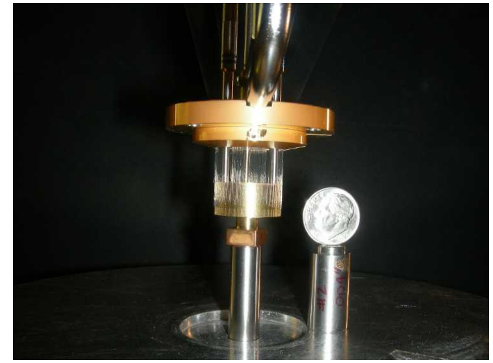
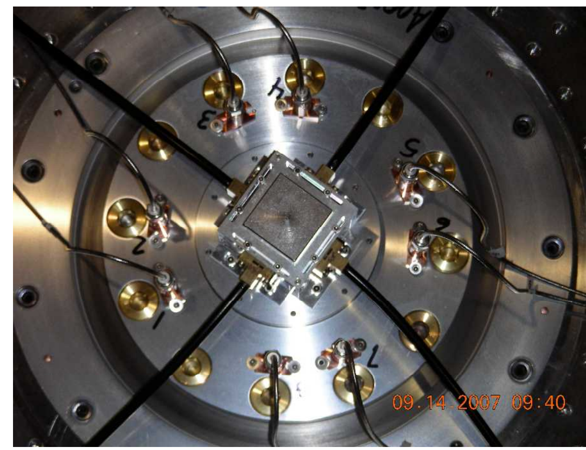
SAND2008-6288C

The refurbishment of Z: goals and results





2008 Dense Z-pinch conference
19 August 2008

Mark E. Savage

The goal of the ZR program is to deliver megajoules of energy to the load

- **Currents of 10 MA/cm require 630 kJ/cm^3**
  - **Load inductance strongly affects the system**
- **Timing synchronization with the backlighter laser must be ~nanoseconds**
  - **Machine jitter must be small**
- **A single module's energy will destroy a load**
  - **Machine pre-fire probability must be small**

A large driver such as ZR is a balance of performance, reliability, and cost

The goal of the ZR pulsed power program is to maximize performance and reliability of the system

- The energy of the system was doubled *within the existing tank*
- The pulsed power components were upgraded to handle the increased energy
- Key subsystems (vacuum, triggering, DAS) have been upgraded for improved performance

ZR is required to do both fast-pulse (120 ns) z-pinch experiments and pulse-shaped (250-500 ns) dynamic material experiments

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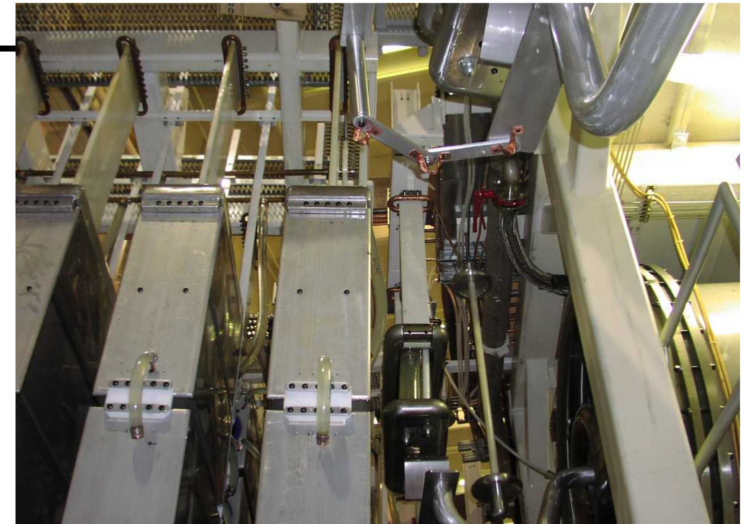
Outline

- ZR technology
- ZR results
- Future work
- Conclusions



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ZR is a large effort

Z$_{20}$*/ZR pulsed power team:* L. F. Bennett, J.R. Blickem, J.P. Davis, D. E. Bliss, W. T. Clark, R.S. Coats, J. M. Elizondo, K. R. LeChien, H. C. Harjes, W. L. Langston, J. M. Lehr, R.W. Lemke, J. E. Maenchen, D. H. McDaniel, M.F. Pasik, T. D. Pointon, A. C. Owen, D. B. Seidel, D. L. Smith, B. S. Stoltzfus, K. W. Struve, W.A. Stygar, L.K. Warne, L.L. Whinnery, J. R. Woodworth, C. W. Mendel, K.R. Prestwich, R. W. Shoup, D. L. Johnson, V. Anaya, J. P. Corley, G. Feltz, D. Guthrie, K. C. Hodge, J. Lott, T. C Wagoner, P. E. Wakeland

The ZR crew and staff: G.L. Donovan, D.S. Artery, T.G. Avila, M.J. Baremore, T.L. Bock, R. Chavez, G.D. Coombs, M.E. Dudley, N.L. Grelle, A.D. Jojola, A.K. Kipp, B.A. Lewis, J.J. Lynch, J.A. Mills, L. Molena, J.K. Moore, D.M. Pariza, D.W. Petmecky, S.D. Ploor, C.D. Robinson, E.L. Ross, S.A. Roznowski, T.M. Schweitzer, J.J. Seamen, J.G. Stewart, D.R. Thomas, H.M. Wagoner, S.D. White, J.M. Wilson, D. Woolcott

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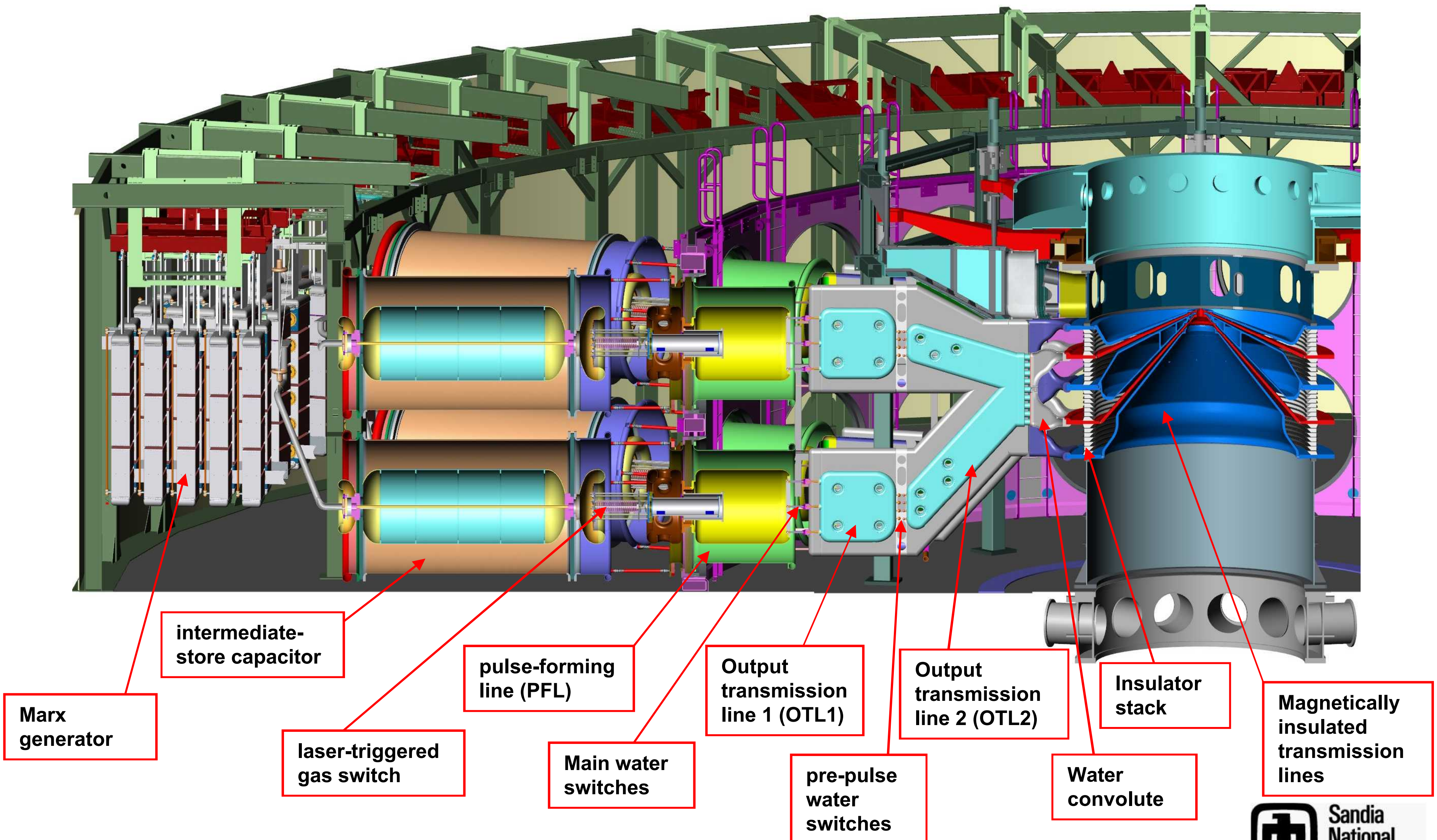
ZR technology

ZR uses three stages of pulse compression to generate 120-300 ns times to peak current



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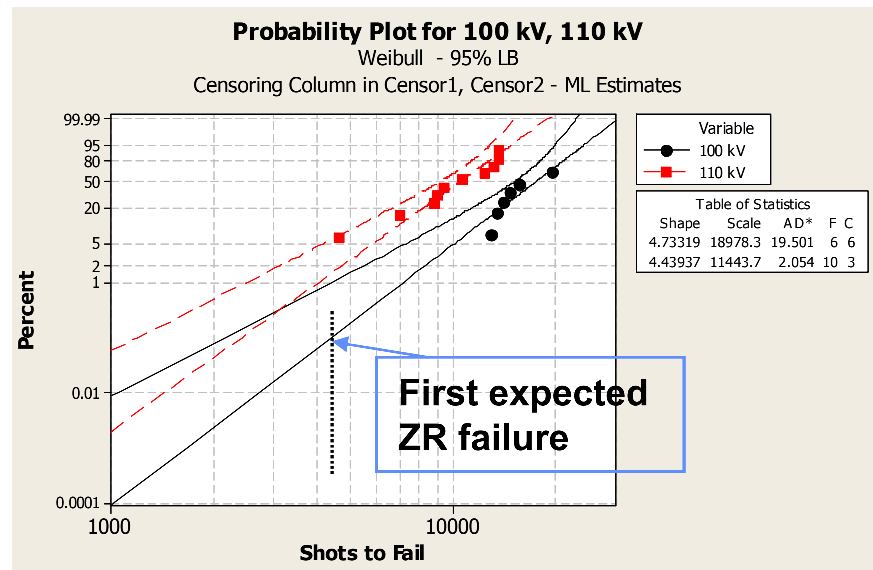
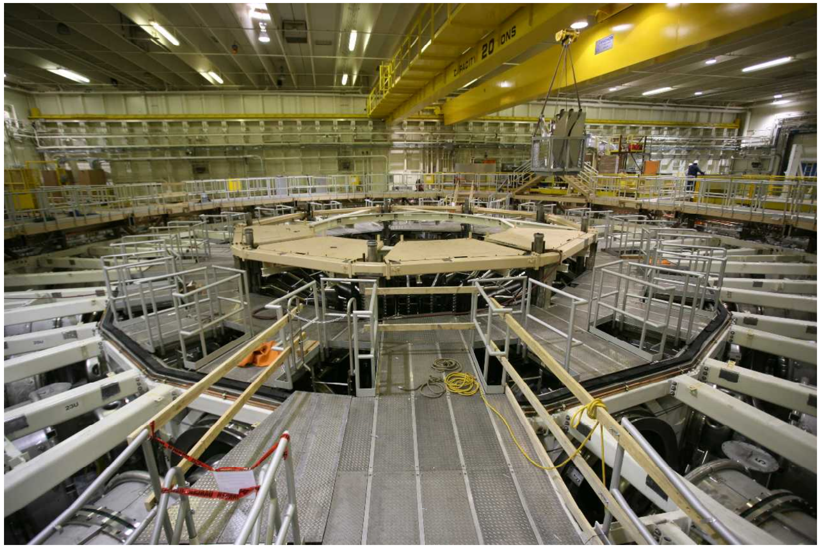
Marx capacitor reliability and cost had large *potential* programmatic impact

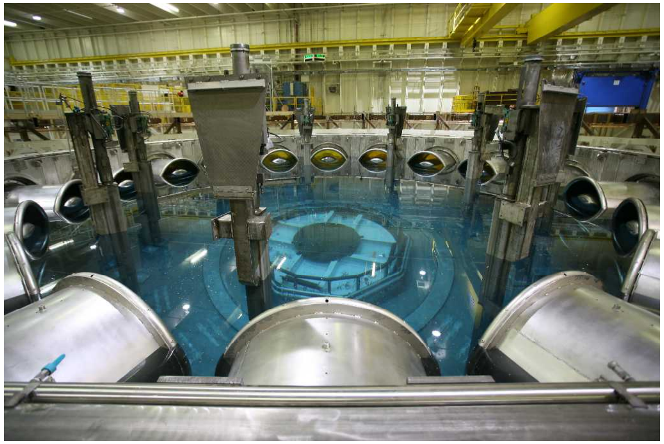
- **Detailed evaluation with a vendor testing requirement eliminated the need for dedicated Marx testing**



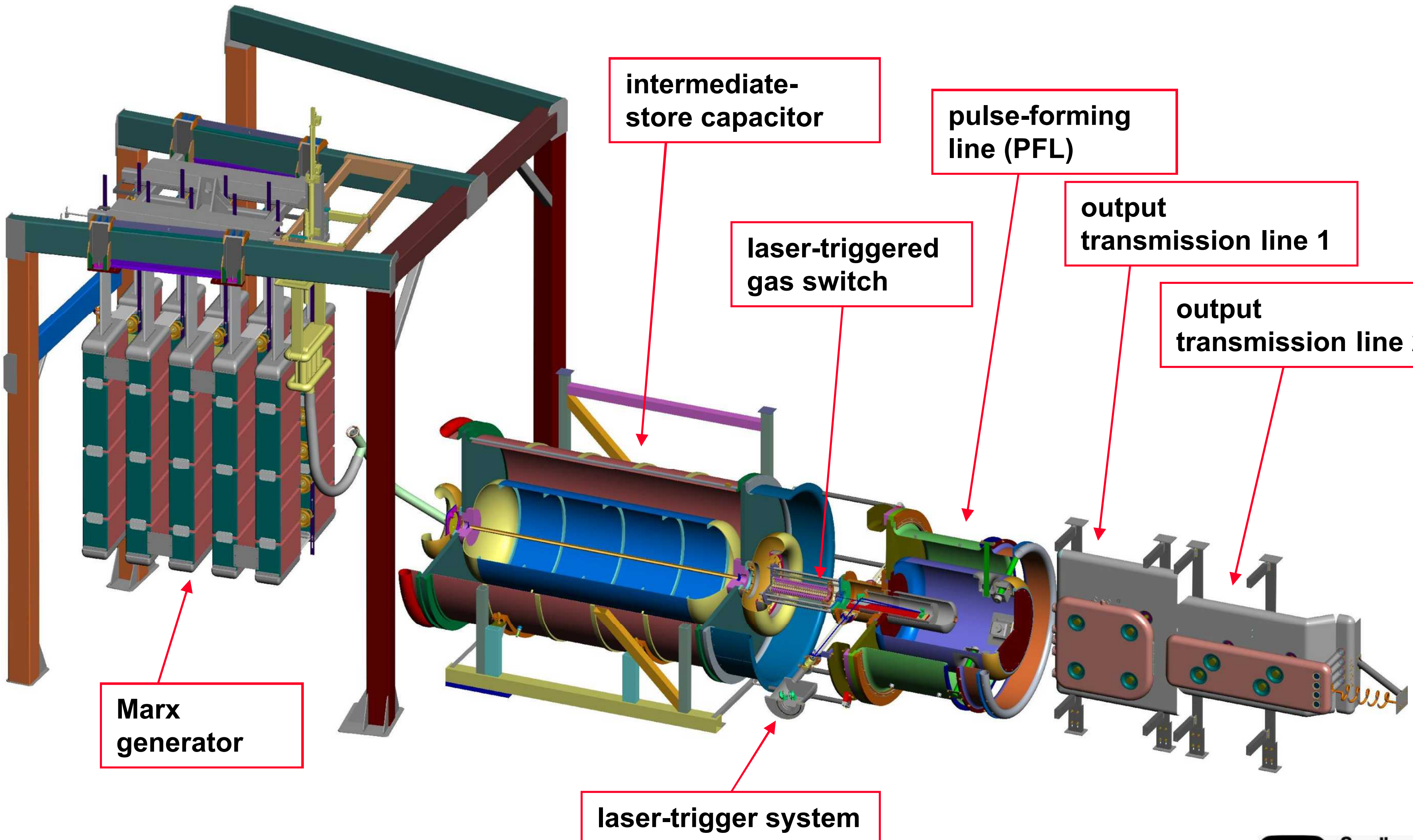
The hardware installation took almost 14 months

- **Every pulsed power component was removed and replaced**





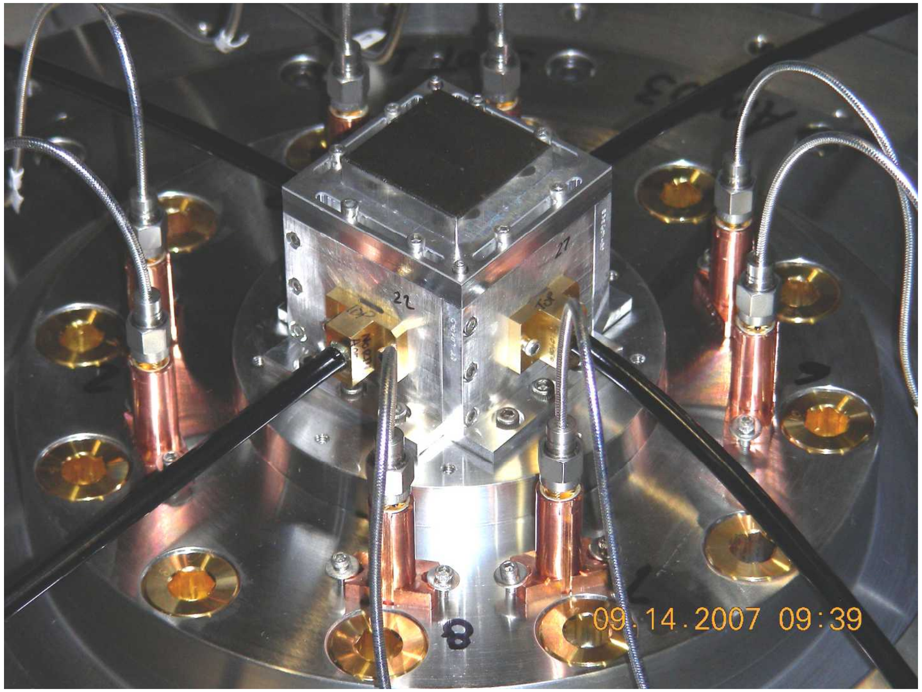
The pulsed power system was developed on a single-line test module



ZR technology

The refurbished Z pulsed power driver has driven currents up to ~26MA into a 2.7 nH isentropic compression load on the 15th shot

- **20 MJ stored at 85 kV Marx charge**
- **~26 MA in the load**
- **All the Marxes, all the laser triggered gas switches, all the water switches and the full vacuum section, including fully-diagnosed isentropic compression loads functioned well**



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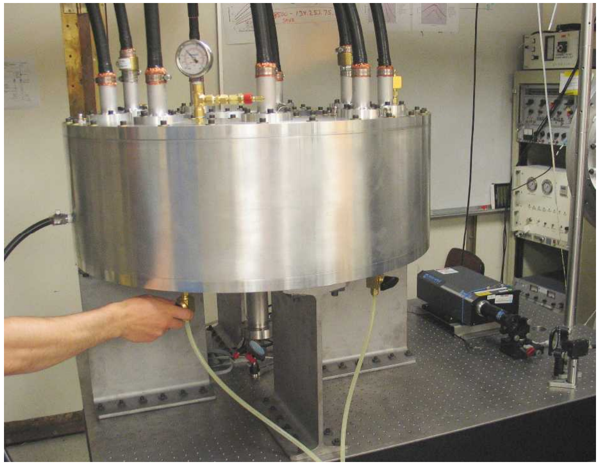
In full voltage mode, ZR has impressive amounts of energy available

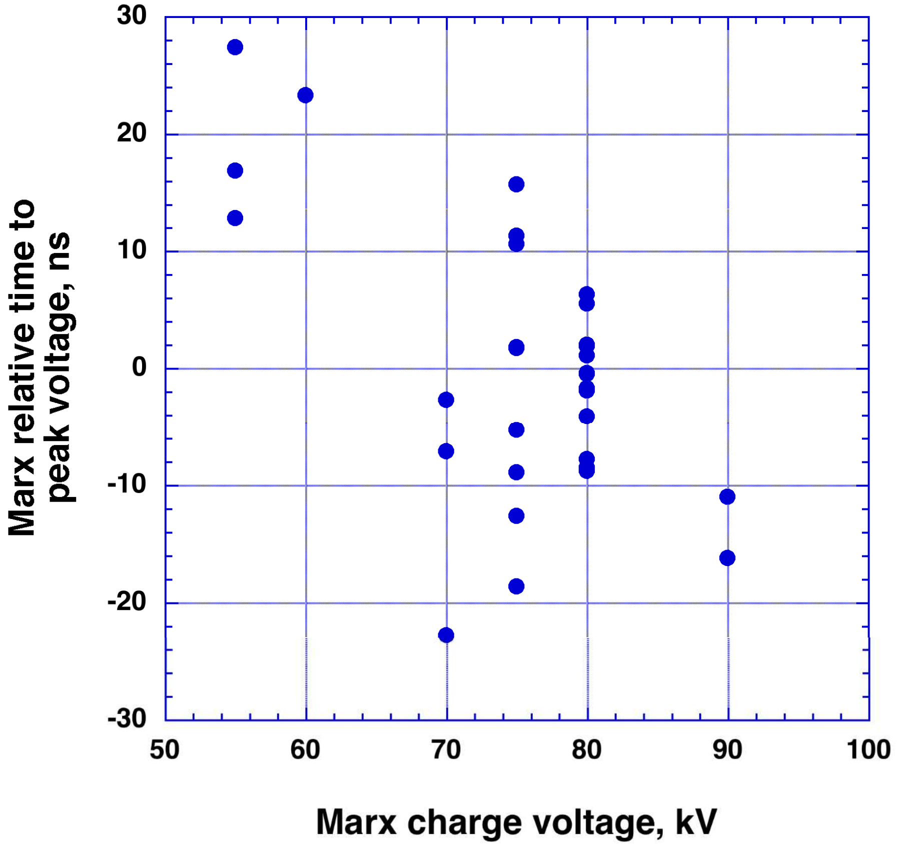
- The wave applied to the vacuum insulator stack has more than 9 MJ *in the first 100 ns of the pulse*
- This is applied to the load with ns accuracy

Precision pulsed power requires robust triggering, accurate alignment, and accurate electrical field-shaping in large mechanical assemblies

ZR uses an advanced trigger generator and selected operating points for stable operation

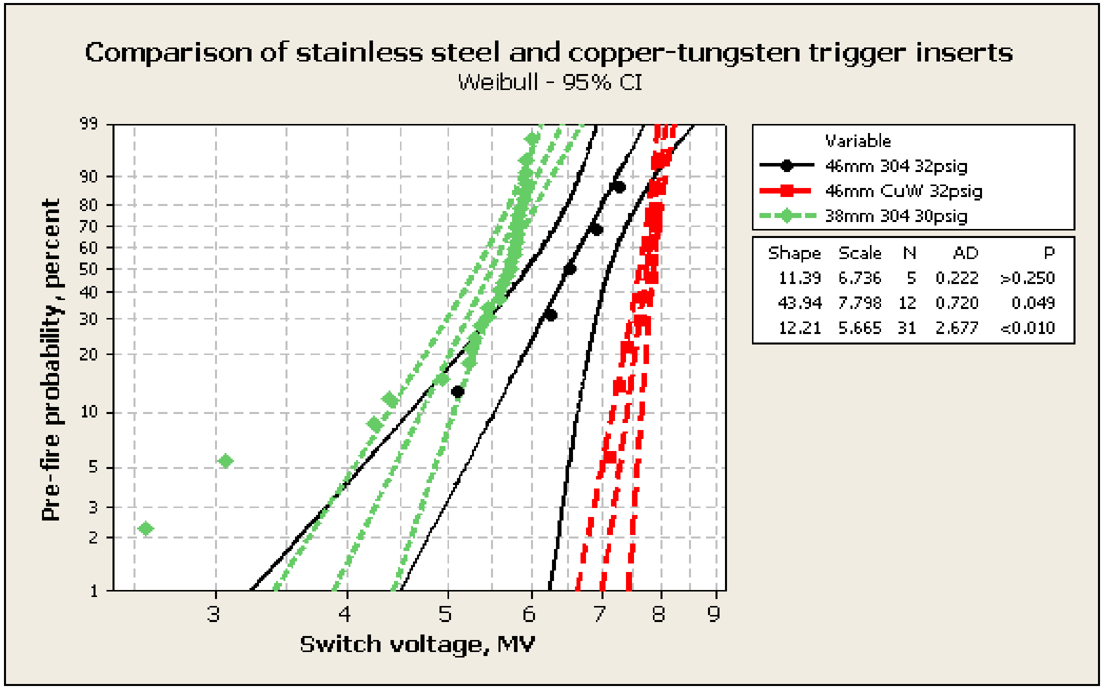
- No part of the machine has a 1-σ jitter greater than 15 ns



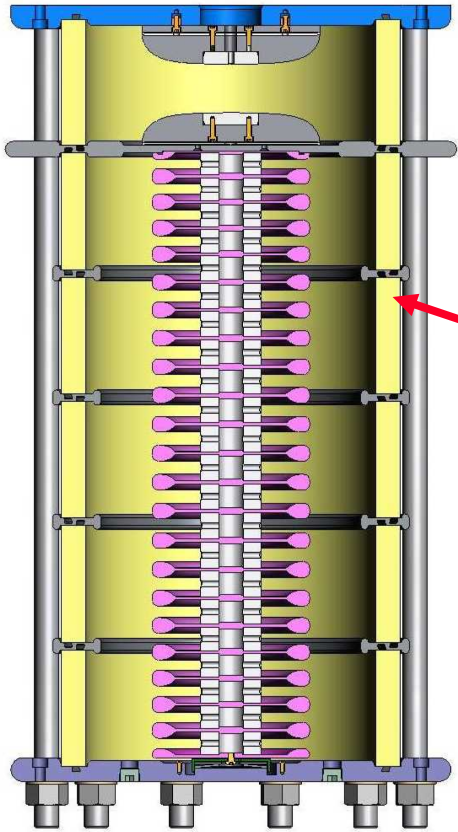


We are able to determine a reliable gas switch operating point from characterization testing

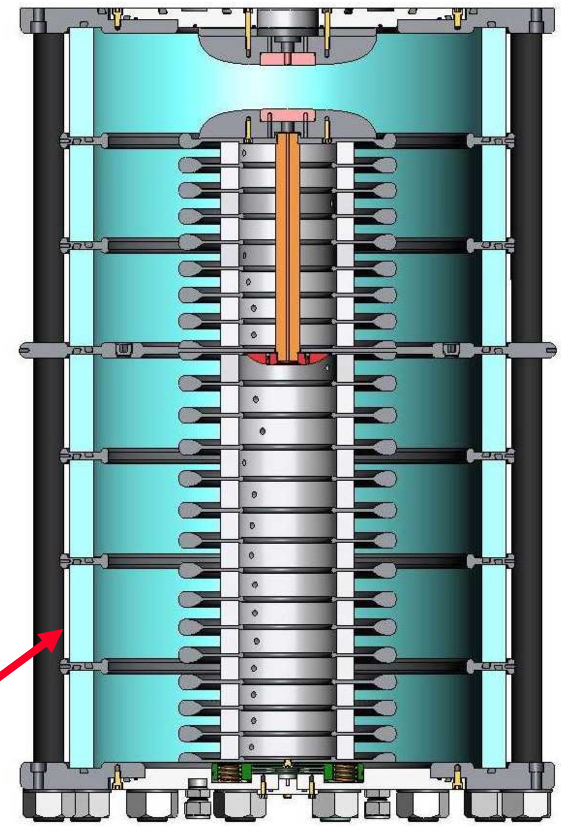
- The ZR gas switches have never pre-fired (some have flashed however)
- We are able to determine the switch operating point and quantify switch reliability and durability



Laer-triggered gas switch design efforts are focused on improving reliability and performance



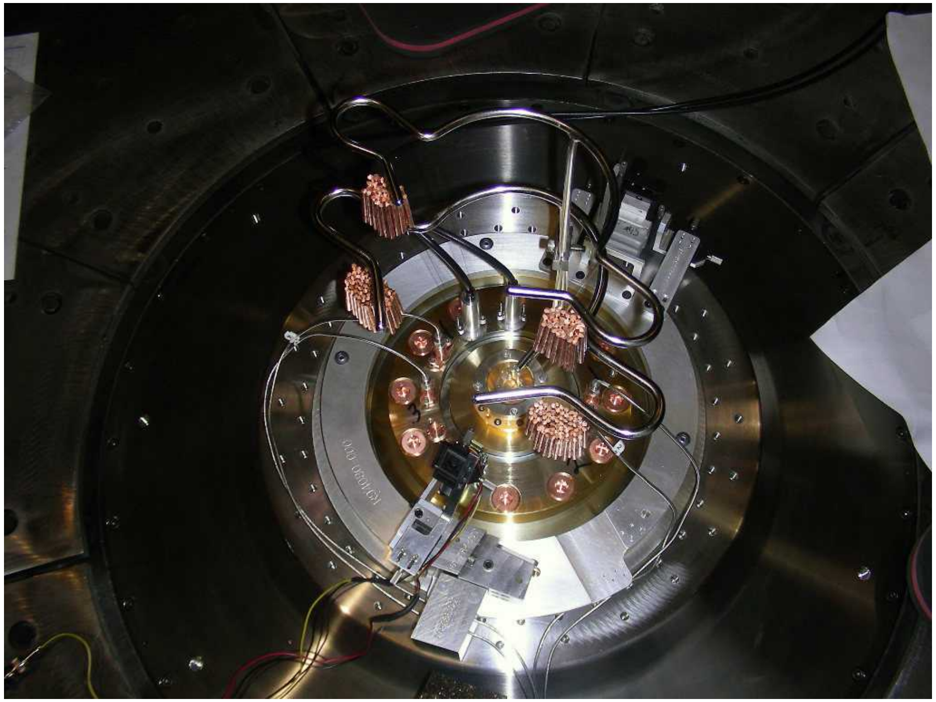
- Segmenting switch insulator to mitigate flashing
- Two ~100 shot runs completed on segmented switch on Z_{20} at 6.1 MV
- Testing to continue on Z with modified designs
- Installing “fast” gas purge system on Z
- Pursuing segmented and cantilevered designs on Z20

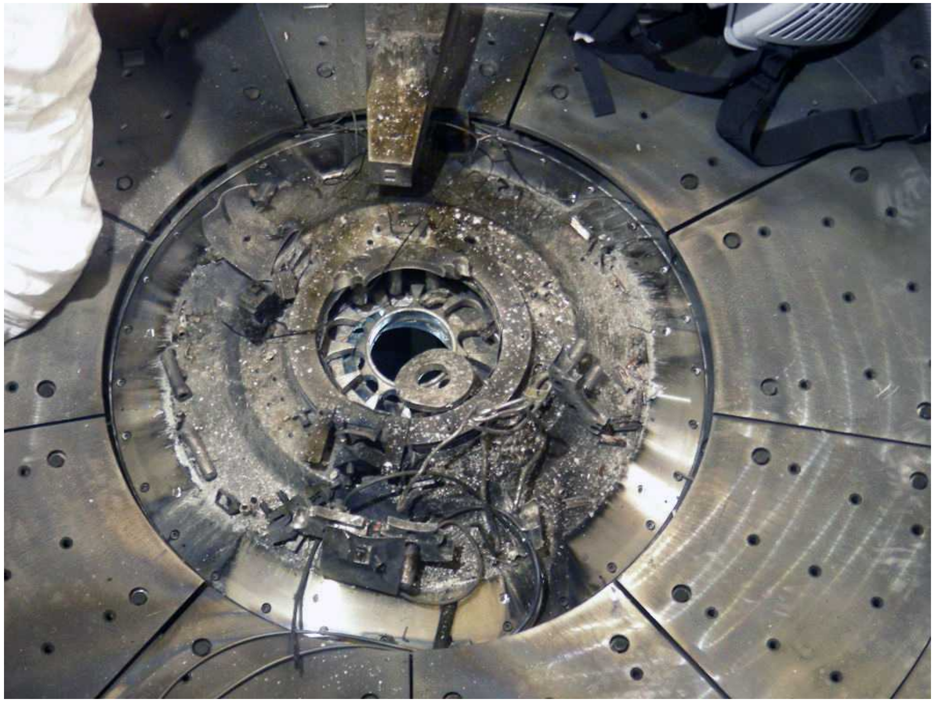


Metal rings segment insulator, otherwise switch is identical to switch currently installed on Z

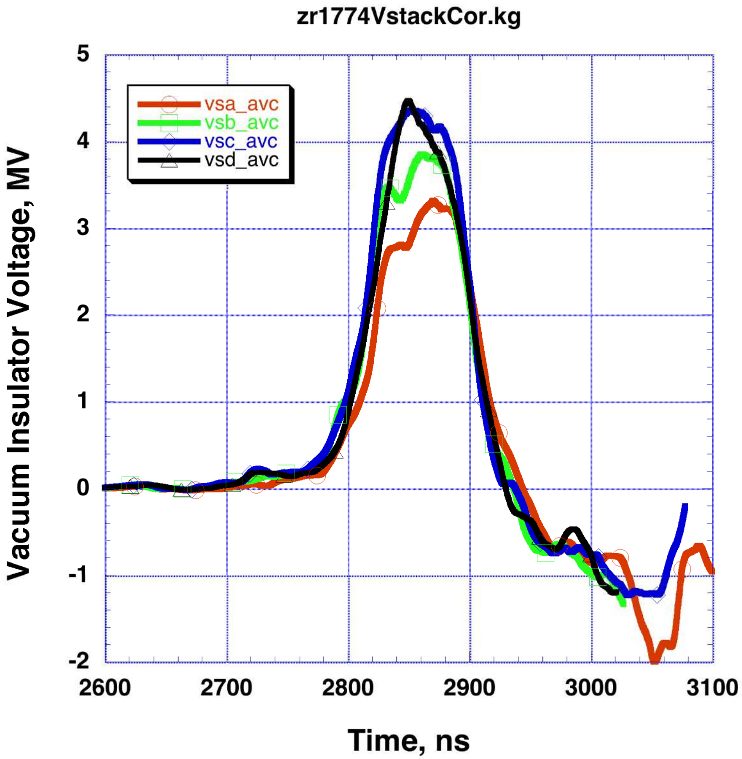
Larger diameter, and other design features, should increase reliability and operable range

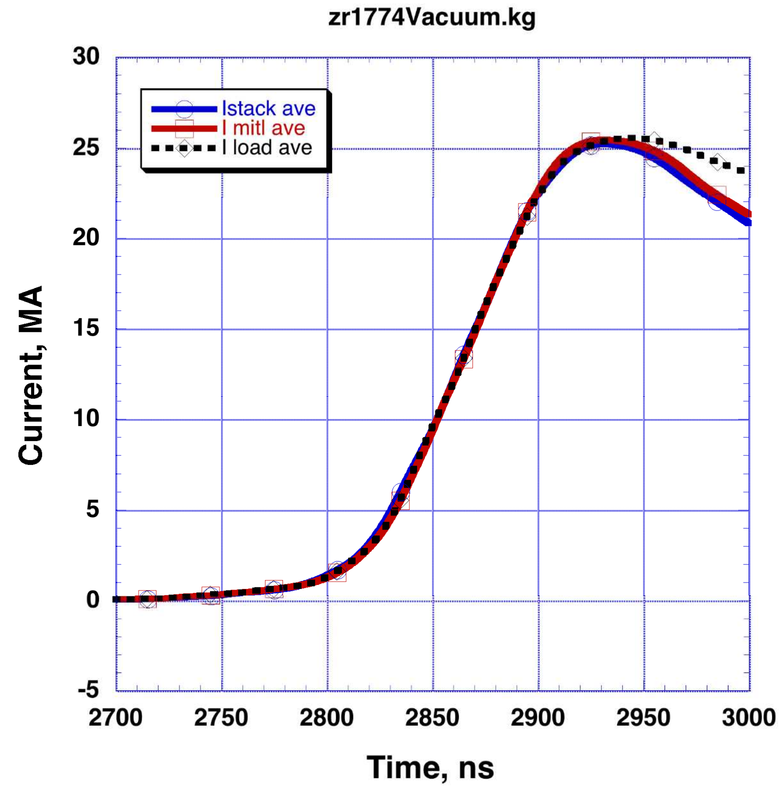
High current z-pinch drivers deliver Mbar pressures to conductors and plasma





ZR has substantial monitoring at the interface and in vacuum, with excellent data quality

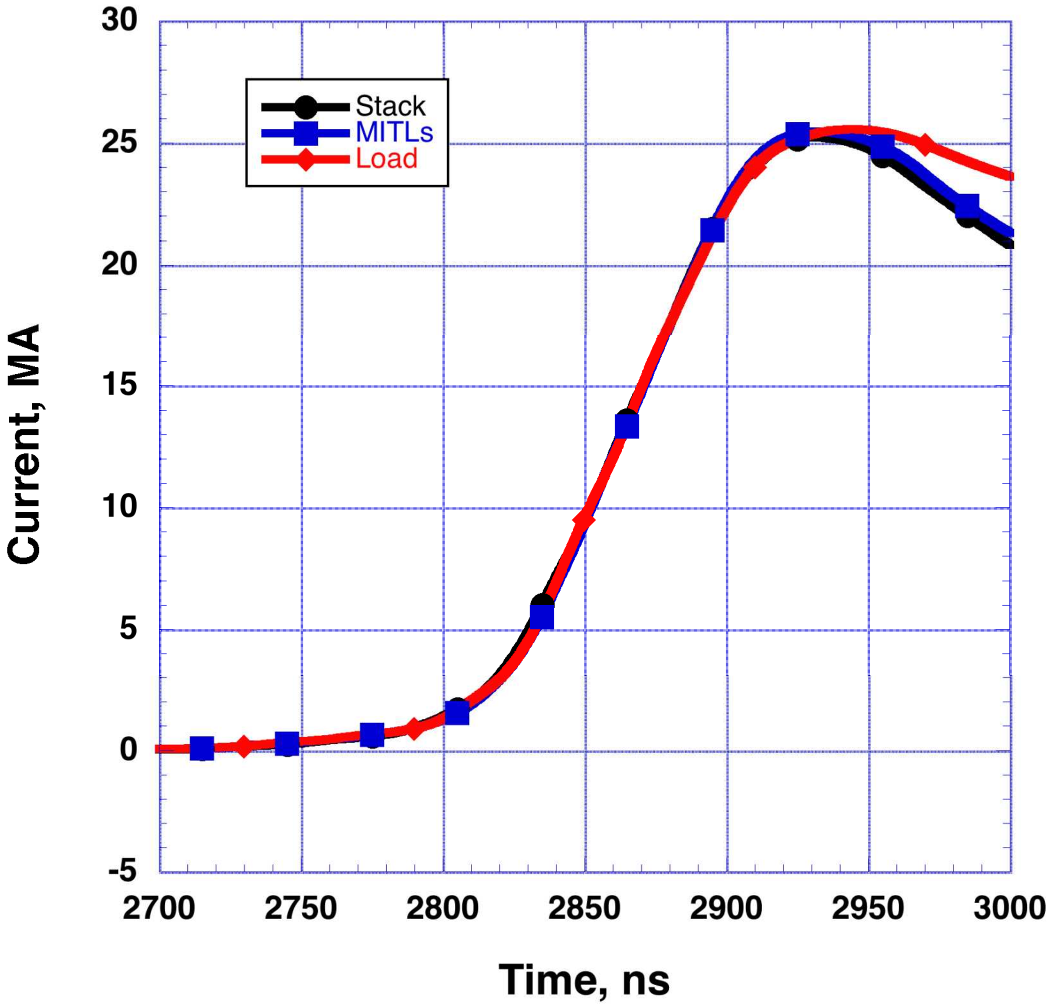




The insulator stack voltage is ~4MV and 110 kV/cm over a large area

Into low inductance loads, ZR delivers 25 MA efficiently from the insulator stack to the load

- **Direct magnetic field measurements at high currents and small radius are difficult**



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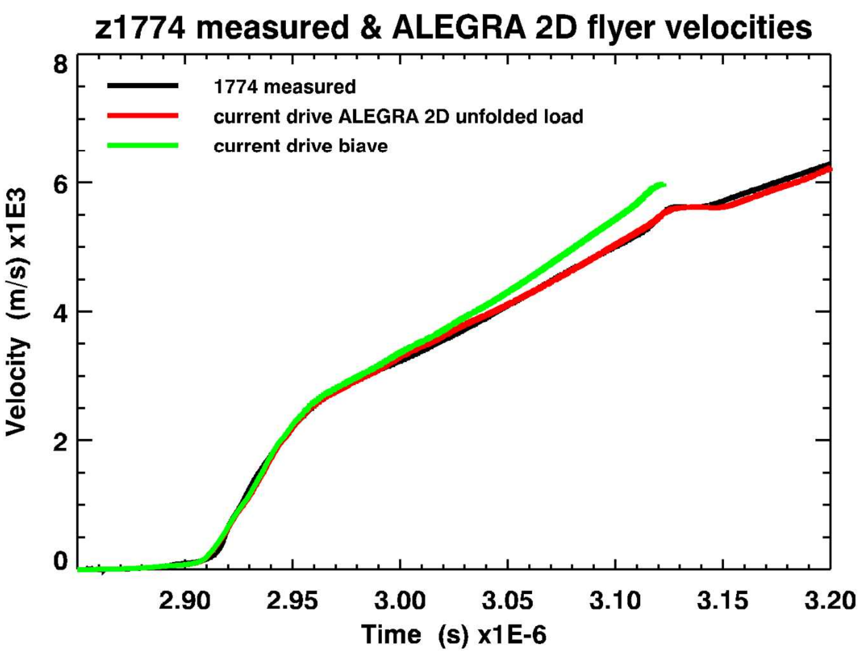
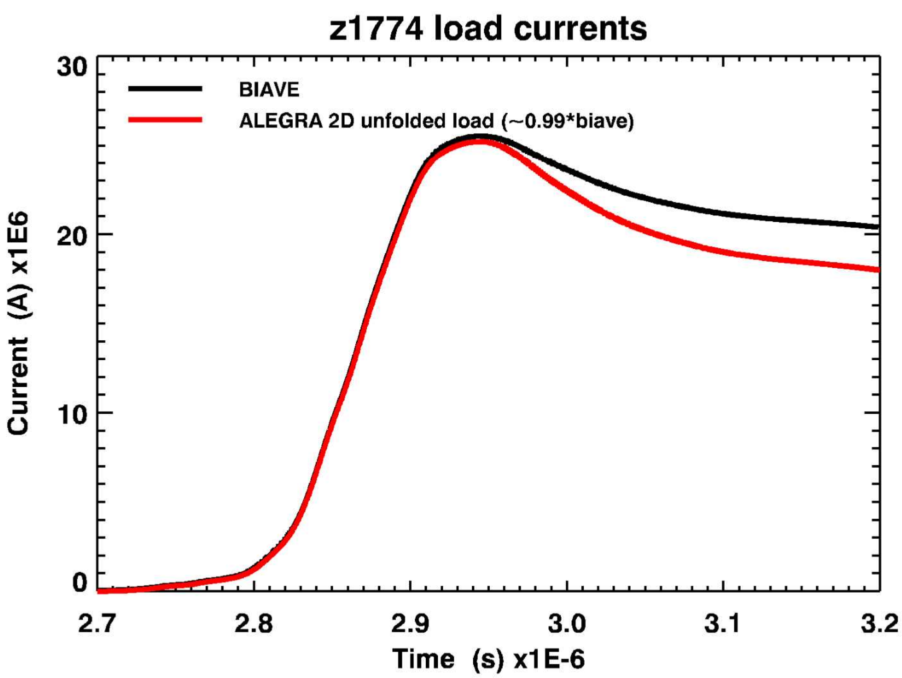
ICE shots allow current measurement *at the load*

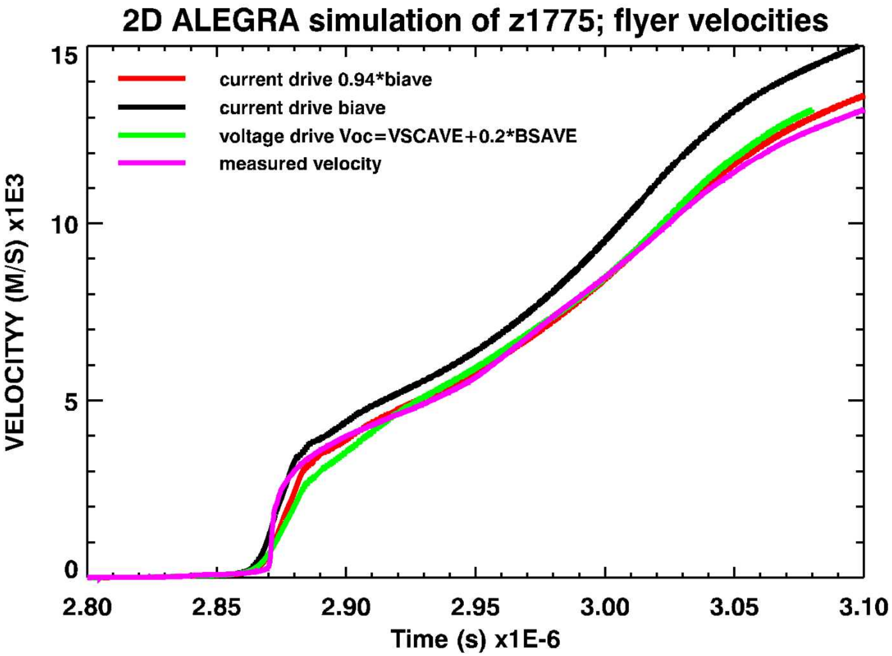


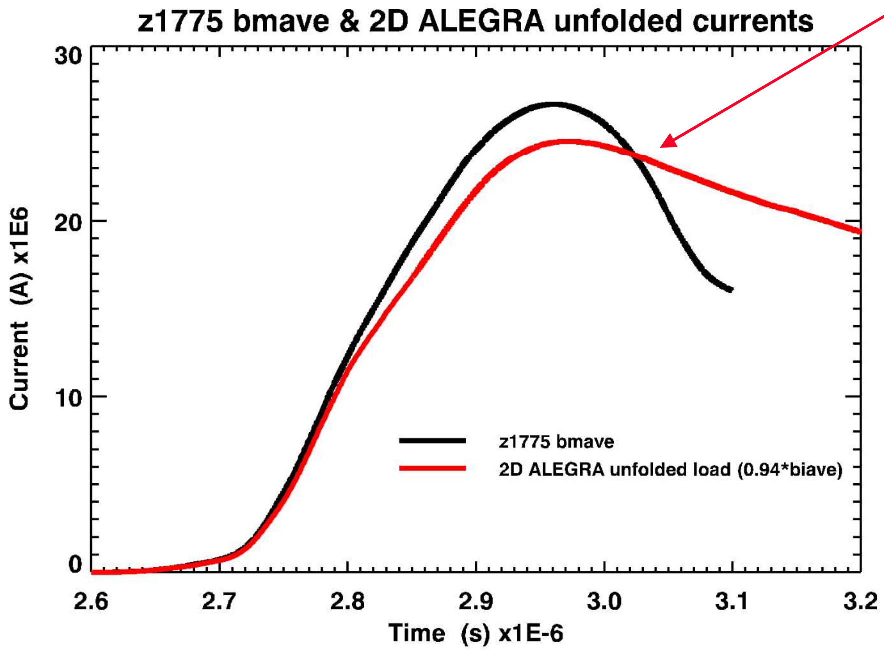


On ZR1774, the load Bdots agree with the flyer unfold to ~2%

The long-pulse shot 1775 shows convolute closure

Current shunt between MITLs and load

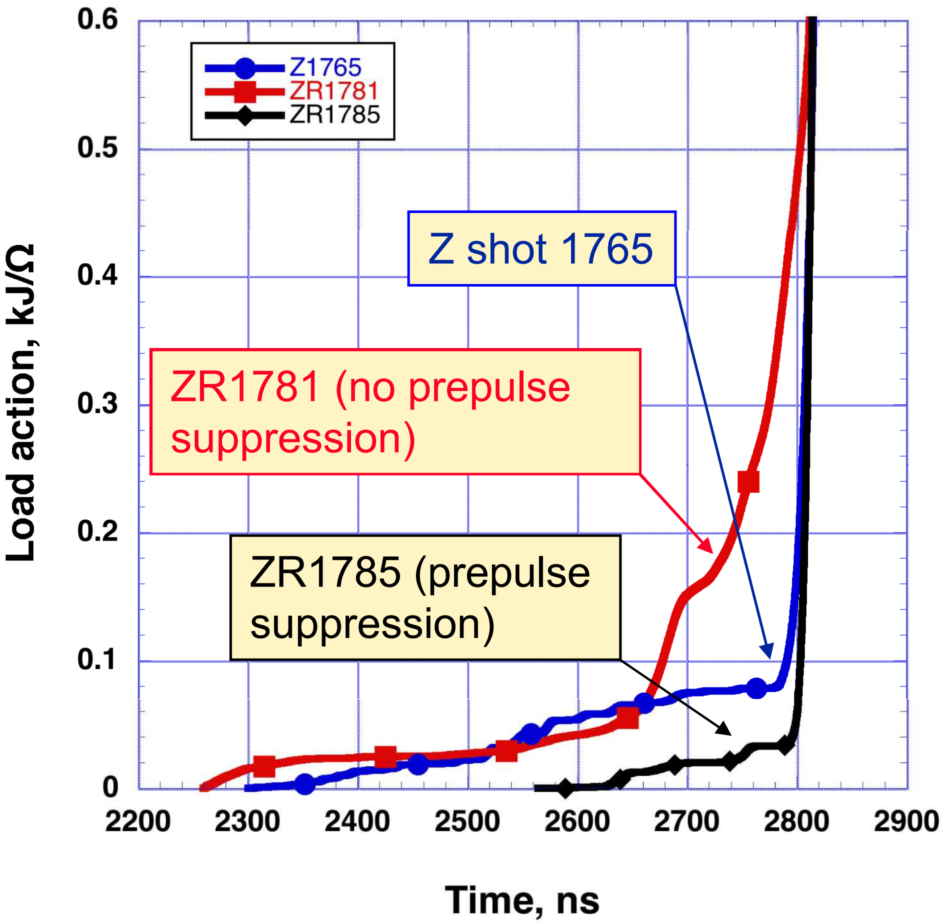




The agreement between the flyer and the Bdots is within reasonable tolerances

Water-switched drivers have pre-pulse due to shunt capacitance of pulse-charged switches

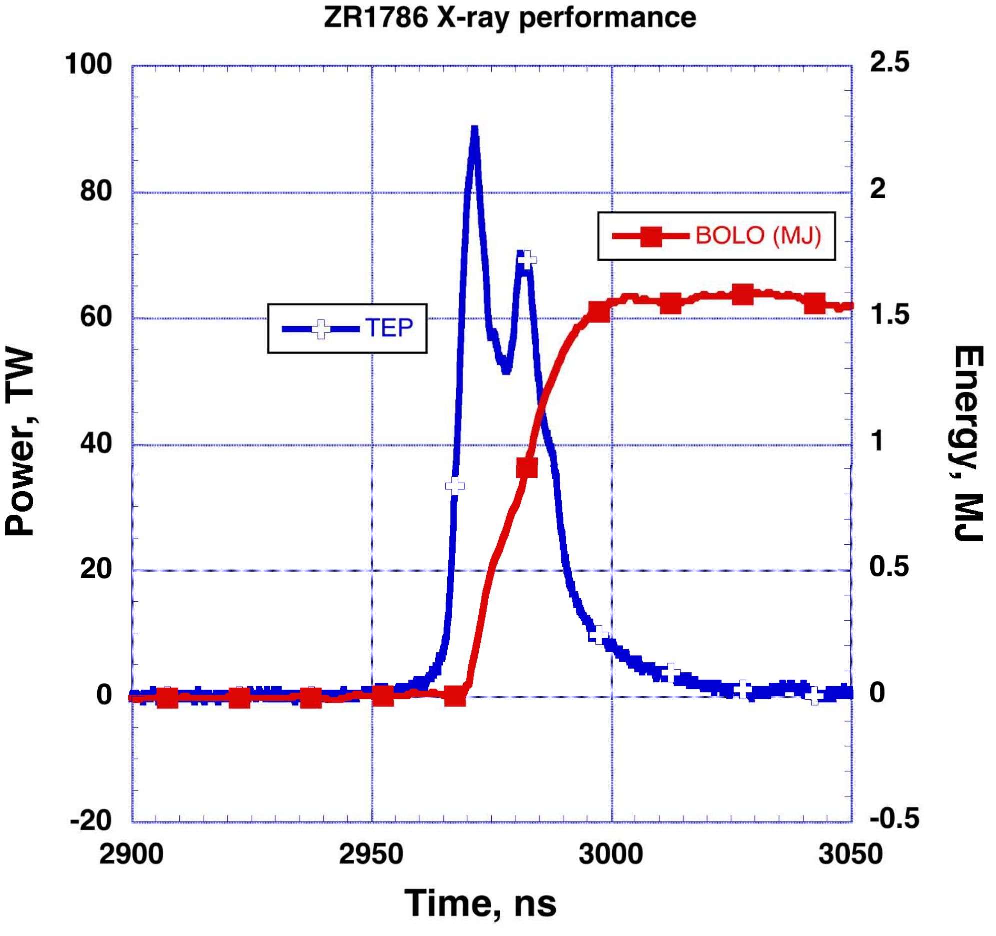
- **ZR can have relatively low prepulse for a large water-switched driver**



200 10μ W wires would see 35 mJ/cm

Z-pinch experiments have been done on ZR

- **The ZR MITLs are not optimized for high-inductance (6 nH) loads**
  - **There is considerable (3MA out of 23MA) loss between the stack and the load on high-inductance experiments**



ZR issues

The ZR insulator stack has been damaged due to machine shock

- Larger than expected dynamic loads have caused cracks in the water-vacuum interface plastic

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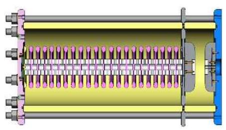
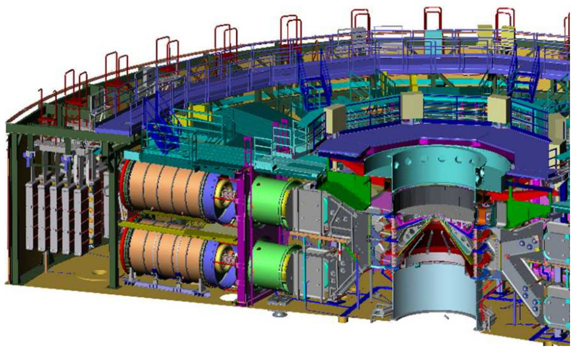
ZR future

FY08 | FY09 | FY10 *

Full ZR characterization / Initiation of user experiments @ 21MA



6.3 MV gas switch & water switch optimization



Routine and reliable User Facility Operation @ 26 MA

Development of a detailed 3D virtual ZR accelerator

Summary

- ZR is coming to life as a user facility for high energy density physics experiments
- ZR has effectively built on the experience of large drivers at Sandia and elsewhere
- Some parts of the system will require additional development and optimization (gas switches, water switches)
- The ZR MITLs will require adjustment for high inductance loads
- The ZR vacuum insulator is being studied to reduce the mechanical damage, with state of the art mechanical tools
- ZR will continue to be optimized and improved to deliver record-setting energies to HEDP loads

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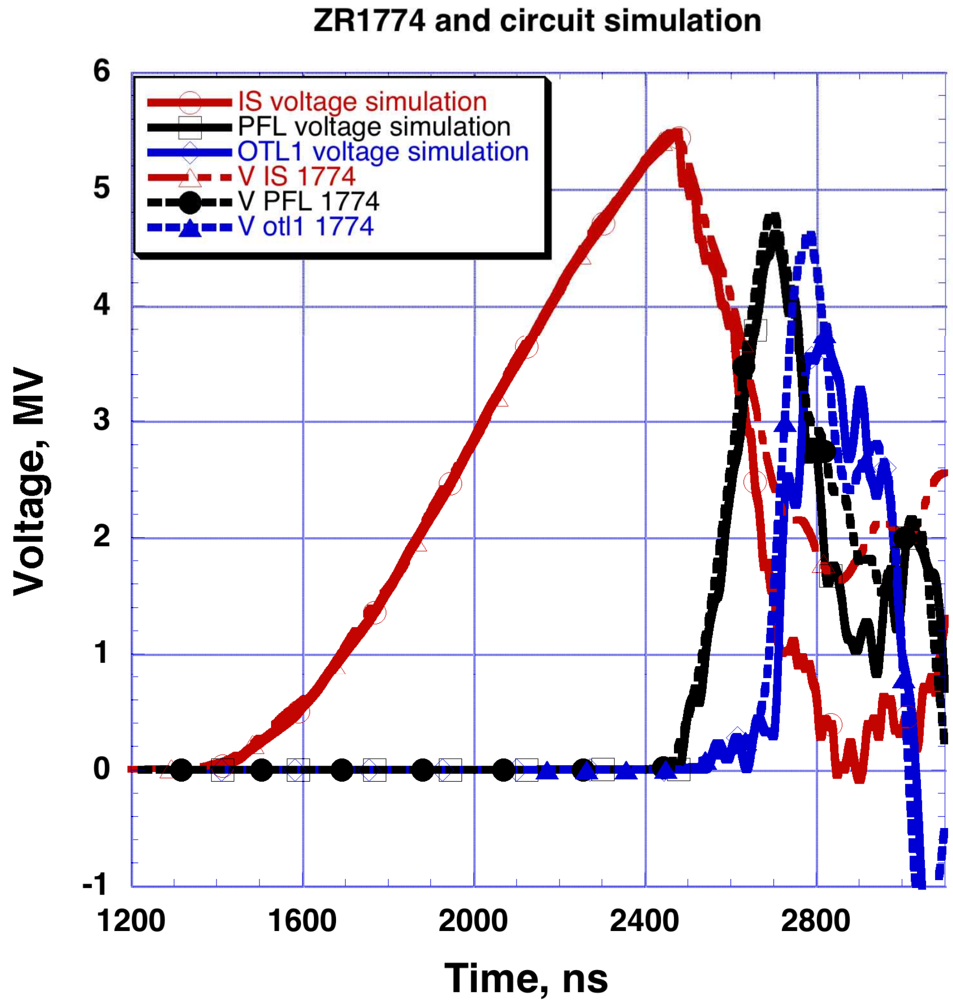
Measurements agree with circuit simulation predictions to within reasonable uncertainties

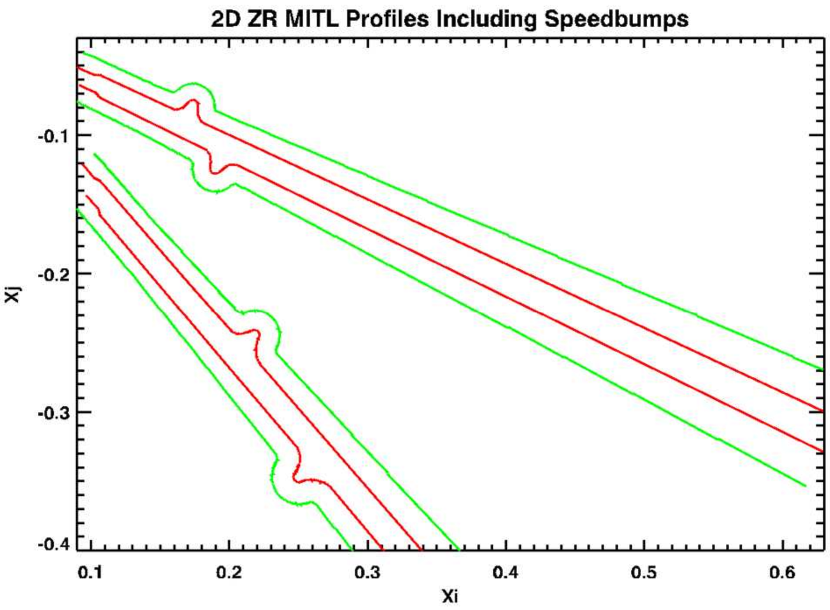
- We are developing two independent 2D transmission-line circuit models of ZR
- We are developing two independent 3D electromagnetic models of the front end of ZR, i.e., two virtual ZR-accelerator models
- This work will improve the agreement between modeling and experiment

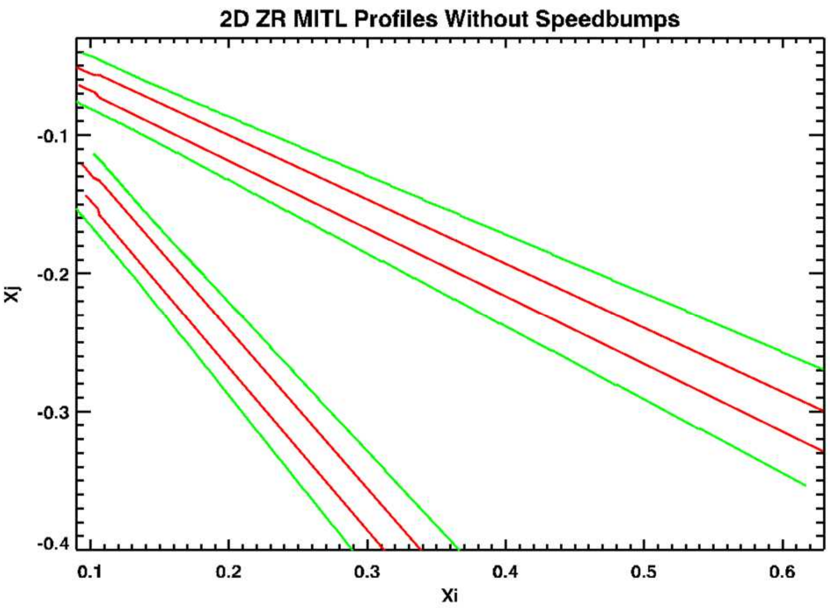


Work is in progress to improve both the circuit models and the measurements

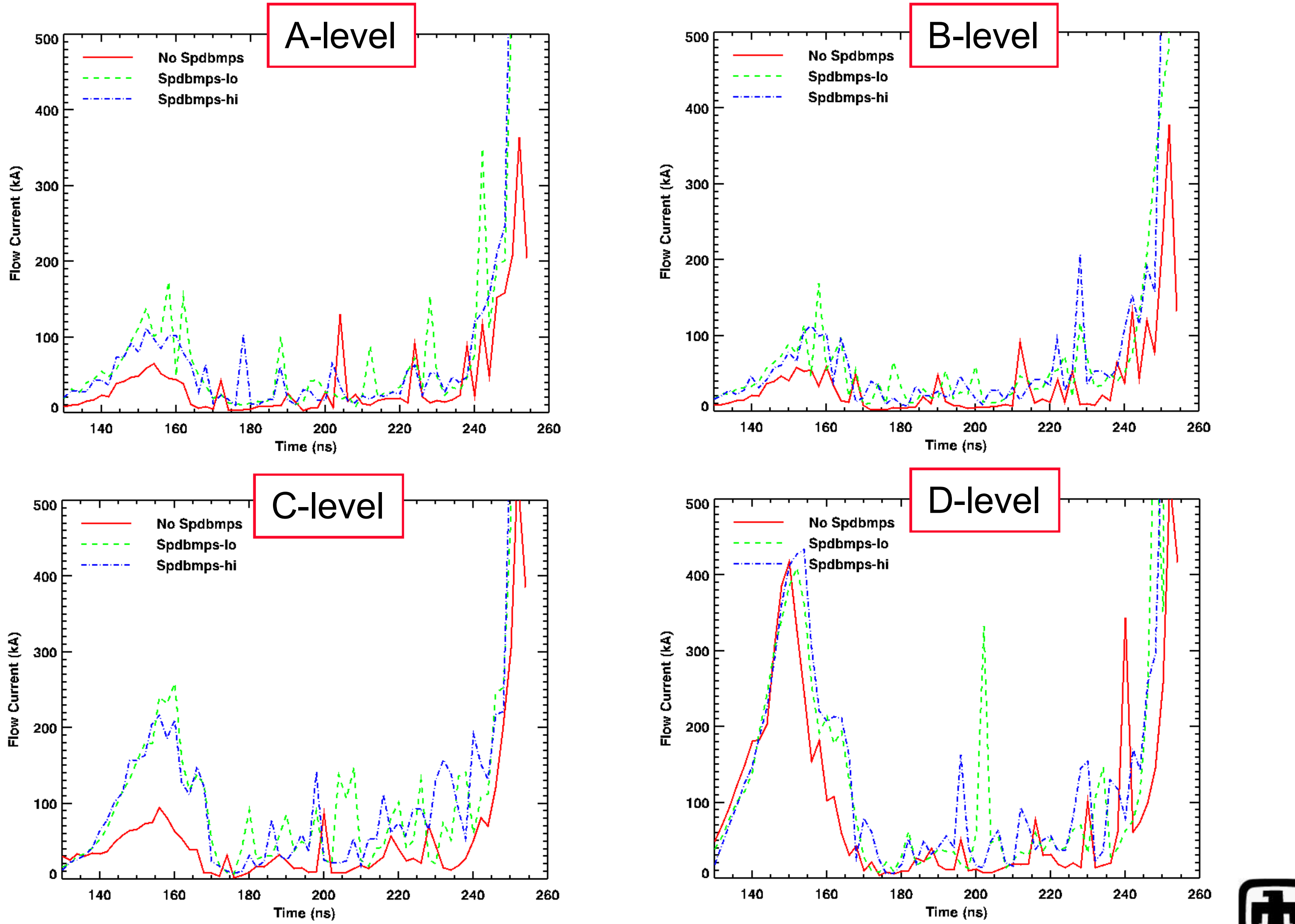
We are able to model the full ZR MITL with time-accurate simulations

- The ZR MITLs are designed with larger gaps than Z (~3% current penalty)
- The ZR MITLs are angled for diagnostic access and mechanical strength (~1% current penalty)
- The ZR MITLs have debris shields to protect the vacuum interface (electron flow penalty)



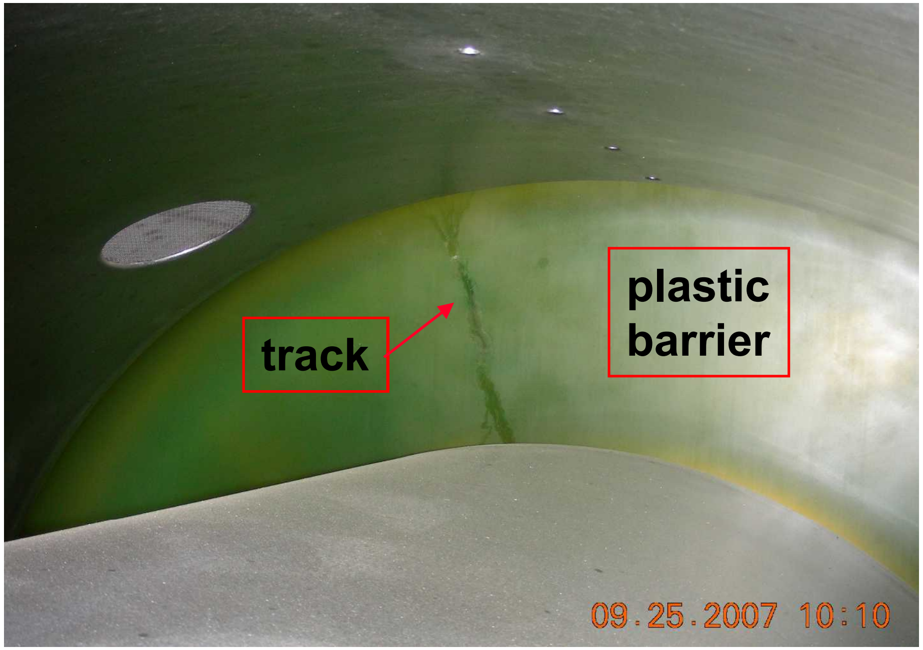


Quicksilver high-resolution simulation shows the debris shields increase the electron flow but not on D-level



The principal issue: debris (from construction) caused the tracking of water-plastic interfaces

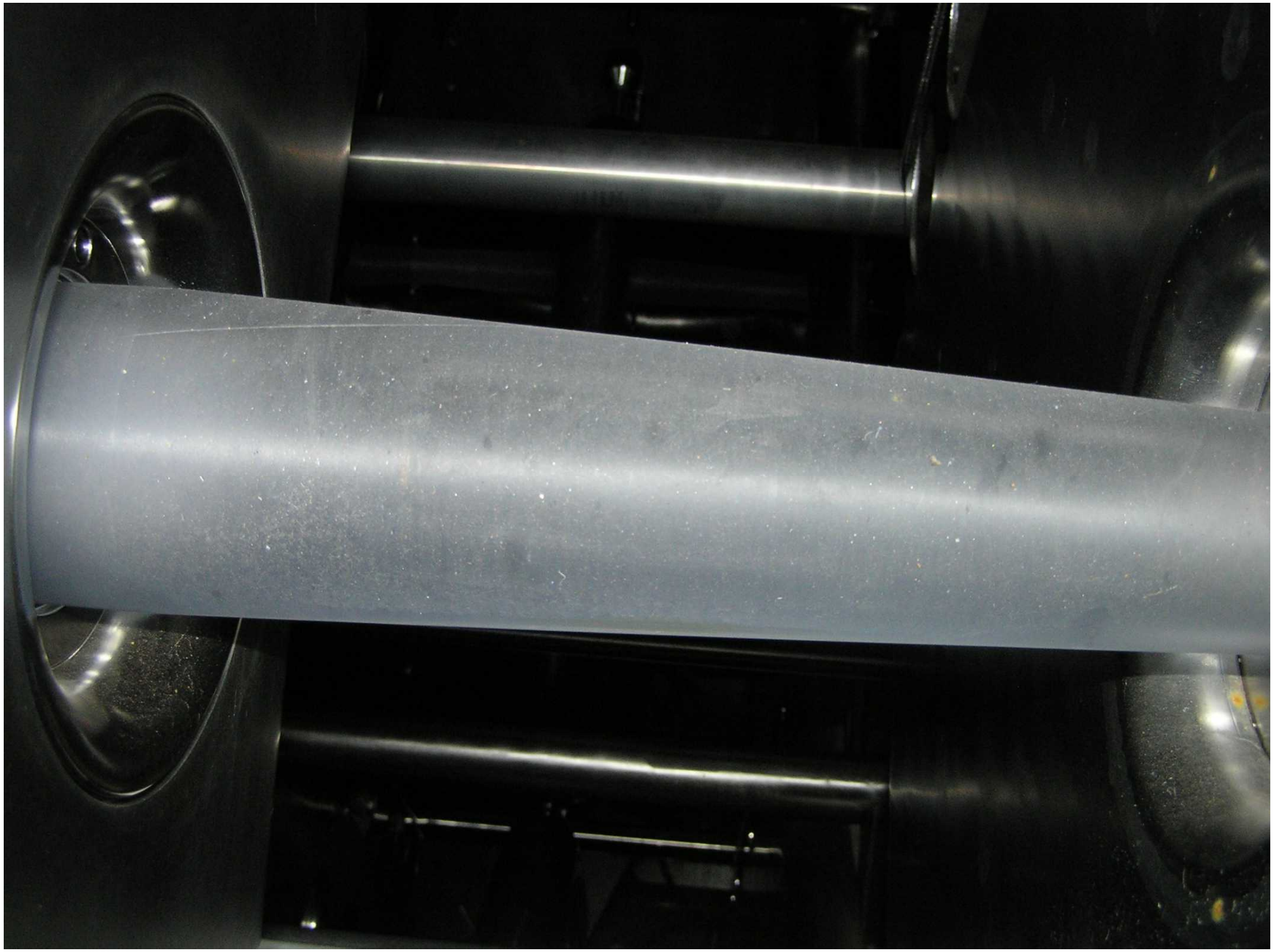
- 28 insulator rods (out of 270 total) tracked on the first ZR shot
- 22 rods tracked on the second shot
- 2 pulse-forming-line (PFL) oil-water barriers (out of 36) tracked on the second shot
- Work is in progress to make repairs, and remove the debris from the accelerator tank



tracked PFL oil-water barrier

The tracking on the first two shots is not surprising given the amount of debris

- Dust, grinding residue, and solid metal chips were present in the water and oil sections



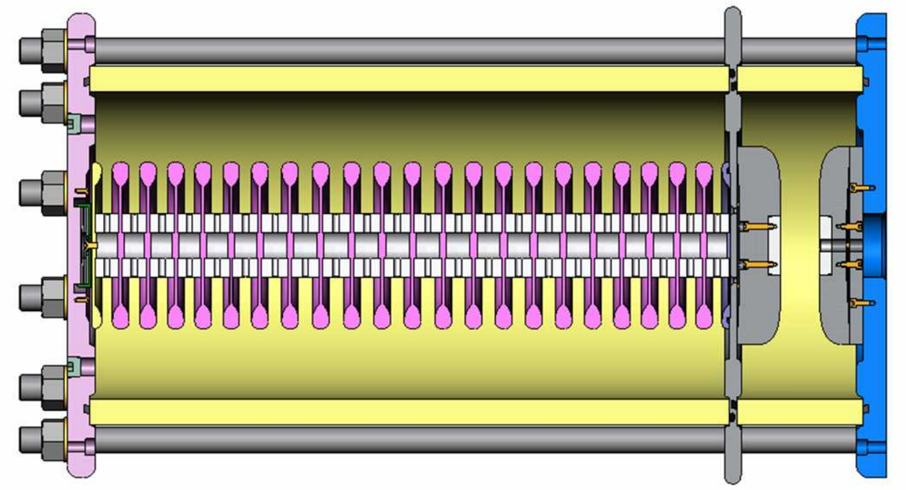
Debris was shaken down by Marx testing and the first shot

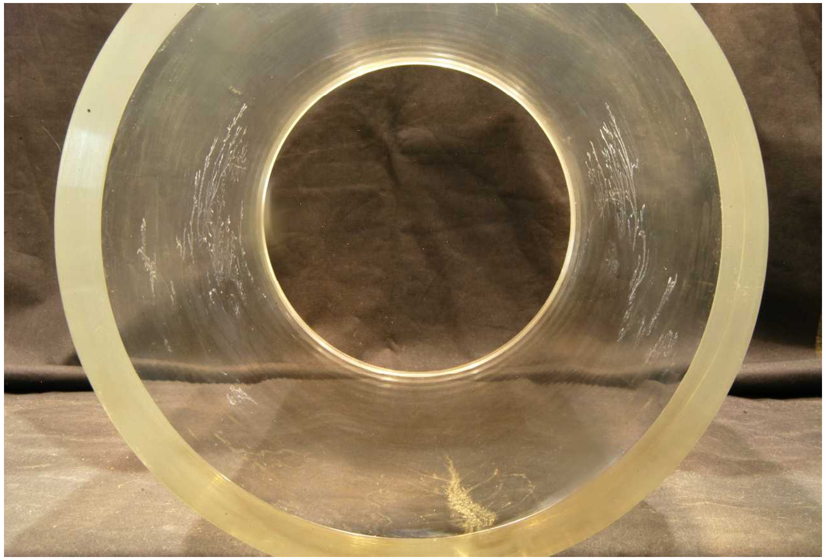
Debris was a significant problem for the initial shots

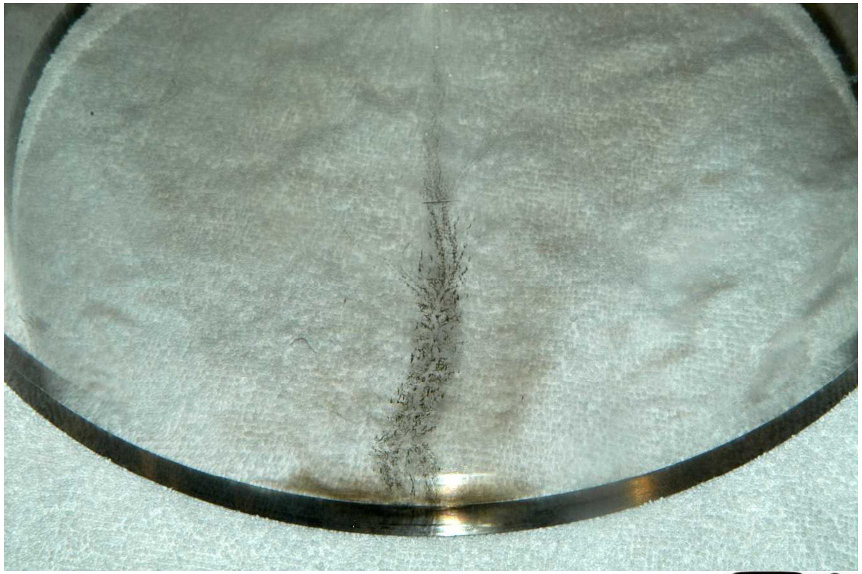
Switch flashing has effected machine performance on the first 15 shots, and it appears to be a system dependant issue

- ***Switch flashes: 54***
- ***Switch replacements: 43***
- ***Probability a switch will flash again within 3 shots: ~50%***

- ***100% of flashes have been within 30 degrees of bottom dead center***
- ***All early modules (prefires) have been flashes***

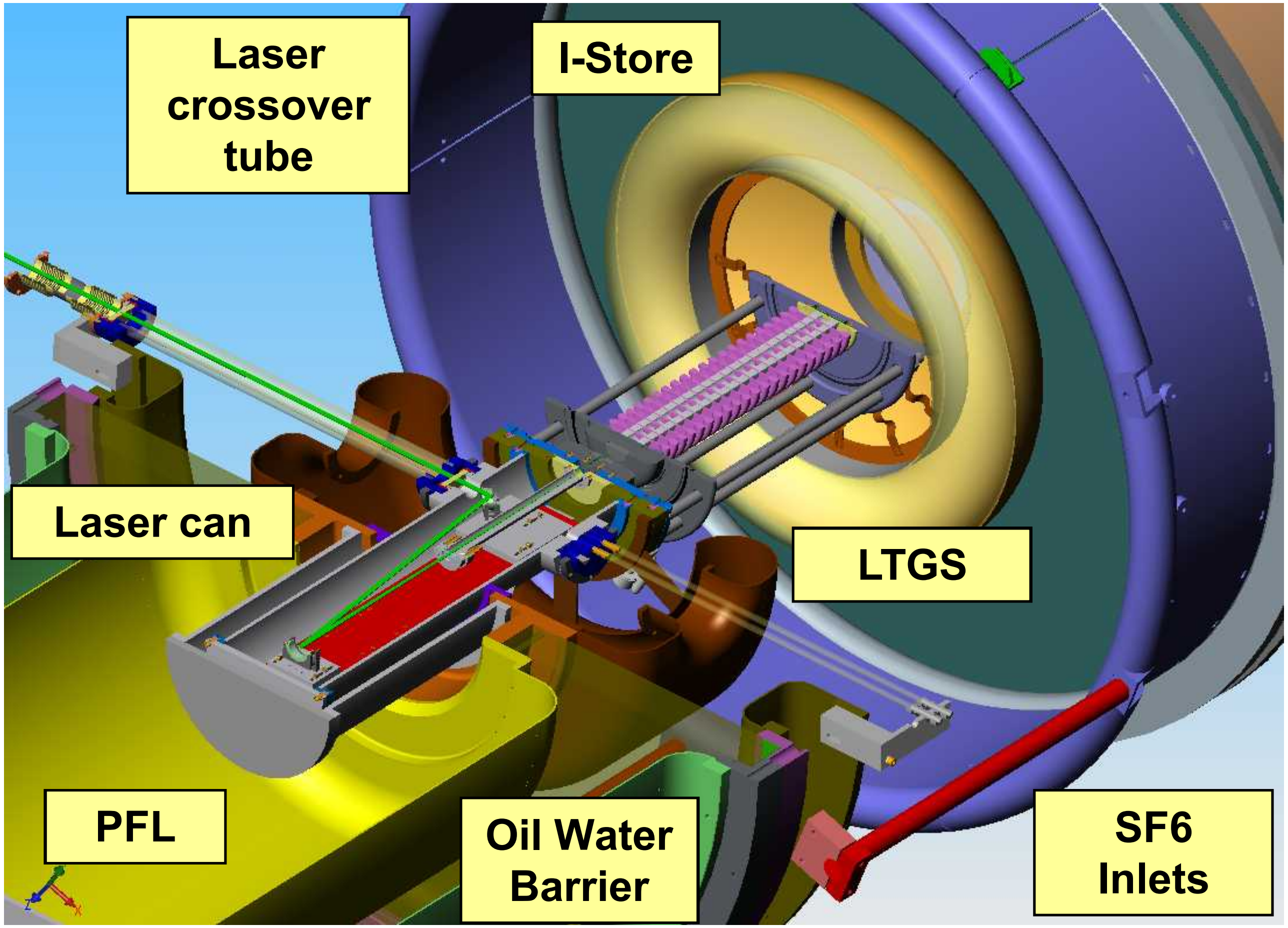






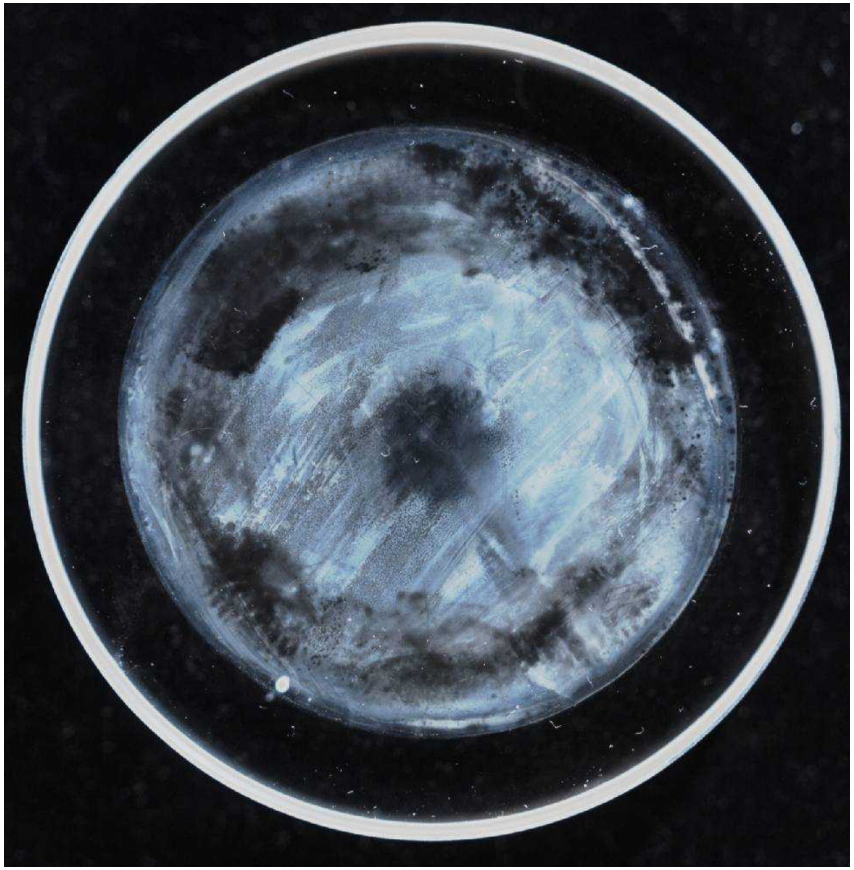
Laser crossover tubes are a maintenance issue

- The crossover tube carries the laser beam to the PFL

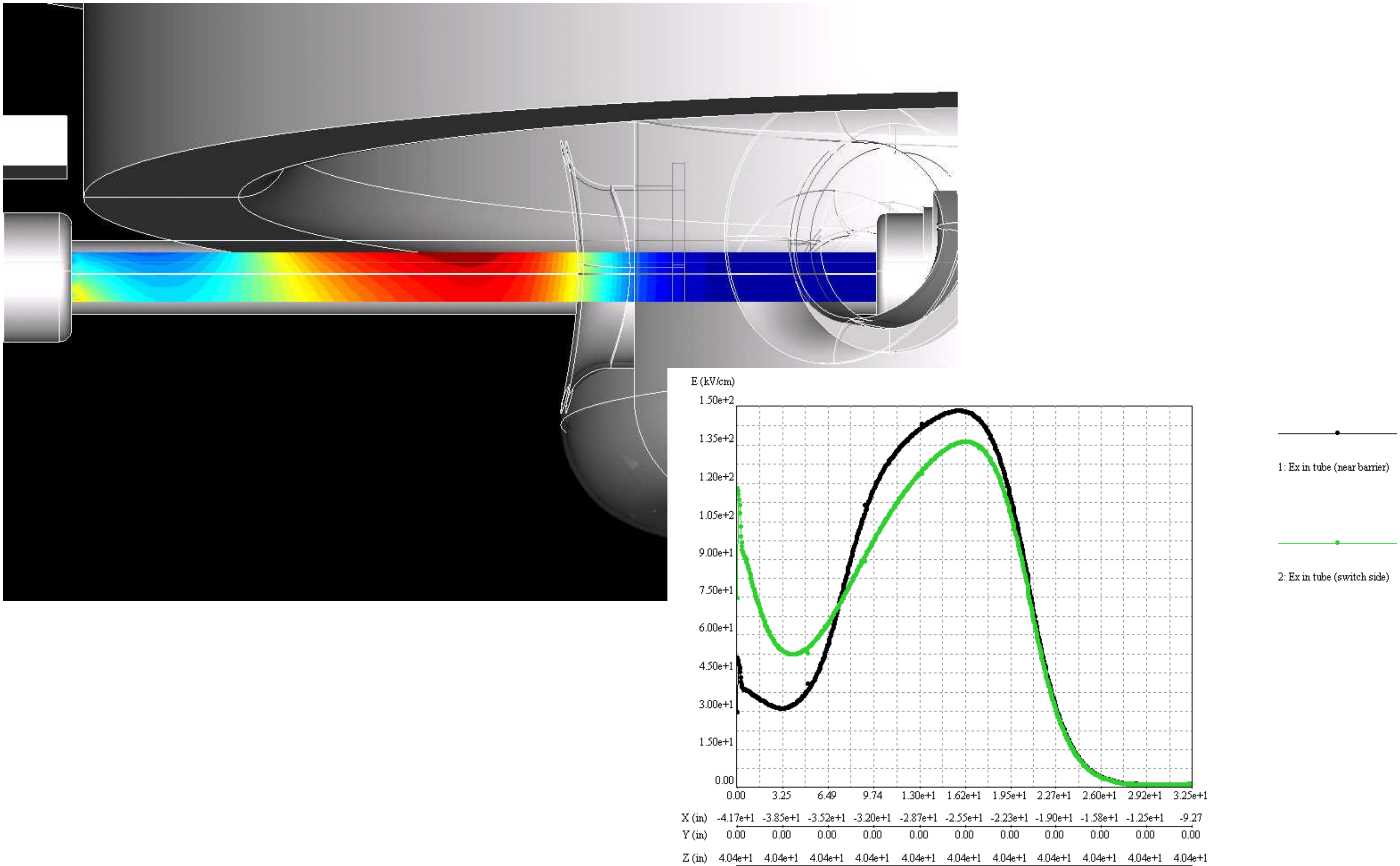


Crossover tube flashes create hydrofluoric acid

Etched windows attenuate the laser beam, preventing switch triggering



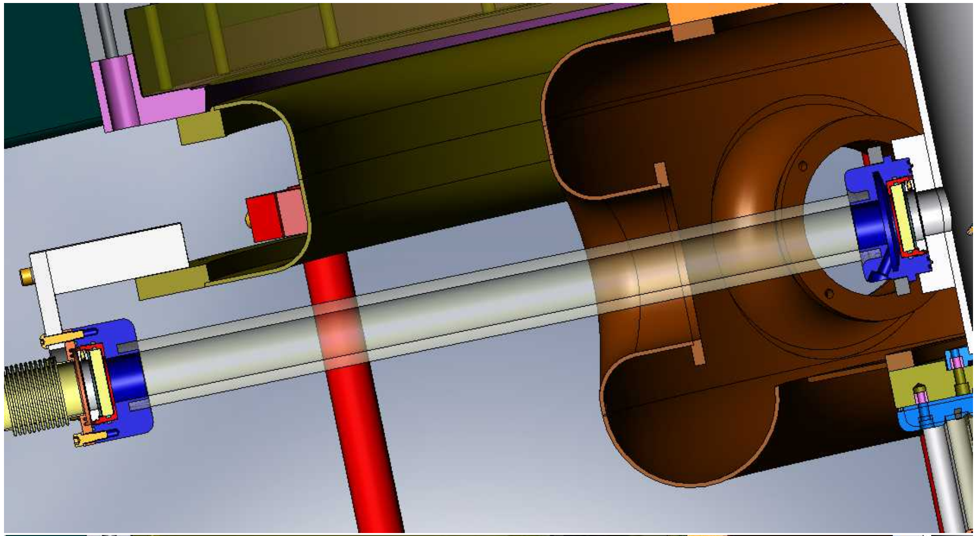
The crossover tube interior operates at 150 kV/cm



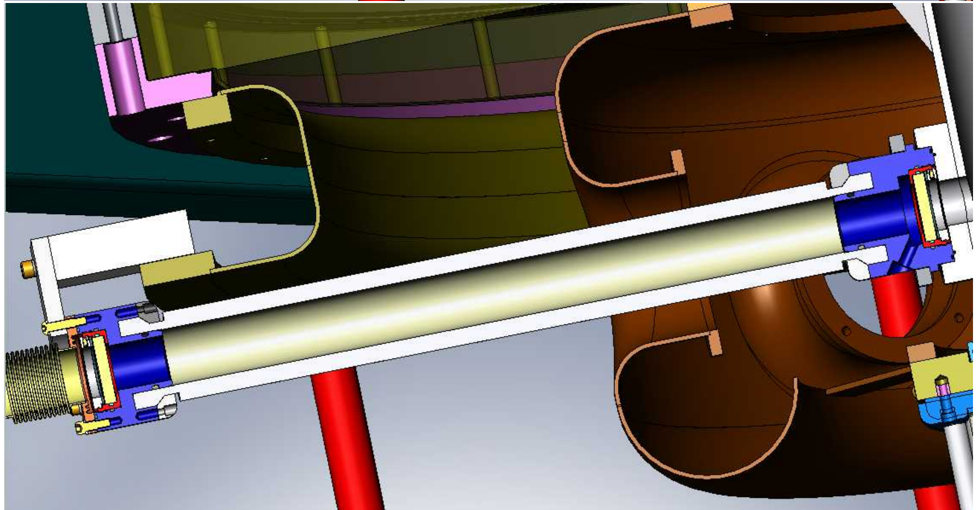
Teflon laser tubes will be tried on ZR, as well as segmenting the insulator

- **Presumably, preventing flashing will eliminate window frosting**

Current crossover tube design



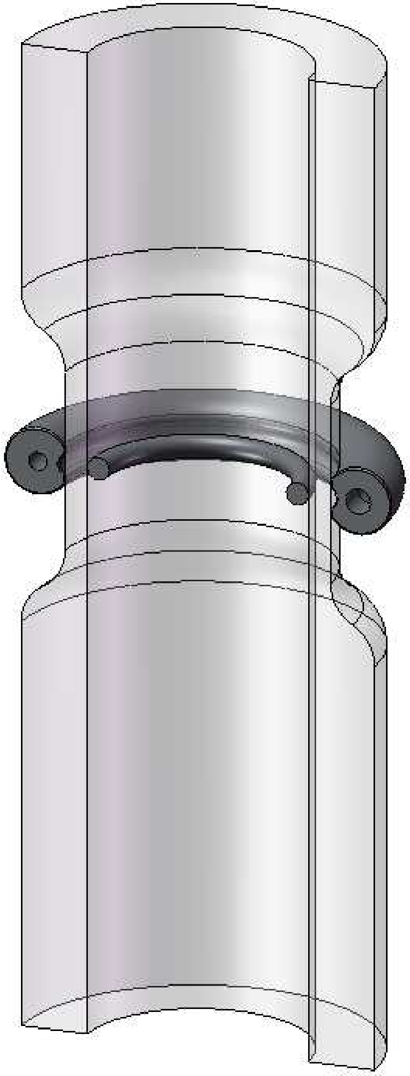
Teflon crossover Tube design



ZR issues

Segmenting the crossover tube will improve reliability

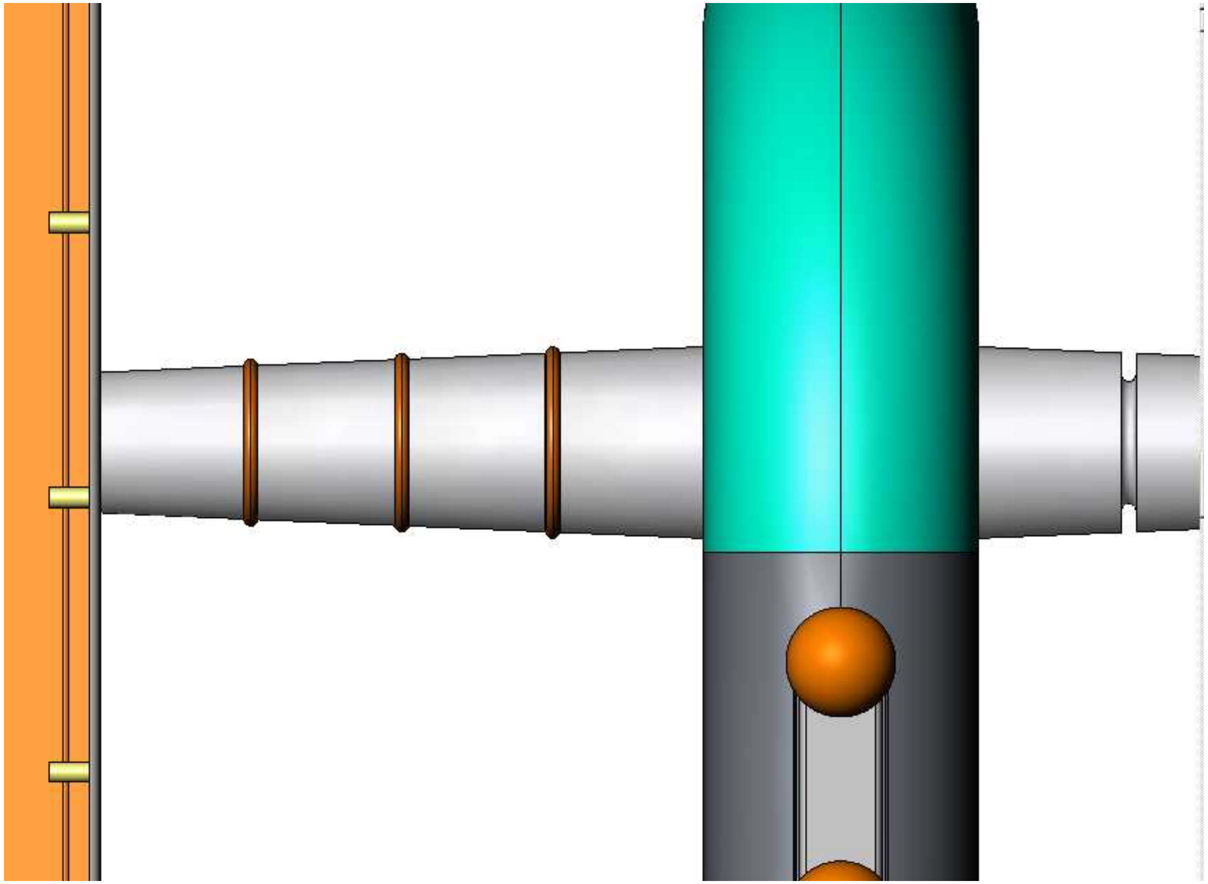
- Flashing is late in time, when fields are lower
  - Segmenting inhibits streamer propagation and is more effective at long times and lower fields



ZR issues

OTL support rod flashing is also late-time and may benefit from segmenting

- Rod segmenting may be done with metal or conductive polymers



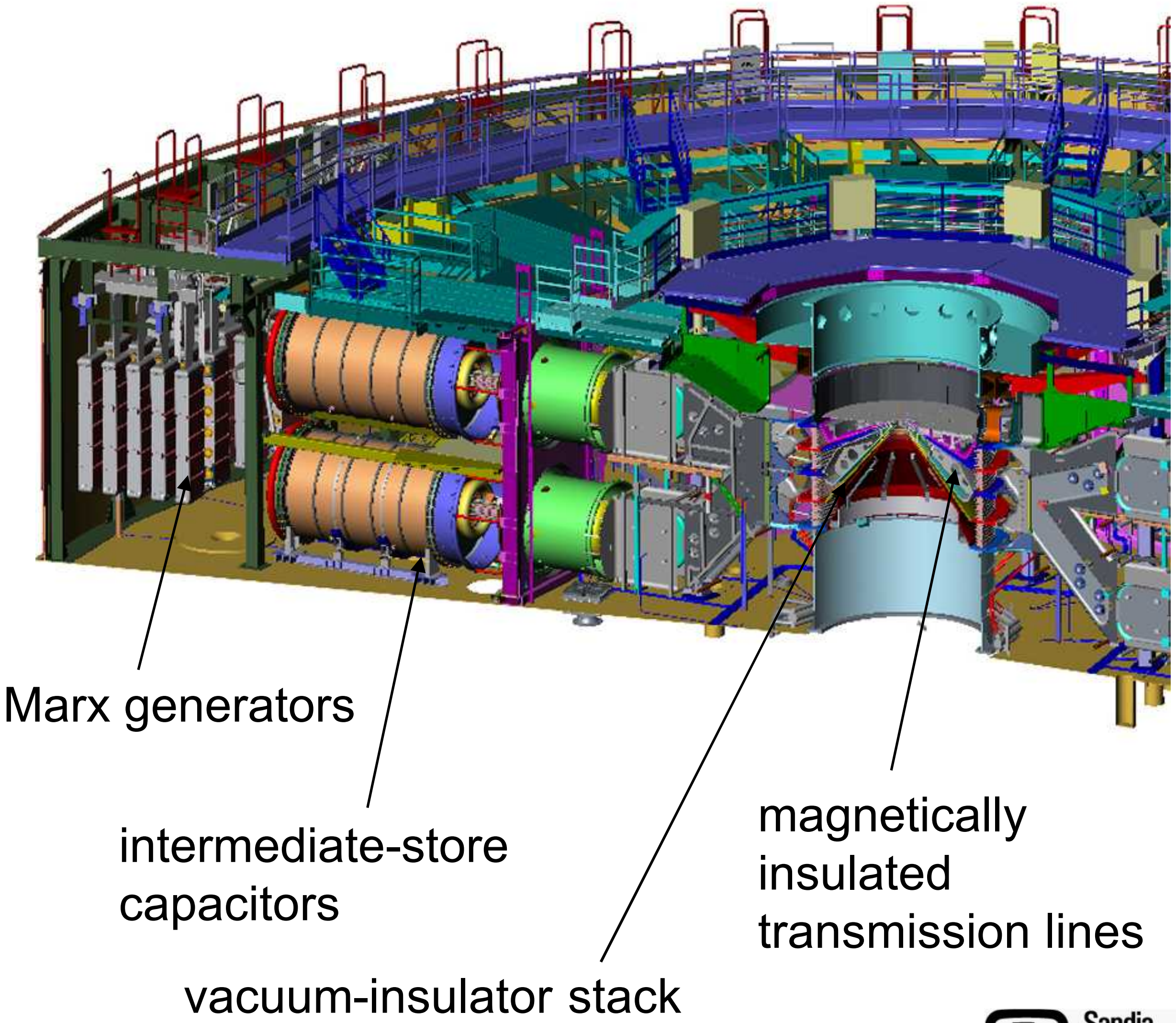
Future work

- Demonstrate routine ZR operation as a full capability,shared national user facility
- Demonstrate reproducible operation
  - ±1 ns and ±1% short-term repeatability
- Develop and verify detailed models for ZR (virtual accelerator)
  - 2-D transmission line circuit models (Bertha and TLCODE)
  - 3-D electromagnetic models (LSP and Quicksilver)
  - Converge to 2% agreement
- Compare models with experimental data
- *Improve facility timing and accuracy in an on-going manner*

A successful ZR shot requires operation of many systems with nanosecond accuracy

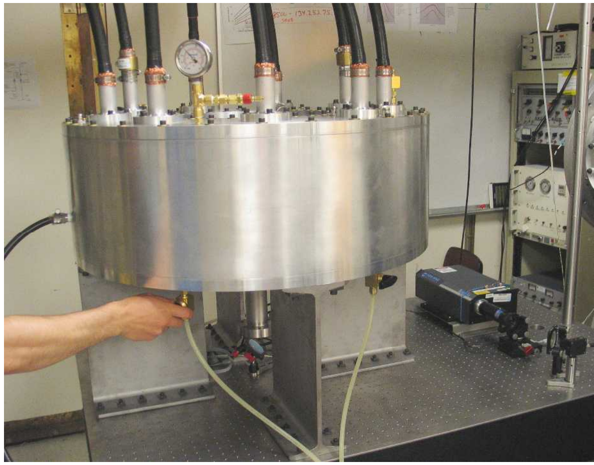
On these shots, the following ZR-accelerator components worked as expected:

- **Control-monitor and data acquisition systems**
- **Primary trigger generator**
- **9 Marx-trigger generators**
- **36 Marx generators**
- **36 intermediate-store capacitors**
- **36 laser-trigger and gas switch systems**
- **Vacuum insulator and magnetically insulated transmission lines**
- **Power-flow diagnostics**



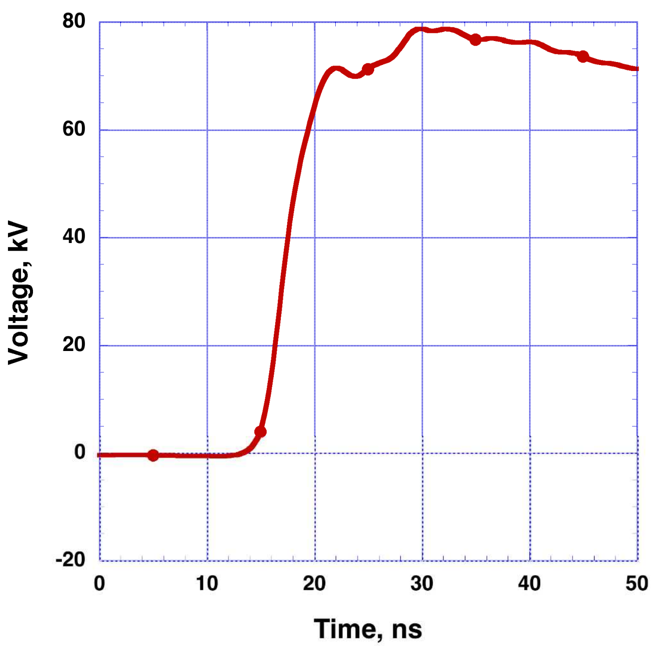
One of the most challenging systems is the primary trigger generator

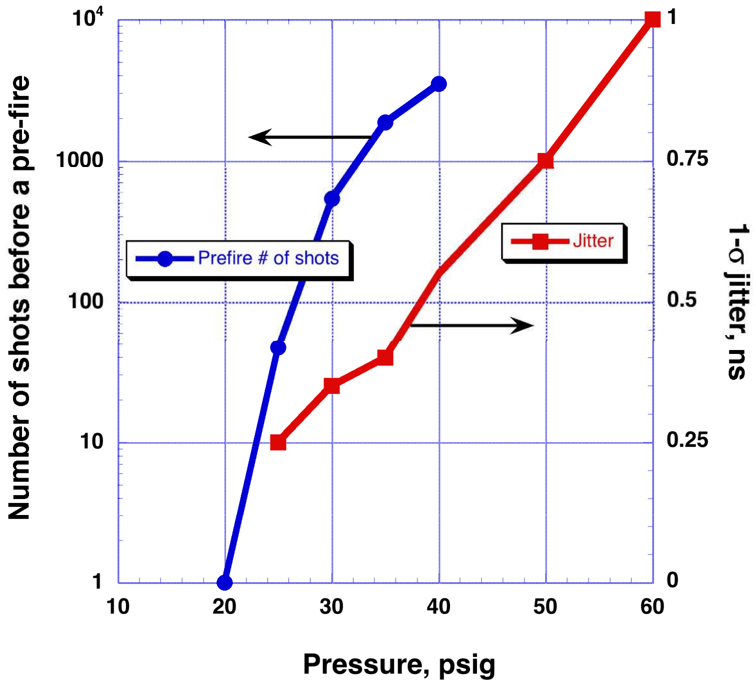
- **The prime trigger amplifies the ~5 V command trigger signal to tens of kV**
- **The LTS-100 has been successful-**
  - **Total spread: 1.1 ns**
  - **Jitter: 560 ps (total system)**
  - **Pre-fire rate much lower than the TG100**



We used our experience with laser-created sparks to optimize the trigger generator

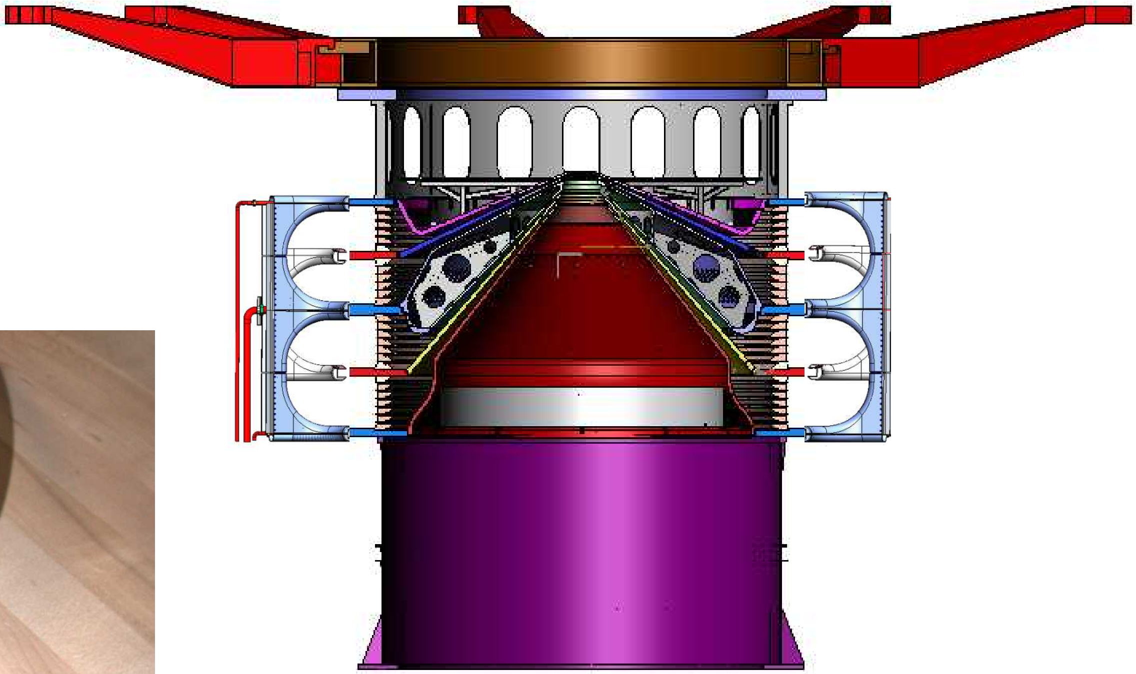
- The system uses a novel switch geometry with laser triggering to minimize jitter and risetime, and maximize reliability
- The system provides ***simultaneously:*** low jitter, fast risetime, and high reliability





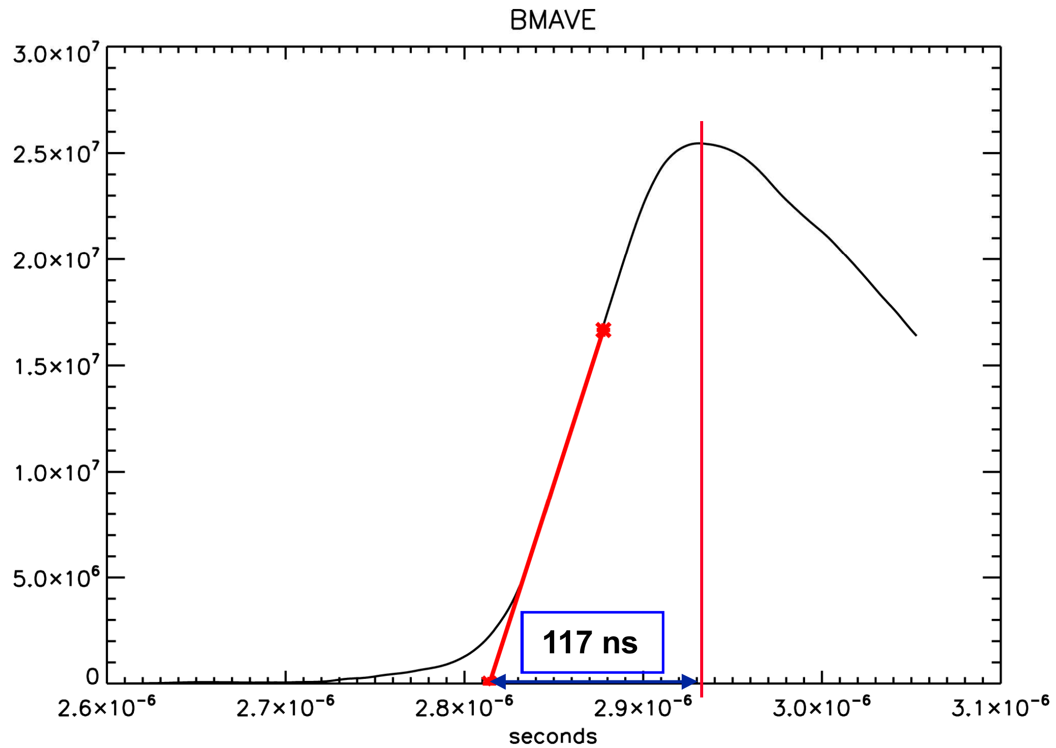
The new ZR stack uses a Sandia-developed conductive polymer to enhance reliability

- **Withstands mechanical load**
- **Tested at ~300 kV/cm**
- **Predicted ZR reliability >99%**



The upgraded Z has delivered 26MA to fixed-inductance 2.8 nH loads in both short-pulse and long-pulse modes

- Current measured by load B-dots as has been done on Z



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The large amount of energy causes motion of the massive tank