ESS Modulator Talk

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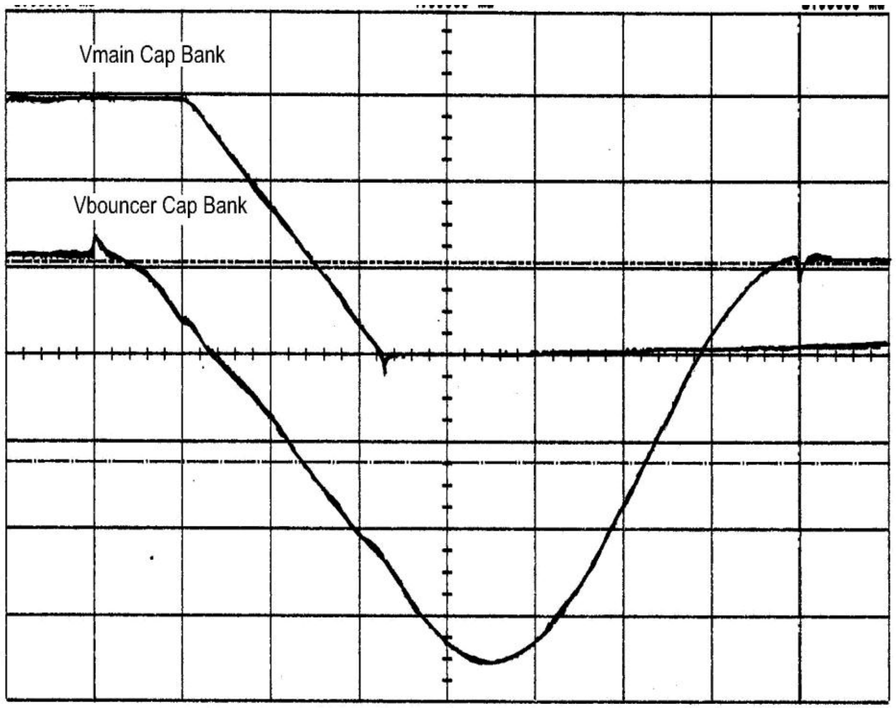
April 24, 2012

- FNAL Bouncer Operation & Status
- Operating History / Failures
- Important Modulator Requirements
- Comments on ESS modulators

Bouncer Modulator Principal of Operation

- Switch connects main capacitor bank to transformer during pulse
- Transformer steps up voltage to klystron
- Capacitor bank voltage discharges by 20% during pulse
- "Bouncer" resonant circuit compensates for main capacitor bank droop



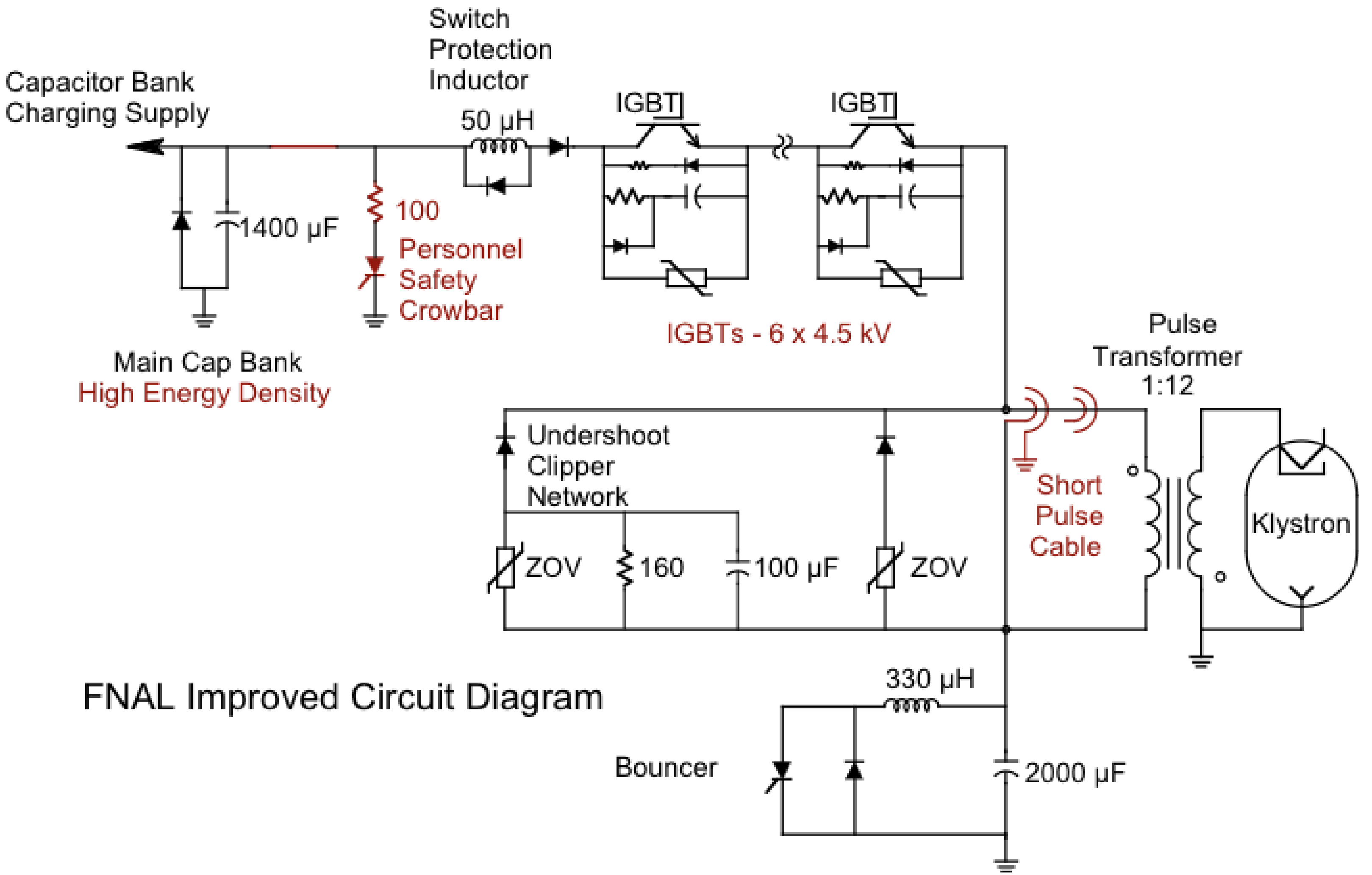
Bouncer Modulator
Principal of Operation

- Main switch opens at end of pulse
- Undershoot network resets transformer between pulses
- Bouncer switch remains closed to recharge bouncer capacitor
- Delay from bouncer pulse start to main switch start set to recharge bouncer capacitor bank

Fault Condition

- Switch MUST open during gun spark to limit energy at klystron
- Undershoot network clamps klystron reverse voltage

FNAL Current Bouncer Circuit

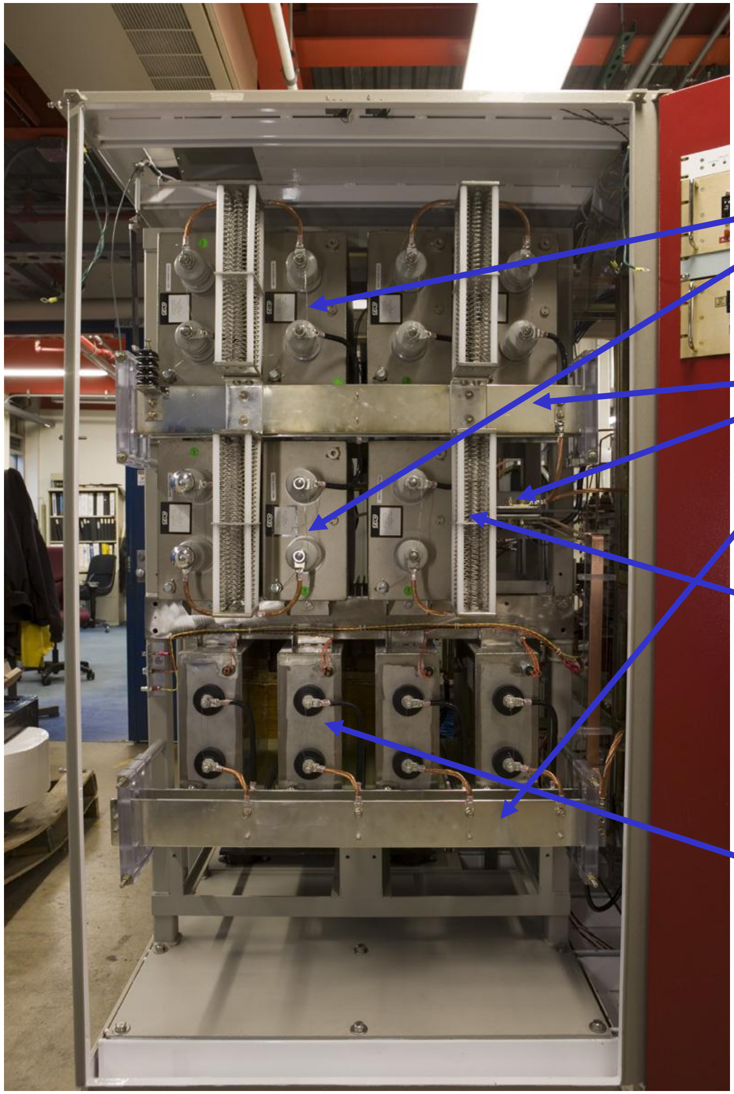


FNAL Improved Circuit Diagram

Latest Changes to Original FNAL Modulator Design

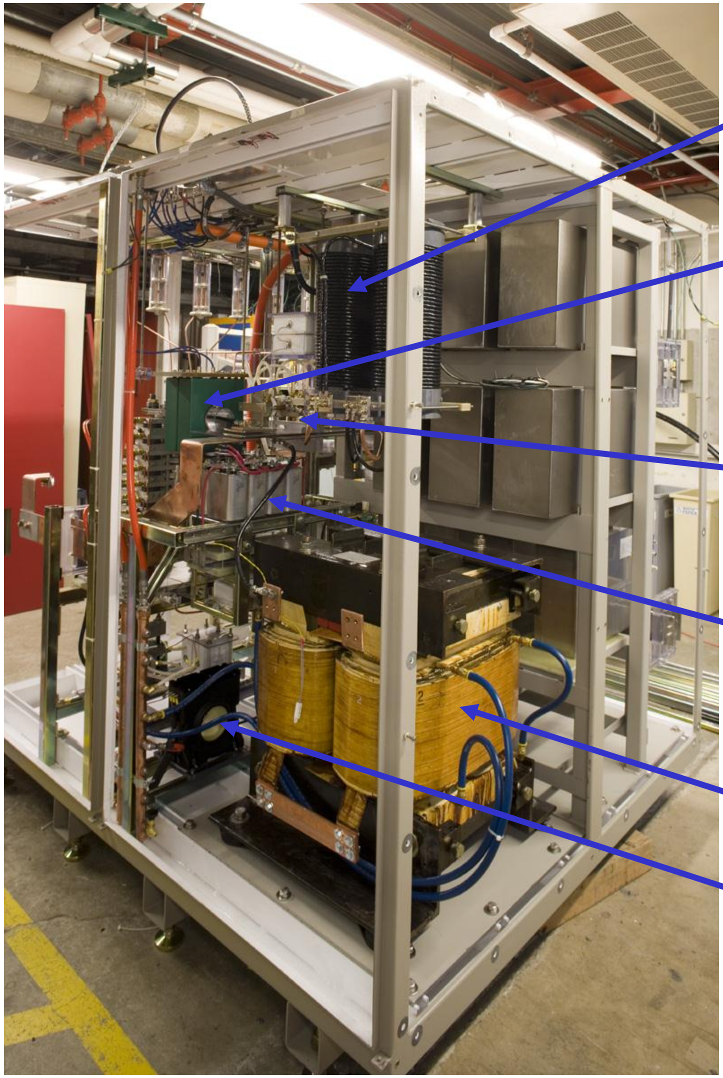
- New Fail Safe Switch Implementation:
  - Originally design had backup switch
    - Required crowbar since backup had lower voltage rating
  - New design has single switch for fail safe (i.e. OFF) operation
    - Use of IGBT switch elements, low turn off energy
  - Design switch with extra voltage margin
    - 190% voltage margin over highest transient
    - MOV for each IGBT
      - 4 kV clamp voltage at rated current of 4.5 kV IGBT
  - Complete redundant controls design
    - No single failure can over ride switch off command
    - Double isolated gate power transformers with fault detection
    - Power loss detection at modulator controls, switch control or gate drive turns off switch
    - Redundant control paths and current sensors and loss of redundancy check

Main and Bouncer Capacitor



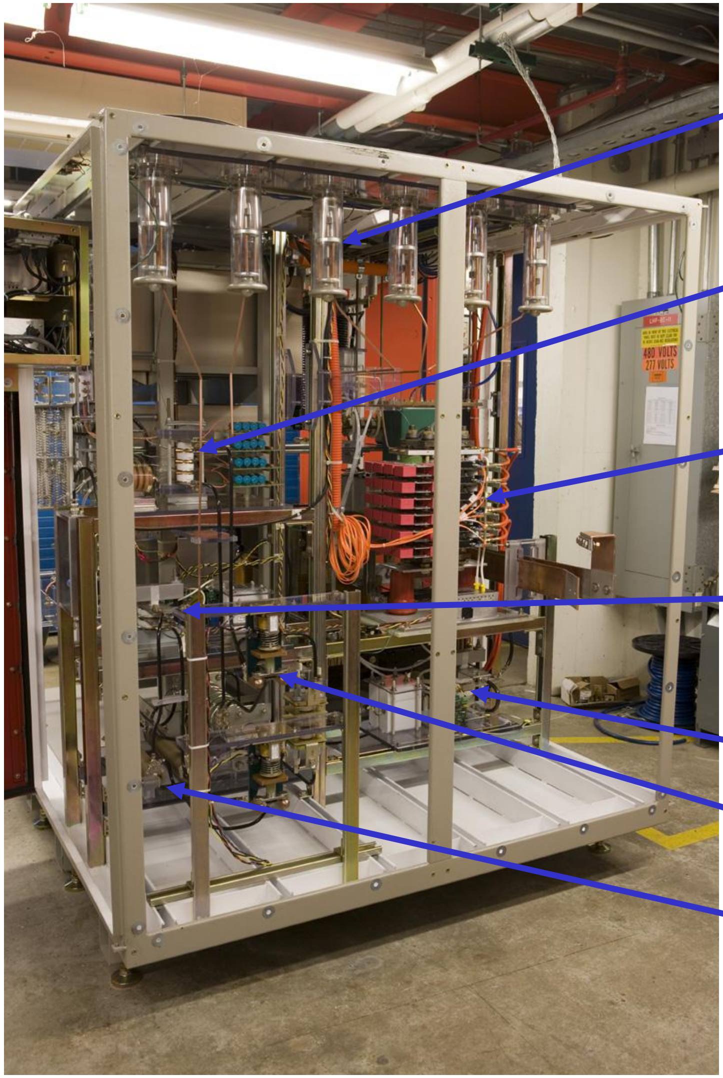
- Main Capacitors
- High Voltage, Low Inductance Buswork
- Current Limiting Resistors
- Bouncer Capacitors

Bouncer and Switch Chokes



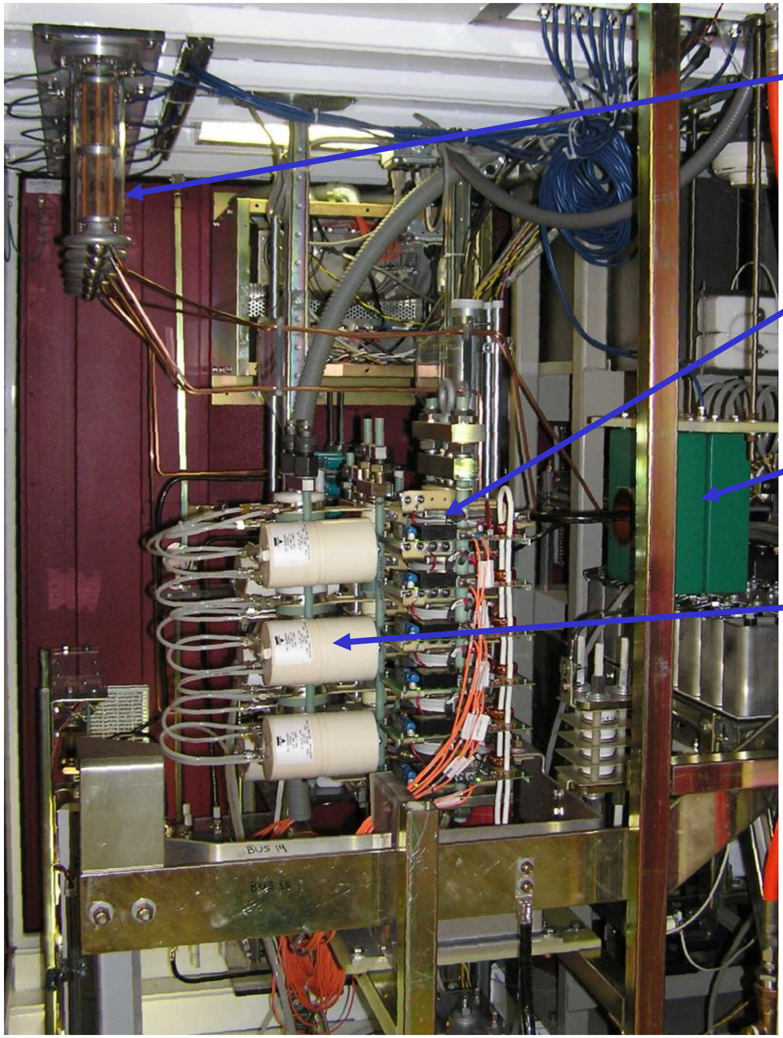
- Switch Protection Inductor
- Main Switch Current Transformers (2)
- Switch Protection Inductor Diodes
- Undershoot Network
- Bouncer Inductor
- Bouncer Current Transformer

Main and Crowbar Switches



- Voltage Dividers
- Main Cap Bank Crowbar Switch
- Main Switch
- Bouncer Cap Bank Crowbar Switch
- Bouncer Switch
- Shorting Relays
- Crowbar Resistors

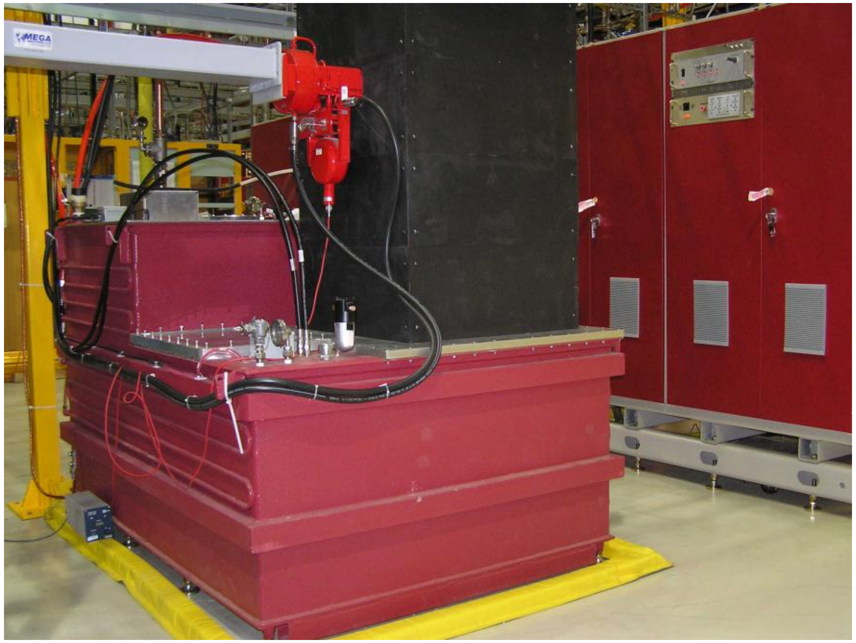
Main Switch Detail



- Voltage Dividers
- Main Switch
- Redundant CTs
- Snubber Capacitor

Pulse Transformer & Klystron

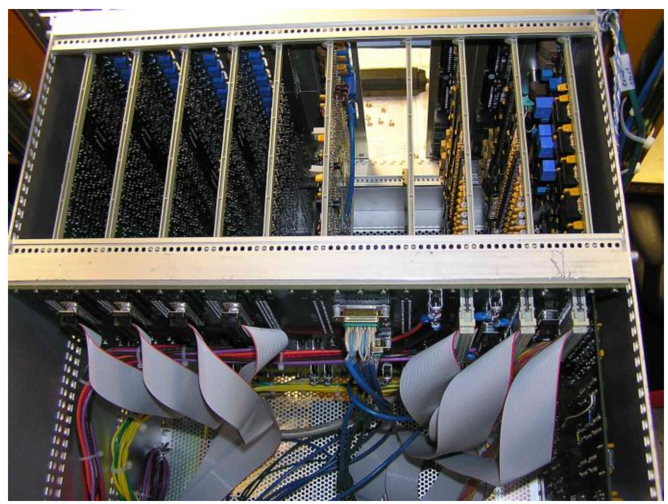
1.6 ms Pulse Transformer



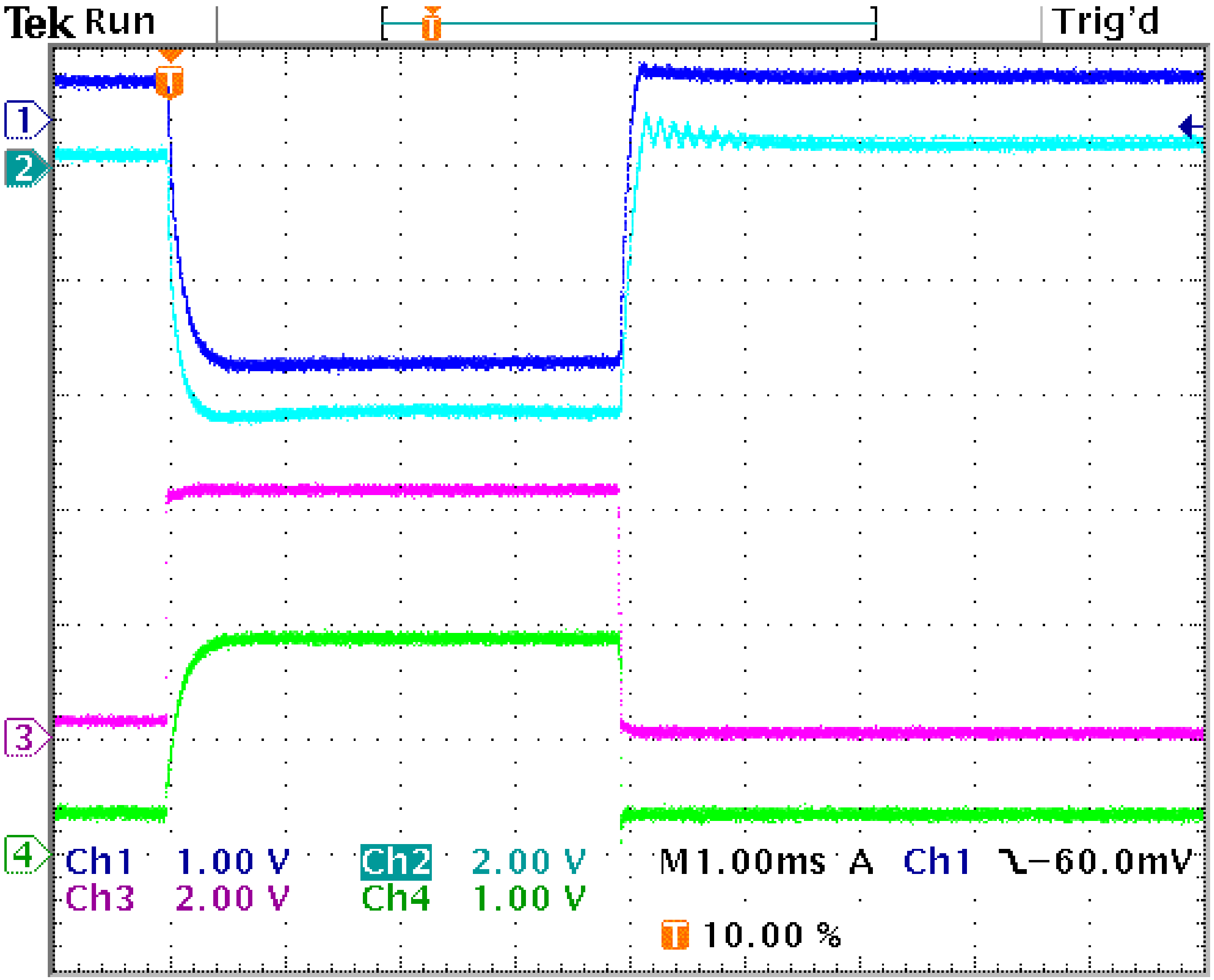
5.1 ms Pulse Transformer

Controls

- Custom hardware better suited to redundant switch control scheme
- Attempt to integrate non-RF interlocks of klystron and modulator
- Attempt to minimize number of connections and point to point wiring

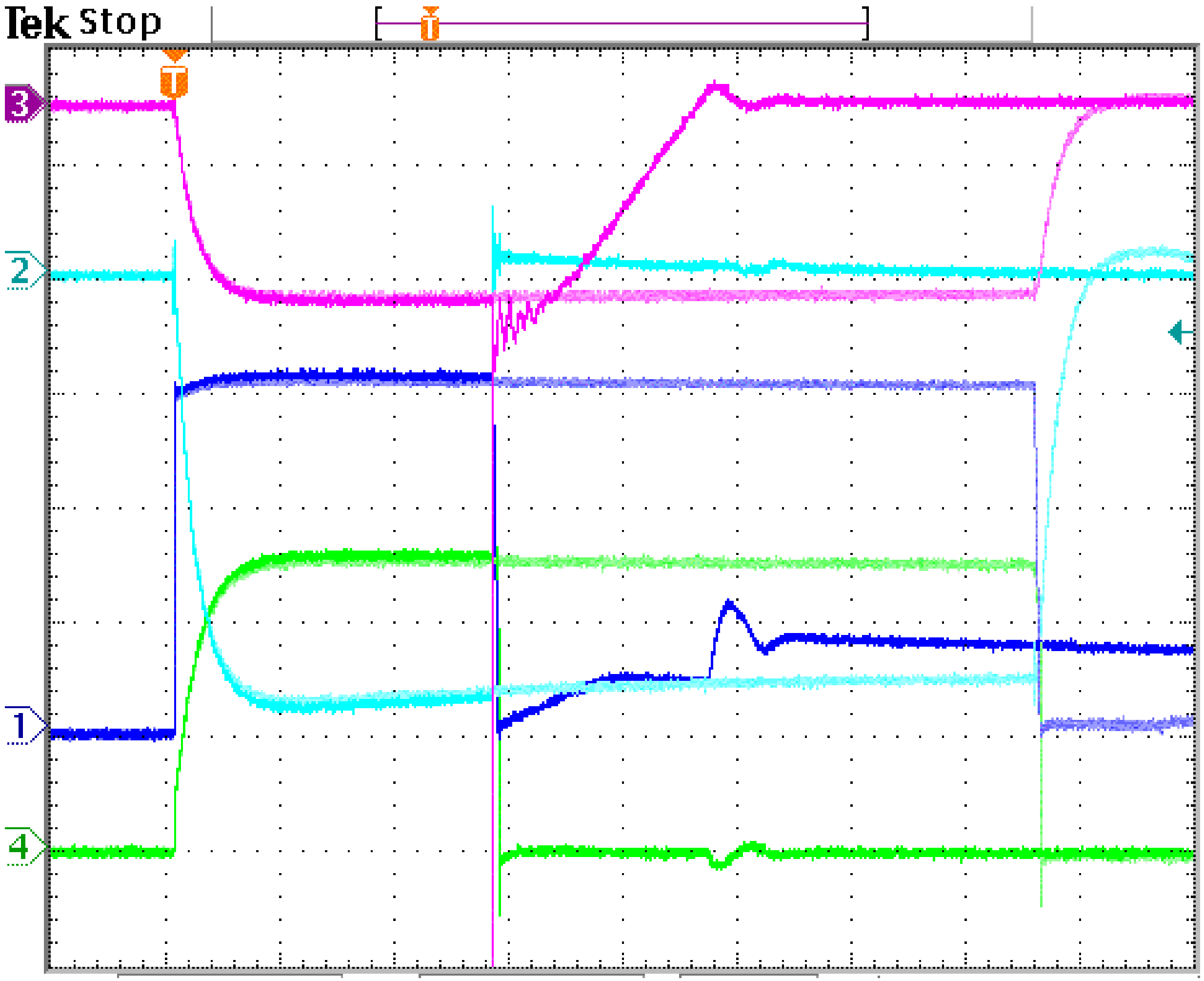


HINS Waveforms (Normal)



- Klystron Voltage (20 kV/V)
- Klystron Current (20 A/V)
- Transformer Primary Voltage (2 kV/V)
- Main Switch Current (400A/V)

HINS Waveforms (Gun Spark)



- Klystron Voltage (20 kV/V)
- Klystron Current (20 A/V)
- Transformer Primary Voltage (2 kV/V)
- Main Switch Current (400A/V)

FNAL Bouncer Modulator History at DESY

- First modulator has run for 40 khours
  - Running since 1993. Version 1 of Bouncer modulator, 2.4 ms pulse transformer
  - 6 GTOs for main switch + 2 GTOs for backup
  - Low energy density capacitors
  - Pulse transformer failure (secondary short)
  - Snubber resistor failure (connector material problem)
  - Main capacitor failure (case rupture)
  - Bad connection in main current path (loose bolted joint)
  - Having more reliability problems now

FNAL Bouncer Modulator History at DESY

- Second and Third modulators ran for ~ 30 khour each
  - Run since 1996
  - Version 2 of Bouncer and 1.8 ms pulse transformer
  - 12 IGBTs for main switch + 3 IGBTs for backup
  - Low energy density capacitors
  - IGBT driver failure (dead chip)
  - Charging / rectifier transformer failure
  - No longer in operations. Used for RF component testing

FNAL Bouncer Modulator History at FNAL

- HINS Modulator
  - Running since February 2007
  - Version 3 of Bouncer and 5.1 ms pulse xfmr
  - 325 MHz klystron, Horizontal w/ gun oil tank
  - 100 kV pulse on short cable from xfmr to klystron
  - High energy density capacitors
  - 6 IGBTs for main switch
  - Pulse length is 4.2 ms, 1 Hz, 2.5 MW Peak

FNAL Bouncer Modulator History at FNAL

- NML “Klystron 6” Modulator
  - Running since June 2010
  - Version 3 of Bouncer and 5.1 ms pulse xfmr
  - High energy density capacitors
  - 6 IGBTs for main switch
  - Pulse length 2.0 ms, 5 Hz, 11 MW Peak
  - Auxilliary snubber capacitor failure
    - No IGBTs failed, No klystron problems
    - Part not necessary, removed from circuit

Important Modulator Requirements

- Earliest specification / requirement is klystron sparking condition
  - Spark collapses output voltage in < 100ns
  - Usually the most difficult requirement and has significant cost associated with it
  - How much energy to let into a gun spark?
  - How does the modulator itself respond to the fast transient of a gun spark?
  - Does a single point failure of any component of modulator give much more energy into a gun spark?

Bouncer Modulator Example

- Spark energy limited to 20 J
  - Fast detection of gun voltage to gun current mismatch.
    - Also detect bad gun voltage or gun current monitor
  - Must remove energy of leakage inductance with undershoot network
    - TWO series undershoot networks, each one sufficient
    - Add MOV to absorb extra energy and limit reverse voltage on klystron
    - Voltage monitoring to make sure one network not shorted

Bouncer Modulator Example

- Spark energy limited to 20 J (contd)
  - Must turn off switch
    - Up to two switch elements can fail shorted and remaining switches still have margin
    - Switch dI/dt limited by pulse transformer leakage inductance
    - Double isolated gate driver transformers so with single failure do not have short
    - Switch will turn off when control power fails
    - Monitor gate power for each IGBT
    - Voltage monitors to detect shorted switch

Bouncer Modulator Example

- Spark energy limited to 20 J (contd)
  - Must turn off switch (contd)
    - Absolute over current protection
    - Two separate current monitors
    - Separate control paths from current monitor to gate control
    - No common element in control of gate signals
    - Check that independent gate controls always agree

Bouncer Modulator Examples

- How does modulator itself respond to spark transient?
  - Pulse transformer
    - Secondary windings need special grading at HV end to handle high dV/dt
    - Voltage and current monitor need higher bandwidth
    - Added low inductance capacitor from primary low side to ground to conduct fast transient
    - Heater leads are inside coaxial shield to prevent voltage spike across heater

Important Modulator Requirements

- Always test modulator for spark condition
  - Test should include full system if modular
  - Test each system for spark response
- Always test a prototype at full operating conditions.
  - Test as long as possible, 1 year preferred
  - Test at maximum peak power, maximum repetition rate, specified regulation
    - Need a load capable of full power

Important Modulator Requirements

- Consider other fault conditions
  - Can switch(es) turn off?
  - Control power failure?
  - Is there a single component failure that damages expensive components?
- Are there controlled/low impedance circuits from high energy sources to loads?
  - Supply and return routing for low EMI?

Bouncer Modulator Example

- Precautionary items added
  - Added 50 uH choke in primary to limit dI/dt if fault at switch output (protect expensive switch)
  - Added 0.05 ohm resistors in series with main capacitor to limit energy into a single faulted capacitor
  - Modulator, charging supply and solenoid each have a water flow switch and a temperature switch for redundancy
  - Triaxial cable from modulator to pulse transformer has large area cores around supply and return to force “noise” currents into return instead of shield

Bouncer Modulator Example

- Precautionary items added (contd)
  - Single point ground of charging supply and modulator, ground current monitor
  - Controls hardware limit voltage, pulse width and repetition rate
  - Redundant control power supplies and detection of failure

Important Modulator Requirements

- Monitors, Controls and Interlocks
  - Sufficient number of voltage and current monitors to isolate problems
    - Build into design, more monitors better for prototype
  - Fast latching of trip status (< μs)
  - What happened first?
  - Filtering of trips consistent with required response time

Bouncer Modulator Example

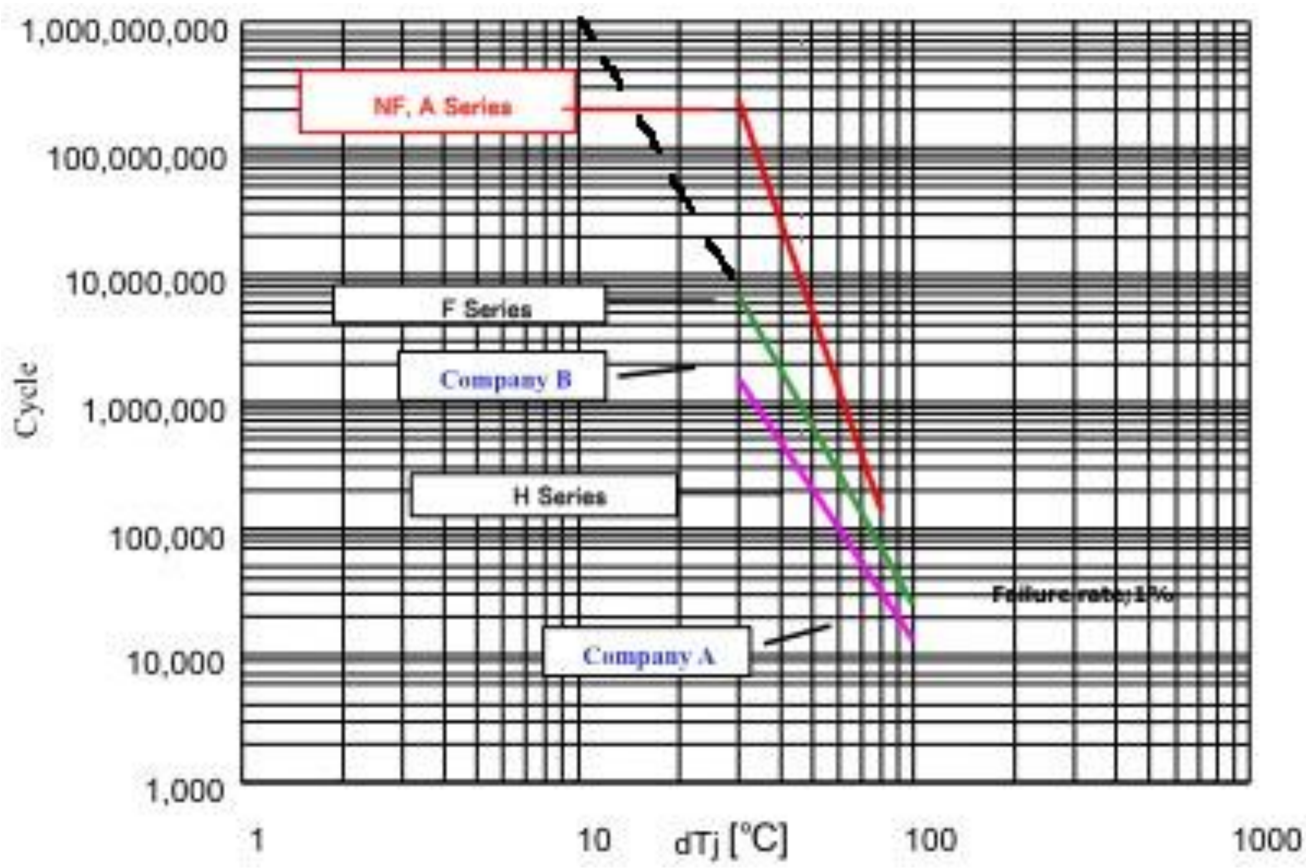
- FNAL custom controls meet all these requirements
  - Thermal trips can have several ms time response and don't need to inhibit mid pulse, avoid noise trips
  - All status latched in a less than a µs. First fault determined
  - All PLC trips have a backup using a different sensor wired directly to modulator interlocks. PLC sums trips into just a few classes.

Important Modulator Requirements

- What is required availability for the system?
  - Availability drives many modulator component choices
    - Voltage stress of components
    - Temperature cycling of components
  - Availability drives how you monitor and fix modulator
    - Is something broken? What? Troubleshooting time?
    - How to isolate occasional problems?
  - Availability drives mechanical design of modulator
    - Ease of repair, working space
    - Leave space for changes, even in production units

Temperature Cycling Curve

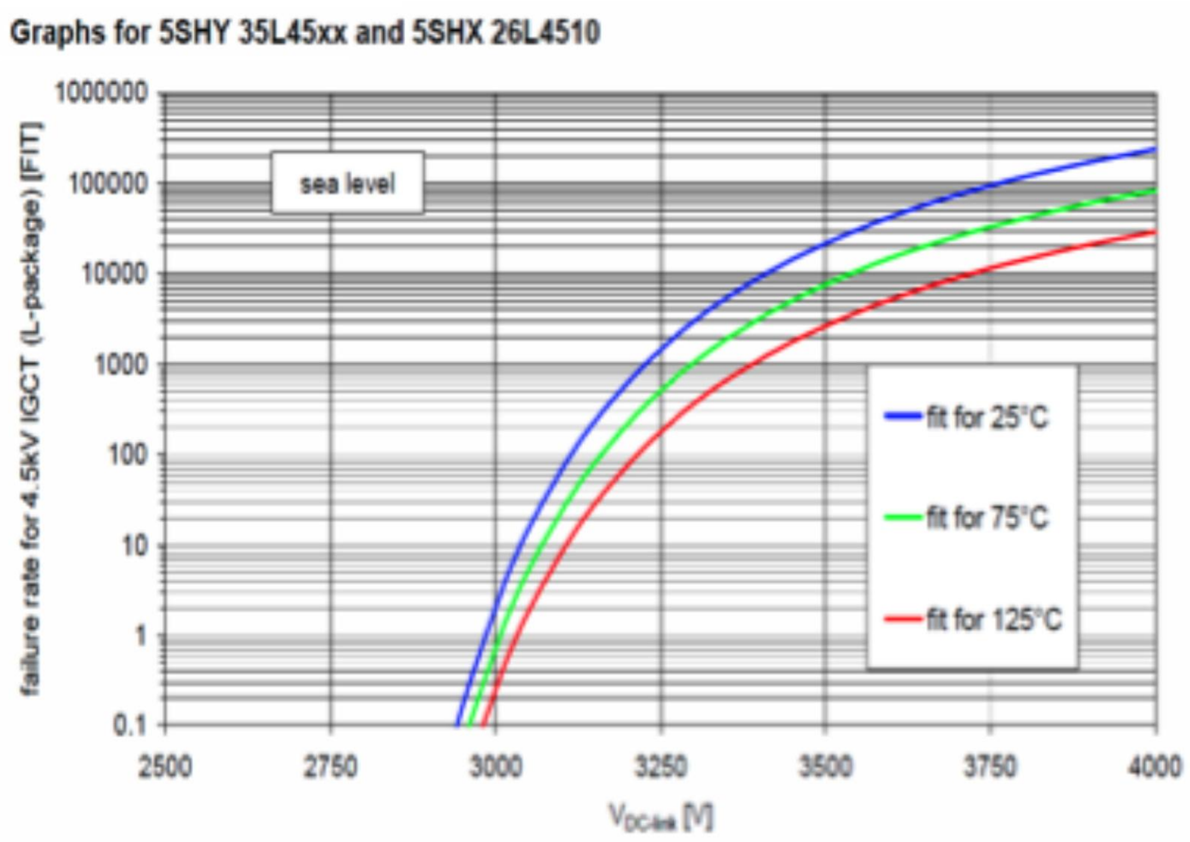
Powerex Data, 1% Failure of Parts, Possible Extrapolation,
14 Hz = 5 10^8 / year



Cosmic Ray Failure Curve

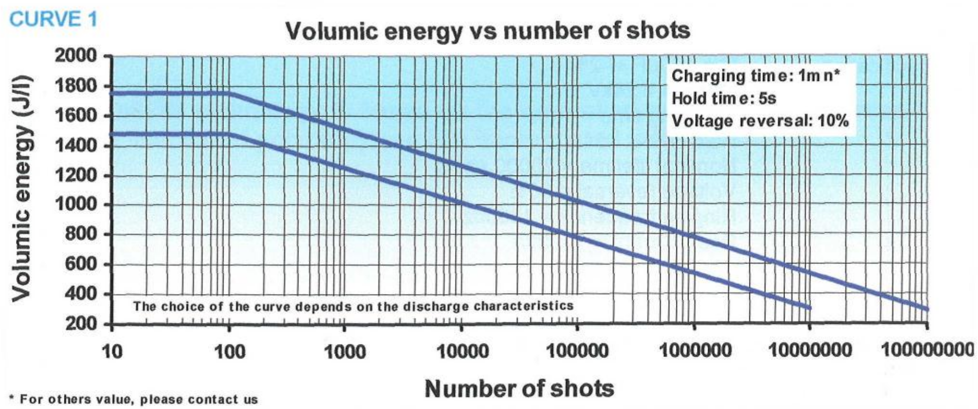
ABB IGCT Data, 1 FIT =1 Failure/10^9 Hrs, ~ 1 / 10^5 years

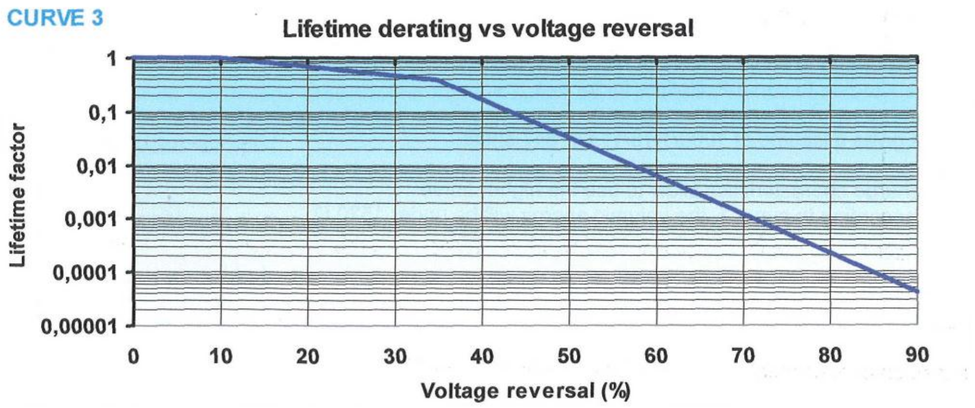
Higher voltage devices have same failure rate at lower fraction of voltage

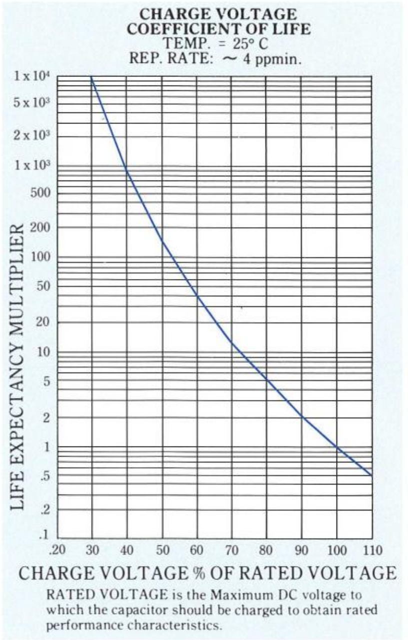


Typical Capacitor Life Curves

AVX and Maxwell Metalized Film Data





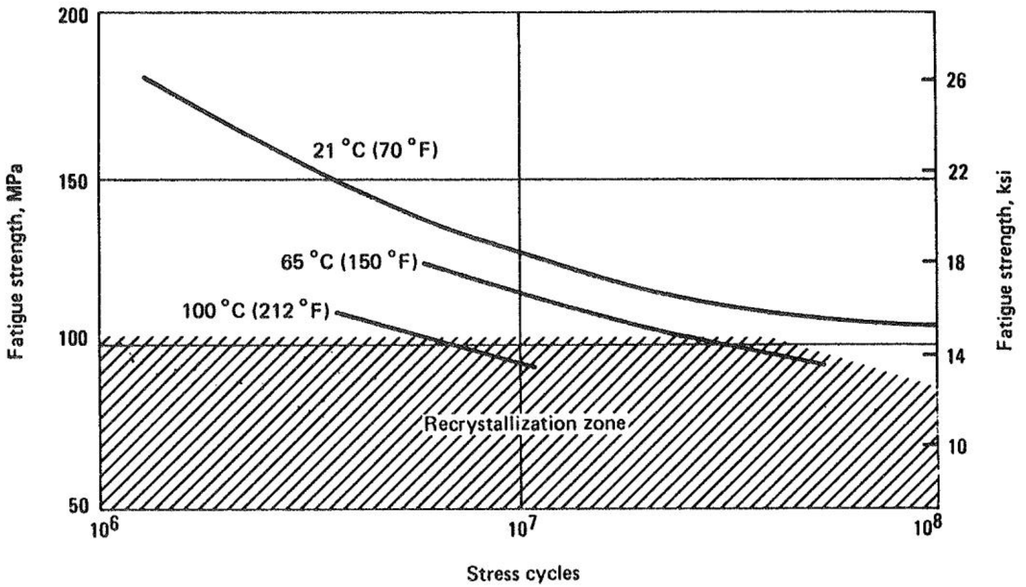


Mechanical Cycling Curve

(Not a problem for most modulators, some magnetic components)

Repetitive Stress, Bipolar (0.5% Extension for C11000 is ~100 MPa)

13-3. Copper Alloy C11000 (ETP Wire): Effect of Temperature on Fatigue Strength



Rotating-beam fatigue strength of electrolytic tough pitch copper, C11000 wire, 2 mm (0.08 in.) diam, H80 temper when tested at various temperatures.

Bouncer Modulator Example

- Required availability high
  - Voltage stress on IGBTs < 50%
  - Junction temperature cycling on main IGBT is 10 C for 10^9 pulses
  - Specified lifetime (10% failure) of main capacitor bank and bouncer capacitor bank was 130,000 hours or 4 x 10^9 pulses each at maximum operating level, repetition rate and temperature

Bouncer Modulator Example

- Required availability high
  - Specified lifetime (10% failure) of bouncer inductor was 4 x 10^9 pulses at maximum operating level, repetition rate and temperature
  - All power components had specified faults that could occur 10000 times

ESS Modulator Comments

- A thorough knowledge of the modulator is a great goal – you will maintain
- Current production schedule (Sept 2013) discourages any unproven design
  - Proven means tested at maximum peak and average power level, repetition rate and pulse length for a year
- Need at least another year to qualify an unproven design

ESS Modulator Comments

- IF production can delayed and ESS decides to go ahead with new topology
  - Consider building two different topologies
  - One prototype based on most recent experience, many lessons learned
    - E.g. Marx P2 could meet many of your design requirements
  - One prototype based on new topology

ESS Modulator Comments

- Modulator stated preference is modular and resonant. How to implement modularity?
  - High availability of modulator *can* be improved with modular components
    - Need redundancy designed in from beginning
    - Single point failures have to be bypassed
  - Where does modularity end? Charging supply? Controls? What is system requirement?
    - Proposed topology from last review had single point failure at high voltage transformer

ESS Modulator Comments

- Modulator stated preference is modular and resonant. Why resonant?
  - Junction temperature and voltage have to be controlled in any case
  - Switching losses are just one contribution to device failure
  - A single on / off transition per pulse has very low switching losses
  - Is low EMI the driving requirement?

ESS Modulator Comments

- Summary Comments
  - Design and test all modulators for spark conditions
  - Specify power components conservatively
  - Need a year of testing on any new design to qualify
  - Current schedule limits choices
  - If schedule allows, consider parallel paths

Thank you

Bouncer Modulator Example

- Monitors, Controls and Interlocks
  - Voltage monitors at input, output and near midpoint point of switch, capacitor bank, bouncer capacitor bank and charging supply. Current monitor for line current, charging current, ground current, bouncer current, switch current (x2) and klystron current.
  - All monitors are differential output, passive, custom current transformers and voltage monitors (corona free)
  - All monitors have a buffered version of signal for use in troubleshooting.
  - Custom interlock and control hardware. Topology best suited for bouncer modulator and redundancy. No problem with manufacturers not supporting backplane. Significant initial manpower.

General FNAL Practices

- Monitors, Controls and Interlocks
  - Contacts have > 20 mA & > 24 V for long term reliability
  - Signals run with return to help reduce EMI
  - Use split lock / spring washers on pulsed equipment
  - Smoke detectors inside high power cabinets for magnetics & capacitors