Solid-State Modulators for the International Linear Collider

ILC Workshop, Snowmass CO
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DIVERSIFIED TECHNOLOGIES, INC.®

Diversified Technologies, Inc., Bedford, MA USA

Diversified Technologies, Inc.

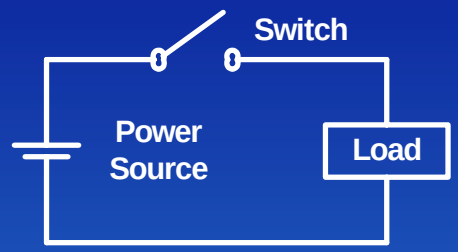
- **Founded 1987 by Dr. Marcel Gaudreau (MIT)**
  - **50 Full Time Employees**
  - **11 PhDs (EE, Physics, Aero)**
  - **Diverse Technical Background**
- **Primary Business Areas:**
  - **High Power Electronic Systems**
  - **System Design and Integration**
  - **Manufacturing/Process Automation Systems**
  - **Consulting Engineering**
- **PowerMod™ Series**
  - **Solid State Modulators, Power Supplies**
  - **1997 & 1999 R&D 100 Award Winner**

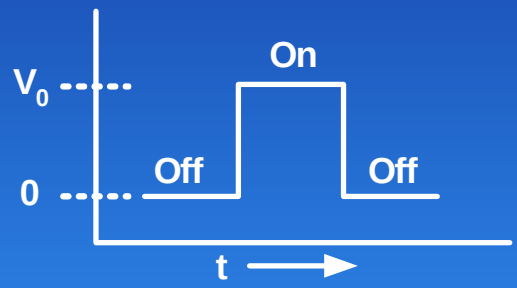
1999 Award Winner

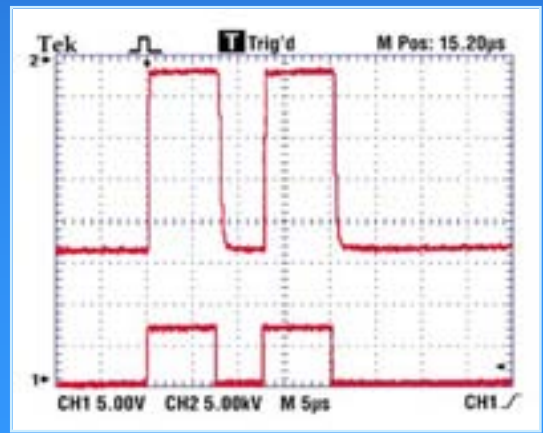
1997 Award Winner

Solid State Switching

- **Series String of Transistors**
  - **All Operate Synchronously**
  - **Patented Design**
- **Very High Voltage and Current Demonstrated**
  - **Up to 200 kV (200,000 Volts)**
  - **Up to 5 kA (5000 Amperes)**
- **Extremely Uniform & Reliable Pulses**
  - **Sub-Microsecond Switching**
  - **Arbitrary Pulsewidth & Frequency**
  - **50 nS – CW; > 100 kHZ Continuous**

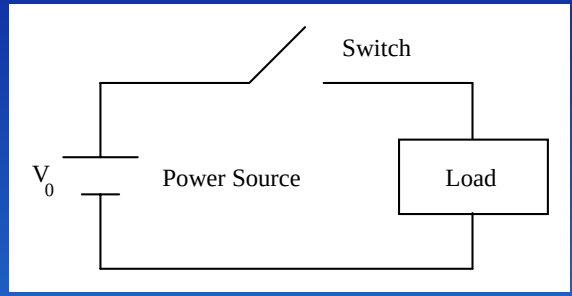


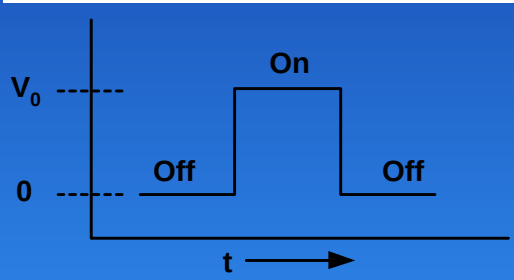


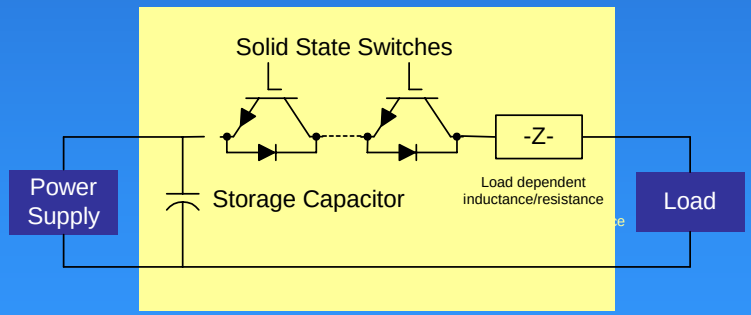


DTI Switches Use Series IGBTs

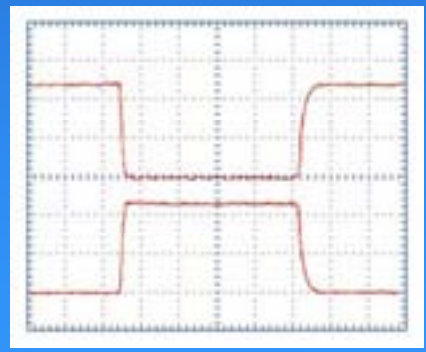
- Lower-voltage IGBTs in series give high voltages
- Fast (<< 1 µs), open and close
- Nearly ideal pulses
- > 200 systems fielded over 10 years







DTI's PowerMod™ Model

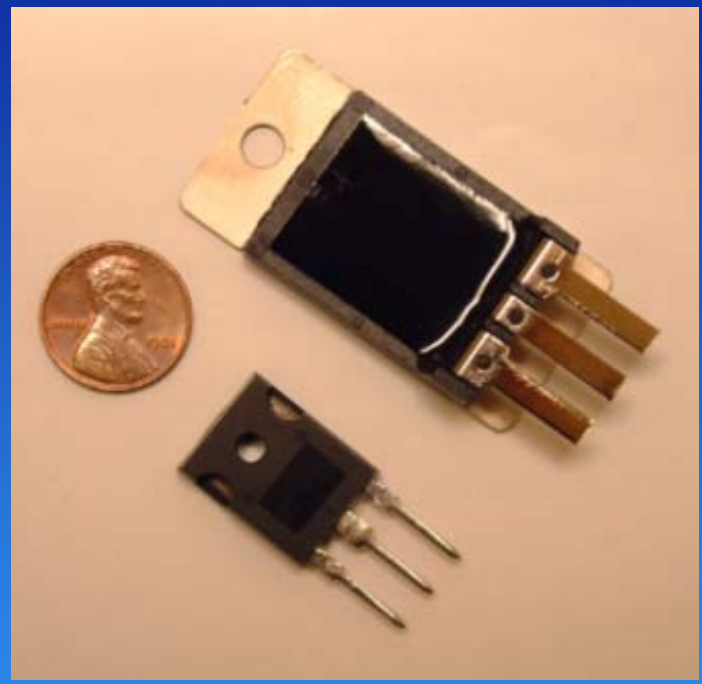


20 kV, 100 A 1 s/div

Smorgasbord of IGBTs & Switch Modules

Development of Pulsed Power Devices

- **DTI is now completing a DOE SBIR for development of pulsed-power optimized packaging.**
- **One early result in this program was the design of the PPT (Pulse Power Transistor, at right), jointly with Powerex, Inc.**
- **This device eliminates problems with in-package inductance imbalances and gate resistance limitations.**



- **Shipped on several commercial systems to date, now in use by many other pulsed power designers.**

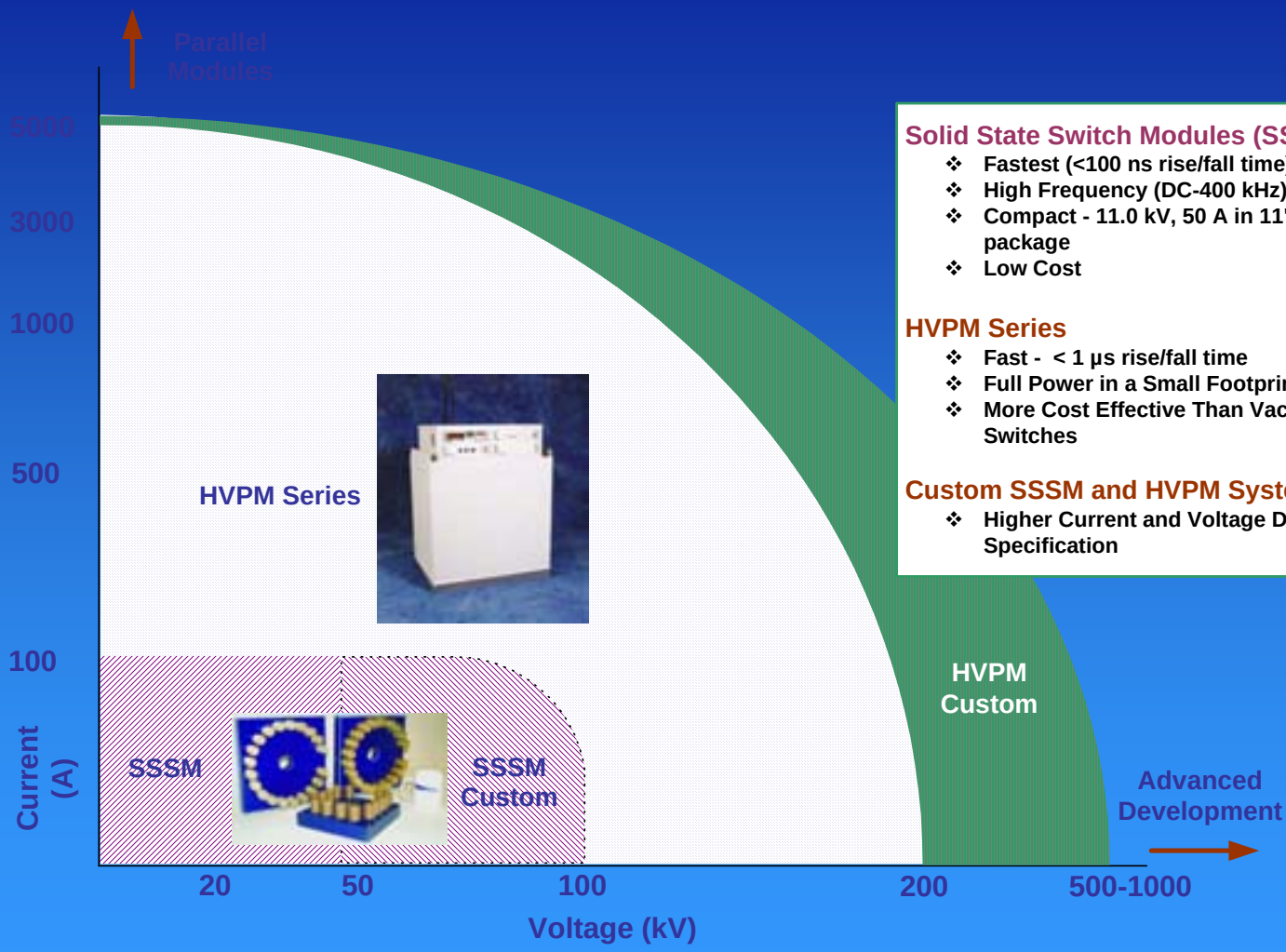
High Power Solid State Systems

- **Very Fast High Current, High Voltage Switches**
- **Built From Solid State Components**
- **Simplified Transmitter Designs**
  - **Increased Reliability**
  - **Inherent Fault Tolerance**
  - **High Efficiency**
  - **Much Less Stress on RF VEDs**
- **Increased Flexibility**

Solid State Switch Modules

HVPS 20-30 Power Supply

DTI Modulator Product Map



Solid State Switch Modules (SSSM)

- Fastest (<100 ns rise/fall time)
- High Frequency (DC-400 kHz)
- Compact - 11.0 kV, 50 A in 11" x 11" x 2" package
- Low Cost

HVPM Series

- Fast - < 1 µs rise/fall time
- Full Power in a Small Footprint
- More Cost Effective Than Vacuum Tube Switches

Custom SSSM and HVPM Systems

- Higher Current and Voltage Developed to Specification

Major Market Applications

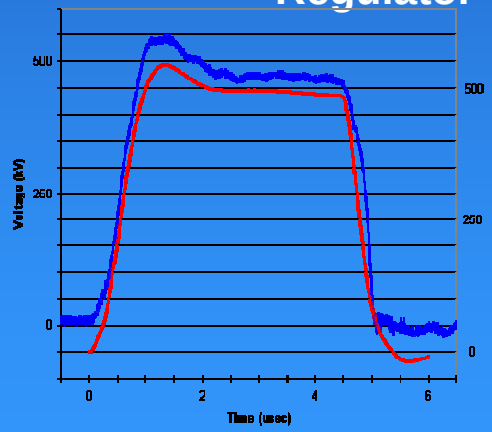
- PEF / Food Processing
- Medical / Industrial Accelerators
- Large Physics Projects (SNS, ILC, ITER)
- Radar Systems

Applications - High Energy Physics

- **Klystron Conditioning & Test**
- **International Linear Collider**
- **Sandia/UCF Lithography**

NLC 500 kV, 500 A Modulator

140kV Buck Regulator



500 kV Pulse vs Prediction

Applications - Food Sterilization

- **Ohio State University Consortium**
  - **Tetrapak, Kraft, Ameriqual, US Army, others**
  - **PEF process is promising non-thermal technology**
- **Bulk food sterilization (Surebeam)**

OSU 65kV bipolar pulser

Applications - Medical / Industrial Accelerators

- **Solid State Modulator Upgrades**
  - **Replace Vacuum Switch Tubes**
  - **Extend Life**
  - **Much Higher Reliability**
  - **Flexibility**
- **Oncology Treatment**
- **Irradiation of Food / Mail**
- **High Power X-Ray Inspection Systems**

15 kV, 2500 A Solid State Switch

Applications - PSII

- Plasma Source Ion Implantation (PSII)
- DTI Switches Power a Run of 1000 GM Pistons at LANL

Applications - Radar

- **Transmitter Upgrades**
  - **AN/SPG-60 Fire Control Radar**
  - **Haystack Deep View Radar (DVR)**
  - **AN/SPS-49 Radar**
  - **MIR Phased Array**
  - **Cobra Judy X-Band**
  - **Gray Star**
  - **AN/SPQ-9A**
  - **Sondrestrom Ionospheric Radar**
  - **W-Band Warloc Transmitter**
- **Replace Obsolescent Components**
- **Increase Reliability & Performance**

AN/SPG-60 Transmitter Upgrade

Gray Star / Cobra Judy

- **High Power Data Collection Radars**
- **Ship Based S & X Band Radars**
  - **Cobra Judy: 16-TWT S-Band Phased Array (CJ-S); 2-TWT X-Band Dish (CJ-X)**
  - **Gray Star: S and X-Band Transmitters Drive a Single Dish Antenna**

USNS Observation Island (top), and USNS Invincible

CJ-X Transmitter Subsystems

RF Head Modulator

Capacitor Bank

HVPSs & Combiner

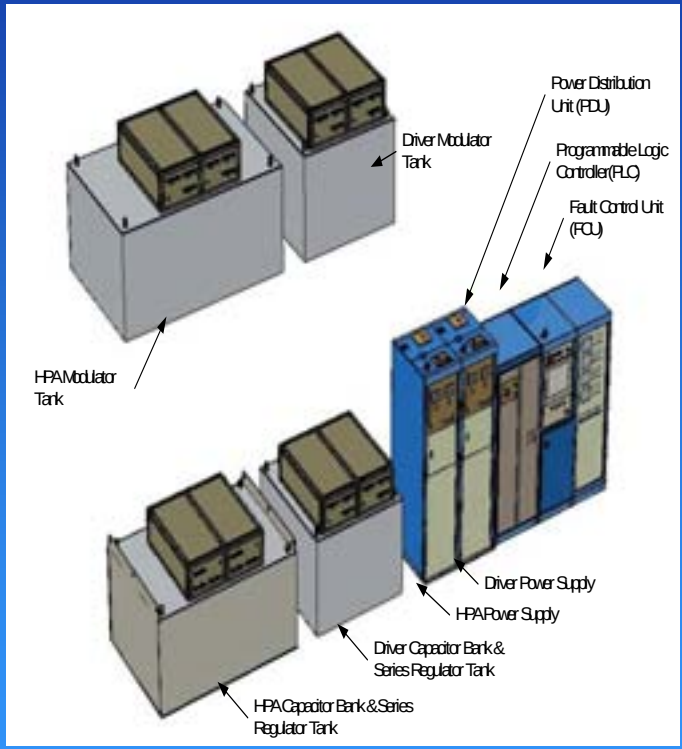
Power Distribution Unit
Transmitter Control & Interface Unit

Solenoid Supply Rack
(Current Monitor & Power Supplies)

Mod Anode PS
Fault Logic Control

Haystack Upgrade (Deep View Radar)

- **W-Band (94 GHz) Gyroklystron Transmitter**
- **DTI Awarded Transmitter Construction Contract 7/04**
- **Supports Two HPAs Plus Driver**
- **Installation 12/05**
- **Expandable to 16 HPAs**



Experience Counts !

- **DTI is the World Leader in HV Solid State Pulsed Power**
- **DTI has patented solid state switch technology, over 15 years of experience, and hundreds of installed systems**
- **DTI has been developing advanced modulators for next generation collider applications for >six years**
  - **hybrid: 90 kV, 5 kA switch w/ 6:1 pulse transformer for 2 NLC klystrons (delivered to SLAC for klystron testing)**
  - **hard switch: 500 kV direct hard switch (studied)**
  - **Marx switch: 500 kV 500 A Marx modulator (in progress)**
  - **pulse-line cable: for NLC grid pulsed SBK (terminated for ILC)**

Challenges for ILC High Voltage Modulators

- **ILC klystrons**
  - **Design TBD – Assumed Similar to Tesla Klystrons**
  - **110 - 150 kV, 120 – 166 A, ±0.5% flattop, 1.5 ms, 5 Hz (higher?)**
  - **~25 kJ Required Per Pulse**
- **Goal - Low Life Cycle Costs**
  - **Minimal Acquisition Cost**
  - **Very High Reliability**
  - **Provide High level of klystron protection**

Major ILC Challenge – Pulse Energy

- **1.5 MJ Capacitors Required to Meet Flattop Requirements Directly**
  - **Capacitor Cost Overwhelms Switch Costs, Dominates Acquisition Costs**
  - **Very Large Modulator Footprint**
  - **Very High Stored Energy Levels**
- **Optimal Energy Storage Assessed at ~ 100 kJ**
  - **Balances Switch and Capacitor Costs**
  - **Achieves Minimal Total Cost**
    - **Lower Capacitance Requires More Compensation Electronics**
    - **Higher Capacitance Increases Capacitor Costs**

Major ILC Challenge – Long Cable?

- **Depending on tunnel architecture chosen, long cables may be needed between modulator and klystron**
  - **adds to arc energy deposited in klystron**
  - **requires additional matching efforts to drive cable without ringing**

DTI redirected from NLC to ILC fall '04

- **In Fall '04, DOE requested that we evaluate options for redirection of existing NLC relevant SBIR contracts for ILC relevance.**
- **We performed preliminary modeling of many topologies for ILC:**
  - **hybrid (ss switch w/ pulse xf) -- hard switch**
  - **PFN -- Marx**
  - **multi-phase array of series boost regulators**
  - **stored energy reduction: bouncers, linear regulators, switching regulators**
- **SBK cable work redirected to hard switch / bouncer**
- **New phase 1 proposed (Dec 04) for Marx switch**

Transformerless Modulators

- **FermiLab / DESY Have Demonstrated Pulse Transformer Design**
  - **Large Transformer Required (V-S Rating)**
  - **Transformer Losses**
  - **Stored Energy Downstream of Switch**
- **Two Transformerless Designs Identified**
  - **Solid State Marx Bank**
  - **Hard Switch**

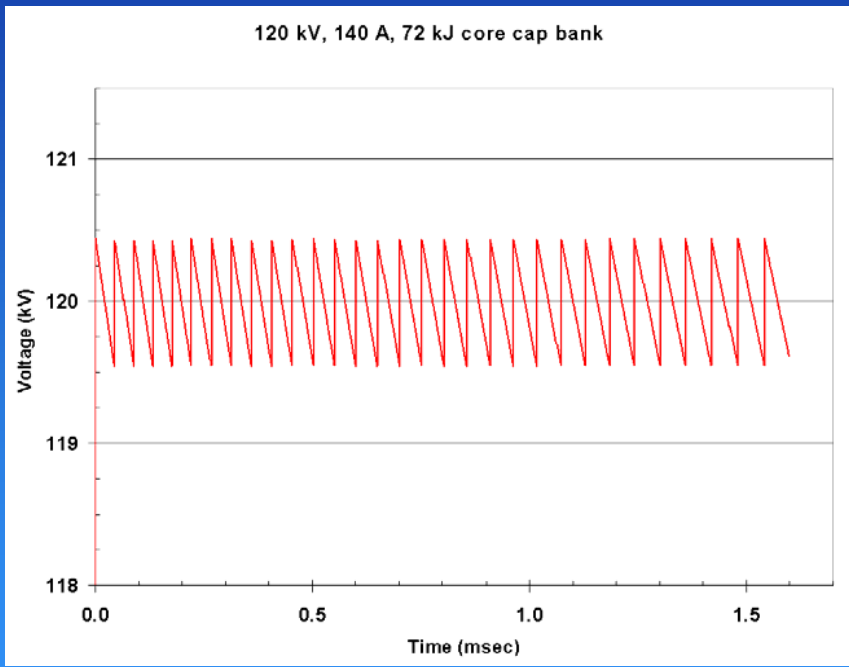
Droop Compensation Possibilities

- **L - charged C (chosen; quickest to build)**
- **Marx Bank (chosen; may be cheapest)**

- **Pulse forming line (sensitive to component tolerances)**
- **Passive L R (too much capacitance)**
- **Charged C - L - C (too much capacitance)**
- **Boost (high switched currents)**

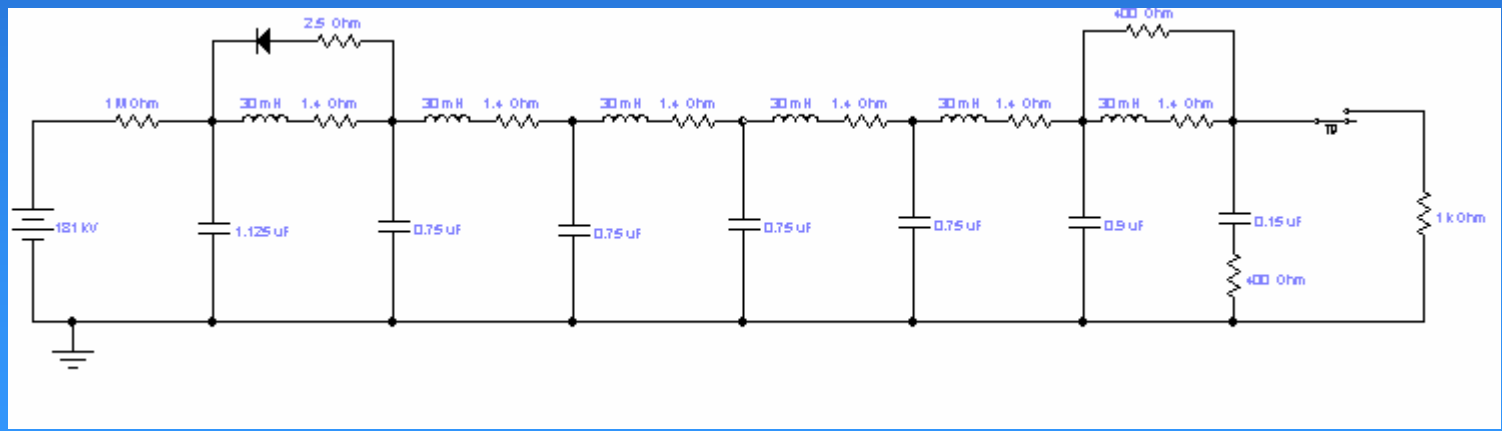
Marx Has Low Stored Energy

- + Only 65 kJ stored
- + Only one power supply
- - ~30 switches individually controlled for trimming
- Submitted as 2005 Phase I SBIR proposal



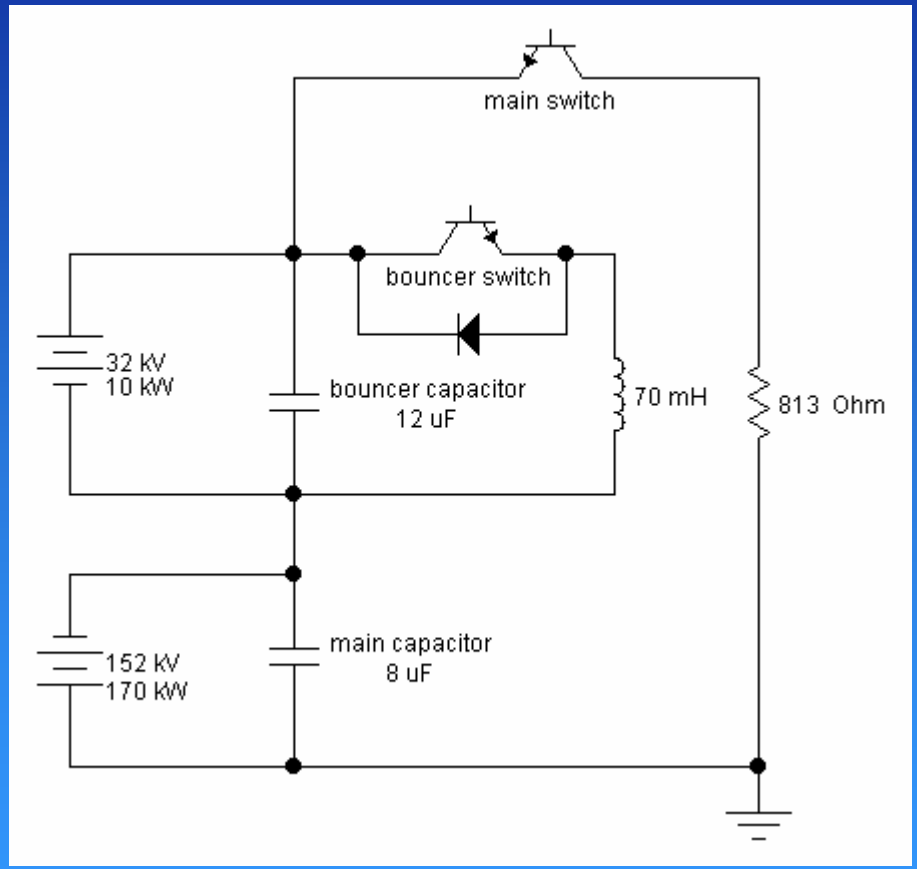
PFN Simple, But Sensitive to Tolerances

- **+ Single switch**
- **+ Low stored energy**
- **- 10% variation in one capacitor puts flatness out of spec**



Selected LC Bouncer

- 8 μF at 152 kV; 12 μF at 32 kV
- 99 kJ stored, 15 x 6.6-kJ caps
- - Two switches, power supplies
- - Large inductor
- + Insensitive to tolerances
- + No transformer
- + Low risk



IGBT Packaging Makes Smaller System

- **Use single-die 4500-V IGBT instead of dual 1700-V IGBT module**
- **5x reduction in switch volume (higher voltage, smaller size)**
- **Developed under DOE SBIR**

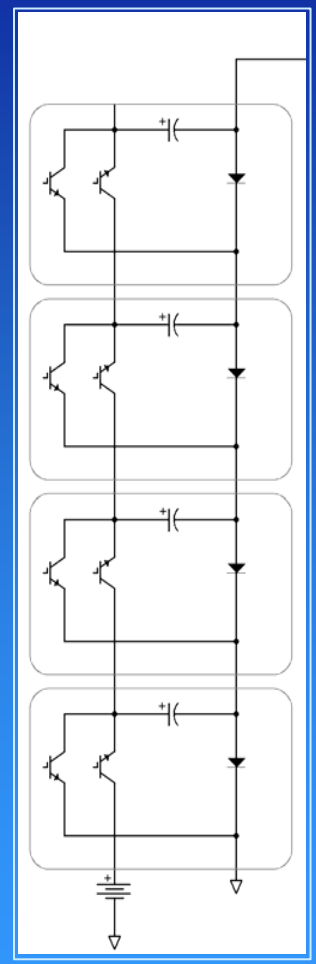
Solid State Marx Bank

- **Demonstrated by DTI, SLAC*, others**
- **Allows Pulsewidth Control (Switches Can Open Under Load)**
- **Capacitors Do Not Fully Discharge Each Pulse – No PFN Required In Each Stage**
- **Stage Voltage is Critical Parameter**
  - **Low Voltage Stages – Many Required, High Charging Currents**
  - **High Voltage Stages – Fewer Required, Low Charging Currents**

* **Collaboration w/ Anatoly Krasnykh, SLAC**

Marx Charging Alternatives

- **Resistor Chain**
  - **Simplest**
  - **High Losses**
- **Diode-Inductor Network**
  - **Limited to Low Duty, Short Pulses**
- **Common Mode Choke**
  - **Selected For NLC Marx (1.5 µs Pulses)**
  - **Limited To Short Pulses**
- **Charging Switch (Selected)**
  - **Higher Cost (2 Switches Per Module)**
  - **Supports Long Pulses**



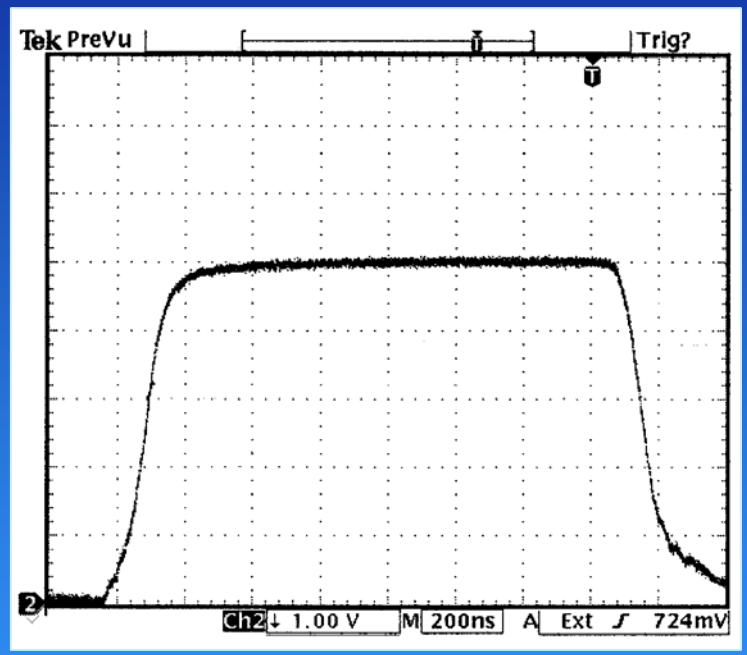
What is the Best Module Size?

- **Smaller (1 - 3 kV module)**
  - **Single IGBT, directly coupled gate drive** — *good*
  - **Fine Voltage Control Over Flattop** — *good*
  - **Large Infrastructure (drive, control, power circuits)** — *bad*
  - **Recharge supply high current** — *bad*

- **Larger (~10 kV module)**
  - **Series IGBT, needs high side drives** — *bad*
  - **Fewer modules needed (about 15)** — *good*
  - **Recharge supply low current** — *good*

- **Optimal - Combination of Both Types of Modules**
  - **Few, High Voltage Modules For Main Pulse Voltage**
  - **Many, Low Voltage Modules For Droop Correction**

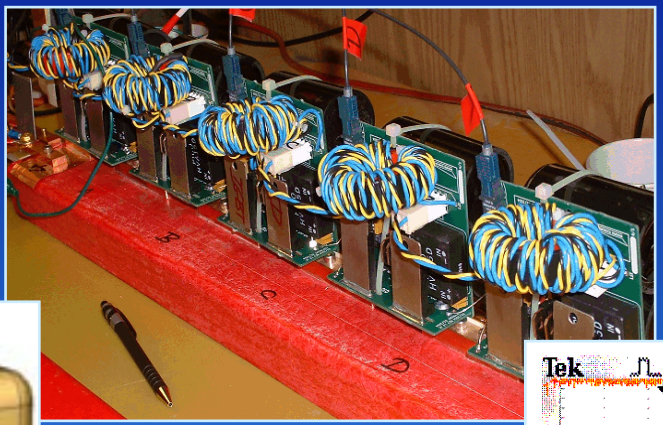
Prototype Marx Bank – 13 kV modules

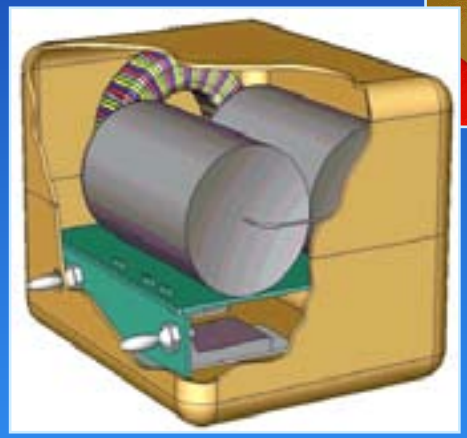


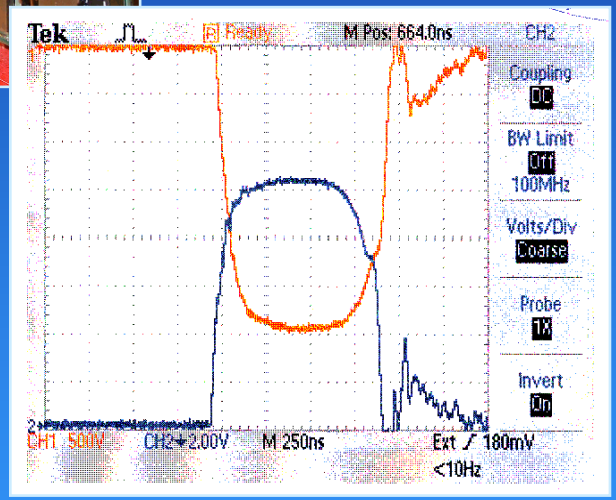
- **Risetime**
  - **150-200 ns (10-90%)**
  - **250-300 ns (0-97%)**

10 kV precharge, 120 Ω load…plot @ 80 A/div

Prototype Marx Bank – 2.5 kV modules





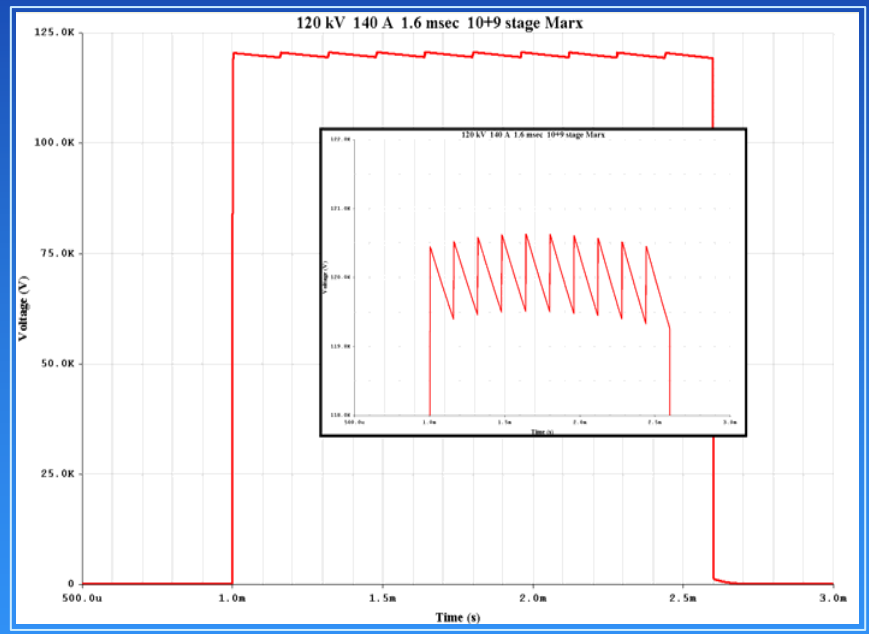


1.6 kV pre-charge, 100 Ω load…red @ 1 kV/div, blue @ 14 A/div

- **Risetime:**
  - ~300 ns (0-97%)
  - ~100-150 ns (10-90%)

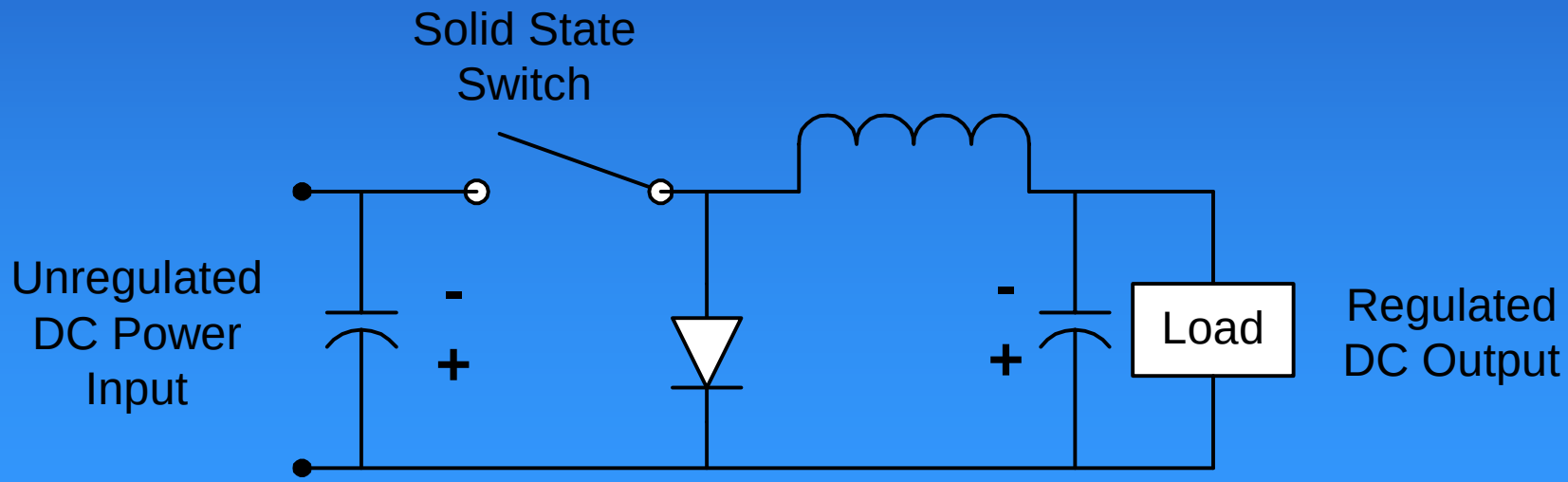
Reduced Capacitor Size – Staggered Switching

- **All High Voltage (7.5 kV) Modules Turned On at Beginning of Pulse**
- **Low Voltage (1 kV) Modules Turned On in Staggered Timing To Compensate for Droop**
- **<0.5% Flattop Maintained**



Marx Bank Power Supply

- **7.5 kV Modules Powered By Buck Regulator From Unregulated 13.8 kVAC Feeds**
- **1 kV Modules Powered By Individual Supplies**
- **Simple, Highly Efficient Design**
- **Most economical supply per watt (for this regime)**
- **Charging Rate Controlled to Prevent Flicker**



Marx Bank Summary

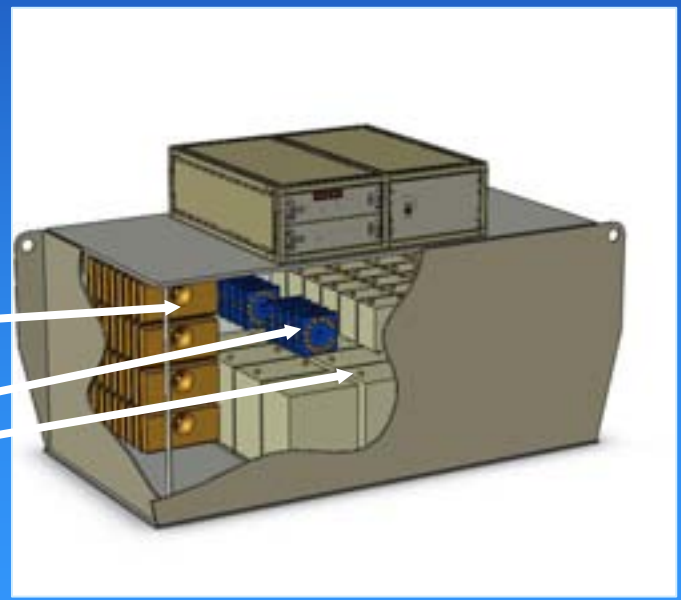
- **# Core Modules - 16**
- **Core Module Voltage - 7.5 kV nominal, 9.0 kV max, 10.5 kV rating**
- **Core Capacitor - 110 µF (6 kJ) each**

- **# Corrector Modules~ 30**
- **Corrector Module Voltage - 900 V nominal, 2.0 kV max**

- **Phase 1 proposed Dec 04, on contract next week?**

ILC Marx Layout

- **Standard DTI HV Design**
  - **HV Systems In Oil Tank**
  - **Controls In "Doghouse" On Lid**
  - **Entire Assembly Lifts From Tank**
- **High Voltage Switches**
- **Low Voltage Switches**
- **Capacitors**



ILC Hard Switch

- **150 kV, 150 A is COTS technology for a DTI hard switch**
- **Program has three goals:**
  - **reduce cost, demonstrate robust operation of minimized switch**
  - **aggressively reduce stored energy with large bouncer correction**
  - **deliver fast-track full specification modulator to ILC community for evaluation and to assist klystron development**
- **Retasking of existing SBIRs approved this summer, work is in progress.**

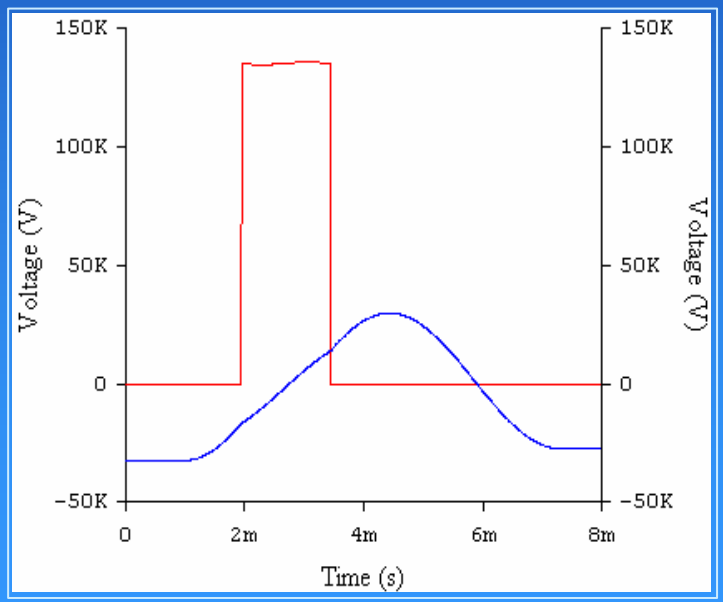
ILC Hard Switch

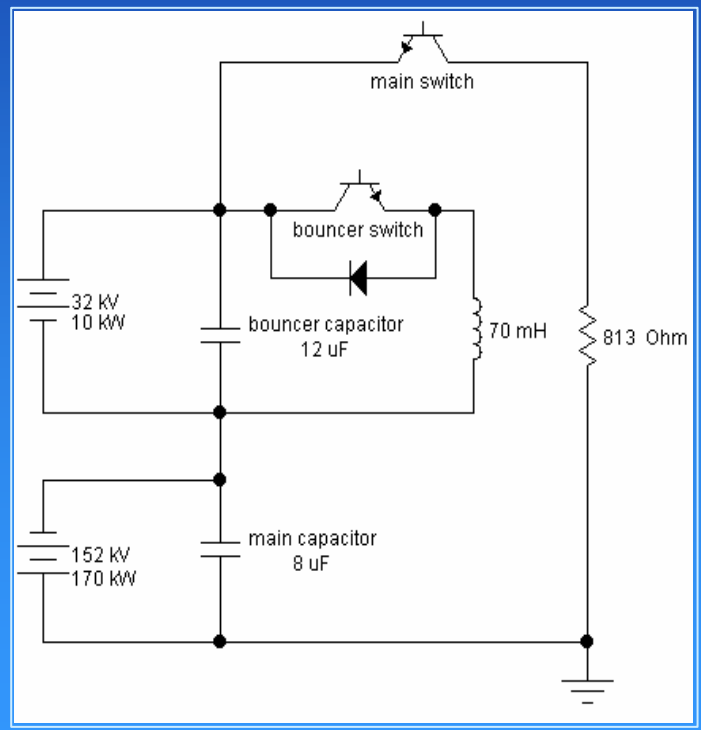
- **Solid State Hard Switch**
- **Up to 200 kV, 5,000 A**
  - **Series IGBT Switch**
  - **Opens Under Load (< 1 μs) For Arc Protection**
- **ILC Requirements Well Within Commercial Capabilities**

150 kV, 500 A Solid State Switch Installed In Sondestrom AB Greenland

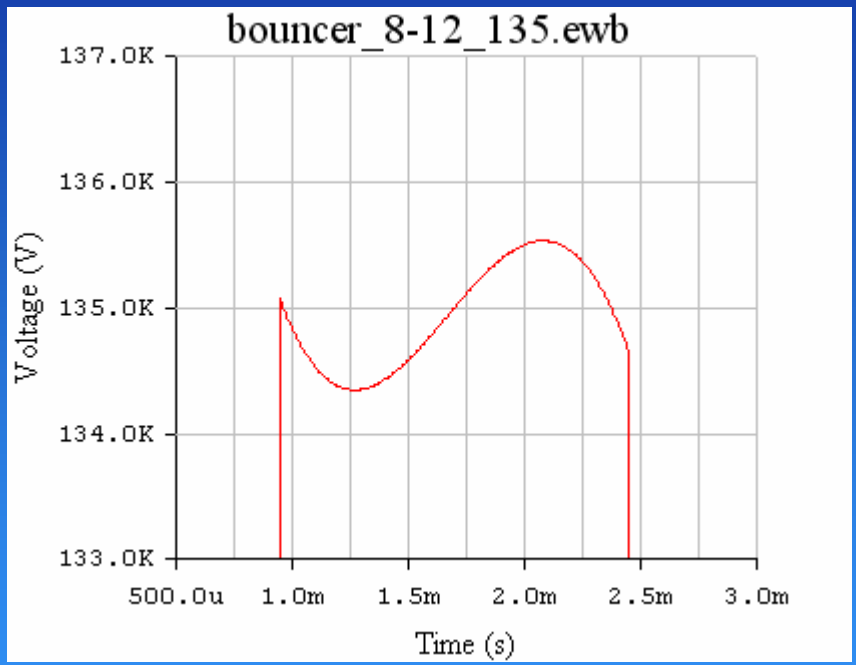
Droop Control

- 100 kJ Stored Energy Gives ~ 12 kV Droop (10%)
- Bouncer Circuit Selected For Compensation

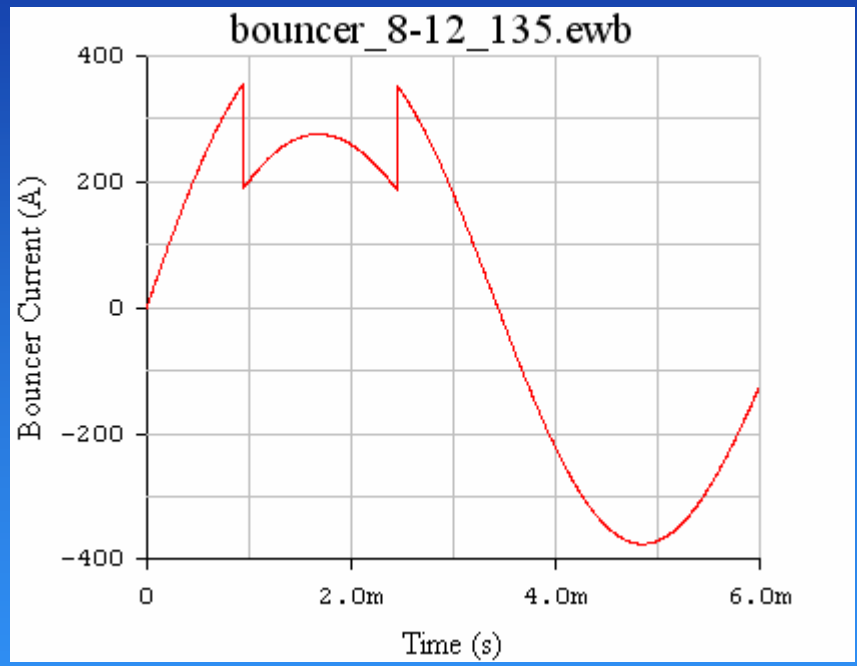




Circuit Simulation Shows Flatness

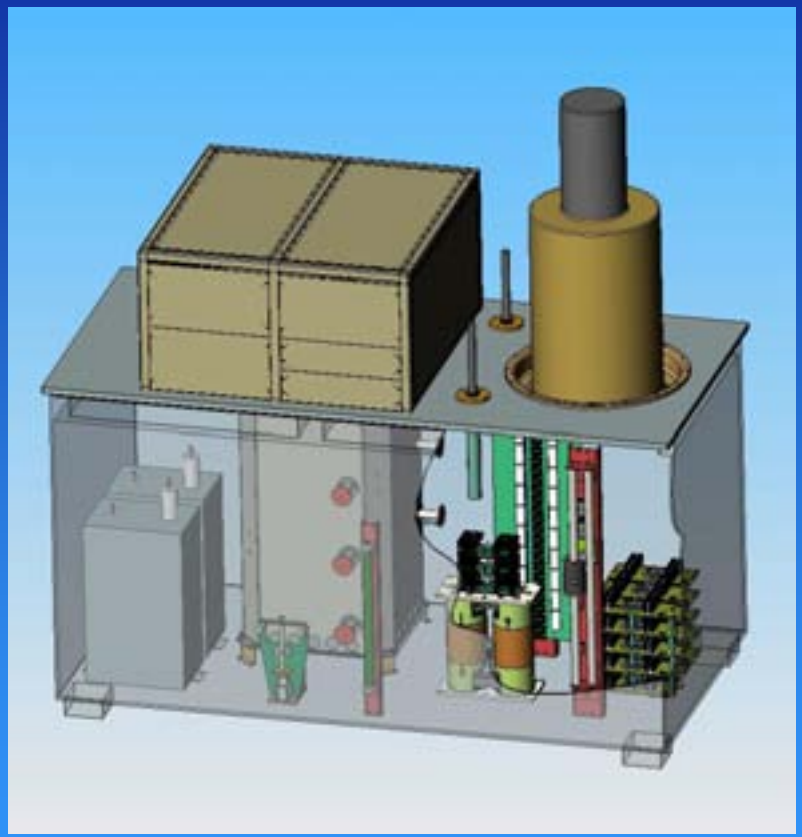


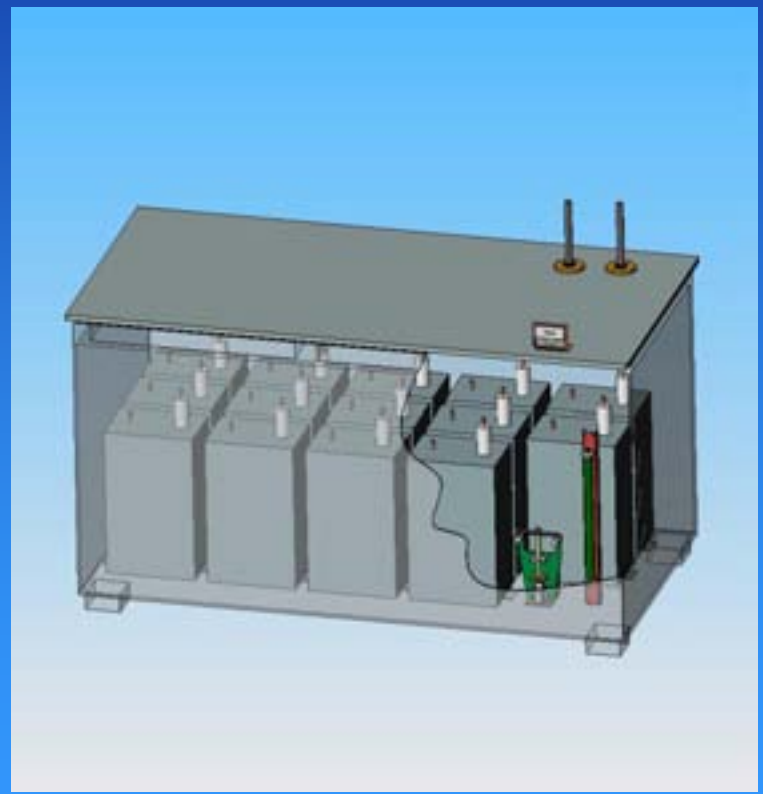
output voltage



bouncer current

Two 4’x8’ tanks (switches, caps)





Summary

- **Two Transformerless ILC Modulators In Development at DTI**
  - **Both Require ~100 kJ of Capacitance**
  - **Similar Acquisition Costs For Both *Switches*, but Marx optimized to minimize cost of power supply**
- **Marx Bank**
  - **Uses Staggered Switching To Achieve Flattop**
  - **Buck Regulator Power Supply From 13.8 kV**
- **Hard Switch**
  - **Uses a Solid State Bouncer**
  - **Commercial Switching Power Supply (480 V)**
- **Both Designs Planned To Be Demonstrated At Full Power Under DOE SBIR Efforts**

Thank You

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