Introduction

Pulsed Power Engineering
Michigan State University
February 3 – 7, 2025

Craig Burkhart and (Guest lecturer) Tony Beukers
SLAC National Accelerator Laboratory

Will Waldron
Lawrence Berkeley National Laboratory

Chris Jensen
Fermi National Accelerator Laboratory

Jared Walden and (Guest lecturer) G. Chris Pappas (retired)
Oak Ridge National Laboratory

Craig Burkhart

- **Experience**
  - 2005 – present Manager/Engineer SLAC National Accelerator Lab Menlo Park, CA
  - 2020 – 2021 ALD Engineering Princeton Plasma Physics Lab Princeton, NJ
  - 1990 – 2005 Senior Scientist First Point Scientific, Inc. Agoura Hills, CA
  - 1987 – 1991 Staff Physicist Pulse Sciences, Inc. Agoura Hills, CA
- **Teaching**
  - US Particle Accelerator School: Pulsed Power Engineering, ‘09, ‘11, ‘15, ’19, ‘22
  - Stanford University: Power Electronics (EE292J), Winter 2012-13
  - IEEE IPMHVC: Power Electronics Short-course, 2012
- **Education**
  - Ph.D. Nuclear Engineering University of New Mexico 1987
  - M.S. Nuclear Engineering University of New Mexico 1983
  - B.S. Chemical Engineering University of Iowa 1981

Will Waldron

- **Experience**
  - 1997 – present | Engineer | Lawrence Berkeley National Laboratory | Berkeley, CA
  - 1995 – 1997 | Engineer | Sperry Marine | Charlottesville, VA

- **Teaching**
  - US Particle Accelerator School: Induction Accelerators, 2019

- **Education**
  - M.S. | Nuclear Engineering | University of California, Berkeley, 2003
  - B.S. | Electrical Engineering | University of Virginia, 1996

Chris C. Jensen

- **Experience**

1990 – present	Pulse Power Engr	Fermi National Accelerator Lab	Batavia, IL
2020 – present	Sr Principal Engr	Fermi National Accelerator Lab	Batavia, IL
2016 – 2023	Dept Head / Engr	Fermi National Accelerator Lab	Batavia, IL
1986 – 1988	Engineer	Raj Technology	Morton Grove, IL

- **Teaching**

CERN PULPOKS Workshop, Magnetics & Cables	2018
Univeristy of Wis Madison, Power Electronics Lab	1989
Stratton College, Intro to Circuits	1986

- **Education**

M.S.	Electrical Engineering	University of Wis-Madison	1989
B.S.	Electrical Engr & Physics	University of Wis-Madison	1984

Jared Walden

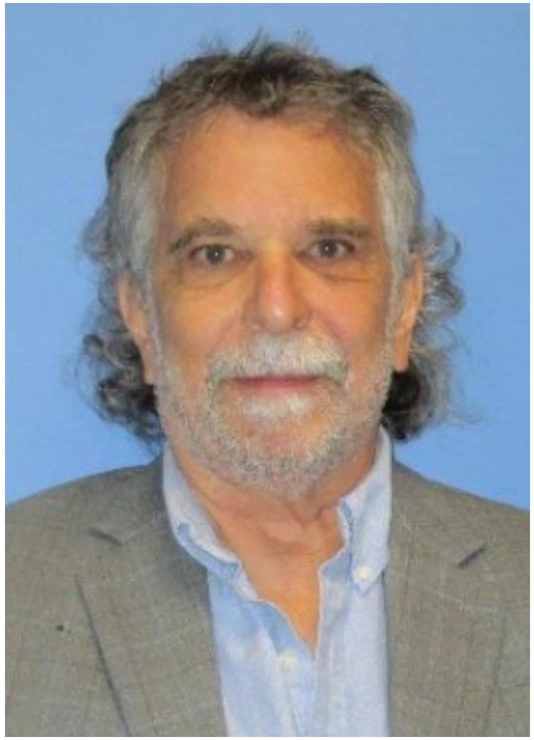
- **Experience**
  - 2021 – present | Electronics Engineer | Oak Ridge National Laboratory | Oak Ridge, TN
  - 2018-2019 | Research Engineer | Western Kentucky University | Bowling Green, KY
- **Education**
  - M.S. | Electrical Engineering | University of Tennessee - Knoxville | 2021
  - B.S. | Electrical Engineering | Western Kentucky University | 2018

Tony Beukers

- **Experience**
  - 2006 – present   Manager/Engineer   SLAC National Accelerator Lab   Menlo Park, CA
- **Education**
  - M.S.   Power Conversion   San Jose State University   2013
  - B.S.   Physics   UC Davis   2006

Chris Pappas

- **Experience**
  - 2018 - 2024 Electronics Engineer ORNL, SNS, Oak Ridge, TN
  - 2009 - 2018 Electronics Engineer LBNL, Berkeley, CA
  - 2006 - 2009 Electronics Engineer Sincrotrone Trieste, Trieste, Italy
  - 1996 - 2006 Electronics Engineer SLAC, Menlo Park, CA
  - 1994 - 1996 Engineer BNL, Upton, NY
  - 1990 - 1994 Electronics Engineer SSCL, Dallas, Tx
  - 1987 - 1990 Electronics Engineer Hughes Aircraft Co, Torrance, CA
- **Teaching**
  - Texas Tech University, Electrical Engineering for non-Majors, 1985
  - Texas Tech University, Electronics Lab classes, 1984
- **Education**
  - MSEE Texas Tech University 1986
  - BSEE University of Texas at Austin 1981



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  - 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), https://www.analog.com/en/resources/design-tools-and-calculators/ltspice-simulator.html
  - 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: https://www.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: https://www.febo.com/pages/docs/RadLab/
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  - ORNL: under contract DE-AC05-00OR22725
  - LBL: under contract DE-AC02-05CH1123
  - Fermilab: under contract DE-AC02-07CH11359

Course Outline

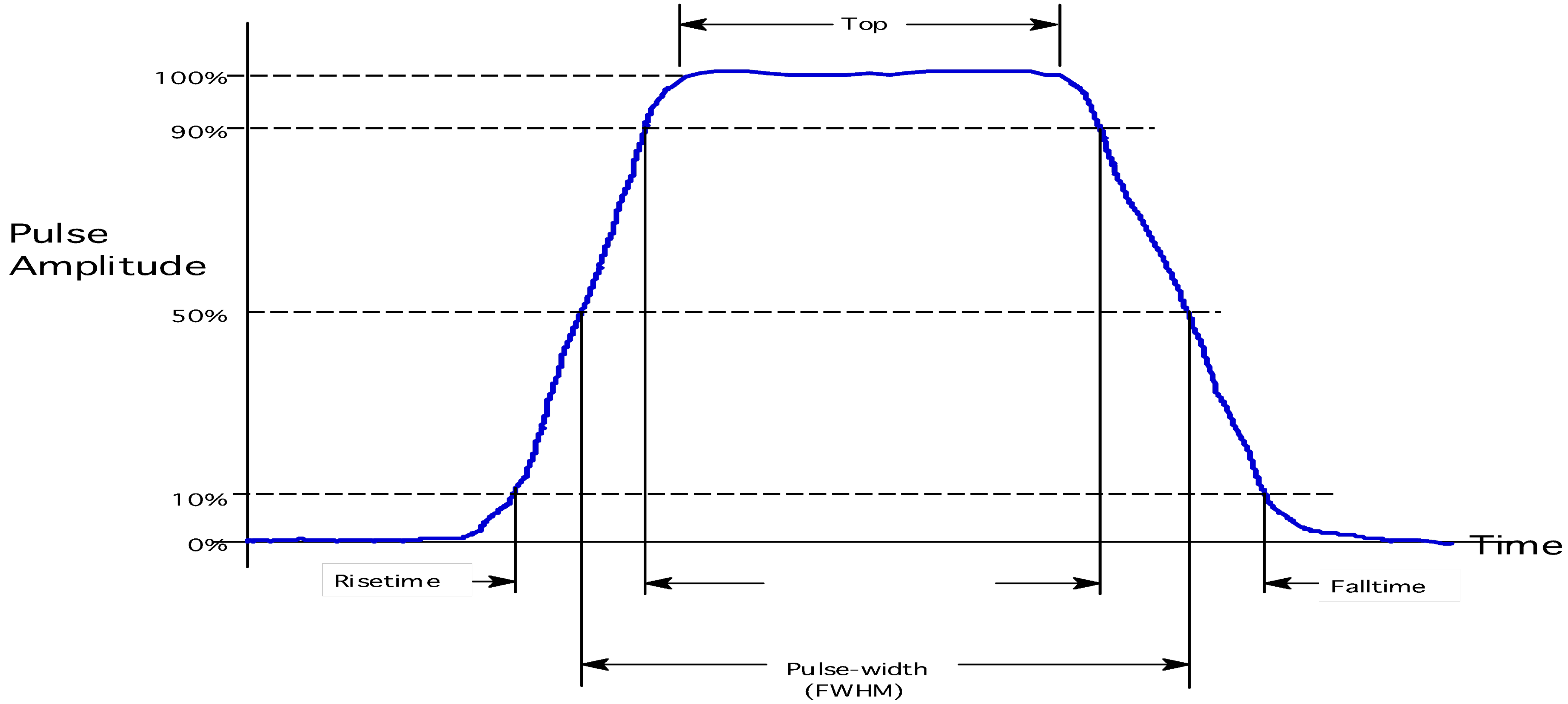
- Introduction (Burkhart)
- Materials/Passive Components and Devices (Jensen)
- Switching Devices (Burkhart)
- Basic Topologies – I (Jensen)
- Circuit Simulation – LTspice (Waldron)
- Basic Topologies – II (Burkhart)
- Engineering Simulation – Quickfield (Waldron)
- Advanced Topologies (Pappas, Walden, Beukers, Waldron, Burkhart)

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 (τ)**: 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)**: τ(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?

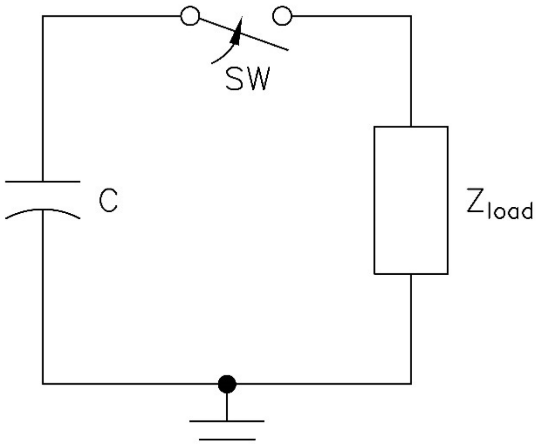
- Applications where large instantaneous power (kW – TW) is required but cannot be applied continuously.
  - Pulsed RF accelerator microwave source (klystron)
    - SLAC 5045 (S-band): 360 kV, 0.41 kA, 3.5 μs, $P_{peak} \approx$ 0.15 GW, $P_{ave} \approx$ 65 kW
    - ILC (L-band): 120 kV, 0.14 kA, 1.6 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
    - ~14X the world's electrical generating capacity (8.4 TW)

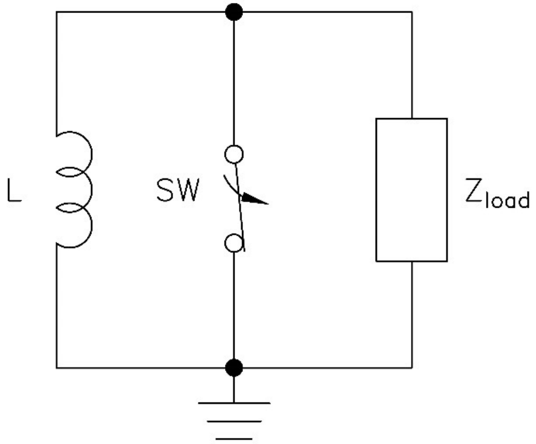
Where Is Pulsed Power Used? (cont.)

- 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





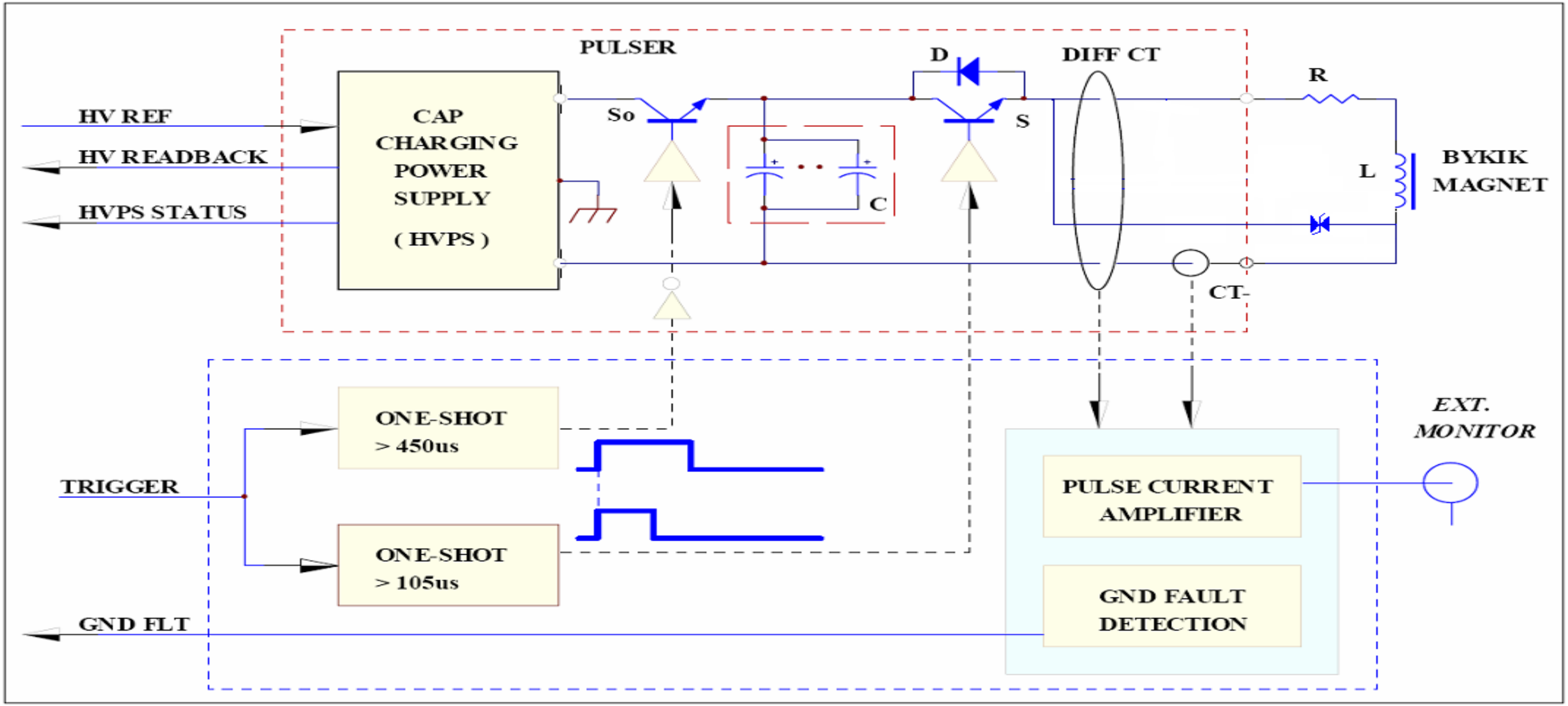
Why Are Other Topologies Required?

- 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

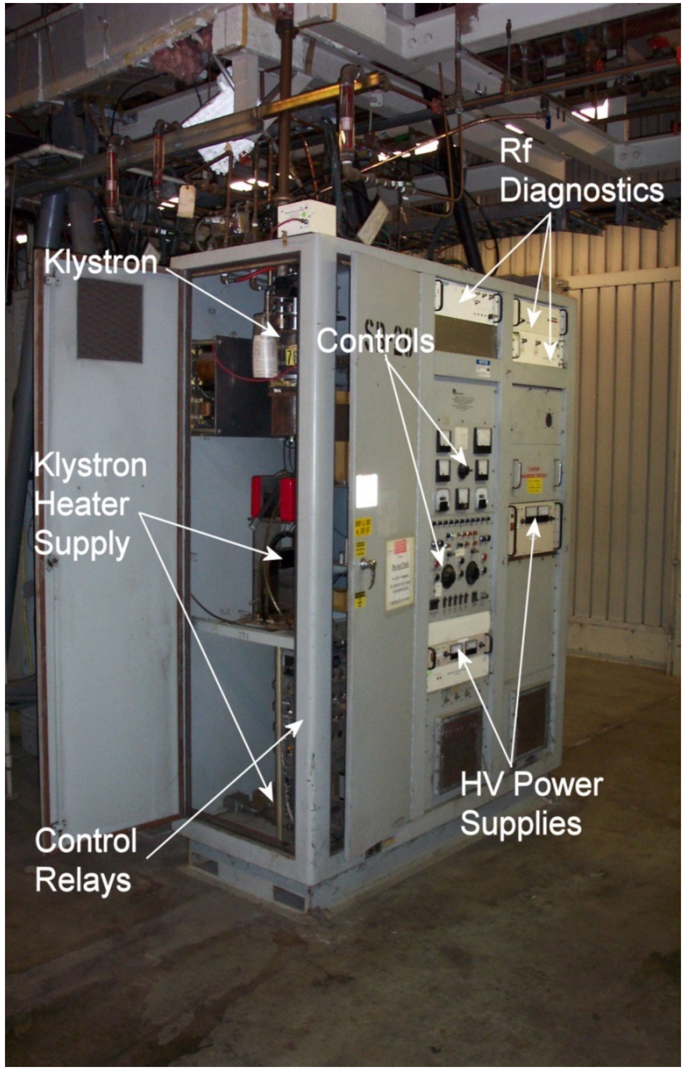
Basic Modulator Topologies

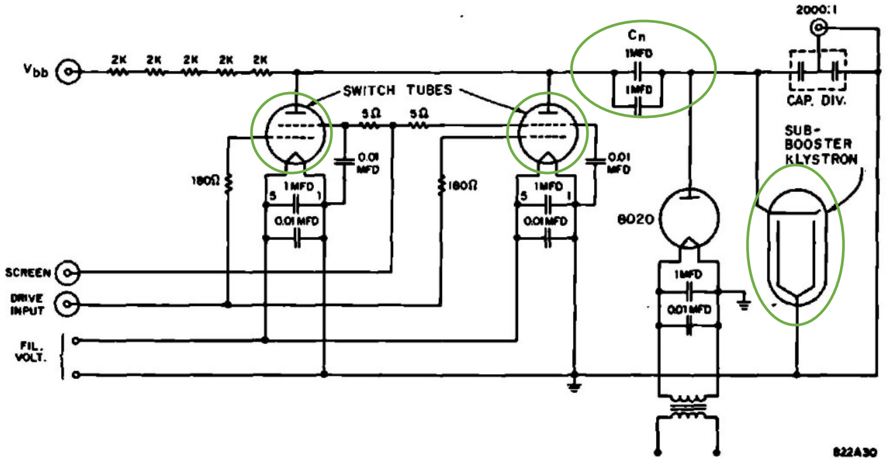
- Capacitor Discharge
  - R, L, C (energy transfer)
  - Circuit behavior: under/critically/over damped
- Hard tube
  - ~Ideal source (large capacitor) controlled by opening/closing switch
  - Traditionally used vacuum tube switch: triode/tetrode/pentrode
  - Modern implementations use solid state switch: 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: SLAC LCLS BXKIK/BYKIK

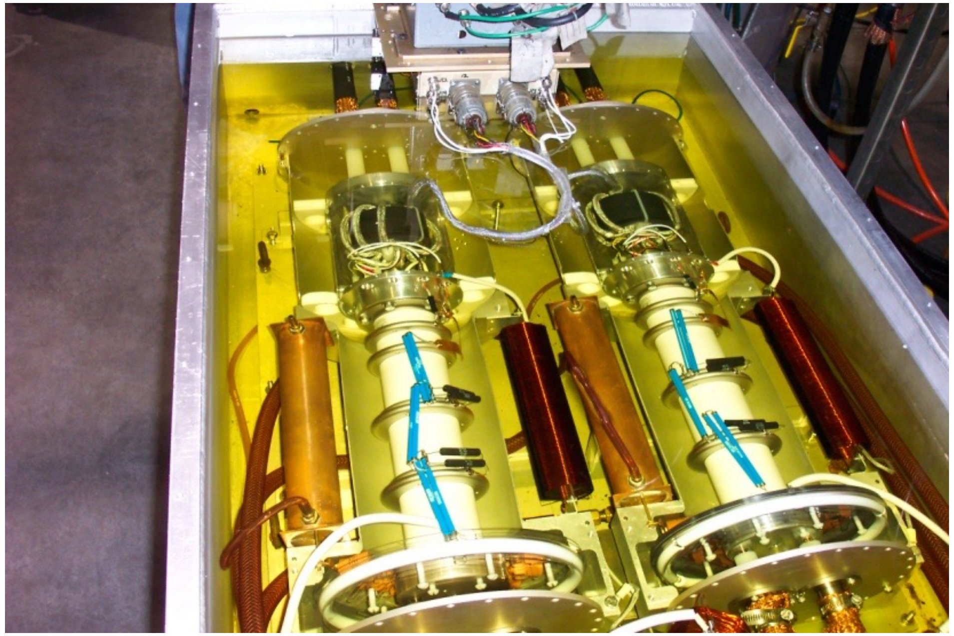


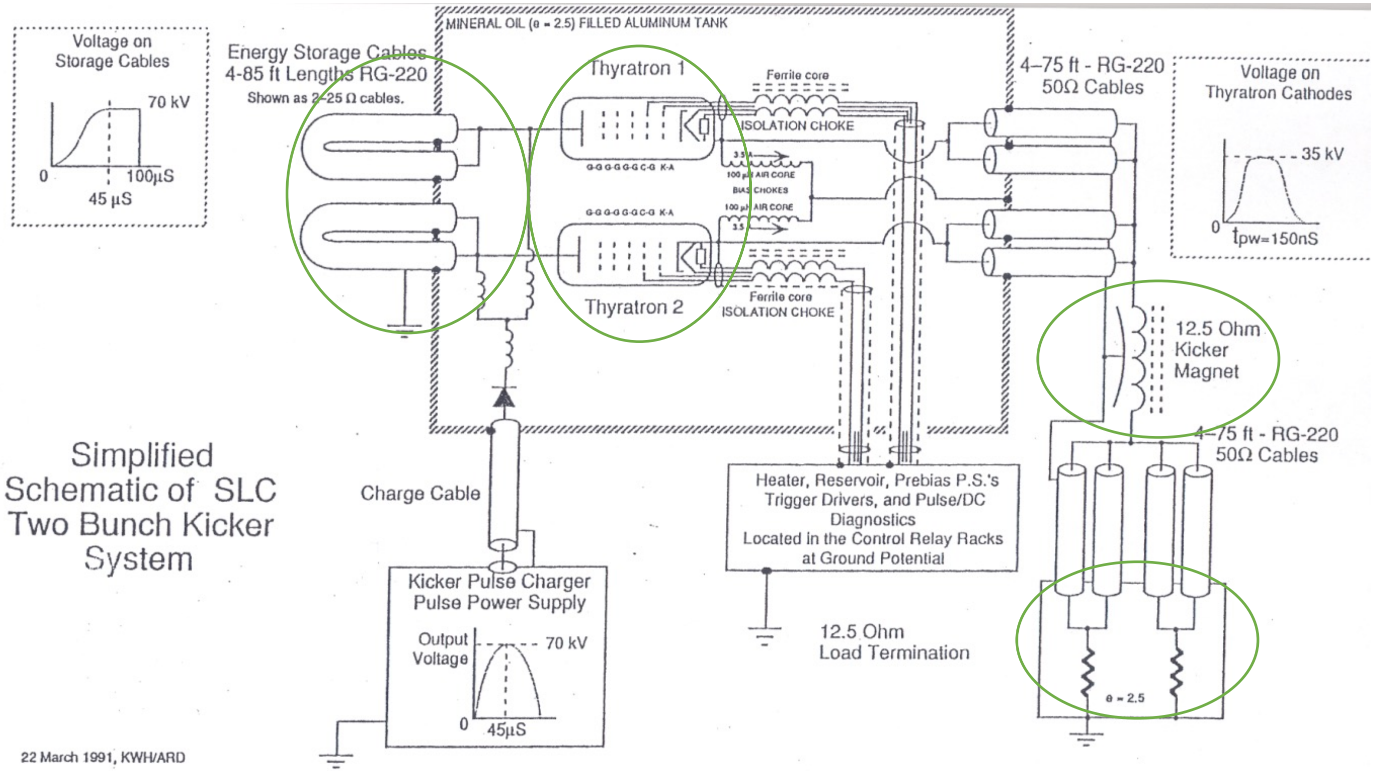
Hard Tube: SLAC Sub-booster



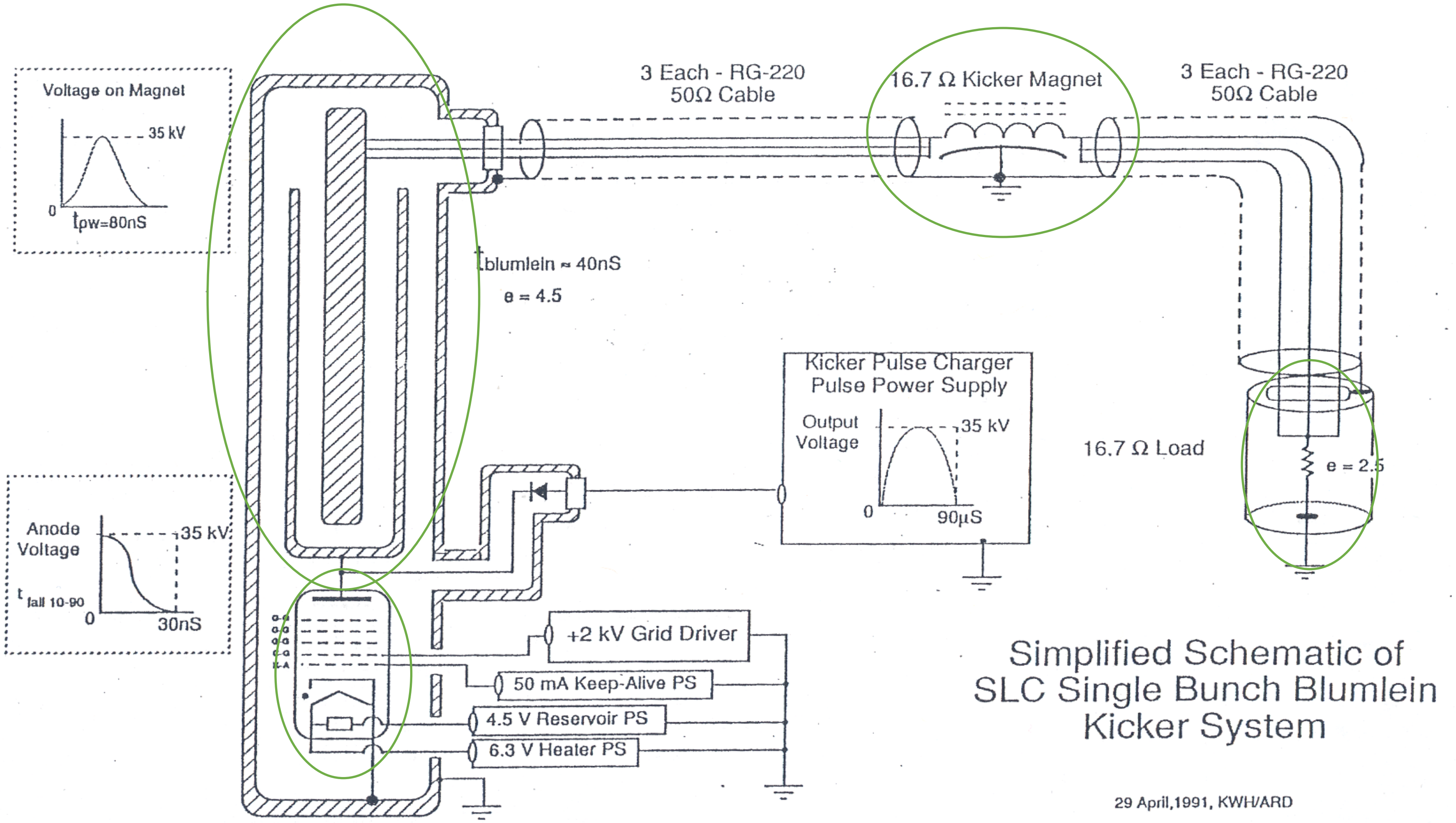


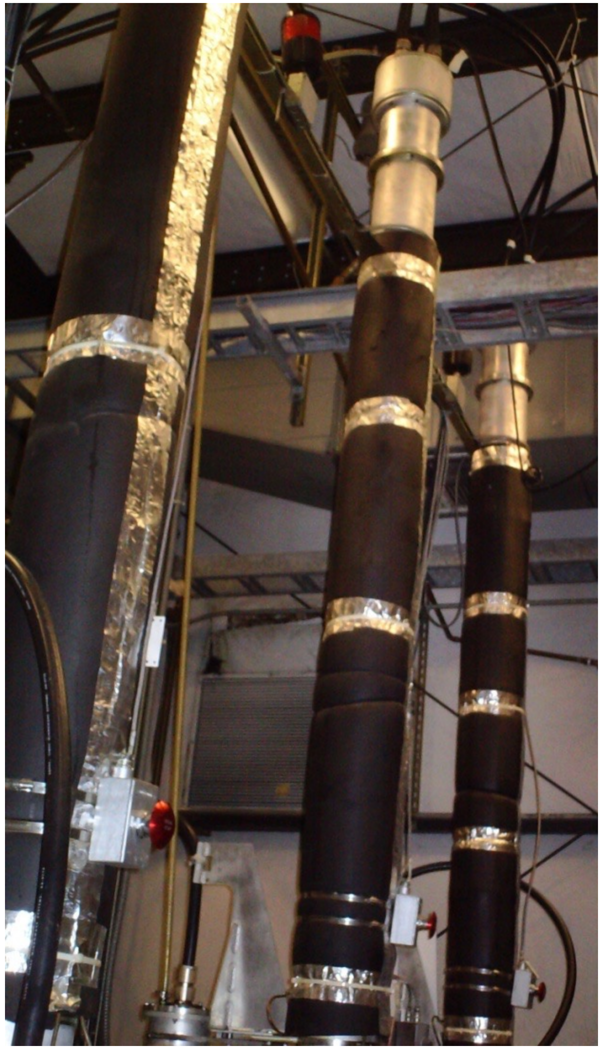
Pulse Forming Line: SLAC North DR Kicker



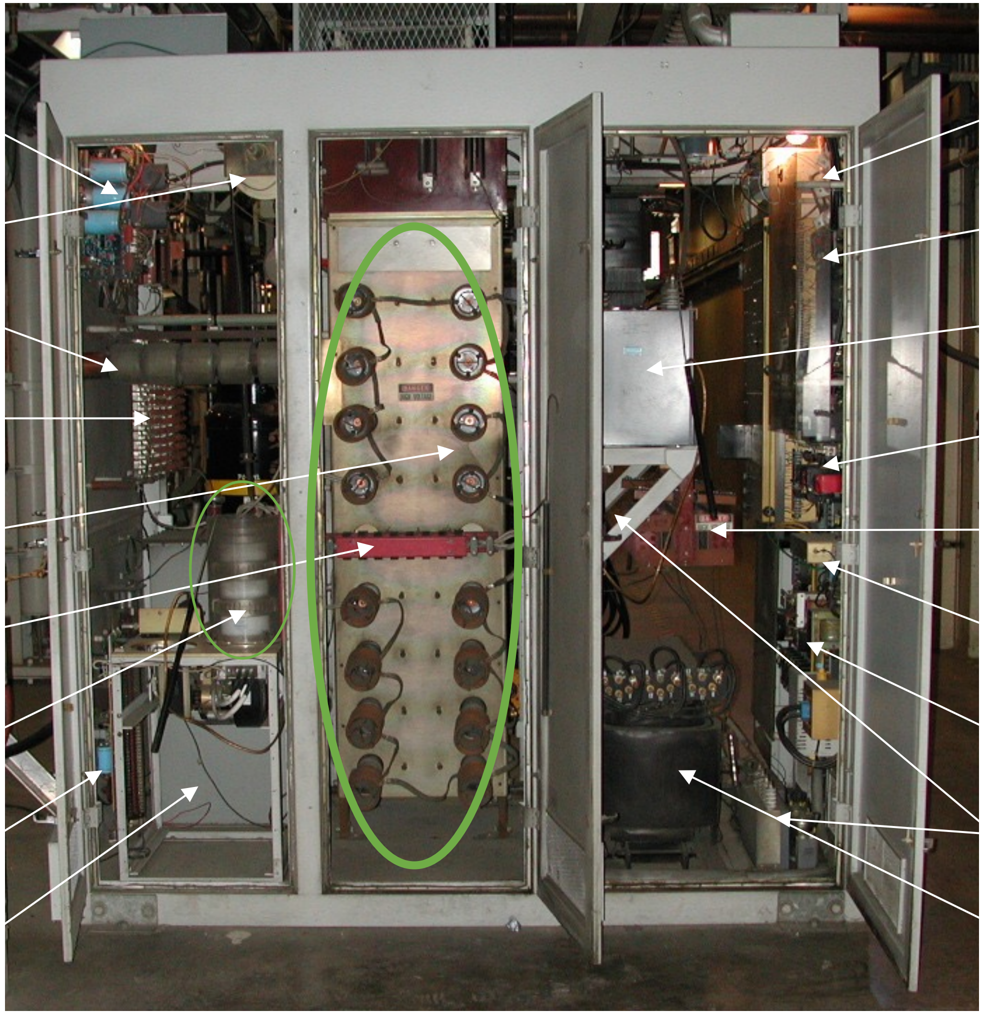


Blumlein: SLAC South Damping Ring Kicker





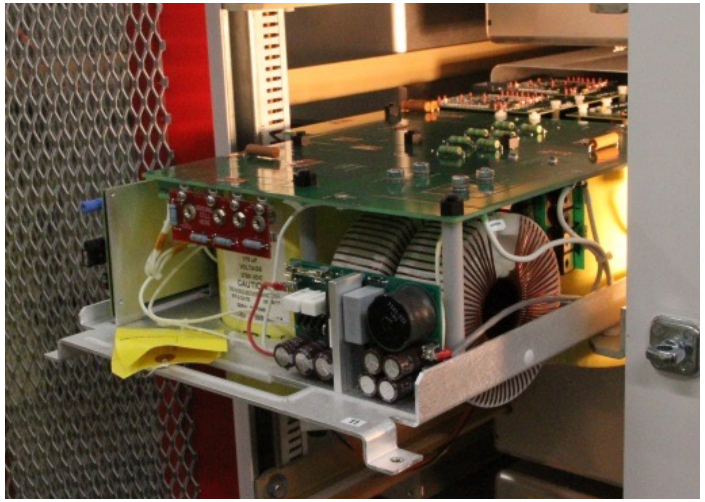
Pulse Forming Network: SLAC 6575

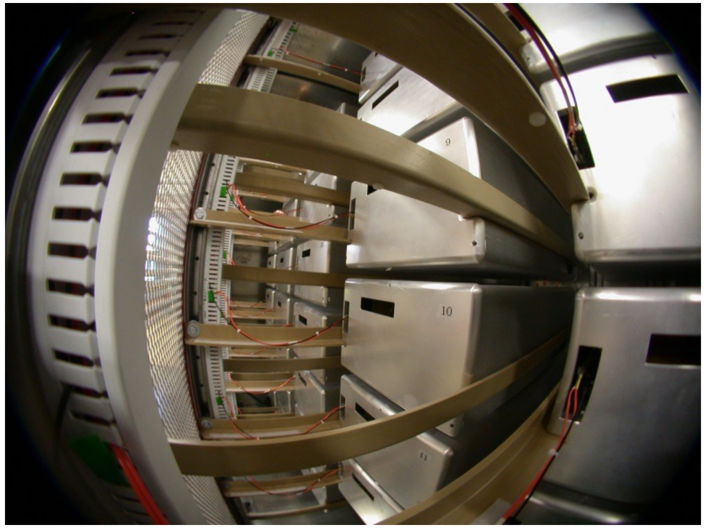


Advanced Modulator Topologies

- Marx
  - Basic Marx
  - Solid state Marx
- Resonant converter-modulator
  - Pulse-step
  - Parallel resonant-converter (HVCM)
  - Alternative Topology (AT-HVCM)
- Adder topologies
  - Inductive
  - Bi-polar adder
- Magnetic pulse compression
  - Magnetic switching
  - Magnetic pulse compression
- Opening switch PFL

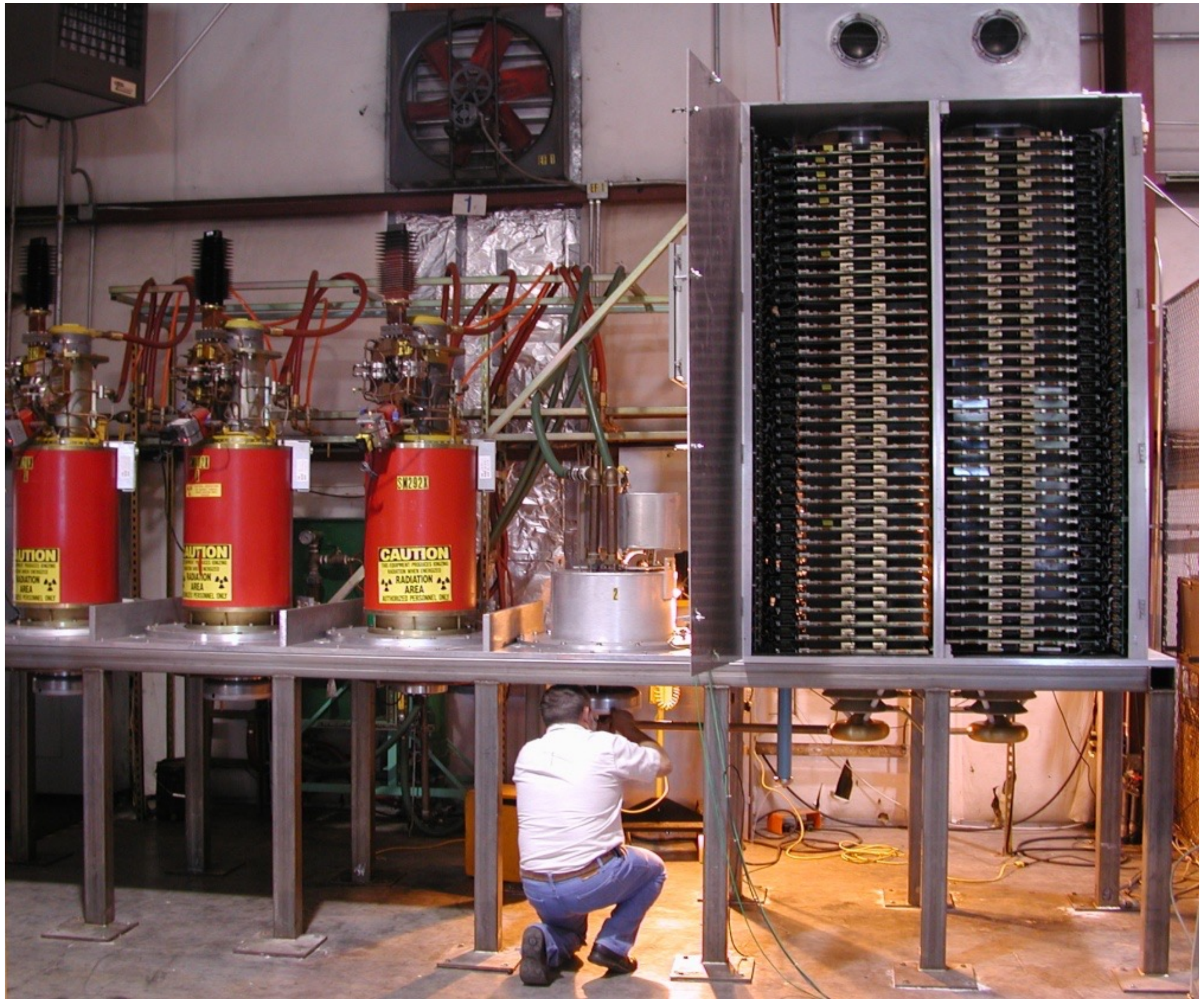
Solid State Marx: SLAC ILC P2-Marx



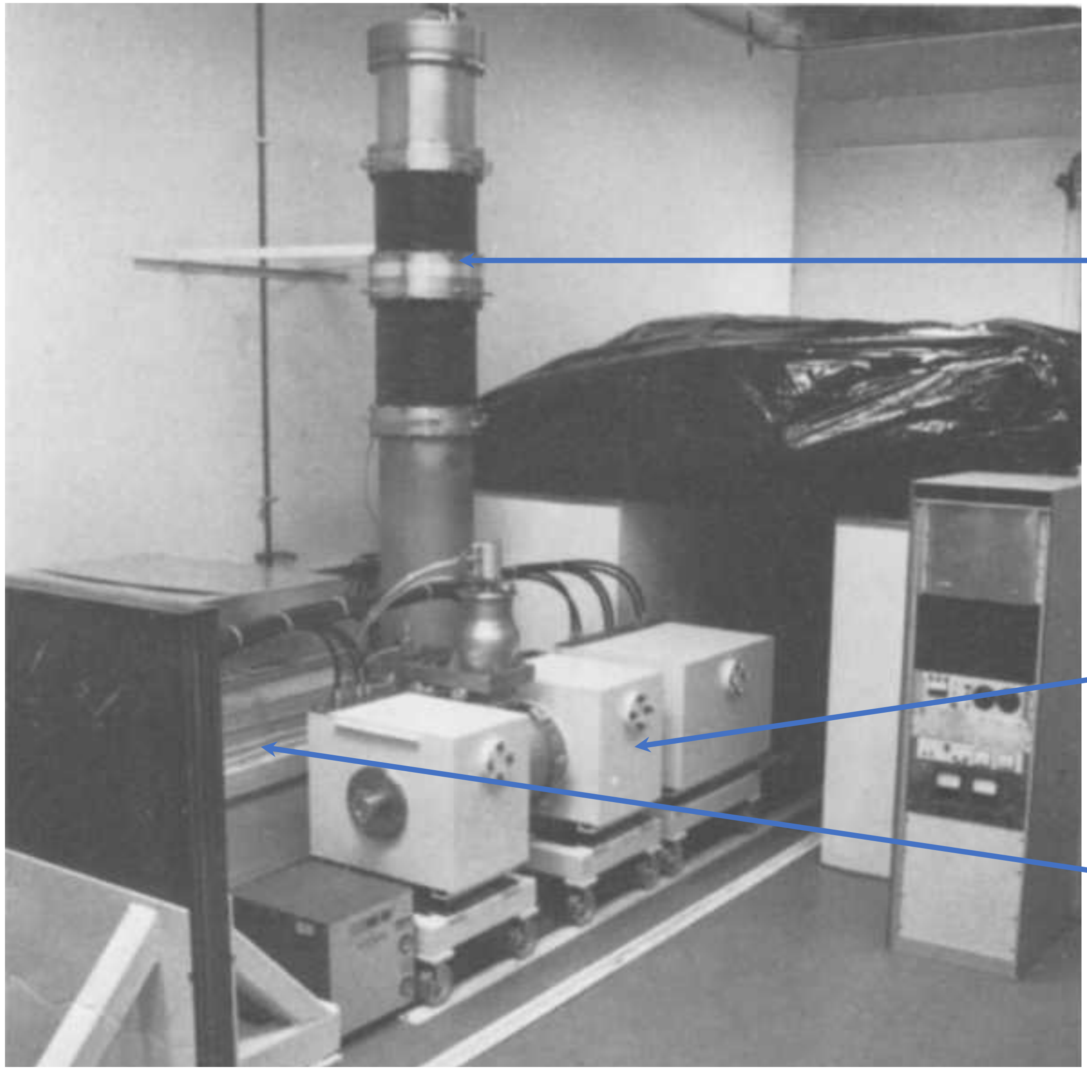


Resonant Converter: SNS HVCM

Inductive Adder: SLAC NLC 8-Pack



Magnetic Pulse Compression: PSI Industrial Induction Accelerator

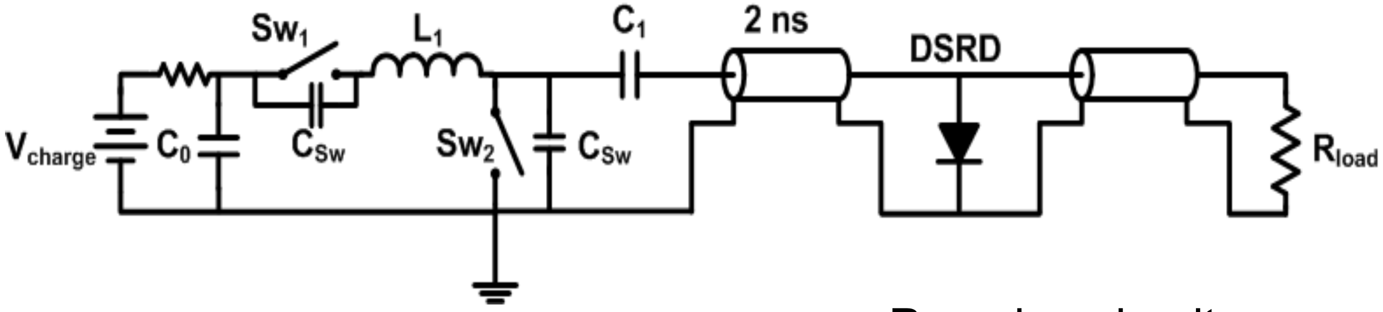


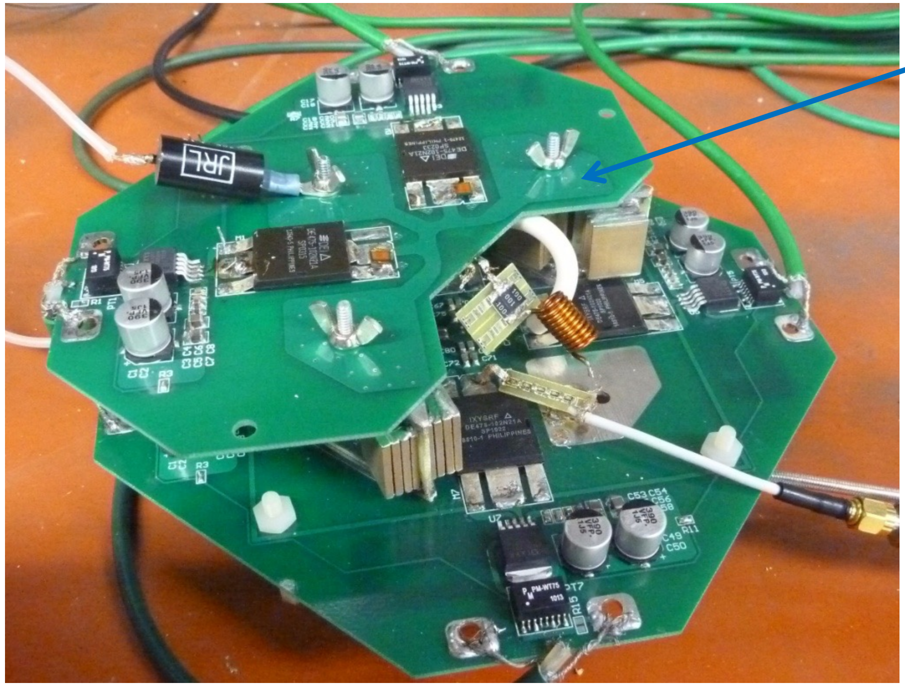
LLNL Mag-1C, stages 3 & 4 compression

Induction linac

Solid state switch and stages 1&2 compression

Opening Switch PFL: SLAC ILC Damping Ring Prototype





Pumping circuit

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

ant *(for scale)*