# Solid-State Modulator R&D at LLNL

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RPIA

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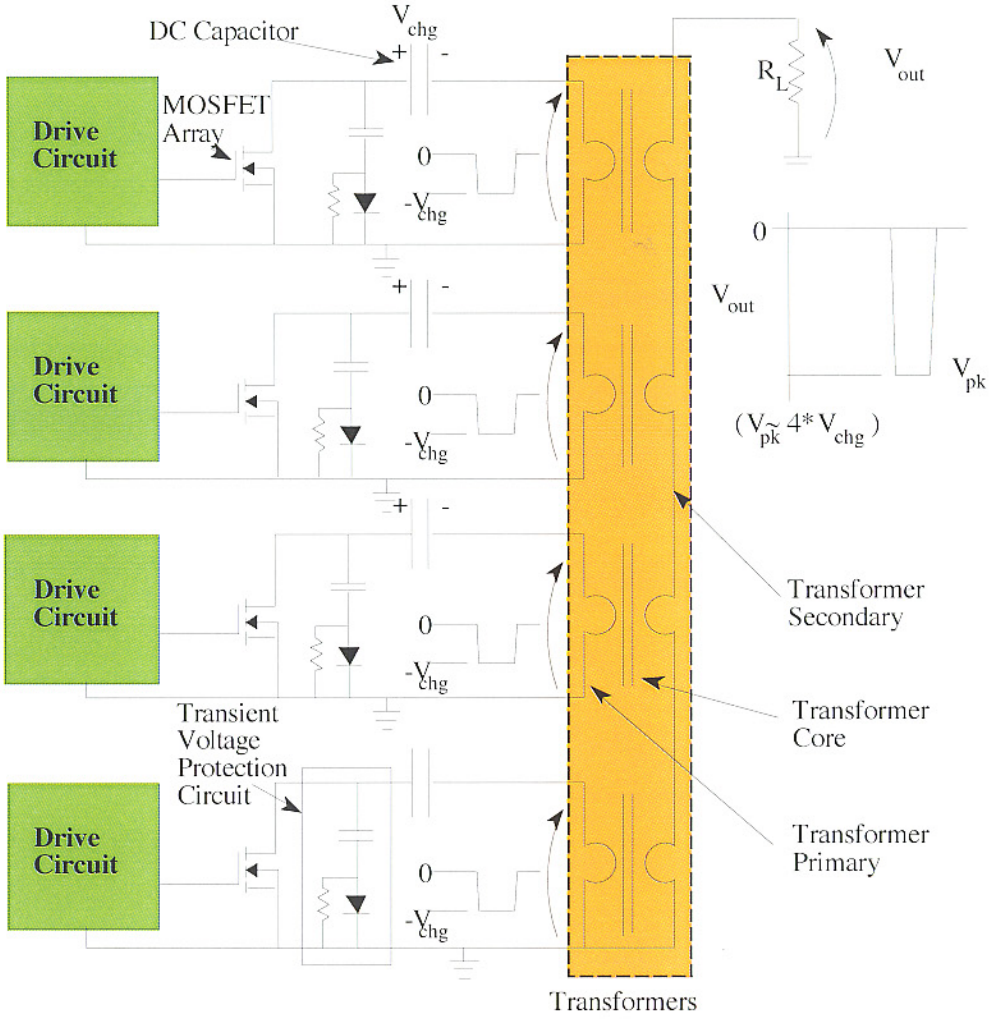
# Solid-State Pulsers

- Inductive Adder Pulsers
  - Circuit Topology
  - Advantages/Issues
- Fast Kicker Pulser for Linear Induction Accelerator
  - Pulser requirements
  - Test Data
- Fast Kicker Pulser for Proton Ring Accelerator
  - Pulser Requirements
  - Test Data
- Klystron Modulator NLC (Next Linear Collider)
  - Requirements
  - Test Data
- Summary

# Simplified Schematic of Inductive Adder



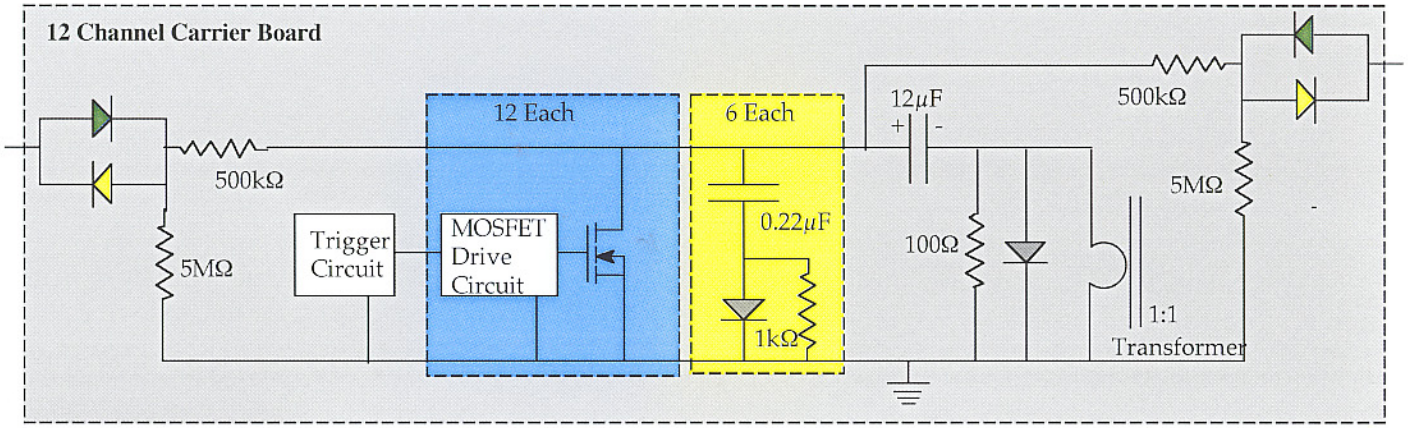
# Adder Circuit Topology

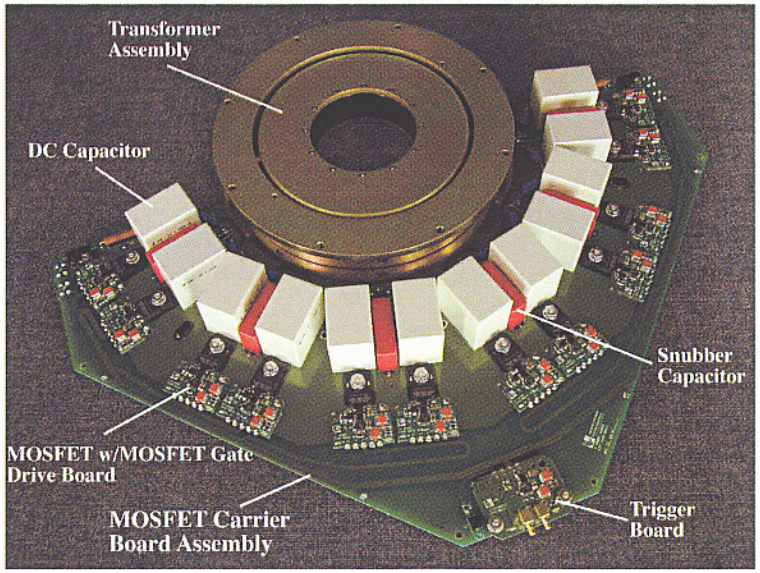
- Advantages
  - All drive components ground referenced
  - No high voltage grading required
  - Pulse format defined by programmable pulse generator
    - Pulse width agility
    - Burst frequency agility
    - High burst frequency >1 MHz
  - Modular - adder consists of stack of identical modules
    - All modules switch same voltage/current
    - All modules triggered simultaneously
    - Scaleable to higher voltages by adding modules

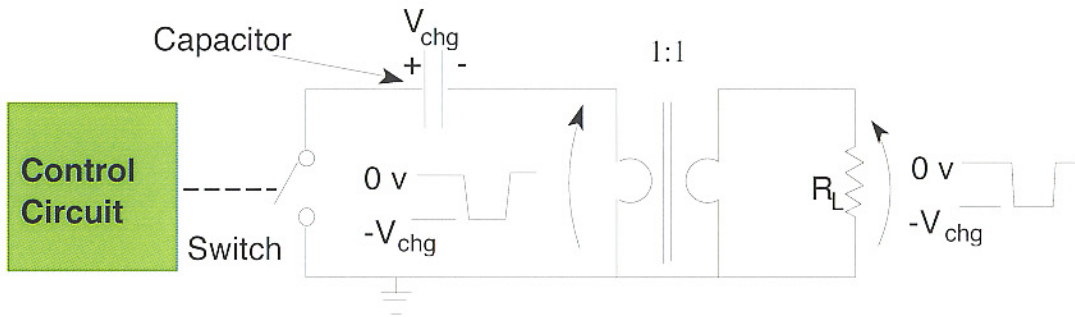
# Adder Circuit Topology

- Issues:
  - Each module handles full load current
    - May require many parallel components (solid-state devices, capacitors, etc.)
    - Parallel switching devices must have low jitter on both turn-on and turn-off
  - Requires very small loop inductance (capacitor, switch, and transformer)
  - Requires very fast opening switch that can interrupt full load current and survive fault currents
  - Fault currents can be very large (adder modules are very low impedance)
  - Cost

# Circuit Schematic -Adder Drive Bd.

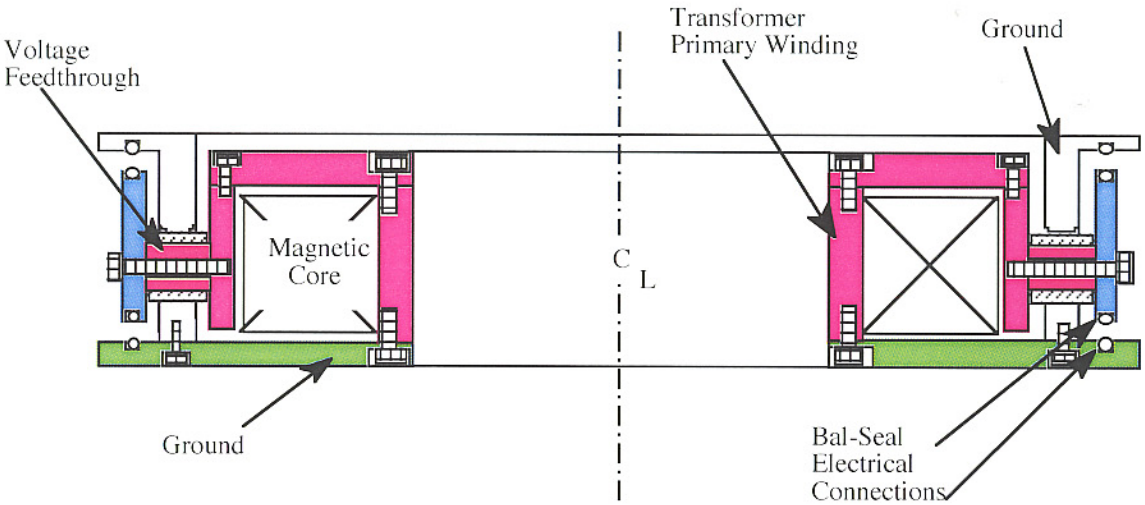


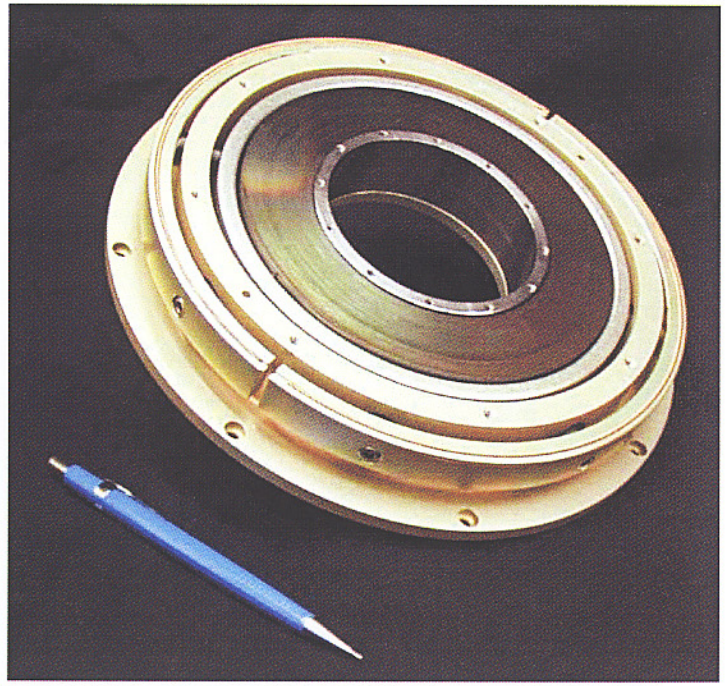



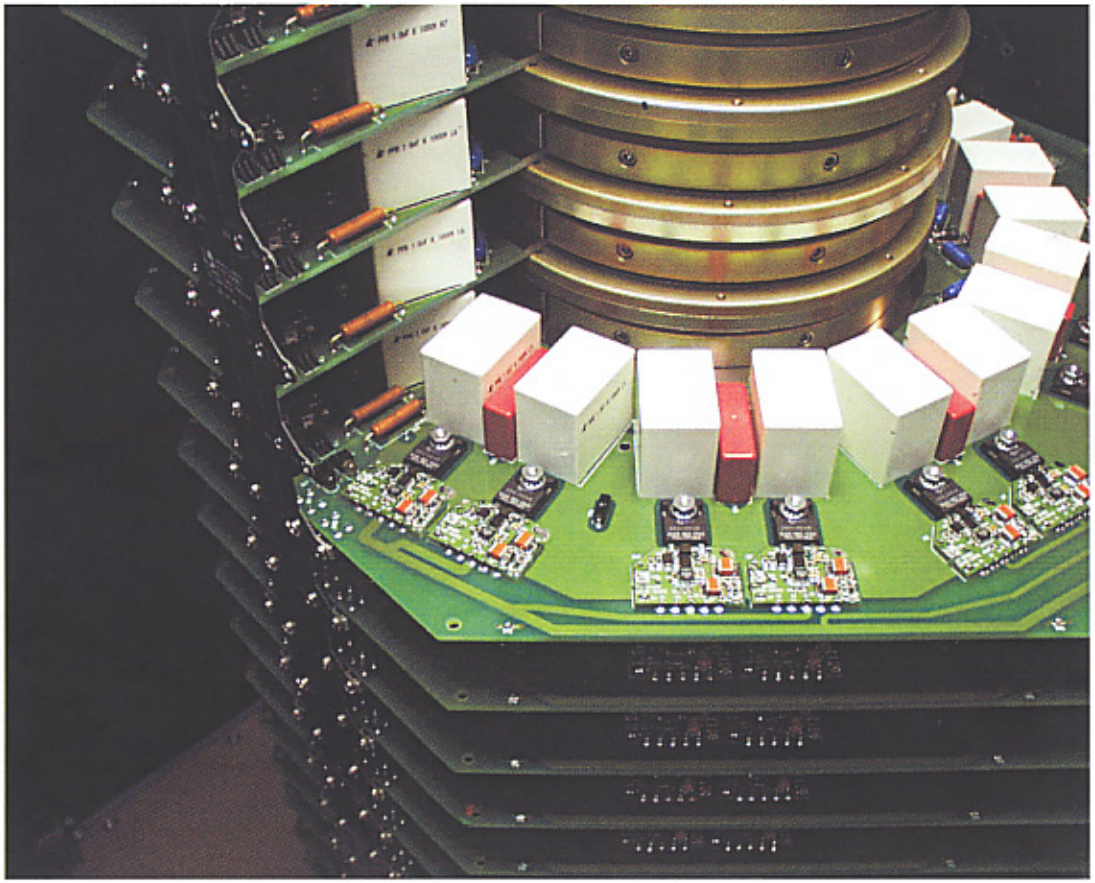

Simplified Adder Drive Ckt.

# Adder Cell Design



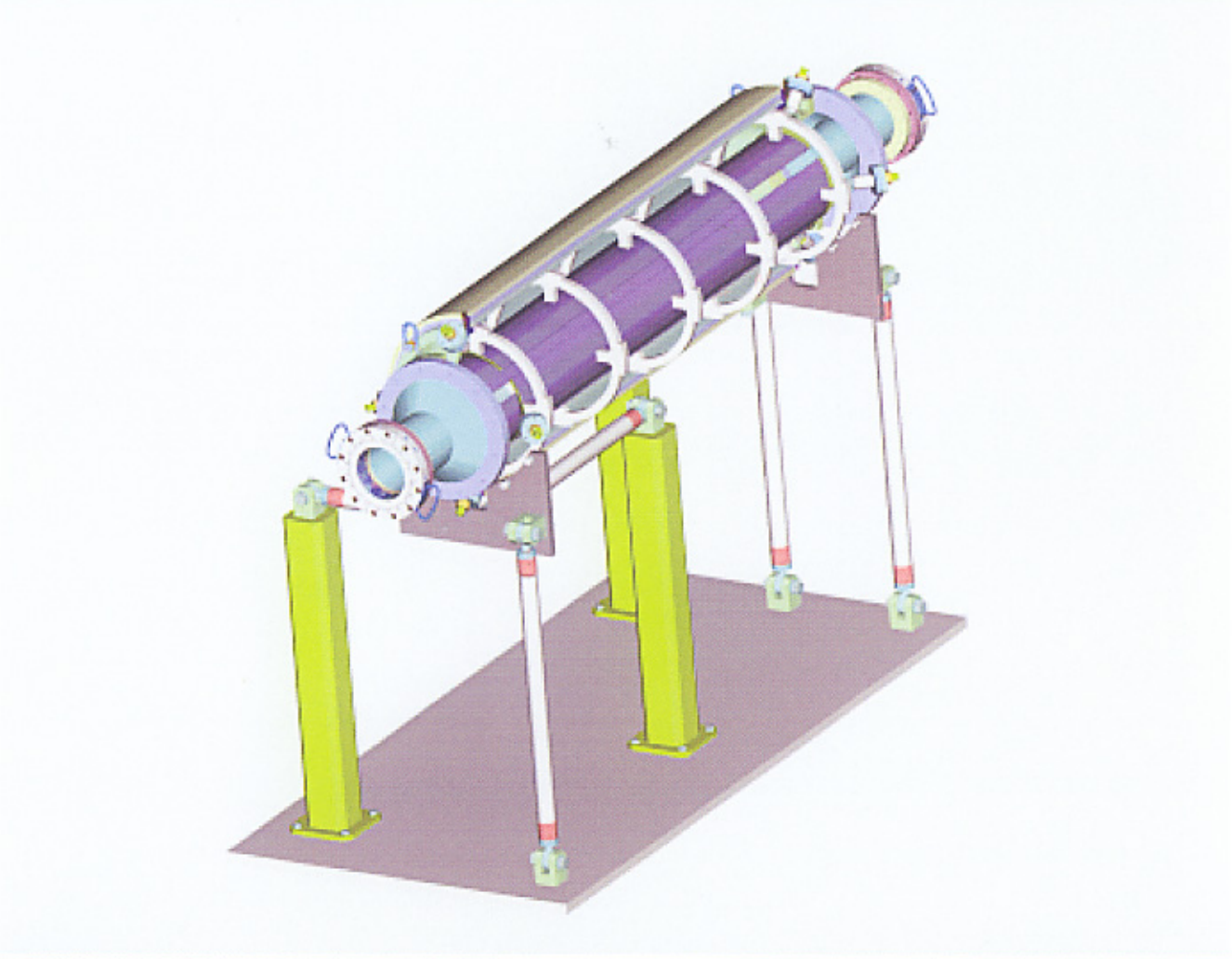
# Prototype Adder Assembly



# Fast Kicker to Chop Pulses out of 20 MeV, 2kA, 2μs Electron Beam from Linear Induction Accelerator

- Fast kickers installed in accelerator beam line feature parallel-plate, stripline geometry
- Fast kickers use the magnetic field and electric field created by fast high-voltage pulses of opposite polarity to steer the beam
- Kicker chops short pulses out of a 2kA electron beam of 2μs duration

# Fast Dipole Kicker - LLNL Stripline Kicker

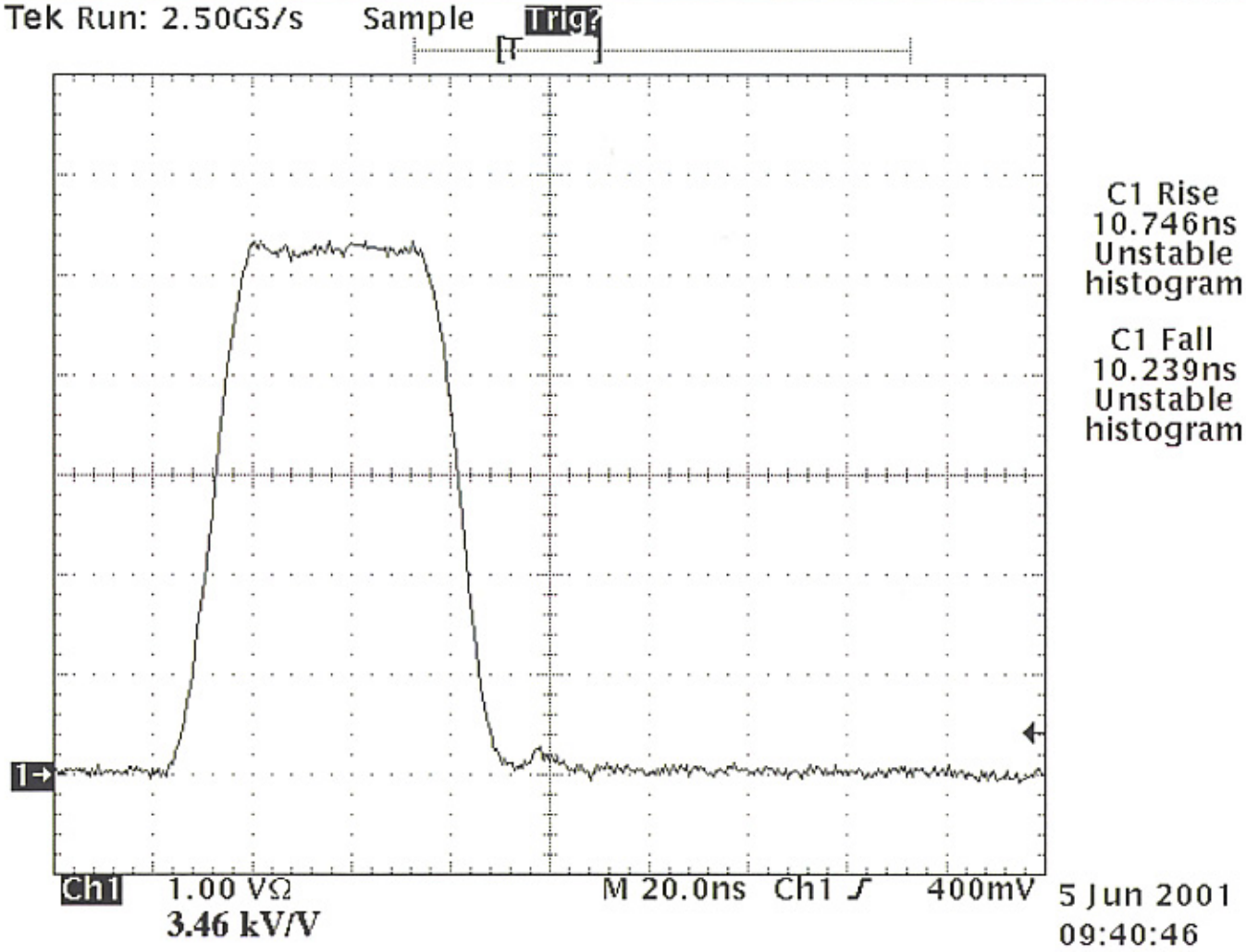


# Kicker Pulser Requirements

- ±18kV ± 10% into 50 ohms
- 10ns rise and fall times
- 16 – 200ns wide pulses during burst: externally adjustable
- Multi-pulse burst
- Total pulse width of 500ns per burst
- Minimum intra-pulse spacing of 400ns

# ±18kV Pulsers for Fast Dipole Kicker

# Output Pulse - 30 ns, 18 kV into 50Ω



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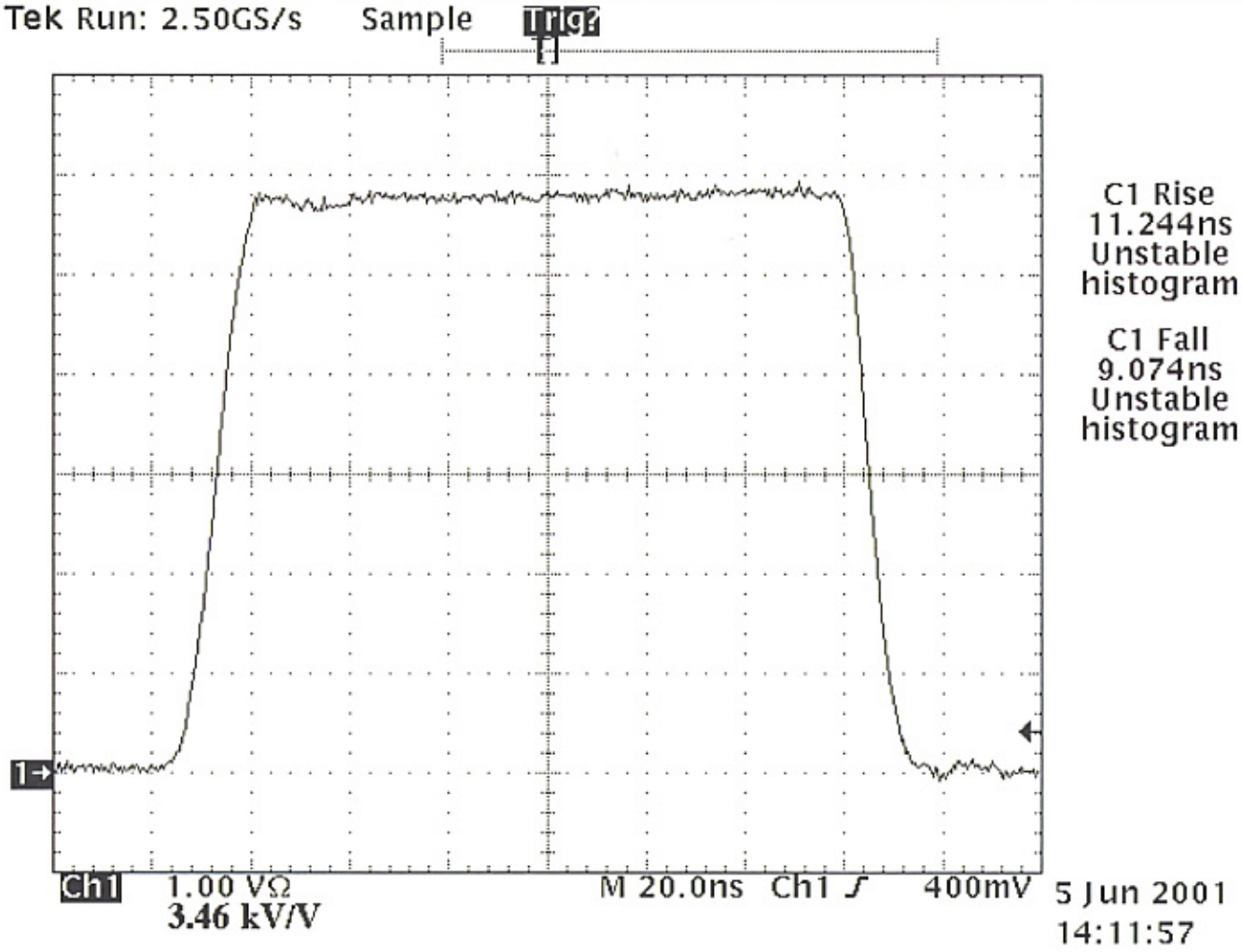
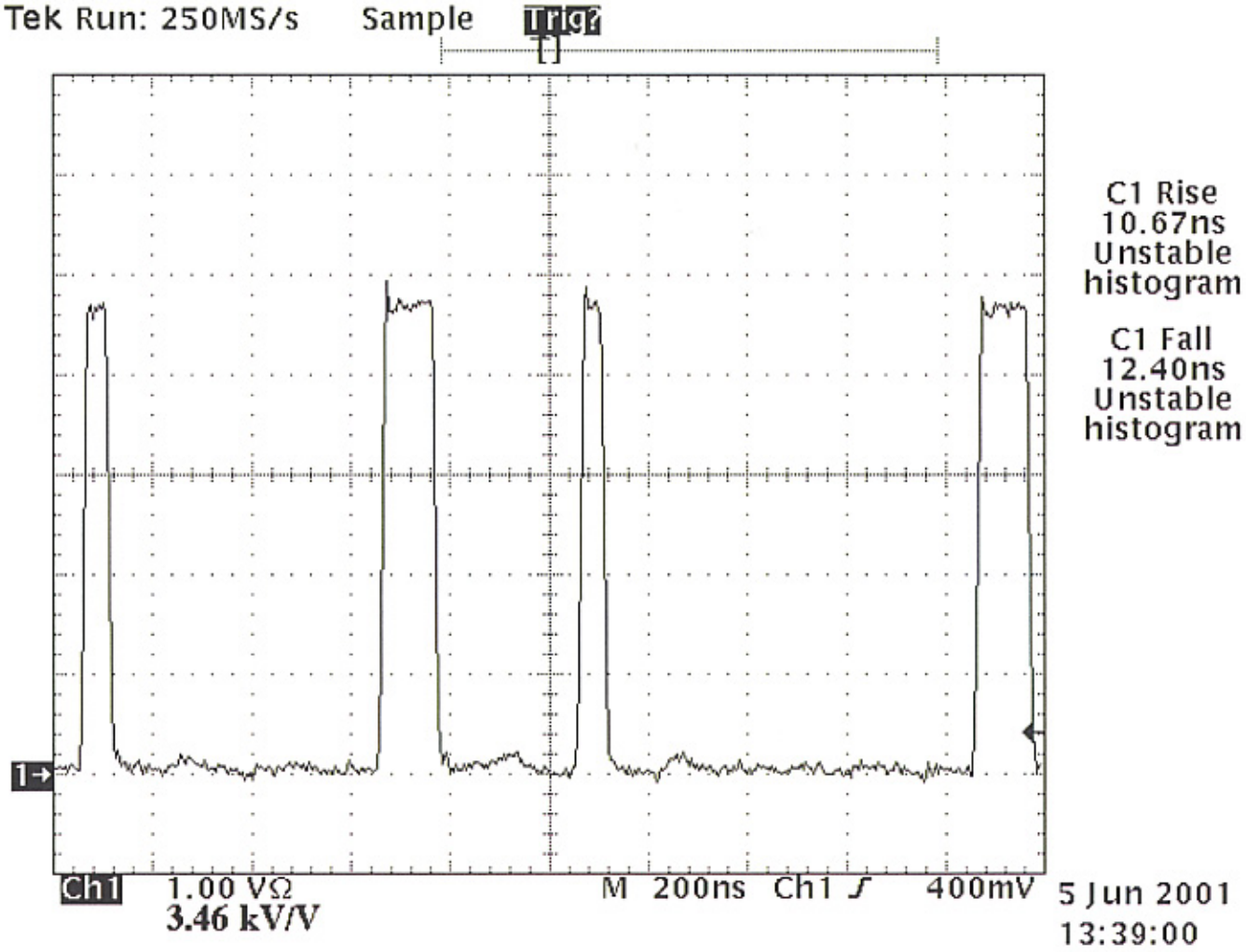
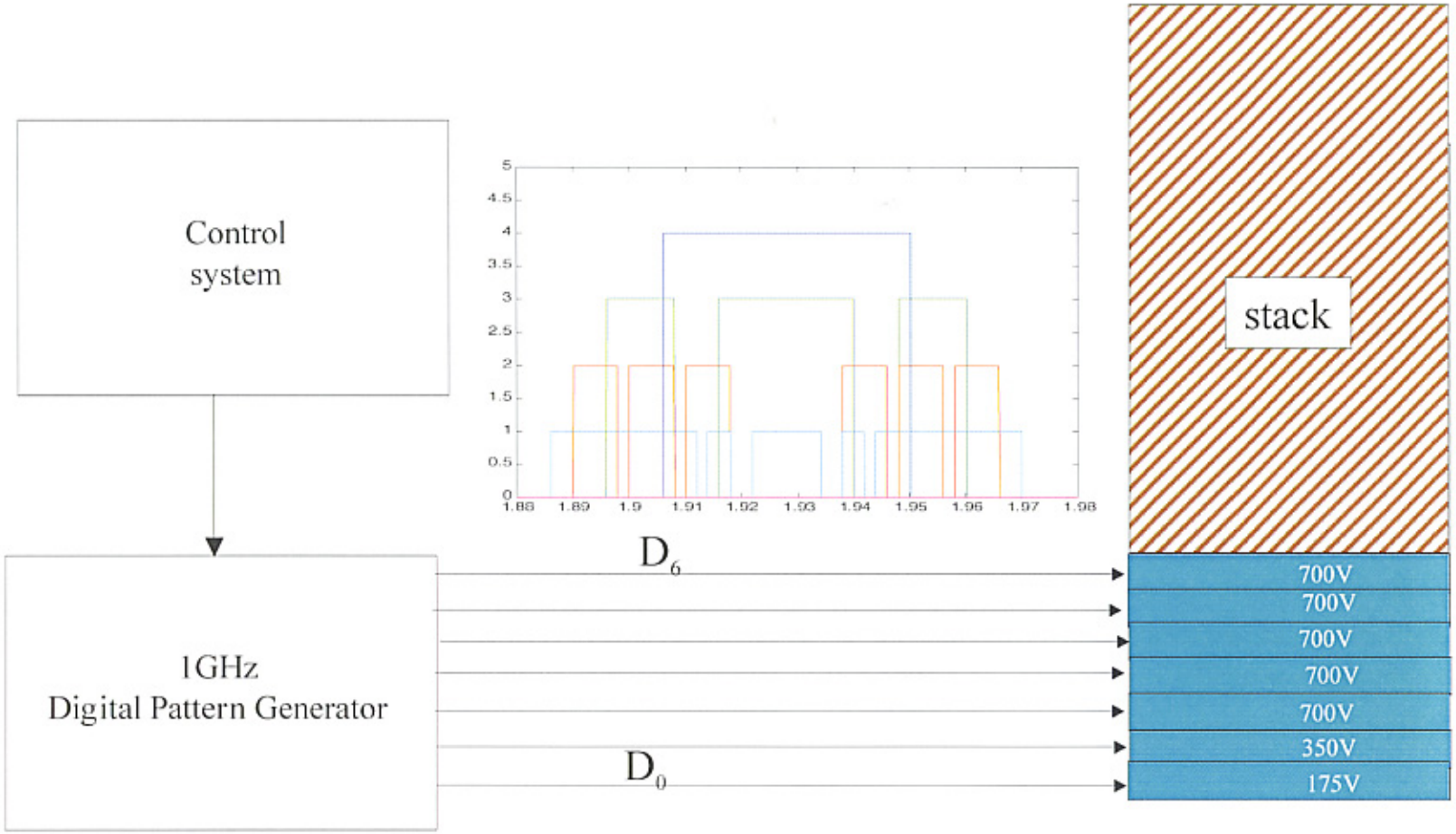
# Output Pulse - 120 ns, 20kV into 50Ω



# 4 Pulse Burst - Variable Pulse Width, Variable Burst Frequency

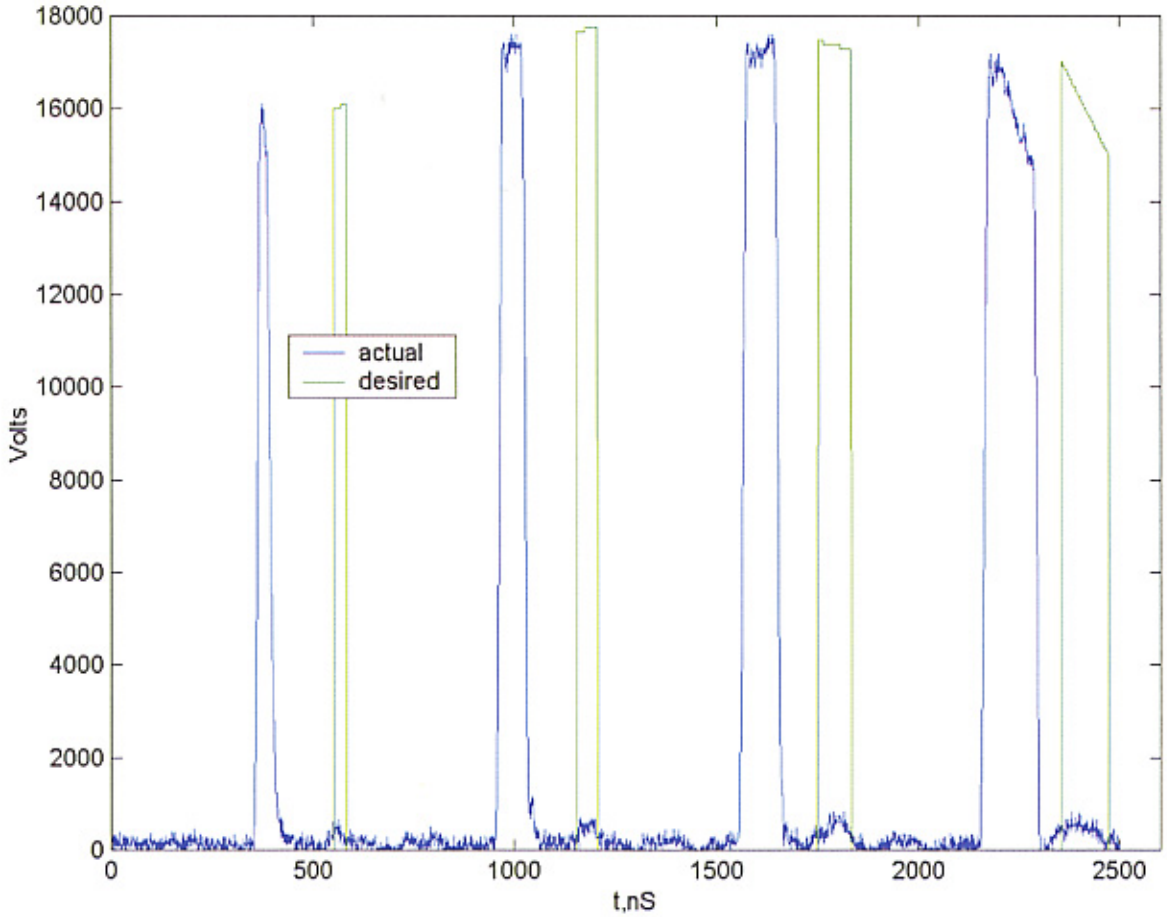


# Digital Modulation



# Modulated Multi-Pulse Burst

Four-Pulse Burst with Amplitude Modulation




# Fast Extraction Kicker for Proton Ring Accelerator

- 50 GeV proton accelerator
- 24 proton bunches supported in ring
- Proton bunches have center-to-center spacing of ~ 200ns
- Ring revolution time ~ 5μs
- Full exploitation of accelerator capabilities requires an asynchronous extraction kicker system

# Extraction Kicker Modulator Requirements

- 50 kV into 50 Ω* (two pulsers required to achieve ±50kV)
- 24 pulse asynchronous burst w/max. 5 MHz burst frequency
- Minimum pulse flattop - 73 ns*
- Maximum allowable risetime/falltime - < 64 ns (0-100%)*
- Pulse flatness < ± 1.0% for each pulse* and entire burst
- Intra-pulse voltage ripple - < 300V within 300ns of pulse falling edge*

- *To be demonstrated in prototype pulser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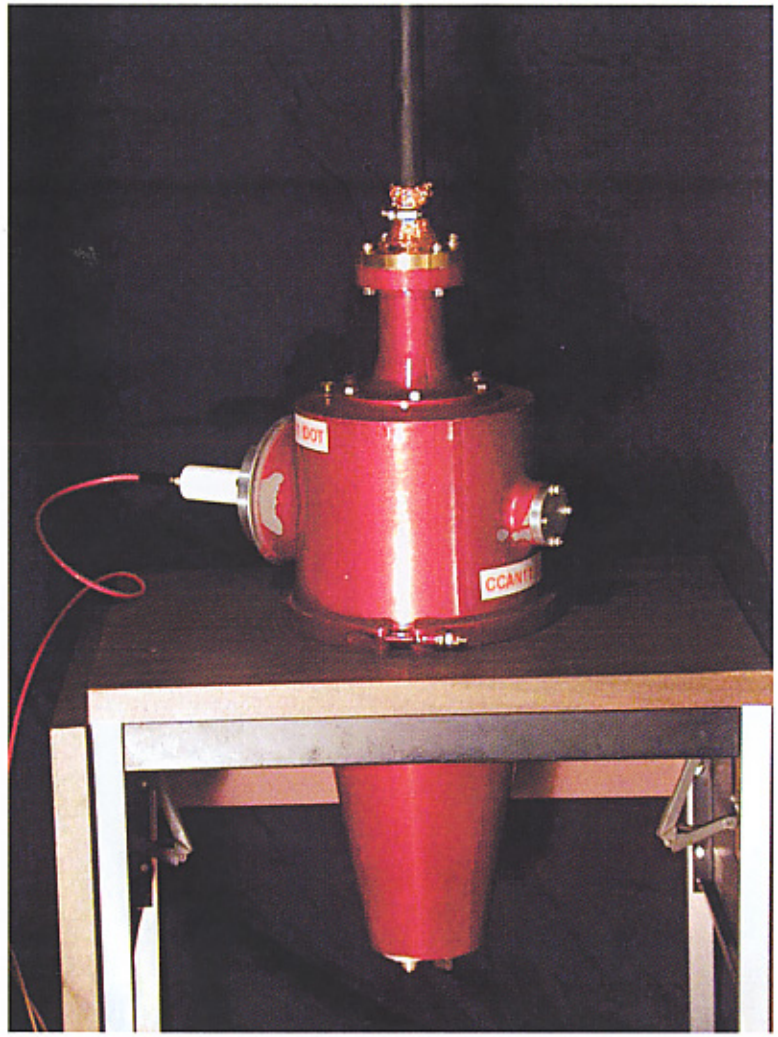
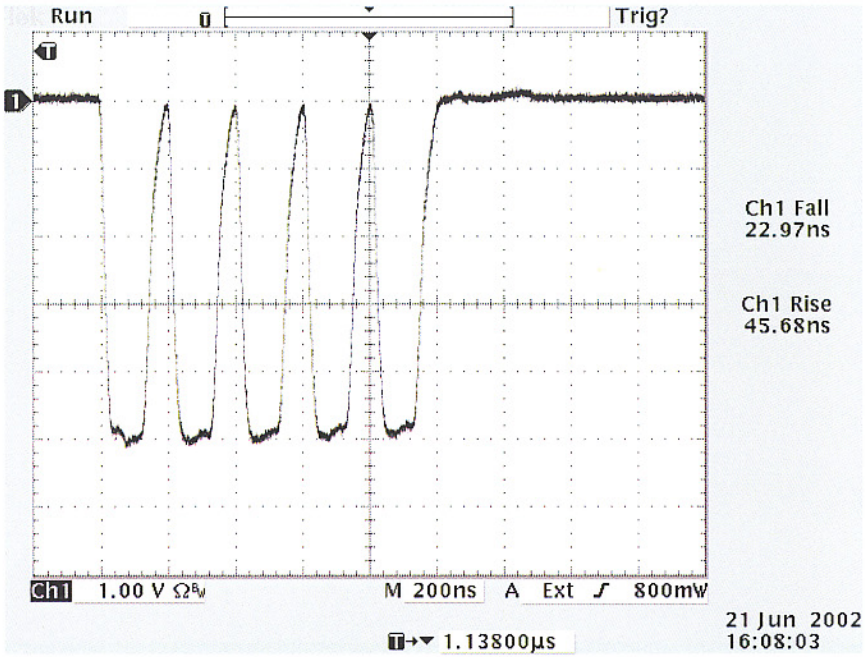
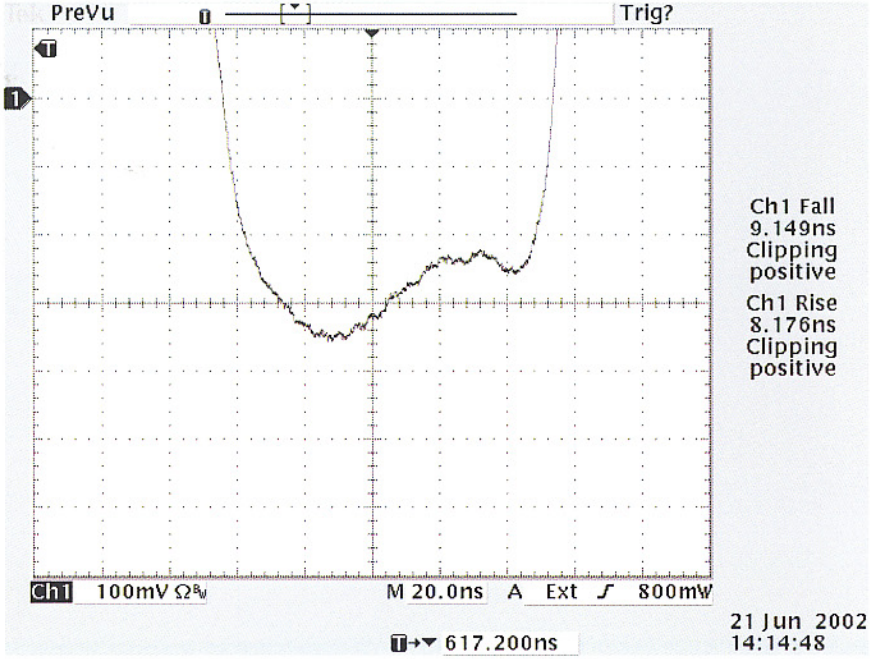
# Prototype 50kV Adder Stack Assembly and Dummy Load



# 50 kV, 5MHz Burst without Reset

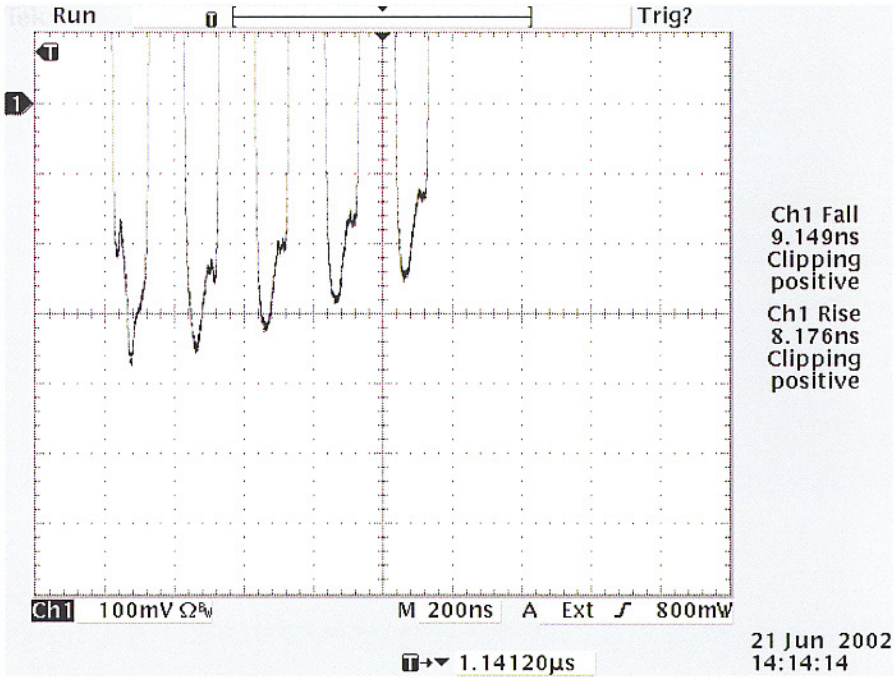



5-Pulse, 5MHz Burst @ 10 kV/div

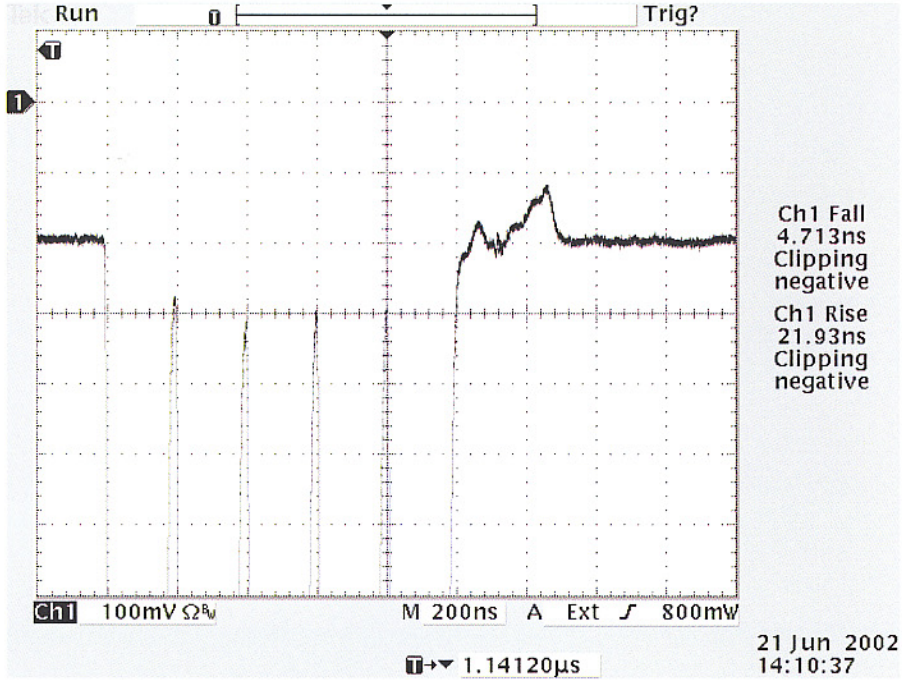



2nd Pulse of 5MHz Burst @ 1kV/div (2%/div)

# Voltage Flattop and Intra-Pulse Voltage: 50kV, 5MHz Burst



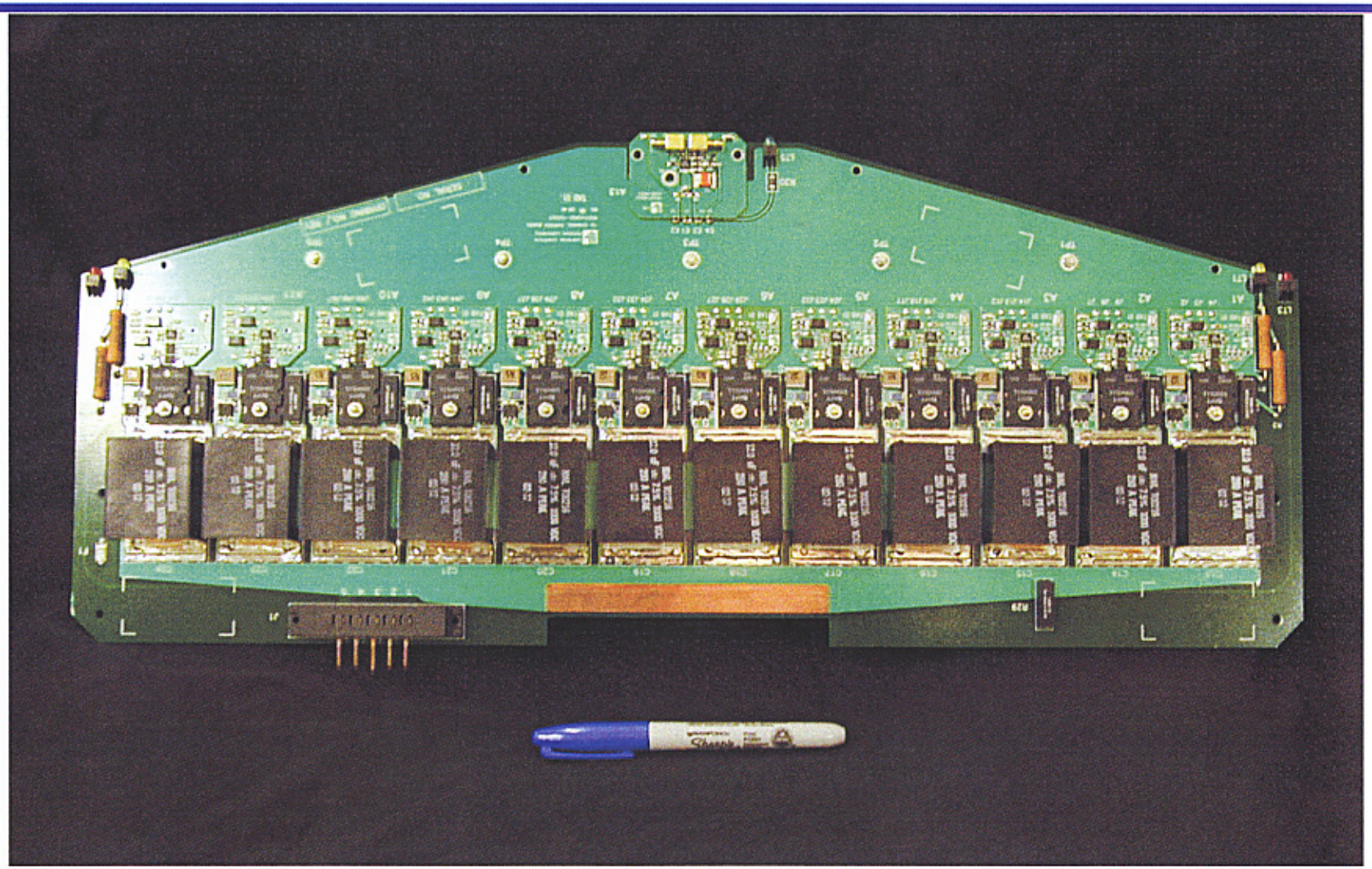

Voltage Flattop



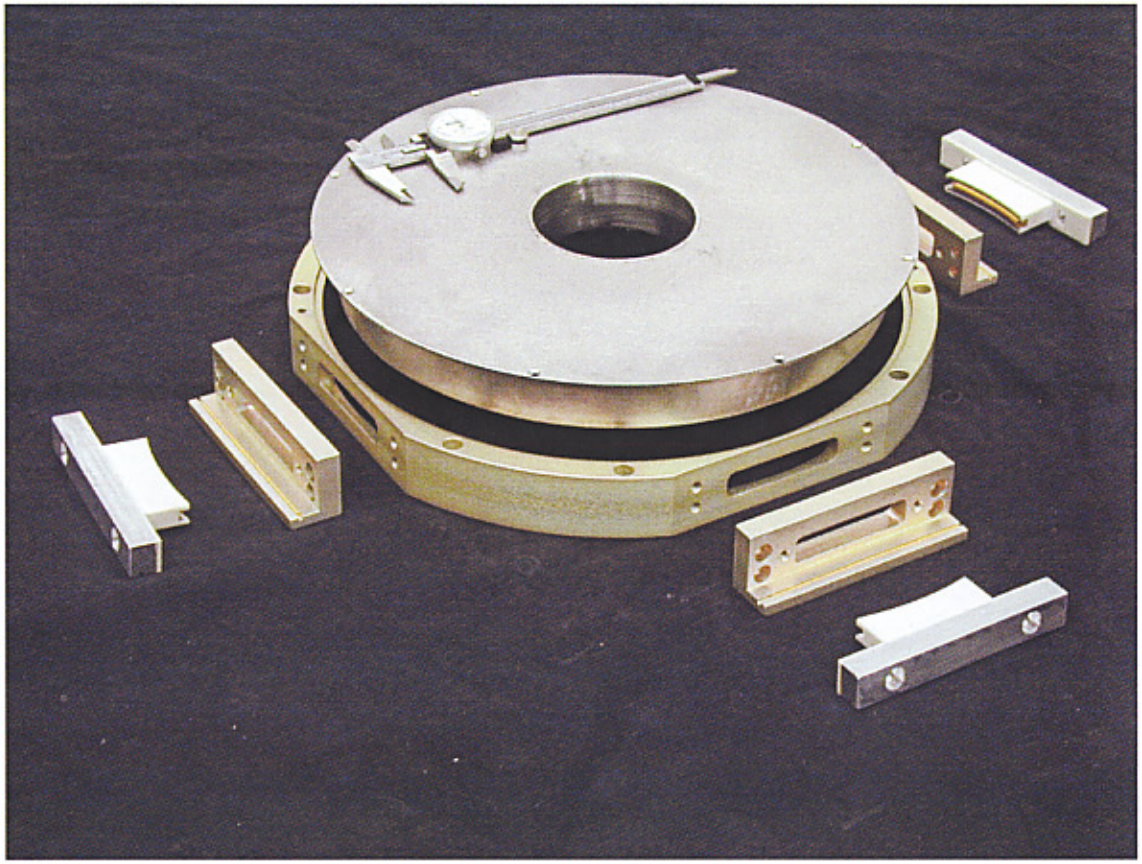

Intra-Pulse Voltage

## Load Voltage @ 1kV/div or 2% / div

# Adder Drive Board - High Capacitance Design

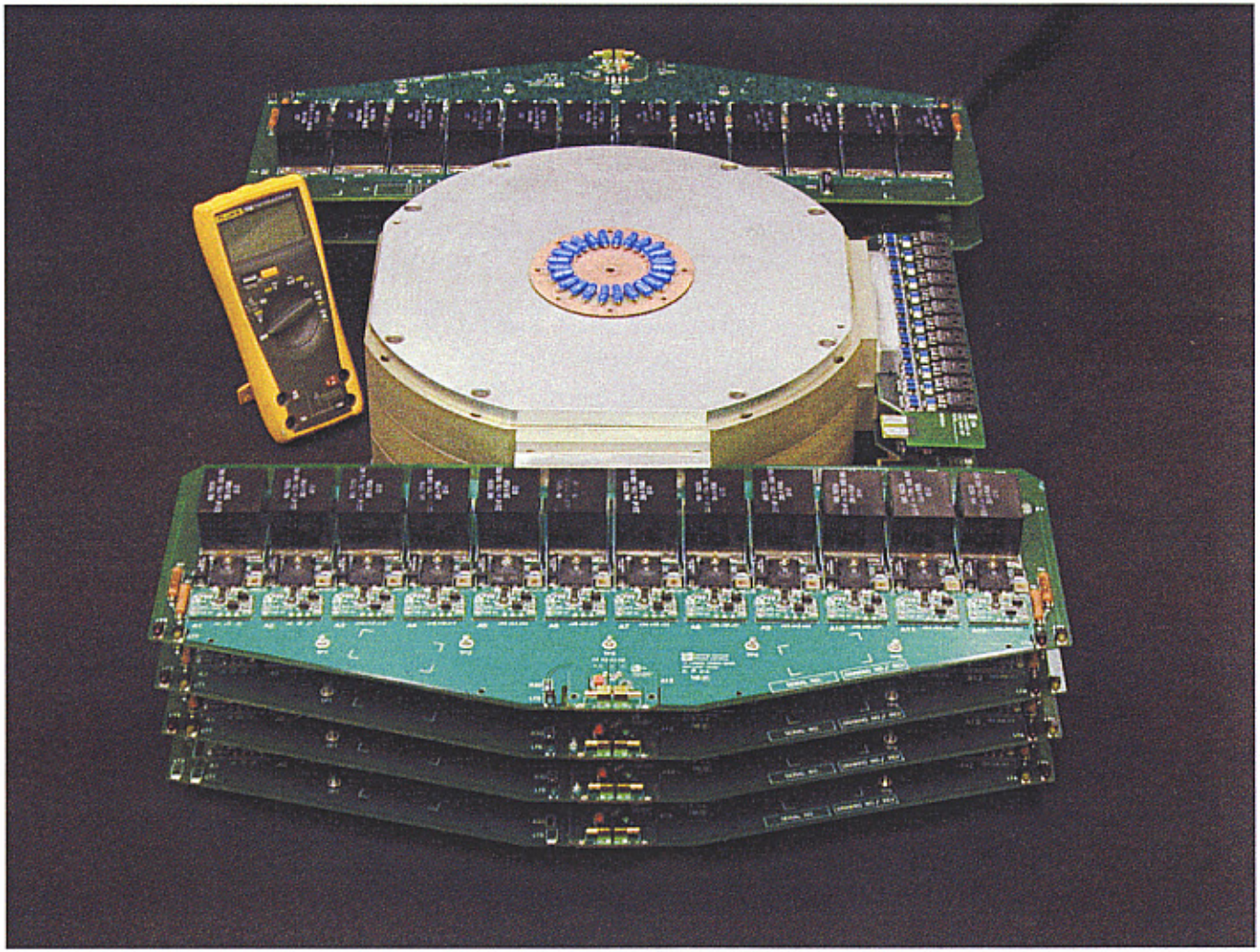


# Full Scale Adder Cell

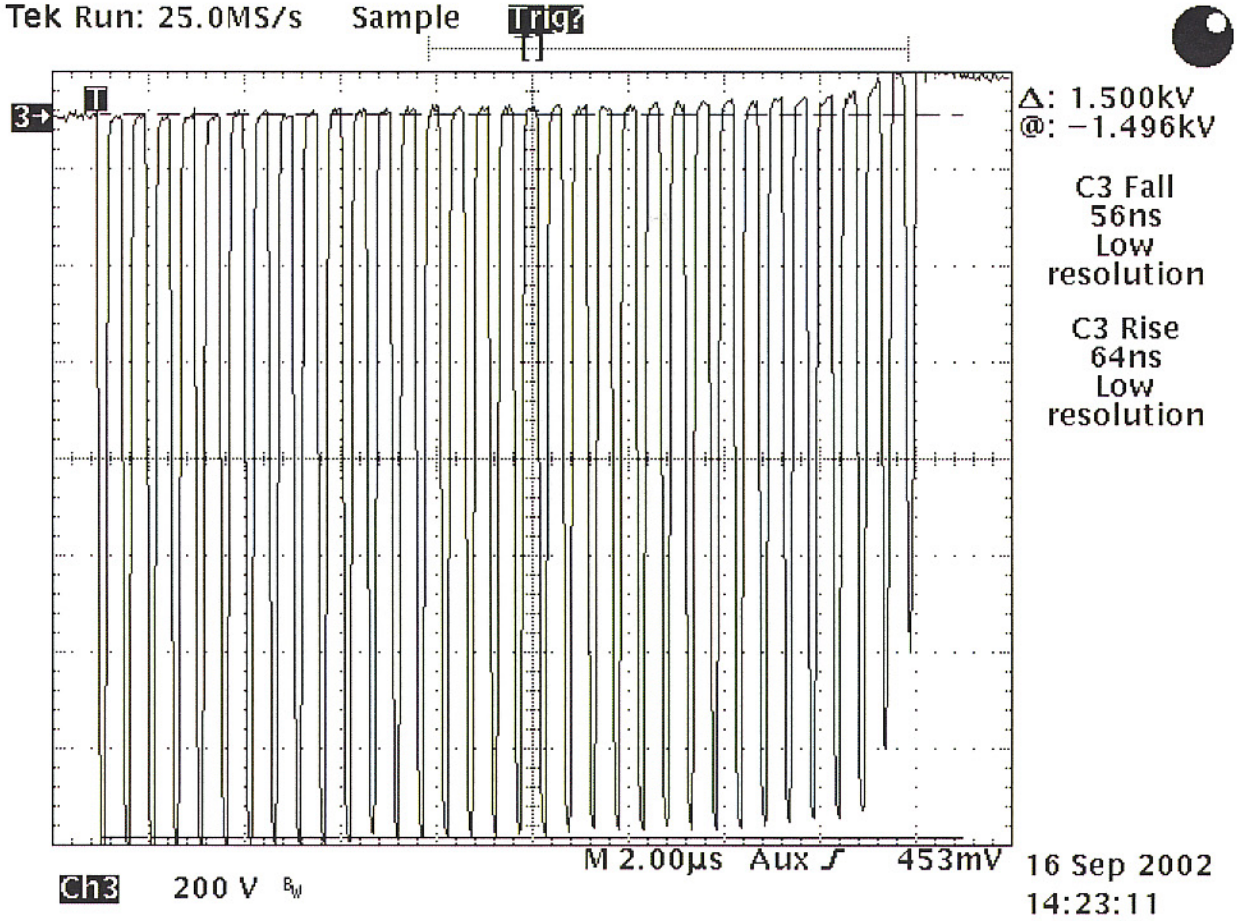


**Adder Cell Designed to Meet 24 Pulse Burst Requirement Shown with Feed-through Connectors**

# 4 Cell Adder Stack with Drive Boards

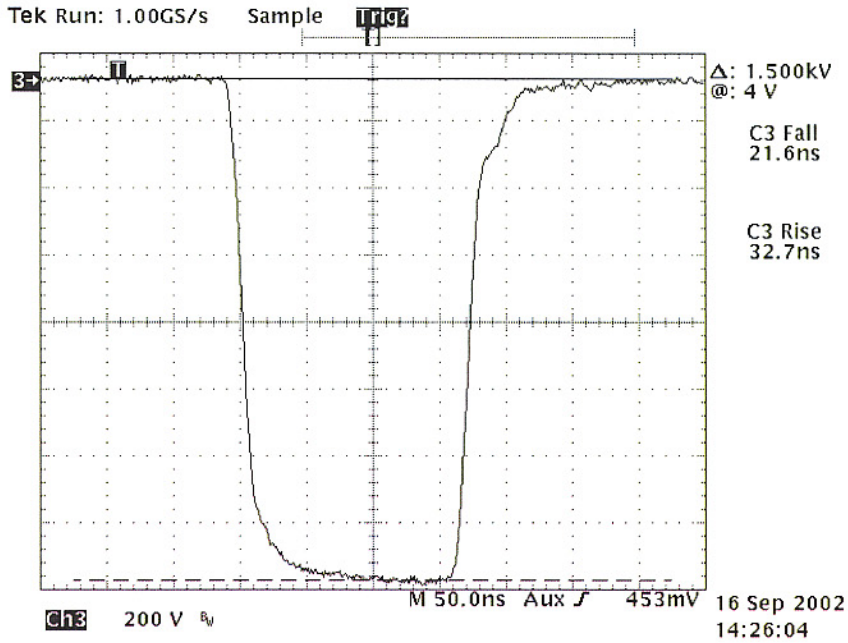


# Volt-second and Voltage Droop Measurements on Adder Modules - 750 Volts/Cell (2 Cells)

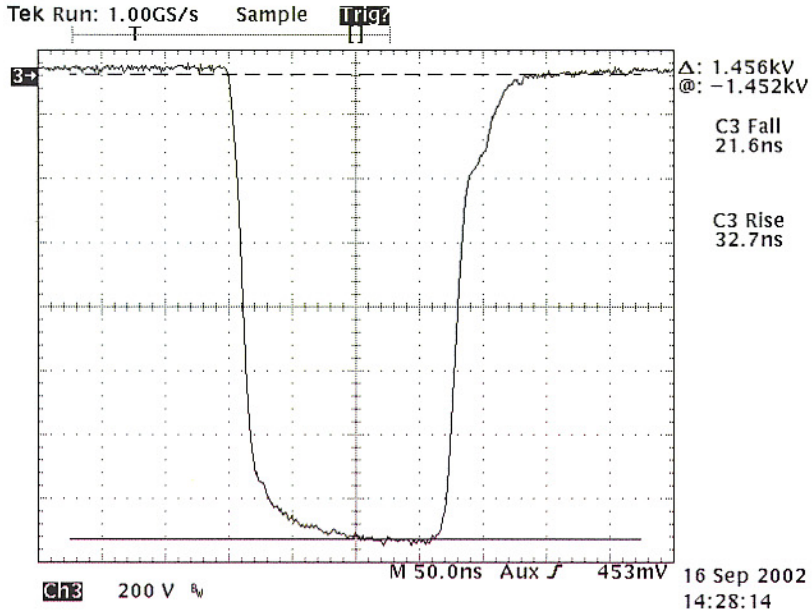



34 Pulse Burst - ~ 150 ns Pulse Width with Reset

# Voltage Droop Measurements on Adder Modules
# $V_{out}$ (2 cells) on 2.125 Ω Load - with Reset




1st Pulse of 34 Pulse Burst




20th Pulse of 34 Pulse Burst

**Voltage Droop ~ 44V/1516V = 2.9% over 20 Pulses.**

# NLC - Collaboration with SLAC for Klystron Modulator Development

- Modulator Requirements:
  - Output Voltage 500kV @ 2kA
  - Pulse-width - 3μs
  - Klystron Efficiency > 80% (rise & fall times less than 400 ns)
  - Repetition Rate - 120 Hz (500kW Average)
  - Lifetime - 30 years
  - Cost < 200k$/ Modulator

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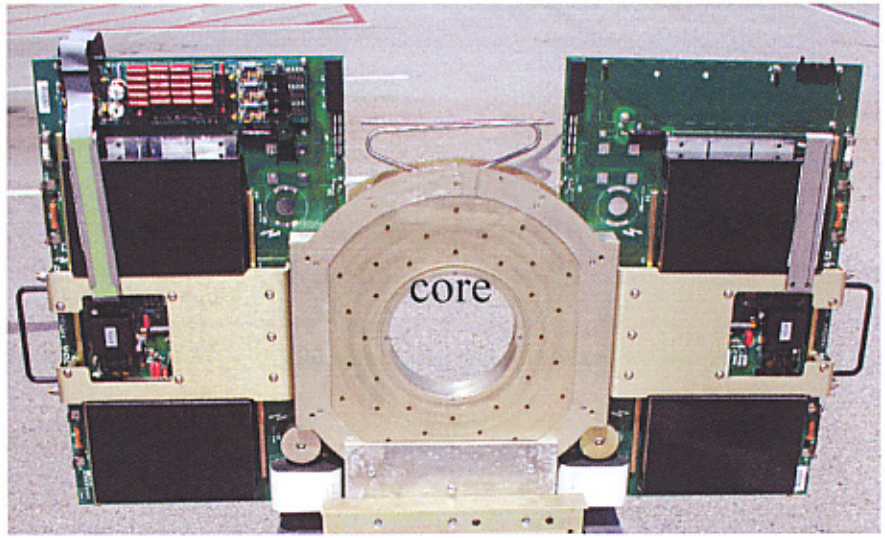
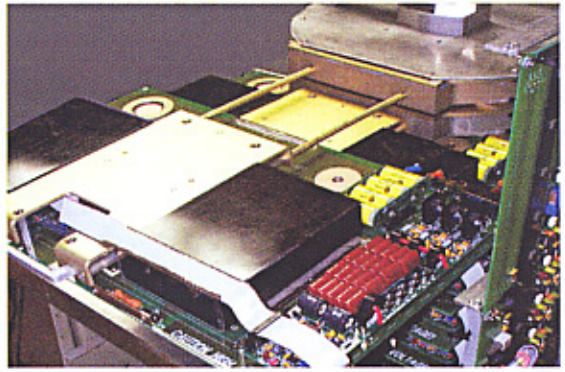
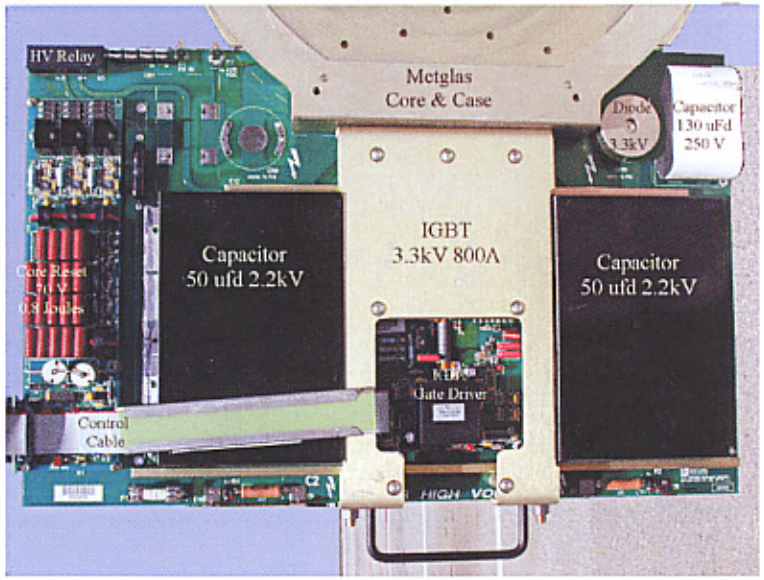
# IGBT Drivers and Core



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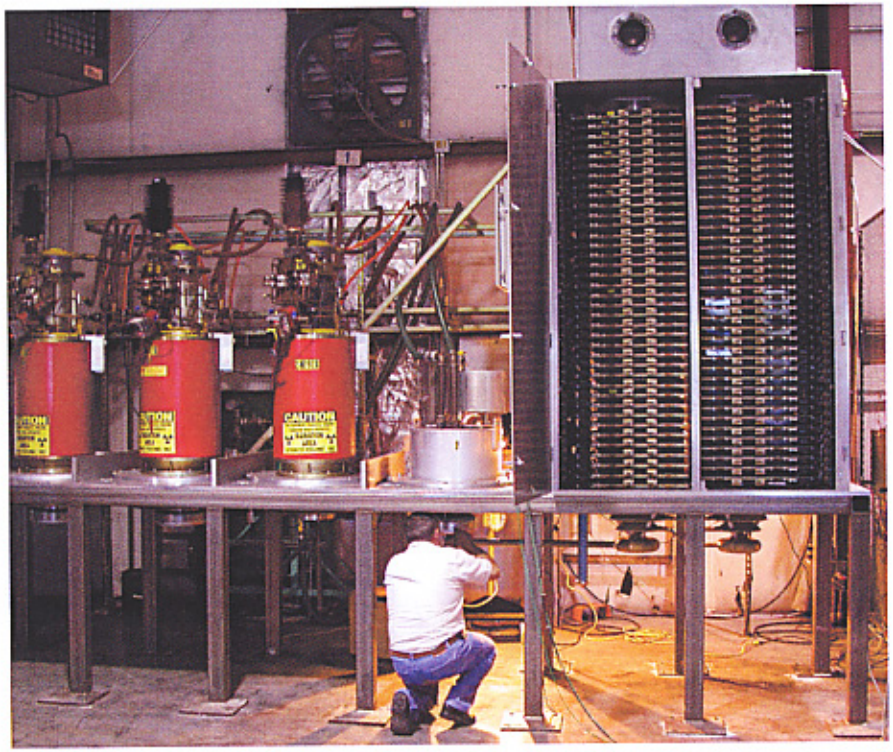
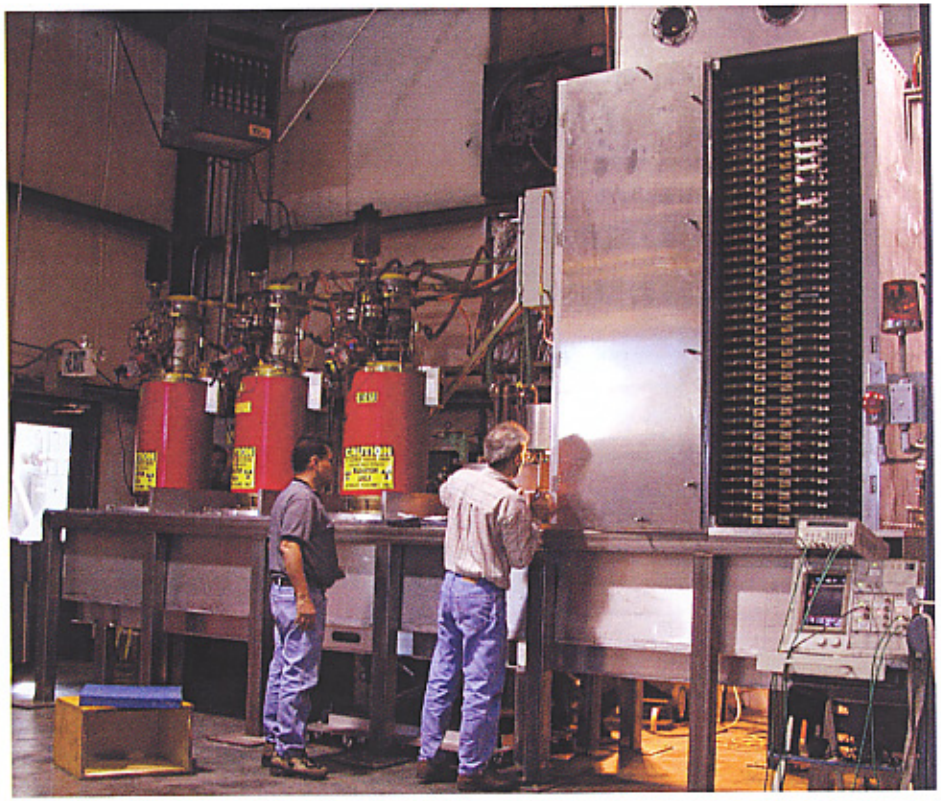
# Prototype Solid State Induction Modulator

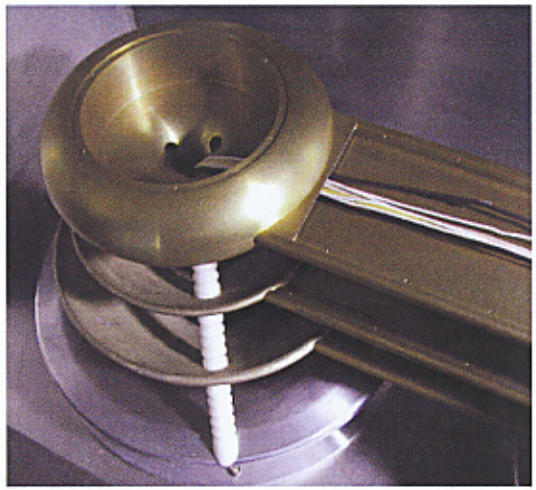


3 turn Secondary with water load

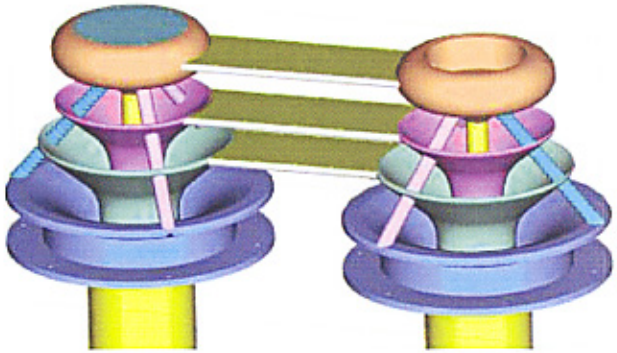


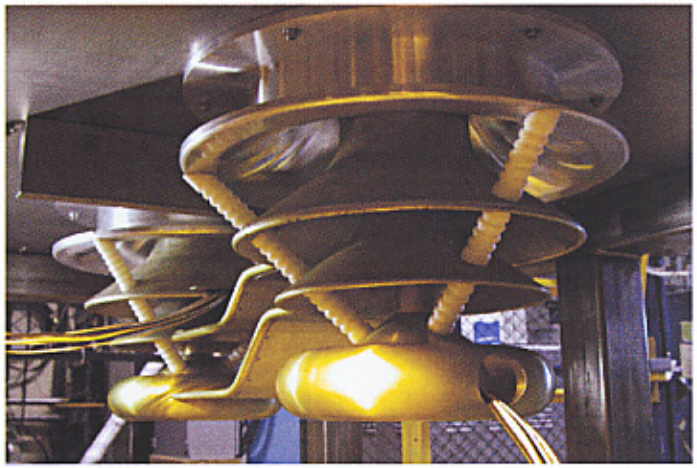
With oil tank installed

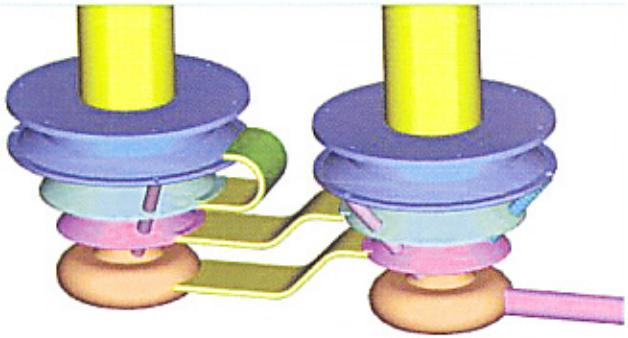
# Prototype Solid State Induction Modulator



- Coaxial Three Turn Secondary End Connection





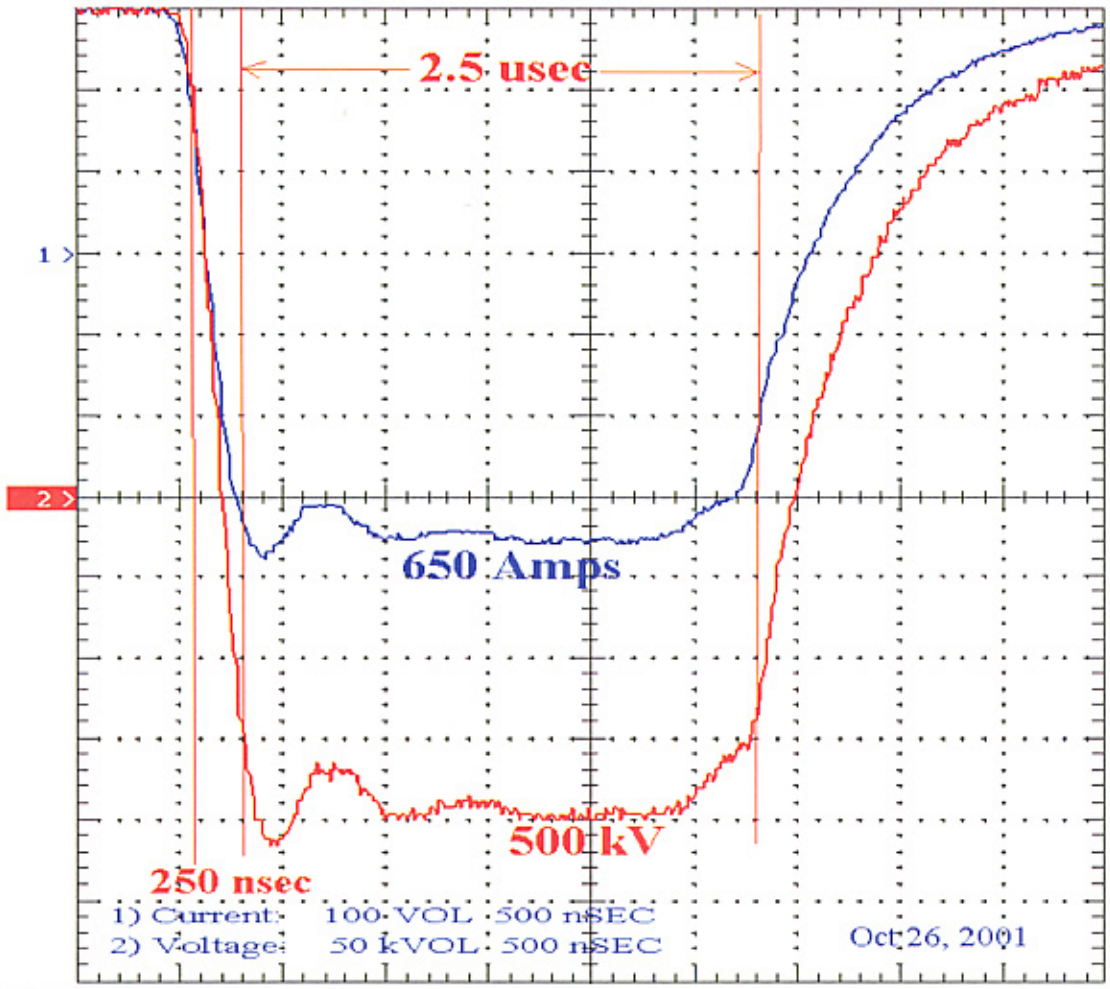


# Prototype Induction Modulator Pulse into Water Load

Three Turn Secondary

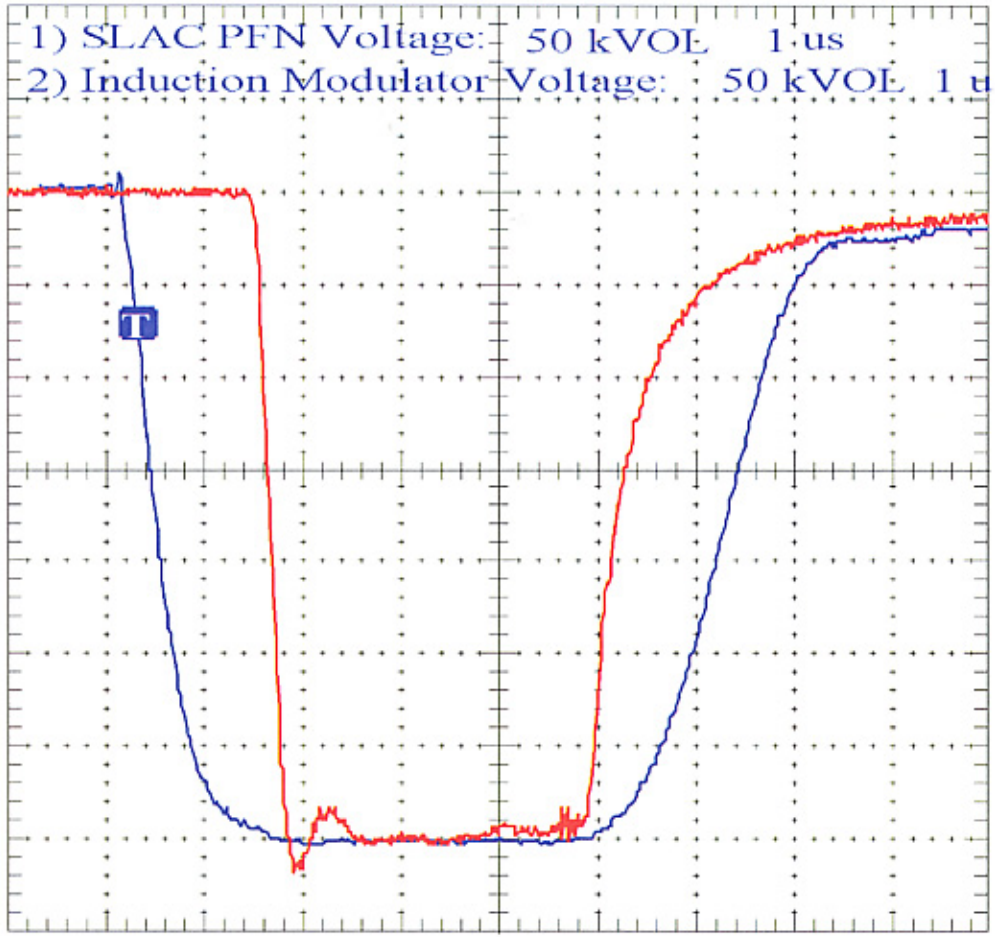
76 Metglas cores

152 IGBT Drivers

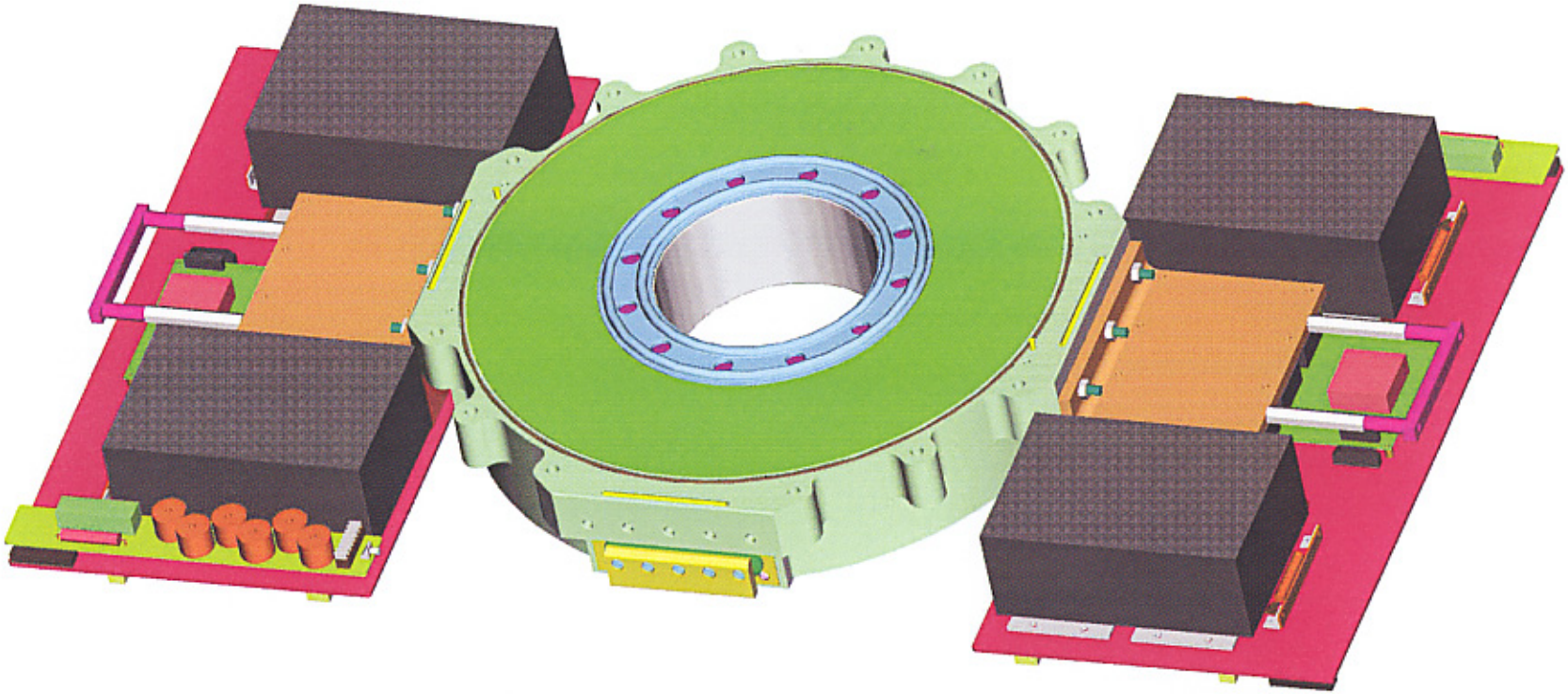


# Comparison: Induction Modulator Pulse with PFN 5045 Klystrons Pulse Voltage

350 kV, 3.0 usec
375 Amps PFN
750 amps Induction Modulator waveform
efficiency ~89%
Overall efficiency >80%



# Production Adder Cell and Drive Boards



# Summary

- Solid-state pulsers (based on modular adder circuit topology) have demonstrated the capability of satisfying fast kicker requirements

- Solid-state adder pulsers are also capable of meeting the needs of very high peak power and high average power applications.