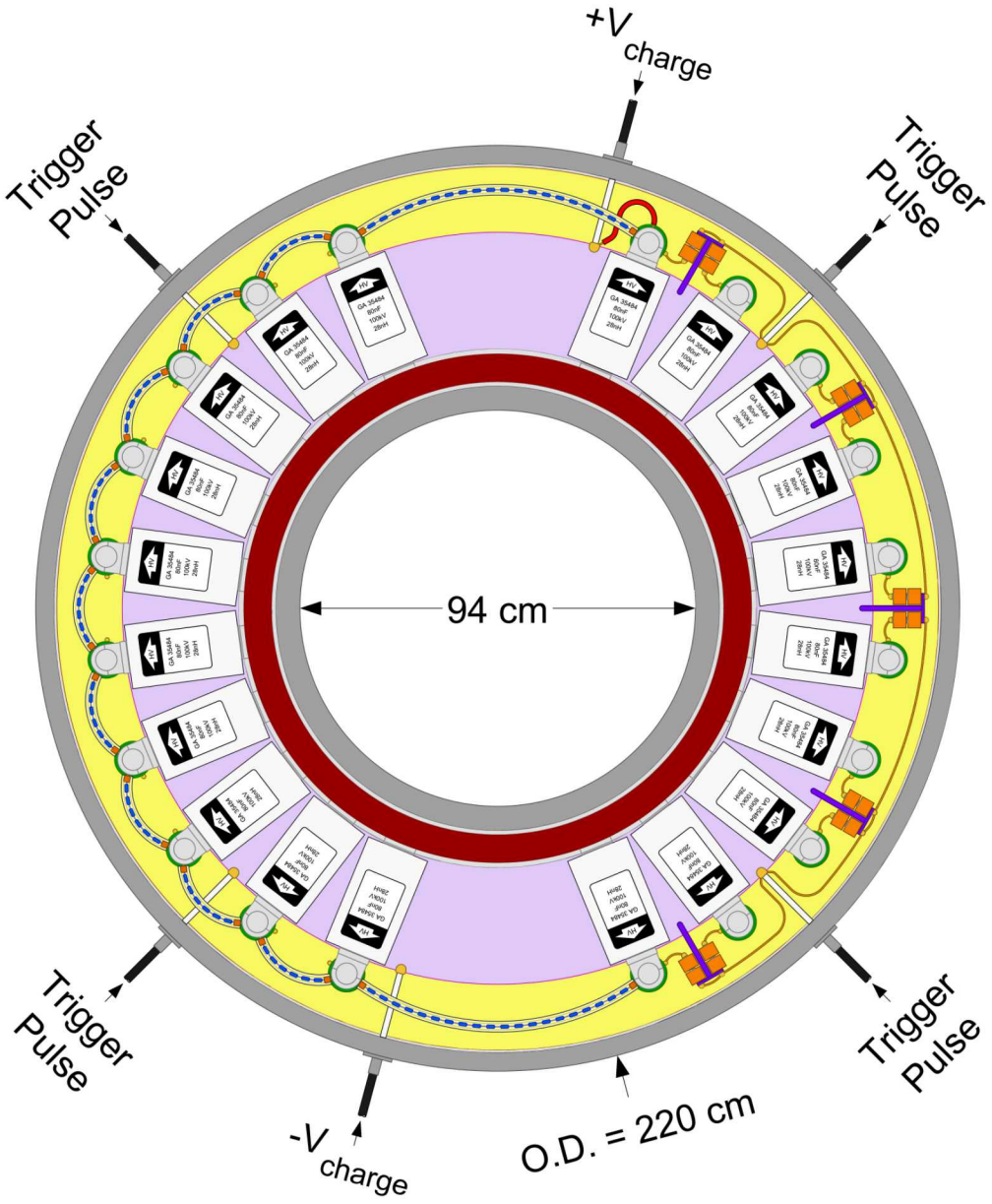
The "Z-Next" 6th generation high current LTD at Sandia

Development

- First high current LTD designed, fabricated and commissioned entirely in the USA
  - Design began in 2016
    - Made for compatibility with "Pluto" cavities
  - Assembled in 2017
  - First ±100 kV charged shot in late 2017

Device parameters/constraints/goals

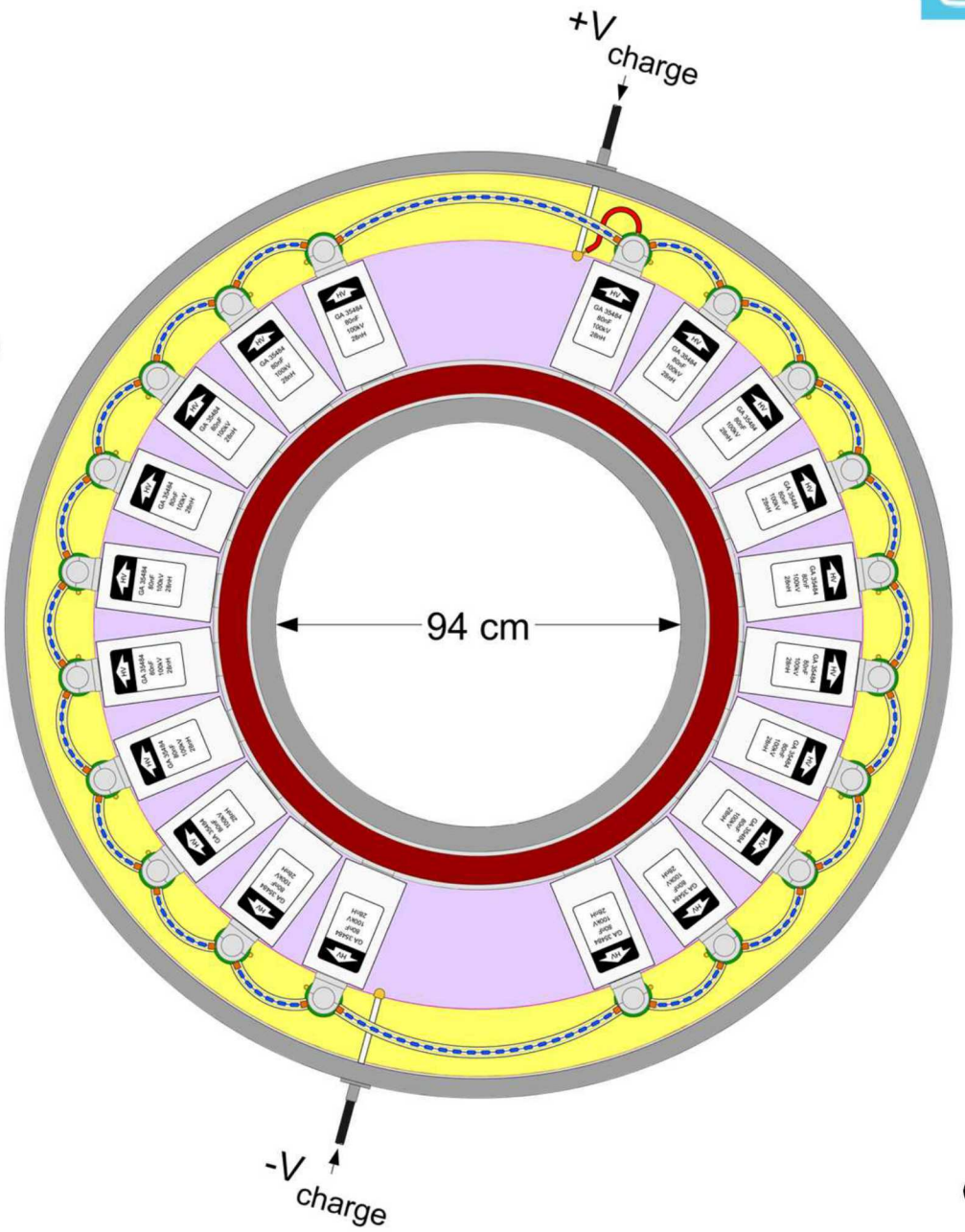
- 2.2 m outer diameter, 0.94 m inner diameter
- Assembled with 20 bricks (4 empty spots)
  - Emulate "Z-300" cavity parameters
- 100 ns rise-time
- ±100 kV charge for 100 GW output
- Accommodate 80 nF capacitors
- Output impedance 0.1 Ω
- Up to 1 MA peak output current
- No aqueous resistors inside cavity



The 6th generation Z-Next LTD

Development of the Z-Next LTD

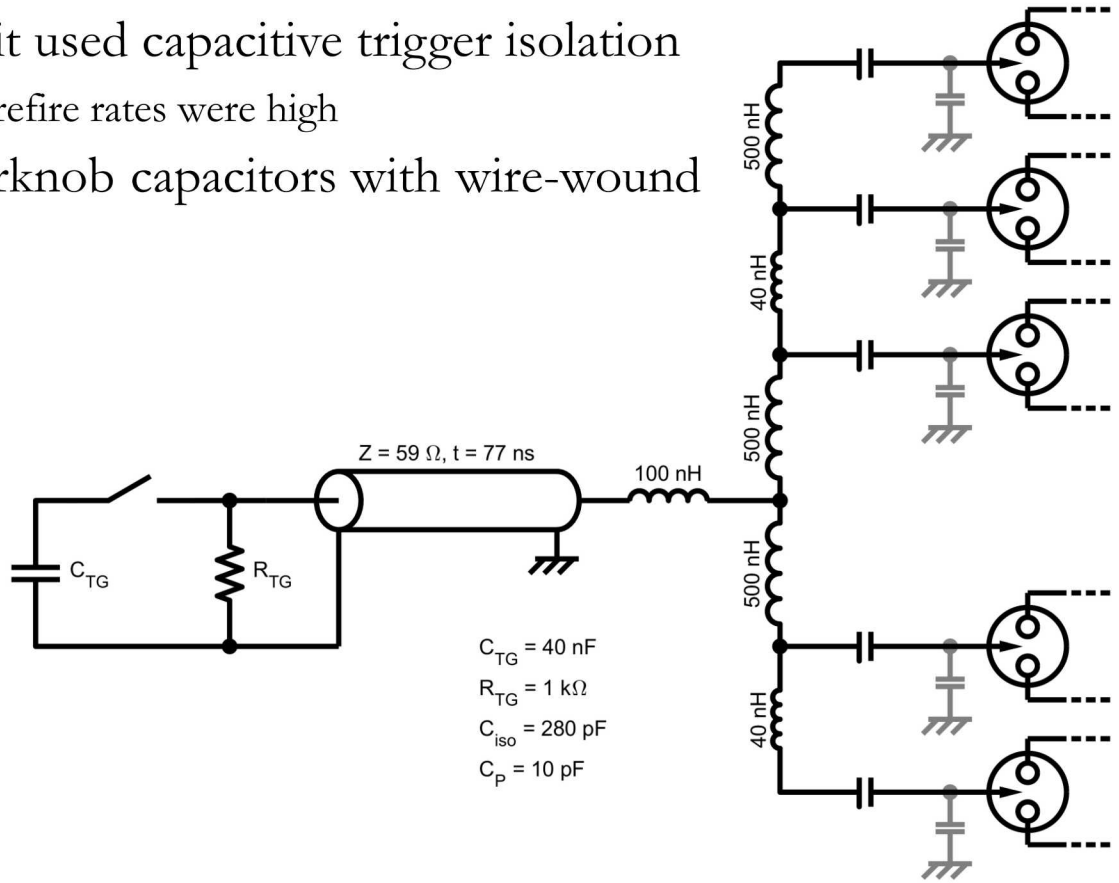
- Charging circuit uses solid carbon composition resistors
- Each charge polarity enters the cavity at a single position
  - Charging is daisy-chained from one capacitor to another through 60 kΩ resistors
  - Each 60 kΩ resistor is composed of six 10 kΩ, high-voltage resistors
  - Each six-resistor chain is encapsulated in vinyl tubing filled with transformer oil
- The 60 kΩ between capacitors prevents the entire cavity from discharging through a switch that prefires
- Eliminating aqueous resistors is desirable
  - Prevents permeation of water into insulating oil
  - Aqueous resistors generally need to be replaced annually

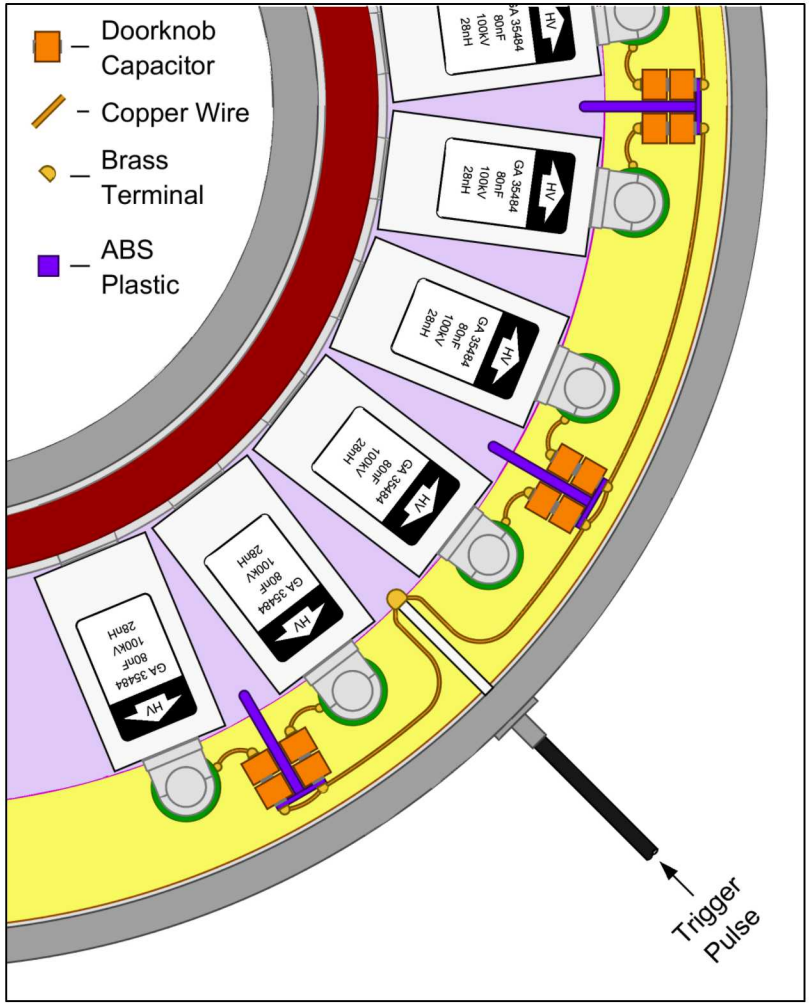


The 6th generation Z-Next LTD

Development of the Z-Next LTD

- Trigger circuit is arranged in four identical quadrants
- Original circuit used capacitive trigger isolation
  - Late-fire and prefire rates were high
- Replaced doorknob capacitors with wire-wound inductors

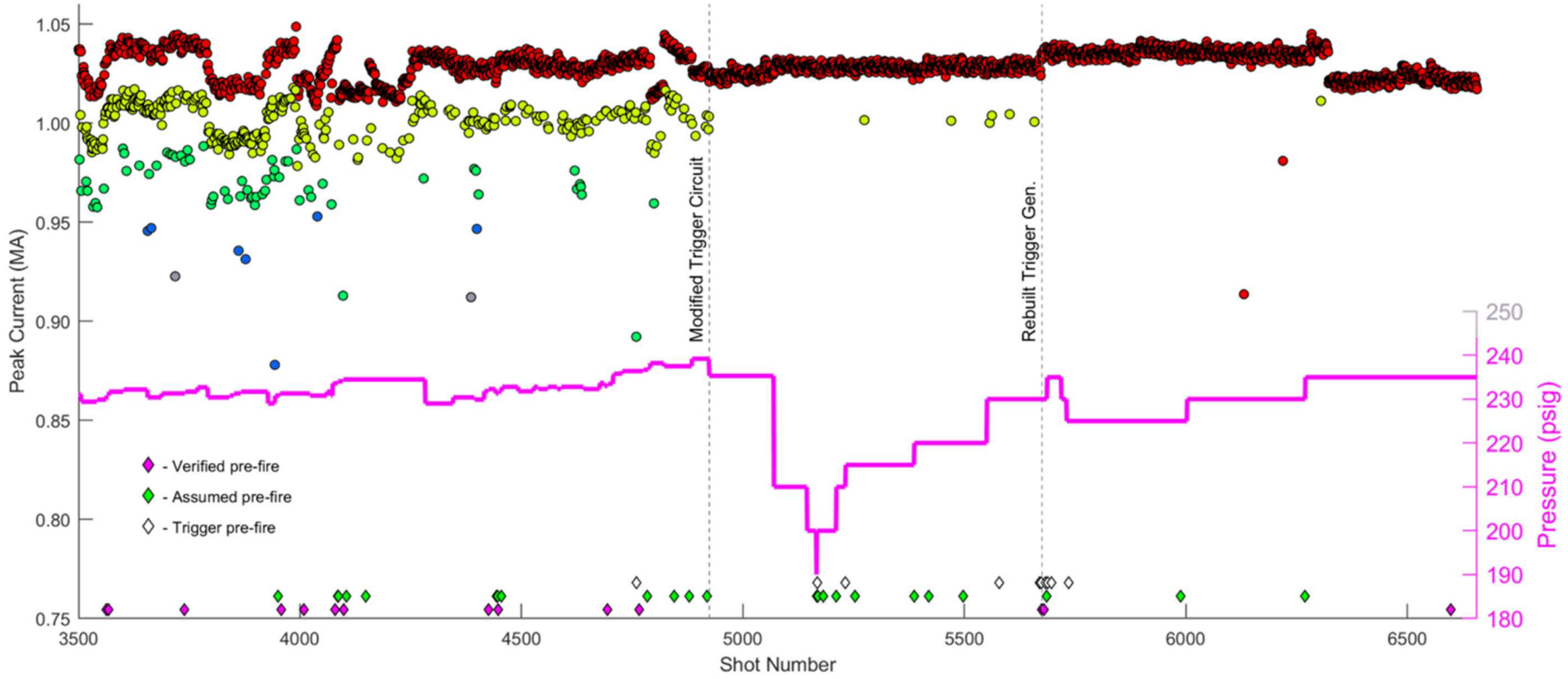




The 6th generation Z-Next LTD

Development of the Z-Next LTD

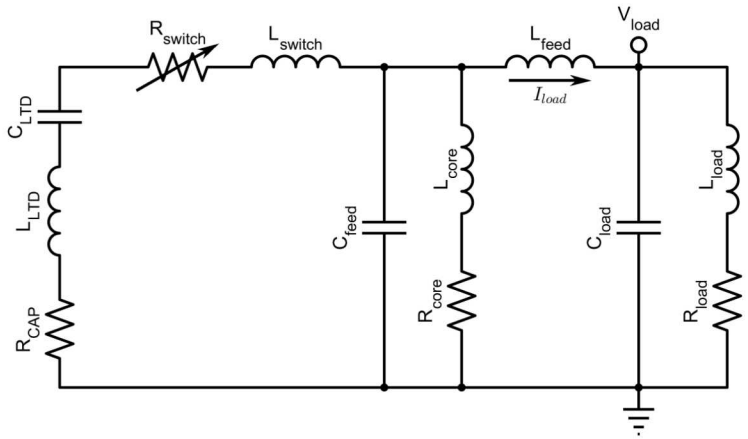
- Replaced doorknob capacitors with wire-wound inductors
  - Prefire rate decreased by ~5x
  - Late-fires nearly completely eliminated, very consistent performance achieved



The 6th generation Z-Next LTD

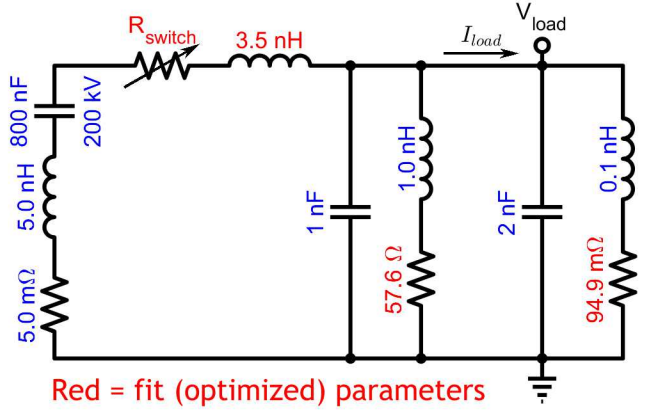
Circuit modeling

- Experimental data is in good agreement with circuit modeling
  - Genetic Algorithm is used to find circuit model parameters that produce optimal fit of BERTHA output to current and voltage measurements from experiment



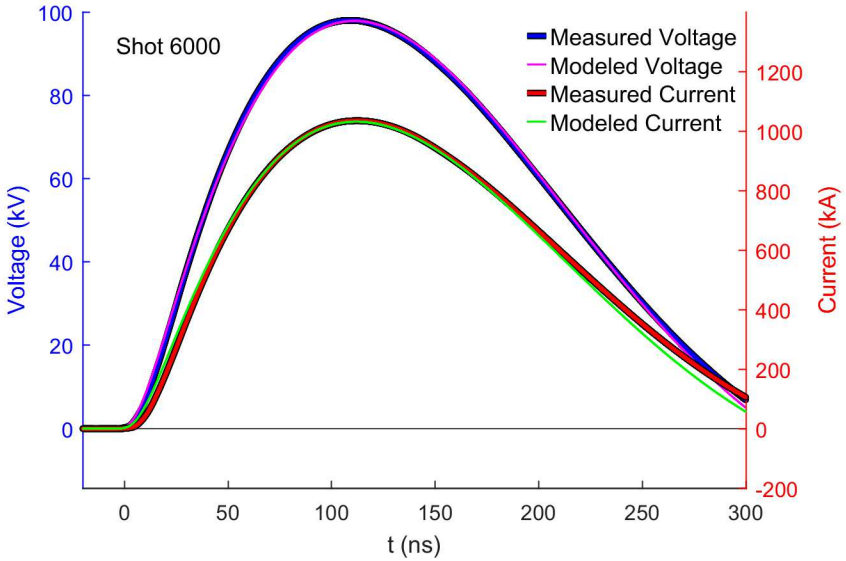
$$R_{switch} = R_{init} \times [\frac{1}{2} - \frac{1}{\pi} tan^{-1}(\frac{t - t_{break}}{\tau_{switch}})]^{\beta} + R_{final}$$

$$R_{switch} = 103.4k\Omega \times [\frac{1}{2} - \frac{1}{\pi} tan^{-1}(\frac{t+5.2}{3.4})]^{4.3} + 5.3m\Omega$$



Red = fit (optimized) parameters

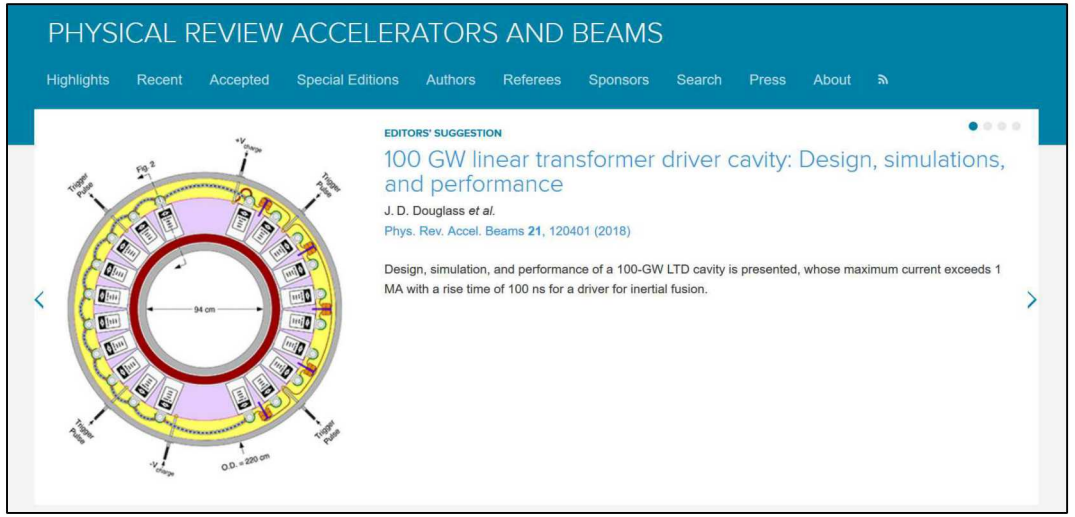
Blue = fixed parameters

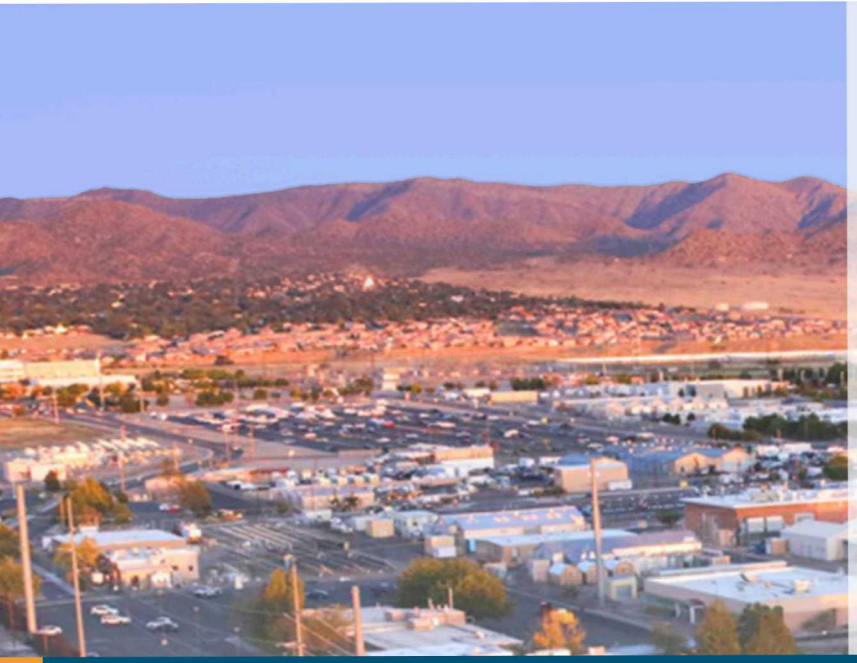


The 6th generation Z-Next LTD

Initial development demonstrated a compact LTD that produces over 1 MA output with impressive reliability and consistency

- Switch late-fire and pre-fire rates were 10^{-4} to 10^{-5}
- Component lifetime and reliability were good
  - One failed capacitor
  - Four failures of standard high-impedance charging resistors
- Results were published in *Physical Review, Accelerators and Beams*, December, 2018





The 6th Generation High Current LTD Operating with 24 Bricks

A compact, 100 kV, 24-brick LTD producing 1.2 MA in 100 ns

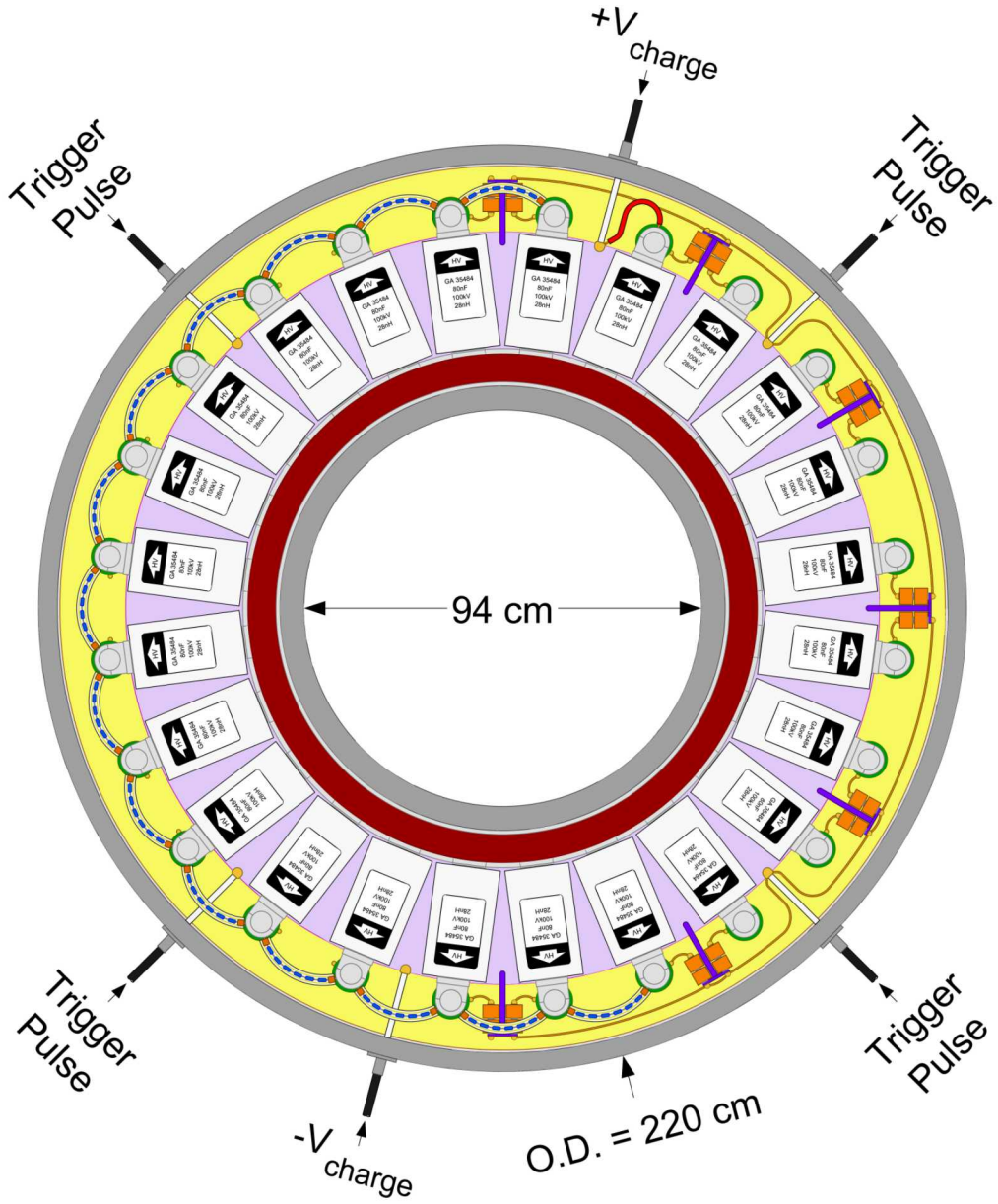
The 6th generation high current LTD in 24-brick mode

Motivation

- Does reduced stress on a larger number of bricks improve reliability?
- Produce the same output power as 20-brick configuration with reduced charge voltage

Device parameters/constraints/goals

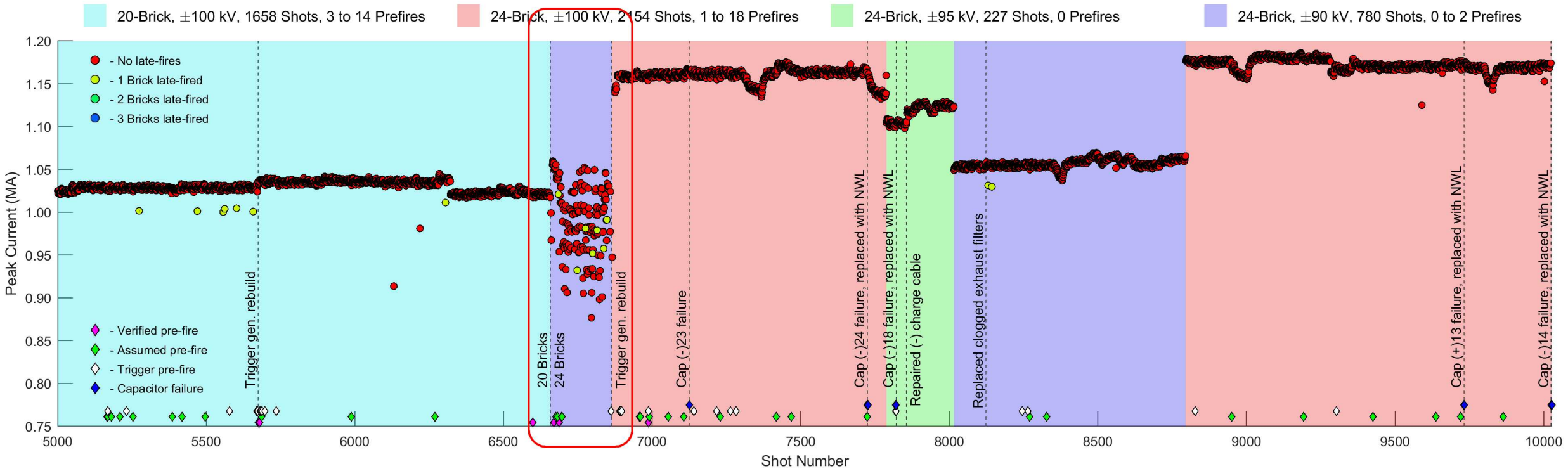
- Installed bricks in the four empty spots
  - 8 new capacitors, 4 new switches
- 100 ns rise-time
- ±90 kV charge for 93 GW
- Output impedance 0.08 Ω
- Up to 1.2 MA peak output current (±100 kV)



The 6th generation high current LTD in 24-brick mode

First run at ±90 kV charge

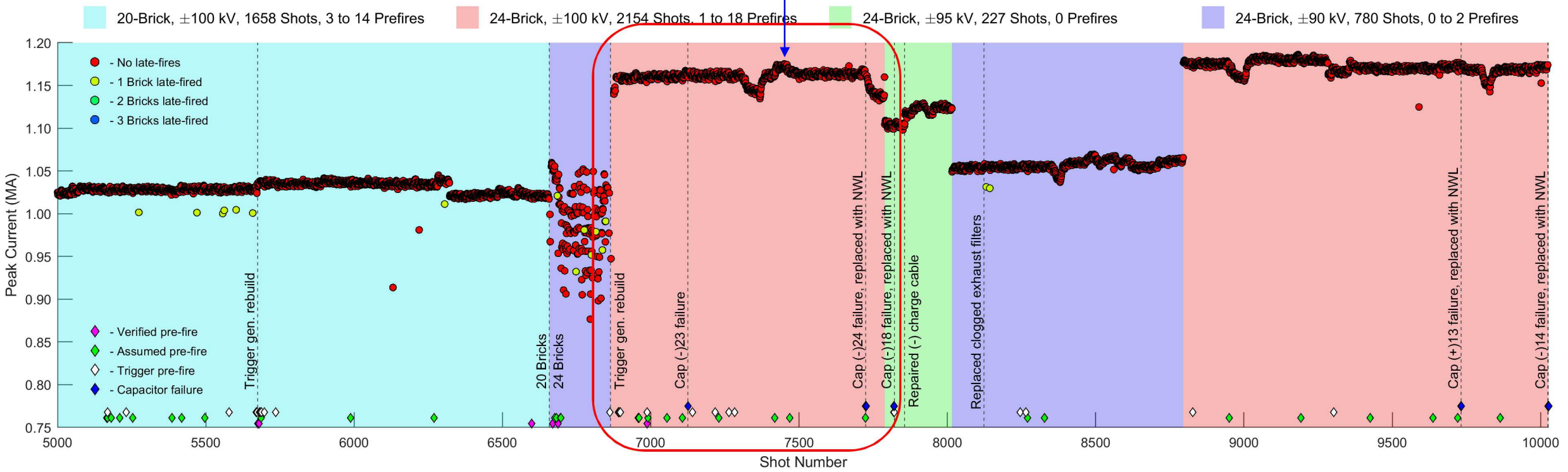
- Terrible results over 208 shots
  - Suspect poor choice of switch pressure and/or trigger voltage settings
  - Trigger generator may have been damaged before campaign started or shortly there after
    - Inductive trigger isolation can be dangerous without well known settings and/or a robust trigger generator



The 6th generation high current LTD in 24-brick mode

For second attempt we rebuilt the trigger generator and returned to known-good settings for ±100 kV operation

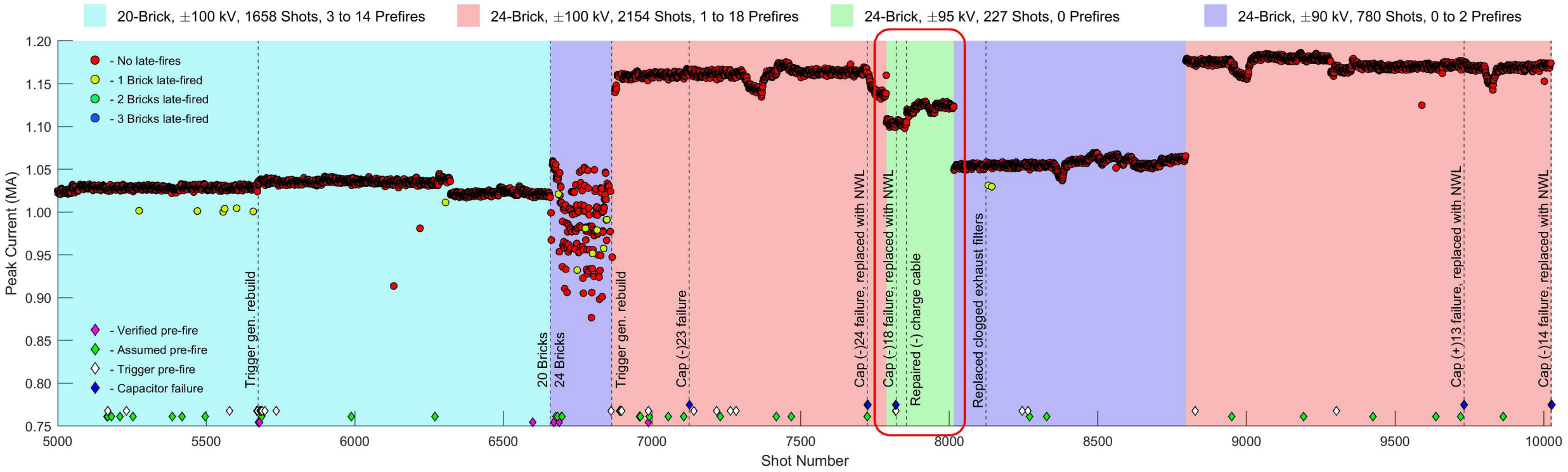
- Good results over 922 shots
  - New record for output current from an LTD: 1.17 MA
  - Only one verifiable prefire
  - Failure of two General Atomics capacitors, one of which only had ~1,000 shots



The 6th generation high current LTD in 24-brick mode

Next, we dropped down to ±95 kV charge (proceeding to ±90 kV with caution)

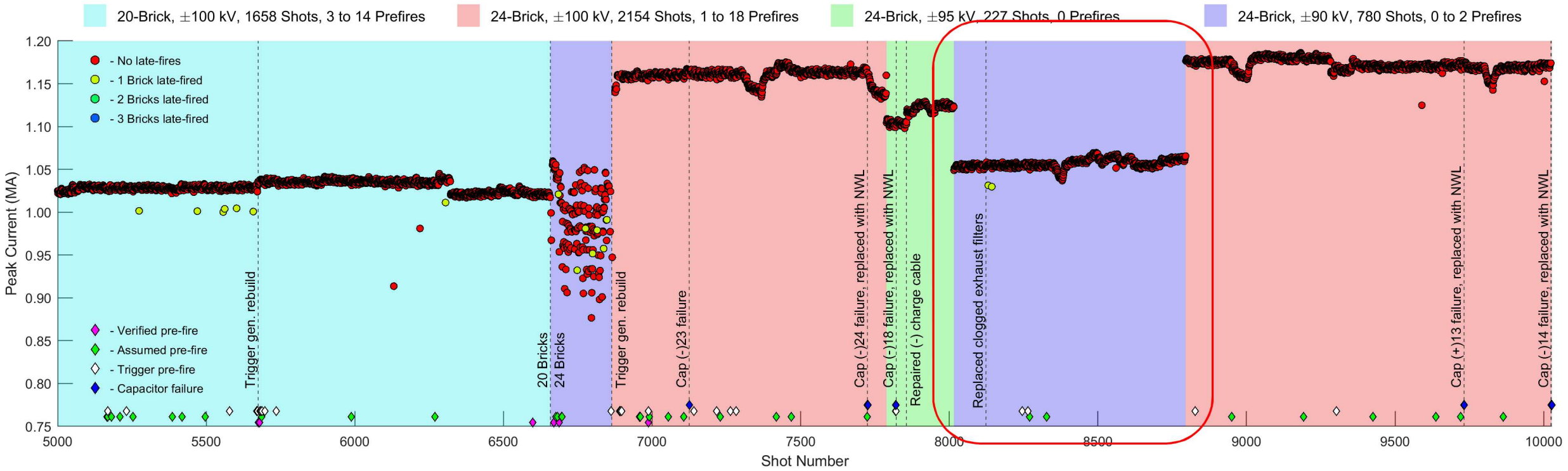
- Great results over 227 shots, zero prefires, zero late-fires
  - Failure of one General Atomics capacitor
  - Found that the negative charge line was constantly arcing through an oil-gap during charge cycle, going on since 24-brick started
    - Could oil arc have been generating bubbles and inducing capacitor punch-through???



The 6th generation high current LTD in 24-brick mode

Dropped down to ±90 kV charge again

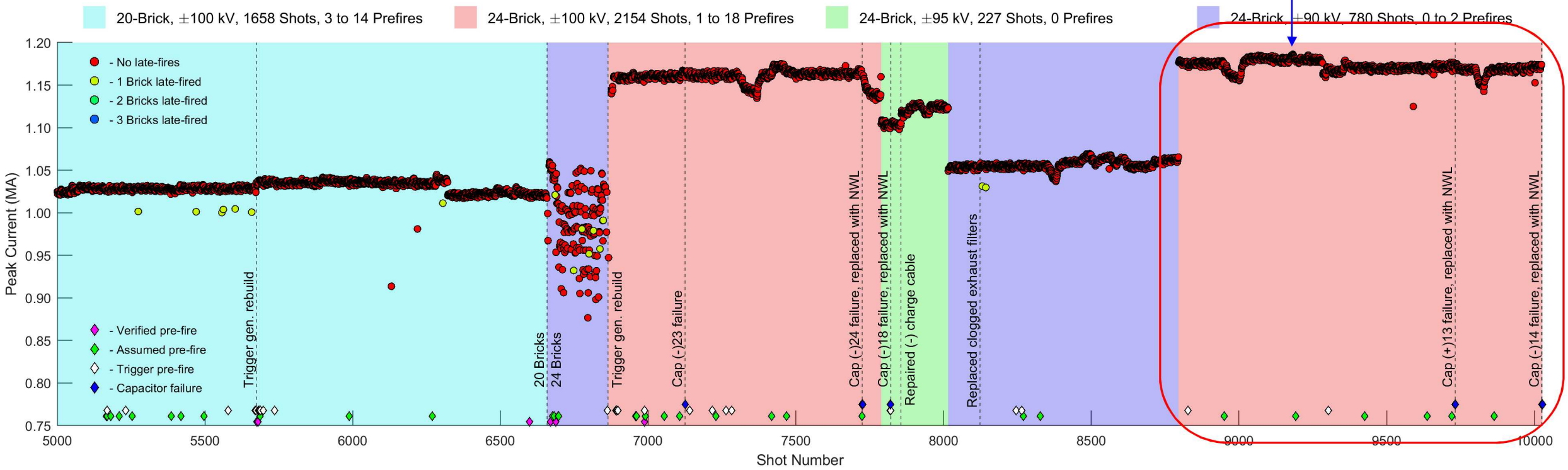
- Great results over 780 shots
  - Zero definitive prefires, only two shots that *might* have been prefires, and just two late-fires
  - Found that switch exhaust gas filters were nearly completely clogged
    - Is high-velocity gas purge necessary for our custom switch???



The 6th generation high current LTD in 24-brick mode

Returned to ±100 kV operation

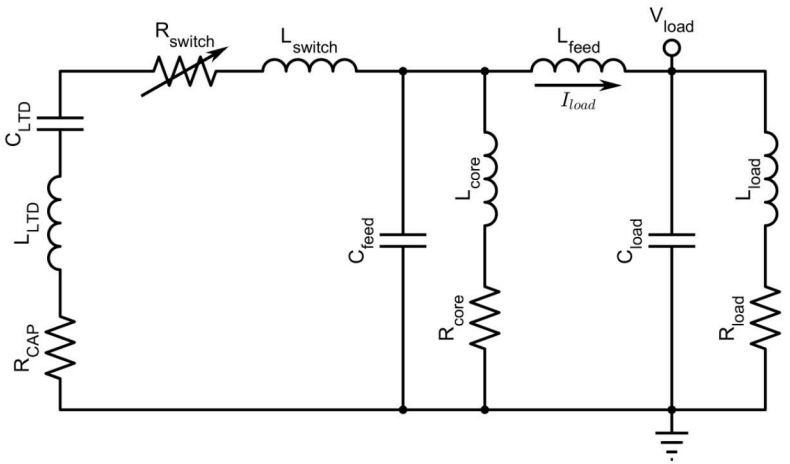
- Great results over 1232 shots, new record for output current: 1.19 MA
  - Zero definitive prefires, only six shots that *might* have been prefires and zero late-fires
  - Two more failed GA capacitors
    - Typical reversal voltage was 10%, at which caps are rated for 10,000 shots, just end-of-life?



The 6th generation high current LTD in 24-brick mode

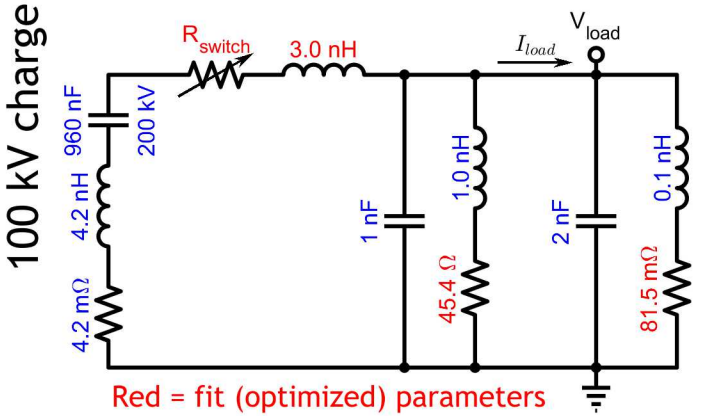
Circuit modeling of 24-brick

- Experimental data is in good agreement with circuit modeling
  - Genetic Algorithm is used to find circuit model parameters that produce optimal fit of BERTHA output to current and voltage measurements from experiment



$$R_{switch} = R_{init} \times [\frac{1}{2} - \frac{1}{\pi} tan^{-1}(\frac{t - t_{break}}{\tau_{switch}})]^{\beta} + R_{final}$$

$$R_{switch} = 120.8k\Omega \times [\frac{1}{2} - \frac{1}{\pi} tan^{-1}(\frac{t+21.9}{4.6})]^{4.5} + 9.2m\Omega$$



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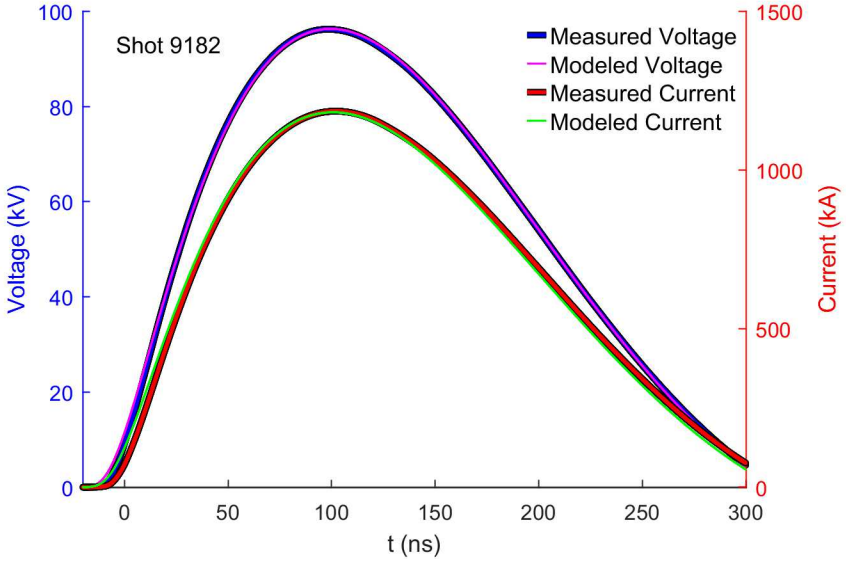
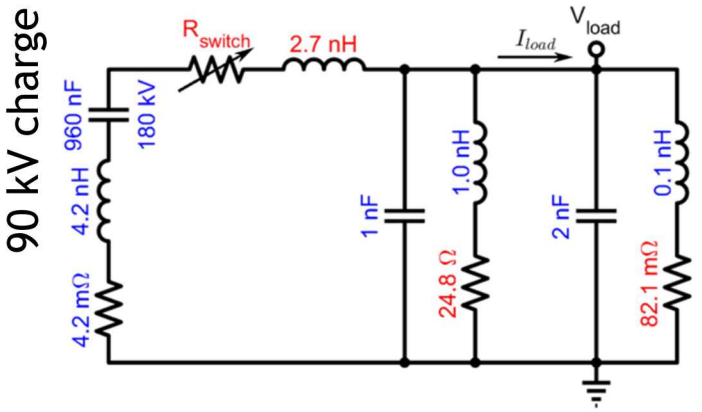
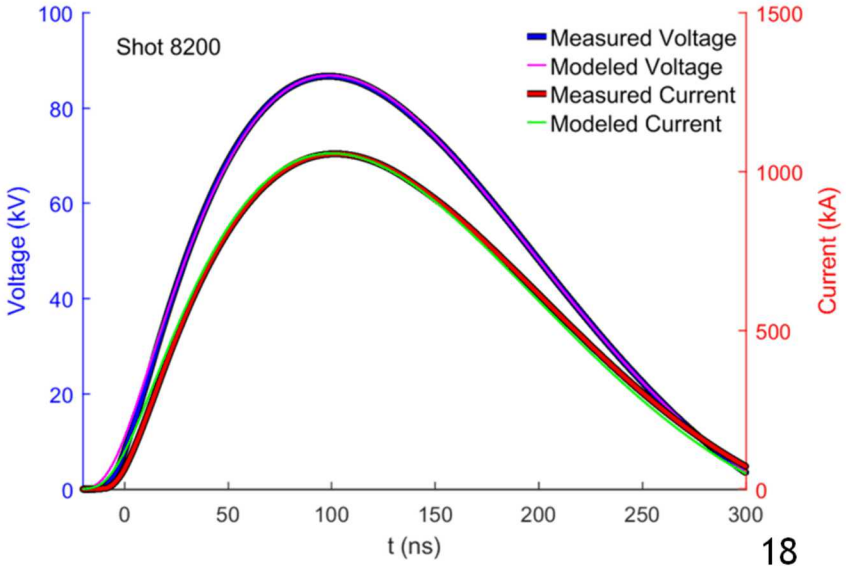


$$R_{switch} = R_{init} \times [\frac{1}{2} - \frac{1}{\pi} tan^{-1}(\frac{t - t_{break}}{\tau_{switch}})]^{\beta} + R_{final}$$

$$R_{switch} = 87.6k\Omega \times [\frac{1}{2} - \frac{1}{\pi} tan^{-1}(\frac{t+24.6}{5.4})]^{4.4} + 9.6m\Omega$$





The 6th generation high current LTD in 24-brick mode

24-Brick operation synopsis

- Not much difference in prefire or late-fire rate from ±100 kV to ±90 kV charge
  - These rates are so low that it's tough to say
- No component failures occurred while operating at ±90 kV charge
- Five capacitor failures
  - Suspect three failures due to bubbles in oil
  - The latest failure may have simply been end-of-life
- Performance of NWL capacitors is encouraging

Future Plans

Outlook for remainder of 2019 through 2020

Future plans

Looking to 2020

- Assemble and commission two new LTDs
  - Total of five operational cavities on-hand
  - Four to fill half of 8-cavity module, one spare
- Assemble and commission (4)8-cavity module from January to August 2020