SLAC Experience

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U.S. DEPARTMENT OF ENERGY | Office of Science

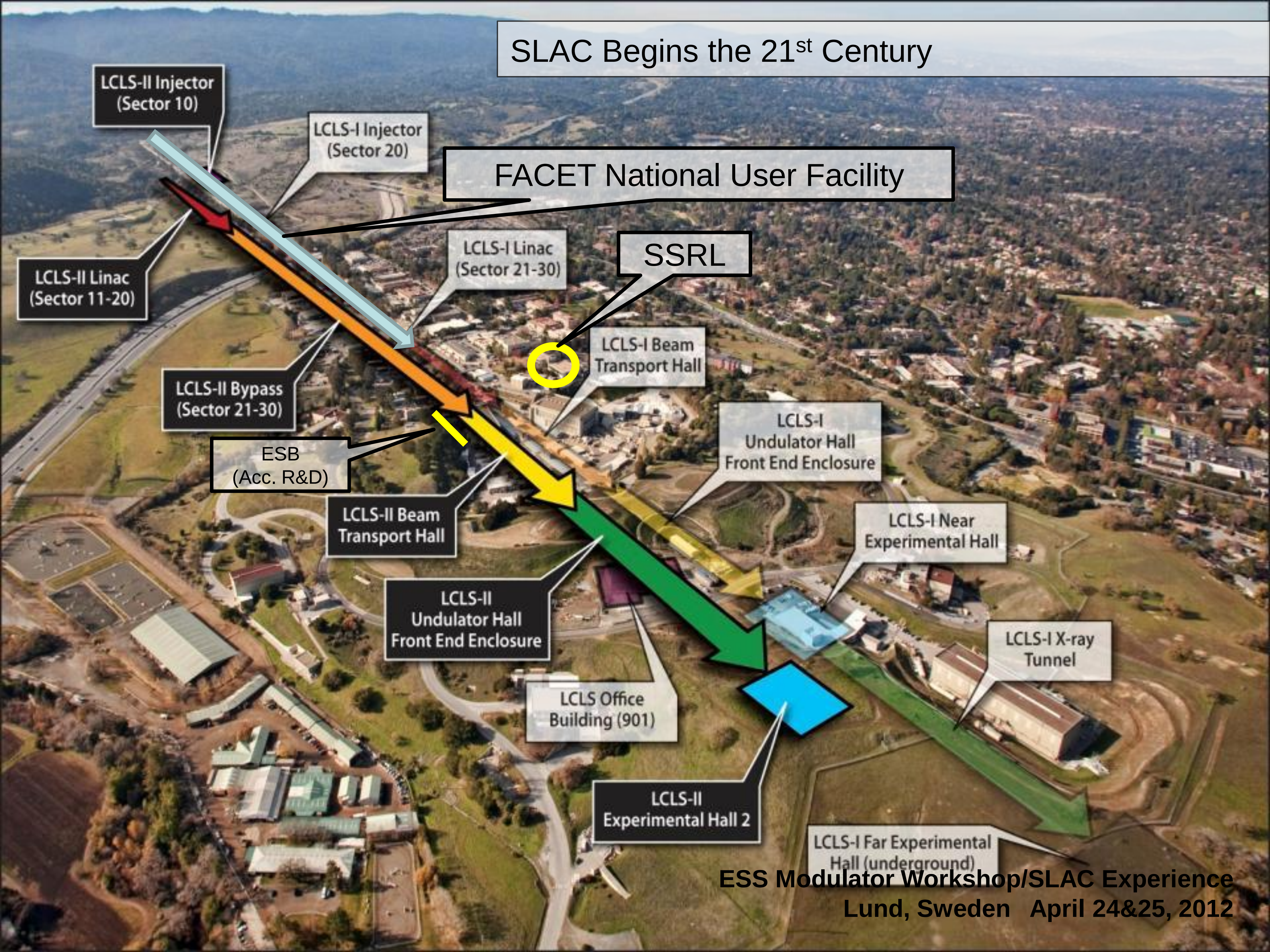
SLAC Experience

- Historic View
  - 6575 klystron modulator
  - B-factory klystron high voltage power supply
  - Lessons on modulator availability
- Future Vision
  - Key features for a modern klystron modulator
  - Solid state Marx modulator

The Stanford Two-Mile Accelerator

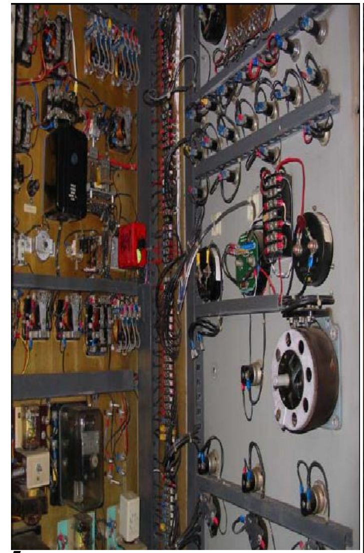
- Commissioned 1966
- ~240 HPRF Stations
  - One klystron per modulator
  - Sixteen modulators per AC-DC converter
- 60's – 70's: fixed target experiments
- 70's – 80's: Positron-Electron Project (PEP)
- 80's – 90's: Stanford Linear Collider (SLC)
- 90's – 00's: B-meson Factory (PEP-II)
- 00's - ???: Linac Coherent Light Source (LCLS)

SLAC Begins the 21st Century

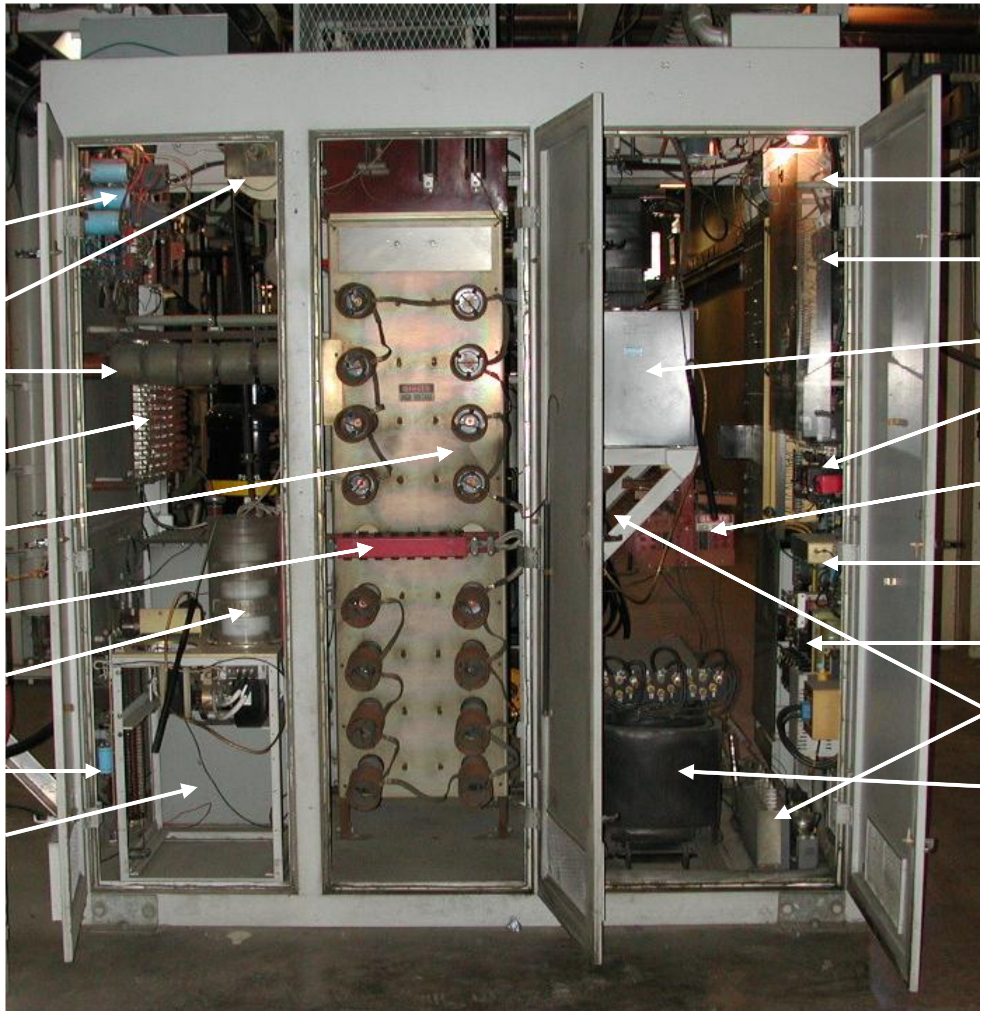


6575 Klystron Modulator

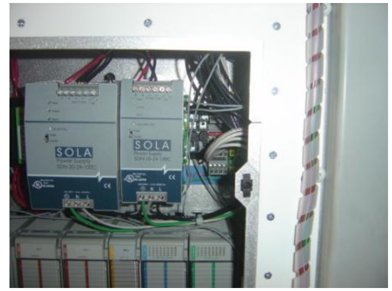
- Type-E Line Modulator
- SLAC Designed
- SLAC Prototyped
- Industry Manufactured
  - Ling LTV Electronics Div.
- Predominantly Original
  - PFN upgraded to 145 MW for SLC
  - Various “upgrades”, many subsequently removed

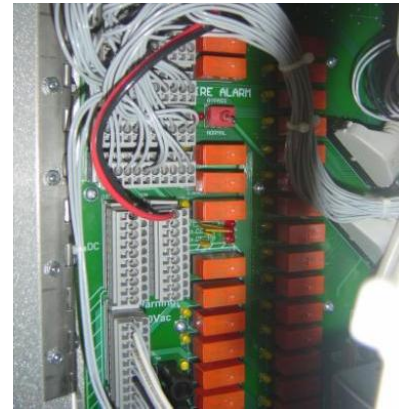


6575 Klystron Modulator

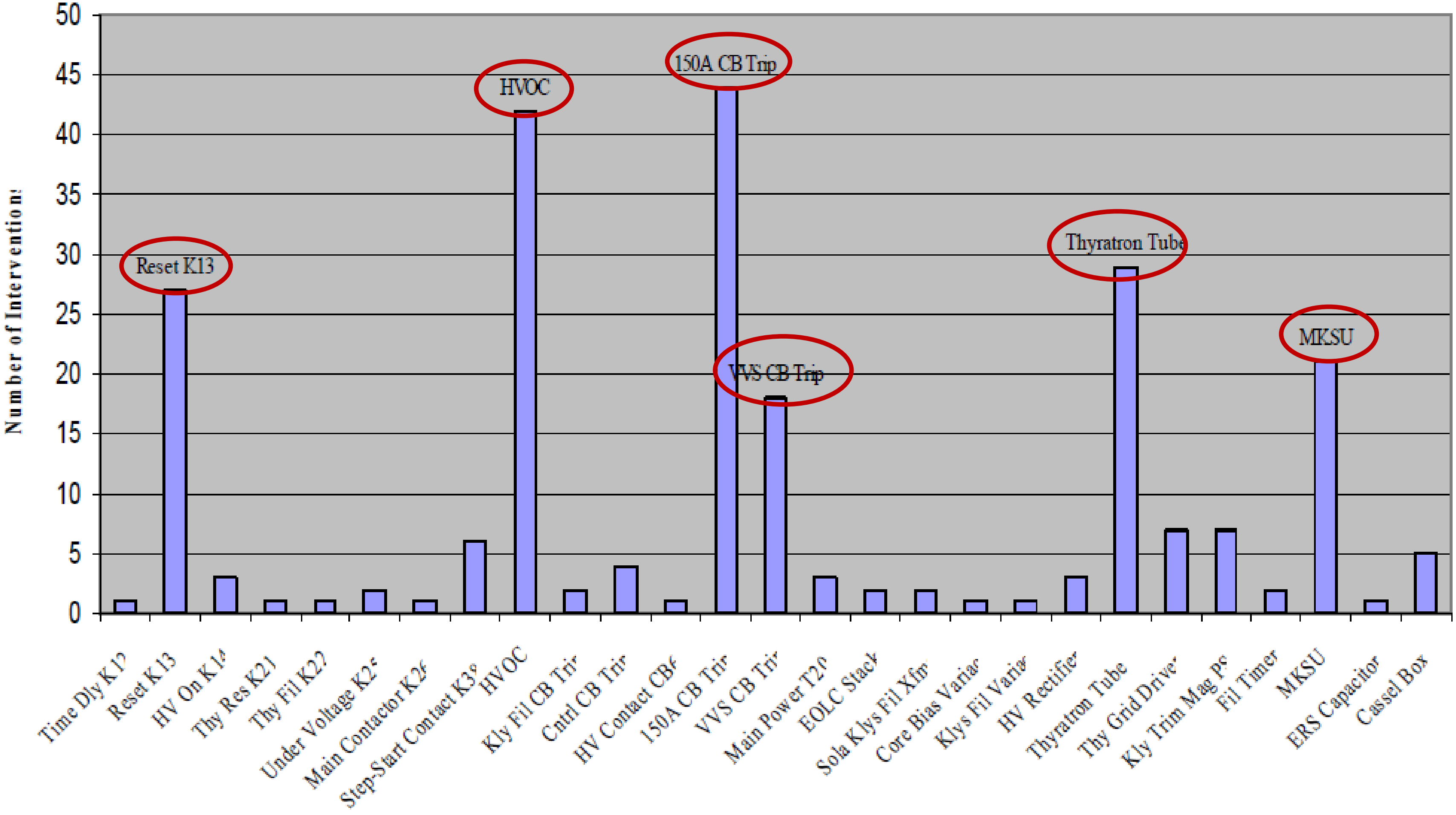


6575 Klystron Modulator Upgrades





6575 Operational History: 3/05 – 2/07



6575 Operational History: 3/05 – 2/07

- Mean Time Between Failure (MTBF)
  - Preceding data: 10 kHr
  - Projected with improvements: 43 kHr
  - Mean time between service calls: 2.4 kHr
- Mean Time To Repair (MTTR): ~1 Hr
- RFARED Operations Support of LCLS HPRF Systems
  - 80 HPRF stations, only 4 are critical (failure → loss of beam)
  - 24/5 coverage (weekend on-call)
  - 12 FTE (~$5M labor, ~$1M M&S)
- LCLS Availability
  - Program goal: 99.92%
  - Run V to date (3.3 kHr): 99.88% (50% over goal)

5045 Klystron Assembly

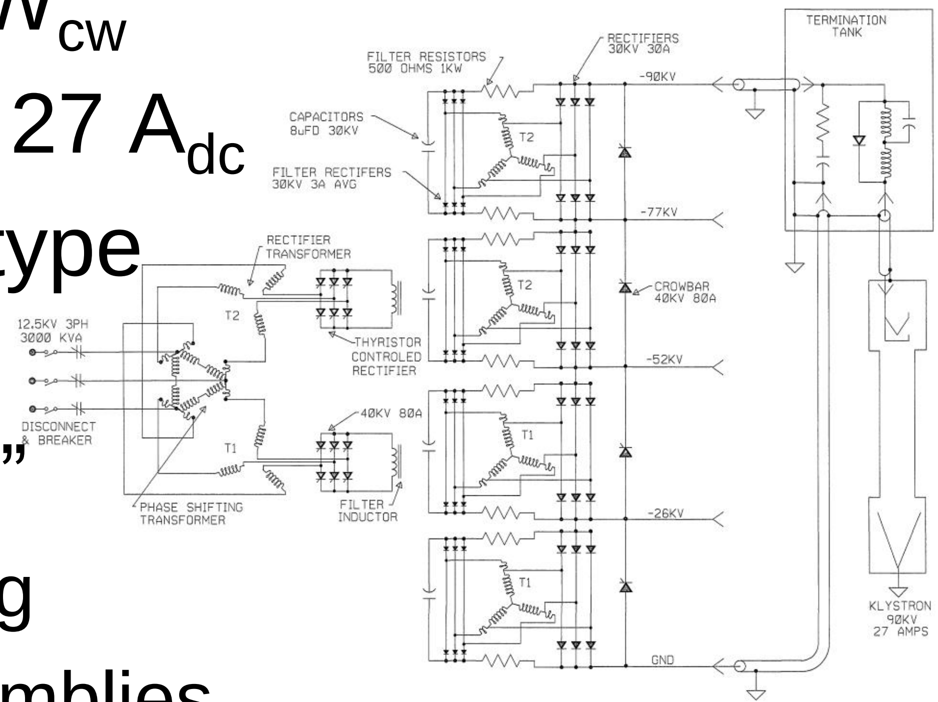
- Assembly Incorporates
  - Klystron, solenoid, pulse transformer, bias choke, voltage divider
  - Mostly passive devices
  - Oil dielectric/coolant
- Klystron MTBF: 80 kHr
- Assembly MTBF: 40 kHr
- MTTR: 250 Hr

SLAC Linac HPRF Power System

- 12.47 kV-Δ / 258 – 595 V-Y, 1.75 MVA
  - Variable voltage source
  - Powers 2 sectors (16 modulators total)
- $\pm 7.5^{o}$ Phase-shifting Transformer
  - $+ 7.5^{o}$ feeds even sectors
  - $- 7.5^{o}$ feeds odd sectors
- Sector Modulators Alternate: Δ–Δ, Δ–Y
  - 30^{o} phase shift between adjacent 6575s
- 6575 Incorporate 6-Pulse Rectifier
- Effectively 24-Pulse Rectifier To AC Line
  - Low Harmonic Distortion
  - Economy of scale for AC-AC conversions

B-Factory Klystron (BFK) Power Supply

- BFK: 476 MHz, 1.3 MW_{cw}
- HVPS: 3 MVA, 90 kV, 27 A_{dc}
- SLAC Design & Prototype
  - ~2-year development
- Industry “Build to Print”
  - Some DFM engineering
  - Some SLAC-built assemblies



BFK HVPS

BFK HVPS Operational History

- Initial Operation (1998)
  - 9 units, 2 failures/week
  - MTBF ≈ 0.8 kHr (MTTR ~ 2 days)
- Improvements
  - Lower capacitor stress
  - Light triggered SCRs
  - Extensive preventative maintenance
  - Improved thermal management (e.g. water cooling)
- Final PEP-II Operation (2008)
  - 15 units, 3 failures/run
  - MTBF ≈ 30 kHr
- SPEAR3 Operation
  - No failures, 1 unit (2^{nd} as spare), Planned Booster upgrade to BFK

Lessons on Modulator Availability, MTBF

- MTBF will be low until design is fully matured
- Design maturation can be realized more economically during the prototype stage
- Design maturation can require years of operational experience
- Environmental conditions can greatly influence MTBF
- MTBF will decrease as components approach end-of-life

Lessons on Modulator Availability, MTTR

- IT WILL BREAK: availability α $MTTR^{-1}$, minimize repair time
- Maintenance staff knowledge will be limited
  - Plug and Play repair paradigm
    - Minimize trouble shooting
    - Minimize field repair
  - "One size fits all" valuable guiding principle
    - Unit-to-unit variations → errors
    - Minimize parts/spares count
  - Integrated diagnostics
    - Everything the machine tells the Tech is one less variable
- Simplify Tech access
  - Speeds repair
  - Minimizes collateral damage
  - Oil is NOT easy access

Key Features for a Modern Modulator

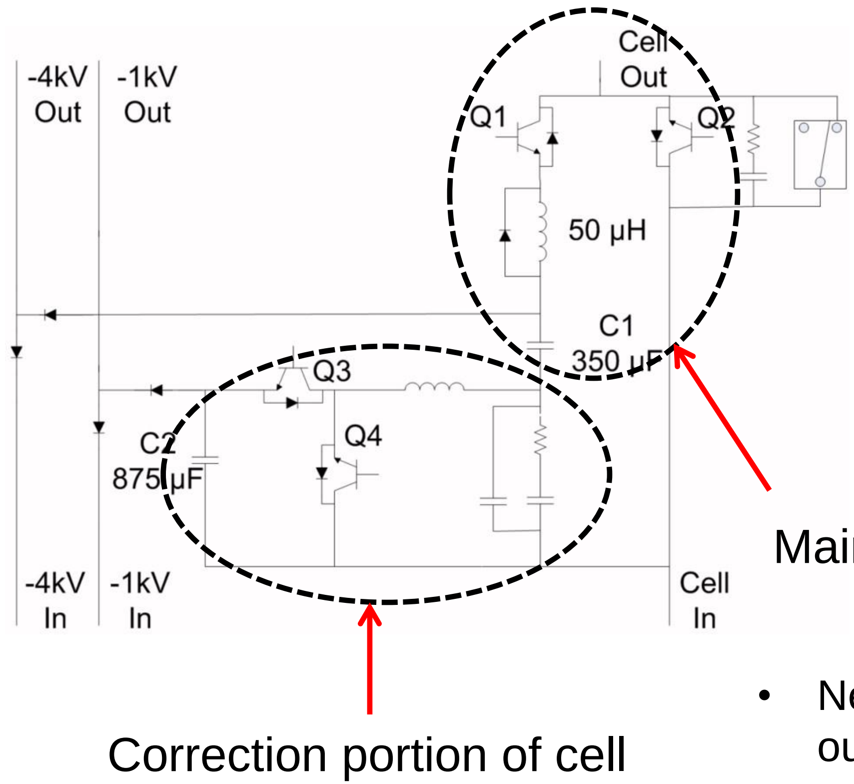
- High Availability (Tel-Com tenets)
  - High Reliability components – Redundancy – Embedded Diagnostics
- Reliability
  - Solid state
  - Engineered component stress; understand how stresses scale
  - Topology that minimizes voltage stress
- Redundancy (N + n)
  - Modularity, minimize single-points-of-failure
  - 30 units at 99% reliability, system; 72.5% (n=0), 95.9% (1), 99.6% (2)
- Greater Complexity
  - Increased prototype-stage development
  - Parametric flexibility; less application specificity
- Use Efficient Scaling for Power Conversion

Solid State Marx; A Modern Modulator

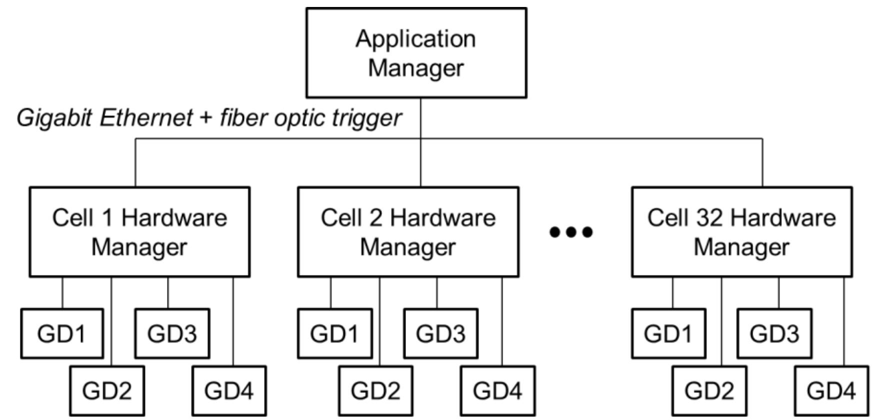
- High availability architecture
- SLAC Marx developed for the ILC, replaced bouncer modulator as baseline design
  - Lower cost, smaller size
  - Higher performance, greater operational flexibility
  - Increased availability
    - High MTBF/lower MTTR
      - Redundant/modular
      - Embedded diagnostics/prognostics
      - Improved maintenance access
- Two generations of modulators have been developed at SLAC, the P1 and P2

SLAC P2 Marx Topology

Single cell simplified schematic

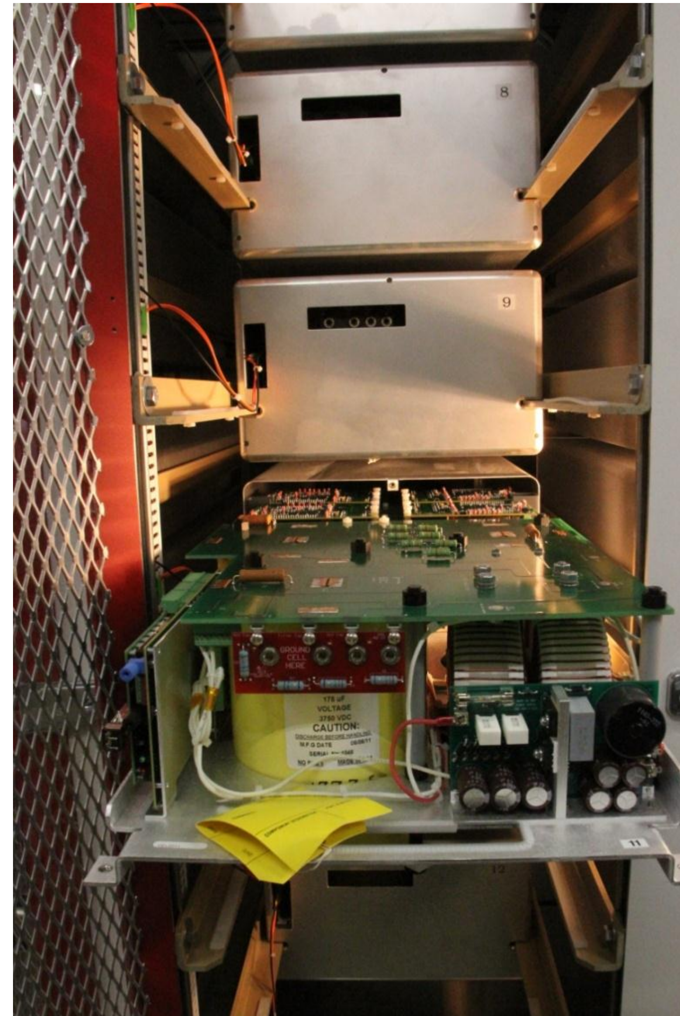


Hierarchical control scheme



- Nested droop correction enables a square pulse output for each cell
  - Chopping is at 1kV rather than 4kV
  - Interleaving cells cancels modulator ripple
  - Switching losses are negligible on 6.5kV switch

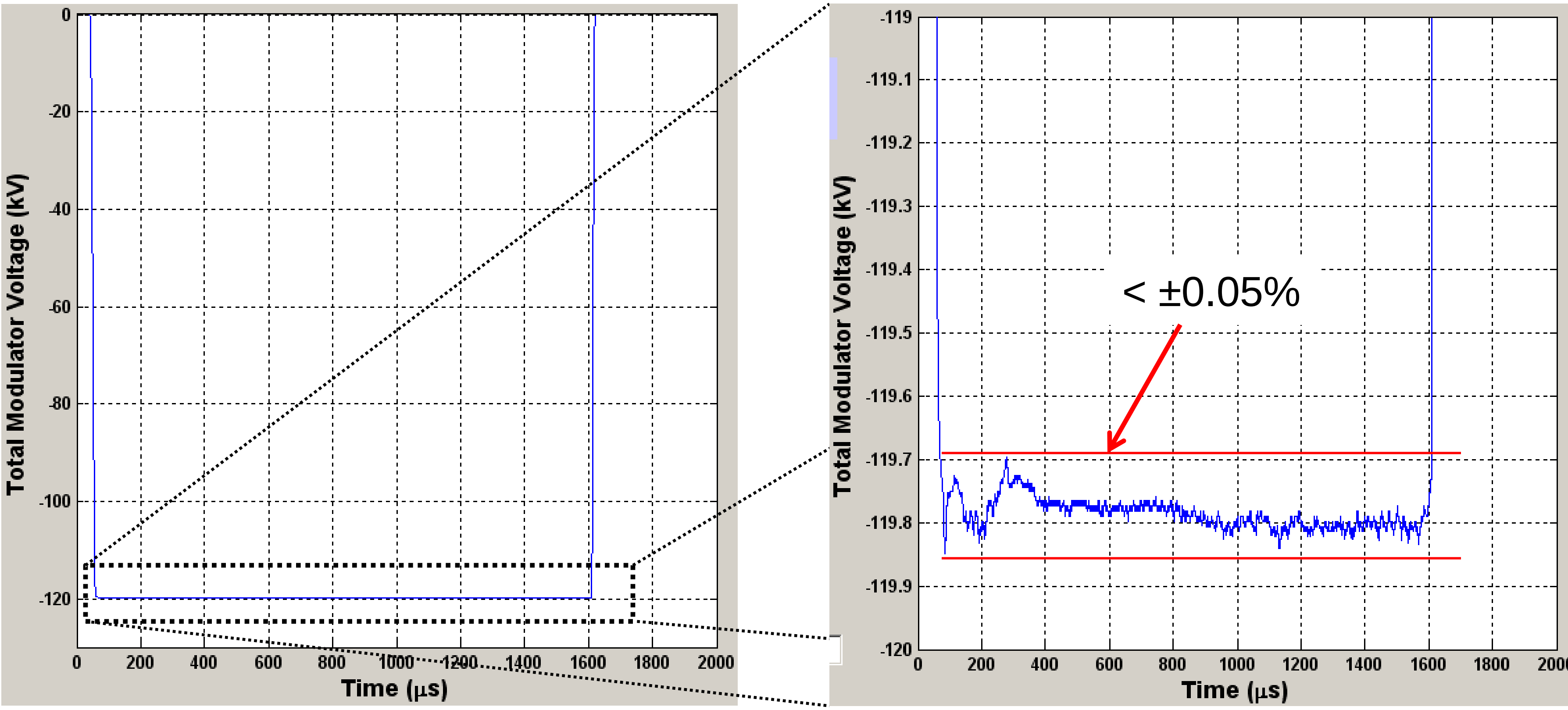
SLAC P2 Marx Photographs



SLAC P2 Marx Design Features

- Components selected for high reliability
- N+2 cell redundancy
- Embedded diagnostics/prognostics, communicate cell status
- High voltage design effectively shields controls from EMI
- Active, closed-loop control regulates output voltage
- Oil free, all-air insulation; easy access
- Man portable modular cell; plug-and-play field service, easily disassembled for shop repair
- DFM: employs PCB-based circuitry and formed enclosures over hand wiring and machined parts
- COTS switching modules

SLAC P2 Marx Performance



- DC to pulse efficiency of >94%
- Active regulation demonstrated

- Pulse to pulse stability <500ppm (not yet fully characterized)
- Ongoing fault/life testing

SLAC P2 Marx Scaled to ESS Parameters

- 4.8 MW (2.8 MW Rf @ 58%), 14 Hz, 3.4 ms pulse
- Assume P2 cell structure, maximum cell operating voltage, and N+2 redundancy

	# of Cells	Max Single Cell Loss	DC to Pulse Efficiency
ILC P2 Marx	32	410 W	95.0%
80kV ESS Marx	23	780 W*	95.8%
113 kV ESS Marx	31	610 W	95.5%

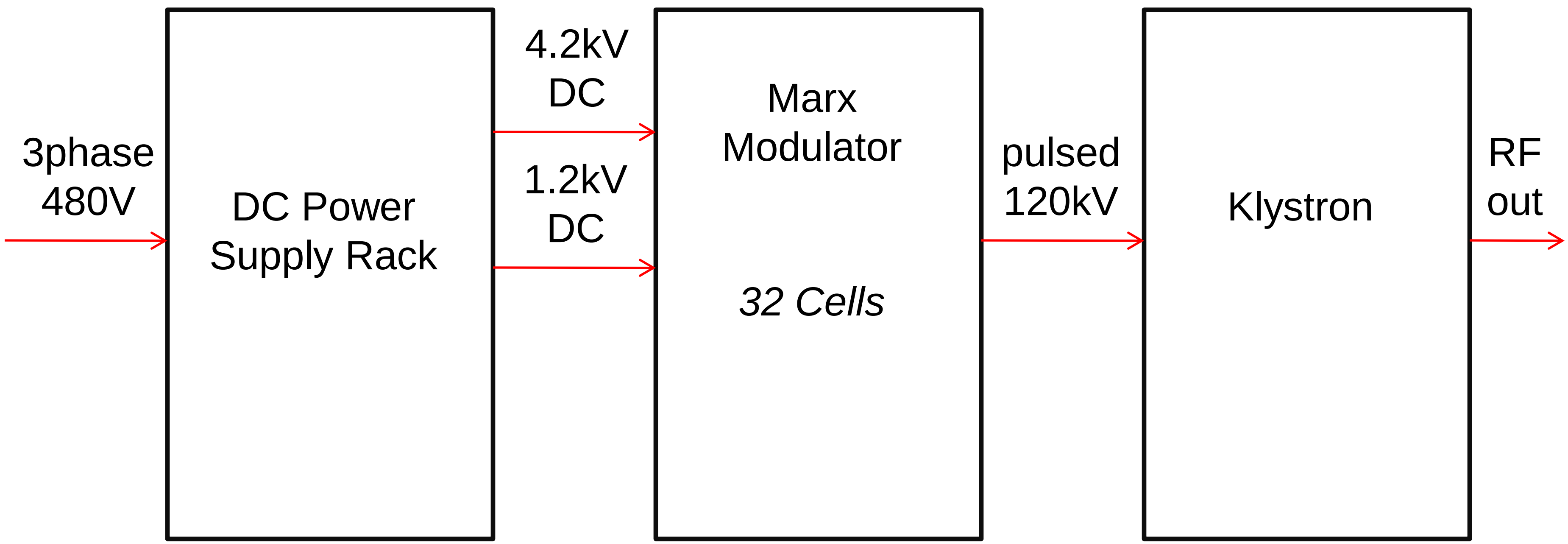
- *Can be accommodated with ~50% volumetric air flow increase compared to the P2 Marx. Heat is removed from modulator via air/water heat exchanger.

Conclusions: Essential Considerations for a Modern Modulator

- Both high MTBF AND low MTTR
- Tel Com high availability tenets: Reliability, Redundancy, and embedded Diagnostics
- Prototype to design maturation
  – Borrow what scales
  – Demonstrate what does not scale
- Solid state Marx topology developed at SLAC incorporates these considerations

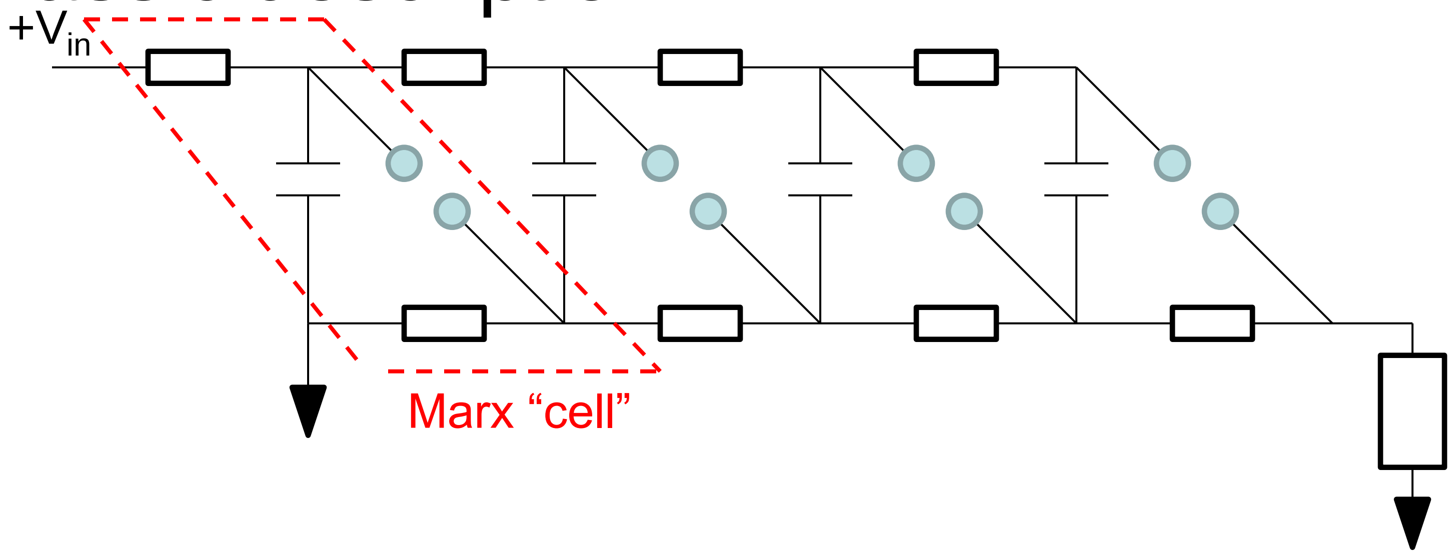
Backup Slides

RF System Overview

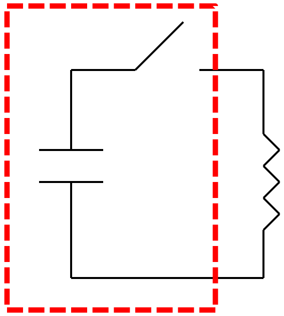


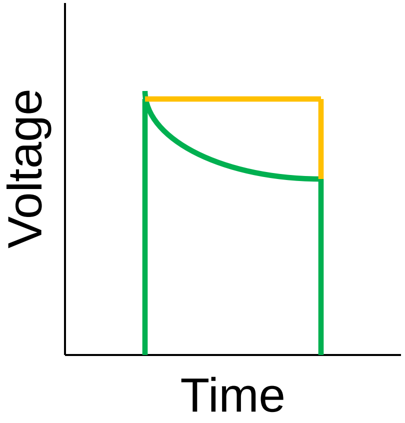
Marx Basics

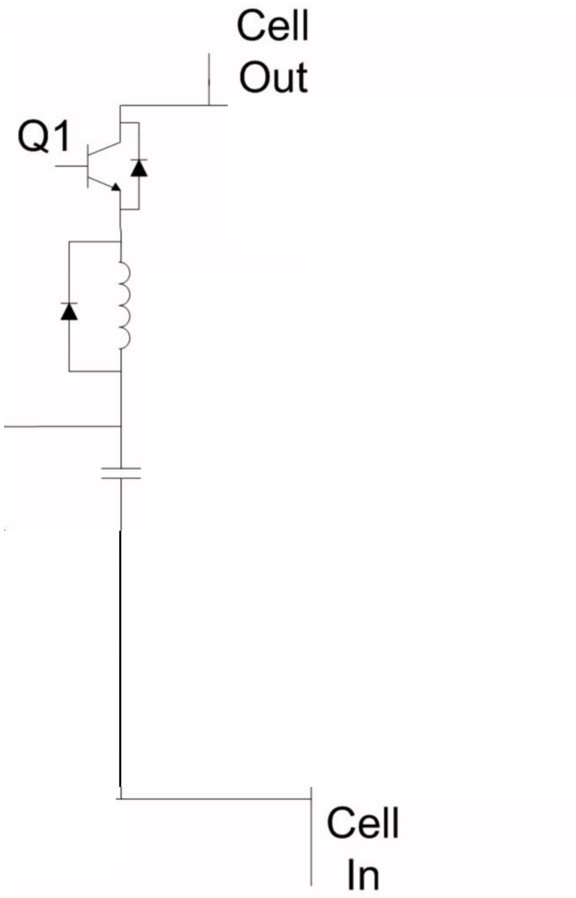
- Classic description:



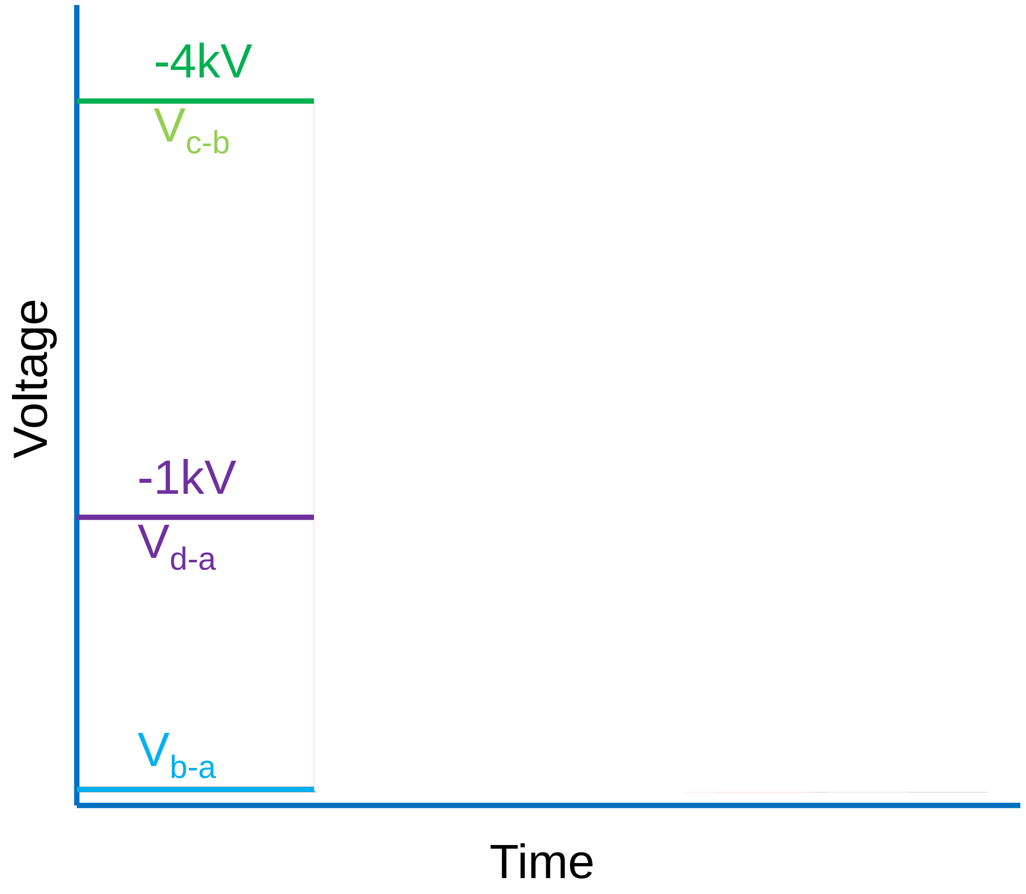
SLAC P2 Marx Cell Schematic

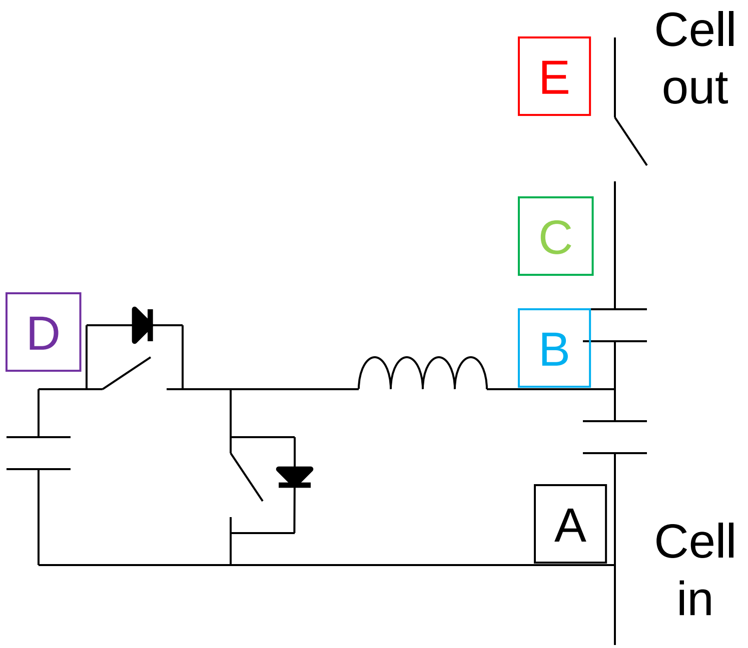






Correction Scheme





(negative bus voltage)