Pulsed Power Engineering Introduction

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Acknowledgments

- Portions of the course material (as noted) were excerpted from:
  - “Pulse Generators for Accelerator Applications” by Edward Cook of LLNL, which was presented at the USPAS 1/13-17/2003, credited E Cook
  - “Pulsed Power Short Course” edited by M. Kristiansen of Texas Tech University, which was presented 1/6-9/2004, credited TTU-PPSC, TTU, or by author
- Course contributions by other members of the SLAC staff
  - Power Systems Development Group: T. Beukers, J. Krzaszczak, and T. Tang
  - Power Conversion Dept.: J. Craft
  - Klystron Dept: A. Krasnykh
- In addition to the aforementioned, supplemental materials presented with this course include:
  - “Principles of Charged Particle Acceleration,” Stanley Humphries Jr., Wiley, 1999, available at fieldp.com
  - “NRL Plasma Formulary,” J.D. Huba, NRL, 2007 edition, available at www.ppd.nrl.navy.mil/nrlformulary
  - “Pulsed Power Formulary,” Richard J. Adler, North Star Power Engineering, 2001 edition, available at highvoltageprobes.com/PDF/formweb1.pdf
  - “The Stanford Two-Mile Accelerator, the Blue Book, Chapter 13-Modulators,” R.B. Neal ed., 1968, available at ww.slac.stanford.edu/library/2MileAccelerator/2mile.htm
- Software
  - QuickField (EM field simulation): QuickField, quickfield.com
  - LTspice (circuit simulation): Linear Technology, linear.com
- Work at SLAC supported by the U.S. Department of Energy under contract DE-AC02-76SF00515

Course Outline

- Introduction
- Materials/Passive Components and Devices
- Switching Devices
- Basic Topologies
- Advanced Topologies
- Diagnostics
- Engineering Simulation
- Circuit Simulation

What Is Pulsed Power?

- The conversion (modulation) of electrical energy from the waveforms typically found in transmission systems (50/60 Hz ac or dc) to pulsed waveforms that are required for specific application.
- Modulators are devices that modulate electrical energy.

Where Is Pulsed Power Used?

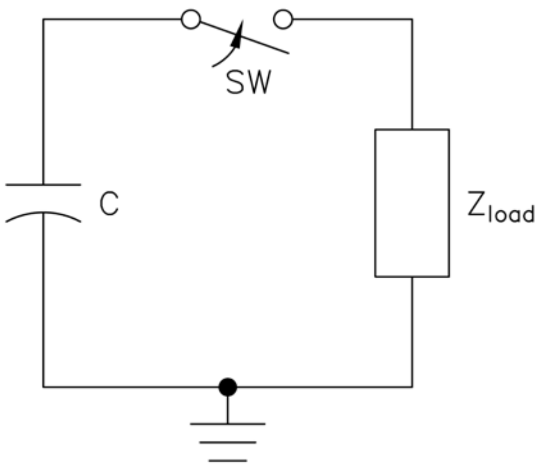
- Applications where large instantaneous power (kW – TW) is required, but cannot be applied continuously.
  - Drive a klystron (rf source) which can only handle an average power that is a fraction of the peak power needed to generate the required rf output.
    - SLAC 5045 (S-band): 360 kV, 0.41 kA, 3.5 μs, $P_{peak} \approx 0.15$ GW, $P_{ave} \approx 65$ kW
    - ILC (L-band): 120 kV, 0.14 kA, 1.6 ms, $P_{peak} \approx 17$ MW, $P_{ave} \approx 0.14$ MW
    - SLAC XP4 (X-band): 500 kV, 0.25 kA, 1.6 μs, $P_{peak} \approx 0.13$ GW, $P_{ave} \approx 50$ kW
  - Charged Particle Induction Accelerator
    - LLNL Advanced Test Accelerator (ATA): 50 MeV, 10 kA, 70 ns, $P_{peak} \approx 0.5$ TW, induction cell cores saturate after ~70 ns
  - Inertial fusion
    - SNL Z-machine: 5 MV, 25 MA, 0.2 μs, $P_{peak} \approx 120$ TW (~40X the world's electrical generating capacity)

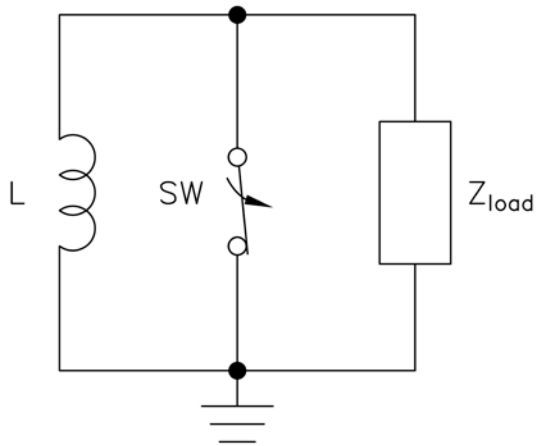
Where Is Pulsed Power Used? (cont.)

- Applications where a modulation pattern is required
  - Corona discharge reactor for electro-chemical processing: a fast rising voltage pulse produces the high energy electrons that catalyze chemical reactions
- Charged particle beam kickers
  - Damping rings typically contain multiple bunches that must be individually kicked in/out of the ring: proposed ILC DR bunch spacing is 3 – 6 ns
  - DARHT-II: kickers chop 4 beamlettes out of 2 kA, 2 μs beam
- Laser/Flashlamp discharges: want short duration light pulses
- Plasma discharges: waveform shape may be essential for plasma
  - Formation
  - Confinement
  - Compression
- "Pattern" radar: information contained in modulation pattern

How Is Electrical Power Modulation Achieved?

- Store energy
  - Capacitor: voltage
  - Inductor: current
- Switch energy to load
  - Electro-mechanical relay
  - Vacuum tube
  - Gas discharge
    - Spark-gap
    - Thyratron
    - Plasma opening switch
  - Solid-state
    - Transistor
      - IGBT
      - MOSFET
    - Diode
      - Avalanche
      - Opening switch
- Match to load behavior





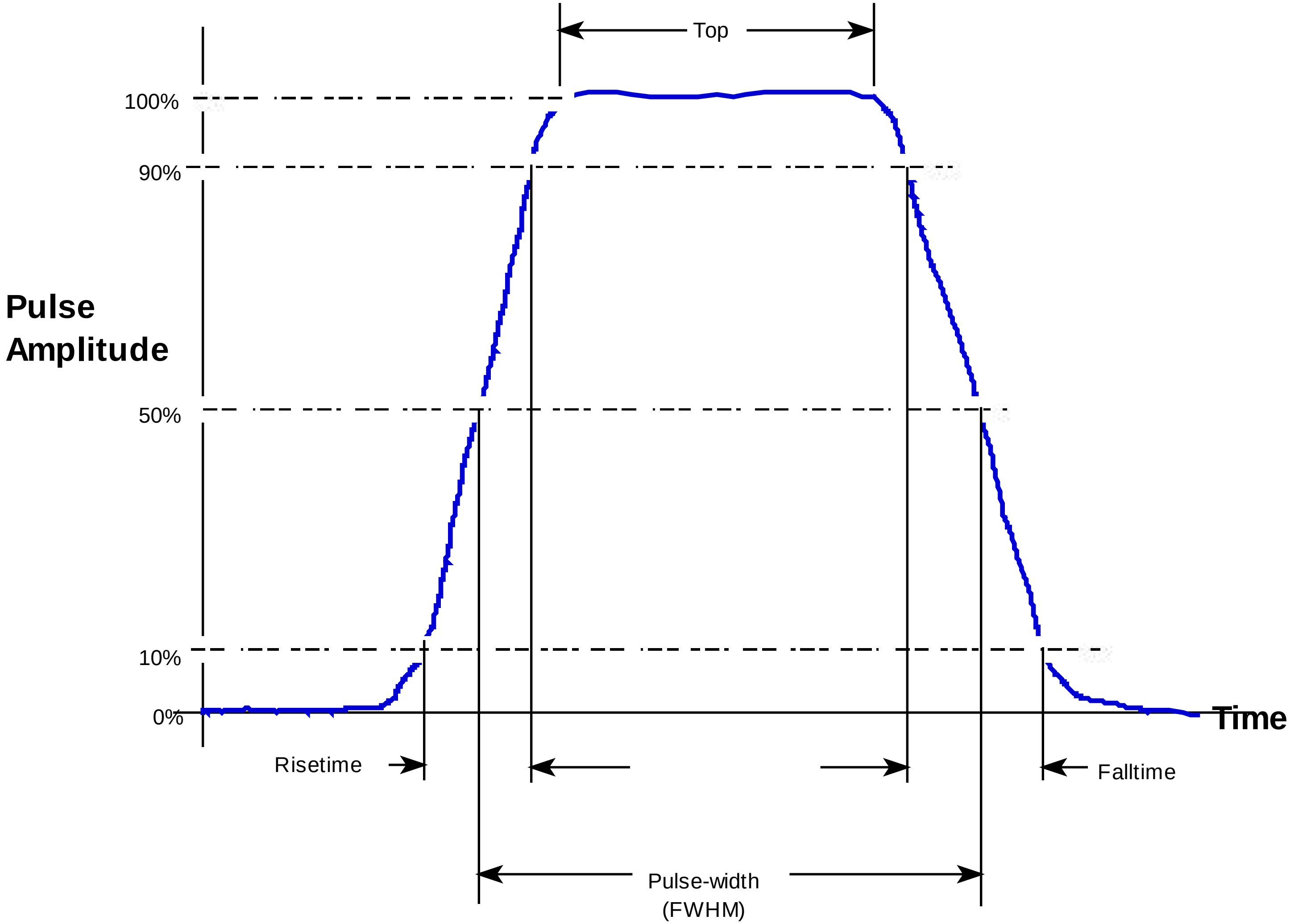
Why Are Other Topologies Required?

- To overcome device limitations
  - Voltage/Current/Power limitations
  - Parasitic behavior: L, R, C
  - Finite switch turn on/off times
  - Switch control requirements/errors
  - Limited lifetime/duty factor/pulse repetition frequency (prf)
- Protect (people and equipment) from device failures
  - Load damage from excess energy deposition
  - Catastrophic release of stored energy
- Cost

Defining Parameters for Pulses and Pulse Generators

- Pulse Duration (τ) - time duration of pulse (may be defined several ways; example: Full Width Half Maximum (FWHM))
- Pulse shape - pulse amplitude as function of time
  - Leading edge (risetime)
  - Top
  - Trailing edge (falltime)
- Pulse power (P_{pulse}) - product of pulse voltage and pulse current
- Peak power (P_{peak}) - largest instantaneous value of P_{pulse} : ($P_{peak} \geq P_{pulse}$)
- Average power (P_{avg}) - $P_{avg} = (\tau/T_r)(P_{pulse}) = \tau*(PRF)*(P_{pulse})$ where T_r is the time interval between the beginning of one pulse and the beginning of the next pulse
- Pulse repetition frequency (PRF) - $1/T_{r)}$
- Duty cycle - $\tau(PRF)$
- Internal impedance - the characteristic impedance or source impedance of a pulse generator

Pulse Shape Parameters

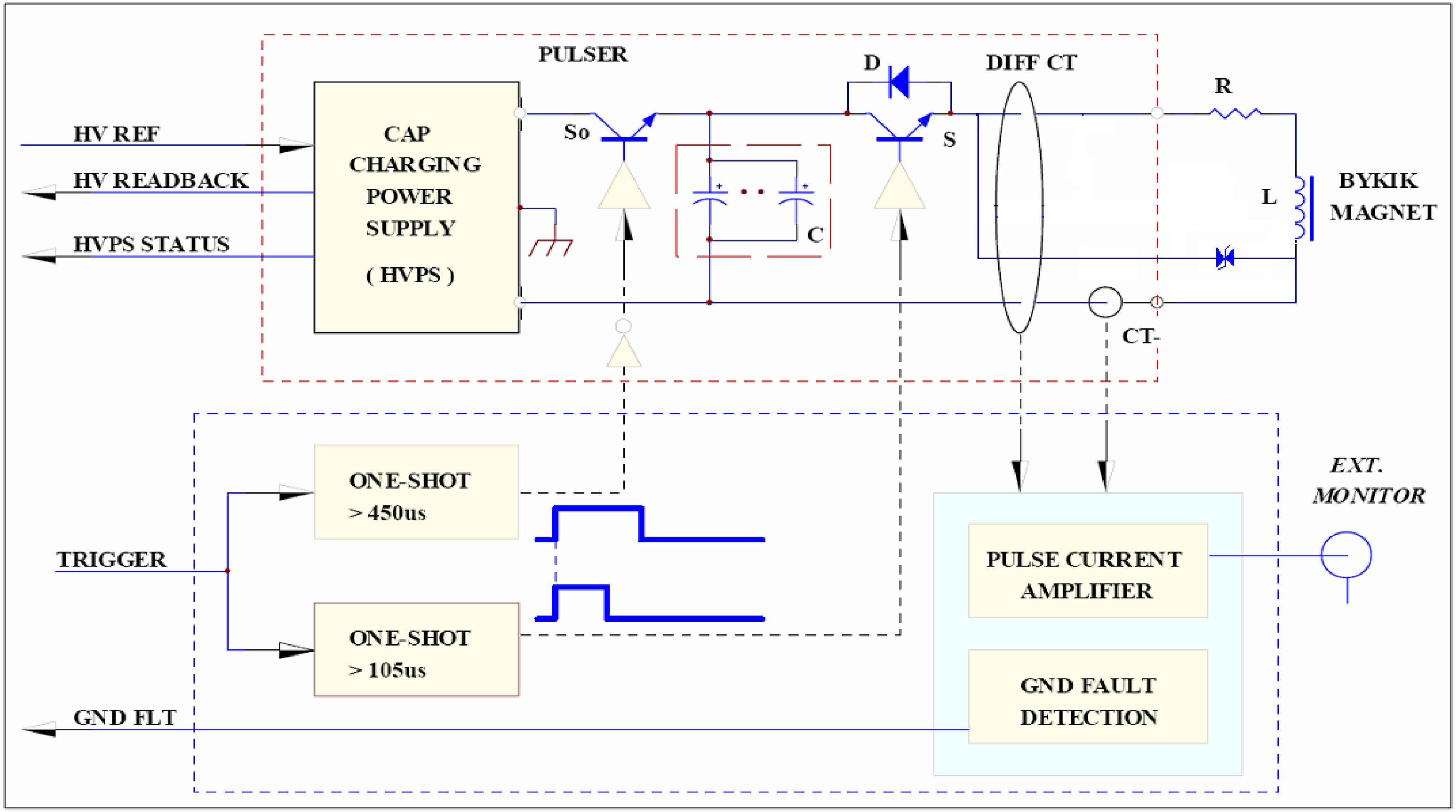


Pulse Waveshape

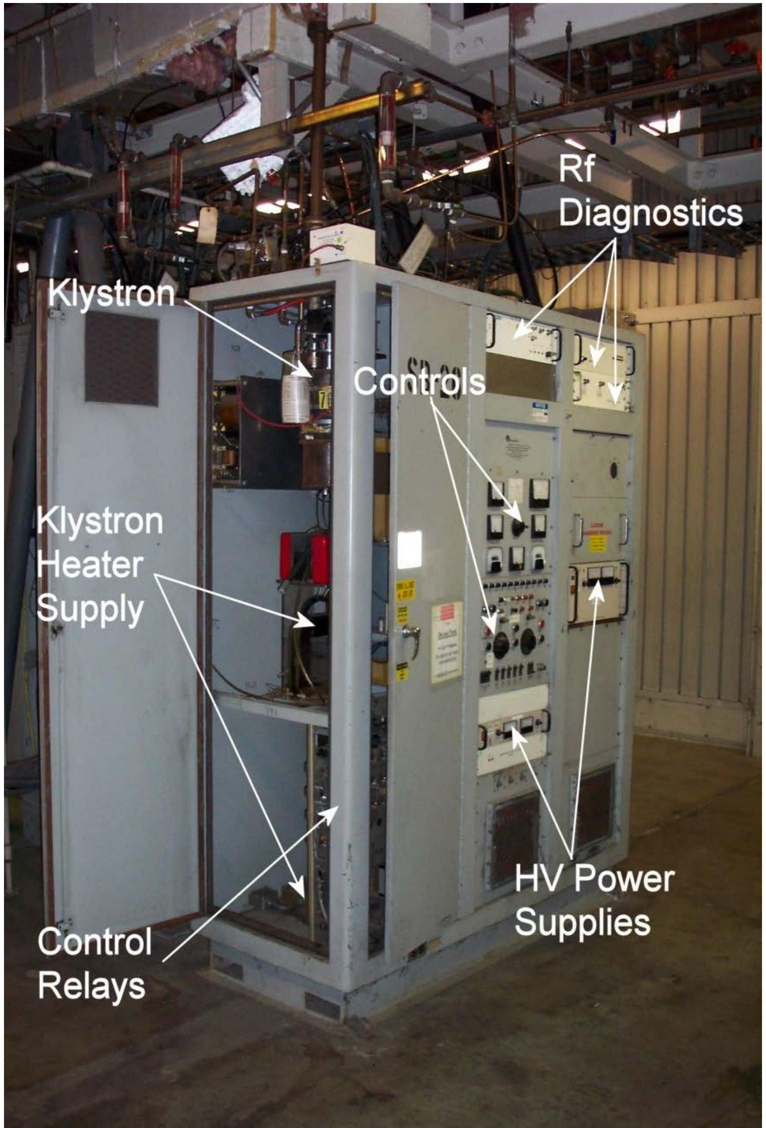
Basic Modulator Topologies

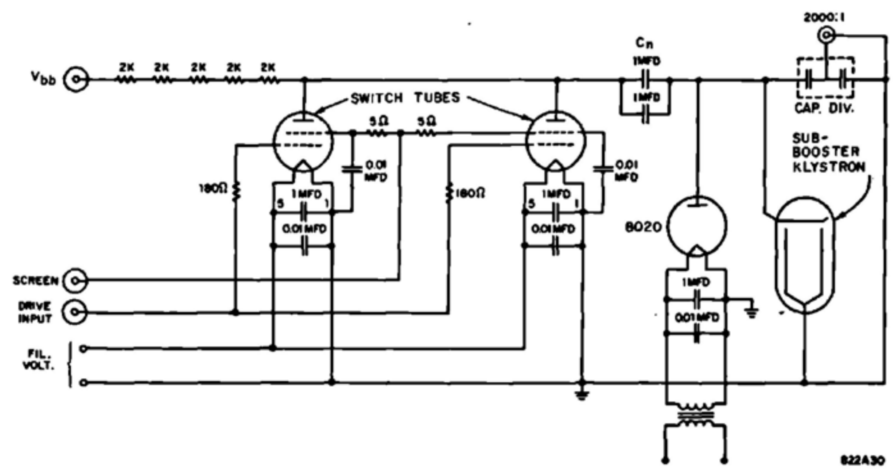
- Capacitor Discharge
  - Load: R, L, C (energy transfer)
  - Circuit behavior: under/critically/over damped
- Hard tube
  - Traditionally used vacuum tube switch: triode/tetrode/pentrode
  - Modern implementations use solid state switch: IGBT, MOSFET
- Line type
  - Pulse forming line (PFL)
  - Pulse forming network (PFN)
    - Discrete element approximation of PFL, used for longer pulse duration
  - Blumlein
    - Nested PFLs
- Transformer coupling of any of the above
  - Transforms V/I/Z from convenient range for modulator to range required for load

Capacitor Discharge: LCLS BXKIK/BYKIK

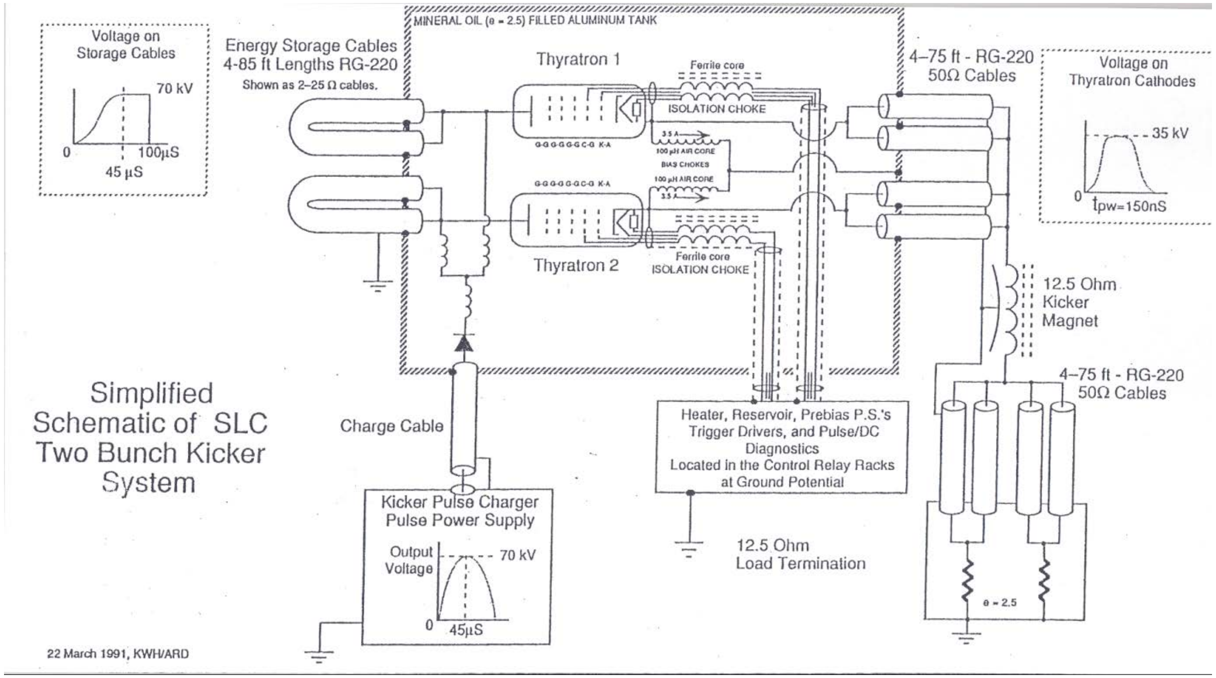


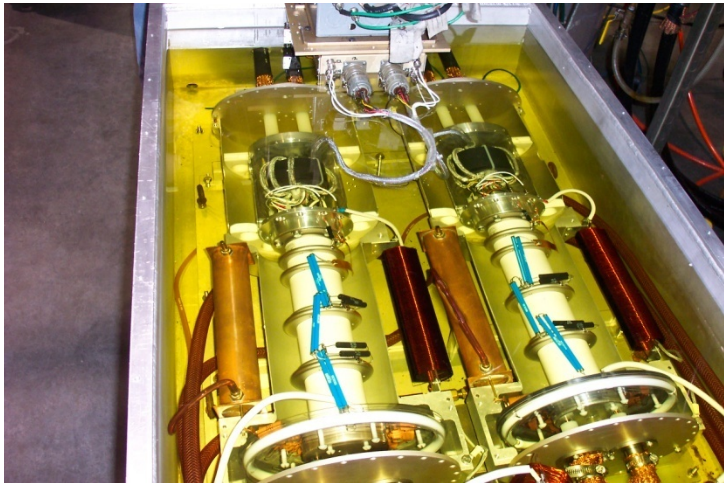
Hard Tube: SLAC Sub-booster



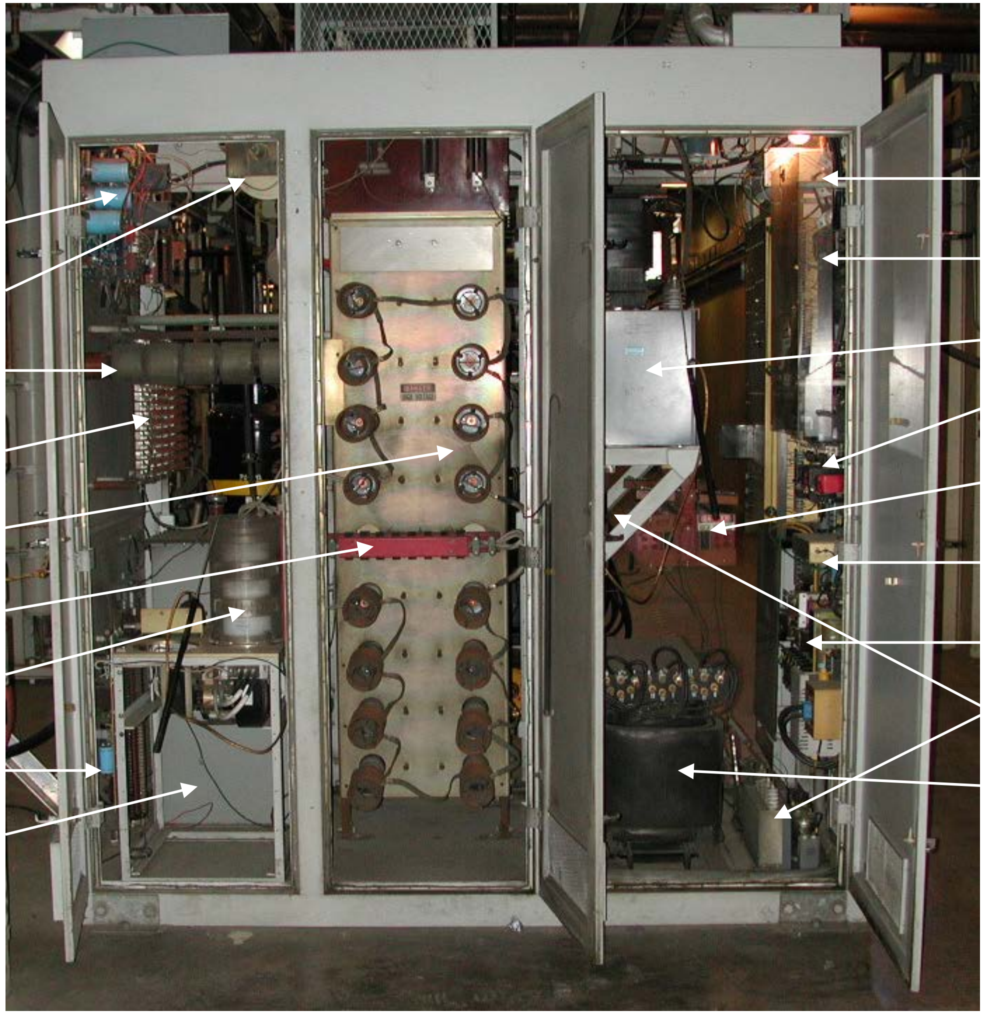


Pulse Forming Line: SLAC North DR Kicker





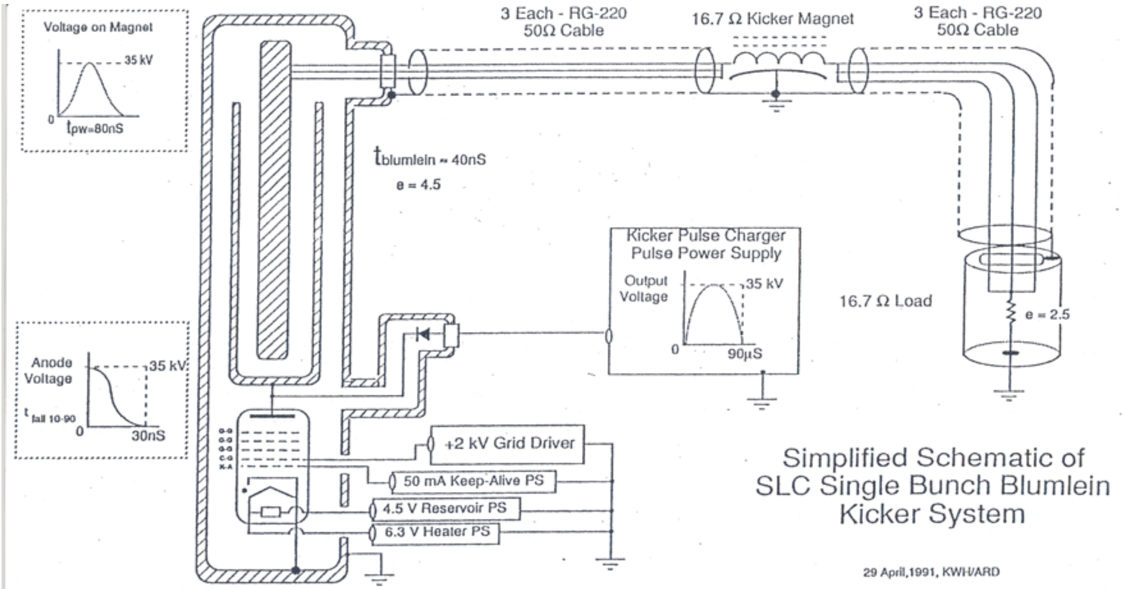
Pulse Forming Network: SLAC 6575

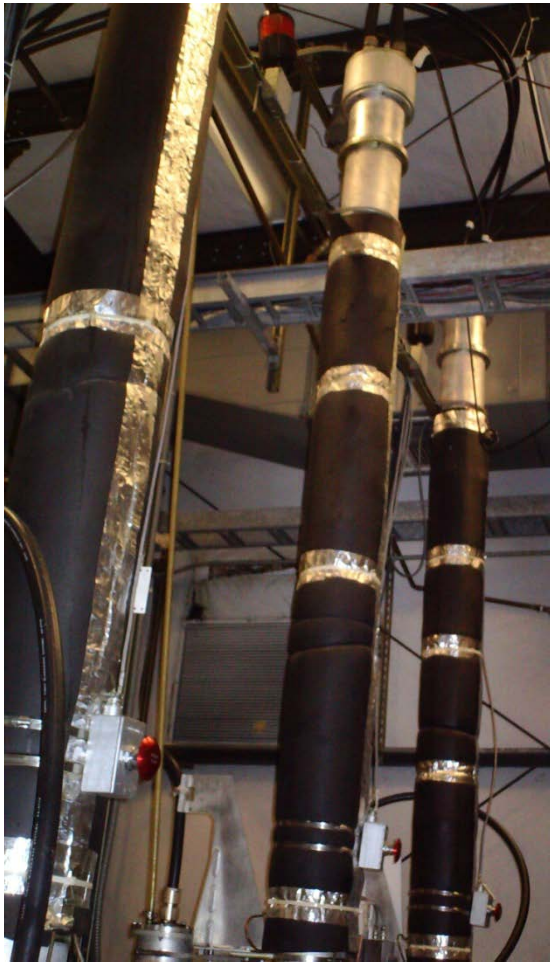


Energy Recovery Circuit
Capacitor Discharge Switch
De-spiking Coil
Charging Diode
Pulse Forming Network
Anode Reactor
Thyratron
Keep Alive Power Supply
Charging Transformer

Step Start Resistors
600VAC Circuit Breaker
Filter Capacitors
Contactors
Full Wave Bridge Rectifier
De-Qing Chassis
Power Supply
AC Line Filter Networks
Power Transformer (T20)

Blumlein: SLAC South Damping Ring Kicker





Advanced Modulator Topologies

- Marx
  - Basic Marx
  - Solid state Marx
  - Inversion generator
  - Stacked Blumlein
  - PFN Marx
- Adder topologies
  - Inductive
  - Transmission line
- Resonant converter-modulator
- Magnetic pulse compression
  - Magnetic modulator
  - Branched magnetics
- Opening switch PFL