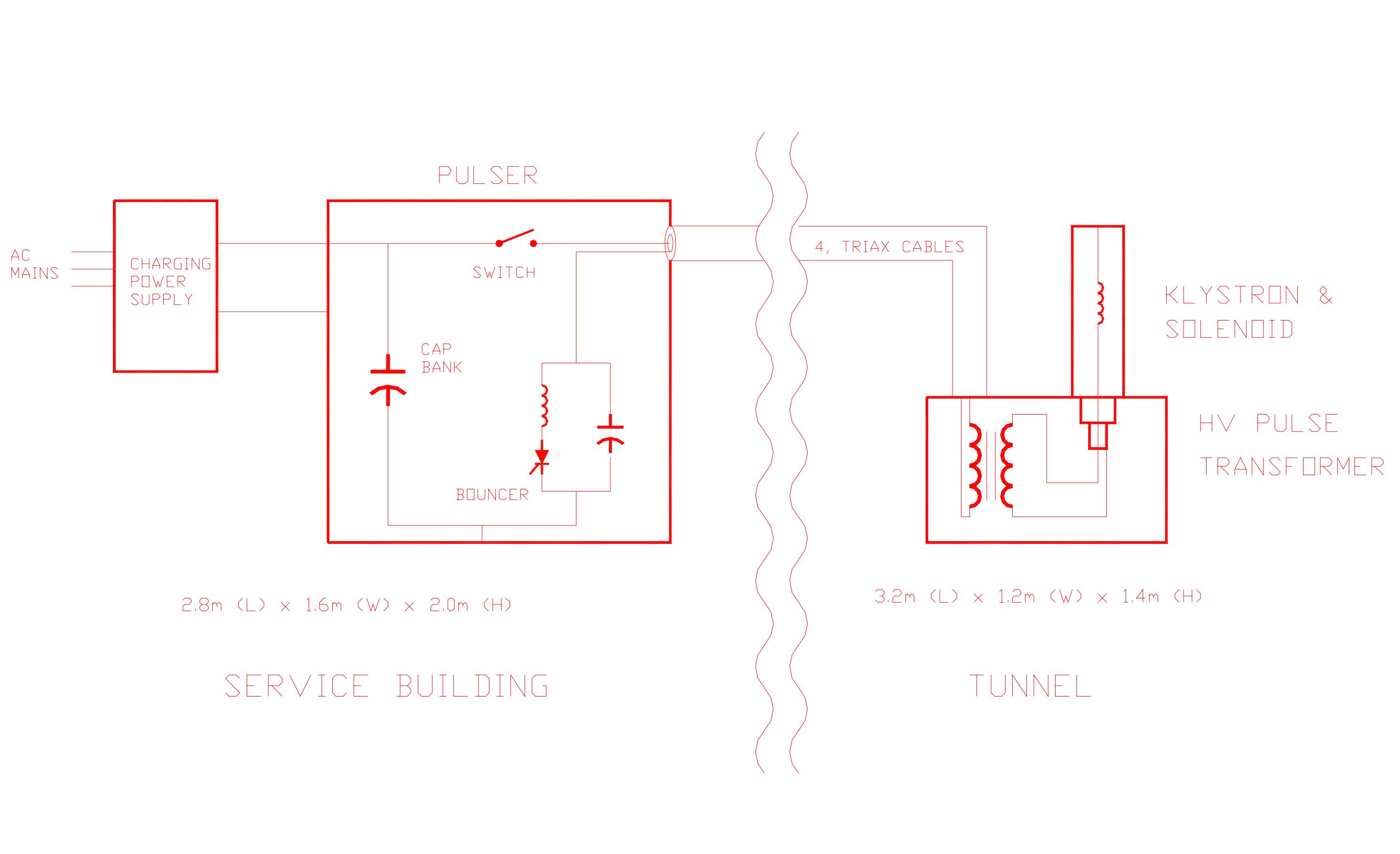
ILC Modulator Talk

- Overview of Existing FNAL Bouncer Modulator
- DESY/PPT Bouncer Modulator
- Efficiency and Cost Comparison
- Optimization / Technology Upgrades
- Other Modulator Types and Related Issues
  - Charging Supply Type / Power Distribution Network
  - Multiple Klystrons on Single Modulator

FERMILAB

ILC MODULATORS



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ILC MODULATOR SPECS
(From TESLA TDR)

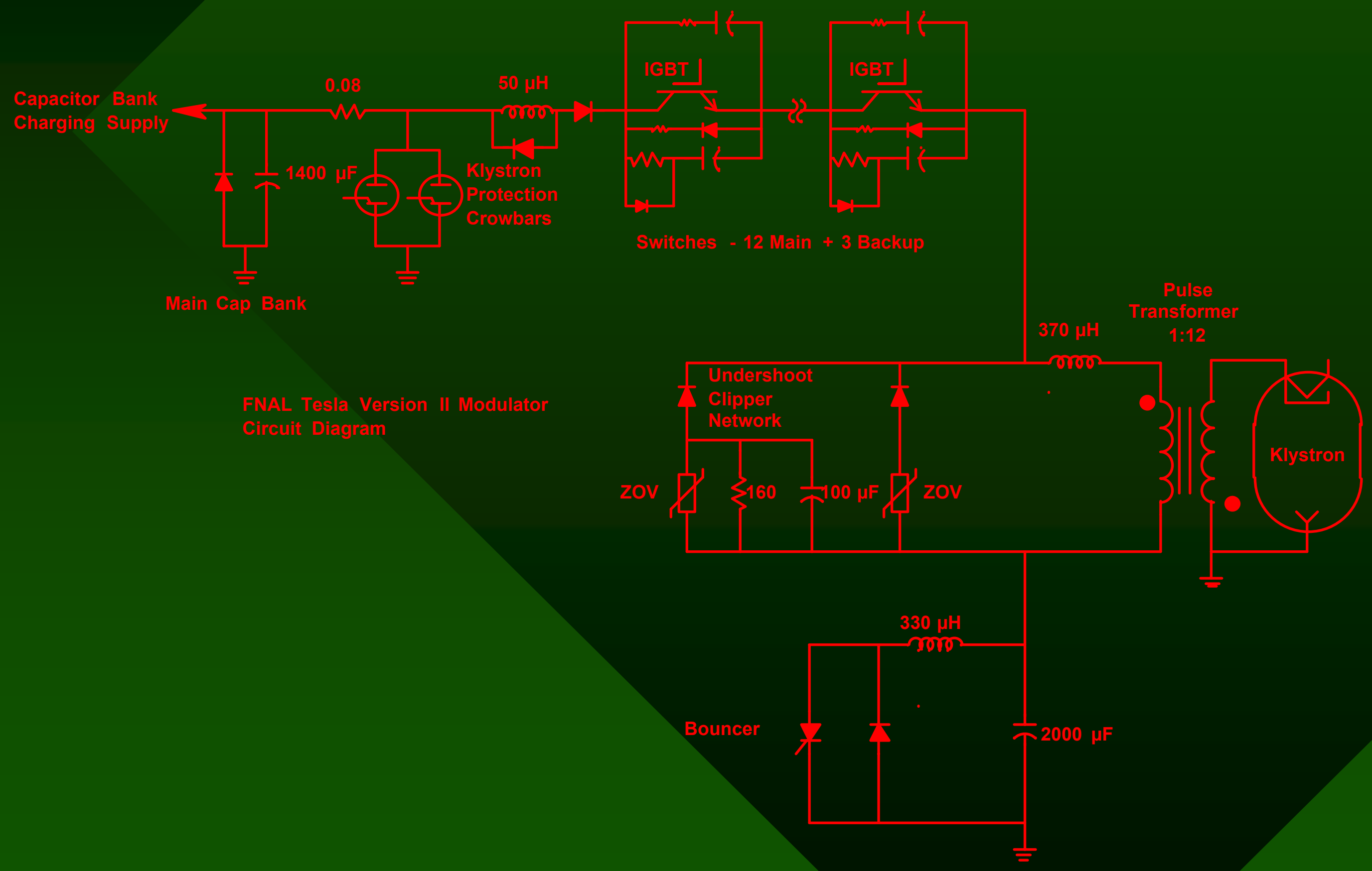
	Typical	Maximum
Klystron Gun Voltage	115 kV	120 kV
Klystron Gun Current	130 A	140 A
High Voltage Pulse Duration (70% to 70%)	< 1.7 ms	1.7 ms
High Voltage Rise and Fall Time (0 to 99%)	< 0.2 ms	0.2 ms
High Voltage Flat Top (99% to 99%)	1.37 ms	1.5 ms
Pulse Flatness During Flat Top	$< \pm 0.5\%$	$\pm 0.5\%$
Pulse-to-Pulse Voltage fluctuation	$< \pm 0.5\%$	$\pm 0.5\%$
Energy Deposit in Klystron in Case of Gun Spark	< 20 J	20 J
Pulse Repetition Rate for 90% of the Modulators	5 Hz	5 Hz
Pulse Repetition Rate for 10% of the Modulators	10 Hz	10 Hz
Transformer Ratio	1 : 12	
Filament Voltage	9 V	11 V
Filament Current	50 A	60 A

Table 3.4.2: *Modulator requirements.*

Bouncer Modulator Operation

- Switch connects main capacitor bank to transformer during 1.7 ms pulse.
- Transformer steps up voltage to 120kV/130A (12:1)
- 1400 uF cap bank discharges by 20% during pulse
- "Bouncer" tank circuit compensates for cap bank droop.
- Switch MUST open during gun spark to remove transformer stored energy and not deposit it at spark site.

FNAL Modulator Circuit



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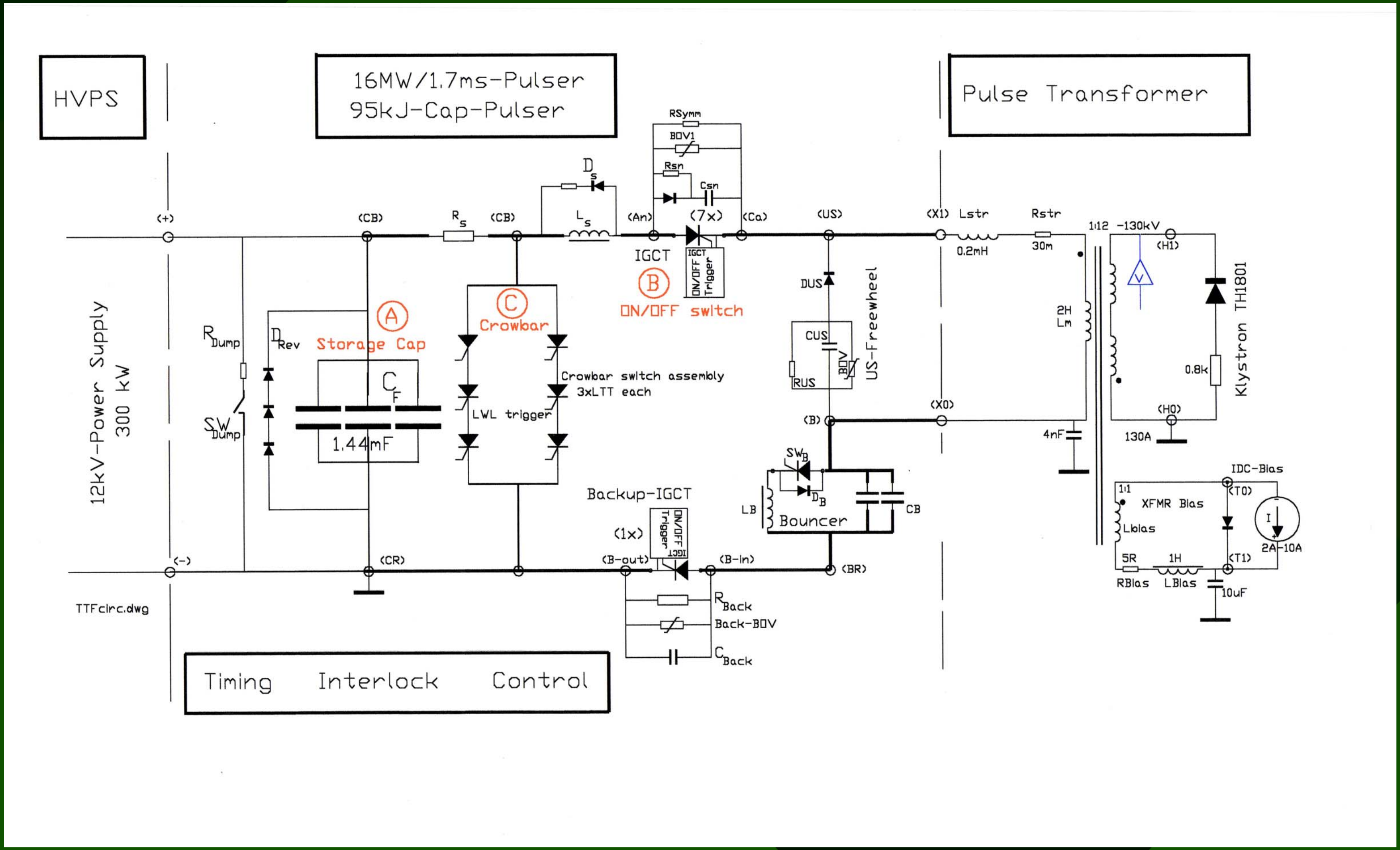
FNAL Modulator History at DESY

- First modulator has run for 25,000 hours (since 1993)
- Second and third modulators have run for 18,000 hours each (since 1996)

DESY/PPT Commercial Modulator

- Main Switch 7 x 4.5 kV IGCTs
- Solid-state Crowbar
- High Energy Density Capacitors
- Backup Switch 1 x 4.5 kV IGCT
- Five units commissioned by PPT/DESY
  - Three units at ~6000 hours each
  - Two units at <1000 hours

DESY/PPT Modulator Schematic



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Efficiency Comparison

- Fermi-Built Modulator System Measured Efficiency 86%
  - Calculated electronic efficiency = 90%.
  - Measured loss in rise time = 3%

    (160 μs to 95% on 2.2 ms pulse)

- DESY Commercial Modulator System Efficiency 85%
  - Stated electronic efficiency = 90%.
  - Stated loss from rise time = 4%

    (100 μs to 80% on 1.7ms pulse)
  - Stated loss from long pulse cables = 2%.

Efficiency Considerations

- Original FNAL Modulators
  - Designed on Short Timescale for Klystron/Cavity Testing
  - High Confidence Component Specifications
  - Efficiency was not the Focus of the Design
- Increase Component Efficiency
  - Component Bidding Evaluation to Include Efficiency Cost Adjustment
  - Minimize Capital Cost + Operating Cost

Efficiency Considerations (contd)

- Improving Rise Time Efficiency Loss
  - Reduce Leakage & Add Peaking Circuit

Calculated Power Loss	As Built (300 µH)	200 µH and Peaking
• Power Loss at 80% Voltage	1.9%	0.7%
• Power Loss at 95% Voltage	5.4%	1.7%
• Power Loss at 98% Voltage	7.3%	1.9%

Cost Comparison

- FNAL Engineering Estimate is 30% more per modulator for 576 units
  - Using anticipated cost saving upgrades

- Factors that may account for this difference:
  - The Fermilab built modulator cost estimate uses Fermilab labor cost
  - The final cost is very sensitive to assumed saving for mass production
    - Fermi assumed 5% reduction in unit price per doubling
    - A rate of 8.2% per doubling would account for the above difference

- THEREFORE, the accuracy of the cost estimate within 30% depends on the validity of the mass production study performed by PPT. Understanding this company's experience (success) with similar studies would be key to placing some confidence level in the cost estimate.

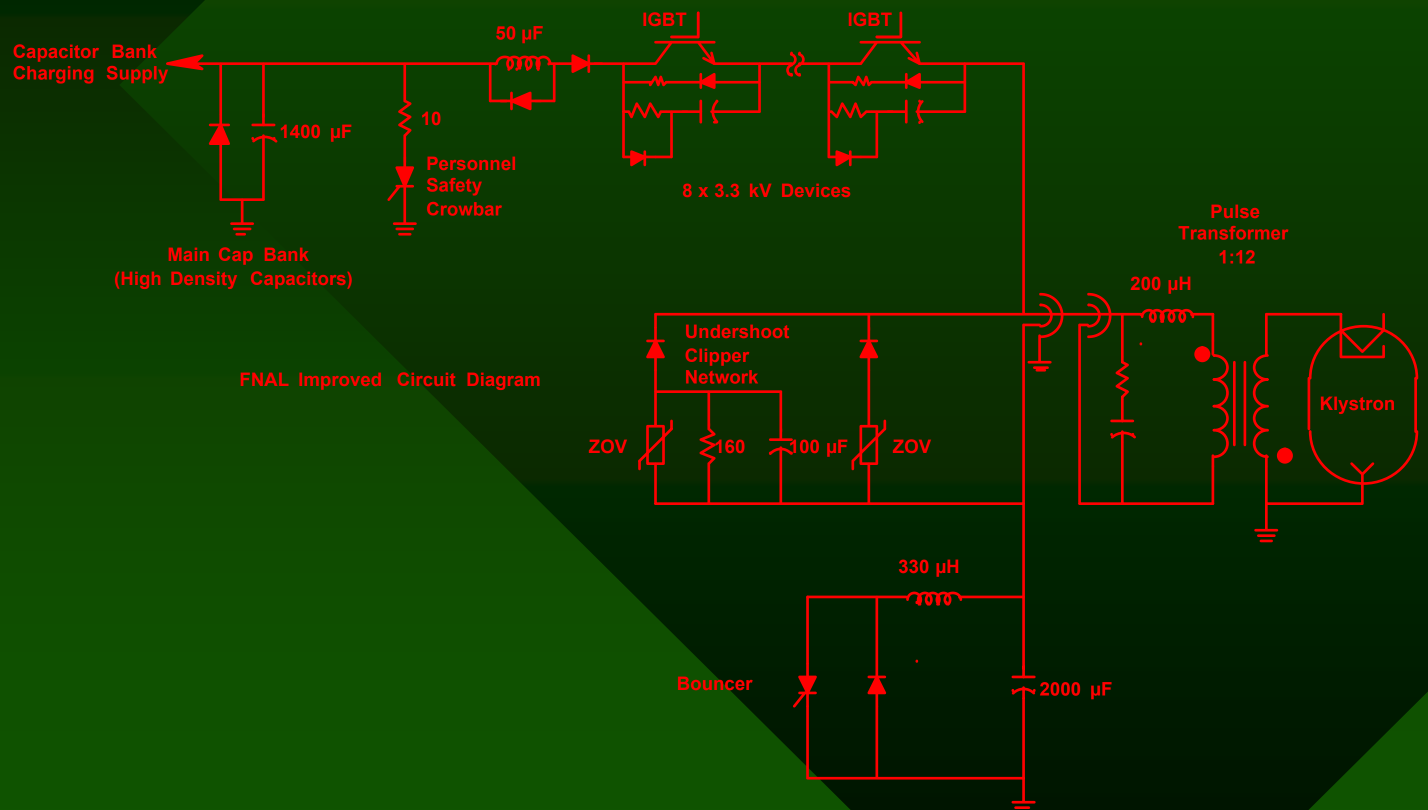
Proposed Changes to Original FNAL Modulator Design

- New Switch Philosophy:
  - Design Single Switch for Fail Safe (i.e. OFF) Operation
    - Combines Original Main Switch with Backup Switch
  - Design Switch with Extra Voltage Margin
    - Required number of devices for worst case plus 2
  - Redundant control paths to turn switch OFF
    - No single failure can override OFF command
  - This design permits the use of a slow, low current crowbar circuit
    - Cost reduction in crowbar switch
    - Small Efficiency Gain
  - Use of IGBT Switch Elements
    - Lower energy to turn off - more consistent with fail safe operation

Proposed Changes to Original FNAL Modulator Design

- New Switch Technology:
  - Using Only New Higher Voltage Devices
    - 50% reduction in cost and physical size
    - DESY / PPT Using 4.5 kV IGCTs
- New Capacitor Technology:
  - Use New High Energy Density Capacitors for Main Capacitor Bank
    - Self Healing Polypropylene / “HAZY” Capacitors
    - Low Current Crowbar allows the use of these capacitors
    - DESY / PPT Uses this style capacitor
- Modulator Controls:
  - Using Surface Mount Components Leads to Fewer Interconnects
    - 25 % Reduction in Parts Cost / 50 % Reduction in Labor
    - DESY / PPT have updated controls

Proposed FNAL Modulator Circuit



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Other Operating Long Pulse Modulators (Courtesy Richard Cassel, SLAC)

- SNS Modulator 125 kV, 34 A, 1.5 ms, 60 Hz
  - High Frequency Switching Power Converter
  - H Bridge and Step Up Transformer
  - Multiple Klystrons per Modulator
- Thomson-CSF Modulator 80 kV, 80 A, 1ms 10 Hz
  - Stacked Switch Mode Power Supplies
  - Made by Commercial Company

Other Modulator Ideas

- Bouncer Type with Multiple Klystrons per Unit
  - More Efficient use of Pulse Transformer
- Marx Bank Generator (R. Cassel, G. Leyh)
  - Update Marx for long pulse using semiconductors
  - Capable of reducing stored energy more than bouncer
- Series Switch / Hard Tube Modulator
  - Larger Capacitor Bank
  - Semiconductor or Electron Beam Tube
- Mismatched Impedance PFN
  - Very Low Impedance PFN and IGBT Switch

Evaluation Criteria for Modulators

(Courtesy of Richard Cassel SLAC)

• Performance	Rise Time, Flat Top
• Safety / Security	Voltage, Stored Energy, Standards
• Cost	Total Cost (Lifetime)
• Efficiency	Rise Time, Losses
• Klystron Protection	Energy in Spark, Redundancy
• Reliability	Failure Rate, MTBF, MTTR
• Maintainability	Complexity, Repair
• Power / Utility Effects	Power Factor, Load Leveling
• Space Requirements	Footprint, Height, Access

Charging Supply Design Choices

- Function almost independent of modulator:
  - Recharge main capacitor bank between pulses.
  - Average Power Level ~ 150 kW at 5 pps.
  - Peak/Average Mains Power Must be Limited
- Design choices:
  - Phase Control + Transformer + Rectifier + Filter Choke (FNAL approach)
  - Switch-mode supplies (DESY approach)
  - Hybrid approaches (Phase Control + Switch Mode)
  - Multiple Modulators on DC Bus

Evaluation Criteria for Charging Supply

- Total (Capital + Operating) Cost
- Reliability / Maintainability
- Reactive Power Factor
- Harmonic Power Correction
- Power Leveling
- Electro Magnetic Interference
  - Can 90MW of switch-mode power act as a good neighbor to other systems on site? Off site?

Charging Supply Criteria (Continued)

- For TESLA operating at 5 Hz, German standard requires less than 0.5% line voltage variations.
- 0.5% is severe restriction on a single modulator
  - Use a dedicated local feeder that can tolerate higher variation
  - FNAL Examples of On Site / Local Power Fluctuations

    Footprint Area (Linac & Booster): 2% of 15 Hz

    Tests Done Recently With MI: 5% with 2 sec. ramp

    MI Pulsed Power: 10% with 1.5 sec. ramp

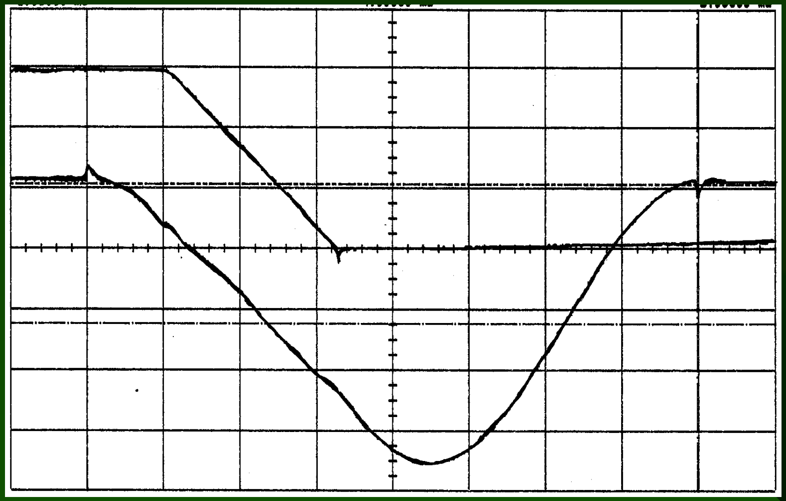
    13.8 kV Distribution Local – not shared with general public
- Load Leveling at Modulator or Distribution Level?
  - Distribution Level - Dedicated for Modulators, Transformer Sizing
  - Modulator Level - Increase Filter Choke, Constant Power Control

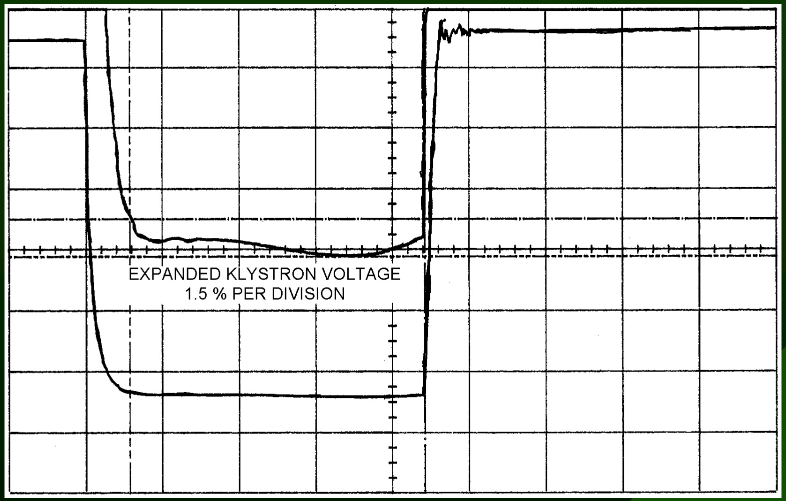
Summary

- Bouncer Modulator is a Reasonable Baseline Design
  - Units have been tested over many years
  - Efficiency is ~ 86% and can be improved
  - Cost Estimates 300k$ ~ 400k$ each for 576 units
  - Upgrades still being investigated
- Other Operating Designs Exist
  - Should be evaluated for use in ILC
- New Designs are also of Interest
  - Full scale prototypes needed for evaluation
- Charging Supply Technology and Power Distribution are Important Issues

END OF PRESENTATION

Measured Voltages





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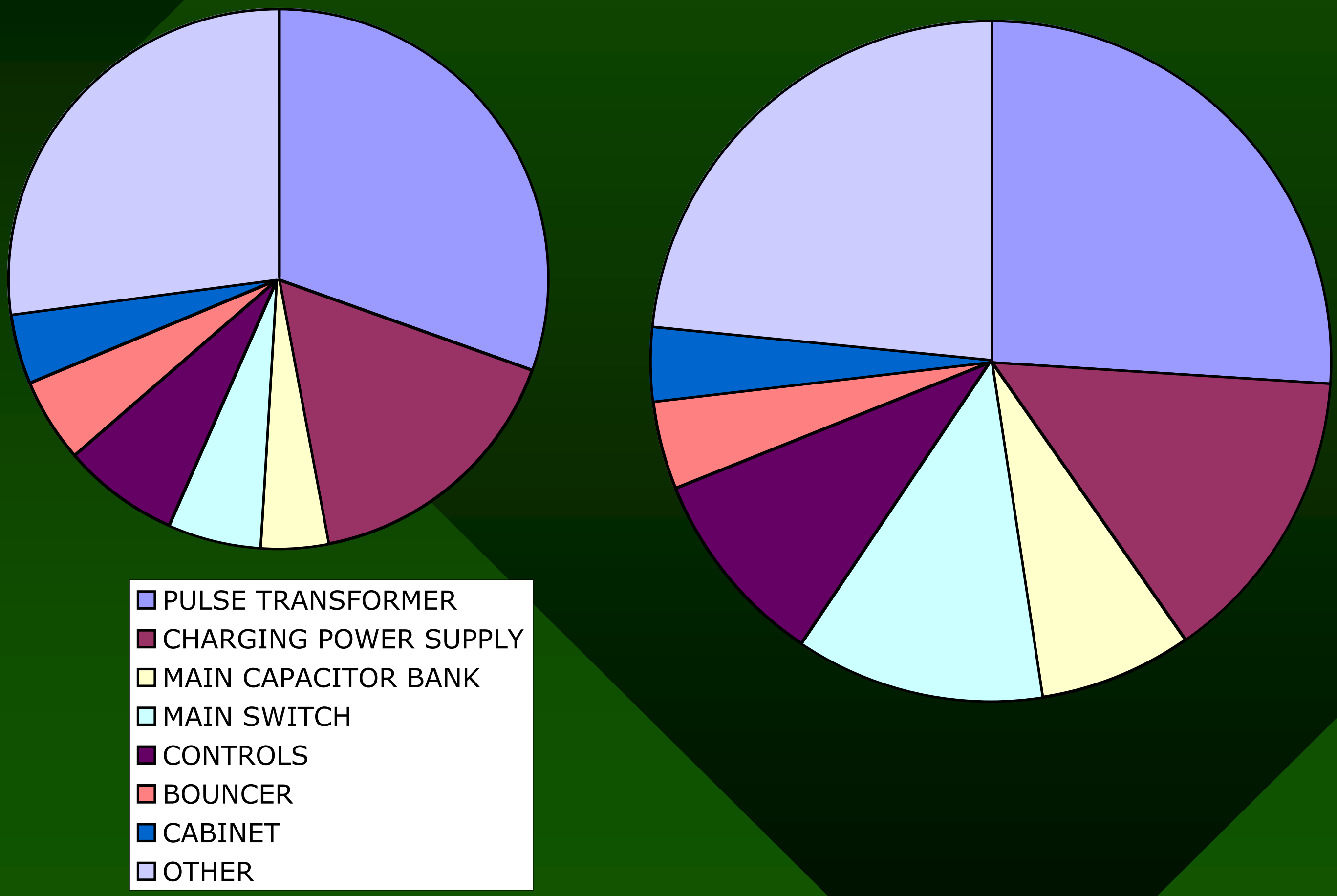
Comparison of Improved Design and Original Design

(Size of Circle Proportional to Total Cost)



FERMI MODULATOR – 572 Units

- COST ESTIMATE FOR 572 UNITS

- SINGLE MODULATOR COST: $735K
- “RULE OF THUMB” for mass production:

  5%/unit decrease for each 2x increase in number of units

  2**x = 580, x = 9.18

  (.95)**(9.18) = .62

  Cost per unit = $458k

- TOTAL: $262M

- NOT INCLUDING INSTALLATION

FERMI-BUILT MODULATOR

❑ Updated Modulator Cost

- IGBT Switch:

  Using New Higher Voltage Devices and eliminating the backup switch:

  - $60k savings in labor and parts

- Main Capacitor Bank:

  Using New “HAZY” Self-Healing Polypropylene Capacitors

  - $30k savings in labor and parts
  - $5k savings in Cabinet, Reduced Service Building Size!

- Controls Upgrade

  $30k Savings in parts and labor