Proton Improvement Plan

UPGRADE PLANS FOR 201.25MHZ RF POWER SYSTEM

Fernanda G. Garcia & Trevor Butler

March 18, 2014
Accelerator and Physics Technology Seminar

Proton Improvement Plan – Linac 200 MHz RF Power Plant

HIGH LEVEL RF SYSTEM

Fernanda G. Garcia, on behalf of the PIP HLRF team

FNAL Linac Topology

35keV	750keV	750keV		116MeV	400MeV
H-	RFQ	buncher	DTL	SCCL - Transition	SCCL

magnetron ion source 35 kV extractor	**Radio Frequency Quadrupole** 201.24 MHz 1.2 m 1 tetrode 175 kW	**Buncher dual-gap cavity** 201.24 MHz 0.2 m 1 pentode 5 kW	**Drift Tube Linac** 201.25 MHz 73 m 5 tanks 5 triodes 5 MW 200 EMQ	**Side-Coupled Cavity Linac** 805 MHz 4 m 2 modules 2 klystrons 200 kW 4 EMQ	**Side Coupled Cavity Linac** 805 MHz 65 m 7 modules 7 klystrons 12 MW 28 EMQ

Total Linac: 145 m
5 Triodes
10 klystrons

Duty cycle:
0.5% RF
0.04% beam

3 different structures
(RFQ, DTL, SCCL)
2 frequencies

Beam current:
34 mA (avg. in pulse)

FNAL Drift Tube Linac

Drift Tube Linac (DTL) occupies the first 73m of the 140m FNAL Linac

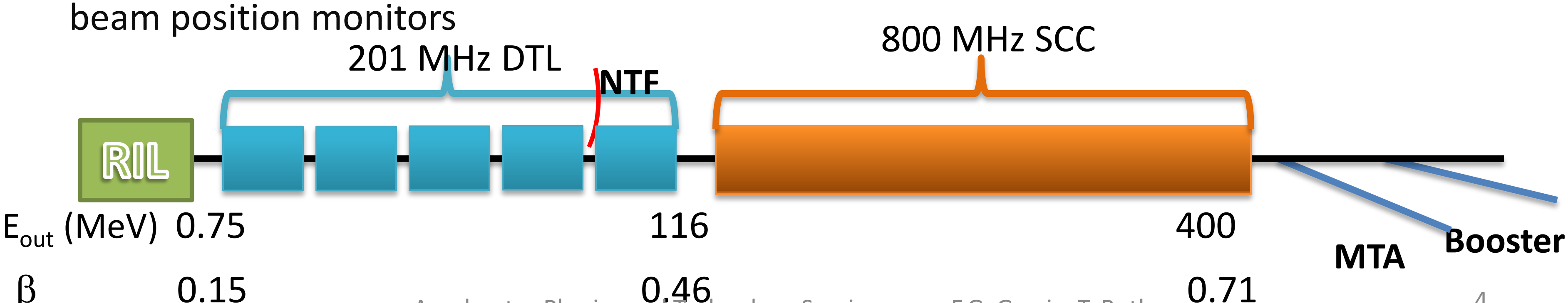
RF amplifier system was designed by Continental Electronics Corporation in the late 1950's

FNAL Linac designed/installed in 1969-1970

H^- accelerated from 0.75 MeV to 116MeV in five tanks, then transferred to side-coupled cavities at $\beta=0.46$

DTL receives pulsed 201.25 MHz RF power via 9 inch diameter coaxial transmission lines from five RF systems outside of the Linac tunnel

Space between tanks are occupied either by beam valves, dipole trim packages or beam position monitors



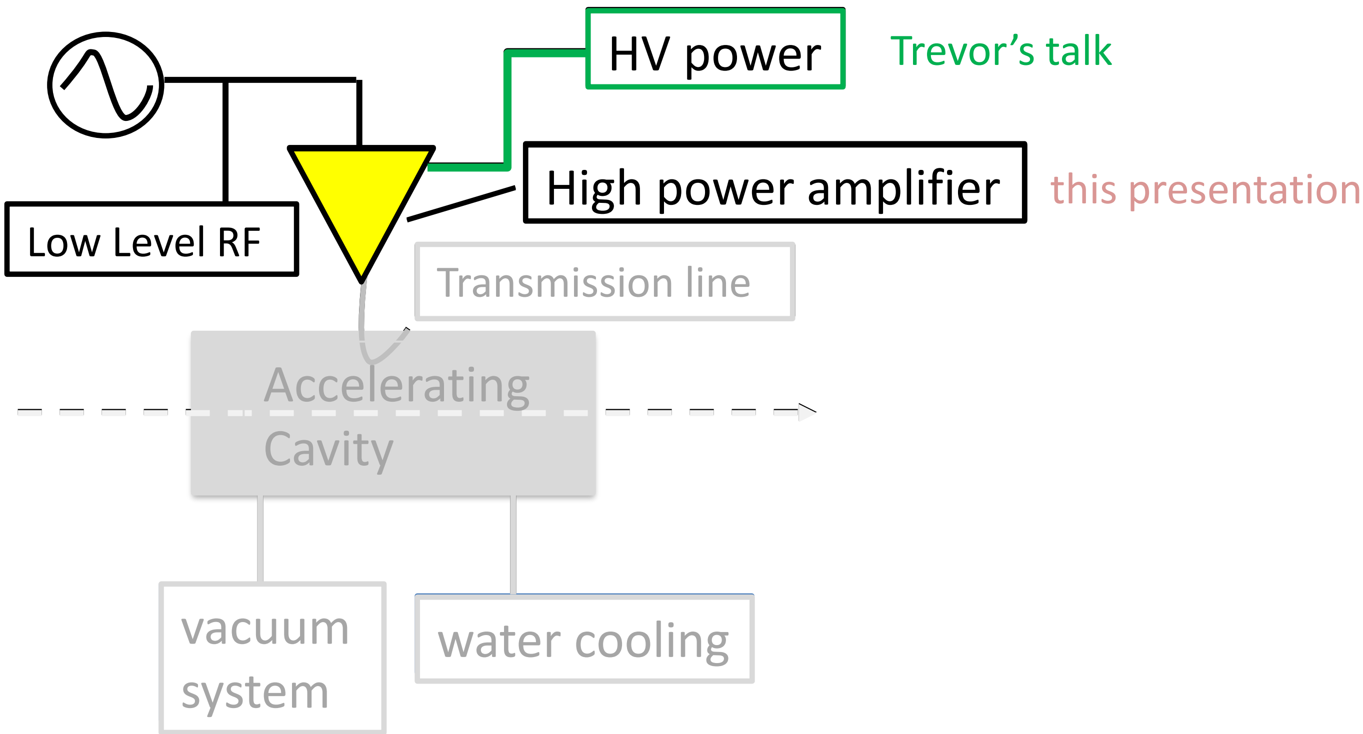
201.25MHz RF Power Plant Concerns

The 201.25MHz RF power system has been a big concern for over a decade in regards long term operational reliability and viability

The 201.25MHz RF power system issues have been documented numerous times during the last decade

1. The specialized maintenance required and extensive downtime generated by the 44 year old modulators
2. The problem with obsolescence components in the modulator
   F1123 switch tubes already 14 year-old discontinued
3. The uncertainty about future availability of the RF final power amplifier tube

RF Power System



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Linac Power Tubes

In order to operate, Linac requires

14 different type of vacuum power tubes

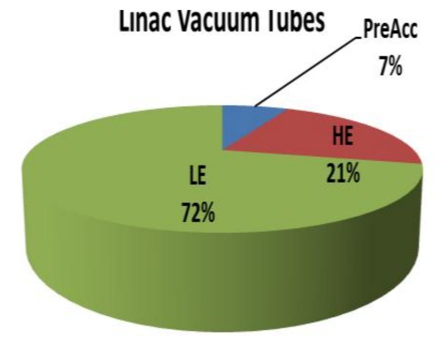
8 different manufactures/distributors

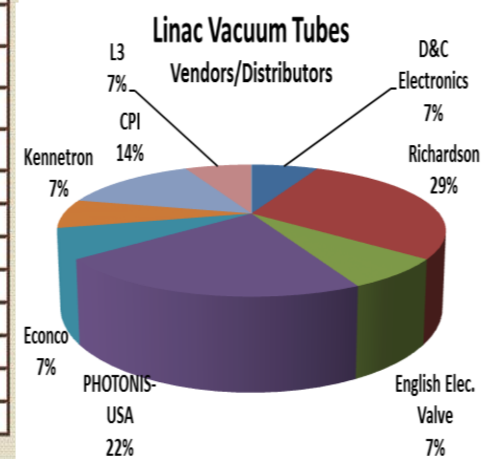
Linac RF Tubes Database

Hel

3CW20000A1 | 4PR250C | CX-1154 | 3CX3000F1 | 4616 | 4E27A15 | 7651 | 7835 | 8613 | F-1123 | GL-7703 | ML-6544 | NL-37248 | 7703LP | L-5859 | VKP-7955 | Types | OnOrder

Tube	Type	Supplier	Lifetime	Usage
3CW20000A1	Triode	D&C Electronics	5	PreAccelerator: Haefley Power
4PR250C	Triode	Amprex/Richardson	3	PreAccelerator: Extractor pulser units.
CX-1154	Thyratron	English Elec. Valve	20	PreAccelerator: 750 keV Chopper system
3CX3000F1	Triode	Richardson	7.1	201.25 MHz Modulator: Switch tube bias regulator tube
4616	Triode	Burle Ind.	2	201.25 MHz Driver - Output: 200 kW drives the cathode of 7835 triode (V4)
4E27A15	Triode	Richardson	7	201.25 MHz Modulator: Switch tube bias regulator tube
7651	Triode	Burle Ind.	3	201.25 MHz Driver - IPA2 Output: 4 kW drives the grid of 4616
7835	Triode	Burle Ind.	1	201.25 MHz Primary Power Amplifier
8613	Thyratron	Richardson	4	201.25 MHz 50kV - Thyratron Crowbar for the 7835
F-1123	Triode	Varian/ITT - Triton.	2	201.25 MHz Modulator Switch tubes: tube discontinued but being rebuilt.
GL-7703	Ignitron	Richardson	0	201.25 MHz Driver Ignitron: 4616 Driver Crowbar circuit
ML-6544	Triode	CPI	1.4	201.25 MHz Driver : Regulation for 4616 screen. Modulator: switch tubes drive
NL-37248	Ignitron	Richardson	5.7	201.25 MHz 50 kV - Modulator Ignitron : Crowbar for the 7835
7703LP	Ignitron	Richardson	3	805 MHz - Crowbar circuit
L-5859	Ignitron	L3	20	805 MHz system Primary Power Amplifier
VKP-7955	Klystron	CPI	20	805 MHz Power Amplifier for TV klystrons





201.25MHz RF Power Plant

RF drive chain – consist of variety of solid state amplifiers, pentode, tetrode and triode vacuum tubes

DTL system requires 75 tubes with 10 different types

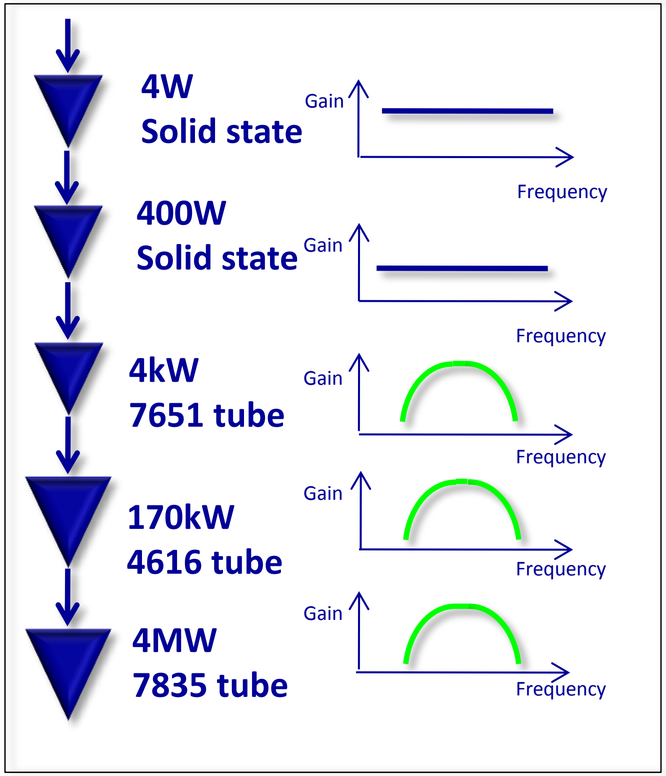
DTL RF **power requirements**

DTL Tank	Energy Out (MeV)	Peak $Power_{tank}$ (MW)	Peak $Power_{+30mA}$ (MW)
1	10.4	0.6	0.8
2	37.5	2.1	2.9
3	66.2	2.7	3.5
4	92.6	2.3	3.0
5	116	2.5	3.2

DTL#3 requires the highest power

station has the most tube rotation

Present RF system



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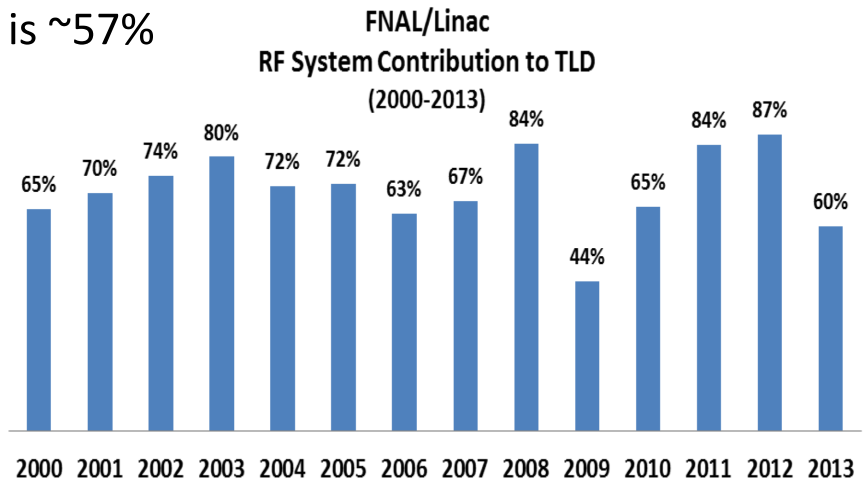
FNAL Linac RF System Downtime

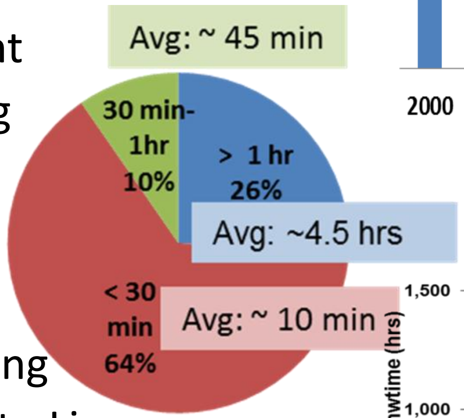
Modulator contribution to **Linac downtime** is ~57%

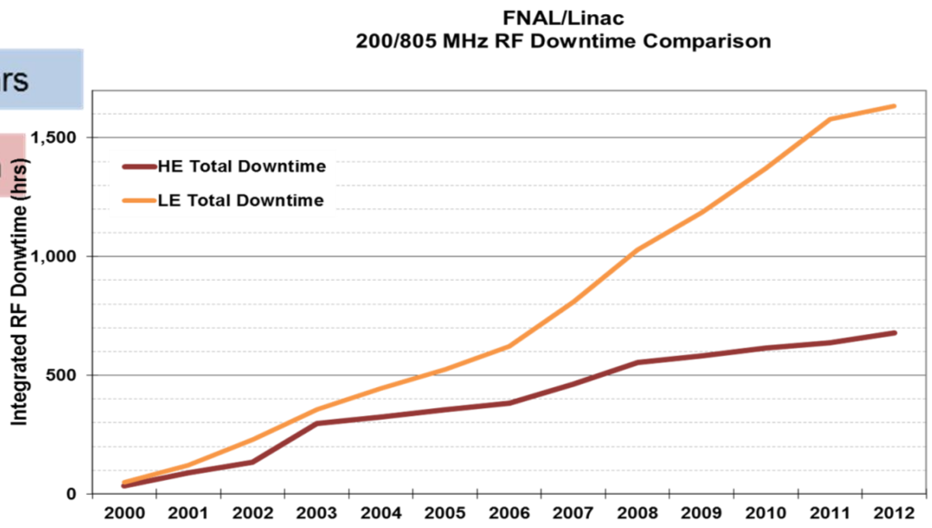
60% higher than driver system



MTBF: ~ 12 hrs

Despite the fact the majority of the modulator downtime is < 30 min, these frequent interruptions to running a smooth program, occupy manpower resources with local response, frequent tuning and constant attention to Linac beam quality. They are also a repeated stress on the system hardware.





see T. Butler's talk

BRIEF BACKGROUND – 5MW TRIODE VACUUM TUBE

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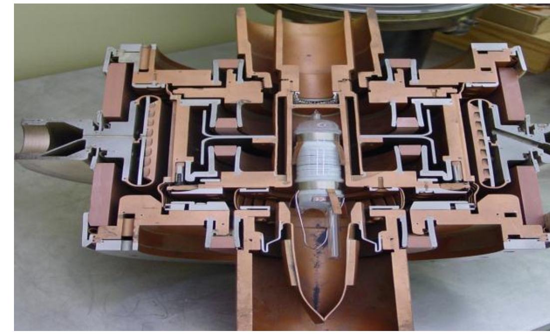
201.25MHz Final Power Amplifier



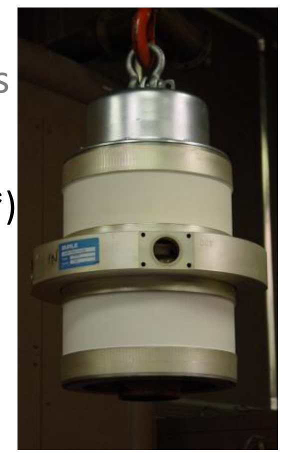
Final power amplifier – aka 7835 or *Burle tube*

Developed and manufactured by RCA Corporation

Single Vendor: Photonis USA (former Burle)

Complex technology

- Circular array of 96 grid-cathode assembly (each ~70Amps DC filament current)
- Multiple intricate parts, labor intensive manufacture process with skilled workers



National Laboratories are the only users (FNAL,BNL,LANL*)

Since startup, 44 years ago, 57 new/rebuild tubes accumulated a total of ~2M filament hours

- Over 25 years of continuous operation

Typical delivery time: 200 days

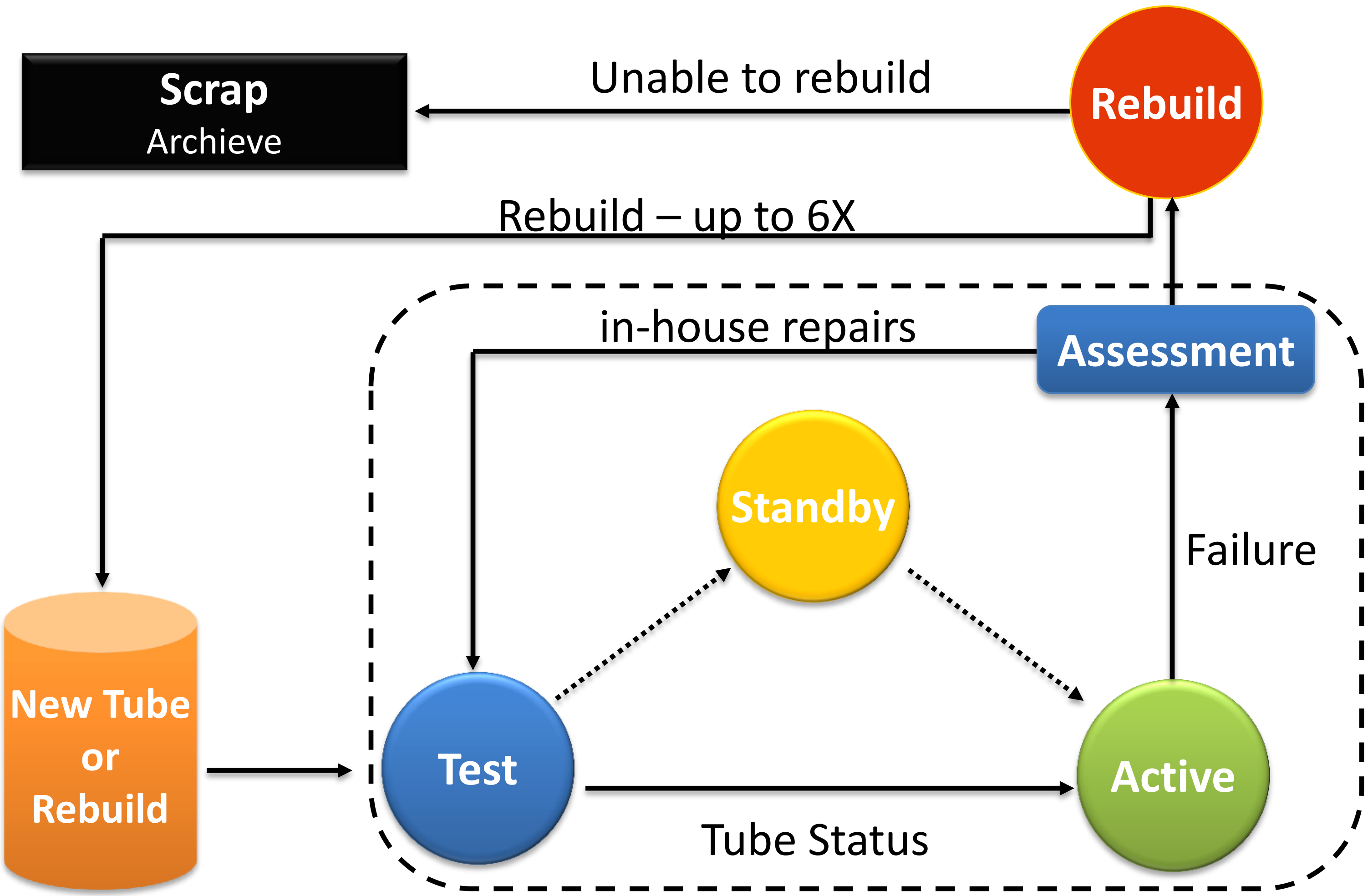
High cost : (FY13) $240k for new and ~ 1/3 of that if rebuild

Operation needs: 5 tubes

Lifetime: ~ 8-10 months

* LANL on path to update their 201MHz RF plant - Thales

7835 Triode tube life cycle



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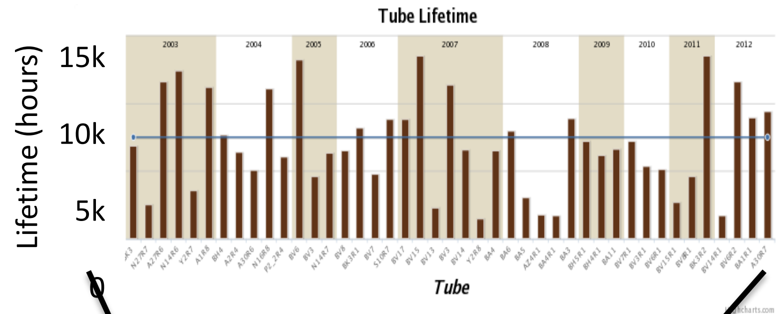
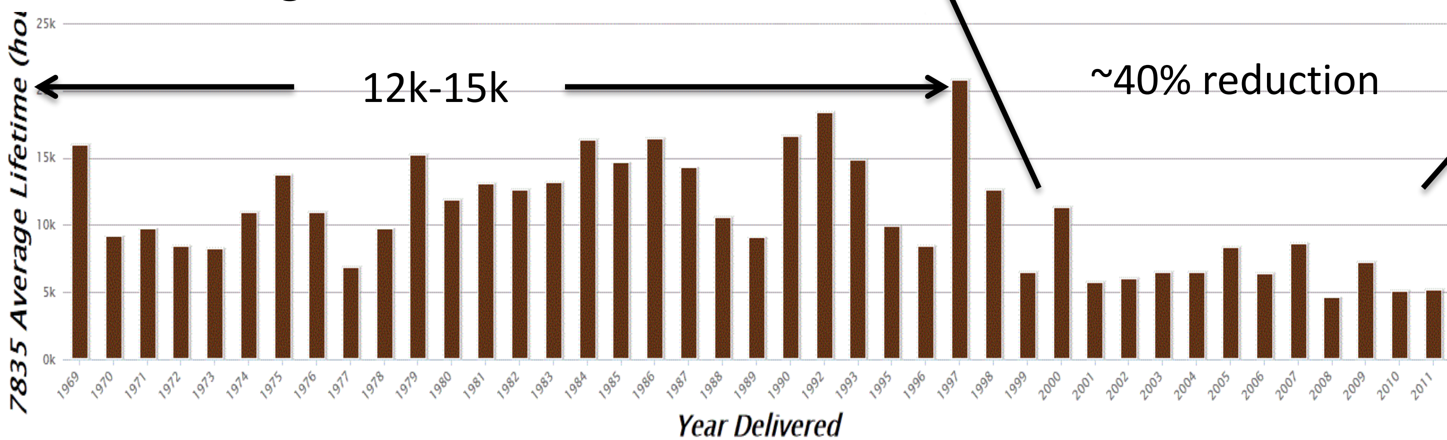
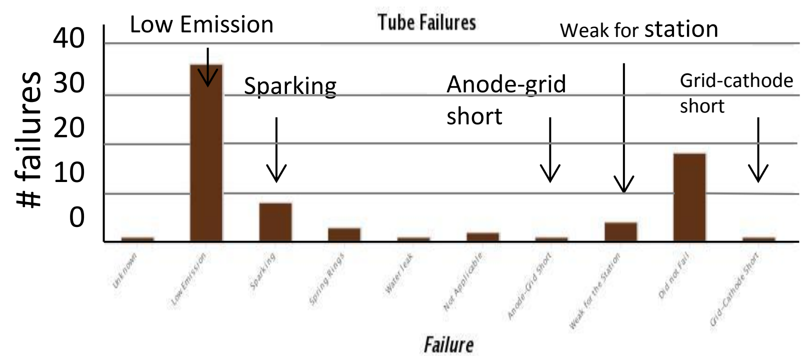
7835 Triode

Average lifetime (10yrs) ~ 7,500 hrs
significant operational consideration because of the high item cost







Primary failure is due to cathode degradation

$250k-$500k cost rebuild/yr (2-4 tubes)

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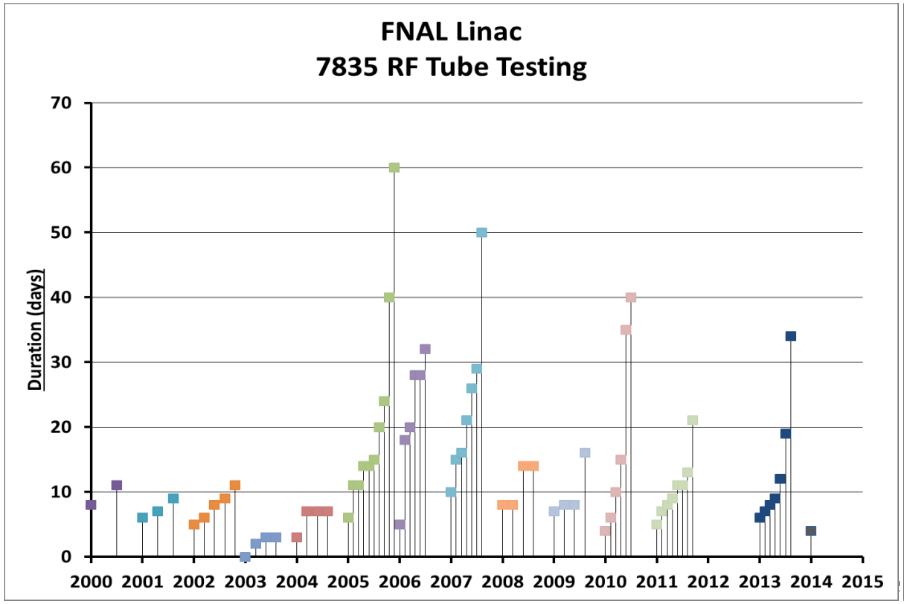
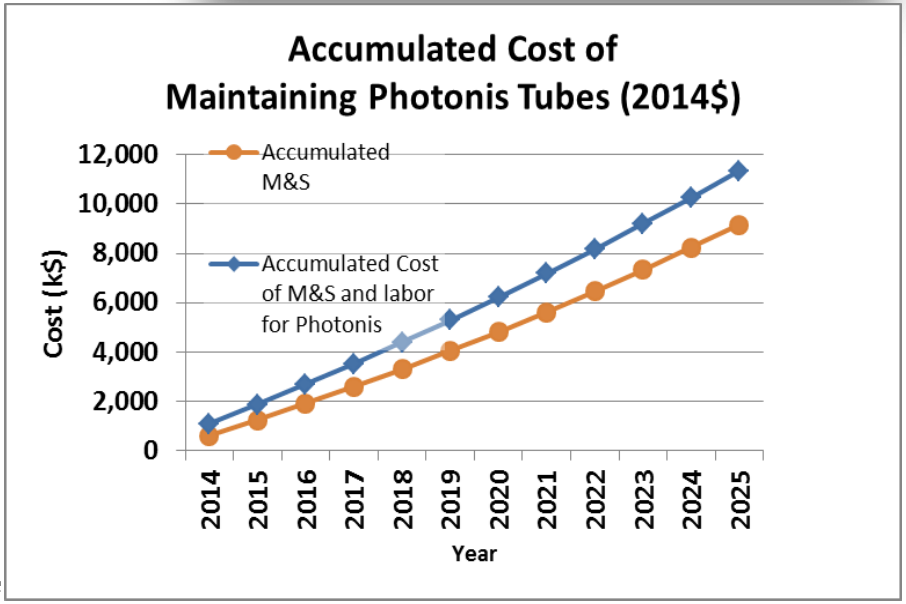
7835 Triode RF Conditioning

- There is no RF conditioning at Photonis
- RF conditioning commonly takes 15 days/tube for 2 Linac techs
  - sometimes double of time for a difficult tube
  - prep work pre/post RF conditioning adds another 2 days
- Typically 6 tubes are conditioned annually
- Time consuming effort (4-6 months)





PIP – 201.25MHZ STRATEGY

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201.25MHz Final Amplifier has been a worry for many years

The risk of retaining the 201.25MHz RF system is that

- power tubes become unobtainable to support operations until 2025
  Pose a threat to declare premature termination of the accelerator based-program
- submit Linac operations to a non-competitive cost increase

Within PIP the plan to address this reliability issue is

- build up 4-year in-house inventory of the 7835
- replace the high voltage modulator with present day technology
- develop a workable plan to replace the final amplifier in case tube line production is discontinued

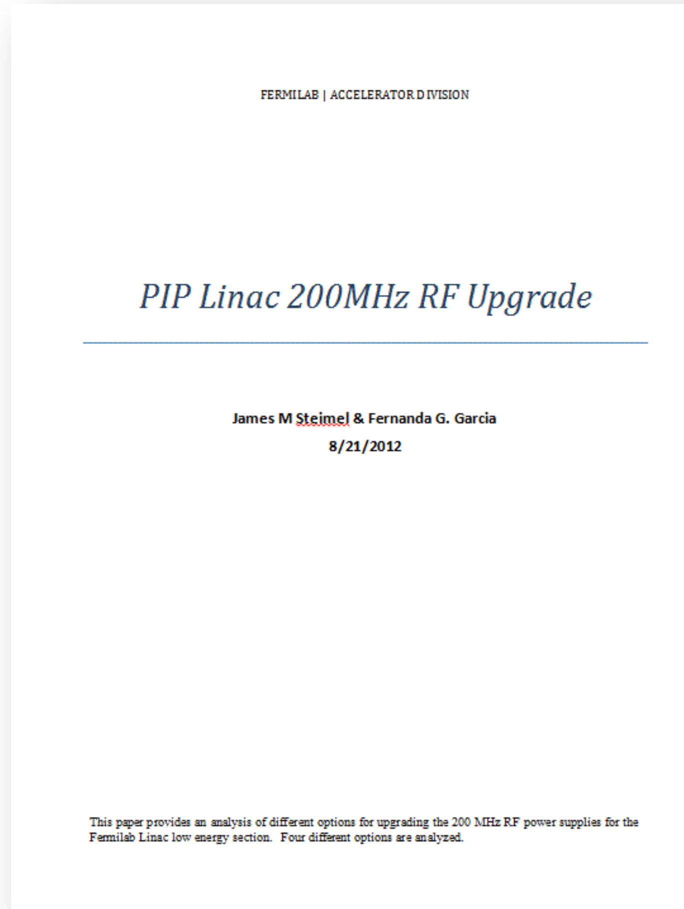
201.25MHz Alternatives Considered

Study made in 2012 discussed alternatives to the triodes, including

- new tetrodes (LANL design)
- klystron-based 200MHz RF
- "SNS-like" 400MHz Linac

The cost took in consideration the following criteria:

- Supply chain
- Technical risk
- M&S/ Labor construction cost
- Construction time
- Labor maintenance cost
- Program interruption time


FERMILAB | ACCELERATOR DIVISION

PIP Linac 200MHz RF Upgrade

James M Steimel & Fernanda G. Garcia
8/21/2012

This paper provides an analysis of different options for upgrading the 200 MHz RF power supplies for the Fermilab Linac low energy section. Four different options are analyzed.

and was evaluated over the expected lifetime of the Linac (2025)

201.25MHz Alternatives Considered (cont.)

	Supplier	Technical Risk	Installation Duration	Impact on Program	Maint. cost (US$M/ yr)	Construction (M&S,US$M/FTE)
No change	Single vendor	None	None	None	1.0	NA/NA
Klystron	Single vendor	no low freq. klystron	3yrs 6mo/SBK	Phase-in lab shut.	0.15	8.4/7.5
Thales	Single vendor	mod. LANL design	2yrs 3mo/amp.	Phase-in lab shut.	1.0	8.0/6.5
400MHz	Multiple vendors	Op. exp.	> 1yr	program planning re-plan	0.3	60.0

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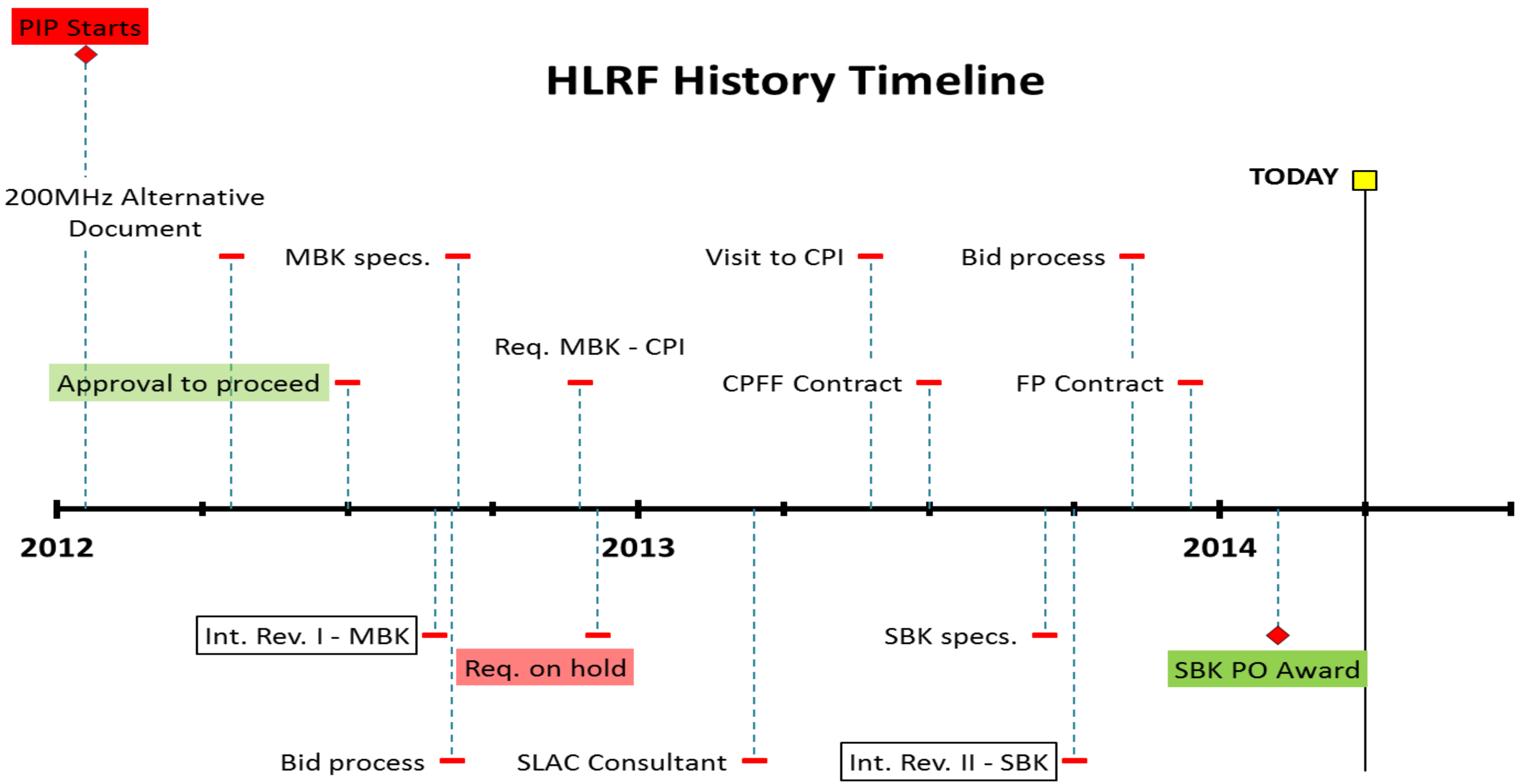
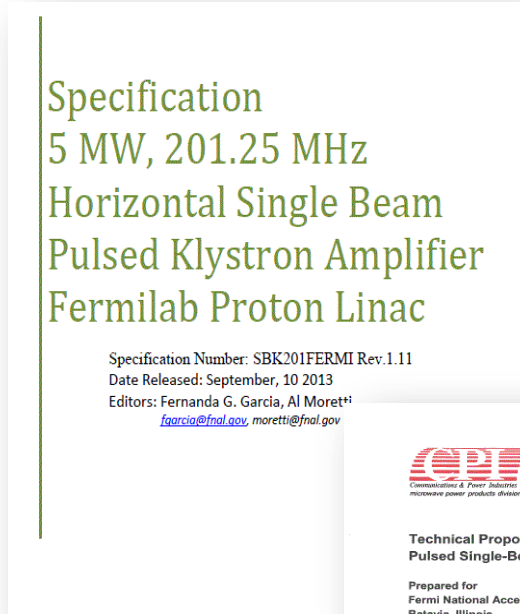
After careful consideration of the possibilities, the 201.25MHz klystron-base RF power system was chosen as a plausible replacement for the 7835 triode



Single Beam Klystron CPI

Design Parameters of SBK201.25MHz

	Design
Frequency	201.25MHz
Cathode Voltage	128kV
Beam Current	92A
Max. RF Peak Power	5MW
RF Pulse Duration	450μsec
PRF	15Hz
Perveance	$2.0\ 10^{-6}\ A/V^{3/2}$
Average Power	34kW
Gain	35dB
No. of Cavities	3
Efficiency	> 45%


Specification
5 MW, 201.25 MHz
Horizontal Single Beam
Pulsed Klystron Amplifier
Fermilab Proton Linac

Specification Number: SBK201FERMI Rev.1.11
Date Released: September, 10 2013
Editors: Fernanda G. Garcia, Al Moretti
fgarcia@fnal.gov, moretti@fnal.gov

Technical Proposal for a 201.25 MHz, 5 MW Peak Pulsed Single-Beam Klystron

Prepared for
Fermi National Accelerator Laboratory (FNAL)
Batavia, Illinois

FNAL Solicitation: 09272013JBH
FNAL Reference: Specification Number: SBK201FERMI Rev.1.11

October 31, 2013

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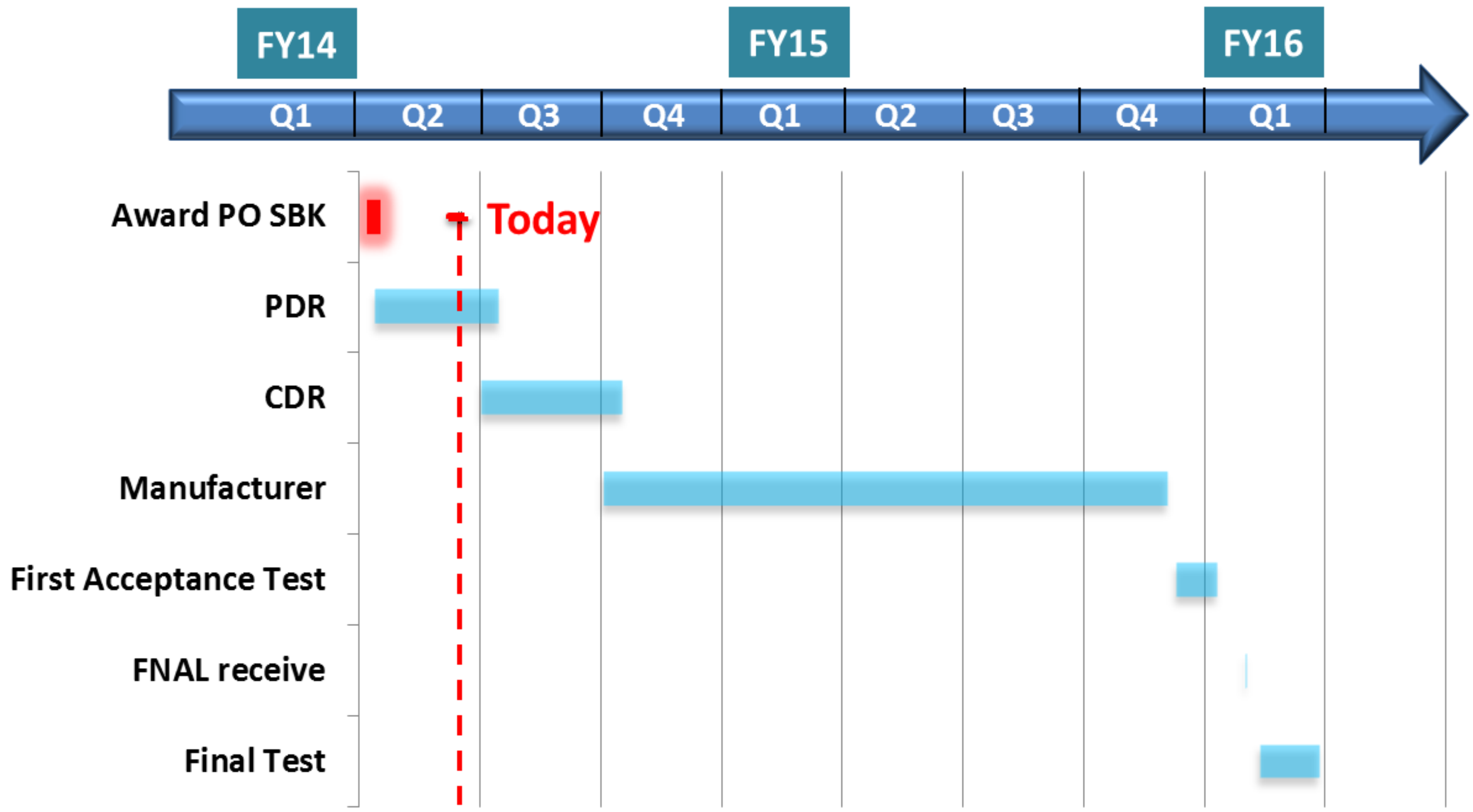
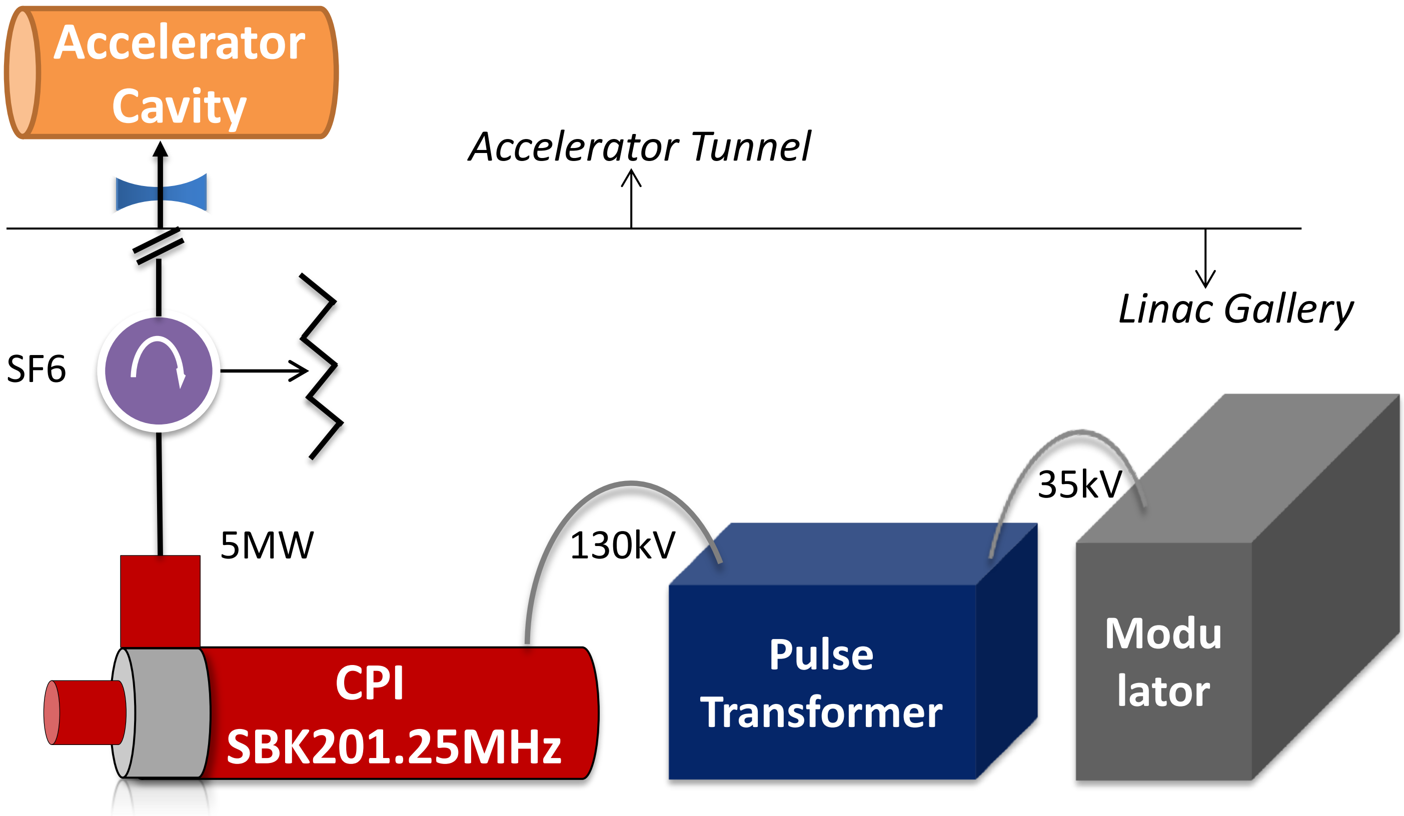
201.25MHz SBK Prototype Manufacture Timetable



PIP *Proton Improvement Plan*

RF System Block Diagram, 201.25MHz, 5MW



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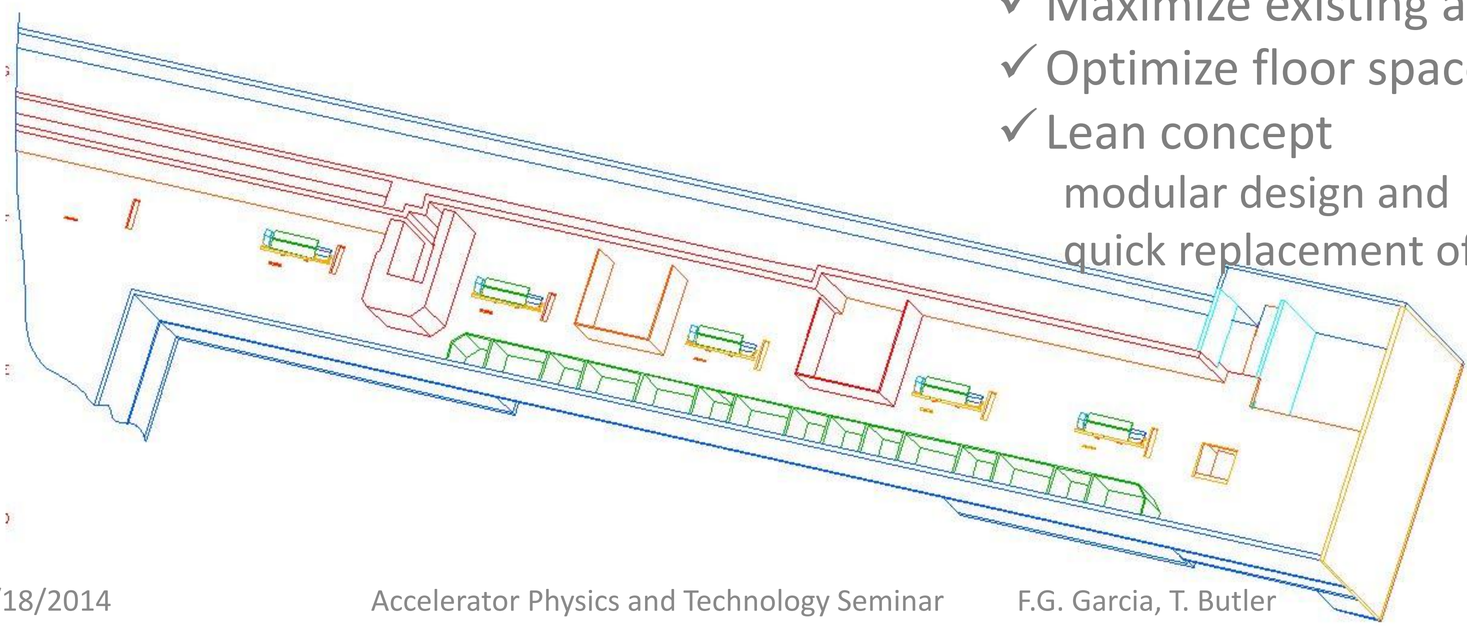
Conceptual Layout of RF Source, 201.25MHz 5MW

The rf production equipment will reside in the Linac surface gallery building

- klystron expect to be 5.7m long
- one klystron per rf cavity
- rf power will be transported in waveguide to the linac tunnel

Final design principles:

- ✓ Maximize existing availability
- ✓ Optimize floor space
- ✓ Lean concept
  - modular design and
  - quick replacement of components



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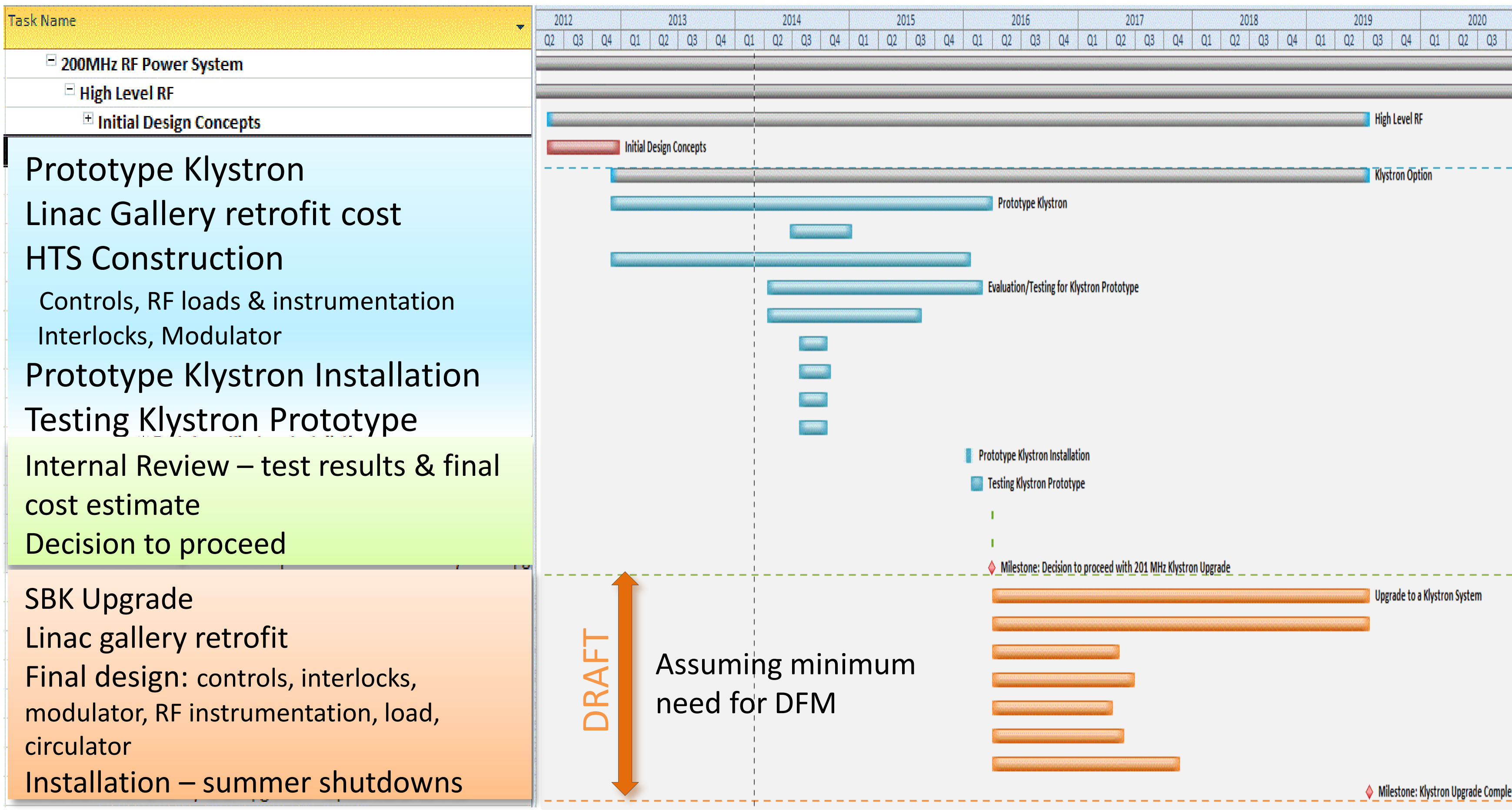
201.25MHz SBK Timetable (Roll up Summary Tasks)

Aggressive schedule – Upgrade complete FY19



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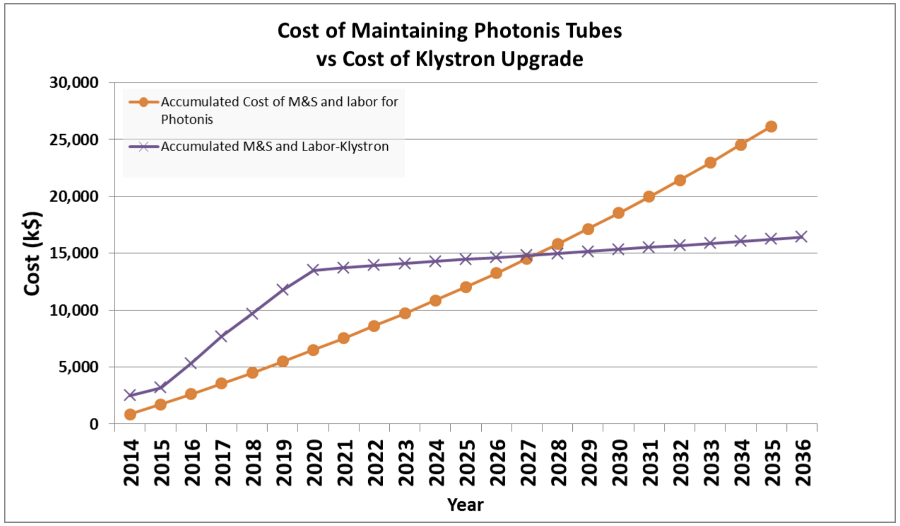
201.25MHz SBK Cost/Resources

Cost Estimate (12.2013)

Project Estimate Cost	$M
Prototype Klystron	1.97
Production Klystron (5)	5.0
HV system	0.6
Passive RF components	0.5
Other Project Cost	0.4
Labor	5.2
TOTAL (fully burdened)	**15**

Period of time to *recoup* upgrade investment: 8-9 yrs



Triode maintenance cost depends on
tube lifetime and
quality of manufacturing process

Conclusions

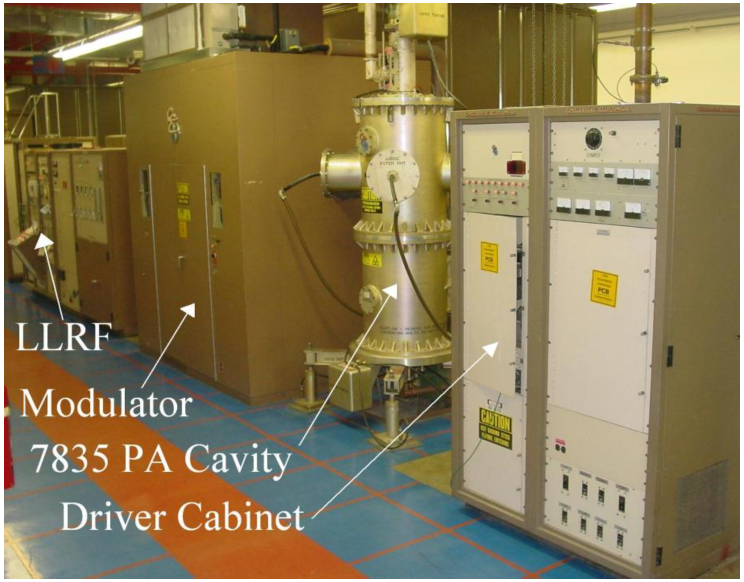
- The PIP HLRF task should be considered as a **strategic decision** for the laboratory
  - **Risk:** premature termination of the accelerator-based program in case power amplifiers are no longer available
  - FNAL has been a risk tolerant operation for near 15 years
  - PIP believes is time to change the position to risk averse by developing alternative that not only has a lower probability of loss, but a lower maximum potential loss as well
- Prototype unit is in progress. Decision to proceed in FY16/Q2
  - Upgrade estimate to take 2-3 years to complete
    - Assuming no change in PIP funding profile
- The community will have two amplifier options: high peak/low average power (SBK) and high average power/lower peak power (gridded tube)

Proton Improvement Plan – Linac 200 MHz RF Plant

201.25MHZ MODULATOR UPGRADE

Trevor Butler, on behalf of the PIP Modulator Upgrade team

PIP *Proton Improvement Plan Linac Modulator Upgrade*



5 LE (201.25 MHz) Linac RF Stations
(0.75–116.5 MeV)

First 200 MeV Beam – Nov 30th 1970

• LLRF System	2 mW
• Pre-Amplifier	4W
• IPA1 – Solid State Amplifier	400 W
• IPA2 – Burle 7651 Tetrode*	4 kW
• Driver – Burle 4616 Tetrode	175 kW
• PA – Burle 7835 Triode	4 MW

- Modulator provides pulsed power to the anode of the 7835 triode
- The 7835 is run grounded grid (cathode driven)
- The PA tube is unstable with low or no RF drive
- The anode/plate voltage is modulated instead of the RF driver amplitude to regulate the cavity accelerating field.
- The modulator requires linear operation of the "switch" tubes to set the accelerating field anywhere from 0.5 to 4 MW.
- The main series regulator tube, (F1123) was discontinued over 10 years ago.

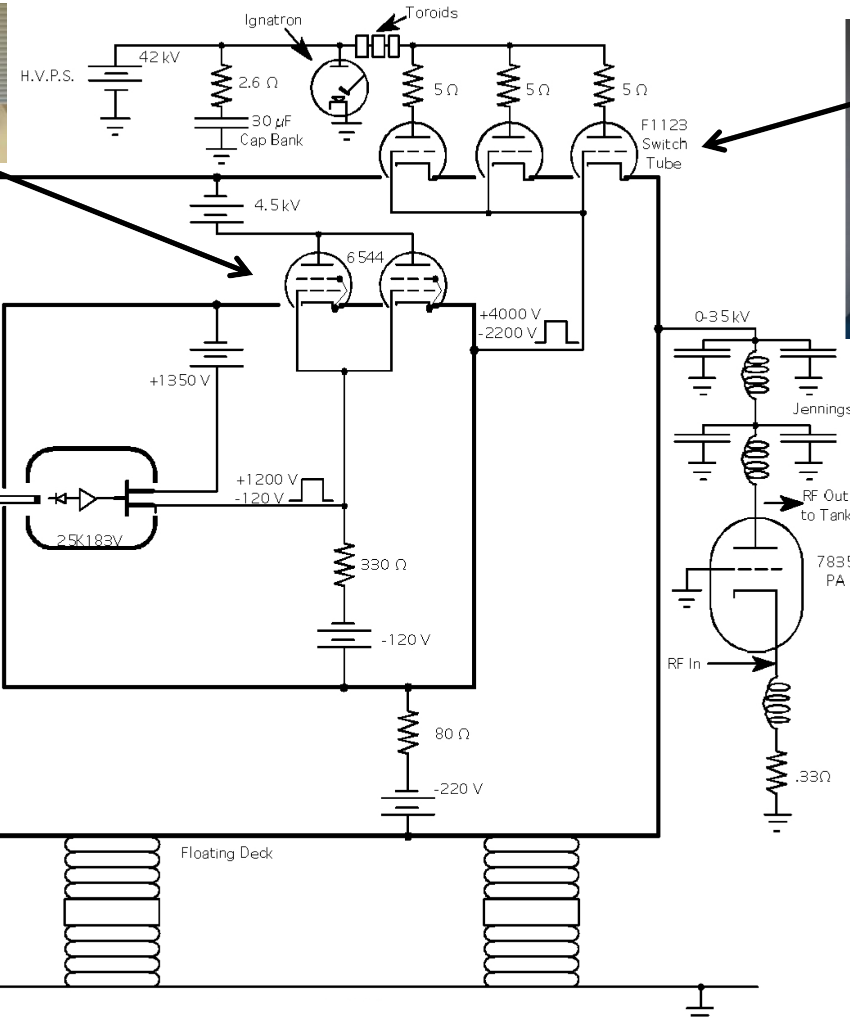
PIP *Proton Improvement Plan Linac Modulator Upgrade*

CPI-Eimac

ML-6544

Power Triode

- Maximum (20 kV, 75 Amp, 1 kW)
- 2.8 kV Typical
- Uses 2 per modulator and 1 per driver screen modulator (5+1 Stations)
- 18 tubes total
- High Production Tube for CPI
- Used in multiple radar and science applications
- Not expected to be discontinued anytime soon



CPI F1123

“Switch” Tubes

operated as

linear amplifiers

50 kV Standoff

~100 Amps each

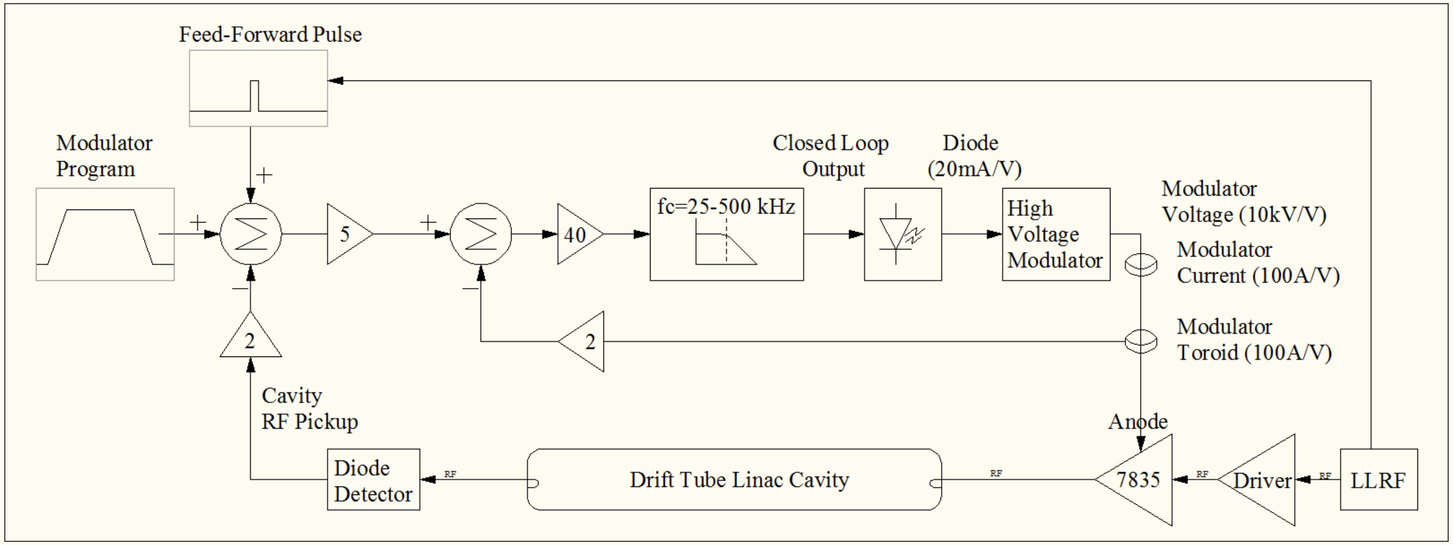
~350 Amps Total

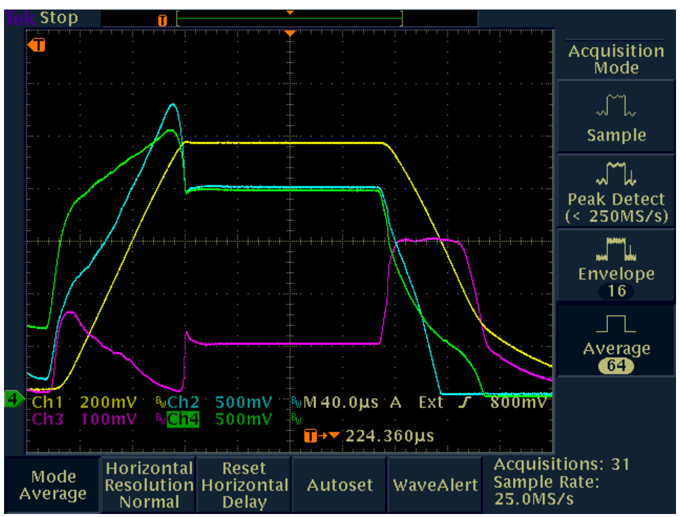
- Manufactured by Westinghouse, ITT, Richardson, Varian, CPI, now ***nobody***
- Use 3 per station (5+1) = 18 total
- Series-pass regulator between the capacitor bank and Burle 7835 Power Triode anode
- ***No replacement part available***
- Rebuilt by Kennetron & Econco

Econco* – Can’t Rebuild Grids

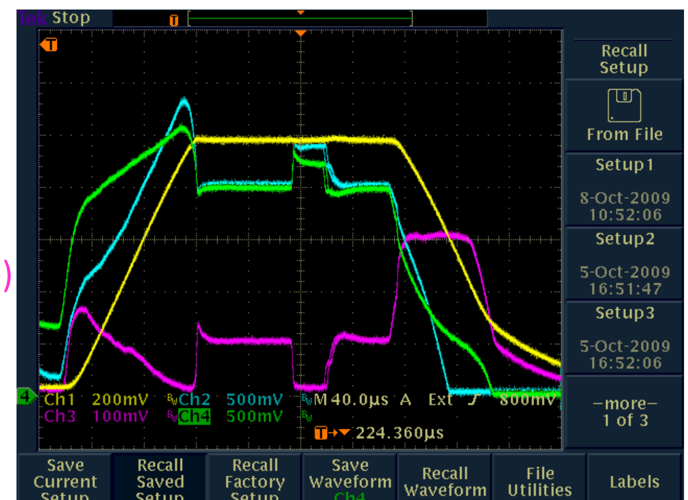
*Problem – Bad grids are a typical type of failure in these tubes. Therefore, they need two tubes (one as a donor) to rebuild a tube with a bad grid

PIP *Proton Improvement Plan Linac Modulator Upgrade*





Ch 1 – Gradient (Yellow)
Ch 2 – Mod Voltage (Blue)
Ch 3 – Forward Power (Purple)
Ch 4 – Mod Current (Green)



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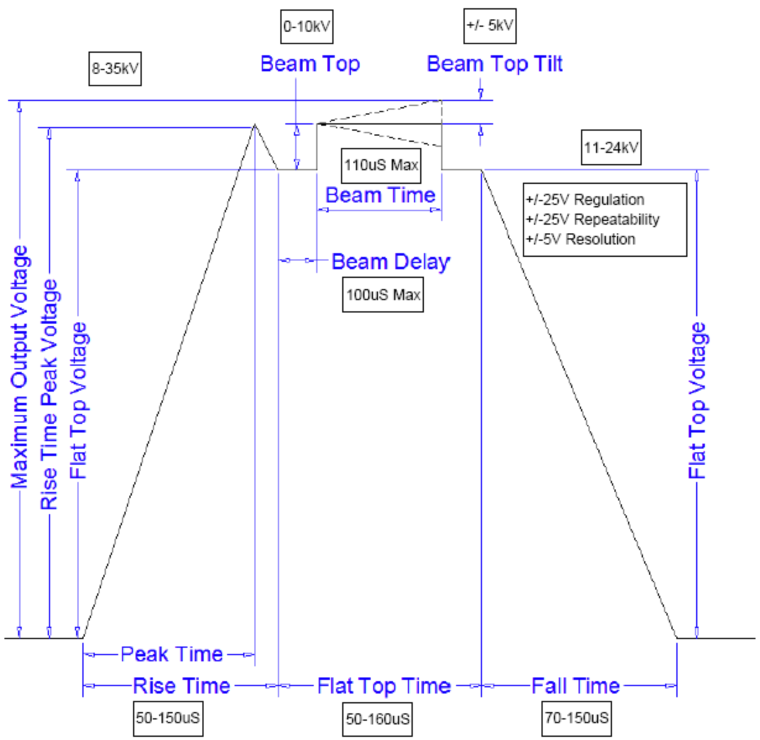
2010 LE Modulator Proposed Solutions

- Replacement of the various power supplies in the Modulator
  - **Would improve reliability and stability**
  - **Still stuck with obsolete switch tubes**
- Replacement of just the F1123 switch tubes
  - **Working with industry, where not able to find a replacement tube**
- Replacement of the Entire Modulator Floating Deck
  - Most elegant and complete solution with minimal downtime
  - Interfacing with present electronics would be simplified since there is only power in and modulator ready interlock out
  - Continental Electronics Inc. designed the original modulator and has developed a design idea for a new tube modulator using a CPI 8973
  - **After extensive review determined that although it is may be possible to replace these tubes with combinations of other tubes on the marker, this would not be and ideal long term solution since tubes are a dying technology for modulator development**
- Build a new modulator based on Marx Generator technology and combining switched cells with linear cells and including a bouncer modulator(2)
  - This ideas abandoned in response to a simpler Marx design to be shown later
- Evaluate a proposed modulator design made by DTI Corporation to a specification similar to our own. This is also early in the review cycle and so have no estimate on time or cost(2)
  - **Details of this will be shown later**

PIP *Proton Improvement Plan Linac Modulator Upgrade*

- With help of EE Support an PS personal, we created the following specifications
- Initial determined that feed forward would work for control topology, eliminating the need for feedback
- Hard specs are 375 amp current, 15 kV/usec slew rate and 1.5 kV steps



#	Specification	Initial	Final	Units	Limit
1	Pulse Repetition Rate	15	15	Hz	max
2	Rise Time	150	150	µsec	max
			50	µsec	min
3	Fall Time	50	150	µsec	max
			70	µsec	min
4	Flat Top Time	150	160	µsec	max
			50	µsec	min
5	Beam Length/Time (Adjustable)	62	110	µsec	max
6	Beam Time Delay (Adjustable)	72	100	µsec	max
7	Peak Voltage Time (Adjustable)	125	150	µsec	max
		110	35	µsec	min
8	**Output Voltage (Adjustable)**	**40**	**35**	**kV**	**max**
		NA	**8**	**kV**	**min**
9	**Output Current**	**350**	**375**	**A**	**max**
10	Beam Voltage Step Size	8	10	kV	max
		5	5	kV	typ
11	**Flat Top Voltage Regulation / Slope (within 150us pulse)**	**80**	**± 25**	**V**	**max**
12	Flat Top Repeatability (Pulse to Pulse)	200	± 25	V	max
13	Flat Top Resolution (Setpoint Adjustment)	15	± 5	V	max
14	Beam Top Repeatability (Pulse to Pulse)	NA	± 10	V	max
15	Beam Top Tilt (Adjustable)	± 3	± 5	kV	max
16	**Slew Rate (Beam Voltage Step)**	**20**	**15**	**kV/µsec**	**min**
17	Slew Rate (Rising Edge)	0.25	1	kV/µsec	max
18	Slew Rate (Falling Edge)	0.5	0.5	kV/µsec	max
19	**Step Size (Rising or Falling Edge)**	**N/A**	**1.5**	**kV**	**max**
20	Modulator Emergency Turn Off (< 2 usec in pulse)	500	400	Amps	max
21	Modulator Emergency Turn Off (< 2 usec out of pulse)	150	100	Amps	max
22	Linearity	± 20	± 20	%	max
23	Gain	10000	10000	NA	min

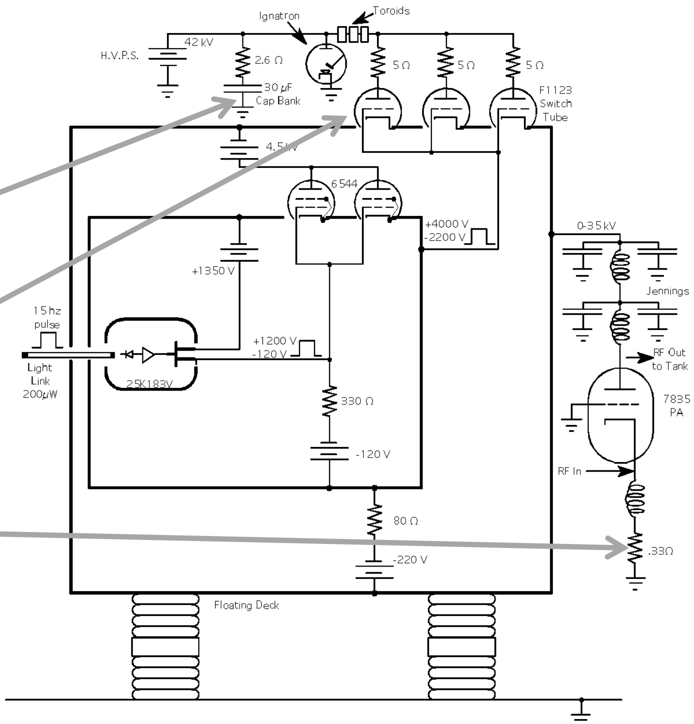
2011/2012 Proposed Solutions

- Besides investigating building a Marx style modulator in house with Accelerator Division EE Support Group, we send the previous specifications to various companies and interested labs (11/22/2011). More on why a Marx design when compared to other will be discussed later
- The following companies did not express interest when contacted
  - Dynapower Corporation – Peter Abele
  - Stangenes Industries Inc. – Magne Stangenes
- The following companies express some interest
  - Diversified Technologies Inc (DTI) – John Kinross-Wright
  - Continental Electronics Corporation – Paul Utay
  - SLAC National Accelerator Laboratory – Chris Adolphsen

PIP *Proton Improvement Plan DTI Proposal*

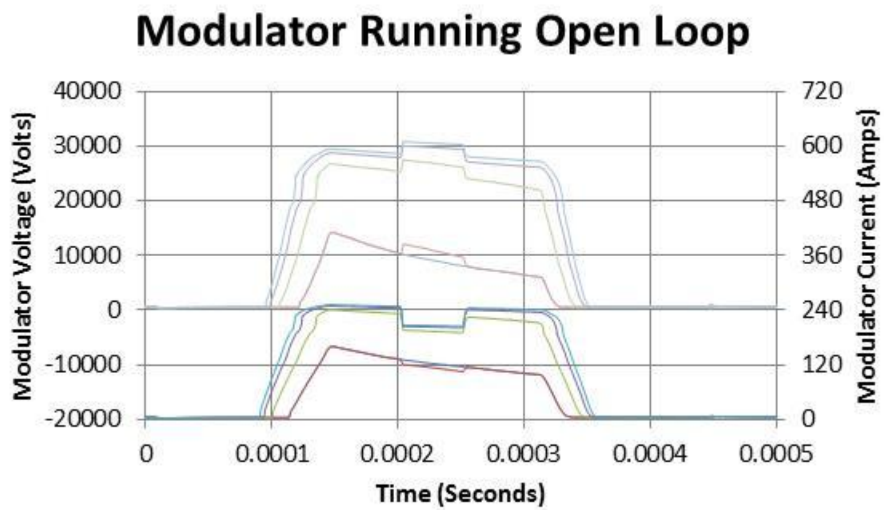
<u>Diversified Technologies Inc. (DTI)</u>

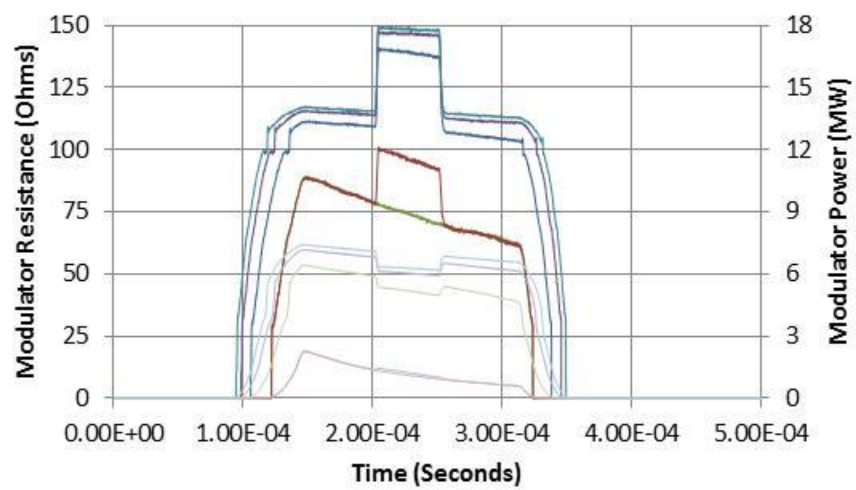
- Did *NOT* propose building a modulator to our specifications
- Instead, they have proposed to change the way we modulate to 7835 using the technologies they have developed
  - Keep the capacitor bank
  - Replacing the modulator switch tube deck with a solid state switch
  - Change the grid to cathode bias of the tube, which is currently done with cathode resistor to ground.
    - This prevents the tube from oscillation when the driver is on, and the interlocks exist to ensure this feature.



PIP *Proton Improvement Plan DTI Proposal*

- **Running the 7835 in the mode is never been attempted before**
- We are unsure of the long term stability of this mode of operation
- **Unsure of the effects on tube lifetime**
- The early papers about the modulator describe this concern and state that it was the reason that they had to build the modulator as it currently is.
- **DTI gave a study plan**
  - Run the modulator in voltage regulation
  - **Add with a "notch" in the middle of the pulse to replicate driver modulation**
- ***Problem- the tube impedance changes based on the applied voltage***
- As the tube impedance increased (when changing the bias voltage between cathode and grid) the power delivered by a constant voltage modulator can **drop power by 24 %.**
- The increase in gain when changing the bias **increases the power by 22%**
- **This gives a net loss of power 2%.**
- The design would also suffer from **large capacitor droop**, unless the capacitor bank size is increased
- Therefore, using a single high voltage switch while performing cathode modulation will not be an effect strategy to mitigate the problems with our present modulator and for these reasons**, we eliminated the proposed DTI topology from consideration.**
- Perhaps cathode modulation could be used as a secondary path to adjust for tube gain changes on a pulse to pulse basis with another modulator design as will be presented later





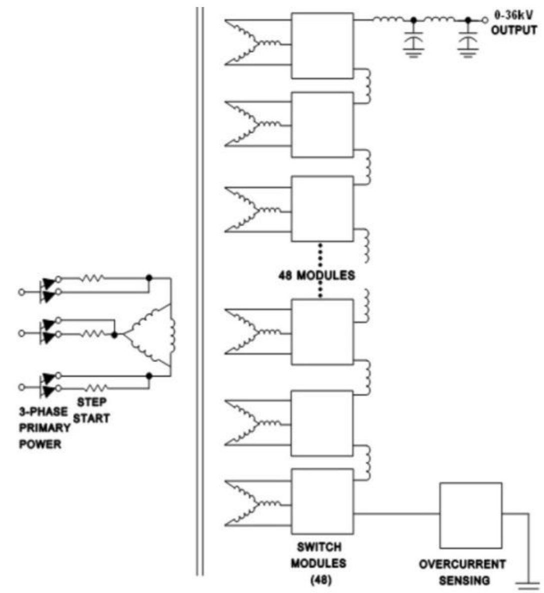
PIP *Proton Improvement Plan Continental Electronics*

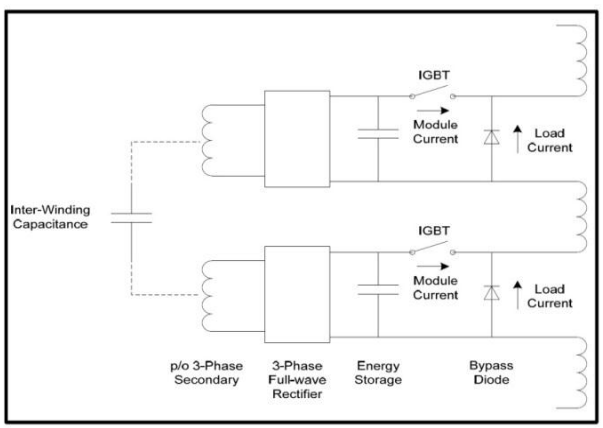
Continental Electronics Corporation

- Original Manufacturer of the Fermilab Linac Modulator
- Solid State Modulator Design & Architecture
- **Similar to Marx modulator except cell receive power large step up transformer**
- Presently manufacturer a similar modulator, but with a larger average power then we require.
- **CEC decided to modify the standard modulator design to included IGBT rated for the full peak load current (400 Amps)**
- Lower average power reduces the size of the transformer, decreasing the parasitic in the transformer, increasing the speed of the modulator

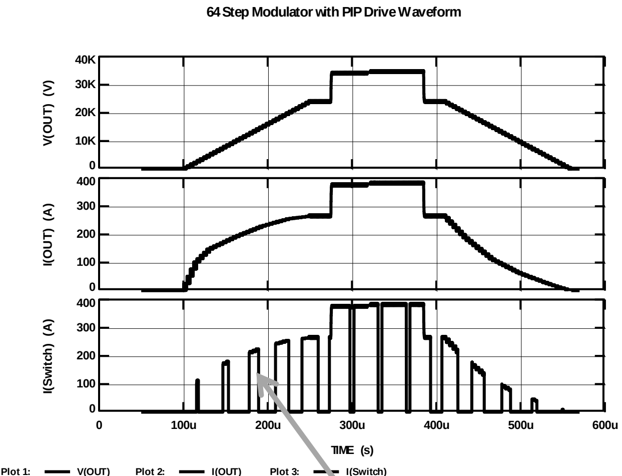
- **Engineering Study Issues ($50k)**
  - Finished 8/15/2012
  - IGBT Thermal Cycling Reliability
  - Capacitor Reliability
  - Corona
  - Single Point Failure Design
  - Fault Energy
  - **Pulse Response & Regulation**

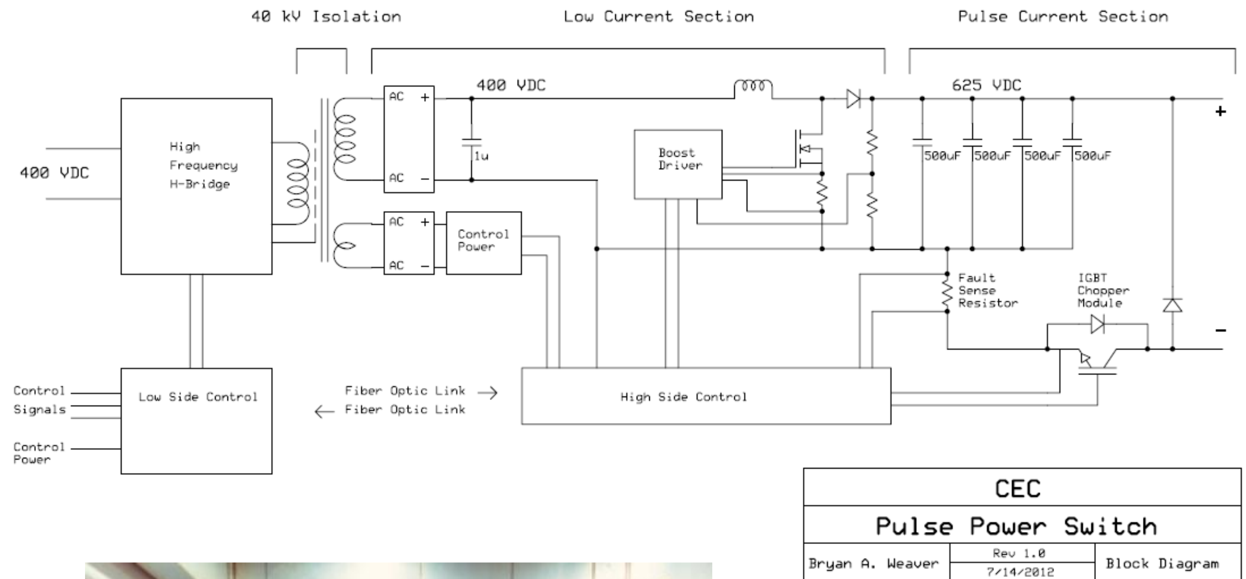
- **15kV/us Slew Rate (Remove filtering on each stage, which would allow for 625 MHz ripple @ 2 MHz giving 18 kV/us)**
- **+/- 25 Volts is the ripple specification (reduced to +/- 50 Volts)**



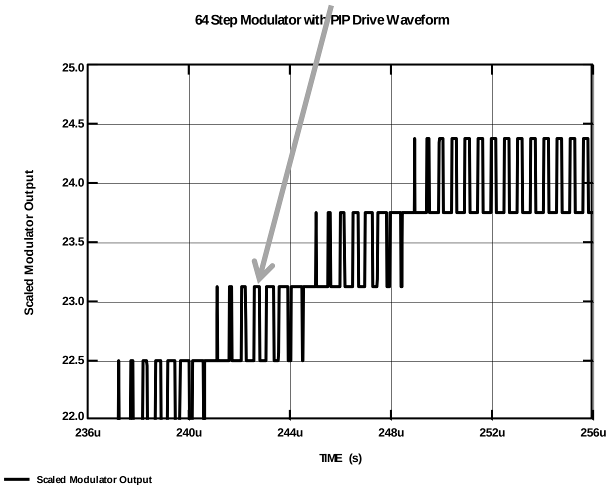


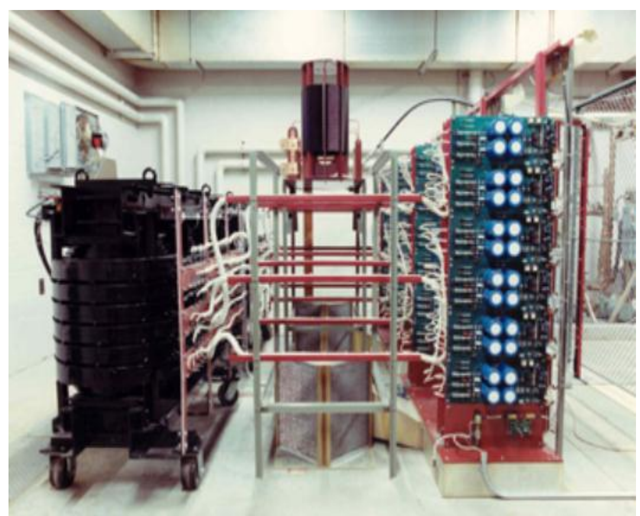
PIP *Proton Improvement Plan Continental Electronics*





PWM of Cells





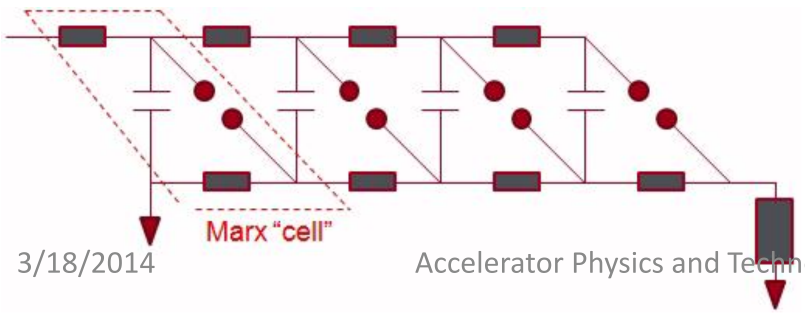
PIP *Proton Improvement Plan Continental Electronics*

<u>Continental Electronics Corporation</u>

- **Presented Cost of Prototype unit at $2M with additional units between $0.75-1.5M**
- Next step would be a another engineering study before building full prototype ($115K)
  - Task 1 – Characterization of the high voltage transformer
  - Task 2 – Detailed design of the proposed Pulse Power Switch
  - Task 3 – Finalized selection of IGBT and Capacitor
  - Task 4 – Power Switch assembly design and fabrication
  - Task 5 – Design and fabrication of Multiple-Switch Assembly
- **Decided to hold on design effort due to higher cost than other proposed designs and focus attention on other designs**
- The modulator was developed to provide AM modulation and can provide 10kHz, full amplitude, modulation
- Can be used with RF feedback, with a bandwidth dependent on the depth of modulation and the response time of the RF system, possibly increasing the effective bandwidth of operation
- ***It is possible to run the system both in feedback for the overall waveform and feed-forward for beam compensation,*** but a study would have to commissioned to study this effect.

Marx Modulator

- The pulsed modulator has evolved over the past 90 years, starting with the spark gap modulators patented by Erwin Marx in 1923
- **A “Marx” modulator is a topology in which capacitors are charged in parallel during the recharge period and discharged in series during the output pulse.**
- The output voltage becomes the charging voltage multiplied by the number of capacitors.
- Without compensation, the voltage on the load will droop due to capacitor discharge
- High voltage generators have historically used gas switching elements for the main high voltage operation, but with the advent of modern high voltage/ current solid-state switches, this topology has become more desirable in replacing standard modulator designs



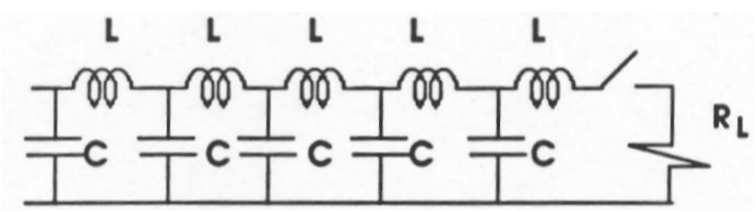
Hard Tube Modulator

- Presented Earlier as the type of modulator that we presently use, along with other laboratories, to power the 7835 triode
- Hard Tube modulator use a high voltage capacitor bank which switches thru a grid-controlled electron tube to regulate the anode on the triode (or any tube amplifiers, such as a klystron).
- **Can be run in feedback or feed forward, since they act essentially as a high voltage operation amplifier**
- Unfortunately they the modulator controls needs to be operated on a high voltage “floating deck” making the **controls complex and hard to maintain**.
- Electron tubes have current limitations and have high losses making them **very inefficient**.
- **Very few manufacturer still make these tubes** and are typically only used in legacy designs and typically never used in new designs unless it is the only option for the voltage and current response
- Could be converted for use on a Klystron with the appropriate step up transformer.

PIP *Proton Improvement Plan Standard Pulse Modulators*

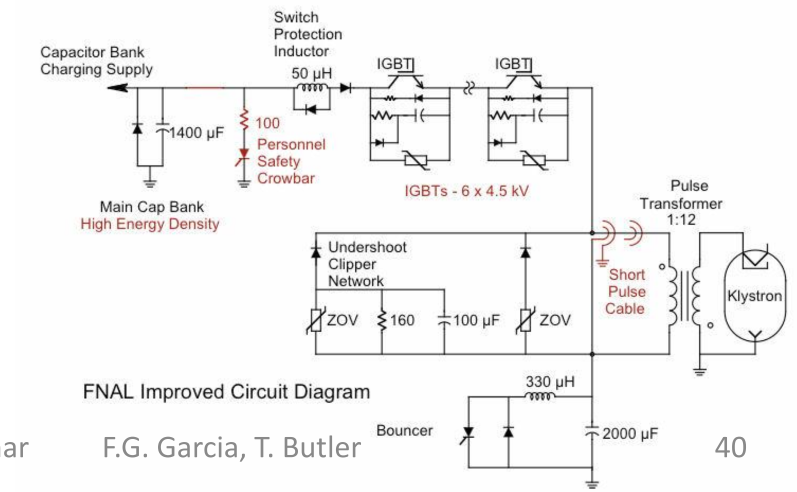
PFN

- The original Marx Pulse shape (without any amplitude) does not meet the specifications of today experiments, leading to the use of a different topology, know as pulse forming networks (PFNs)
- PFN is an electric circuit that accumulates electrical energy over a comparatively long time, then releases the stored energy in the form of a relatively square pulse of comparatively brief duration for various pulsed power applications.
- **Essential, they are a lumped element transmission line**
- Energy storage components such as capacitors, inductors or transmission lines are charged by means of a high voltage power source, then rapidly discharged into a load via a high voltage switch.
- A Limited to fixed impedance load
- **PFN have fixed pulse width, rise & fall time**
- The longer the pulse desired, the more lumped elements are needed, increasing the size and cost of using the PFN modulator
- **No ability to wave shape after lumped network original tuning**



Series Switch / Bouncer

- A series switch design uses a single large capacitor(s), incorporating many times the energy derived in a pulse, to keep the droop low since the switch cannot regulate the output voltage as was possible with the hard tube modulator
- **Adding a "Bouncer" section reduces the stored energy requirement by compensating for the voltage drop in the main capacitor**
- The Bouncer circuit is a resonant inductor and capacitor, which is fired in series with the load to cancel the voltage droop by timing the linear section of the oscillating bouncer voltage to coincided with the timing of the main, reducing voltage droop from >10% to <1%
- **A bouncer modulator shown below is planed to operate the 201MHz Single Beam Klystron**

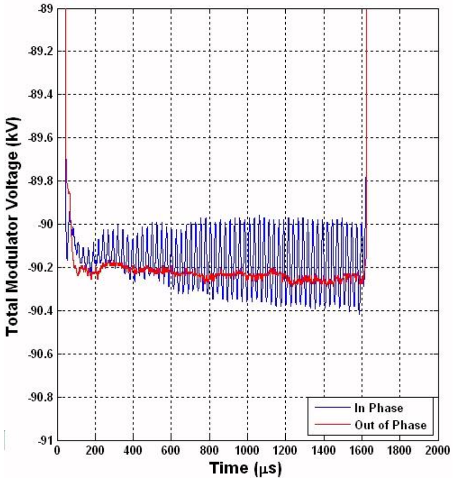


PIP *Proton Improvement Plan SLAC F1 Marx*

- The SLAC P2 MARX Modulator
- Developed for the ILC Program
- -120 kV 140 amp 1.7ms
- 32 Marx cells
- -4 kV supply per cell
- Hardware & Control Developed
- Desire to utilize technology for additional applications
- Number of cells, cell capacitance, and component selection can be optimized for different applications

<u>3 Engineering Studies Performed 2012-2014</u>

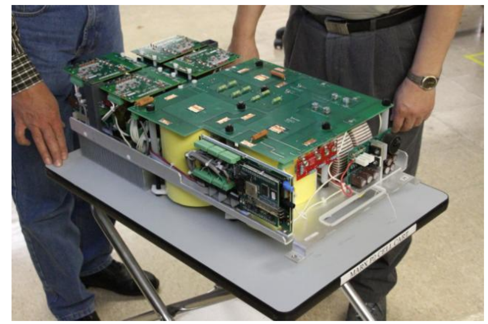
- Study 1 – Test the feasibly of modifying the P2 design to replace our switch tube based modulator at a cost of $57k (8/21/2012)
- Study 2 – Modify two Marx cells and the test stand to accommodate the Fermi cell parameters. Demonstrate the transient waveform characteristics at the single and two cell level at a cost of $74k (4/26/2013)
- Study 3 – Test different control system architectures to determine optimal way to create required waveform for operating the 7835 to compensate for beam loading and create stable waveform at a cost of $46k (3/31/2014)



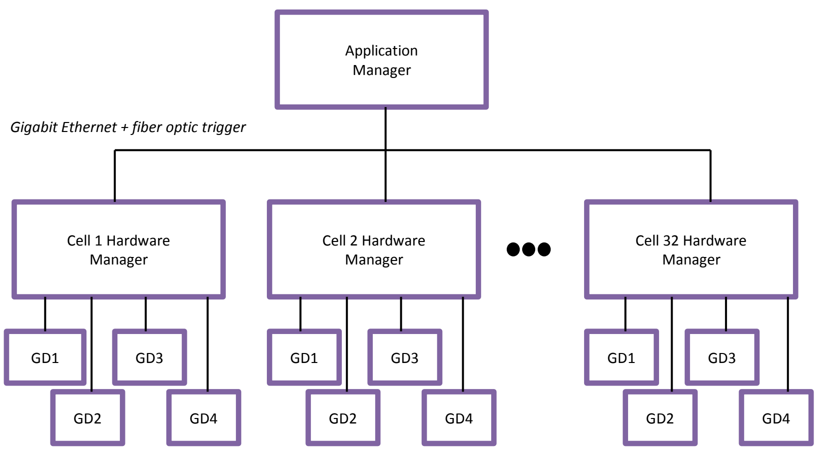
The SLAC P2 Marx: Re-usable Concepts

- The topology

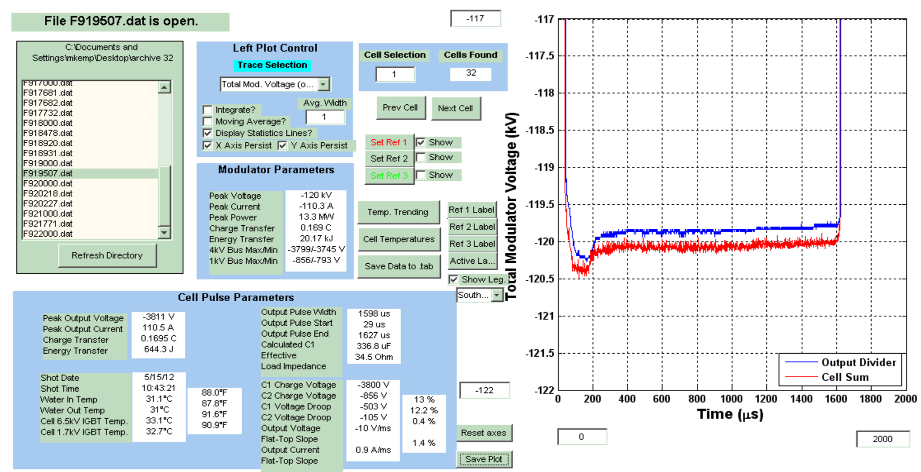
- Maintainability and layout



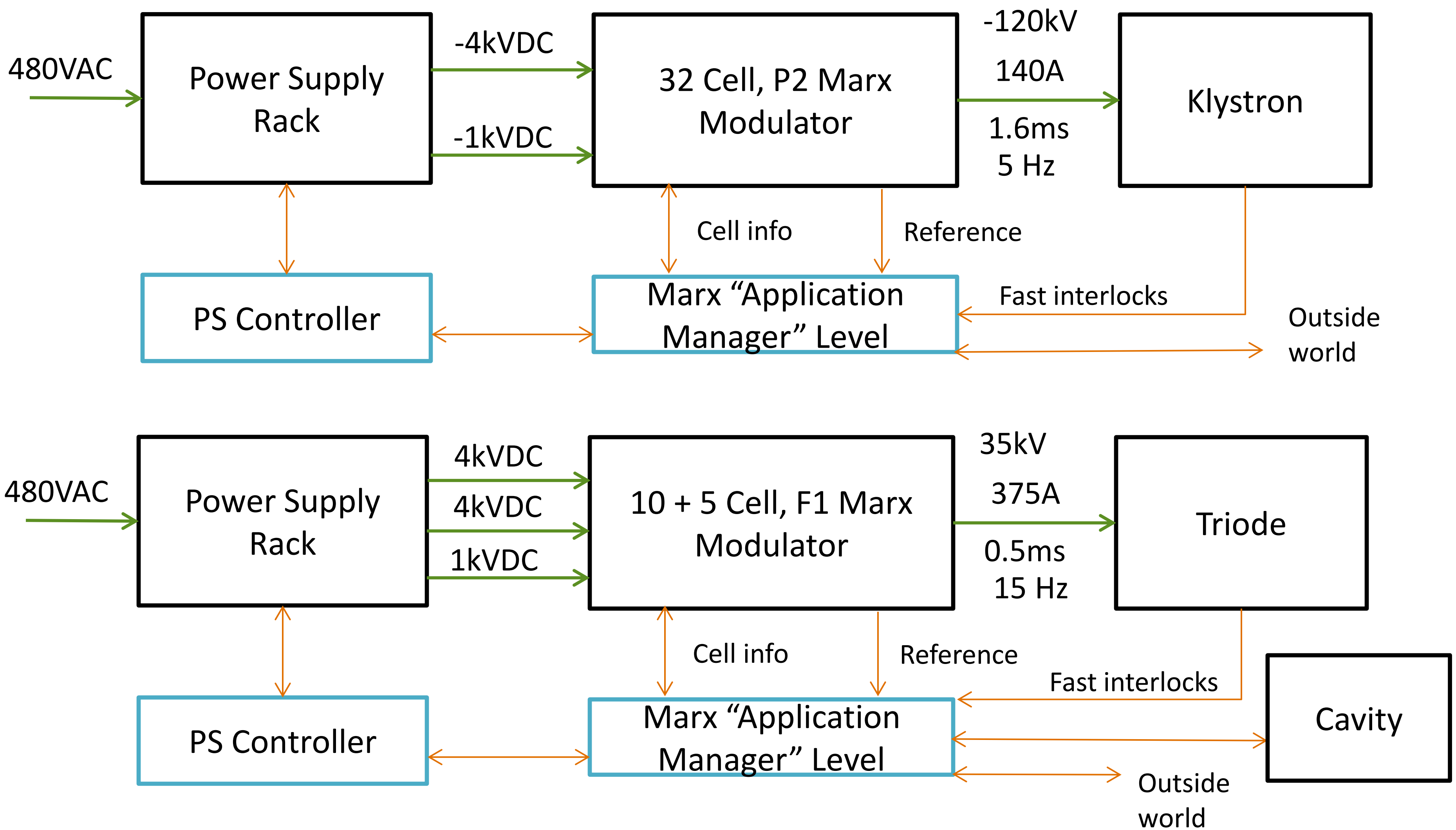
- Controls platform



- Solid state experience

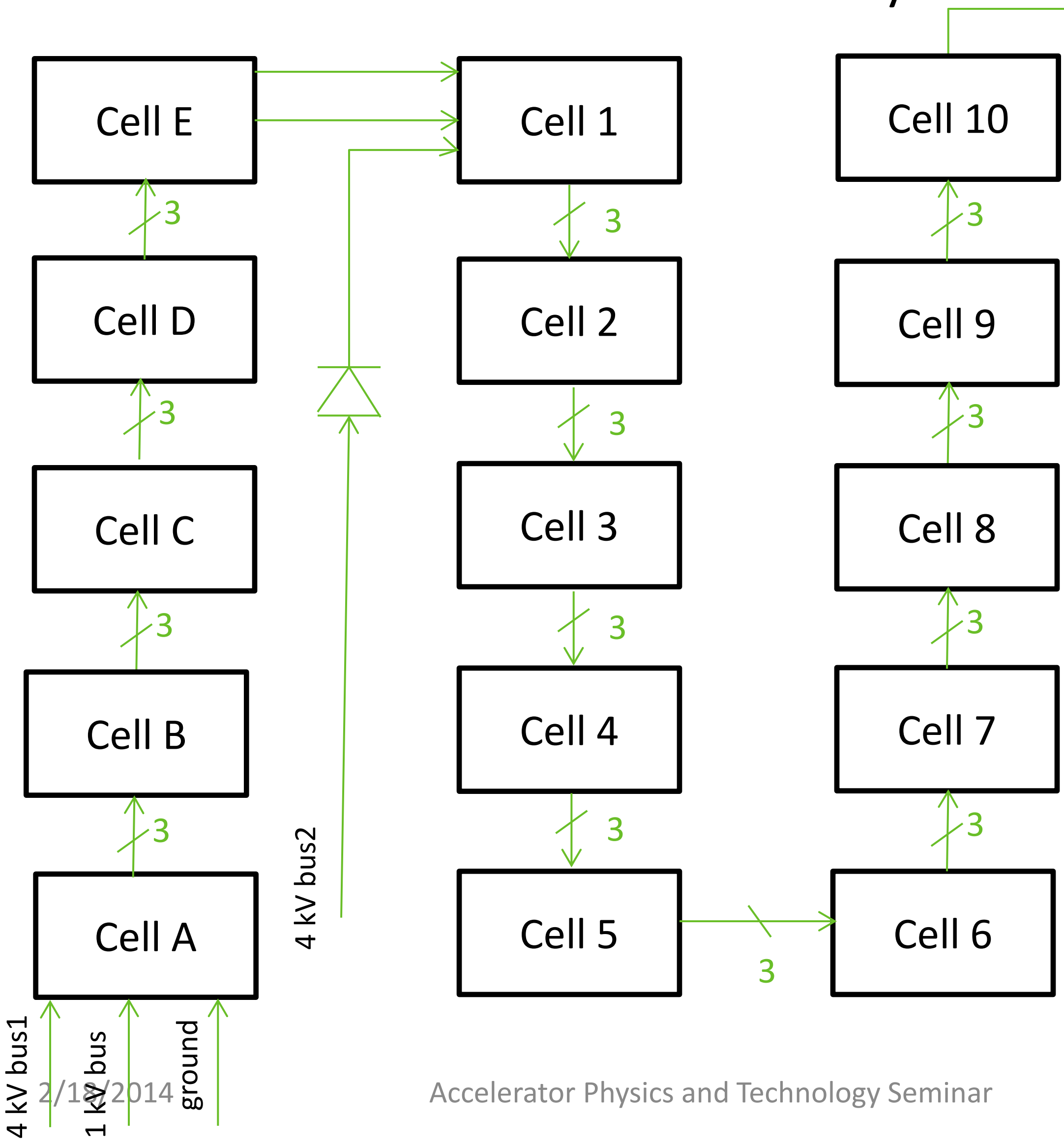


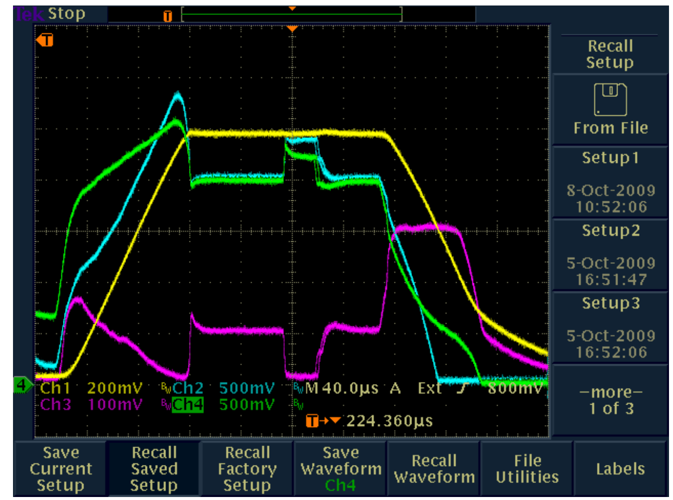
PIP *Proton Improvement Plan SLAC F1 Marx*



PIP *Proton Improvement Plan SLAC F1 Marx*

SLAC F1 Marx System Outline





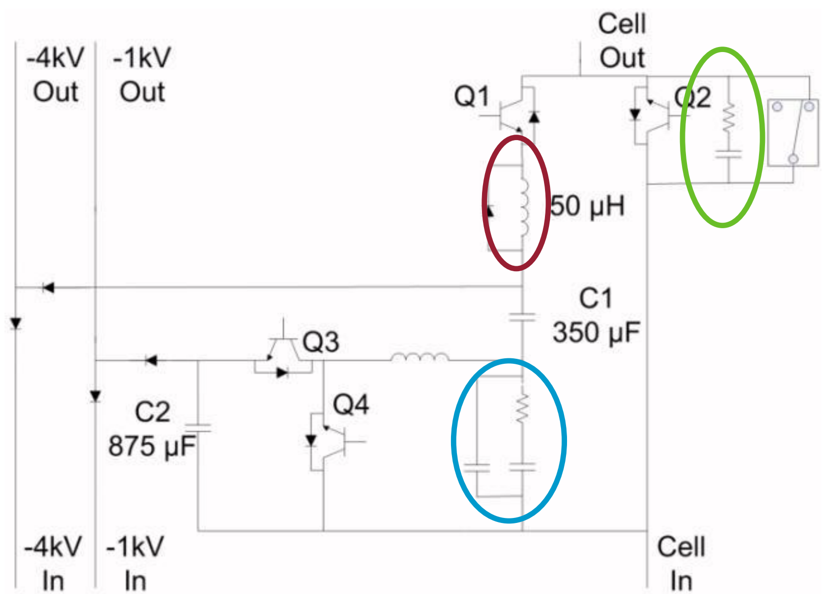
- Three independent bus voltages
- Two types of similar cells
  - Vernier for Fast Response
  - Main for Slow Response

PIP *Proton Improvement Plan SLAC F1 Marx*

SLAC F1 Marx Cell Structure

- Cell snubber (Green)
- di/dt limiting inductor (Red)
- PWM filter (Blue)

- Maximum cell dv/dt and di/dt
- Maximum / Minimum cell slope
- PWM currents
- Ripple



Three control parameters

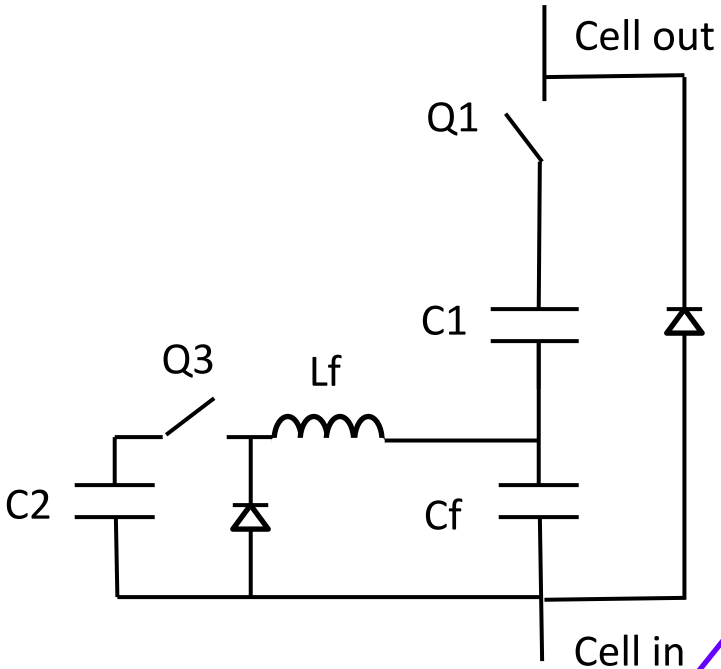
- 4kV bus voltage
- Turn on/off timings for the main IGBT
- PWM timings for the correction IGBT

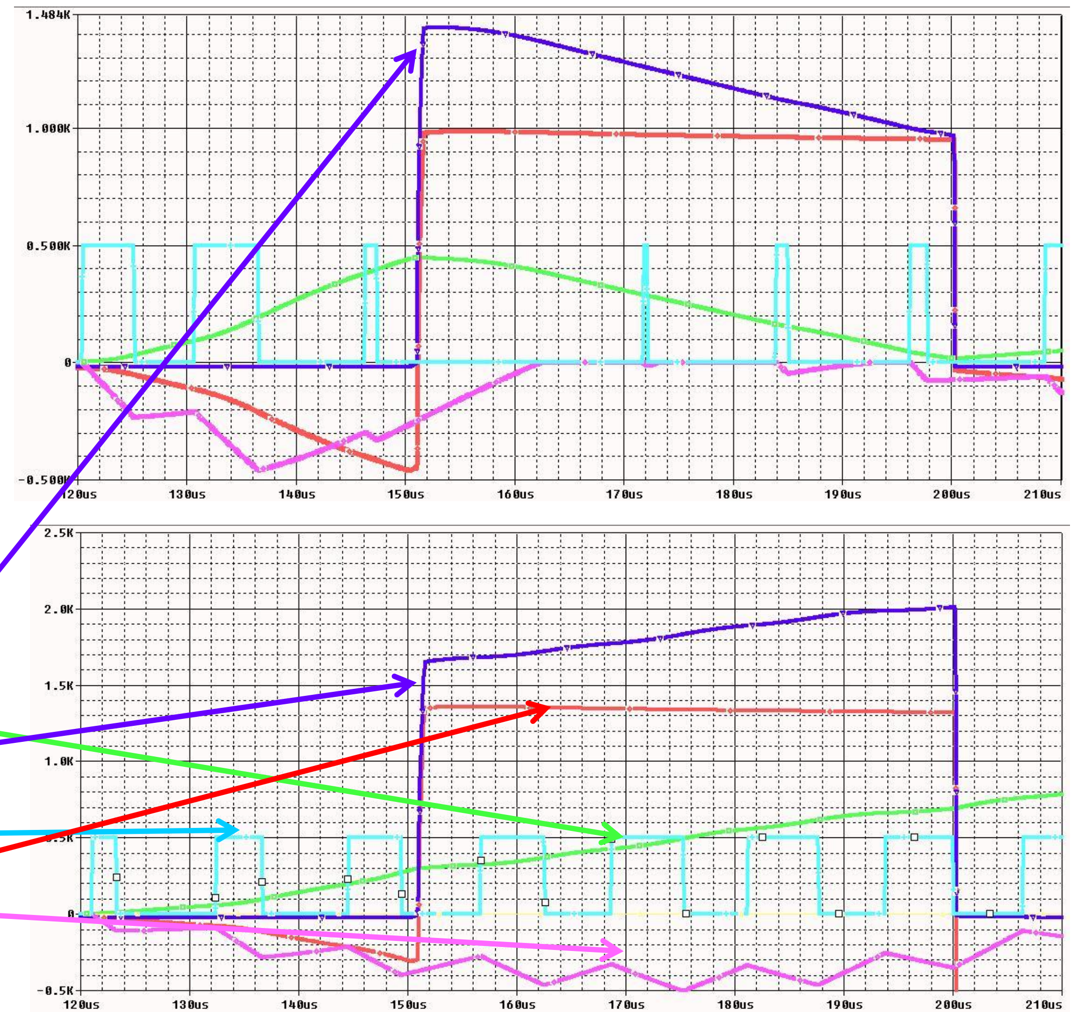
Hardware determines the filtering characteristics of the output

- We set a "slow" maximum dv/dt for the main cells
- We set a "fast" maximum dv/dt for vernier cells

PIP *Proton Improvement Plan SLAC F1 Marx*

SLAC F1 Marx Circuit





Green: voltage across Cf

Purple: Cell out – Cell in

Blue: Q3 timings

Pink: Lf current

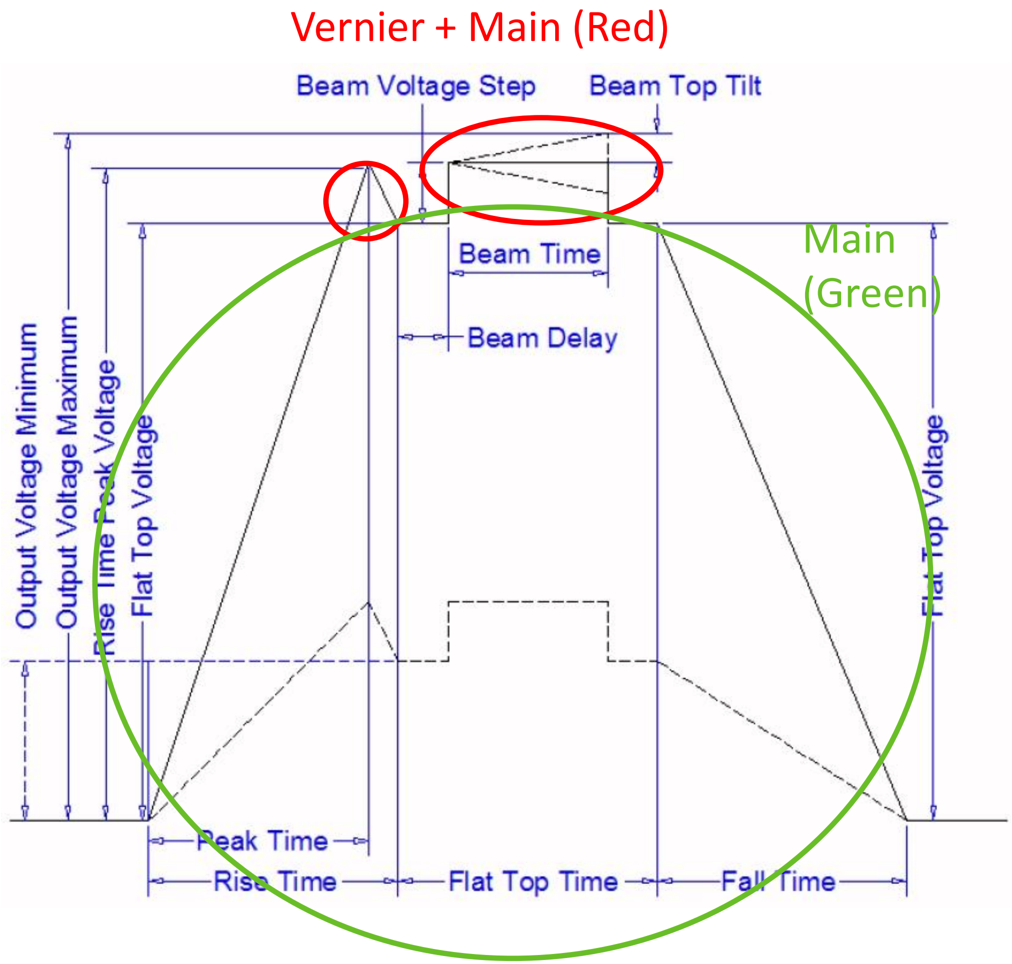
Red: C1+Q1

PIP *Proton Improvement Plan SLAC F1 Marx*

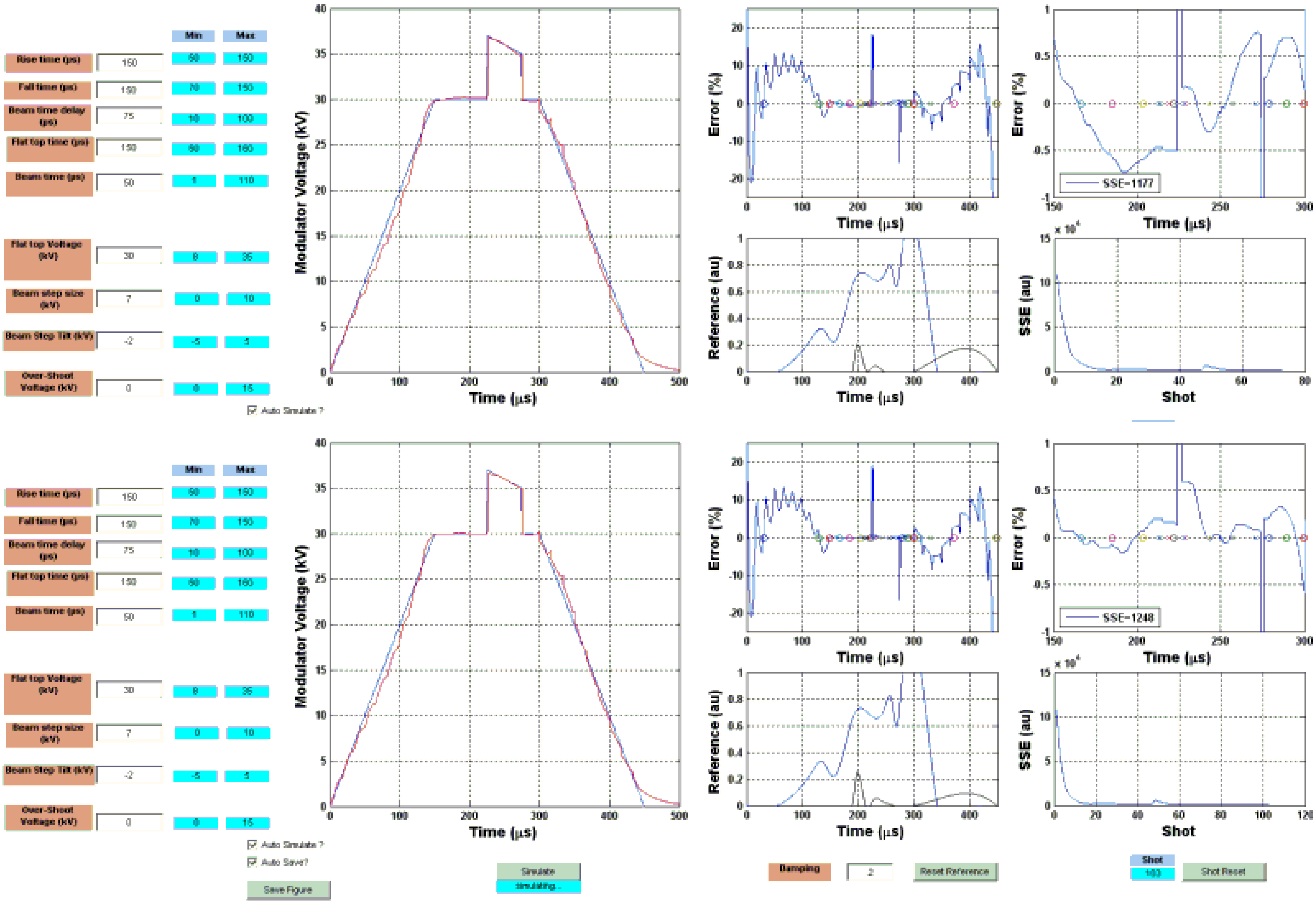
SLAC F1 Marx Control Algorithms

- Made initial assuming that short-term tube drift is minimal and feed-forward can be used
- Feedback is only possible with this design by changing the original design philosophy, since the P2 Marx design stores the PWM waveform shapes and can only update waveforms between pulses
- Instead, we can use the cavity gradient as the waveform the feed-forward algorithm uses to create desired modulator voltage waveform
- Pulse Width Modulation Control
  - All cells are fired as a collection of individual cells, each with the same PWM table
  - The vernier cells use the same PWM timings and same turn on and off
  - Unlike the P2 Marx, every main cell will use the same PWM timings, but with staggered turn on and off
  - Like the ILC P2 Marx, both the Main and Vernier cells are interleaved to reduce waveform ringing
  - Since interleaving works better when more cells are used, this design will require all main cell to be on during flattop and all vernier cells to be activated during beam time, requiring the power supply voltage to be set accordingly

SLAC F1 Marx Cell "Roles"



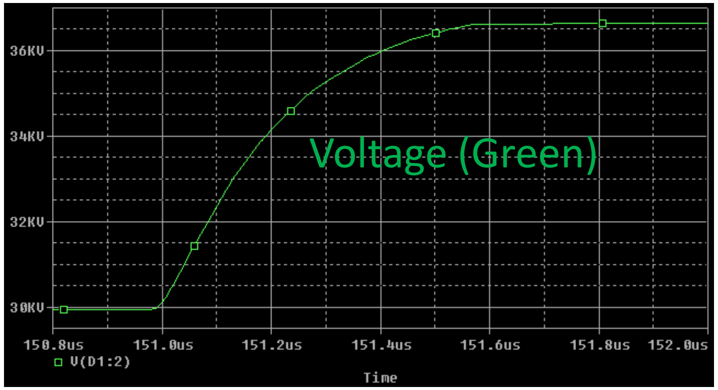
PIP Proton Improvement Plan SLAC F1 Marx



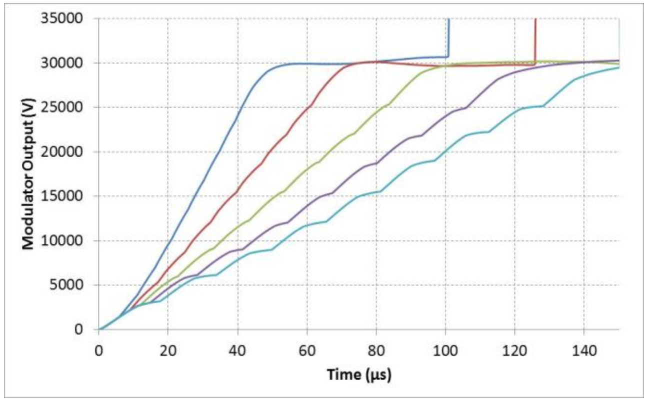
SLAC F1 Marx Simulation Results

Transient Behavior Beam-step rise-time

5.2kV/.36us = 14.4 kV/us



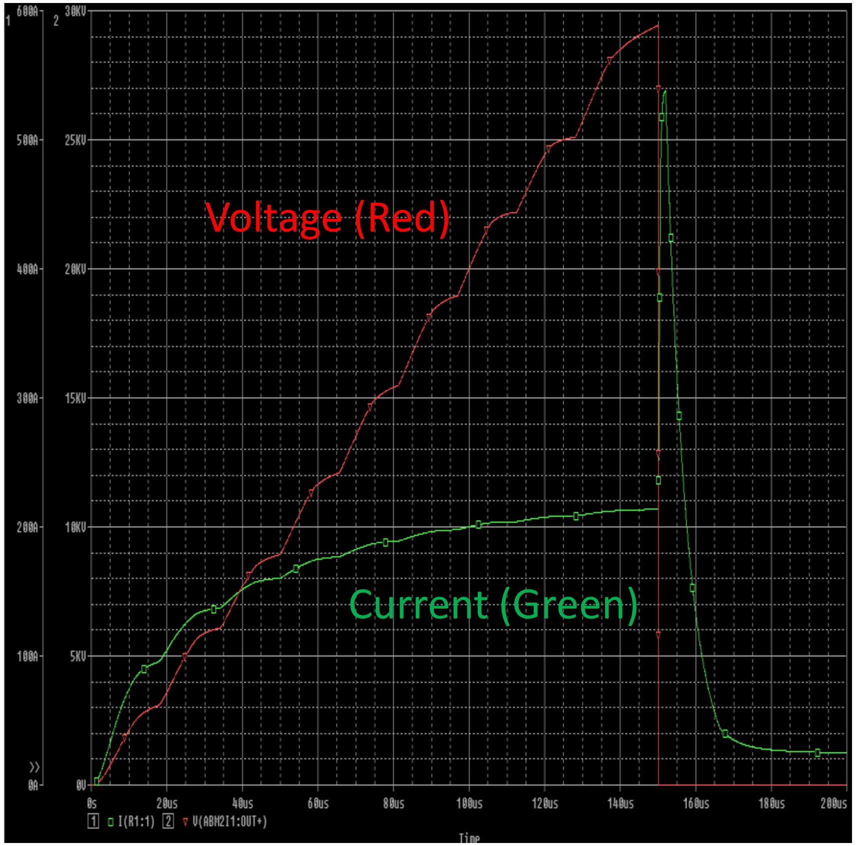
Same cell snubbers are used, turn-on timing is swept from min to max



The load is shorted at t=150 µs

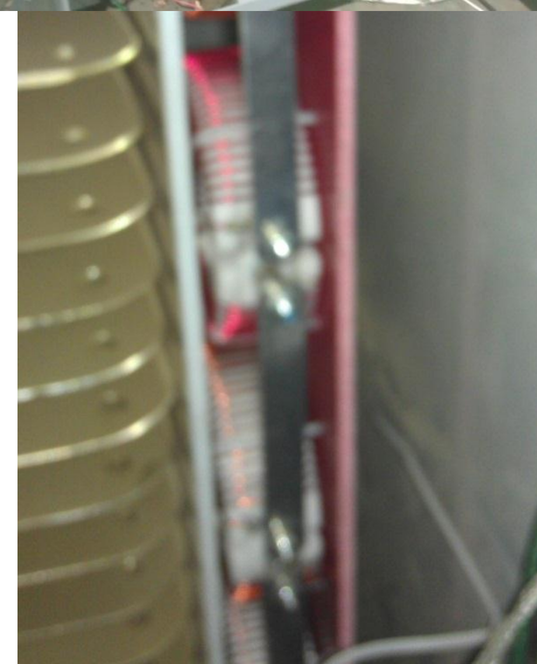
The cells initiate turn-off at >400 A

Energy = (500A*50V*5us) = 0.125 Joules



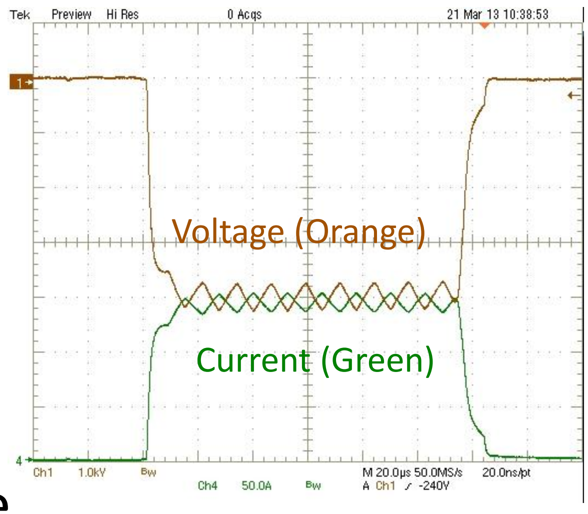
PIP *Proton Improvement Plan SLAC F1 Marx*

Two Cell Demonstration

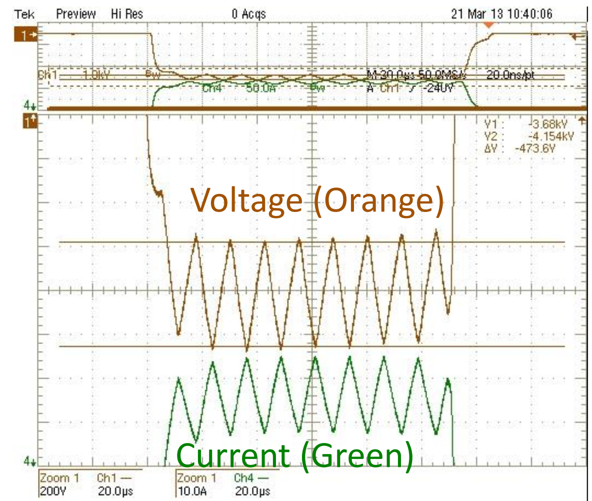


PIP *Proton Improvement Plan SLAC F1 Marx*

Full Scale

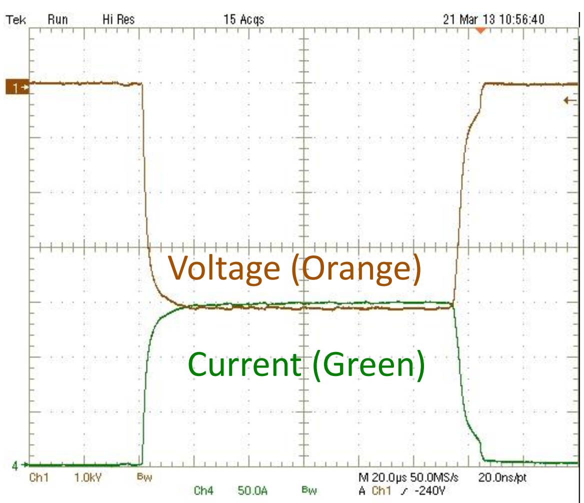


In-Phase

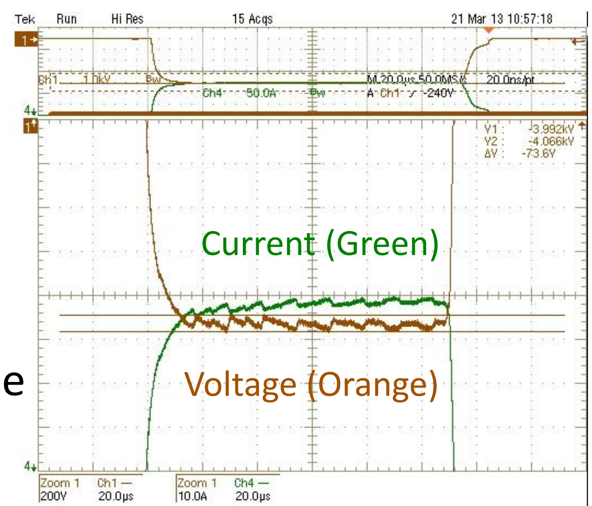


473 V_{ripple}

Zoom-In



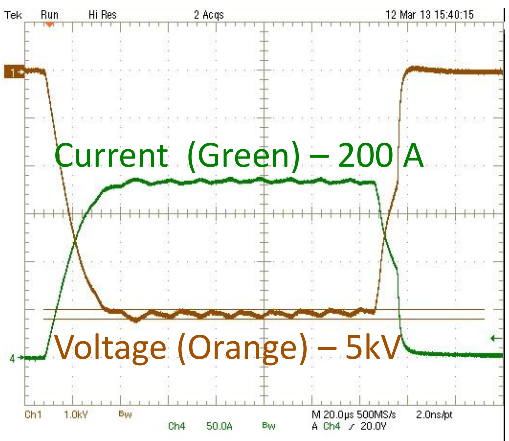
Out of Phase

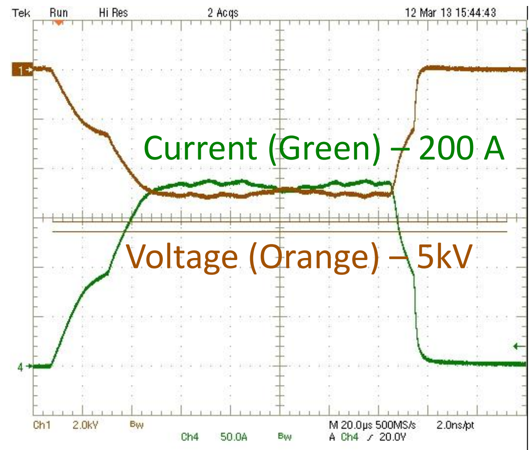


74 V_{ripple}

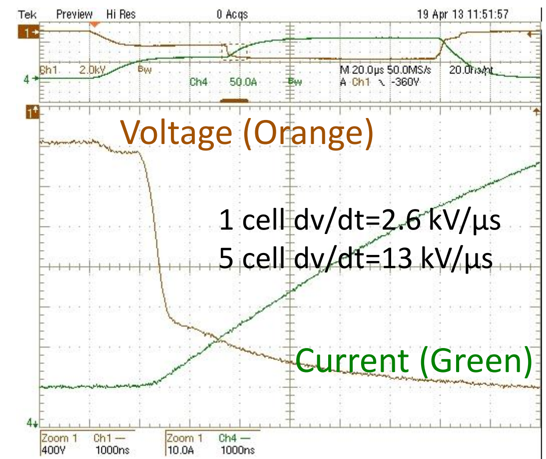
PIP *Proton Improvement Plan SLAC F1 Marx*

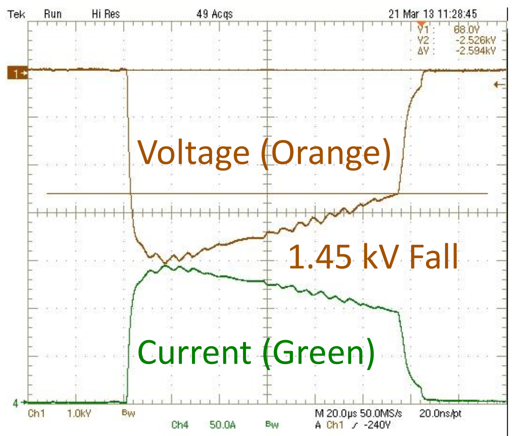
SLAC F1 Marx Main Cell Variable Rise time

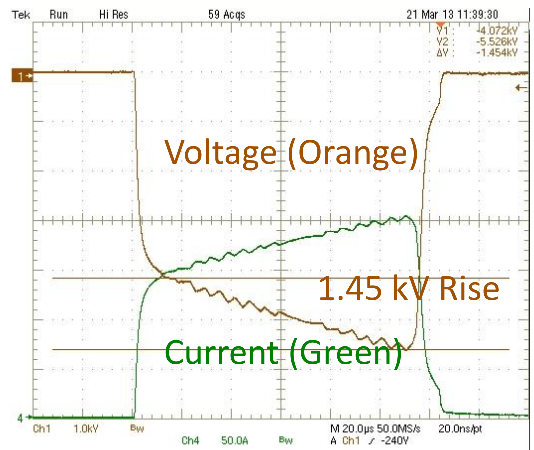


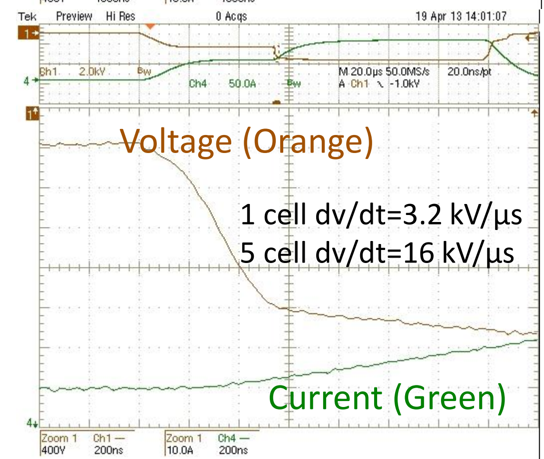


Lowered Gate Resistance









Lowest Gate Resistance

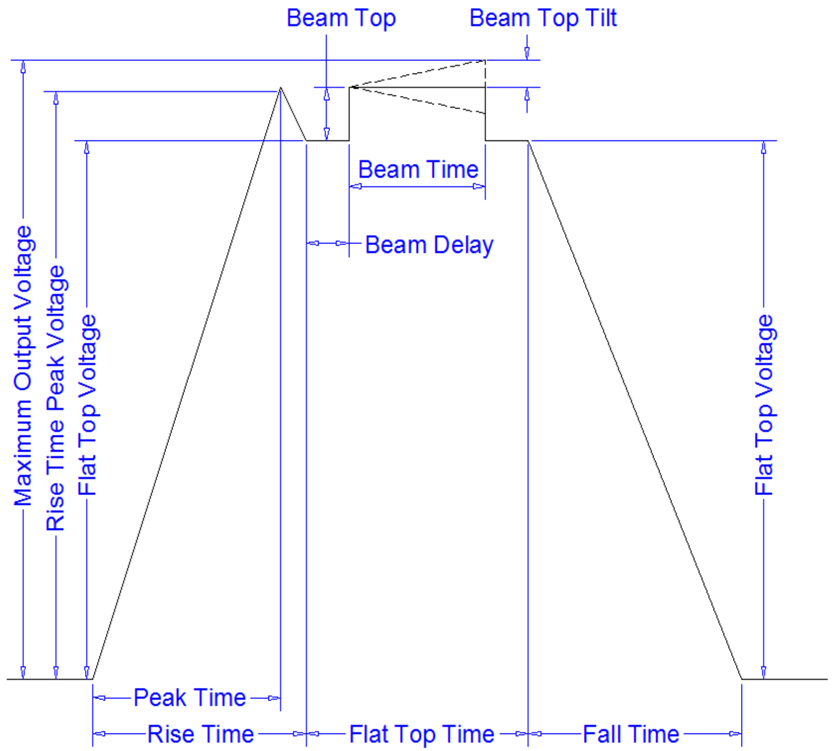
SLAC F1 Marx Two vernier cells ramping up & down

SLAC Design Cost & Conclusions

- **Initial Cost to build one prototype including all technical, engineering, manufacture, delivery and testing is ~ 1.4M**
- **Cost for each additional modulator ~ 600k**
- **Total Cost for additional work to complete $4.4M**
- This cost estimated includes contingency and inflation factors
- Although both SLAC and Fermilab EE Support are proposing a Marx modulator design, both design have significant differences
  - For example, the SLAC design sets the pre-beam flattop level by adjusting the main cells HV power supply and turning all cells on
  - The Fermilab design keeps all cells near the maximum voltage levels and adjust the number of cells (along with the Regulating Cells) to set the pre-beam flattop level.
- The SLAC design appears at the present time to meet all of the design specifications of the modulator
- The desire is to build a mini-prototype that could be used for testing of both stages of cells
- **Integrating into existing control infrastructure would be more challenging then the EE support design due to local expertise**
- **Although feedback is not possible with the P2 Marx design, an additional voltage independent Marx stage, with 4kV of range, could be added to the F1 Marx design to convert the system to operate with some feedback. This design would have limited voltage range and complex controls. Some preliminary design work is progressing.**

PIP *Proton Improvement Plan EE Support Marx*

- EE Support looked at the specifications and determined the most difficult parameters
  - Beam Top Tilt Adjustment: +/- 5 kV
  - Beam Voltage Step Slew Rate: 15 kV/usec
  - Flattop/Beam Regulation: +/- 25 V
  - Repeatability: +/- 10 V
  - Maximum spark Energy: < 5 Joules
- Like the SLAC design, the approach was to create a Marx Modulator to replace the current modulator.
- Unlike the SLAC design, this modulator was designed to meet the specifications and not modified from existing design.



PIP *Proton Improvement Plan EE Support Marx vs SLAC*

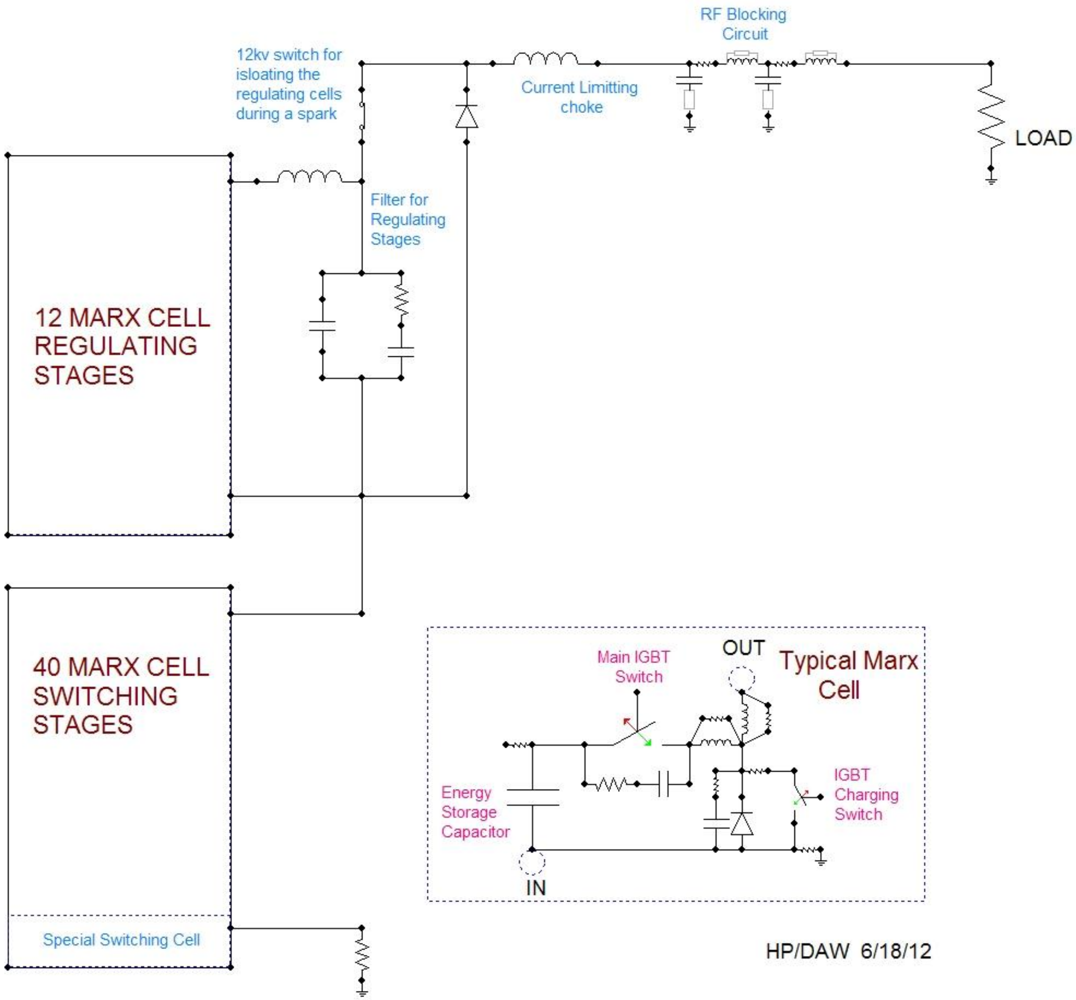
Fermilab EE Support

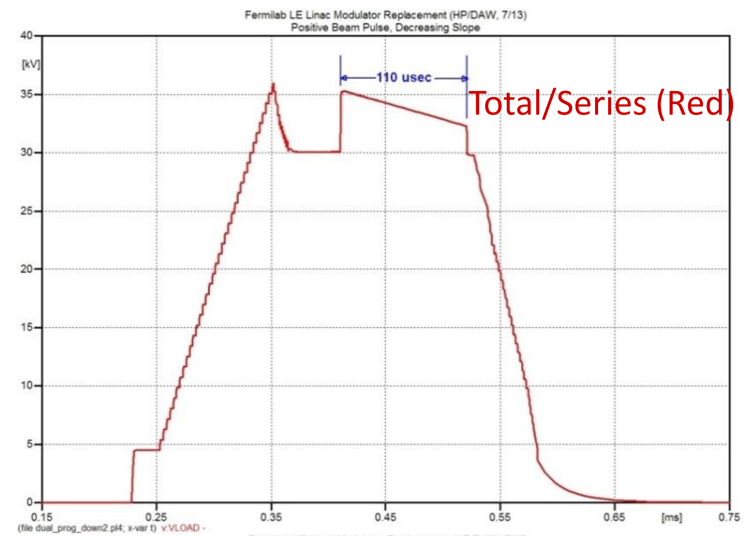
- Use 3 groups of Marx Cells connected in series
- 53 Total Cell Marx Modulator
- 40 Cell Marx-type, Switching stages
  - 950 volts per cell
  - Generates basic waveform
  - Stair Step Rising and Falling Edge
  - Produces fast beam pulse rise/fall
- 12 Cell Marx-type, Regulating stages
  - 950 volts per cell
  - Compensate for capacitor droop
  - Provide necessary beam top tilt
  - Sets the pre-beam flattop level
- 1 Cell Marx-type Adjustable Stage
  - Used to set the beam step level

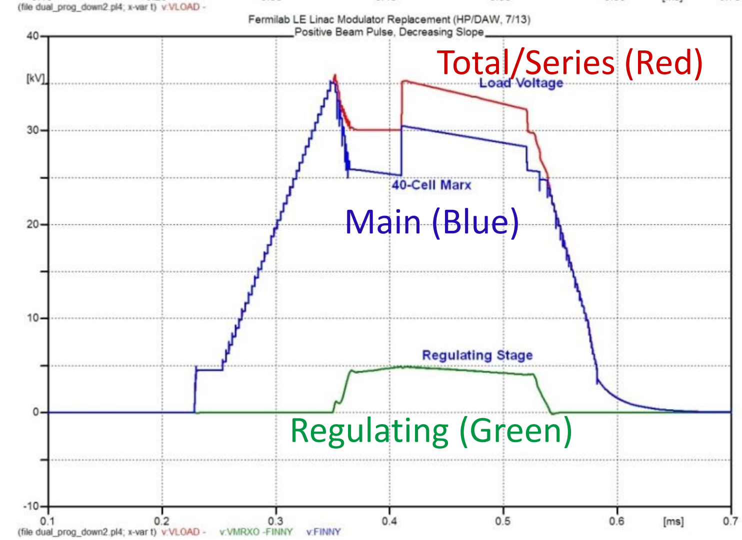
SLAC

- Use 2 groups of Marx Cells connected in series
- 15 Total Cell Marx Modulator
- 10 Main Cells (small dV/dt)
  - 4 kV Main Capacitor
  - 1 kV PWM Section
    - Compensate for capacitor droop
  - Generates Basic Waveform
  - Stair Step Rising and Falling Edge
- 5 Vernier Cells (large dV/dt)
  - 4 kV Main Capacitor
  - 1 kV PWM Section
    - Compensate for capacitor droop
    - Provide necessary beam top tilt
    - Used to set the beam step level
  - Produces fast beam pulse rise/fall

PIP *Proton Improvement Plan EE Support Marx*







PIP *Proton Improvement Plan EE Support Marx*

40-Cell Marx Stages (950 Volts each)

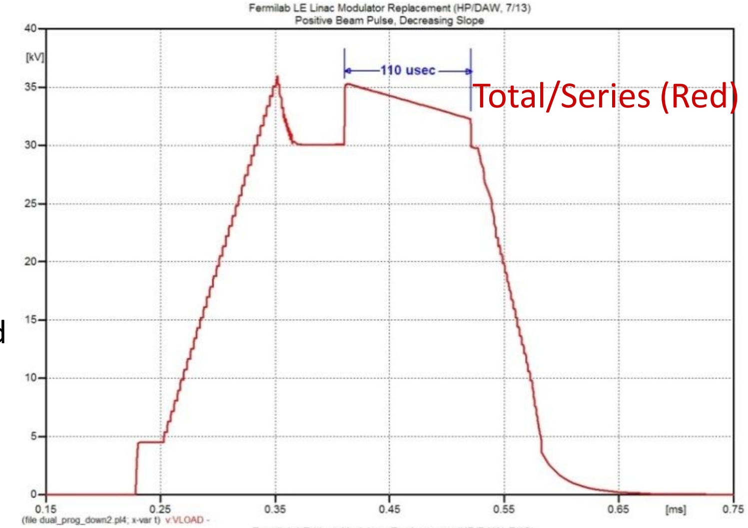
- On the peak overshoot and rising/falling edges, only the 40 Cell Marx is used
- There is no compensation for capacitor droop during these times.
- To achieve the large beam step, one or more of these 40 cells is used.

12-Cell Marx Stages (950 Volts each & Filtered together)

- **Used for precise control of flat top and beam tilt**
- Compensates for known capacitor droop & the rising/falling tilt on beam with the ~ 11.4 kV of voltage for these Marx Stages providing the required overhead
- During flattop, these cell are switched at a 1 MHz to create the regulating stage voltage seen above
- Assuming the voltage of the one extra adjustable 0-950 Volt Marx cell is set properly, this regulating stage does not have any jumps during the beam time pulse start
- ***Required slope compensation calculated using desired waveform and cell capacitance.***
- ***These cells can be driven by a feedback signal generated from a gradient error (limited bandwidth).***
- **Apply feed-forward learning in the final system**
- MECAR (Main Ring Excitation Controller & Regulator) type learning system could be applied to voltage program using a cavity gradient waveform as a reference.

1-Cell Marx Stage (Adjustable 0-950 Volts)

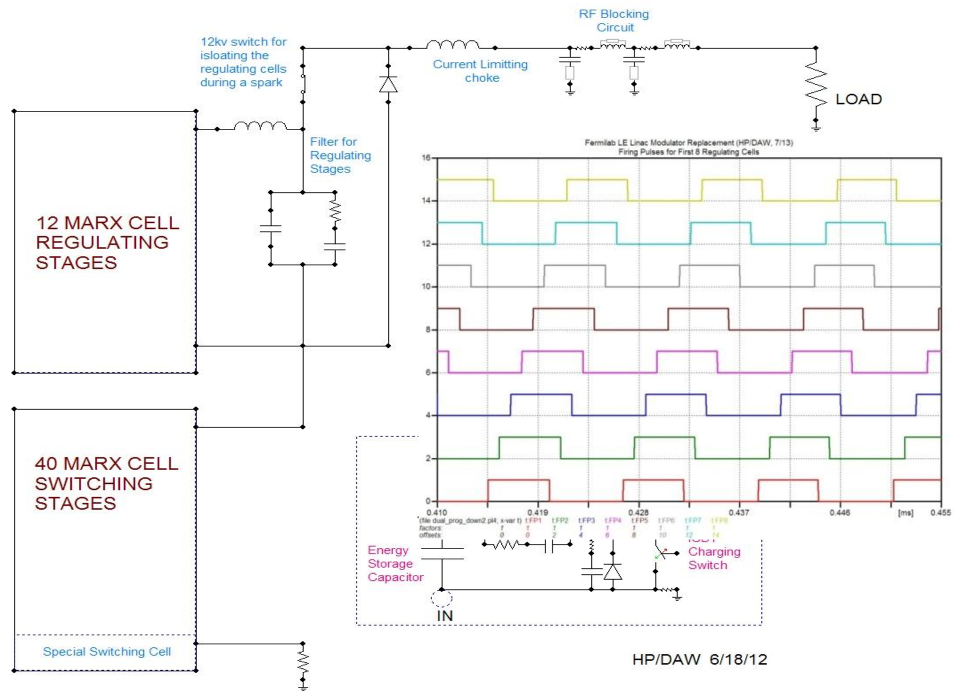
- Since it is desired to **set the beam step to accuracy** greater than the 950 Volt charge of each cell, an extra adjustable 0-950 Volt Marx cell will be required to set this voltage

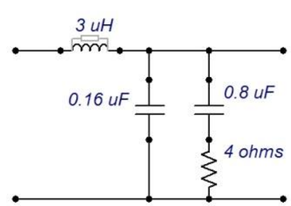


PIP *Proton Improvement Plan EE Support Marx*

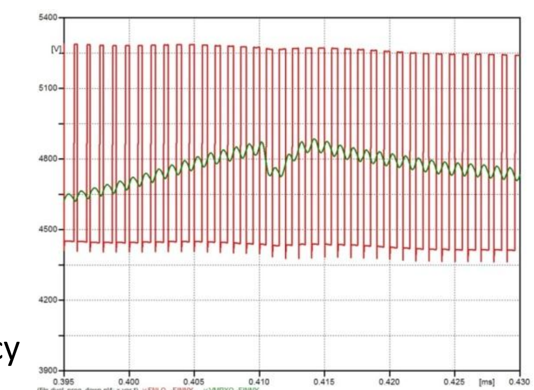
EE Support Marx Regulator Stage

- 950 Volts Marx Stages – 12 Cells total
- All cells operated using the same pulse-width modulated waveform
- **Individual Cells are fired at a 80 kHz Rate**
- **Cell are interleaved / staggered in phase by 360° / 12 cells = 30° per cell**
- After interleaving, the cell are collectively running at 12*80 kHz = 960 kHz ~ 1 MHz Rate
- To minimize IGBT stress, each cell is held on for a minimum of 1 usec and at most for 11 usec's to set the voltage output
- Regulating cells are only activated during flattop and beam pulse to reduce switching loses.
- Minimum "on" voltage = voltage of one stage
- Maximum voltage = 11 x voltage of one stage
- Cell maximum voltage output is 11 x 950 ~ 10 kV
- Typically run near ½ maximum to increase the tilt adjustment range





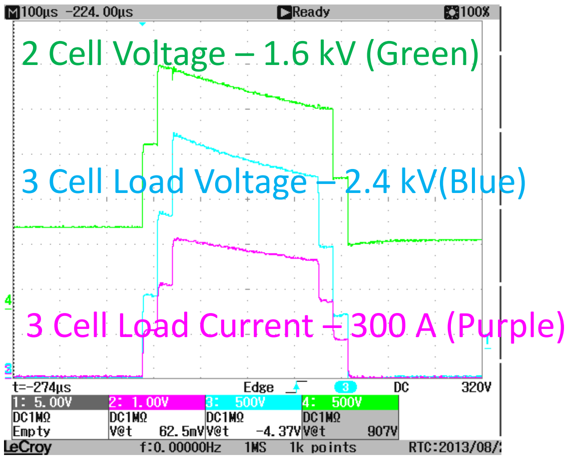
274.602 kHz Frequency

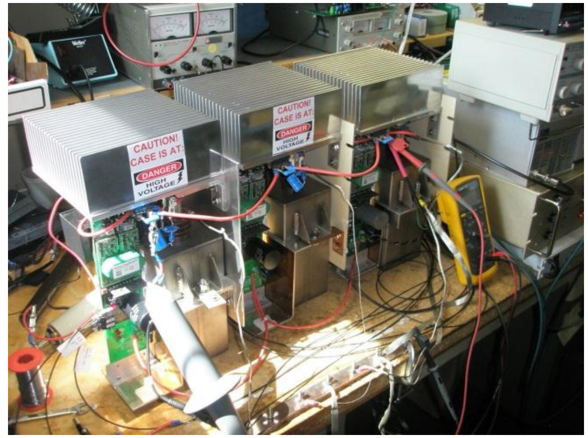


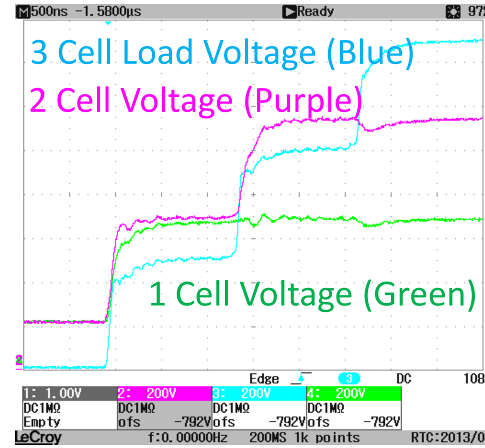
PIP *Proton Improvement Plan EE Support Marx*

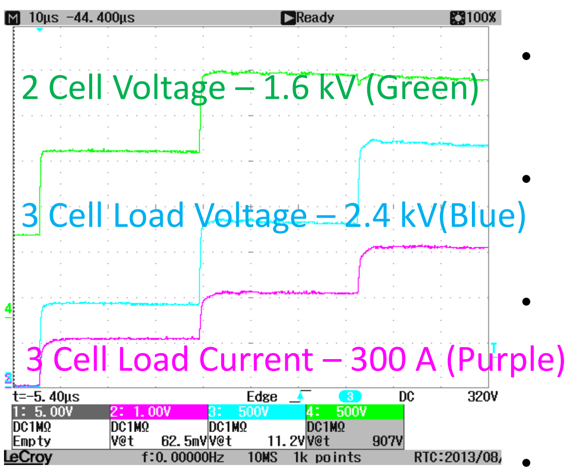
3-Cell test (900 V/cell with 8.3 Ohm Load)

Turn-on Ringing, cells switching within 600ns

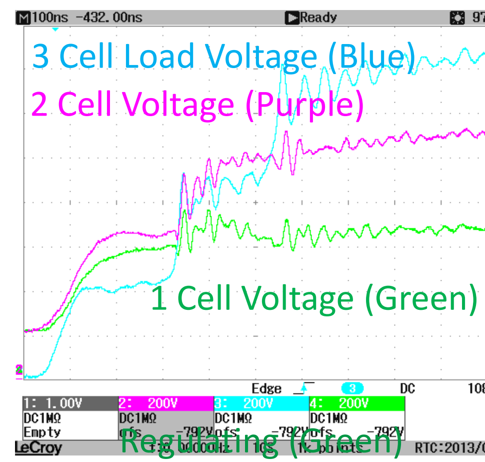




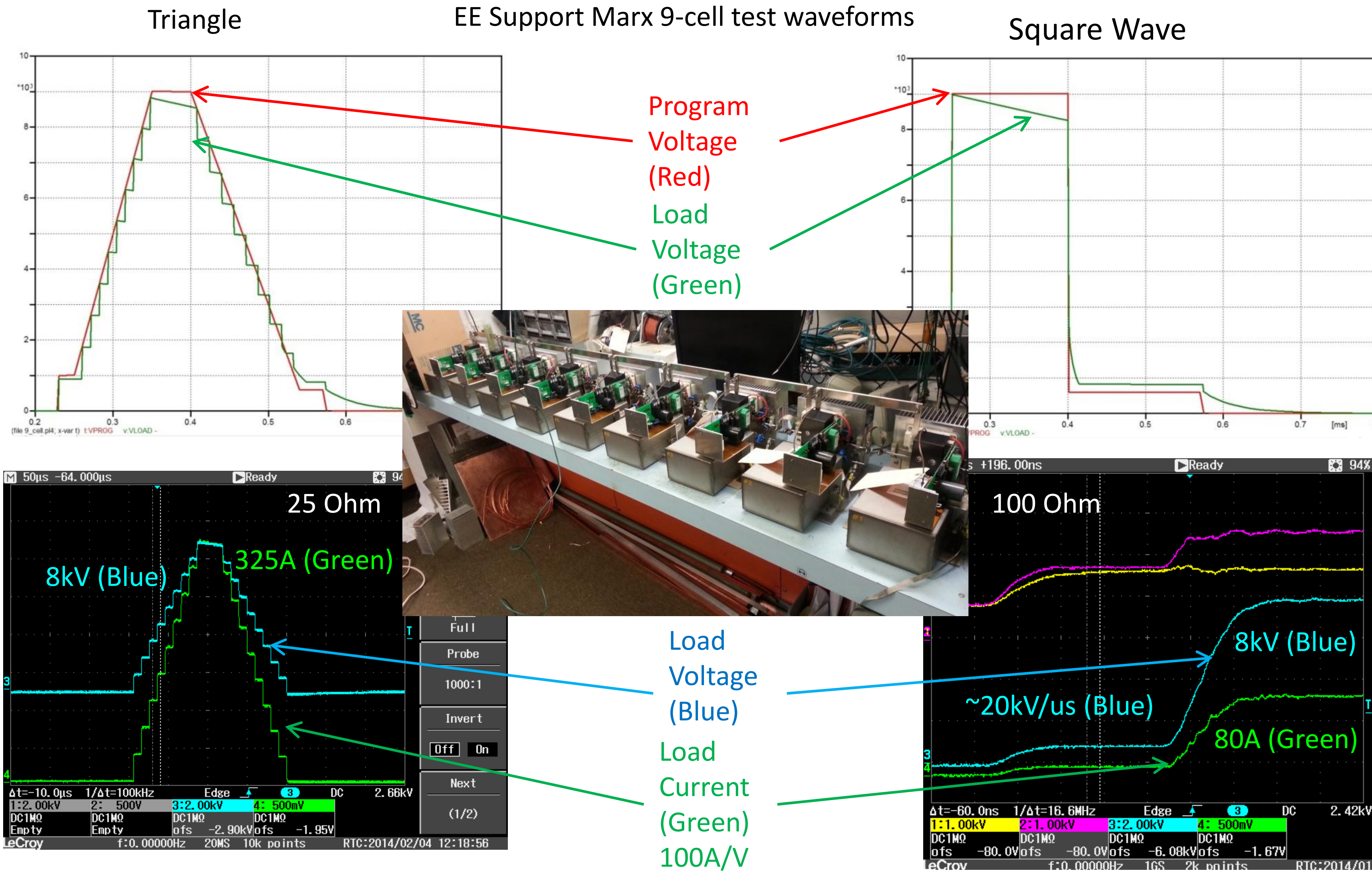




- **Oscillations when switching the cells < 600 ns apart at lower currents**
- Determined the cause of the oscillations due to the **internal IGBT diode turn-off before diode is fully on.**
- When testing at a higher current, the **ringing went away since the diode is at higher current during turn-off.**
- **Controls can be designed to limit main cell switching during turn on to 1 us**, which should not be a problem with the rise and fall time requirement of modulator
- For final design, this effect will ***not be present*** during beam flattop or beam time since it is only a lower current effect noticed during testing.



PIP *Proton Improvement Plan EE Support Marx*



PIP *Proton Improvement Plan EE Support Marx*

EE Support Marx Upcoming Studies

- Build Interleaved Regulator for Regulating Stage
  - Note that in this development, only 8 stages will be used for the regulating stage testing
  - Pulse one cell ON, then make 4 kV 8-cell interleaved pulse.
  - 1 us spacing, 2 us minimum time, 8 us cycle, 96 us pulse length.
- Short circuit response of 9 cell design modulator
  - Freeze signals for 8 us then turn OFF.
- Build the designed Regulating Stage PWM Filter
- Work on design control system for the Marx Modulator

Transforming Marx Modulator designed for 7835 triode to Klystron Load

- With the appropriate scaling factor, any of the proposed solid state modulators could be converted to a Klystron Load
- This would be an option to convert any prototype design solid state modulator for use in a Klystron
  - Would be useful in doing lifetime testing of any solid state design
  - Would maximize use of the prototype modulator if the klystron option is chosen in the future, even if another type of modulator was chosen for the final klystron design
  - Bouncer design would likely require 1:12
  - Marx Modulator would require 1:4 turns ratio
- Using data scaled from the latest procured pulse transformers, the cost to build a either turns ratio would be about $75k.

PIP *Proton Improvement Plan EE Support Marx*

Cost

- Initial Cost to build one units without technical labor or engineering costs was calculated at **$385k**
- Revised Cost for Parts after 9 cell development is **$300k**
- Technical Labor estimated at $300k with $150k of engineering labor, totaling $450k of labor
- **Total Cost of Prototype ~ 750k**
- **Cost for each future modulator ~ 600k**
- **Total Cost for additional work to complete $3.75M**
- Important Items to Note
  - No overhead, project management, or contingency included.
  - Additional costs to interface to existing Linac controls system are likely.
- Assuming 15% Inflation and 20% contingency, this brings total to $750K + 5*$600k*1.35=$4.8

Conclusion

- Meets Fermi specification with all solid-state design
- Ability to add feed-forward/feedback signals
- Can be used for a klystron with a suitable HV pulsed transformer.
- Fermi labor, if available, reduces the project cost
- Significant progress can be made with minimal M&S over the next year by building just a few Marx cells and designing controls.
- Local knowledge of modulator design details will add in testing and integrating into existing control infrastructure.

PIP *Proton Improvement Plan Linac Modulator Summary*

- The present modulator, although performing well, **is not a viable long term solution** since there are suppliers for the main switching tubes (now obsolete) and since the power supplies and related electronics are also becoming obsolete and hard to repair.
- The original specification only listed voltage characteristics, and not control topology
- Initially assumed feed-forward alone will work, but have new evidence to suggest feedback may be required
- Not only can the modulator be design to have feedback control, but is my be possible to do feedback through the driver

Ongoing Work

- Finish controls study by SLAC to determine operating mode for F1 Marx
- Finish development and testing of EE Support 9 Cell Mark Modulator
- Perform more studies on operating RF stations to determine the effect of feedback versus feed forward
  - Perform open loop tests (Current Regulation)
  - Preform amplitude and phase measurements for RF and beam
  - Add an integral term to the present feedback loop
  - Convert the system to constant voltage regulation
  - Perform Driver Modulation tests

	Initial Design Study(s)	Full Prototype M&S plus Labor	Final Build of 5 more modulators	Total Cost and Completion
Fermilab EE Support	$50k (M&S)	$750k	$3-4M	$3.8-4.8M
	FY12-FY14	FY15	FY15-FY18	Oct 2018
SLAC	$177K	$1.38M	$3.07M	$4.5M
	FY12-FY14	FY15	FY16-FY18	Fall 2018
Continental Electronics	$50k	~$2M	5*(750k-1.5M)	$5.9-9.6M
	FY12	FY15	FY16	FY17

PIP Proton Improvement Plan Linac Modulator Summary

Continental Electronics Corporation Solid State Modulator

- Initial studies indicate that the design may work
- More studies would need to be performed to test hardware and controls ideas before considering as a viable option.
- **Advantage – The ability too do direct feedback and quick delivery available**
- **Disadvantage – Significantly higher cost than the other designs without meeting all design specifications**

SLAC F1 Marx Modulator

- Has been and still is being studied as a possible replacement.
- Both computer modeling and **hardware development has been done** modifying the ILC base P2 Marx Modulator to work with the voltage slew rate and peak current required in the Fermilab Linac.
- This design is cost competitive since much of the development work has already been done for ILC.
- **Advantage – most of the cell and controls development completed**
- **Disadvantage – new development is required determine feedback methodology and cost is high.**

Fermilab EE Support Marx Modulator

- **Designed using the Linac specifications, leading to a different chosen cell voltage and topology.**
- Using a lower cell voltage than the SLAC design, create the ability to limit the step size turning ramping
- **Using three types of Marx sections enables control of the waveform more suited to the critical parameters of the desired voltage waveform.**
- Design is cost competitive to the SLAC design and meets all parameters.
- **Advantage – The ability to add feed-forward/feedback signals and local knowledge of modulator design details will add in testing and integrating into existing control infrastructure.**
- **Disadvantage – No previous experience building Marx, but a lot of overall modulator knowledge**