SLAC Project-X RF Power Program

Chris Adolphsen

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- 1.3 GHz, 30 kW CW Sources
- 650 MHz, 30 kW CW Sources
- Modulators for the 1.3 GHz Pulsed Linac

Introduction

- SLAC RF Experience
  - Extensive S-band (2.9 GHz) and X-band (11.4 GHz) rf technology development for room temperature linacs
  - During past six years, focused on L-band (1.3 GHz) rf technology (Modulators, Klystrons, RF Distribution and Power Couplers) for the ILC program at ~ 6 M$/year
  - In 2009-10, started efforts on 1.3 GHz CW rf sources, kickers and the MI rf cavity. Recently funded at 400 k$ for studies of 650 MHz CW rf sources and long-pulse modulators

1.3 GHz, 30 kW CW Sources

Chris Adolphsen and Heinz Schwarz
SLAC

IOTs

- Good efficiency (~ 60%) and would take advantage of TV transmitters for lower frequency systems – however 1.3 GHz only recently developed, little reliability data (short cathode-grid spacing), low gain, 2x higher voltage modulator than klystron and needs more development
- IOT manufacturers: CPI (30 kW), E2V (16 kW – no longer in catalog), Thales (16 kW) and recently Mitsubishi (built 30 kW prototype for KEK ERL program)
- Costs for turn-key systems with 100 k$ CPI 30 kW IOT range from 400 – 900 k$ based on quotes from Bruker, ETM, DTI and Continental for small quantities

Klystrons

- Good efficiency (~ 60%) and high gain, but 'slow' approach to saturation compared to IOTs
- Klystron manufacturers: CPI sells a 'reliable' 11 kW tube and has a design for a 30 kW tube (would build one for 440 k$) and Toshiba is developing a 25 kW tube (probably for KEK)
- For the 12 GeV upgrade at JLab, they chose klystrons over IOTs for their 1.5 GHz, 13 kW sources. L3 is currently building 24 (out of 84 required) at 45 k$ each. They claim the modulators would also be ~ 50 k$, so using two such tubes (modified to 1.3 GHz) could cost as little as 200 k$ and be industrialized to a large extent

Solid State Transmitters

- Reasonable efficiency (~ 50%), high gain, modular design provides high reliability but cost on high side (although may lower over time with advances in cell phone transmitters)
- At the 2010 CW rf workshop in Spain, much interest in solid state approach, especially in Europe where the 352 MHz SOLEIL solid state source will be upgraded and the approach will be adopted by ESRF
- Bruker makes a 10 kW single rack unit that sell for 162 k$ - combining three for 30 kW would cost around 500 k$. Also seems like there is a lot of Asian companies marketing lower power, lower frequency devices

Bruker 10 kW CW Source

Consists of eight 1.25 kW water-cooled modules - each module has eight 160 W, isolated transistor units that are summed in a coaxial combiner – the output of the each module drives a common WR650 waveguide – no solenoid, HV PS, filament PS nor vacuum pump

1.3 GHz Cost Summary

CPI quotes

IOT VKL9130A, 30 kW CW	$95k
KLYSTRON VKL7930A, 30 kW CW	
Prototype from existing design including NRE	$435k
(considered more reliable than IOT by CPI)	

Transmitter quotes (30kW CW, IOT based):

Continental Electronics Corp.	
Prototype including IOT	$850k
ETM Electromatic Inc.	
Prototype including IOT	$797k
Quantity > 5	$500k
DTI Diversified Technologies Inc.	
Prototype including IOT and output Isolator	$600k
Quantity 64	$400k
BRUKER (France)	
Transmitter without IOT	230 kEuro x 1.4 = $320k

1.3 GHz Cost Summary (cont)

Solid State Power Amplifier s

BRUKER (France)

Single Rack SSPA (3*10kW CW) (Commercial Product)	3*120kE x 1.4 = $504k

INTEGRA Technologies, Inc. (USA)

Double Rack SSPA (25kW CW)	$785k
NRE	$415K
Single Sub-Module (2kW CW)	$30k
NRE	$25k

FY11 SLAC Program

Recently Funded by PX to:

- Compare possible 650 MHz, 30 kW sources (IOTs, Klystrons and Solid State) in terms of performance and cost
- Evaluate vendors and kW level 650 MHz solid state sources and see where we can collaborate with RRCAT and BARC
- Indentify modulator and 1.3 GHz klystron designs for a 5 ms or 25 ms pulsed linac (the ILC sources are designed for 1.6 ms pulses)

650 MHz, 30 kW CW Sources

Chris Adolphsen, Heinz Schwarz and
Rosa Ciprian

SLAC

CPI 80 KW, 650 MHz, CW IOT

CPI/Microwave Power Products (MPP) offers IOT's for particle accelerator applications. Integral Cavity Inductive Output Tubes (IC IOT) have been created by utilizing the fundamental electrical design of our external cavity IOT used in terrestrial UHF television broadcasting and incorporating conventional klystron cavity and coupling technology. The VKP-9070A is an IC IOT that provides 80 kW CW from 650 to 805 MHz. CPI also offers IC IOT's that provide 90 kW CW at 500 MHz and 30 kW CW or 90kW pulsed at 1300 MHz.

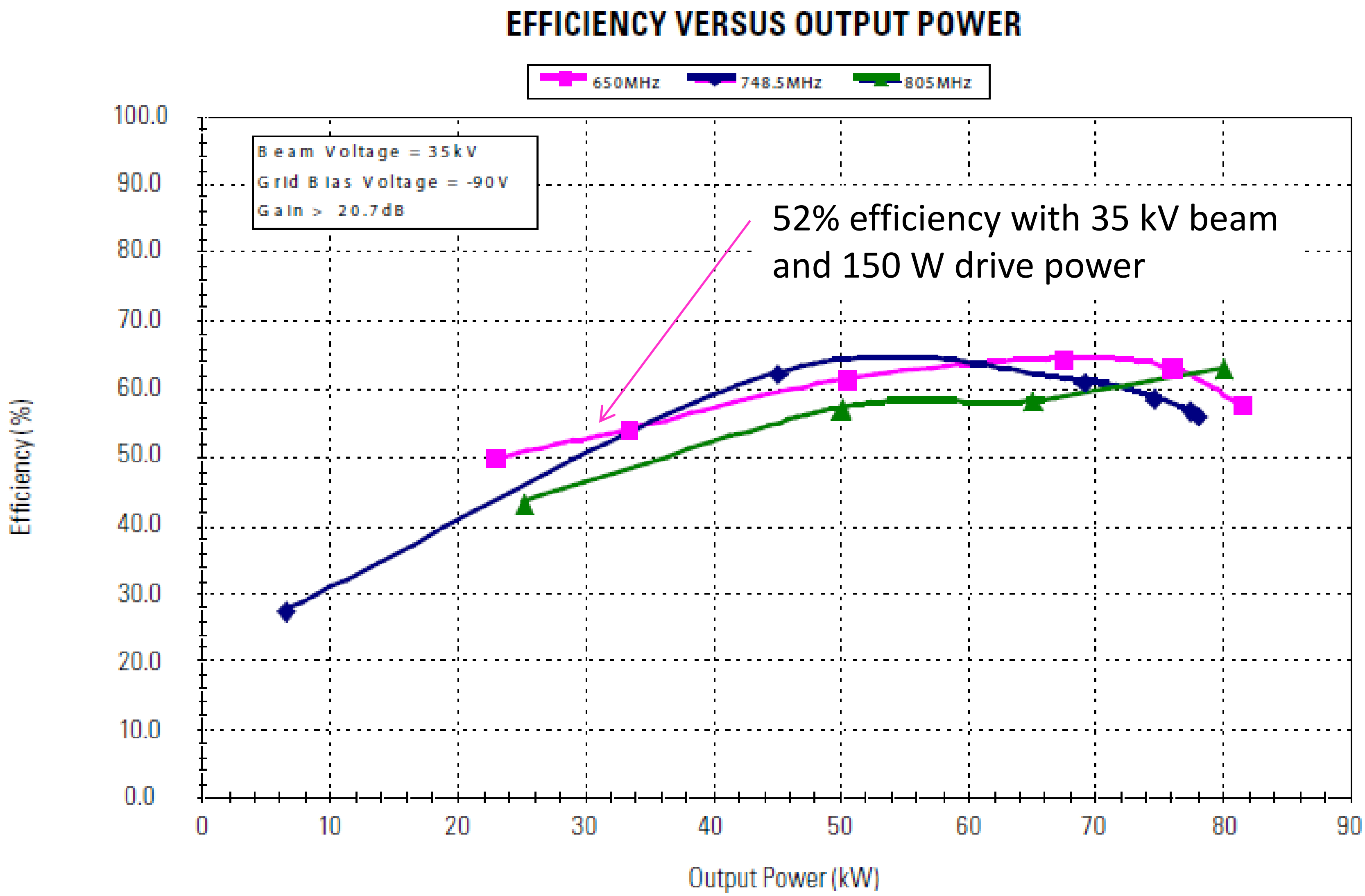
FEATURES

- Coaxial Output Window with Alumina Ceramic
- Water-cooled collector, cavity, and coupling loop
- Air cooled input circuit and electron gun
- Compact size with "collector (water) down"
- Requires VYW-9070A (Magnet, I/P circuit, & Stand)

VKP-9070A with VYW-9070A

2/11 Quote for a VKP9070A with Magnet = 128 k$

CPI IOT Performance at 30 kW



OUTPUT POWER VERSUS DRIVE POWER

650 MHz, 30 kW RF Solid State Amplifier Objectives

- Achieve 30 kW by combining modules with an output power of 2-2.5 kW.
- Ideally each module should include its own power supply and a pre-amp such that the drive power is ~ 0 dBm.
- Water cooled with water temperature in the 20-35 degC range.
- Distributed power supplies so the system reliability is improved and single point of failure (power supply) is avoided.
- Status:
  - Working on building and testing a single 1-2 kW module based on RF power FETs. We are buying some RF power FETs, an RF power load (2.5kW) and a 650 MHz phase locked oscillator. SLAC has all other components required to implement this step.
  - SLAC is also seeking for companies to manufacture the 650MHz, 2 kW modules, which we can combine, to get to the 30kW requirement.

Rosa Ciprian

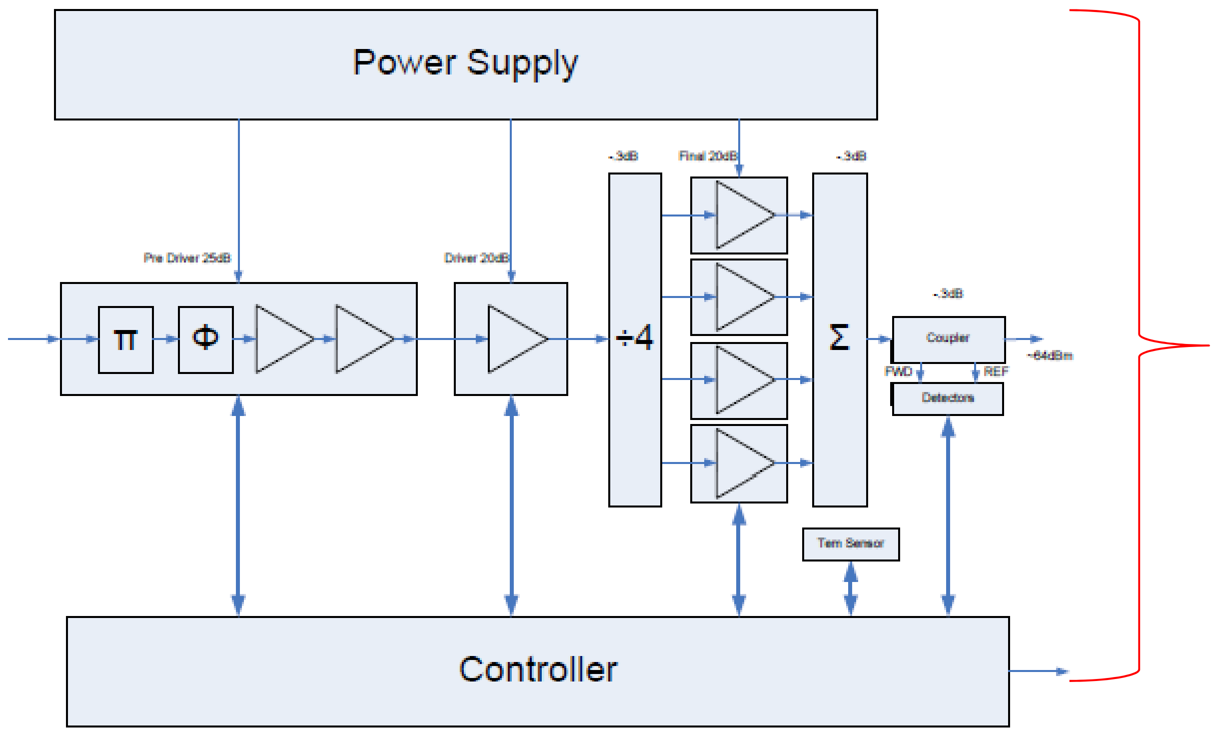
Located in Inglewood, CA

Company Information Summary

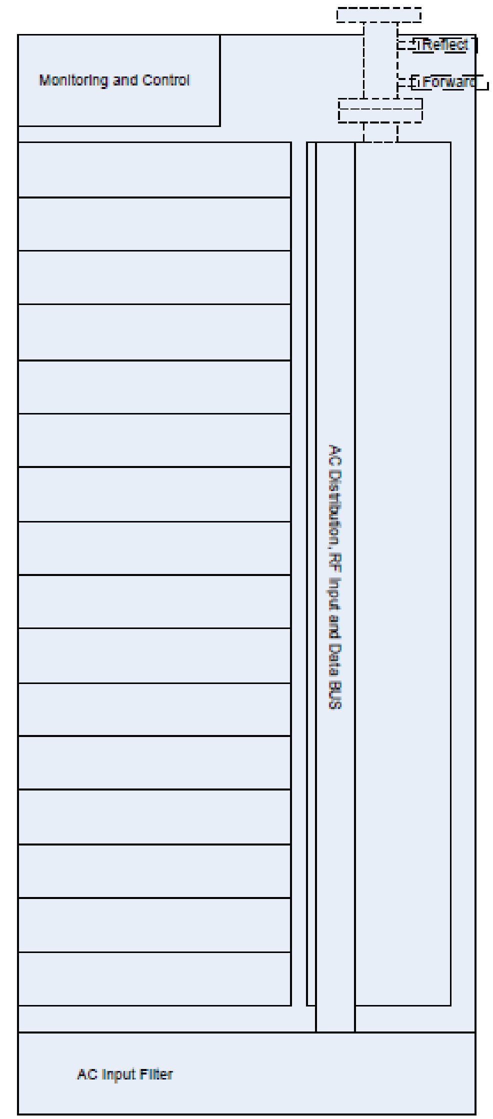
Business	
Name of Business	Empower RF Systems, Inc.
Type of Business	Corporation: State of California
Business Classification	Small Business
Manufacturer	RF & Microwave High Power Amplifiers, Systems, Modules and Multi-Function Modules
Time in Business	Since 1999
Quality Control	ISO 9001-2008
Facility Size	25,000 Square Feet in Inglewood, 4,000 Square Feet in New York
Product	
Applications	Broadband, Matched Band, General and Personal Comm. Systems
Markets	Military, Commercial, Industrial and Medical
Represented	National and International
Key Personnel	
President	Effi Bainvoll
Chief Executive Officer	Barry Phelps
Chief Operating Officer	Cordell Sweeny
V.P of Sales	Jon Jacocks
V.P of Engineering	Paulo Correa
Director of Operations	Bob Biedka
Staff	5 Department Managers 19 Degreed RF Engineers 10 Design and Drafting 12 RF/Microwave Technicians
Total Number of Employees	90

Empower 30 kW, 650 MHz Proposal

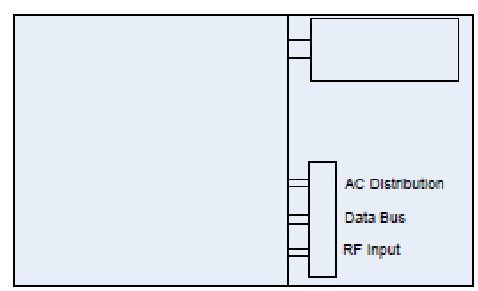
One of 16, 2.2 kW Units



Side View of Rack



Top View of Rack



Empower Proposal (cont)

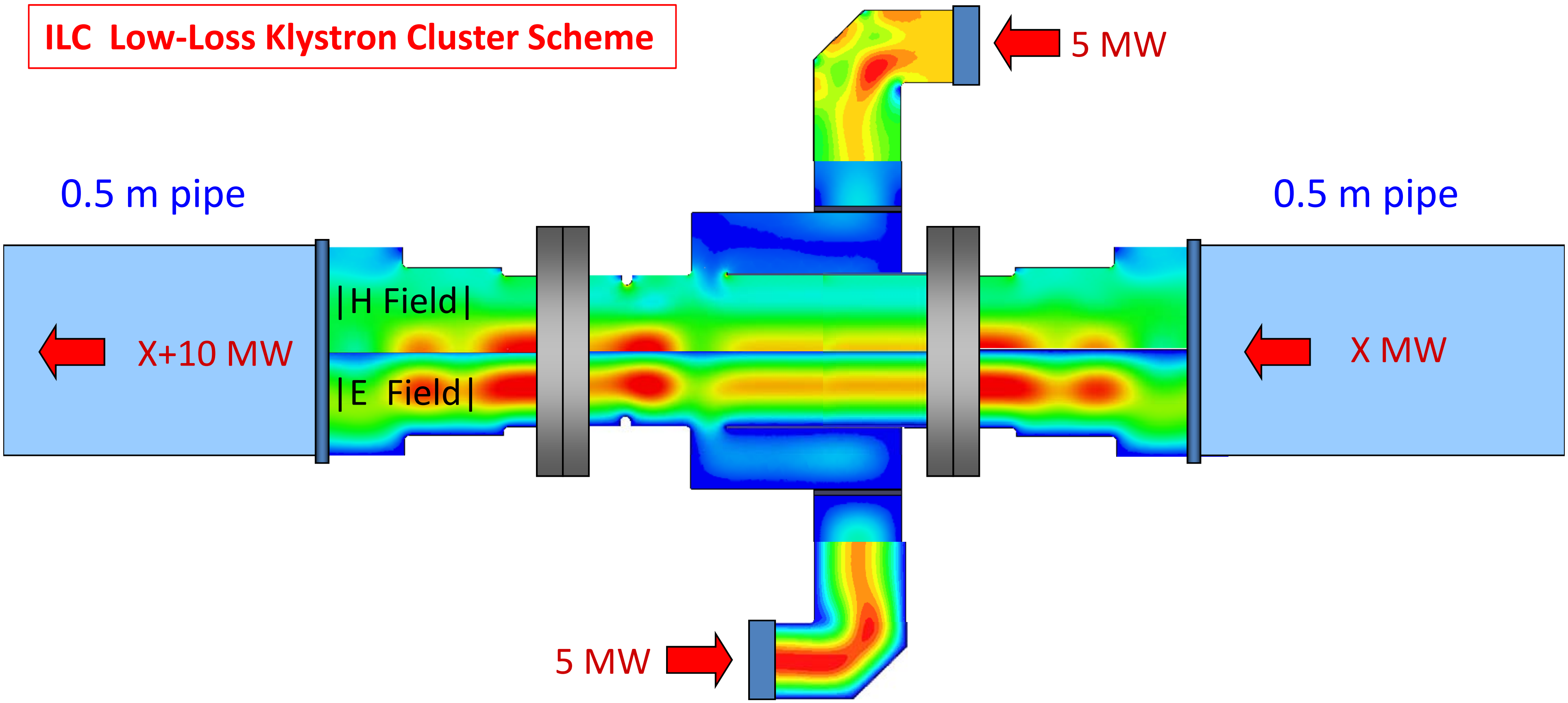
- Single 19" rack, 1 m deep for the stand-alone 30 kW system (power supply and combiner included).
- 16 modules at 2.2kW each
- The combiner would be placed in the back of the rack
- 480 VAC input and filter at the bottom of the rack.
- Monitor and control at the top of the rack
- About 0.2dB losses in the combiner where the transformation to 50 ohms is made. The combiner material could be aluminum or copper; it is effectively a coax with coderite for spacers (thermally stable).
- 6¼ inch coax for the output.
- Might consider hot swappable units, but it is not a requirement.
- Inputs to the system are: AC input, Data bus, and RF driver.
- Each module has a microprocessor, which is Ethernet connected to the rest of the system.

Empower Proposal (cont)

- Each module contains 4 pallets with 500 W transistors operating at 300W.
- Each module contains a temperature sensor in the cold plate.
- Same pallet for the driver.
- The pre-driver has amplitude and phase control.
- Efficiency is in the 50-60% range.
- No single point of failure (independent modules)
- PS and RF are mounted on the water-cooled cold plate. Cooling water in the 20-30 C.
- Pallets are tested at 85 degC on the cold plate.
- Shutdown automatic sequence controlled at a higher level.
- Isolator at each output of the 2 kW modules or at the input of the combiner, the later is the one preferred by Empower.

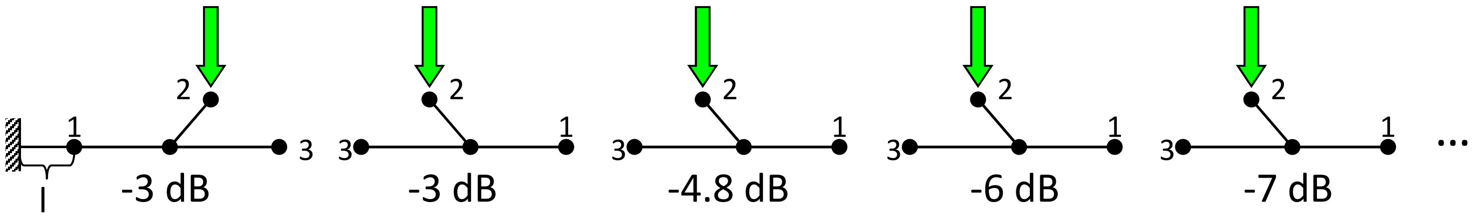
Combining 2 kW RF Sources

Use same vector adder approach as being pursed at SLAC for combining 30, 10 MW 1.3 GHz sources, but use different modes

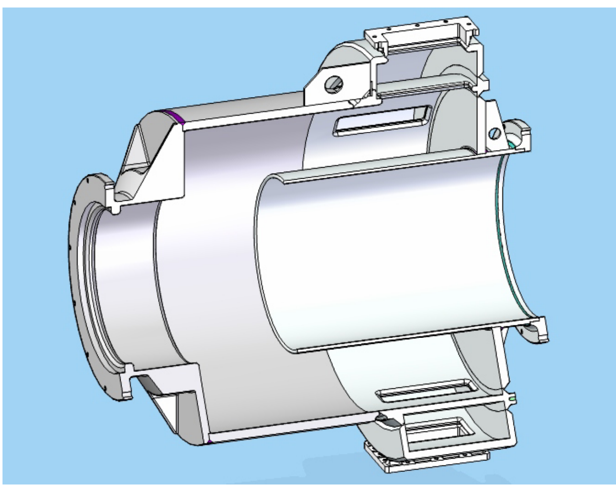


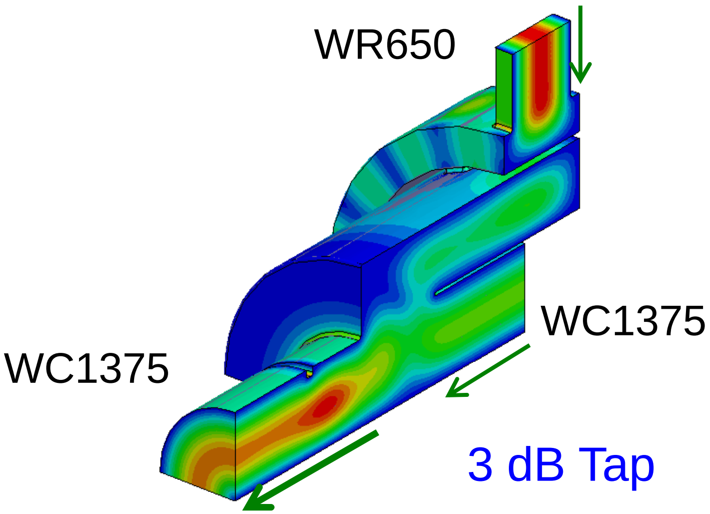
Adjust Coupling as Power Increases

Power Combining:



But instead of using TE01/02 taps as shown below, use a compact planar or coaxial geometry

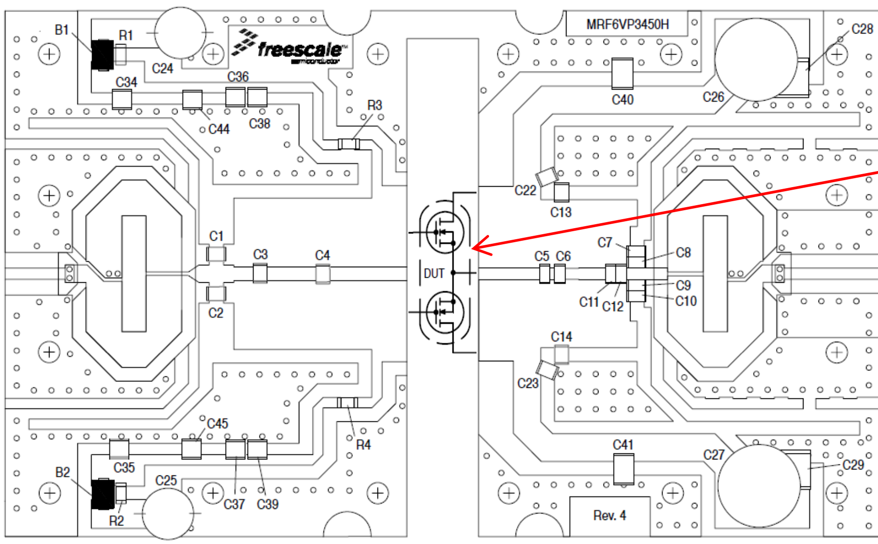


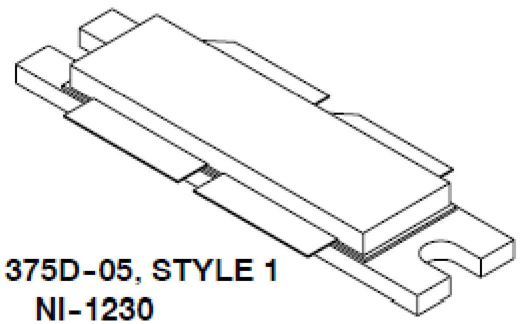


Will Also Test Freescale 500 W, 650 MHz FETs Using Their Evaluation Boards

RF Power Field Effect Transistors

N-Channel Enhancement-Mode Lateral MOSFETs





CASE 375D-05, STYLE 1
NI-1230
MRF6VP3450HR6(HR5)

Characteristic	Symbol	Min	Typ	Max	Unit
Typical Pulsed Performances (In Freescale Broadband Test Fixture, 50 ohm system) V_{DD} = 50 Vdc, I_{DQ} = 1200 mA, P_{out} = 520 W, f = 470-860 MHz, 50 μsec Pulse Width, 2.5% Duty Cycle					
Power Gain	G_{ps}	—	20.5	—	dB
Drain Efficiency	η_D	—	50	—	%
Input Return Loss	IRL	—	-3	—	dB
P_{out} @ 1 dB Compression Point, Pulsed CW (f = 470-860 MHz)	P1dB	—	520	—	W

650 MHz Cost Summary

IOT

CPI VKP9070A, 80 kW max, CW	$128k

Solid State Power Amplifiers

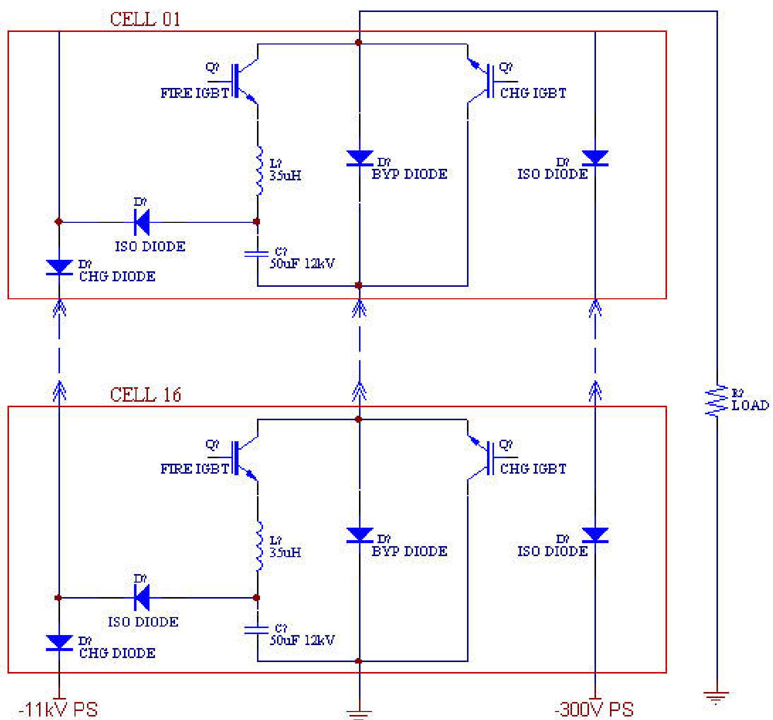
EMPOWER RF Systems, Inc.	
Single Rack SSPA (30 kW CW)	$467k
NRE	$53K
Single Sub-Module (2kW CW)	$28k
includes Power Supply and Driver	
NRE	$1.4k
INTEGRA Technologies, Inc.	Waiting for a Quote
Freescale Semiconductor	
MRF6VP3450H (650MHz/500W) and a test circuit	$1.5 k
MRFE6VP61K25H (600MHz/1250W) and test circuit (modify to 650 MHz)	$0.9k

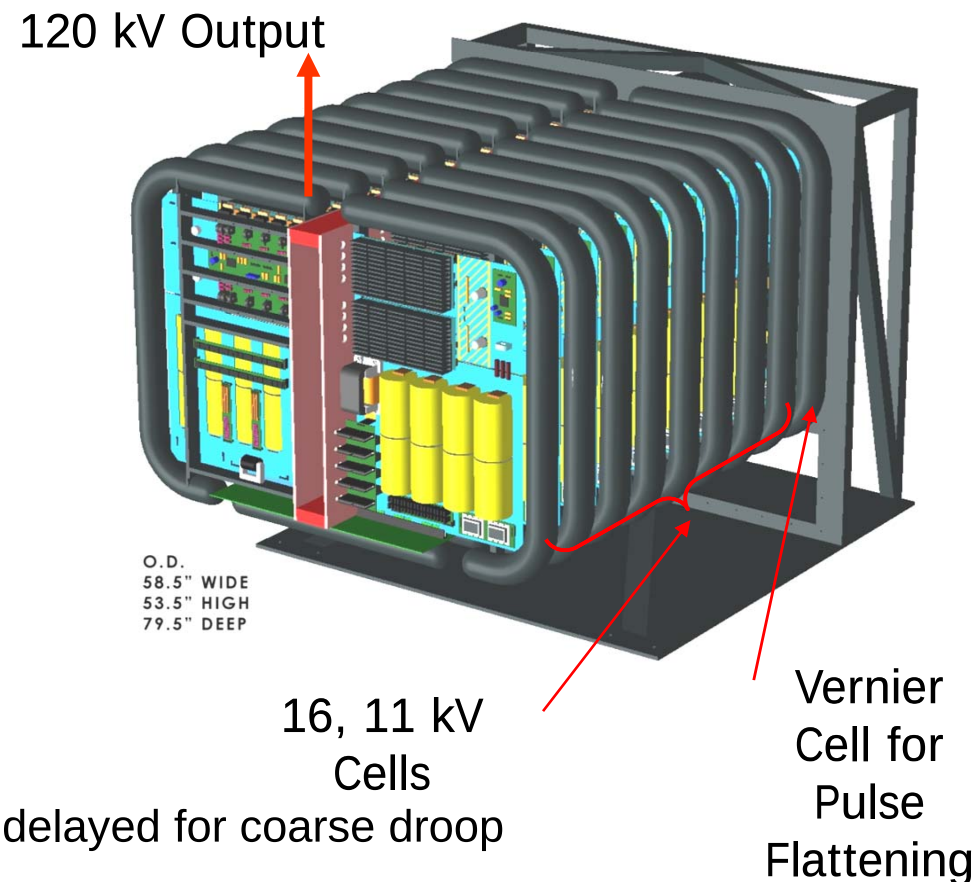
Modulators for the 1.3 GHz Pulsed Linac

Mark Kemp, Craig Burkhart and Chris Adolphsen
SLAC

SLAC P1 Marx Modulator for the ILC

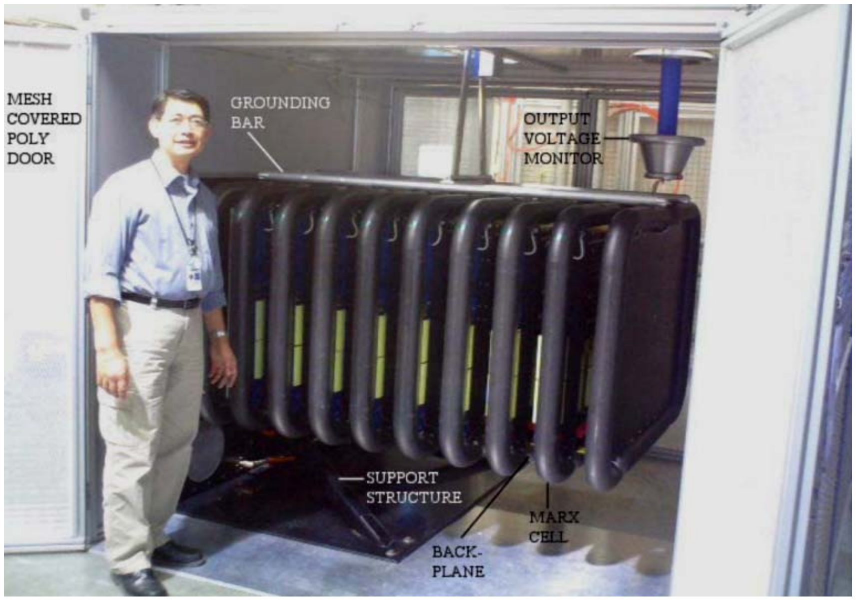
(120 kV, 140 A, 1.6 ms, 5Hz)

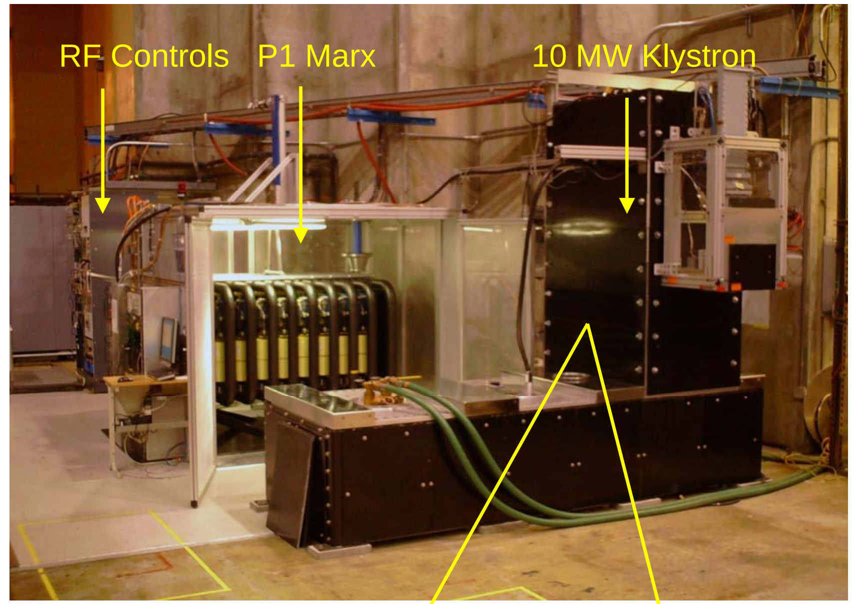




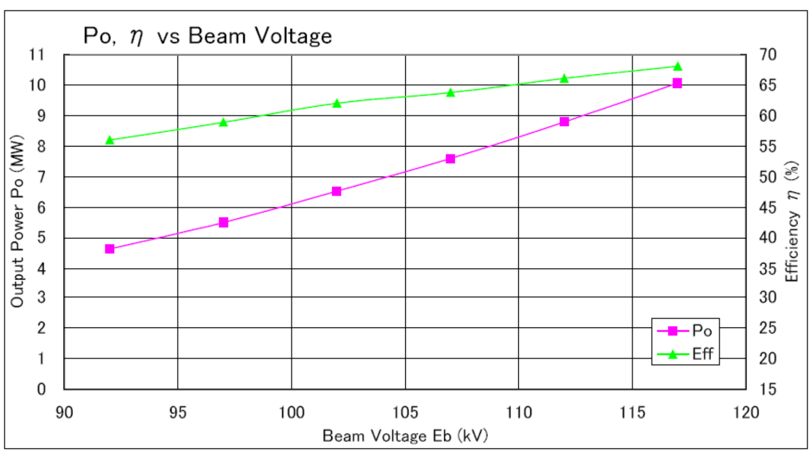
- 11 kV per cell (11 turn on initially, 5 delayed for coarse droop compensation)
- Switching devices per cell: two 3x5 IGBT arrays
- Vernier Cell ('Mini-Marx') flattens pulse to 1 kV

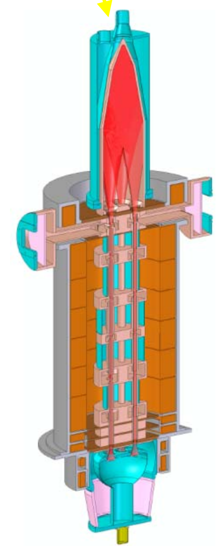
P1 Marx Test Stand at SLAC ESB



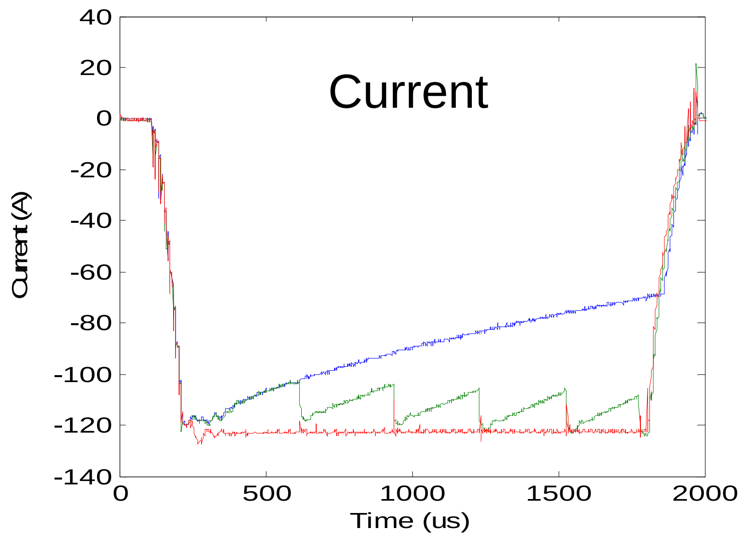


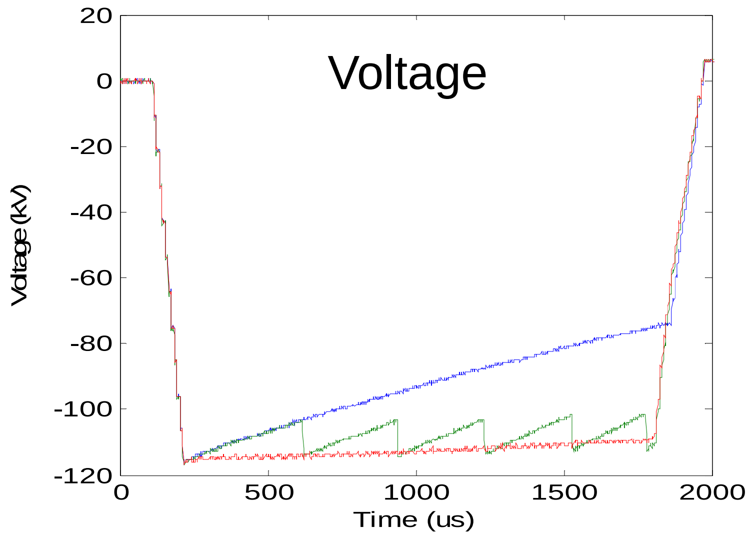
Toshiba MBK Measurements of Efficiency and Output Power -vs- Beam Voltage





Marx Output with Different Levels of Droop Compensation





Blue: no droop compensation

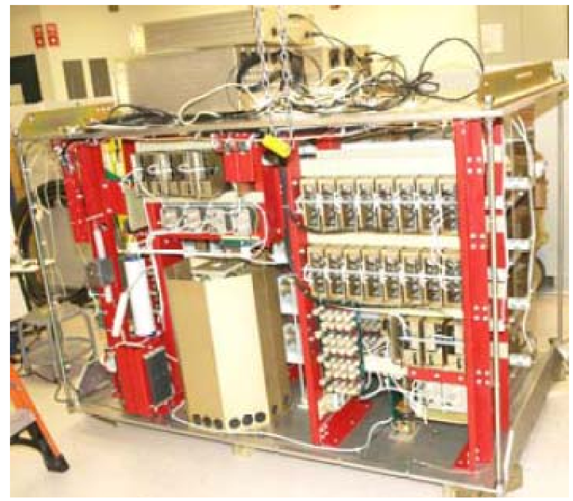
Green: with only delay cells

Red: with delay cells and Vernier – flat with 3% saw-tooth modulation

Diversified Technologies Inc. (DTI) Marx Modulator

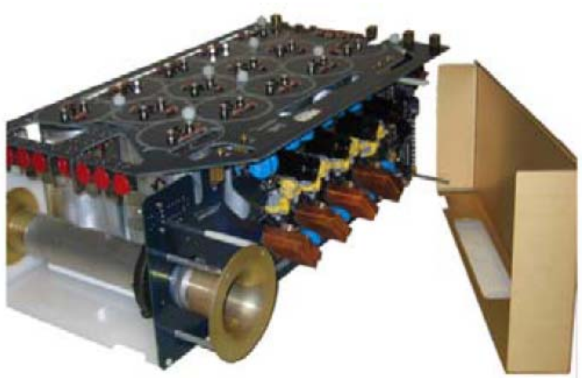
This Marx was SBIR funded and will be delivered to SLAC after it is modified to improve ease of use. It has 6 kV cells that are immersed in oil, electrolytic capacitors (half the droop) and 900 V vernier cells.

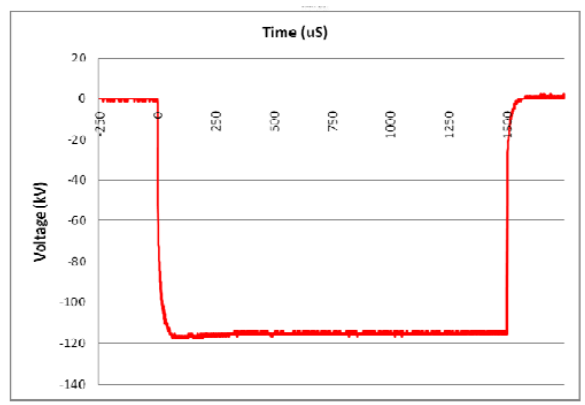
Full Unit



Inside Layout

Marx Cell





Measured Voltage Waveform

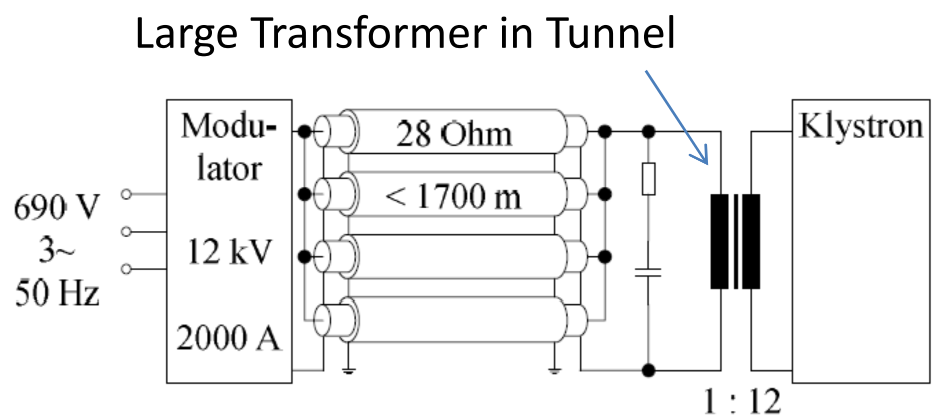
Long Pulse Modulator
Initial Scoping

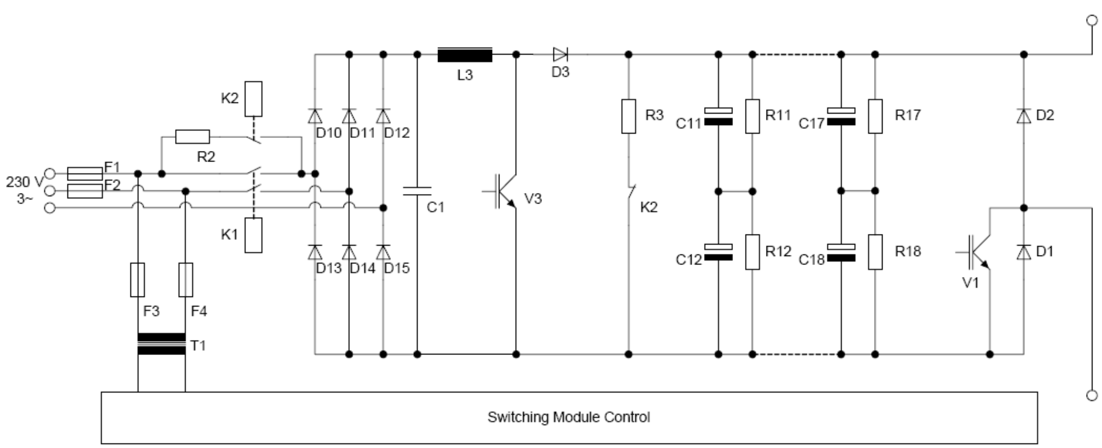
M. Kemp

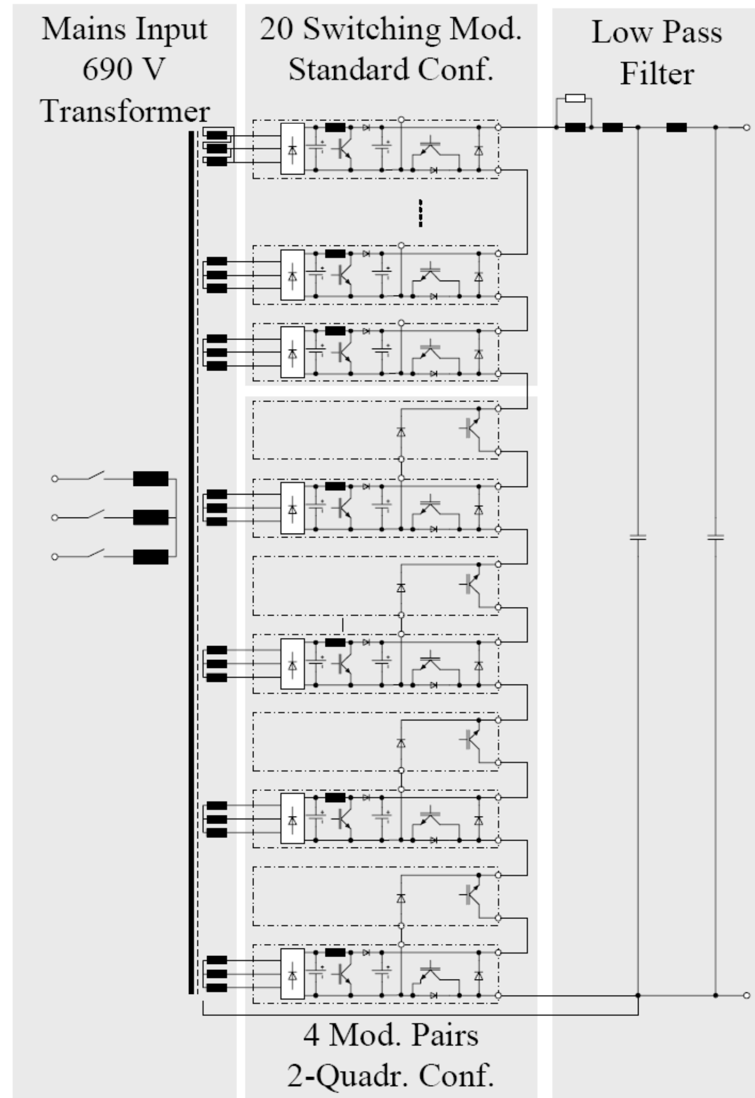
PX Long-Pulse Modulator Scoping

- Initial scoping performed without knowledge of klystron specifications
- Several topologies identified as candidates. Focus initially on scaling of SLAC P2 Marx
- Scaling parameters of interest include cost, size, and effect on facility mains
- After klystron is identified, will further analyze potential modulators and advantages and disadvantages of each

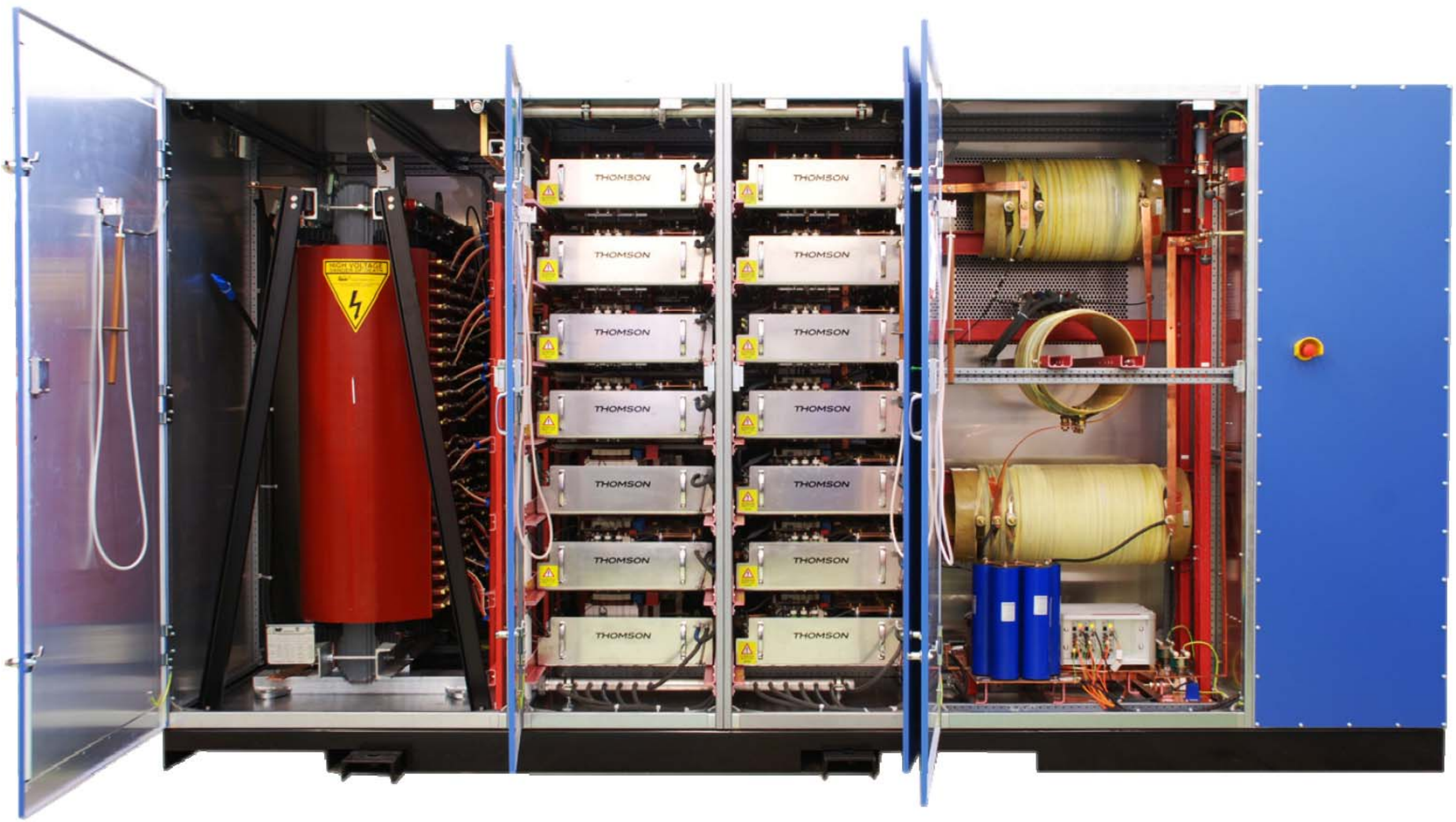
Thompson Modulator for E-XFEL



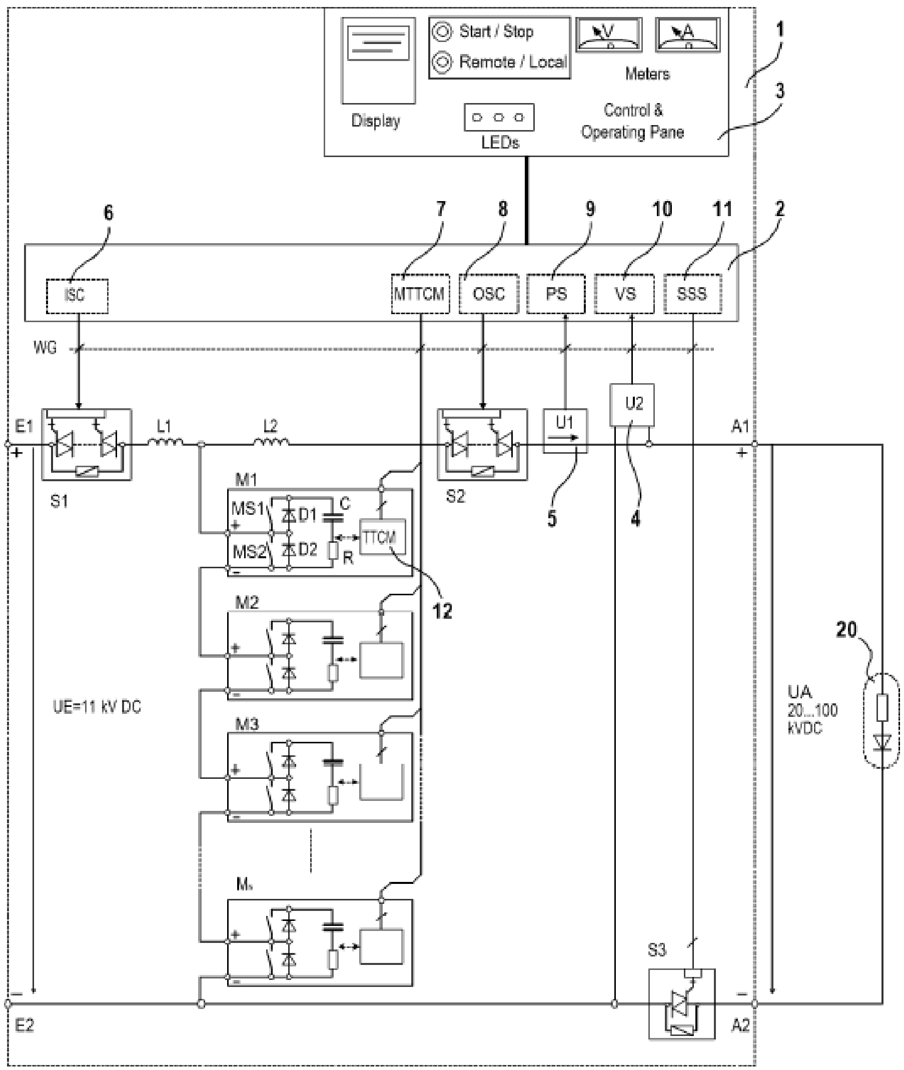


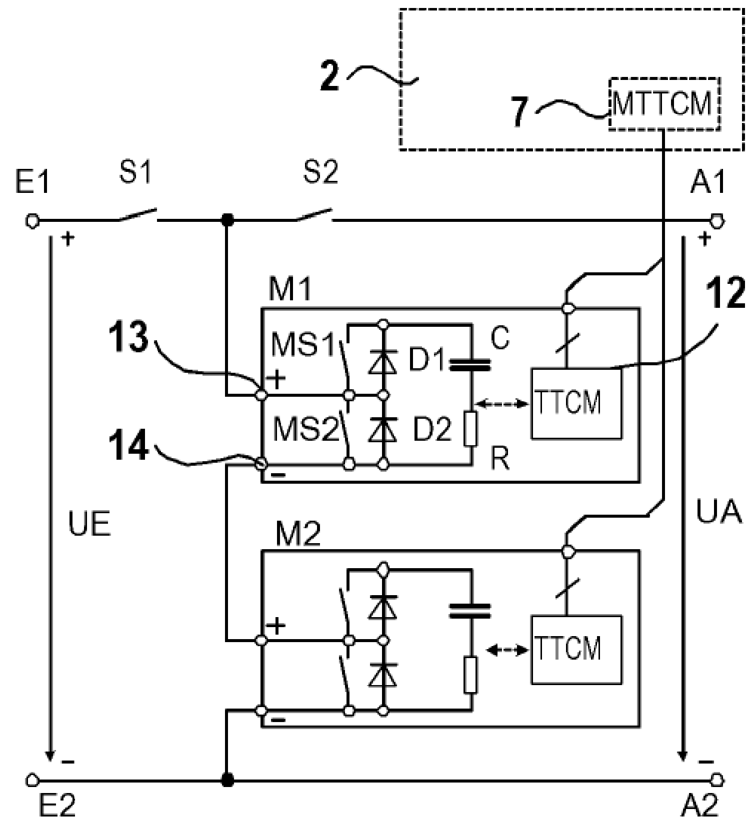


Thompson Modulator 12 kV Pulser

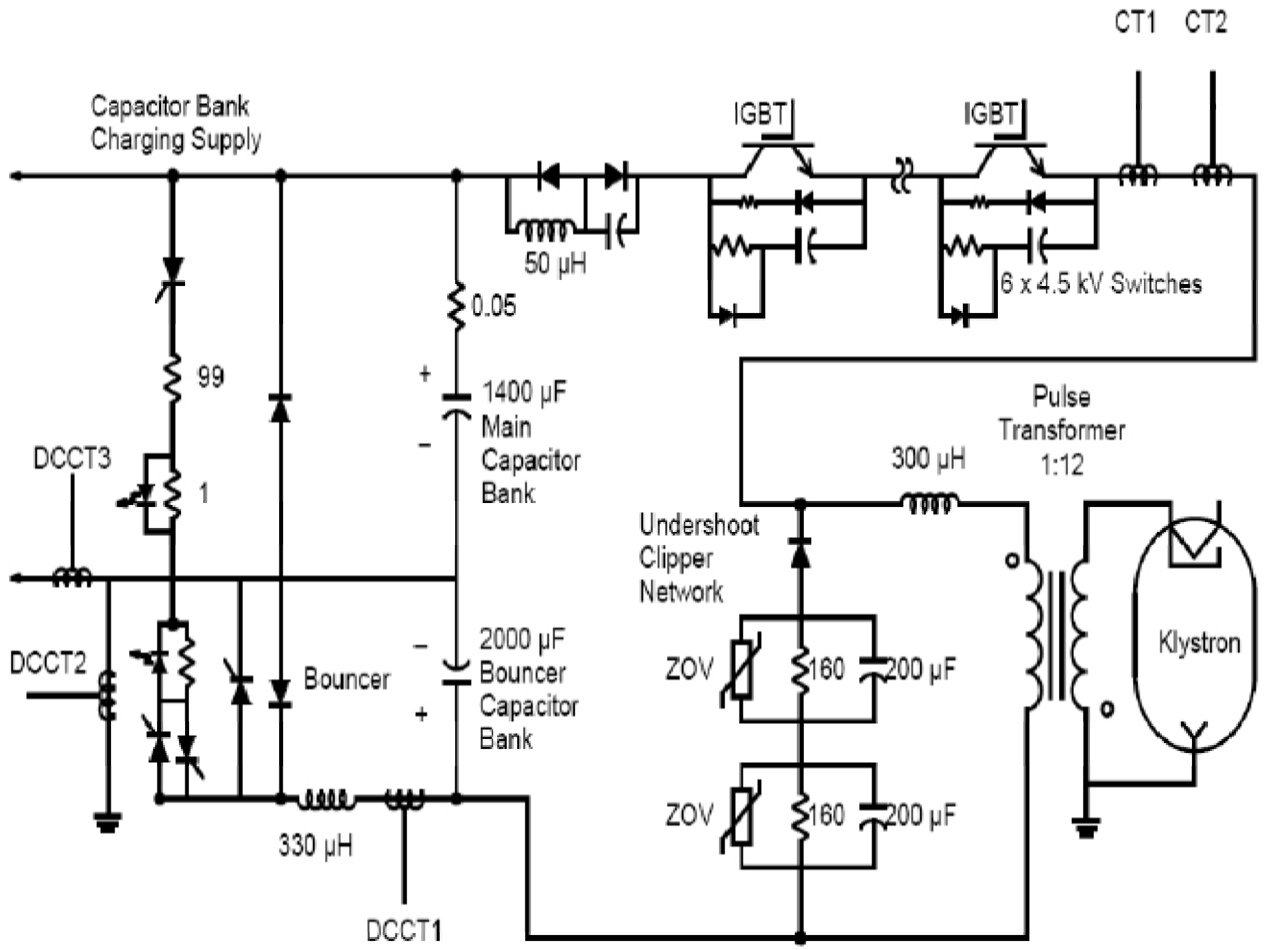


Transtechnik Modulator

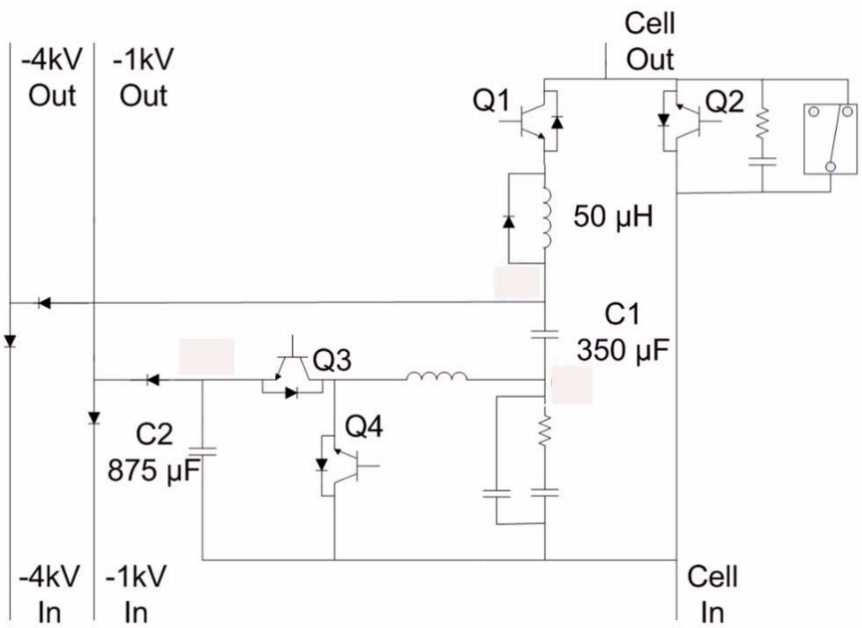


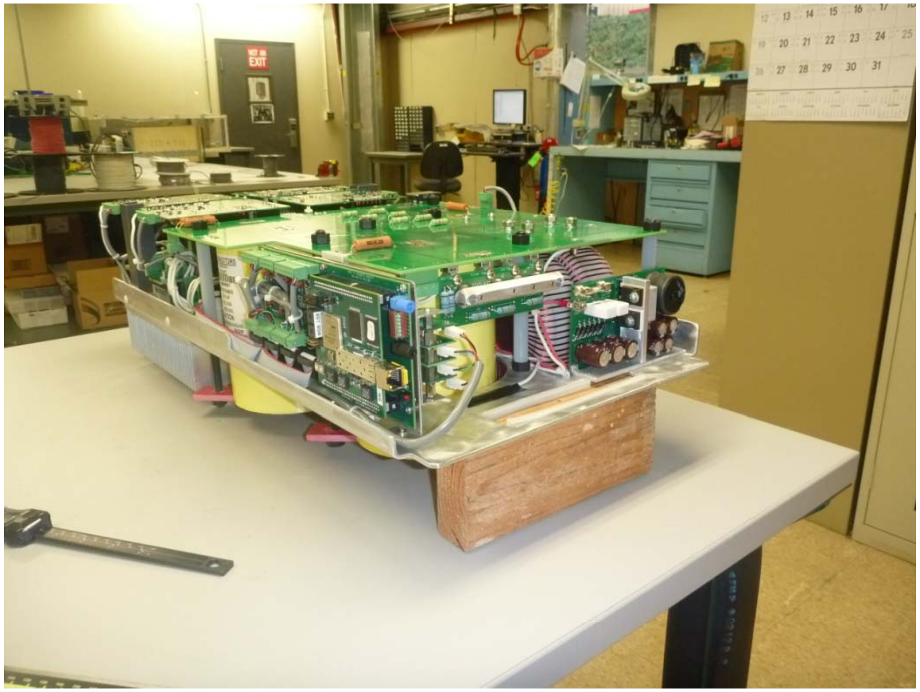


FNAL Bouncer



SLAC P2 Marx


Cell
Out
-4kV
Out
-1kV
Out
Q1
Q2
50 µH
C1
350 µF
Q3
Q4
C2
875 µF
-4kV
In
-1kV
In
Cell
In

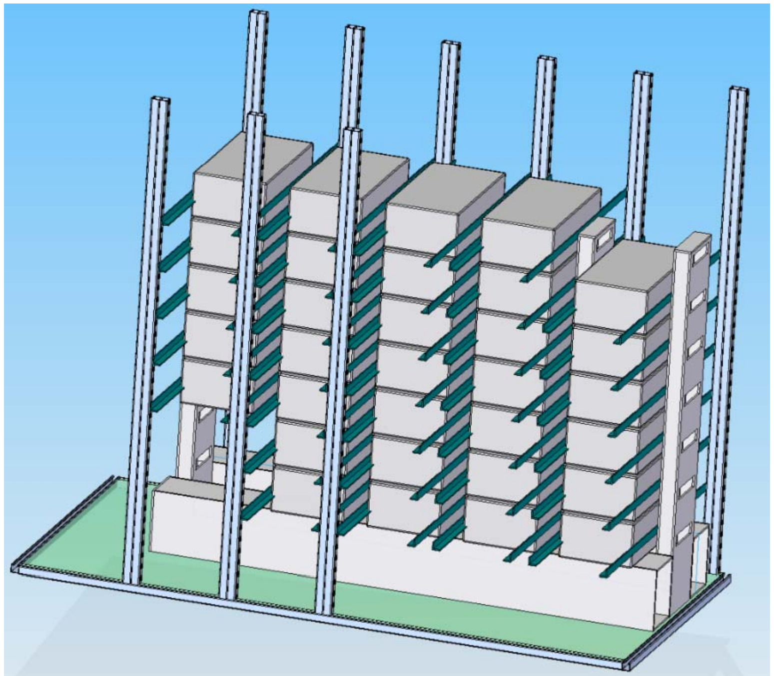


- Below are assumed parameters for initial scoping (obviously must be refined, but presented here to illustrate issues of interest)
- Assume P2 design, and simply adjust energy storage and some components

	A (ILC, P2)	Short pulse	Long Pulse
Output Voltage	120 kV	120kV	120kV
Output Current	140 A	140 A	140 A
Pulse Width	1.6 ms	5 ms	25 ms
Pulse Repetition Frequency	5 Hz	5 Hz	1 Hz
Average Power	134kW	420 kW	420 kW

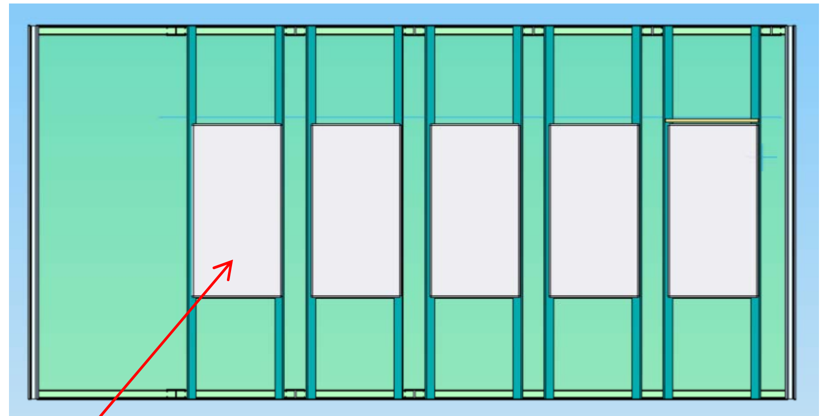
- Issue 1: Energy storage
  - For simplicity, accept P2 energy density and droop as baseline
  - ILC/P2
    - C1=350 μF/cell
    - C2=875 μF/cell
    - $E_{store,modulator}$ **~ 0.09 MJ**
  - PX short pulse
    - C1=1.1mF/cell
    - C2=3.8mF/cell
    - $E_{store,modulator}$ **~ 0.25 MJ (3.1x P2)**
  - PX long pulse
    - C1=5.3mF/cell
    - C2=22mF/cell
    - $E_{store,modulator}$ ~ **1.2 MJ (15x P2)**

- Issue 2: Volume



	Depth	Width
P2 baseline	4.5’	9.5’
P2 topology- 5ms	6.5’	9.5’
P2 topology-25ms	14’	10.5’

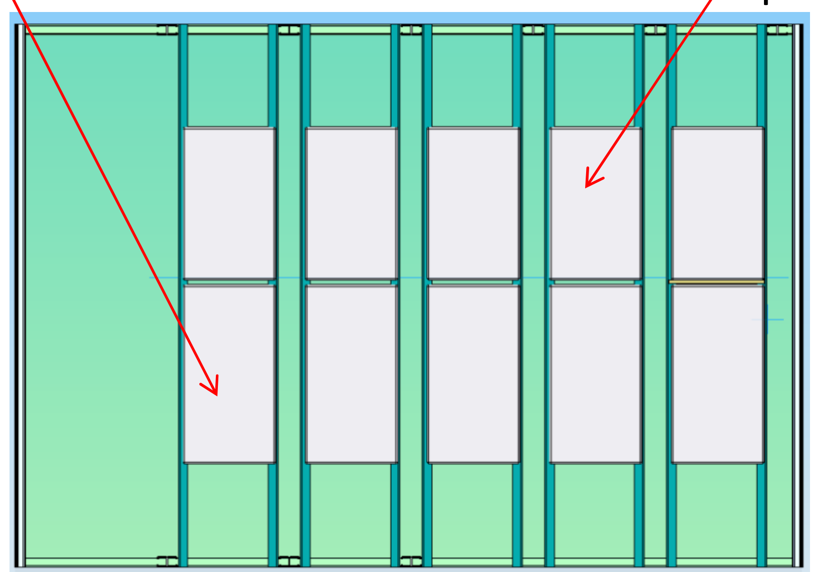
Top view: P2 Marx



Cells

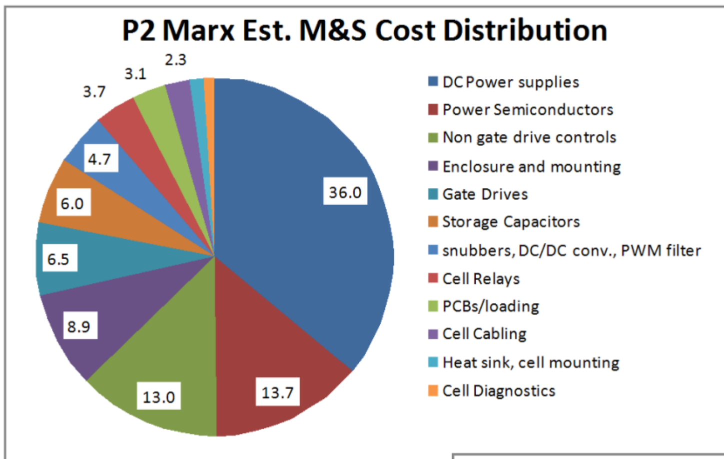
Top view: 5-ms Marx

Added capacitors

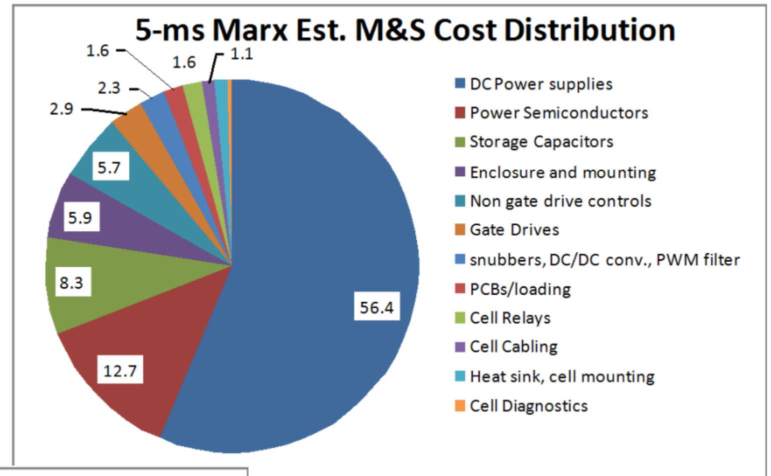


- Issue 3: Effect on mains
  - IEEE 519 sets Total Harmonic Distortion (THD) < 5% with, in general, no harmonic > 3% (in some cases harmonics < 11 can be up to 10%)
  - For the P2 Marx topology, the modulator has gaps in DC current draw during the pulse. The DC supply should therefore actively provide an appropriate interface between the mains and the modulator to limit current THD
  - A simple figure-of-merit:
    - $P_{DC,avg}$ *duty factor/p.r.f => minimum energy for DC supply to absorb from mains during pulse
    - P2 Marx => 0.230 kJ
    - PX short-pulse => 2.2 kJ
    - PX long pulse => 11 kJ
    - Thompson modulator topology, PX long pulse => 431 kJ
      - (1-D)*P/prf

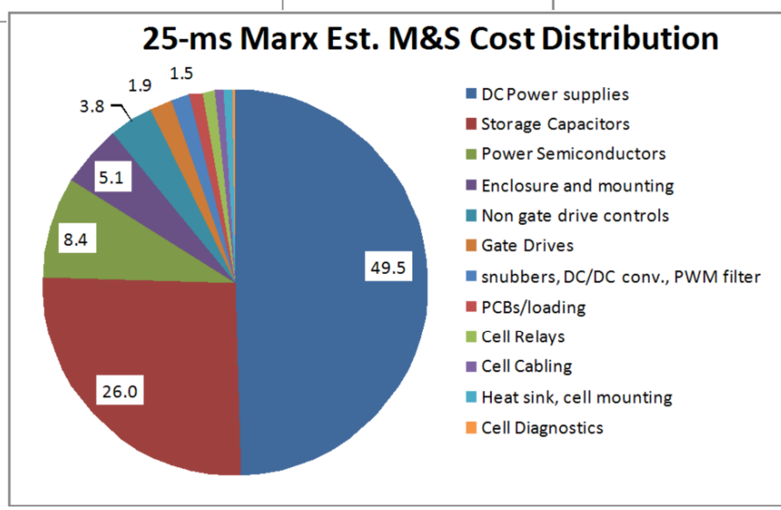
- Issue 4: Cost scaling from P2 Marx
  - No volume scaling
  - Assume no increased efficiencies
  - Assume similar design



P2 M&S



2.3x P2



3.4x P2

Summary

- SLAC has rf resources and expertize to contribute significantly to Project X.
- Coming up to speed on low power CW rf systems (have built 1.2 MW, 476 MHz CW klystrons for the SLAC B Factory) – also hope to contribute to the NGLS (CW SC linac driven soft X-Ray FEL)
- Willing to collaborate on CW efforts, perhaps in the rf combining systems for which we have much experience