# Pulsed Power Engineering: Introduction

U.S. Particle Accelerator School
University of New Mexico

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June 24 – 28, 2019

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

# Acknowledgments


- The authors wish to acknowledge the contributions of current and former colleagues
  - A. Benwell, T. Beukers, J. Craft, A. Krasnykh, J. Krzaszczak, K. Macken, and T. Tang: SLAC National Accelerator Laboratory
  - E. Cook: Lawrence Livermore National Laboratory
- Our thanks for software tools provided at no cost to the USPAS
  - Tera Analysis – producers of QuickField (EM field simulation), http://quickfield.com/
  - Linear Technology Corp. – producers of LTspice (circuit simulation), http://www.linear.com/

- Students may find the following supplemental materials useful when working in the field of pulsed power engineering:
  - "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.nrl.navy.mil/ppd/content/nrl-plasma-formulary
  - "Pulsed Power Formulary," Richard J. Adler, North Star Power Engineering, 2002 edition, available at www.highvoltageprobes.com/downloads
  - "The Stanford Two-Mile Accelerator, the Blue Book, Chapter 13-Modulators," R.B. Neal ed., 1968, available at: www.slac.stanford.edu/library/2MileAccelerator/2mile.htm
  - "Pulse Generators," G.N. Glasoe & J.V. Lebacqz eds., 1948, available at: www.jlab.org/ir/MITSeries.html


- Work at SLAC supported by the U.S. Department of Energy under contract DE-AC02-76SF00515

# Course Outline

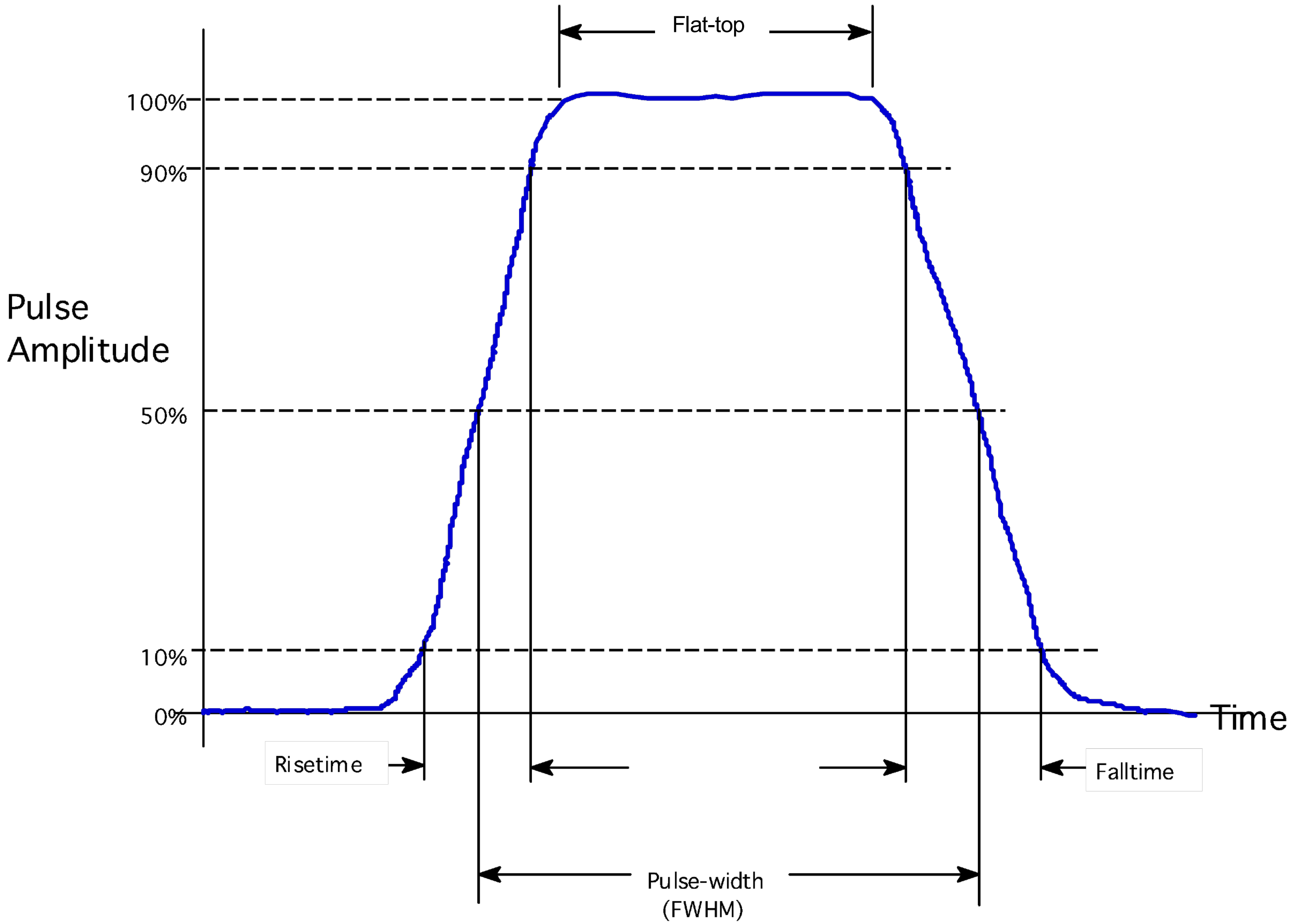
- Introduction
- Switching Devices
- Materials/Passive Components and Devices
- Basic Topologies
- Advanced Topologies
- Engineering Simulation – Quickfield
- Circuit Simulation – LTspice

# 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 temporally and amplitude modulated waveforms that are required for specific application.

- Modulators are devices that modulate electrical energy.

# Pulse Shape Parameters



# Defining Parameters for Pulses and Pulse Generators

- Pulse-width ($\tau$): time duration of pulse (may be defined several ways, e.g. flat-top, or Full Width Half Maximum (FWHM))
- Rise-time: time duration of leading edge (typically 10 – 90% of maximum, may be 0 – 100% in critical applications)
- Fall-time: time duration of trailing edge (typically 10 – 90% of maximum, may be 0 – 100% in critical applications)
- Pulse repetition frequency (PRF): number of pulses per second
- Duty cycle (or duty factor): $\tau$(PRF)
- Pulse power ($P_{pulse}$): product of pulse voltage and pulse current
- Pulse energy ($E_{pulse}$): time integral of $P_{pulse}$ over duration of pulse
- Peak power ($P_{peak}$): maximum instantaneous value of $P_{pulse}$
- Average power ($P_{avg}$): $P_{avg} = (E_{pulse})$* (PRF)
- Internal impedance - the characteristic impedance or source impedance of a pulse generator

# Where Is Pulsed Power Used?

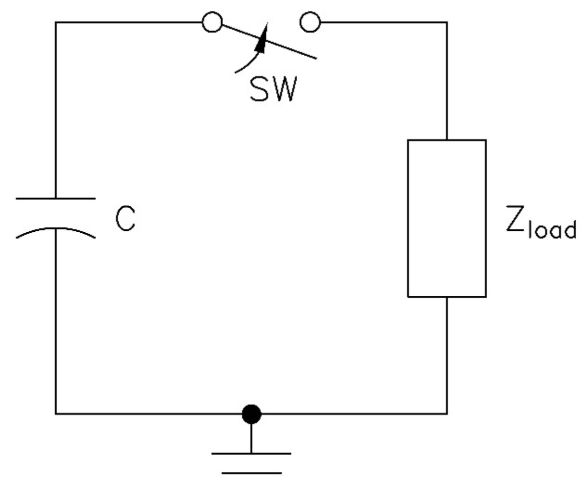
- Applications where large instantaneous power (kW – TW) is required, but cannot be applied continuously.
  - Pulsed RF accelerator microwave source (klystron)
    - SLAC 5045 (S-band): 360 kV, 0.41 kA, 3.5 μs, $P_{peak} \approx 0.15$ GW, $P_{ave} \approx 65$ kW
    - ILC (L-band): 120 kV, 0.14 kA, 1.6 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
    - Average power capacity of both tube and structure is a fraction of peak power required for particle acceleration
  - 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

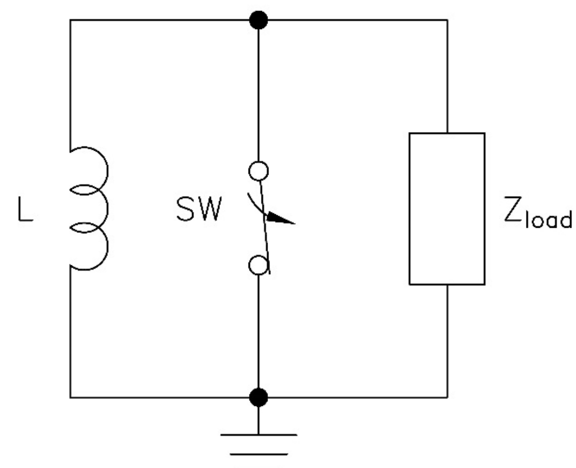
# Where Is Pulsed Power Used? (cont.)

- 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
  - “Pattern” radar: information contained in modulation pattern
- 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, 3 – 6 ns
  - DARHT-II: kickers chop 4 beamlets out of 2 kA, 2 μs beam
- Plasma discharges: waveform shape may be essential for plasma
  - Formation
  - Confinement
  - Compression
- Laser & flashlamp discharges: want short duration light pulses

# 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
- Commutate pulse



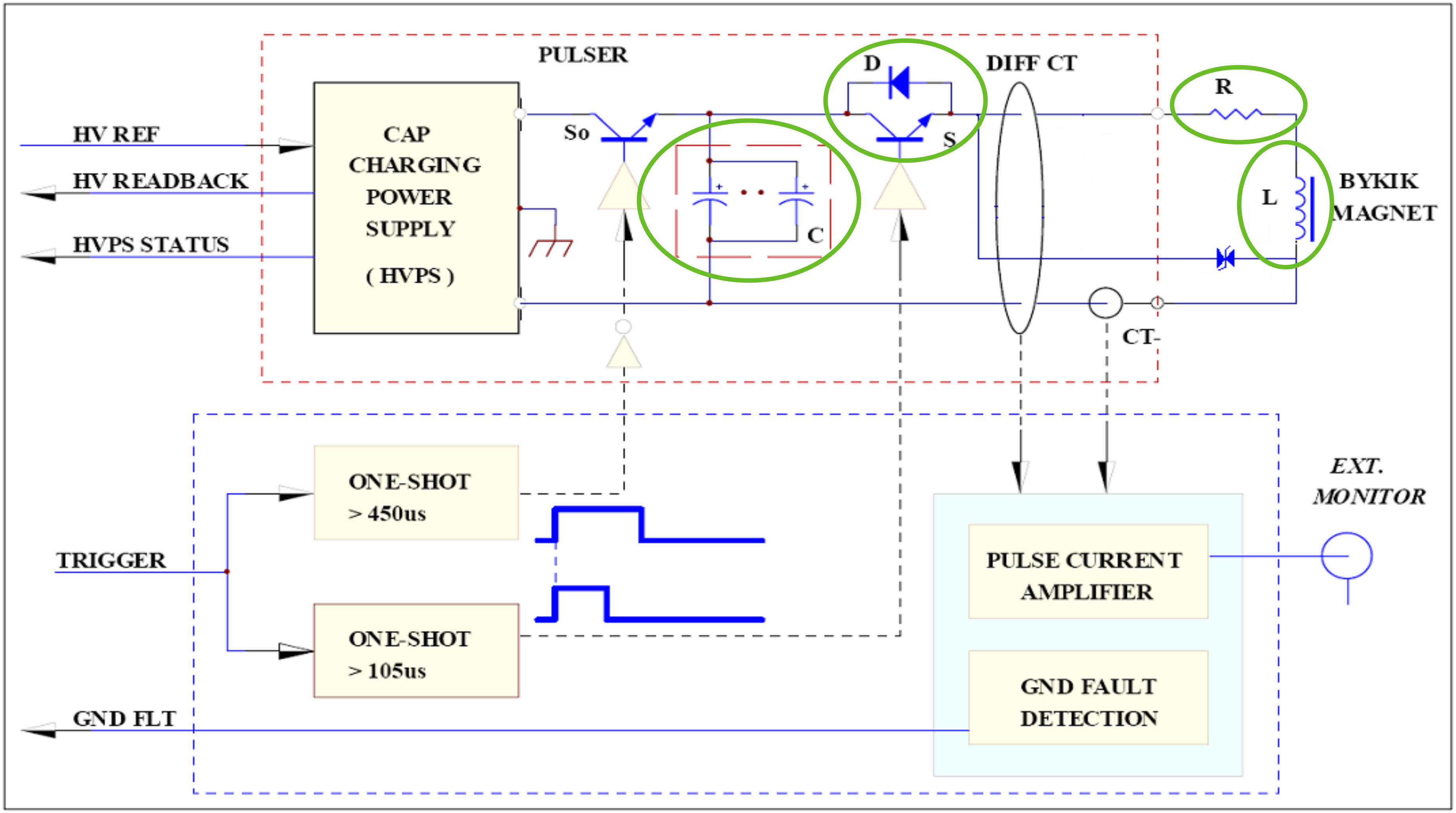
# Why Are Other Topologies Required?

- 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

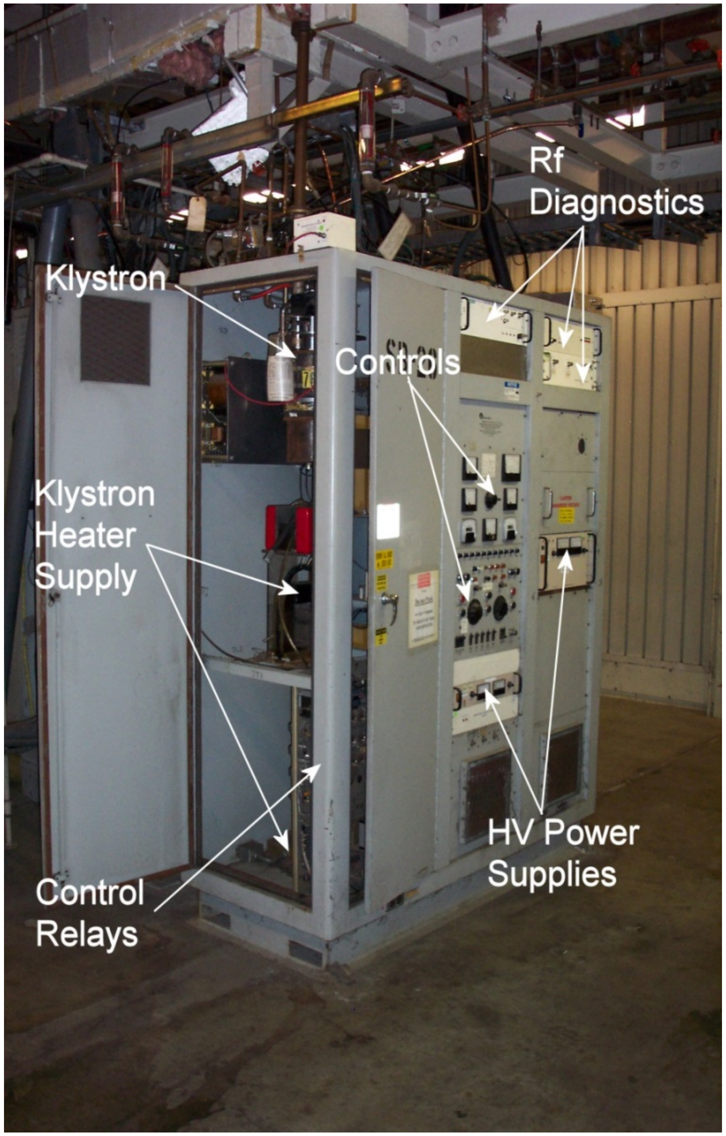
# Basic Modulator Topologies

- Capacitor Discharge
  - R, L, C (energy transfer)
  - Circuit behavior: under/critically/over damped
- Hard tube
  - ~Ideal source (large capacitor) controlled by opening/closing switch
  - Traditionally used vacuum tube switch: triode/tetrode/pentrode
  - Modern implementations use solid state switch: IGBT, MOSFET
- Line type
  - Transmission line energy storage controlled by opening or closing switch
  - 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

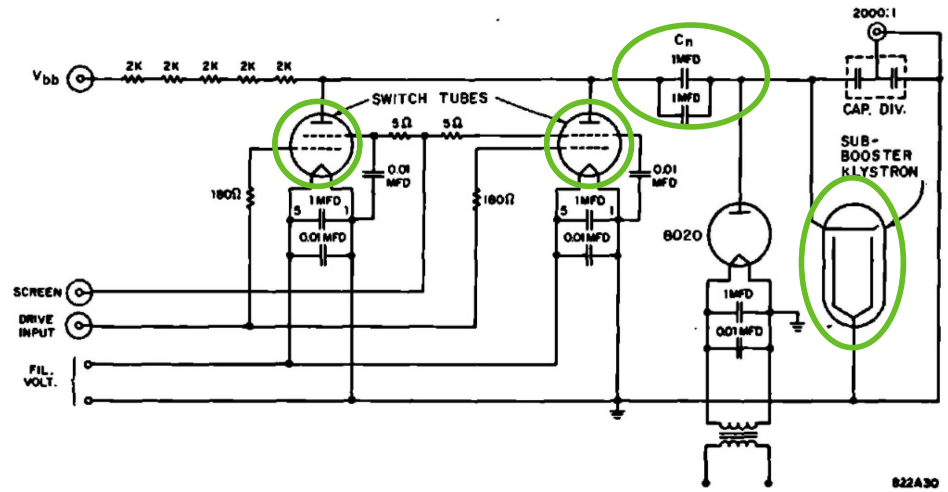
# Capacitor Discharge: LCLS BXKIK/BYKIK



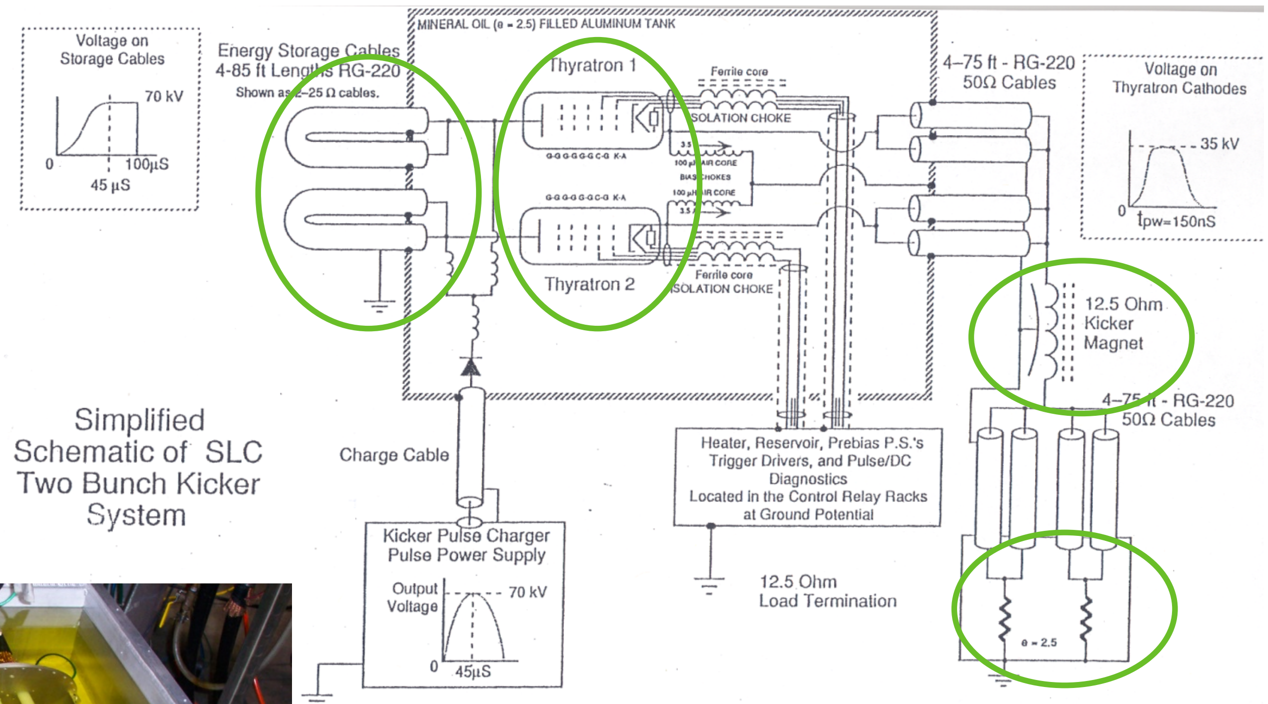
# Hard Tube: SLAC Sub-booster

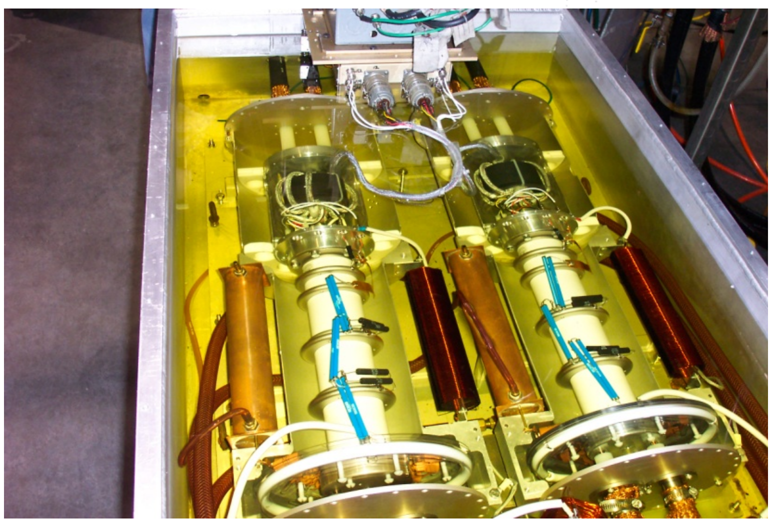






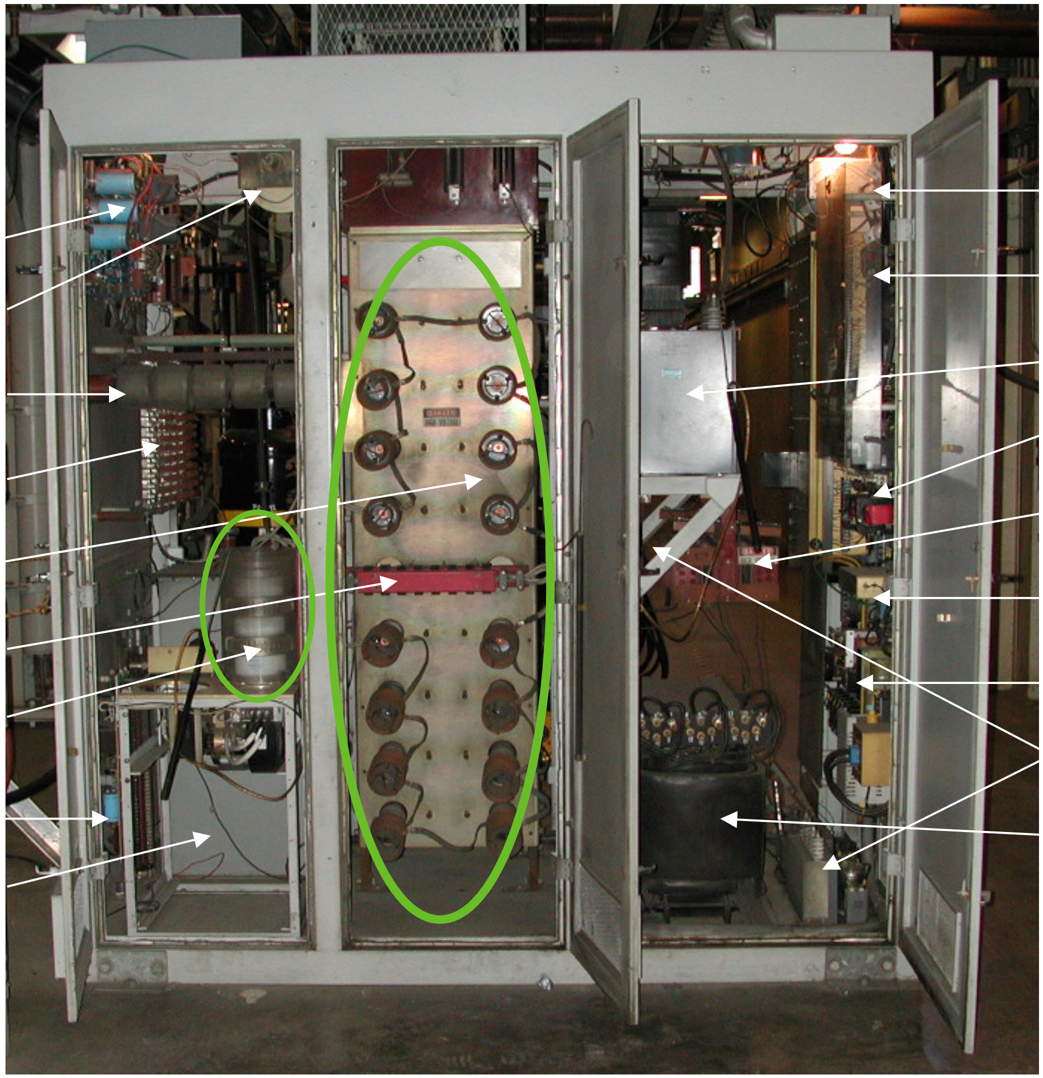
# Pulse Forming Line: SLAC North DR Kicker



# Pulse Forming Network: SLAC 6575

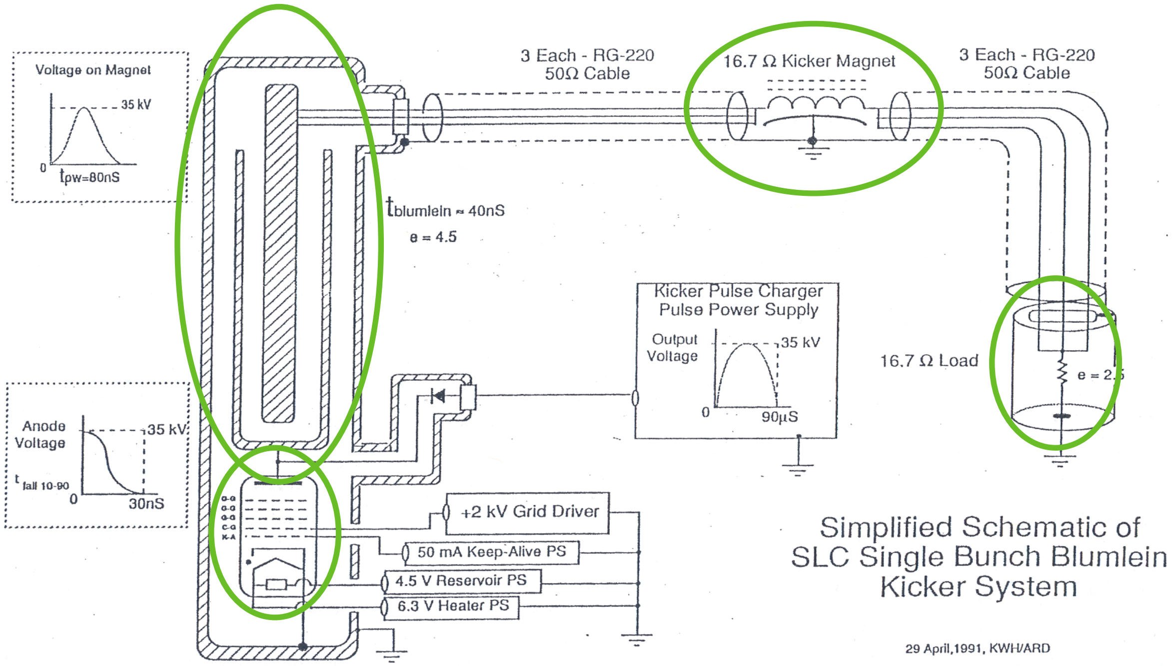
SLAC



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)

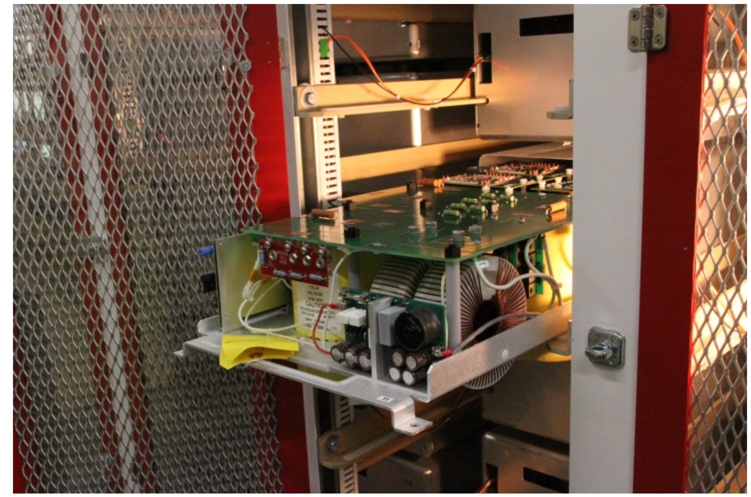
# Blumlein: SLAC South Damping Ring Kicker

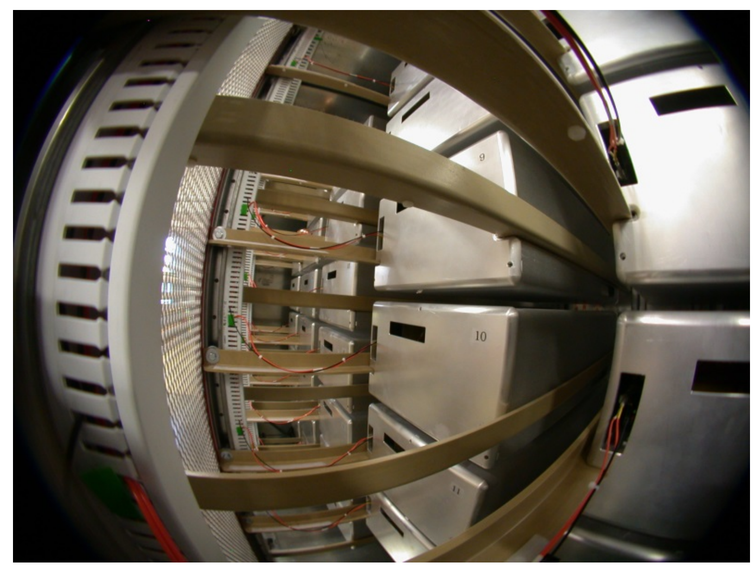



# Advanced Modulator Topologies

- 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

# Solid State Marx: ILC P2-Marx

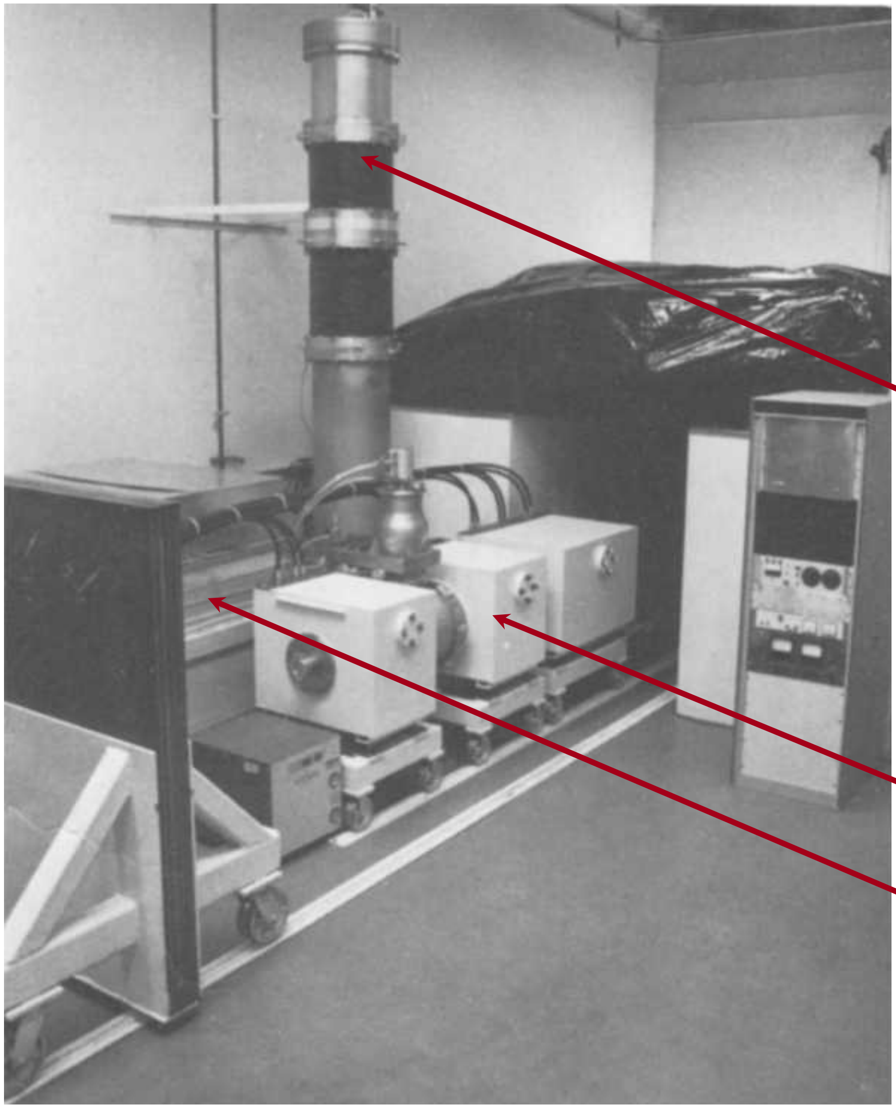




# Inductive Adder: NLC 8-Pack

# Resonant Converter: SNS HVCM

# Magnetic Pulse Compression: Pulse Sciences, Inc. Industrial Induction Accelerator

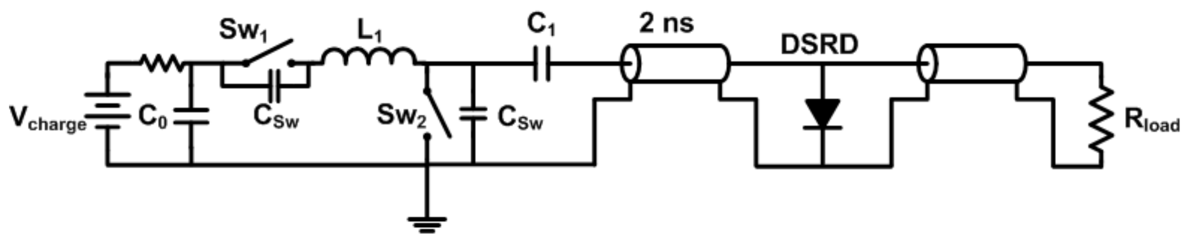


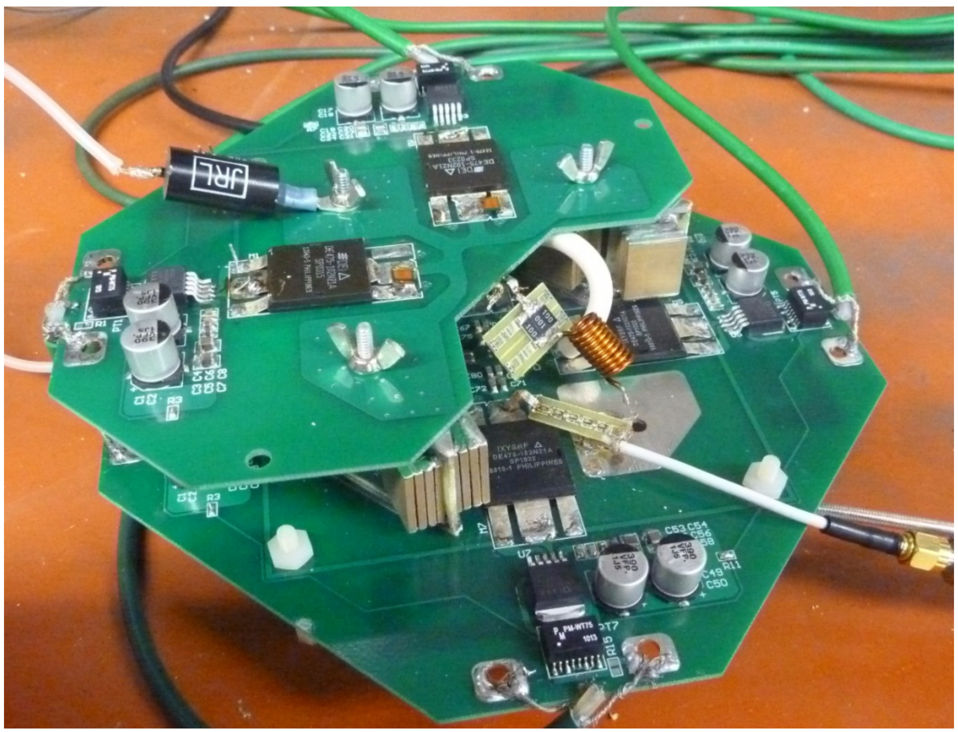
LLNL Mag-1C, stages 3 &4 compression

Induction linac

Solid state switch and stages 1&2 compression

# Opening Switch PFL: ILC Damping Ring Prototype



Pumping circuit

5 kV, 200A DSRD (*Ioffe Institute)*

ant *(for scale)*