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LTD Development at Sandia National Laboratories

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PRESENTED BY

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Outline

- Brief history of LTD development at Sandia
- The 6th generation "Z-Next" LTD
  - Motivation for a new LTD
  - Early development
  - Issues encountered
  - Modifications
  - Recent results
- The path ahead for high-current LTD development at Sandia
  - Plans for the immediate future
  - Looking further…

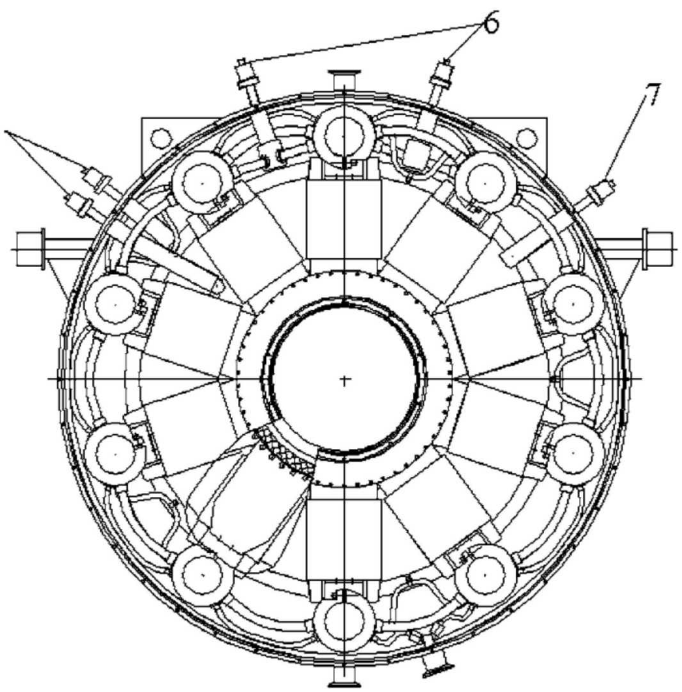
Brief History of LTD Development at Sandia

2004 to 2018

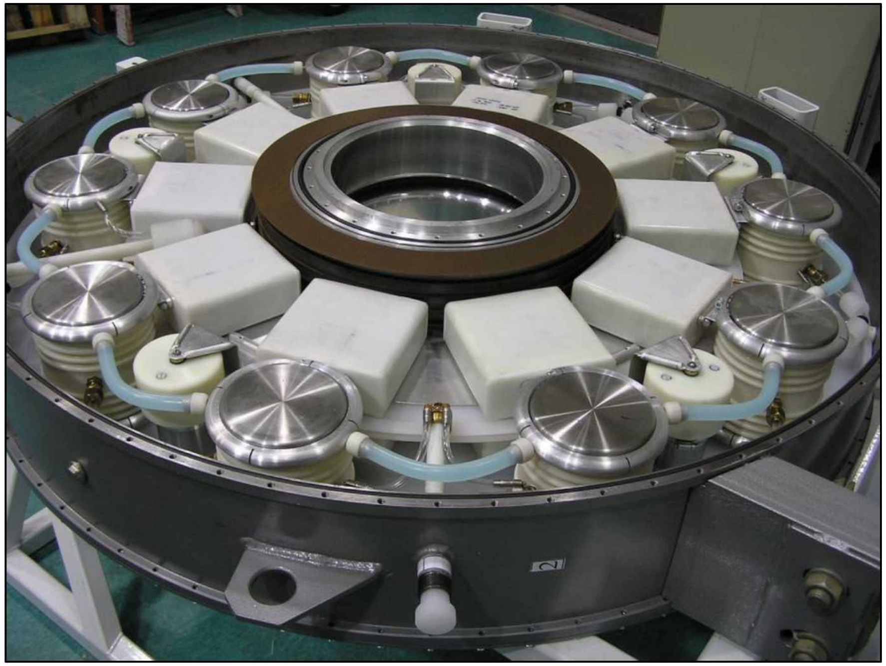
Brief History of LTD Development at Sandia

2004 - LTD-R (aka LTD-100)

- Russian made LTD with ~50 ns rising pulse for radiography
- Peak output current of 125 kA
- Predecessor to Ursa Minor (first seven cavities)



- A. A. Kim et. al, ICHPPB 2002



Brief History of LTD Development at Sandia

2004 - LTD-1

- First Russian made "high current" LTD
- 2-m diameter
- 75 ns rise-time
- ±90 kV charge, 40 nF caps
- 450 kA peak current, 40 GW
- Intended for "ZX" IFE program

Brief History of LTD Development at Sandia

2006 - LTD-II

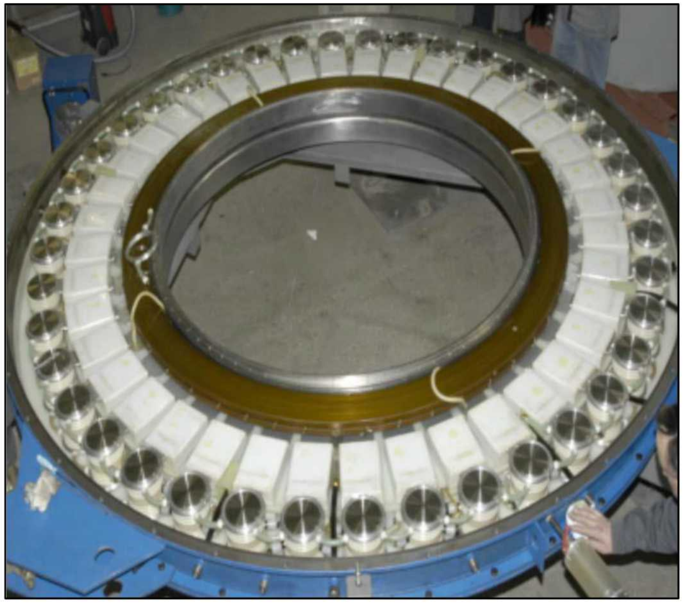
- Second Russian made "high current" LTD
- 2.1 m diameter (increase from 90 kV to 100 kV)
- 20-bricks
- 75 ns rise-time
- ±100 kV charge, 40 nF caps
- 500 kA peak current, 50 GW
- Intended for "ZX" IFE program

(No picture available)

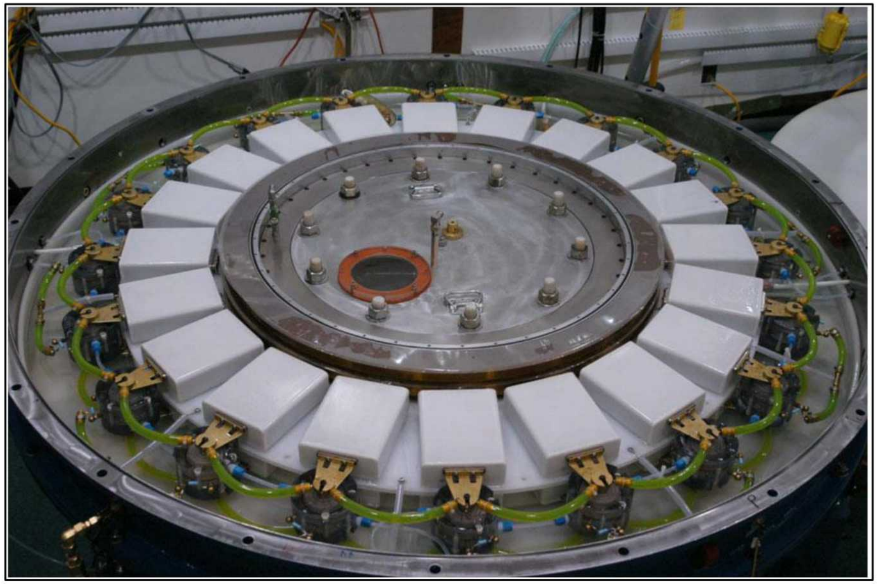
Brief History of LTD Development at Sandia

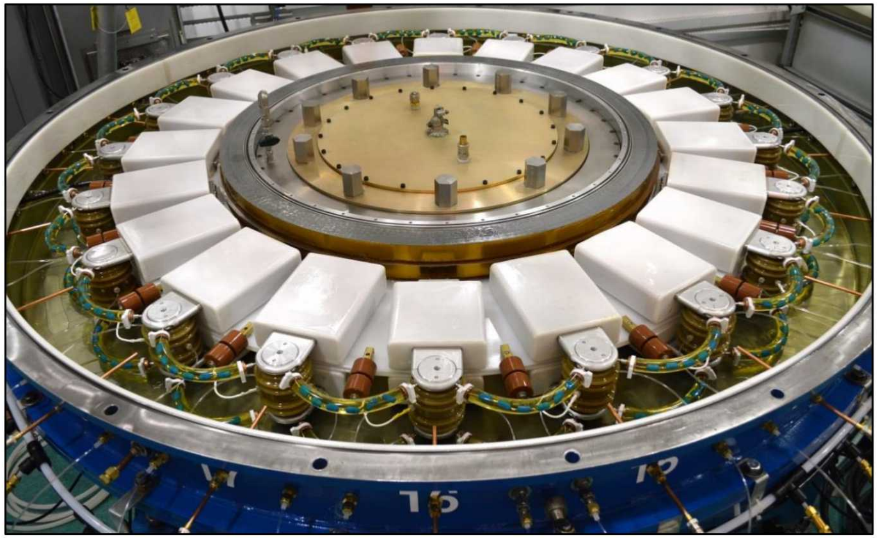
2008 – 1MA LTD (Mykonos cavities)

- First Russian made megaAmpere LTDs
- 3-m diameter
- 36 to 40-bricks
- 100 ns rise-time
- Up to ±100 kV charge, 40 nF caps
- 1-MA peak current, 80 GW per cavity
- Intended to demonstrate muti-cavity module, high current and high voltage



Brief History of LTD Development at Sandia

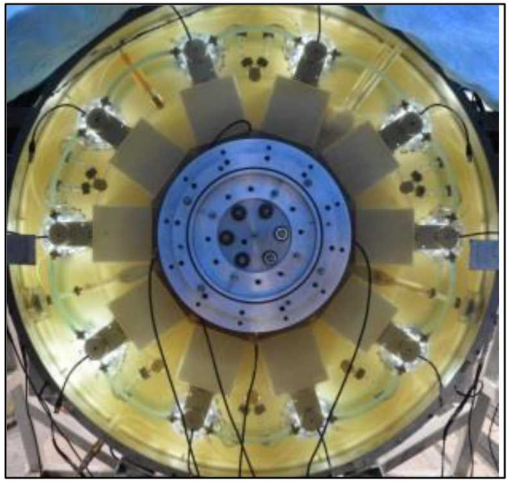




2010 – LTD-III

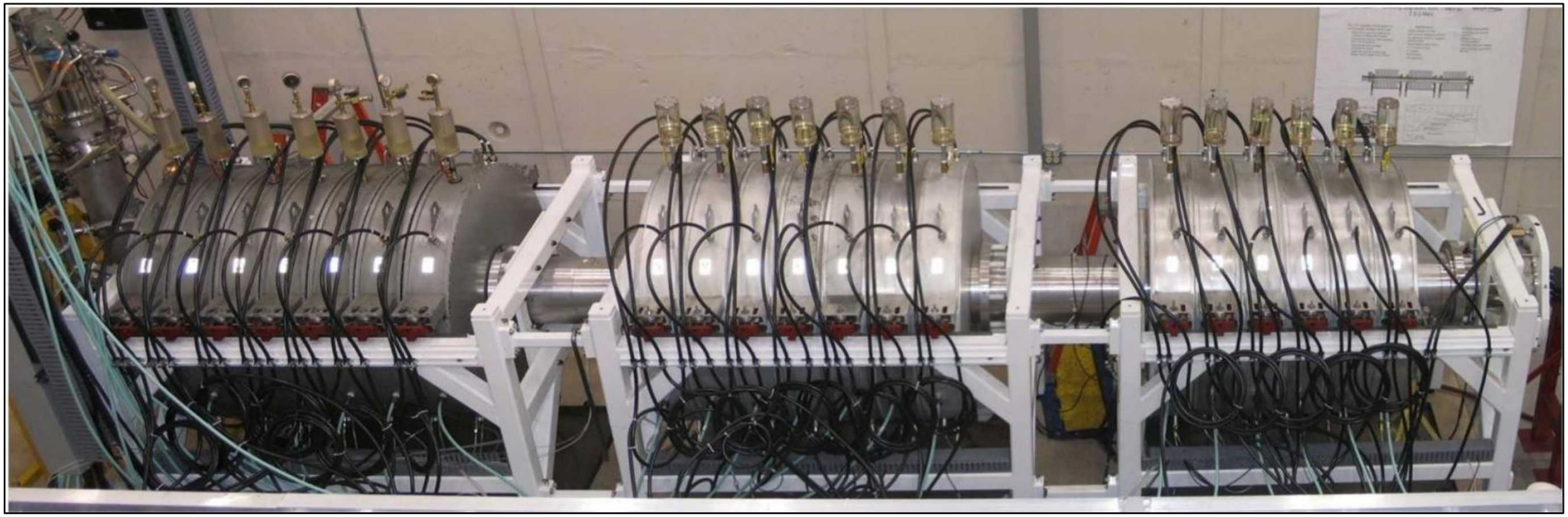
- Russian made “high current” LTD
- 2.1 m diameter, 20-bricks
- 75 to 100 ns rise-time
- ±100 kV charge, 40 to 60 nF caps
- 810 kA peak current, 80 GW
- Test bed for LTD component experimentation and refinement
  - First use of Metglas cores
  - Numerous switches evaluated
  - Tried mixing different capacitor values
  - Experiments with various types of charging resistors
  - Employed various triggering topologies
  - Developed diagnostics for full switch coverage

Brief History of LTD Development at Sandia



2010 – Ursa Minor

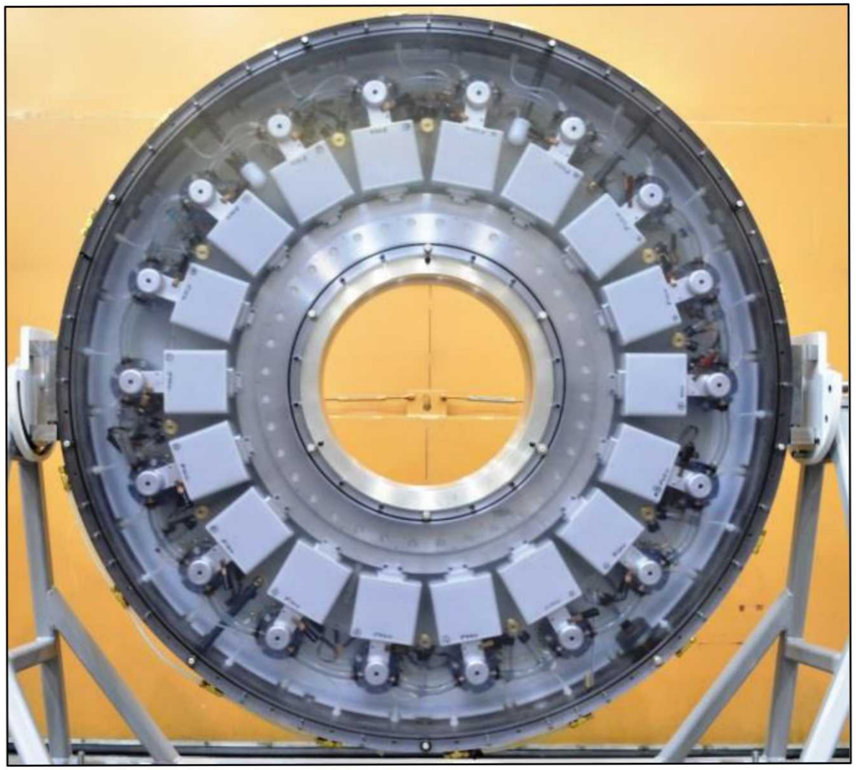
- 21-cavity LTD module for radiography
- 7 Russian made LTD-R cavities, 125-cm OD
- 14 US made cavities inspired by LTD-R 128-cm, OD
- ~50 ns rise-time
- ±100 kV max charge, 20 nF caps
- Up to 2.5 MV output



Brief History of LTD Development at Sandia

2014 – 18-Brick Cavity

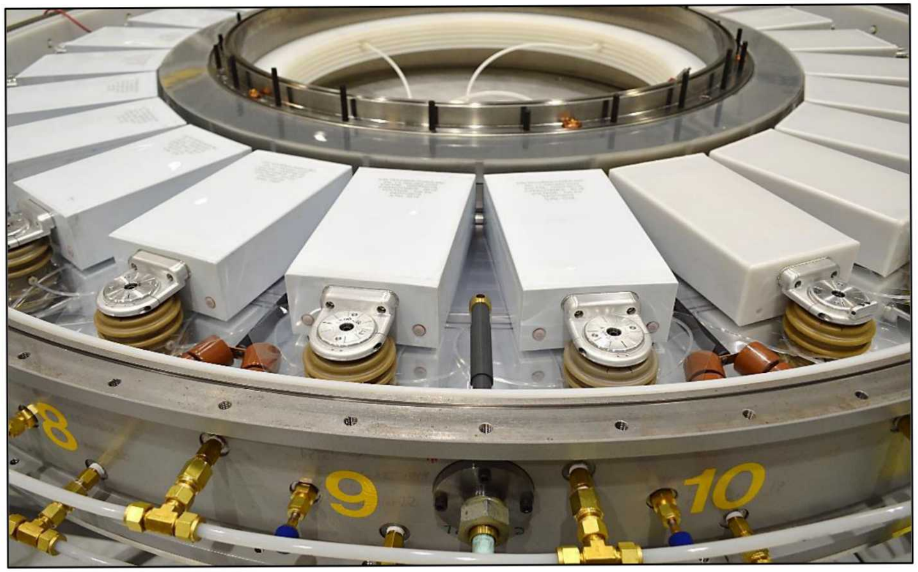
- High power LTD for radiography
- 2-m diameter
- ~50 ns rise-time
- ±100 kV max charge, 12 nF caps
- 2 built, one given to LLE, other remains at Sandia



Brief History of LTD Development at Sandia

2014 – LTD-IV (Pluto)

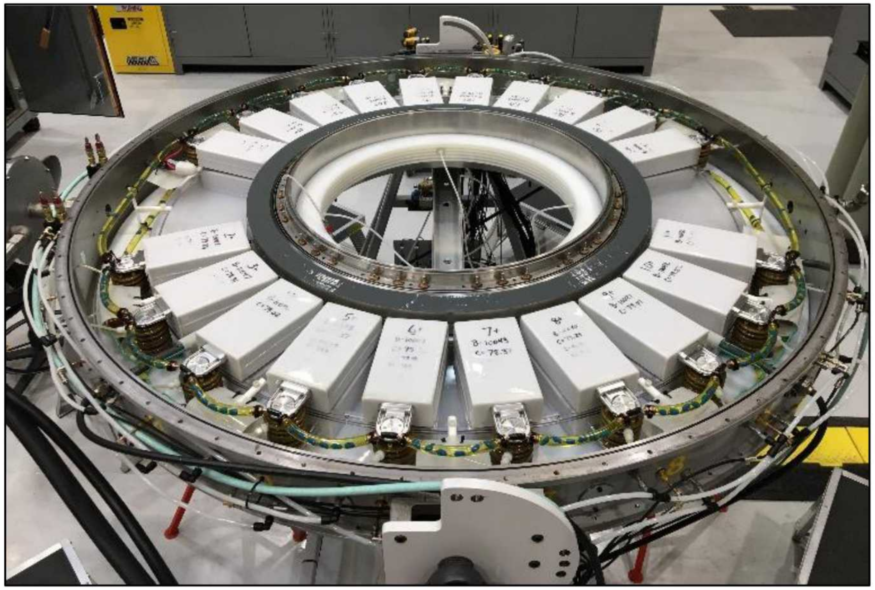
- First US made "high current" LTD
- 2.2-m diameter, 24-bricks
- 100 ns rise-time
- ±100 kV charge, 40 nF to 80 nF caps
- 1.1 MA peak current
- Demonstration cavity for proposed 50-stage LTD module to produce a 12-MeV x-ray source
- Tested caps from various vendors
- Evaluated performance of various custom switch designs

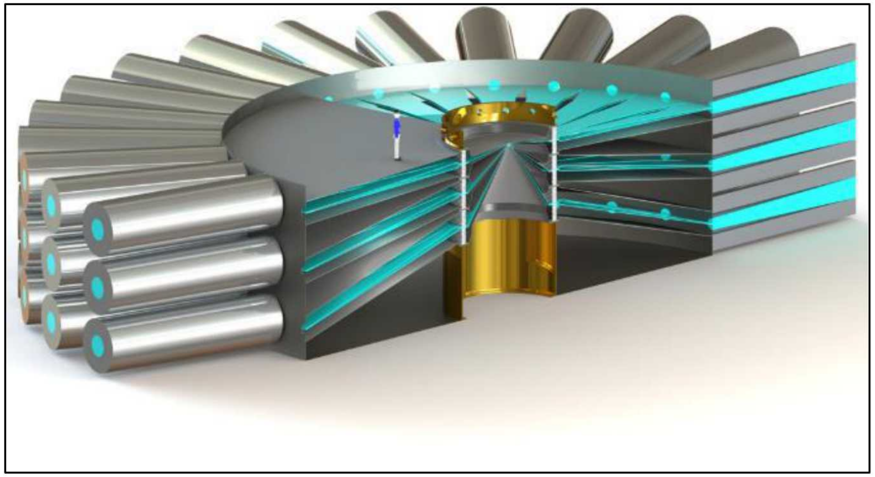


Brief History of LTD Development at Sandia

2017 – "Z-Next LTD" (LTD-IV)

- First US made "high current" LTD
- 2.2-m diameter, 20-bricks
- All components designed to minimize inductance at considerable cost
- 100 ns rise-time
- ±100 kV charge, 80 nF caps
- 1.05 MA peak current
- Demonstration cavity for +50 MA IFE driver with 9,000 cavities





Brief History of LTD Development at Sandia

Comments on 14 years of LTD development at Sandia and elsewhere

- Experiments that do not work are practically never published
  - Ask around before trying a "new" idea, chances are good that SNL has already tried it
- The published record on LTD development is not the complete story
  - It has been a long and painful path to get to the performance and reliability we have today
  - Most LTD designs did not work "out-of-the-box", revisions of critical components were required
  - Authors often report the maximum capabilities of a design, not typical operating conditions
  - Be skeptical of statements like "Not a single pre-fire was recorded…"

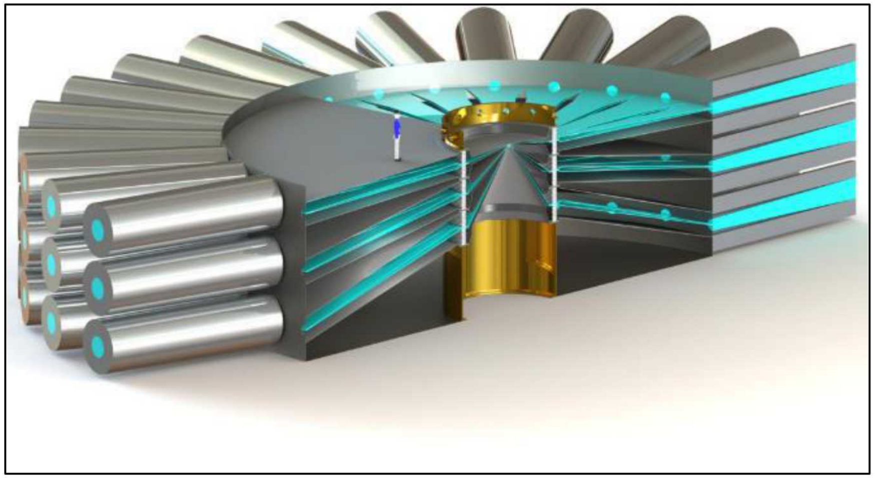
The 6th Generation "Z-Next" LTD

2017 to Present

The 6th Generation "Z-Next" LTD

Motivation for the latest high-current LTD at Sandia

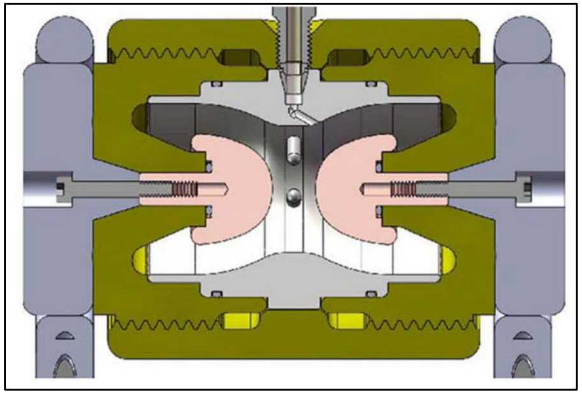
- Much has been learned from LTD-I through LTD-III
- High-current LTDs still considered experimental technology
  - They generally did not work "out-of-the-box"
- Maturity level required to justify an LTD-based Z-Next (IFE driver) needed to be demonstrated
  - With 9,000 cavities the pre-fire rate needs to be very low (1/1,000)
  - Catastrophic component failures (inside cavities) must be very rare
- Needed to demonstrate the compact (2-m) technology operating in a multi-cavity module

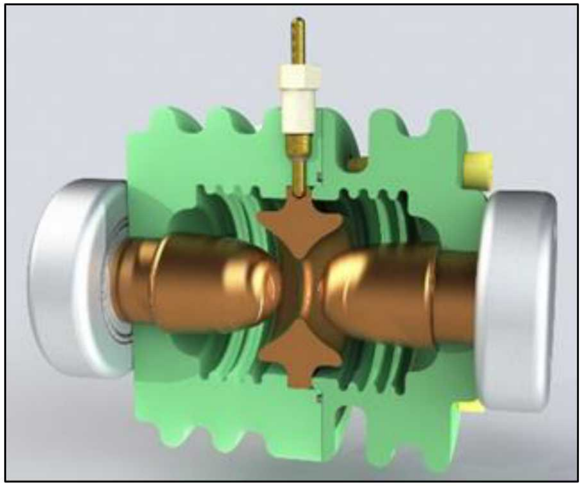


The 6th Generation "Z-Next" LTD

Development of the Z-Next LTD

- Switch development and testing
  - Russian multi-gap switches considered bulky and difficult to assemble
  - L3 switches considered to have larger OD than necessary and high jitter*†
  - Custom Sandia switches were the most compact and had the lowest jitter*
- Went through several custom 200 kV switch design iterations
  - Started with a fairly complex switch with exotic materials intended for very high pressure
  - By the third revision the switch had half as many parts, was much easier to assemble and is now very reliable
  - Main lessons learned:
    - Keep it simple!
    - Eliminate trapped air volumes (like at the bottom of blind tapped holes)
    - Need to consider neighboring structures and churning oil
    - Maximize gas flow (large ports)
    - Copper-Tungsten electrodes are worth the extra cost, 75/25 W/Cu seems to work just as well as 80/20





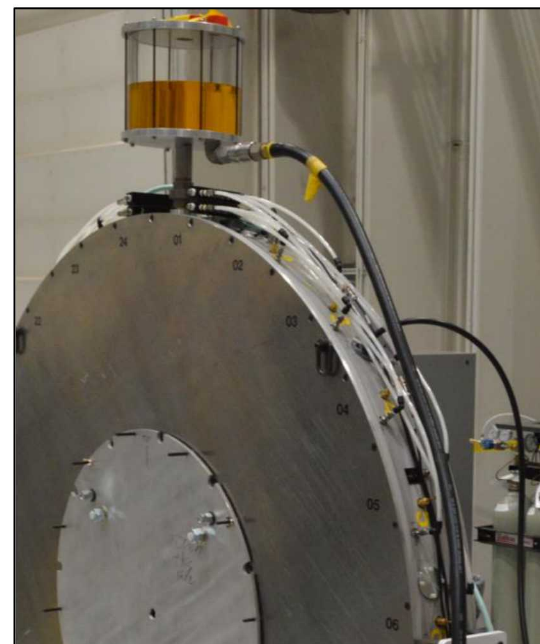
- Latest custom switches have over 6,000 shots on them and exhibit no degradation
- Oil-contaminated switches that were rebuilt (cleaned) resumed ideal operation without any conditioning

* Switch testing reported by J. R. Woodworth et. al, PRSTAB 2010
† Other testing indicates superior jitter from modern L3 switch – J. Leckbee 2014

The 6th Generation “Z-Next” LTD

Development of the Z-Next LTD

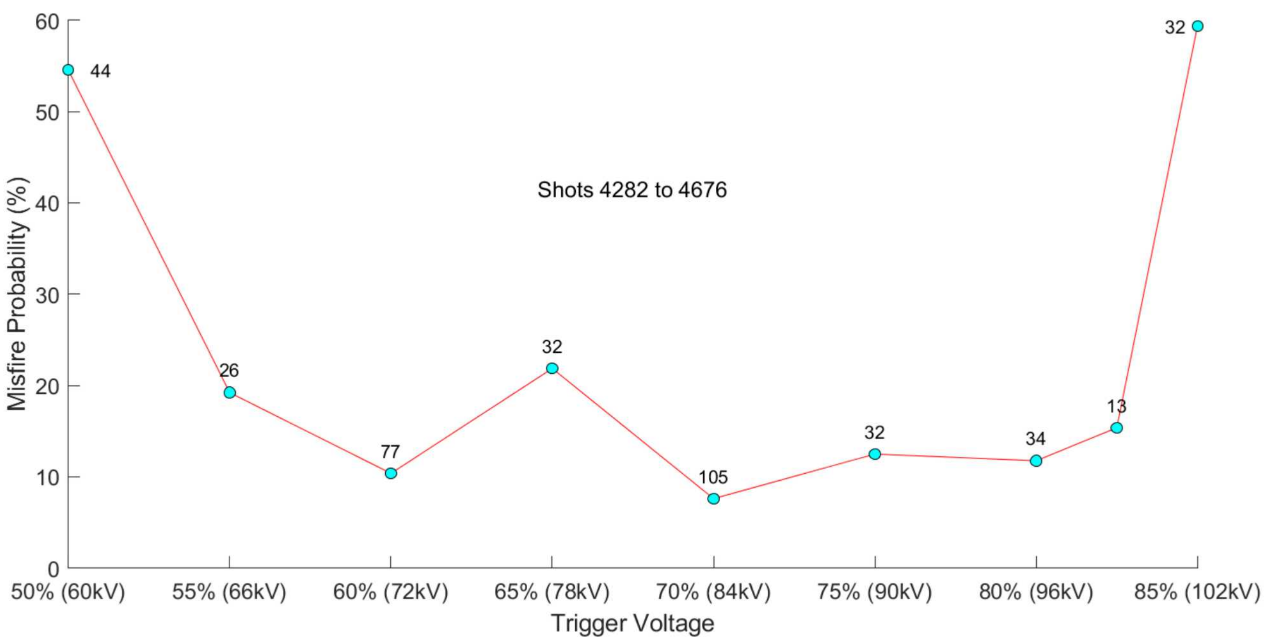
- Trigger wire routing was changed
  - Trigger wire was originally routed in a groove along the outer edge of the middle insulator
  - Dendrite growth in the polycarbonate middle insulator motivated relocation
  - Trigger bus wire now runs outside of the switches about 1.0” inside the cavity wall
- Gas line plumbing modified for improved flow and isolation
  - Early-on single-brick testing pre-fire rate was high
    - Increased gas flow (flush/purge) possible solution to pre-fires
    - Parallel gas line provided higher gas flow
  - Early-on single-brick testing switch failure was common
    - Parallel gas lines helped prevent oil cross-contamination of switches
    - One-way check valves were also tried but provided no benefit
  - More recently, series connected lines have demonstrated that parallel routing is not necessary



The 6th Generation "Z-Next" LTD

Development of the Z-Next LTD

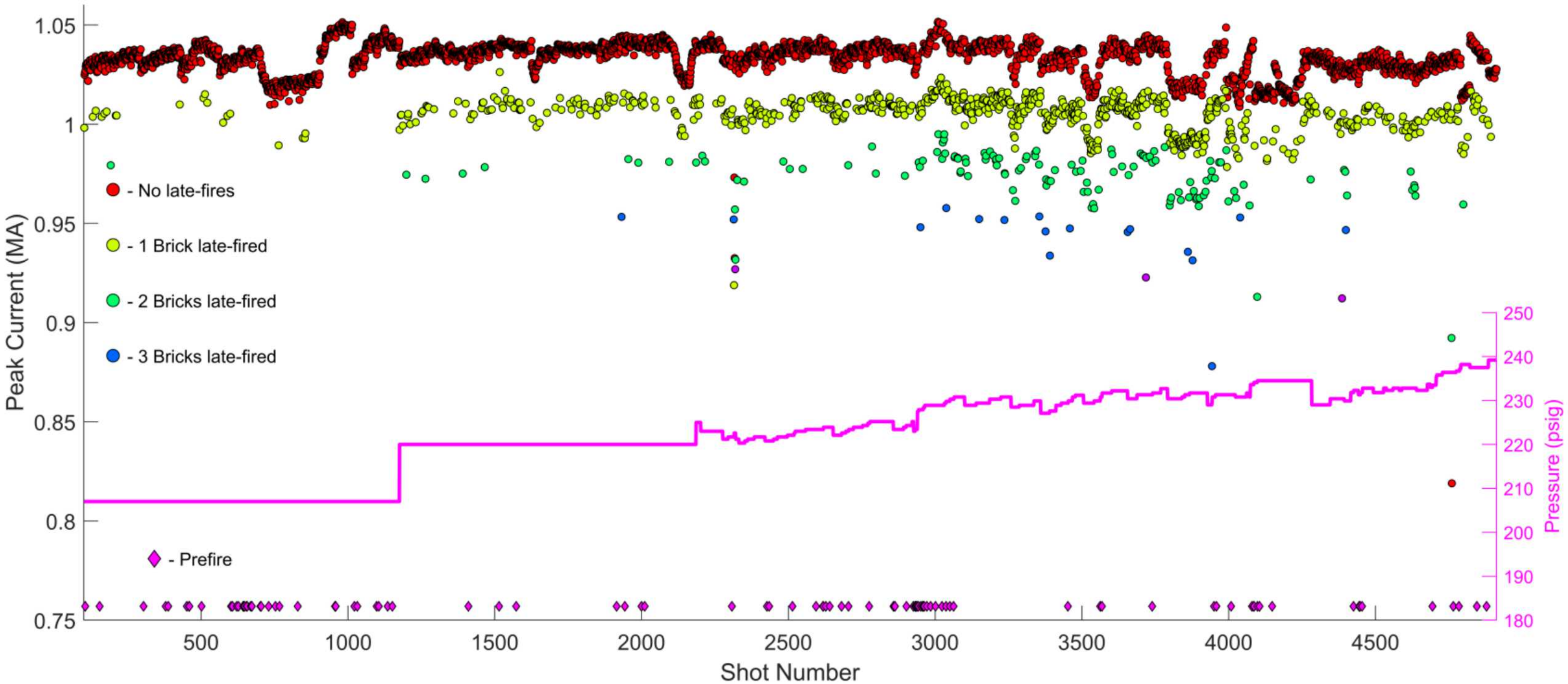
- Early-on pre-fire rate was high
  - Switch gas pressure was increased to discourage pre-fires
    - 10% increase in gas pressure reduced pre-fires by ~2x
  - Gas pressure increase also resulted in more late-firing switches
    - 10% increase in gas pressure increased late-fire rate by ~5x
  - Trigger voltage was increased in an attempt to improve late-fire rate
    - 20% Trigger voltage increase had no significant effect
    - 30% Trigger voltage increase made late-fire rate worse



The 6th Generation “Z-Next” LTD

Development of the Z-Next LTD

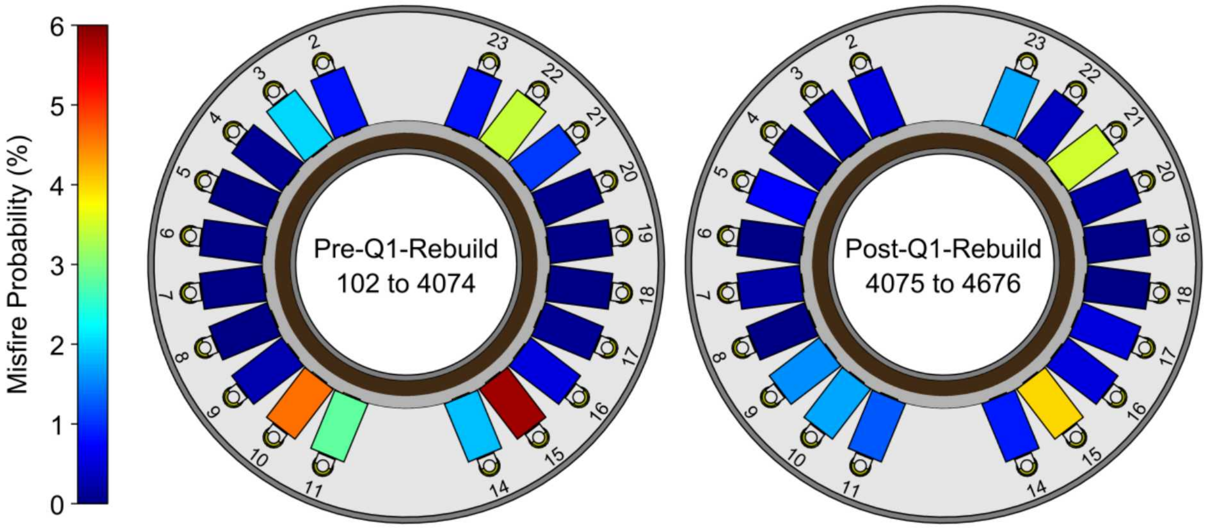
- Switch late-fires are considered far less serious than pre-fires
- As development continued the occasional pre-fire would usually motivate a slight increase in switch gas pressure with the hope of completely eliminating pre-fires
  - The switch gas pressure was steadily increased over the course of ~5,000 shots, eventually reaching 240 psig
  - The switch late-fire rate demonstrated a correspondingly steady increase
  - Pre-fires remained stubborn



The 6th Generation "Z-Next" LTD

Development of the Z-Next LTD

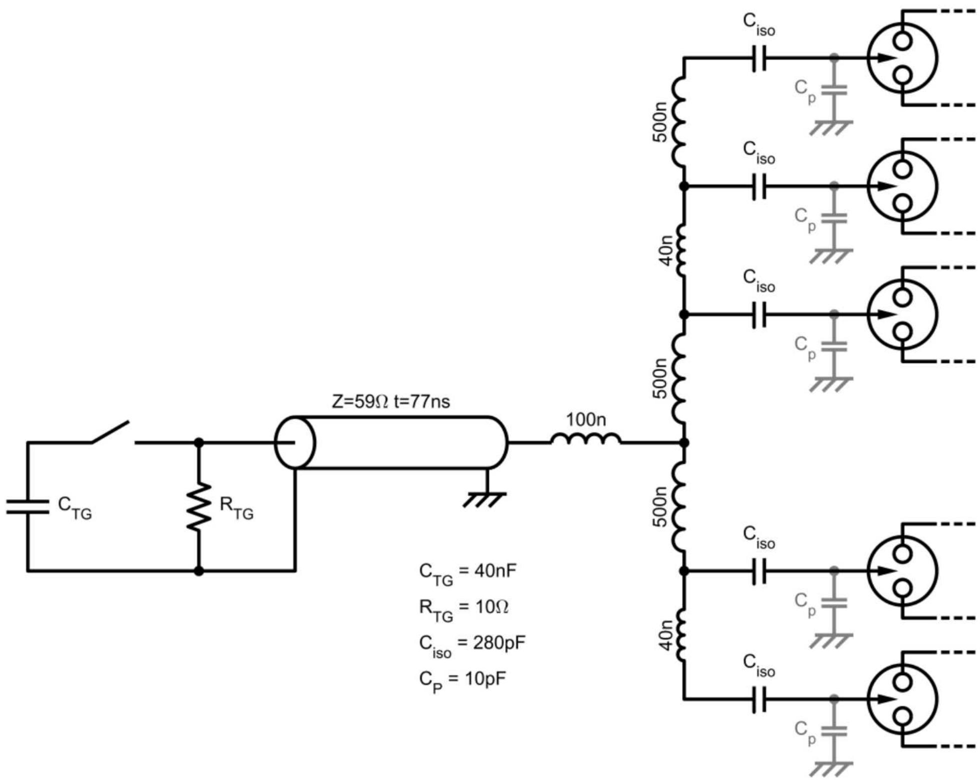
- Switch late-fires are considered far less serious than pre-fires
- However, our late-fire rate had gotten *really* bad
- Data analysis clearly indicated that late-fires were not randomly distributed among the 20 bricks in the cavity
  - Late-fires were strongly correlated with switch position on the trigger bus
  - Bricks 6, 7, 18 & 19 practically NEVER late-fired!
  - Merely opening the cavity for inspection affected the late-fire distribution in the cavity

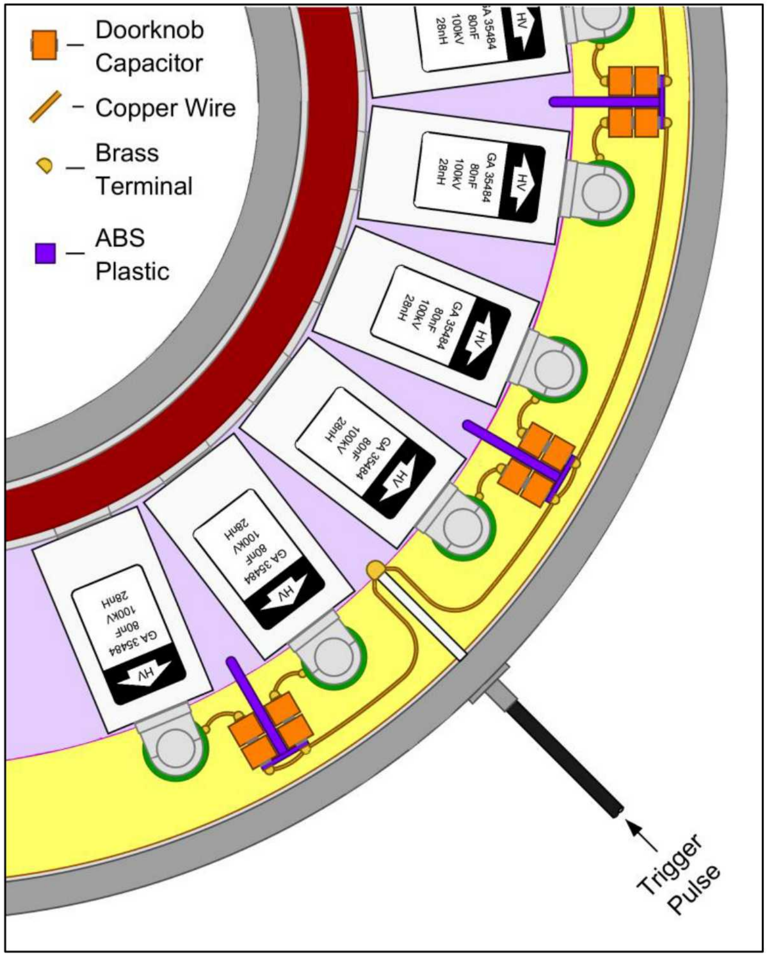


The 6th Generation "Z-Next" LTD

Development of the Z-Next LTD

- Trigger circuit is arranged in four identical quadrants
  - Each quadrant triggers five bricks
  - Trigger routing varies and is not symmetric
  - Original trigger circuit used capacitive coupling to isolate switches and trigger generator in case of malfunctions (DC blocking)

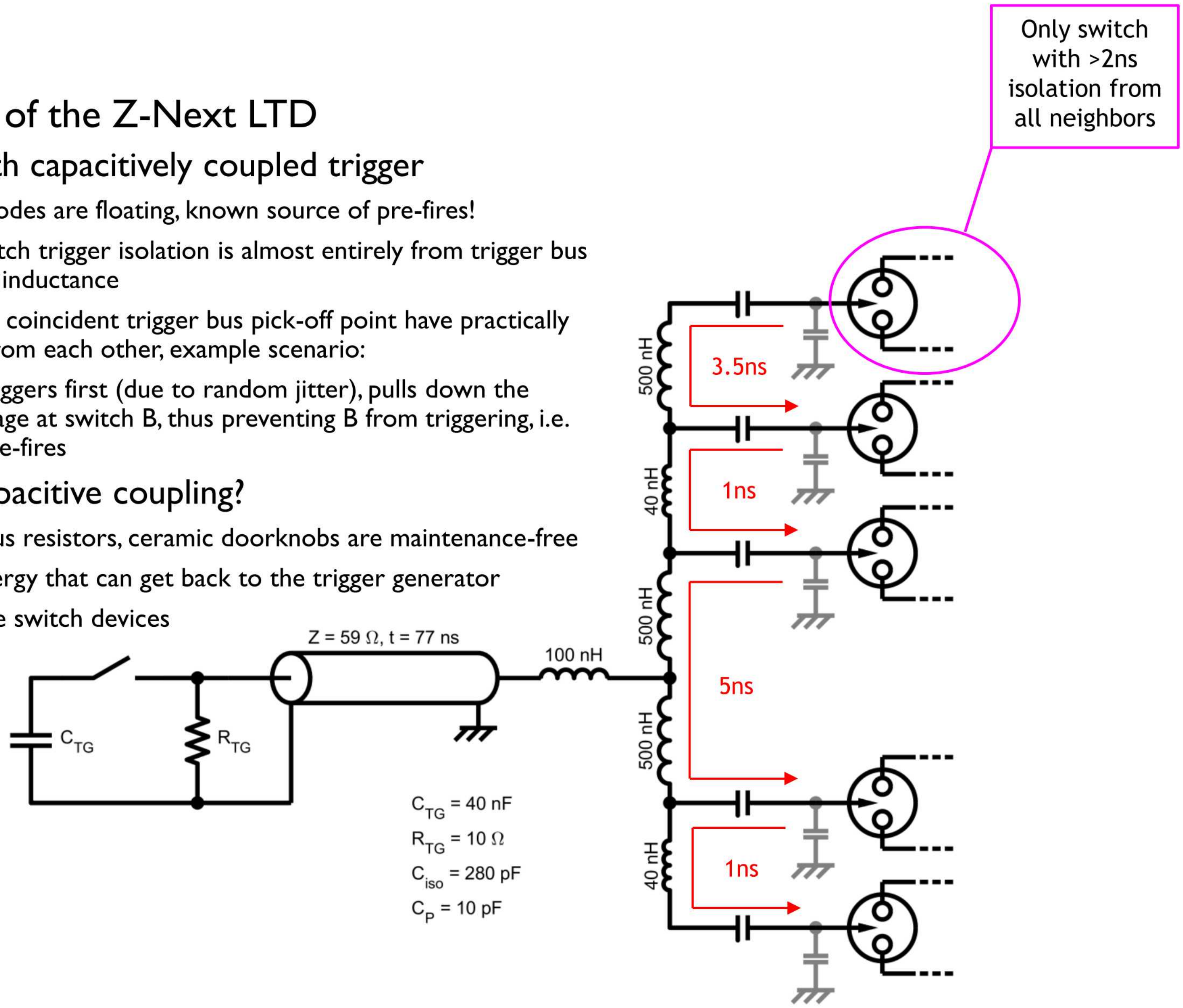




The 6th Generation "Z-Next" LTD

Development of the Z-Next LTD

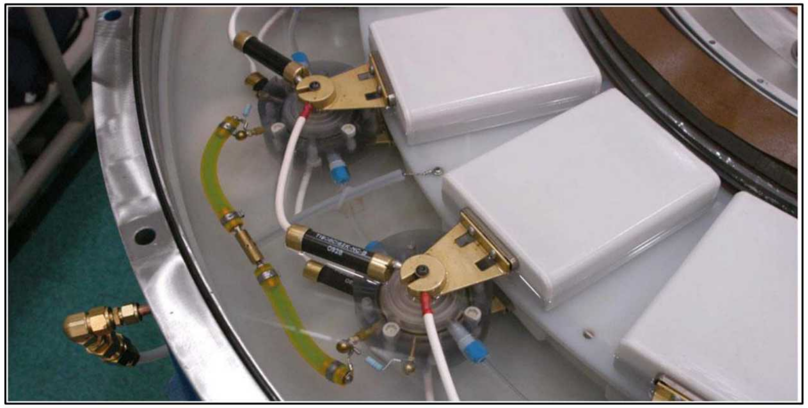
- Problem with capacitively coupled trigger
  - Trigger electrodes are floating, known source of pre-fires!
  - Switch-to-switch trigger isolation is almost entirely from trigger bus wire parasitic inductance
  - Switches with coincident trigger bus pick-off point have practically no isolation from each other, example scenario:
    - Switch A triggers first (due to random jitter), pulls down the trigger voltage at switch B, thus preventing B from triggering, i.e. switch B late-fires
- Why use capacitive coupling?
  - Unlike aqueous resistors, ceramic doorknobs are maintenance-free
  - Limits the energy that can get back to the trigger generator
  - Ideal for single switch devices

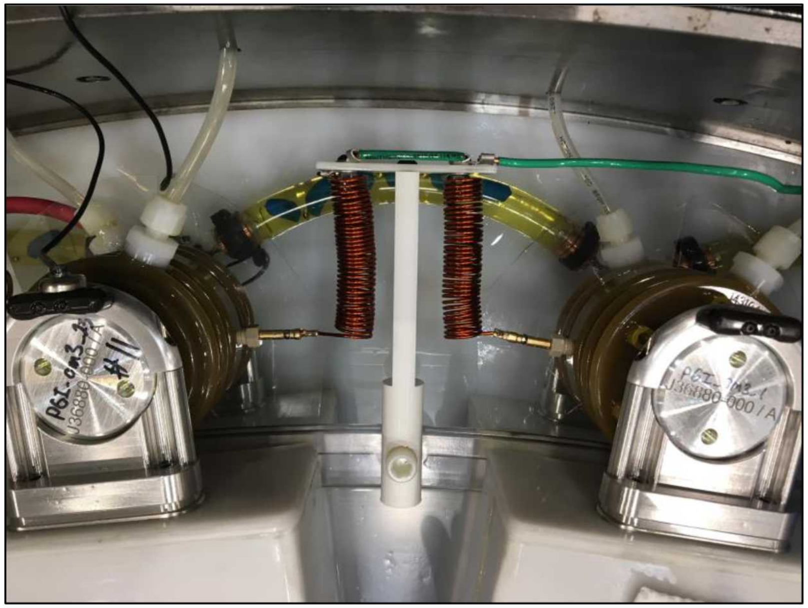


The 6th Generation “Z-Next” LTD

Development of the Z-Next LTD

- Alternatives to capacitively coupled trigger
  - Conventional LTD uses resistive isolation
    - Provides ~20ns switch-to-switch isolation
    - Switch trigger electrodes pulled to ground through trigger generator, should help prevent pre-fires
    - Limits energy fed back to trigger generator
    - Resistors permeate water and need to be replaced annually
  - Inductive isolation is an emerging option
    - Wire-wound inductors ~10uH
    - Deployed by Zhou et. al in China
    - Used on Sphinx Marx generator at Sandia since 2014
      - Nylon all-thread form left in place
    - Provides ~20ns switch-to-switch isolation
    - Switch trigger electrodes are well grounded through trigger generator, should help prevent pre-fires
    - Maintenance free
    - Ringing gain produces higher voltage at switch trigger pins
    - Does not limit energy coupled back to trigger generator

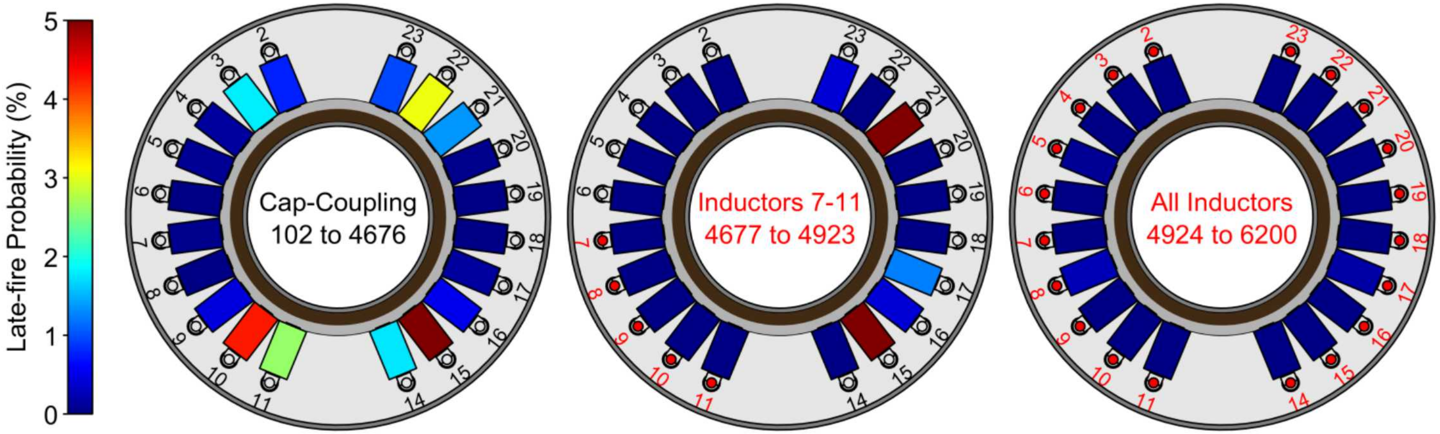




The 6th Generation "Z-Next" LTD

Development of the Z-Next LTD

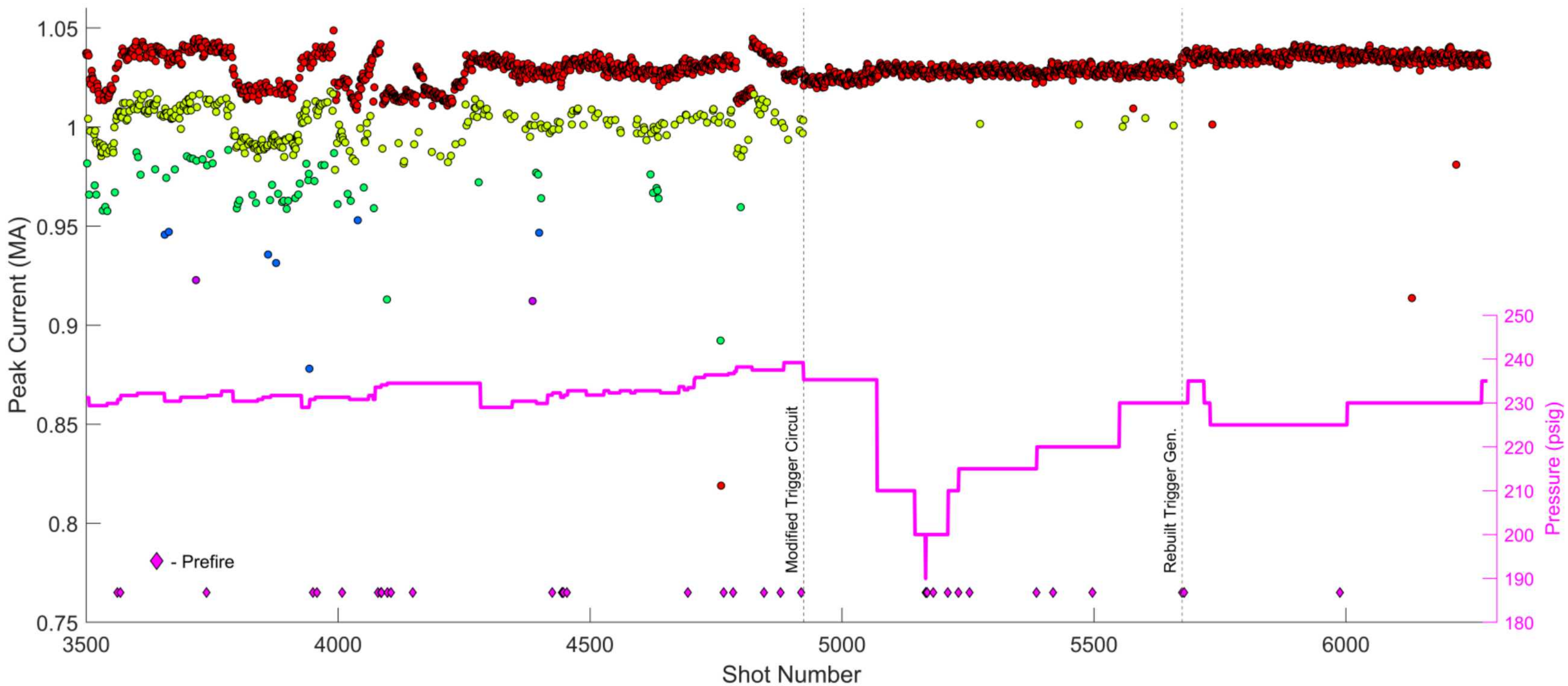
- Results from inductively isolated trigger circuit
  - Started by fielding inductors in one quadrant
    - Ran for ~250 shots with zero late-fires in the inductor quadrant
    - Opened cavity for inspection, found turn-to-turn arcing in some inductors
    - Modified inductor dimensions for larger turn-to-turn gaps
      - Wound on 1"-8 all-thread, 3" long, stretched to 3.5" installation
    - Installed revised inductor design in all bricks
  - The only late-fires that have occurred since inductor installation were during attempts to find minimum trigger generator charging voltage
  - Pre-fire rate has also decreased to it's lowest value ever: 0.3%
    - Despite accumulation of over 6,000 shots on switches



The 6th Generation "Z-Next" LTD

Development of the Z-Next LTD

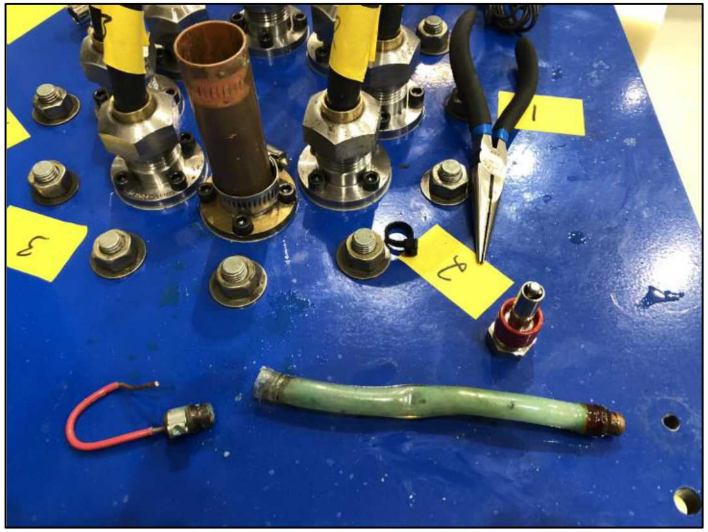
- Results from inductively isolated trigger circuit
  - Consistency of output and rate of pre-fires and late-fires is unprecedented for a high-current, 100-ns LTD

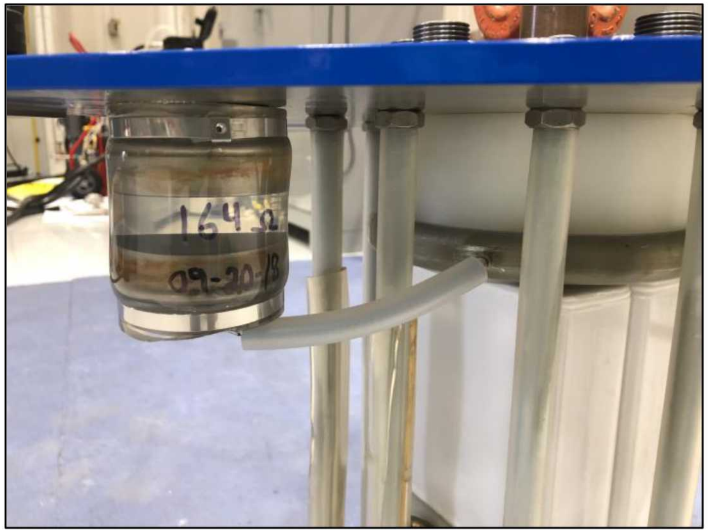


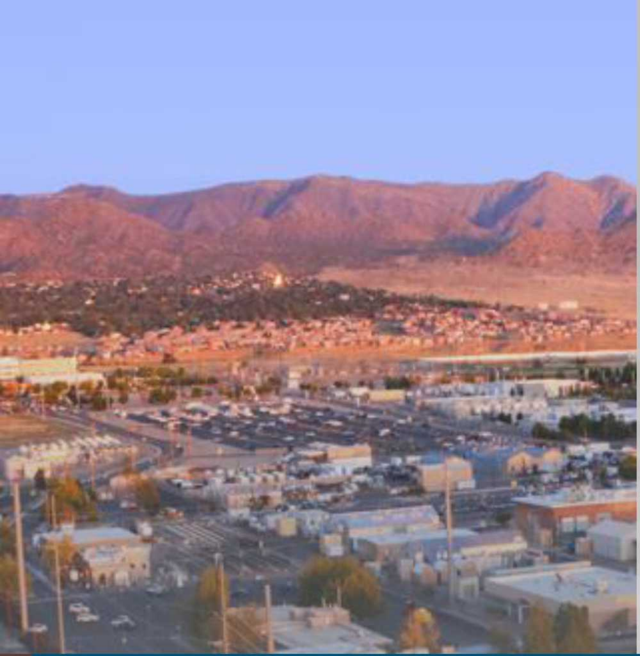
The 6th Generation “Z-Next” LTD

Development of the Z-Next LTD

- Results from inductively isolated trigger circuit
  - Pre-fires occurred while investigating lowest practical operating gas pressure and trigger voltage
  - These pre-fires appear to have rapidly degraded the grounding resistor in the trigger generator
    - Degraded resistor results in quasi-floating switch trigger electrodes
    - Floating trigger electrodes produces more pre-fires
    - Snowball effect
  - Original grounding resistor not intended to handle much energy or sustained high voltage
  - Trigger generator was rebuilt with a robust grounding resistor
    - Appears to have solved trigger generator issues







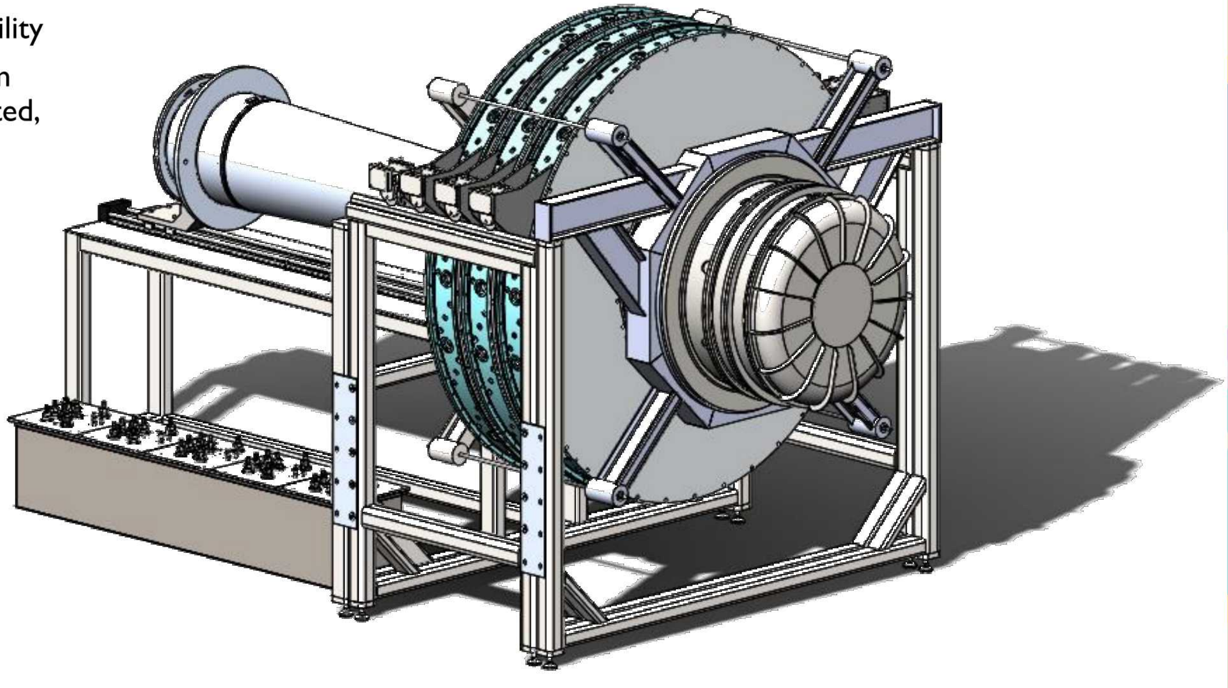
The Path Ahead for High-Current LTD Development at Sandia

Four year outlook

Future High-Current LTD Development at Sandia

Plans for the immediate future

- Assembling two more cavities identical to the "Z-Next" LTD
  - All hardware is on-hand
  - Estimated completion in early 2019
  - Aim to verify that "known-good" hardware configuration and operating regime is transferable between identical LTDs
  - Intend to verify reliability of capacitors from other vendors
- Design and procurement of components for a 10-cavity module
  - Expected to be operational in 2021
  - Emphasis on modularity and portability
    - Aim to demonstrate that a system with many LTDs can be constructed, operated and maintained in a practical way



Future High-Current LTD Development at Sandia

Looking further…

- Proposal to start design and procurement of a 42-cavity "Z-Next" module in 2021 is in the works
  - Strong support from DOE
  - Will serve as a versatile testbed
    - Power flow
    - Insulator flashover
    - Dielectric bulk breakdown
    - Pulse shaping
  - Demonstration of LTD module maturity
    - Precursor to +50-MA IFE driver