SAND2009-3481C

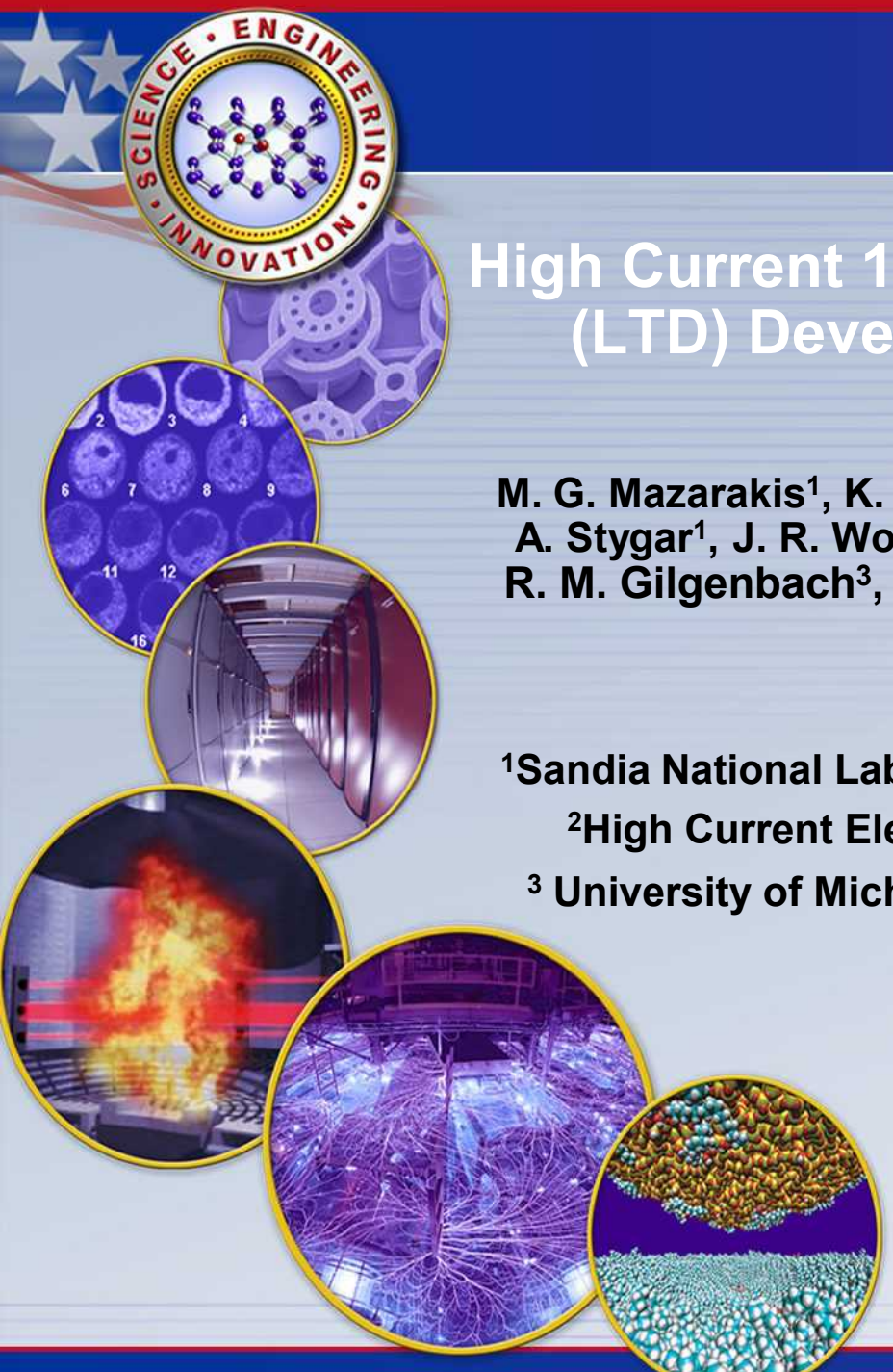
High Current 1-MA Linear Transformer Driver (LTD) Development at Sandia National Laboratories

M. G. Mazarakis[1], K. R. LeChien[1], W. E. Fowler[1], J. L. Porter[1], W. A. Stygar[1], J. R. Woodworth[1], A. A. Kim[2], V. A. Sinebryukhov[2], R. M. Gilgenbach[3], M. R. Gomez[3], J. C. Zier[3], D. M. French[3], Y. Y. Lau[3], W. Tang[3]

[1]Sandia National Laboratories, Albuquerque, NM, United States

[2]High Current Electronic Institute (HCEI), Tomsk, Russia

[3] University of Michigan, Ann Arbor, Michigan, United States



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LTD Technology is a New Paradigm in Accelerator Physics.

- Sandia, the High Current Electronics Institute at Tomsk, Russia, and the University of Michigan, are the leaders toward the development of a new class of very compact, high current, high voltage, very fast (70-100-ns) accelerators based on the LTD (Linear Transformer Driver) technology.

- The salient feature of the the new technology is switching and inductively adding the pulses at low voltage straight out of the capacitors through low inductance transfer and ferromagnetic core isolation (basic unit = stage or LTD cavity).

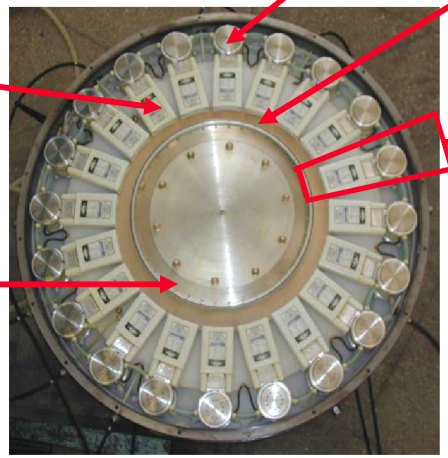
- We can inductively add stages (cavities) in series in a voltage adder configuration (like HERMES III) to get Multi-Megavolt outputs.

- We can add in parallel many voltage adders to get both Multi-Megavolts and Multi-Mega-amps.

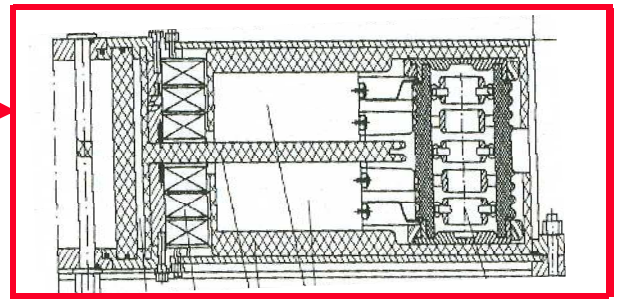
Presentation Outline.

- Introduction
  - What is an LTD cavity.
  - What is an Inductive LTD voltage adder.
  - Conceptual Z-pinch driver designs.
  - High current 0.5-1-MA LTD cavities built and tested.
- Advantages as compared to conventional pulsed power.
- LTD development as building blocks for future Z-pinch drivers.
  - 0.45-MA LTD I prototype cavity.
  - O.5-MA LTD II
  - 1-MA cavities.
  - 1-MA LTD five cavity voltage adder experiments.
  - Improved LTD cavity components development.
- Summary
- Future plans

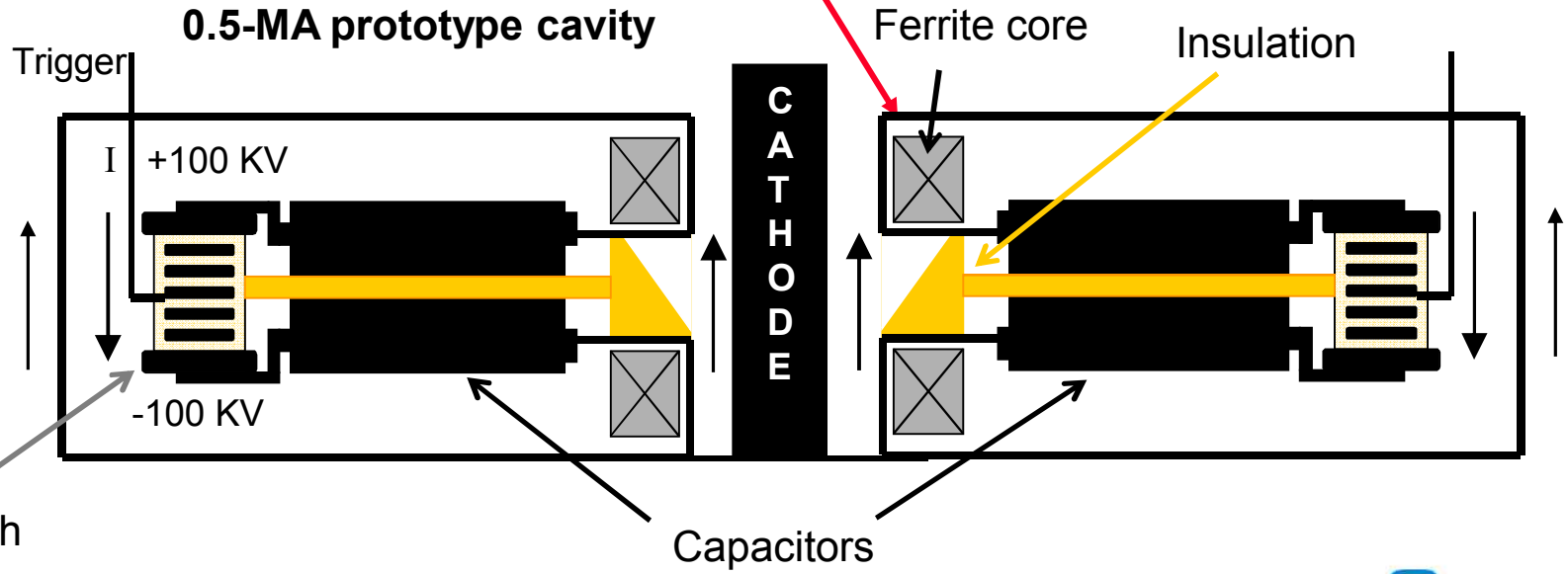
The fast LTD cavity is an induction accelerator cavity which encloses the pulse producing circuits ("bricks").



0.5-MA prototype cavity



Brick side section



We have build and tested three different size fast LTD cavities

- **LTD I & LTD II**
  - –20 bricks
  - –40 nF caps (single ended)
  - –Matched load : 0.17 - 0.2 Ohm
- **LTDR**
  - –10 bricks
  - –20 nF caps (double ended)
  - –Matched load : 0.5 Ohm
- **LTD-Z (1-MA)**
  - –40 bricks
  - –40 nF caps
  - –Matched load - 0.112 Ohm

LTD I & LTD II 450 - 500-kA

LTDR 200-kA

J. Leckbee, *et. al., in Proc. of the 15th Pulsed Power Conference* (2005) p. 132

LTD-Z (1-MA)

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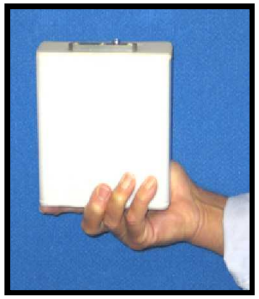
The LTD cavity construction is very robust containing only 3 basic components.

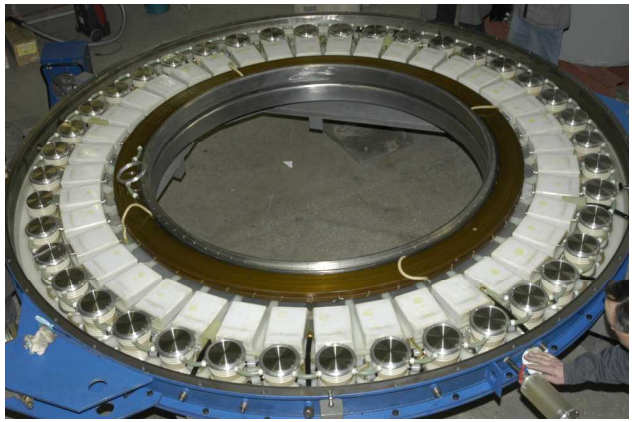
Only 3 basic components

switch



capacitor

ferromagnetic core



1-MA LTD

An LTD Voltage Adder is an adder that connects in series a number of inductively isolated LTD cavities.

LTD-Z five 1-MA cavity Voltage Adder

A. A. Kim, M. G. Mazarakis, *et. al.*, Accepted for publication Phys. Rev. ST Accelerators and Beams (May 2009)

LTD-R seven 200-kA Voltage Adder

A. A. Kim, *et. al., in Proceedings of the 14th IEEE International Pulsed Power Conference* (2003) p. 853

J. Leckbee, *et. al., in Proceedings of the 15th IEEE International Pulsed Power Conference* (2005) p. 132

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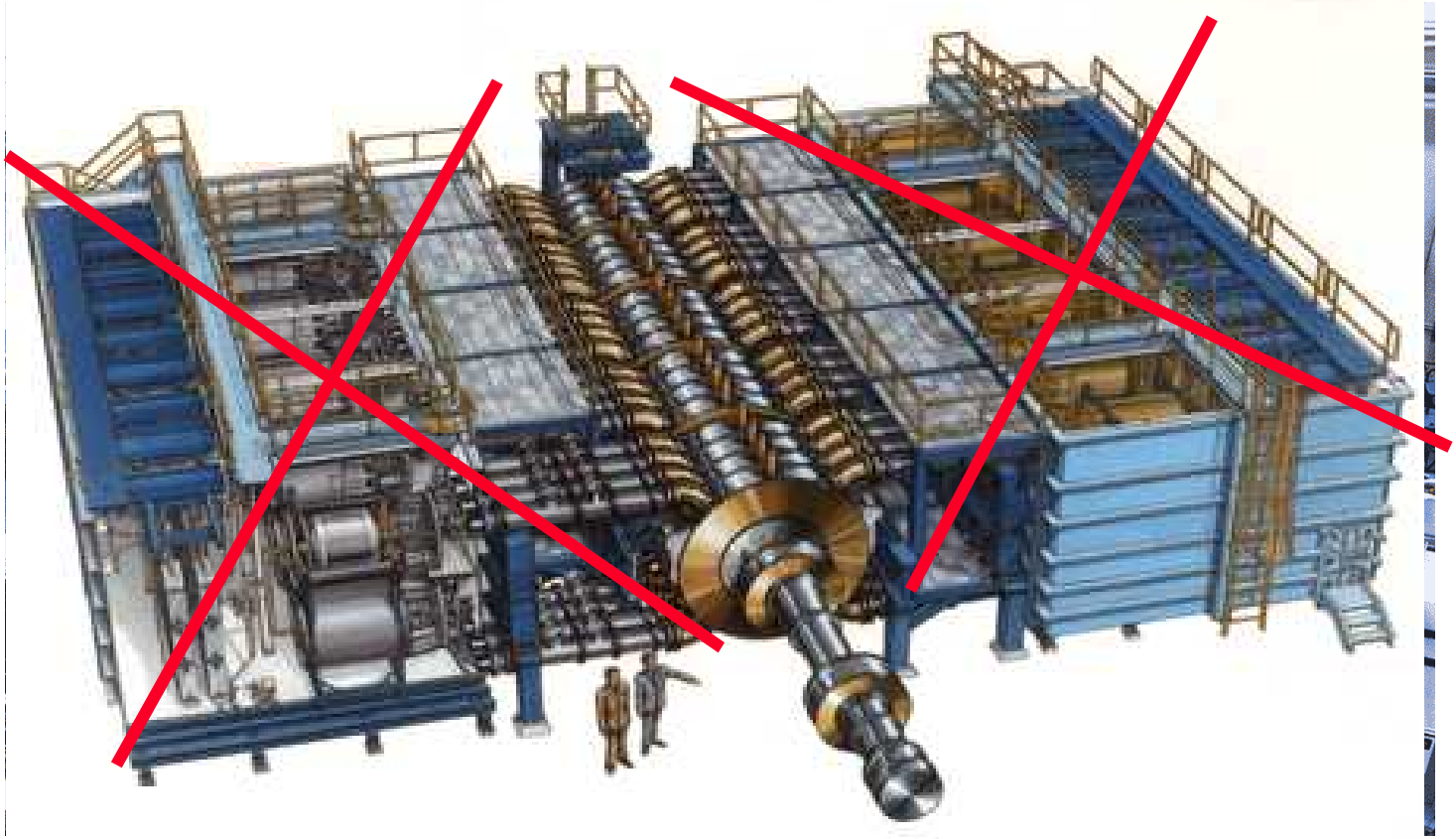
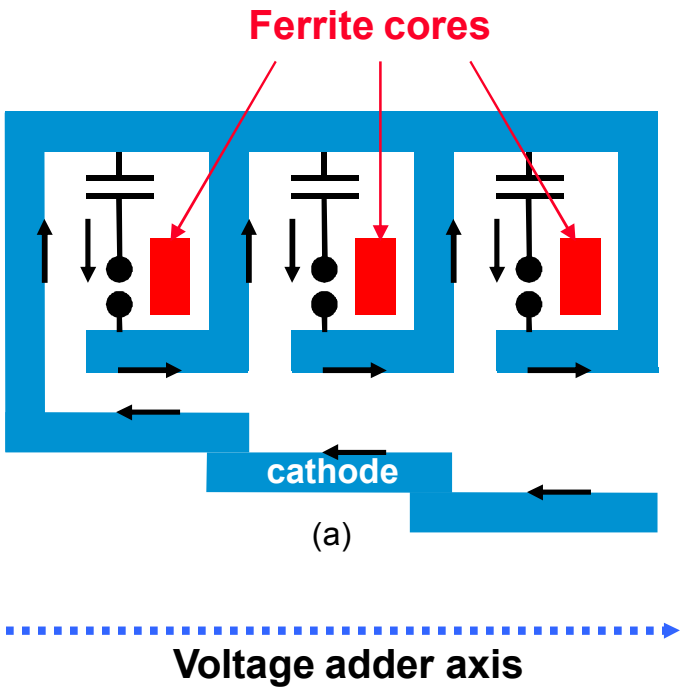
A 1-MA, 20-MV LTD voltage adder will look like the HERMES-III center section but with smaller diameter.

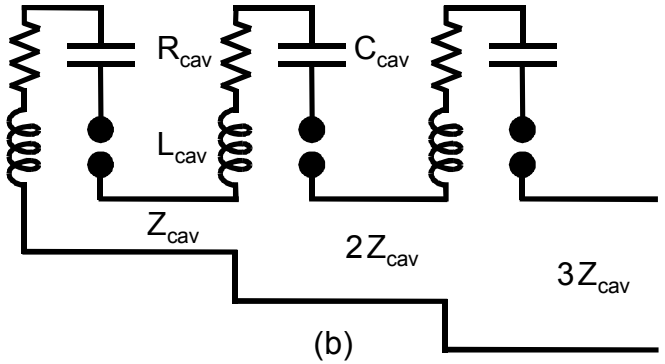
LTD drivers are very compact.
No need for multistage pulse compression.

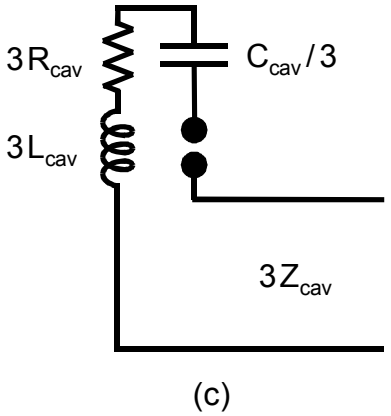


HERMES III

To first order, an n-cavity LTD module can be modeled as a simple RLC circuit.

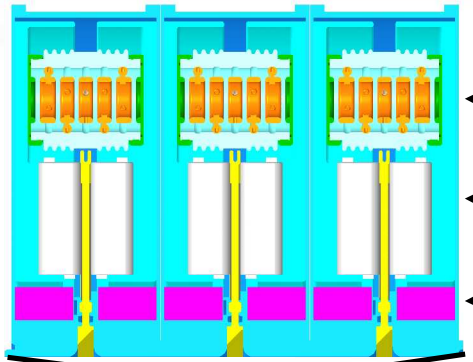






M. G. Mazarakis *et al*. "A Compact, High-Voltage E-Beam Pulser," 12th IEEE Pulsed Power Conference, Monterey, California, July 1999.
Pulsed Power Conference Proceedings p. 412

Each LTD module consists of a large number of annular LTD cavities connected in series.



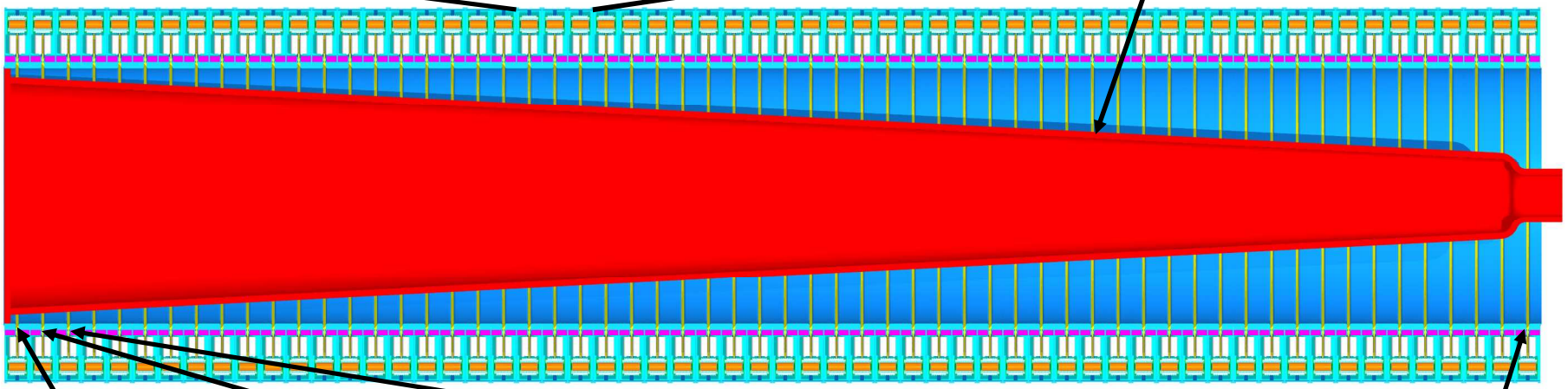
expanded view of 3 1-MA LTD cavities

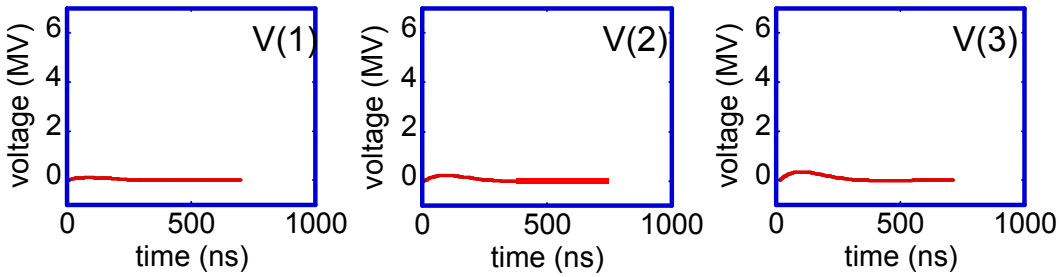
60-cavity annular LTD module

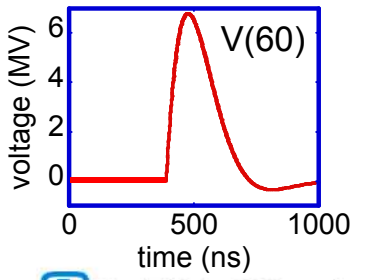
central conical conductor

$\eta_{energy} = 70\%$

3 m







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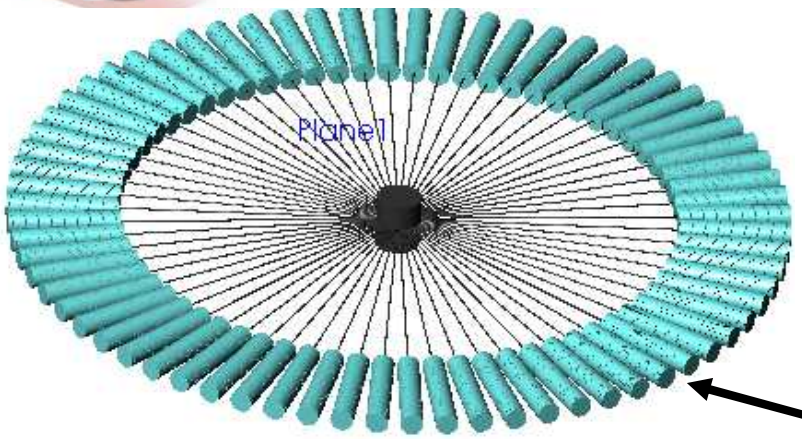
2D electromagnetic simulations confirm that an LTD module launches a clean traveling wave.

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

W. L. Langston et al, to be published.

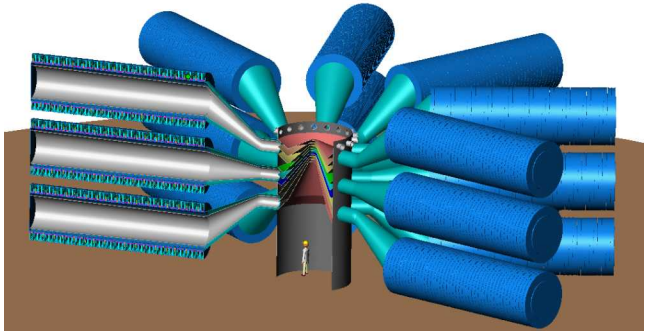
Conceptual designs of z-pinch drivers with multiple 1-MV, 100-ns LTD voltage adders connected in parallel.

With our future very low inductance switches and high density capacitors the designs could shrink dramatically.

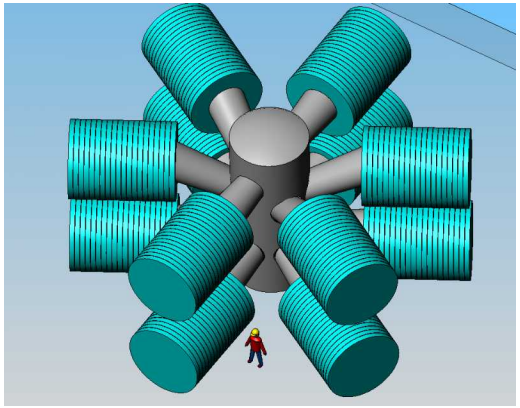


0.5 Petawatt driver

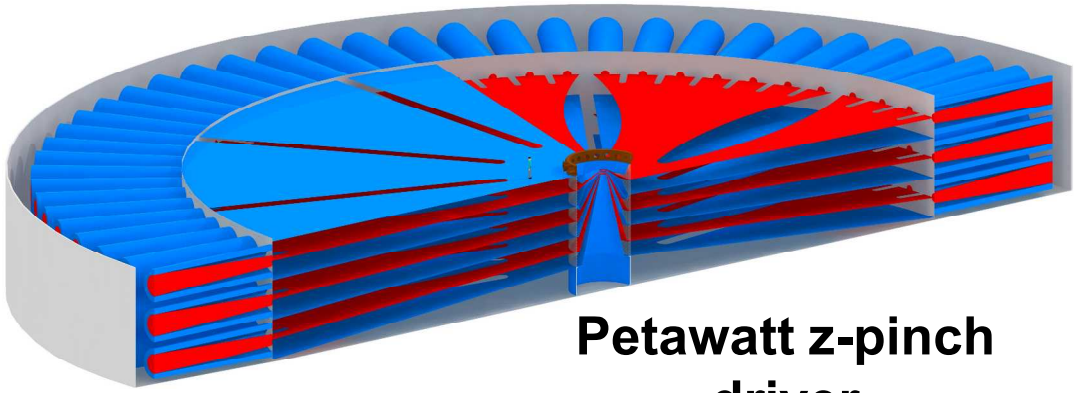
1-MA, 7-MV voltage adder module



ZR equivalent



Saturn equivalent



Petawatt z-pinch driver

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We have built and operated several 0.5 to 1-MA LTD cavities and one 5 cavity, 1-MA voltage adder.

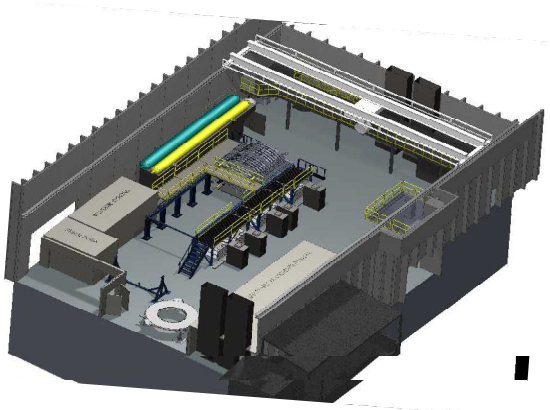
- Two 500-kA, LTD I and LTD II, cavities were constructed and operated.

- We have built eleven 1-MA LTD-Z cavities as building blocks for high current Z-pinch drivers.

- A five LTD-Z cavity voltage adder was assembled and tested with diode and resistive loads.

- A 1-MA LTD-Z cavity is currently in operation at Michigan University MAIZE laboratory testing MITLs, convolutes, and Z-pinch loads.

- MYKONOS laboratory is in progress to house ten 1-MA, 1-MV, 10-cavity voltage adder.



MYKONOS laboratory

LTD's compare favorably with conventional pulsed power.

- **Conventional:**
  - DC charged Capacitors
  - **5 stages of pulse compression** (Marx, water capacitors, laser triggered 6-MV gas switches, water switches, pulse forming lines)
  - ~6 MV, 100 ns pulse
  - ~35% Efficient

- **Linear Transformer Drivers**
  - DC charged Capacitors
  - **Direct DC to 100 ns pulse conversion** (low voltage 200kV max. components)
  - Add stages in series (like Hermes III) to get
  - ~6 MV, 100 ns pulse
  - ~70 % Efficient

Easily rep-ratable (IFE application)

We have fired the prototype LTD I cavity for over 13,000 shots in rep-rated mode at 85 kV.

cavity performance:

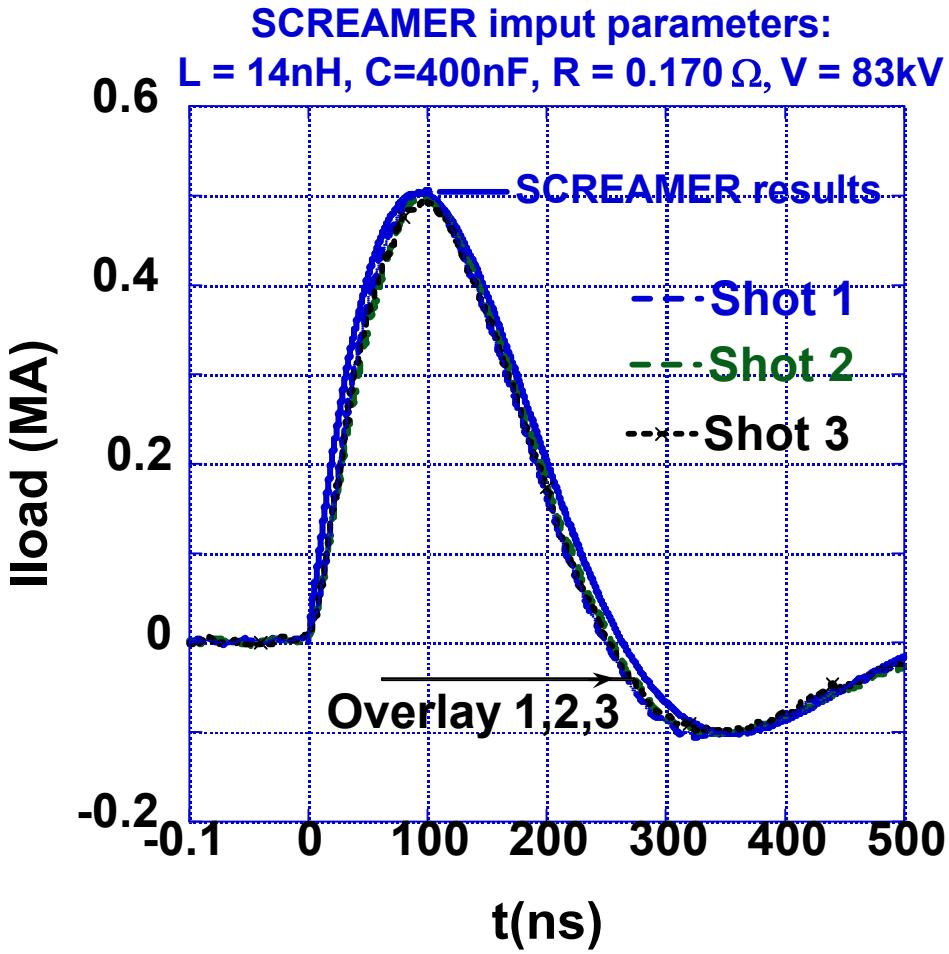
- timing jitter = 2 ns (1σ)
- voltage and current reproducibility = 0.3% (1σ)
- peak power = 0.042 TW
- output energy = 4 kJ
- electrical efficiency = 70%
- maximum rep-rate = 0.097Hz

We have demonstrated successful operation of two capacitors and a single switch ("brick") on over 37,000 shots.

M. G. Mazarakis, W. E. Fowler, S. T. Rogowski, and R. A. Sharpe (to be published).
A. A. Kim and colleagues (to be published).

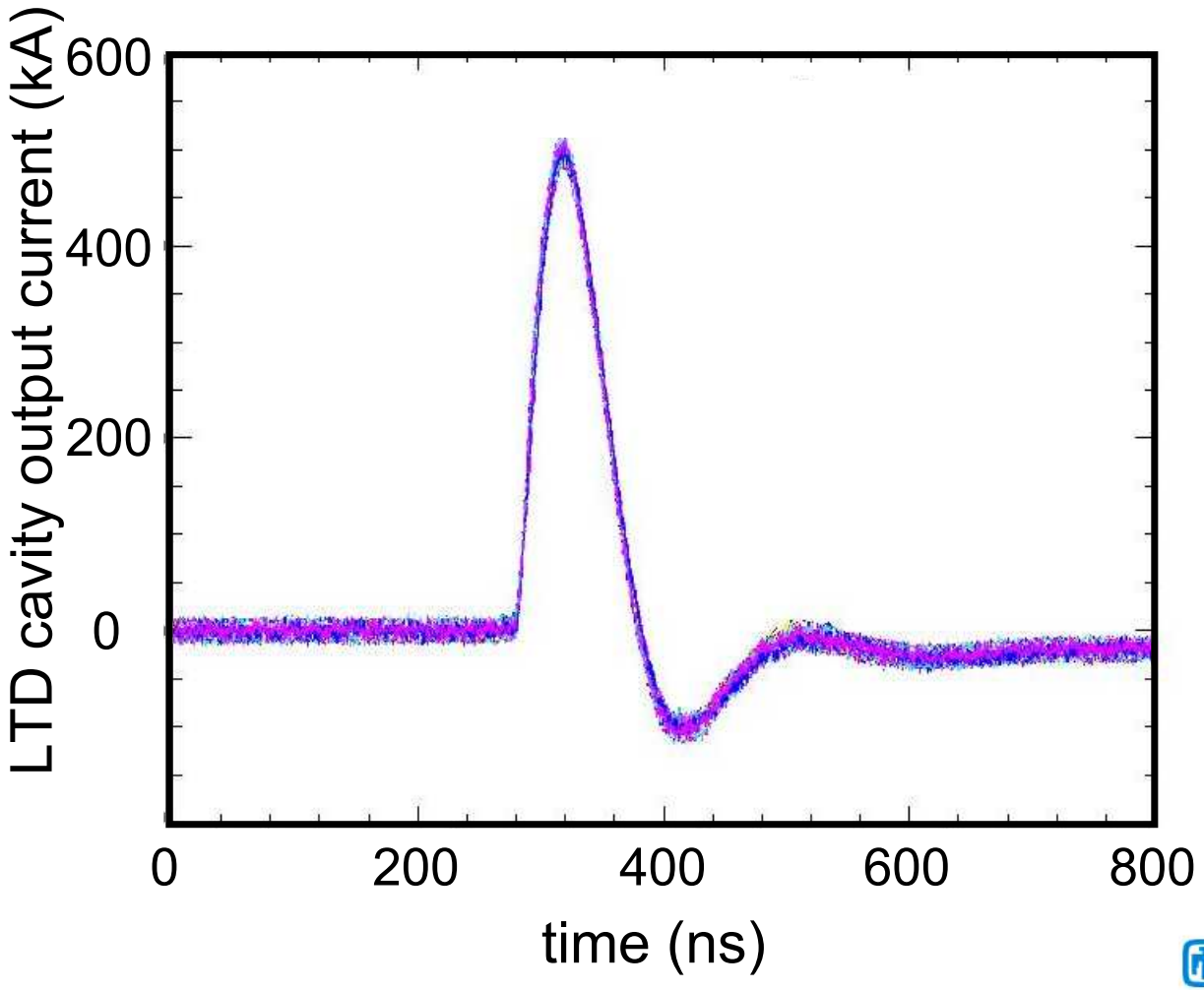
The LTD I exceeded 13,000 shots at 85-kV in a rep-rated mode at 0.034 to 0.097 Hz.

- Cavity performance very reproducible.
- Output wave forms follow very closely code simulations.



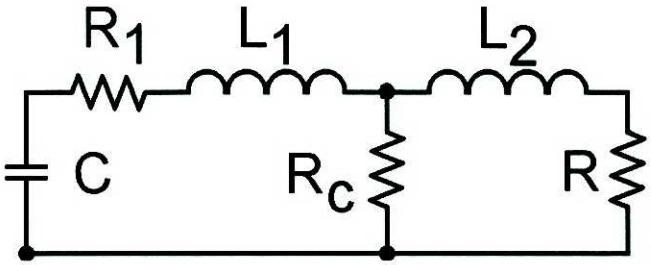
Data confirm that LTD's are very reliable.

Overlay of 200 consecutive Shots

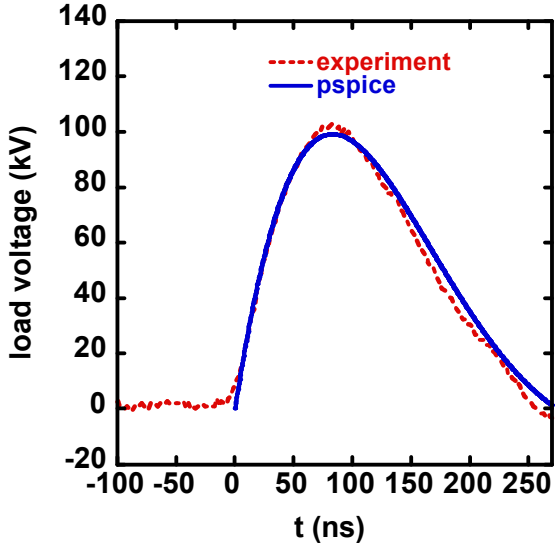


We have fired 10,000 shots with the second LTD II cavity in rep-rated mode and at +/-100 kV charging.

- We fired 200,000 switch shots with no pre-fires.
- Results are in good agreement with simulations (utilized a more realistic circuit).



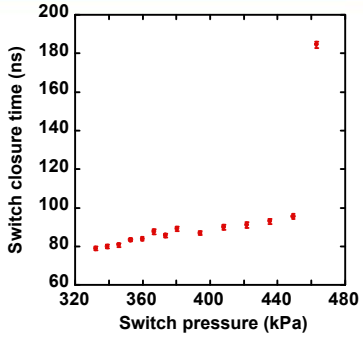
C = 400nF
R_1 = 0.033Ω
L_1 = 12nF
R_C = 1.3 Ω
R = 0.2 Ω

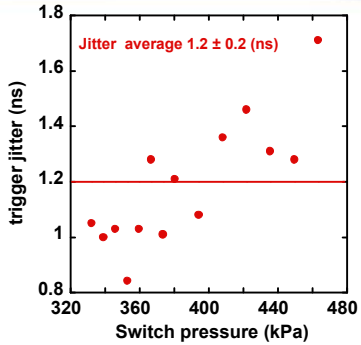


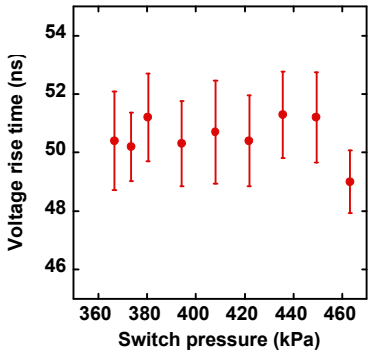
M. G. Mazarakis, W. E. Fowler, S. T. Rogowski, and R. A. Sharpe (to be published).
A. A. Kim and colleagues (to be published).

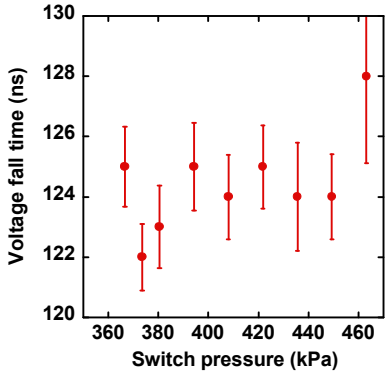
We have fired 10,000 shots with the second LTD II. We met all our preset goals.

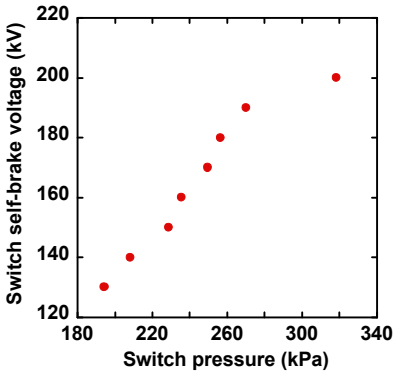
1. Switch closure time: 80-100ns
2. Switch closure jitter: 1.2ns ± 0.2ns
3. Pulse rise time: 55.5 ± 1.5ns
4. Pulse fall time: 124± 1.4ns
5. FWHM: 132 ± 2.5
6. Pulse amplitude: 98.08± 0.02kV
7. No pre-fires at 350-460 kPa
8. Self-brake curve

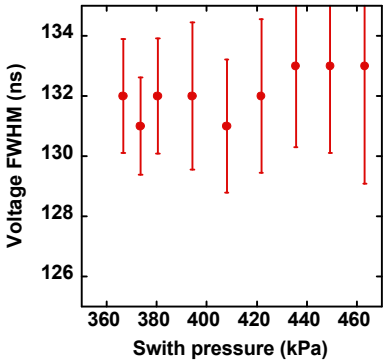


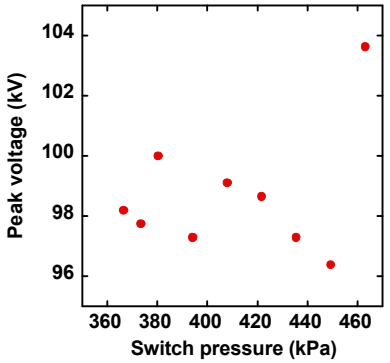












M. G. Mazarakis, W. E. Fowler, at al.,

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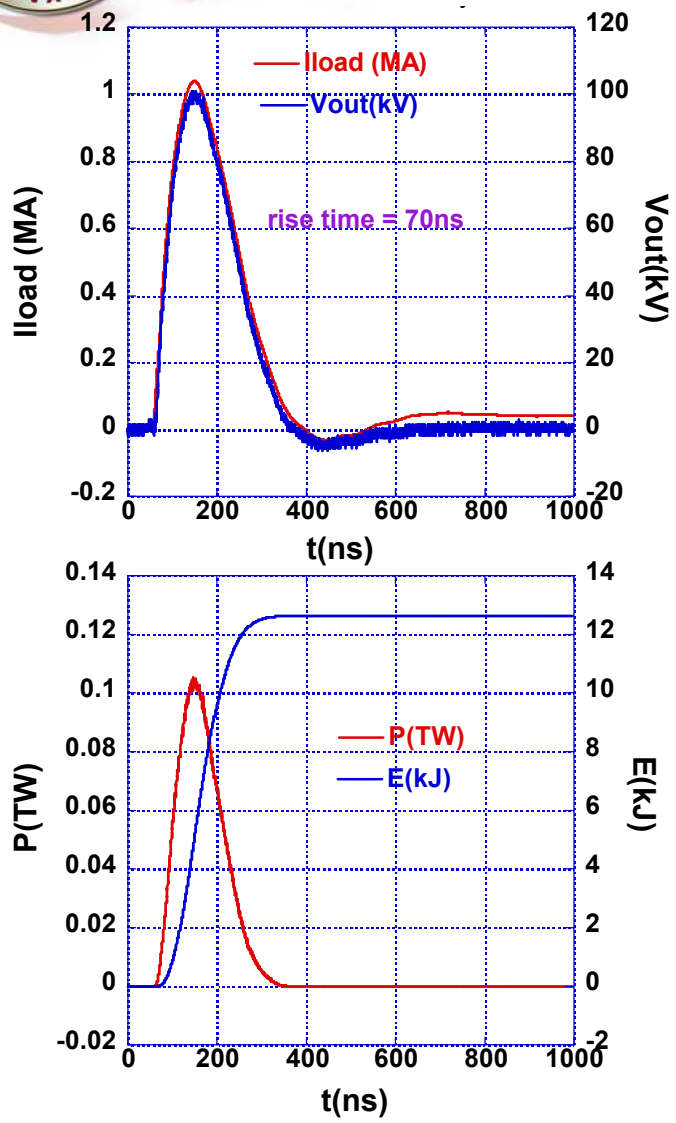
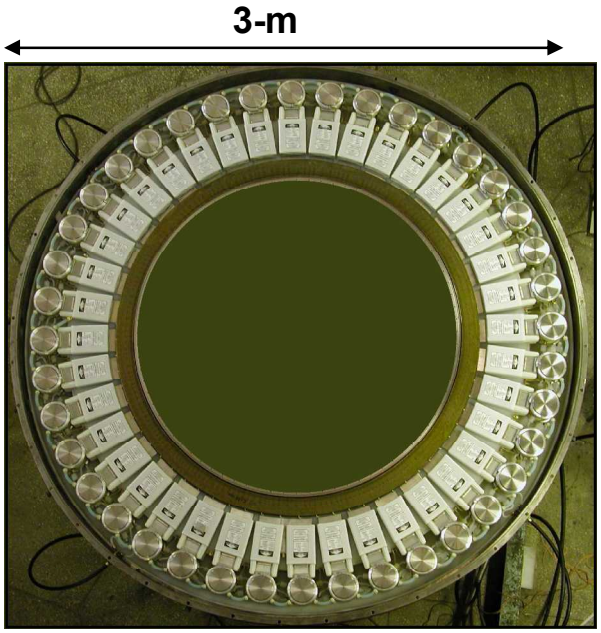
The 1-MA, 100-GW, LTD cavity performed as predicted by simulations and analytical calculations.





1-MA, 100-GW, 70ns LTD cavity
(top flange removed)

80, 40-nF caps ,

40 switches, ±100 kV

0.1 Ohm load **0.1TW**

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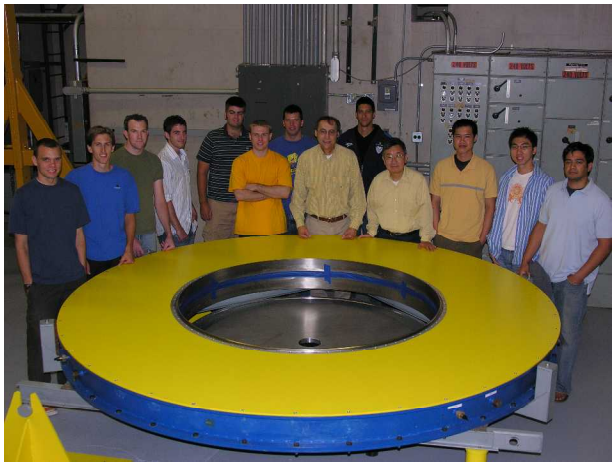
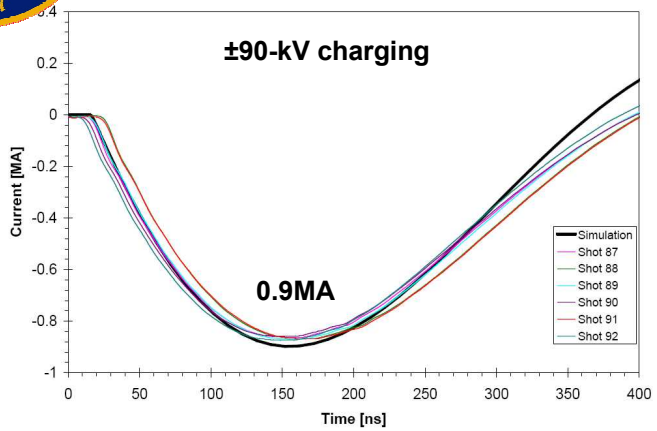
A 1-MA LTD-Z cavity is currently in operation at Michigan University testing MITLs, convolutes, and Z-pinch loads.

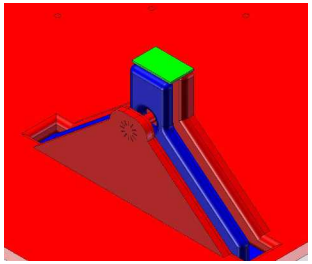
Please see also papers IO4D-3, and IP2D-42

MAIZE Laboratory team and 1-MA LTD-Z cavity.

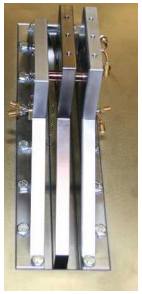




Resistive load in Vacuum chamber Filled with SF_6



Convolute design



Convolute hardware installed

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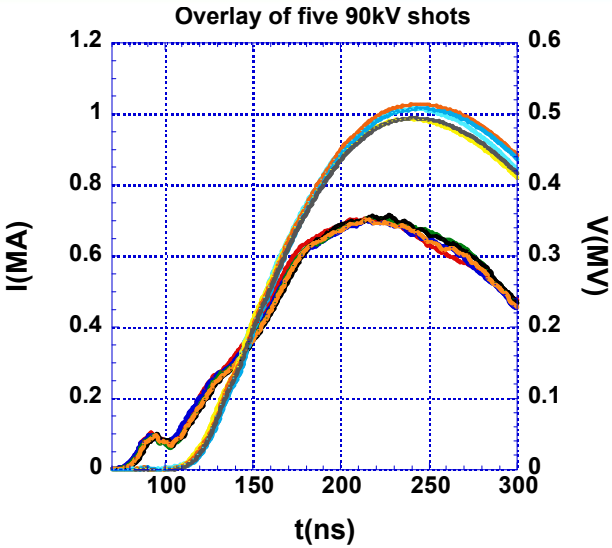
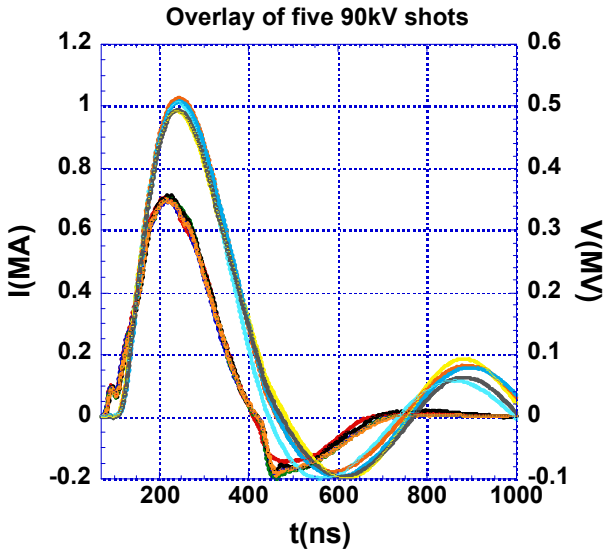
We have conducted 5-cavity LTD module experiments jointly with the HCEI in Tomsk, Russia.





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We are developing improved LTD components.

- **Develop a low-inductance low-resistance basic LTD circuit (brick).**
  - **Develop reliable lower inductance gas switches.**
  - **Encapsulate two capacitors and one switch in one solid unit.**
  - **Develop low inductance semicircular capacitor housing enclosing more than one capacitor.**
  - **Investigate alternate LTD cavity structures.**
  - **Design advanced low leak current ferromagnetic cores.**
- **Develop high energy density capacitors.**
- **Develop compact, lower cost, optically controlled triggering system. (S. F. Glover)**

Boris Kovalchuk →
open air 1-MALTD-Z

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We have developed alternative lower inductance and resistance switches.

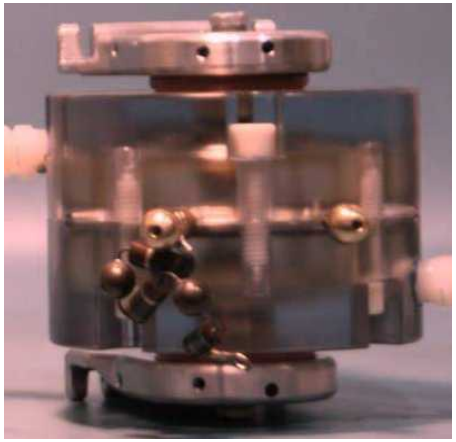
Inductance Matters

Accelerators built with low inductance resistance
Bricks would need fewer 'bricks'. It will cost less.

HCEI switch inductance ~120nH

Both switches have ~ 80nH inductance

L3 switch



Kinetic, LLC

Joseph R. Woodworth *et al.*, to be published

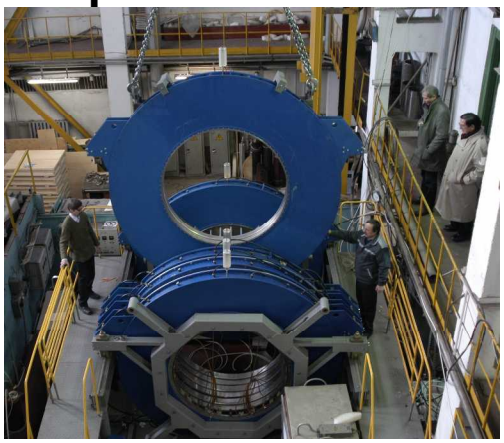
Summary of the High Current, Fast (100-ns), LTD experimental test results.

- Two-capacitor, one-switch circuit (brick) tests:
  - Fire 37,000 shots with no switch or cap failure at 0.03 Hz.
- 0.45-MA LTD I prototype cavity: Fire ~ 13,000 shots (= 260,000 switch firings) with no component failures. Measure jitter (2-ns), reproducibility (0.3%). electrical efficiency (70%) with no pre-fires, rep-rated operation close to 0.1 Hz.
- 0.5-MA LTD II cavity fired 10,000 times (= 260,000 switch firings) at ± 100kV charging. Similar as LTD I performance.
- 1-MA, 100-kV LTD stage individually tested met 0.1 TW output design specs.
- First tests of a five stage voltage adder with resistive and diode loads demonstrated successful energy, power addition and transmission to the load.
- Developed and tested to 5,000 shots two type of low inductance switches.

Future Plans.

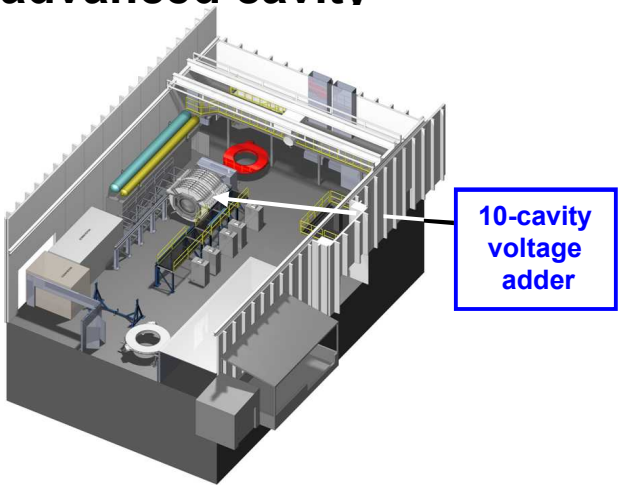
- Install and operate 10-LTD-Z cavity, 1-MA, 1-MV voltage adder in our new MYKONOS Laboratory. First ever voltage adder to be operated with water dielectric (no MITL,s).
  - Fire 10,000 shots (= 4,000,000 switch firing) at 2 shots/minute with resistive load.
  - Evaluate pulse shaping.
  - Evaluate intra cavity pulse shaping.
  - Evaluate feasibility for very high fluencies x-ray radiography.

- Utilize the LTD II (→LTD III) cavity as test bed for advanced cavity component evaluation.

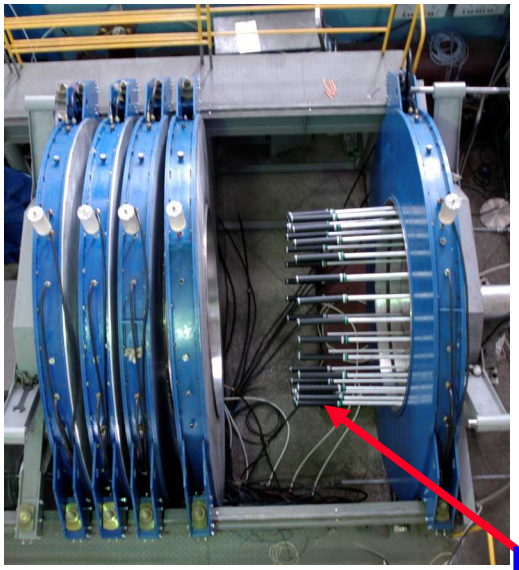


Tomsk
HCEI

Sandia
MYKONOS

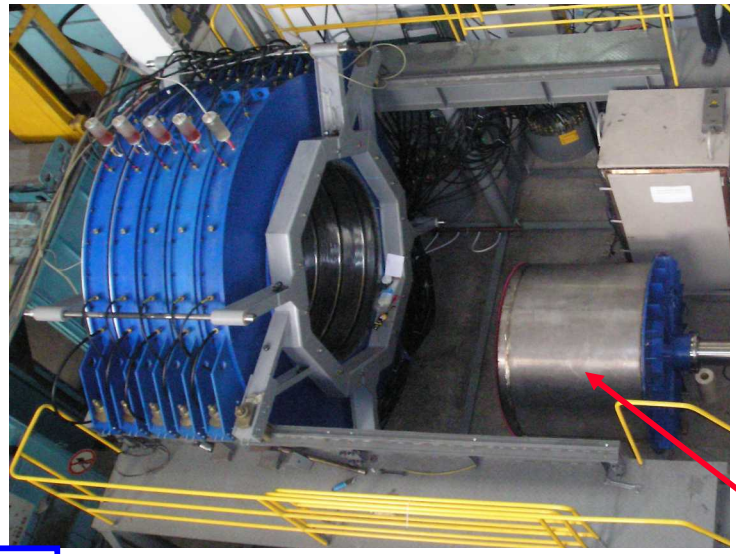


A five cavity 1-MA LTD module was built and tested with resistive and vacuum diode loads



resistors

Resistive load Experiments.



cathode electrode

Vacuum diode load experiments.