Modulator R&D at LBNL

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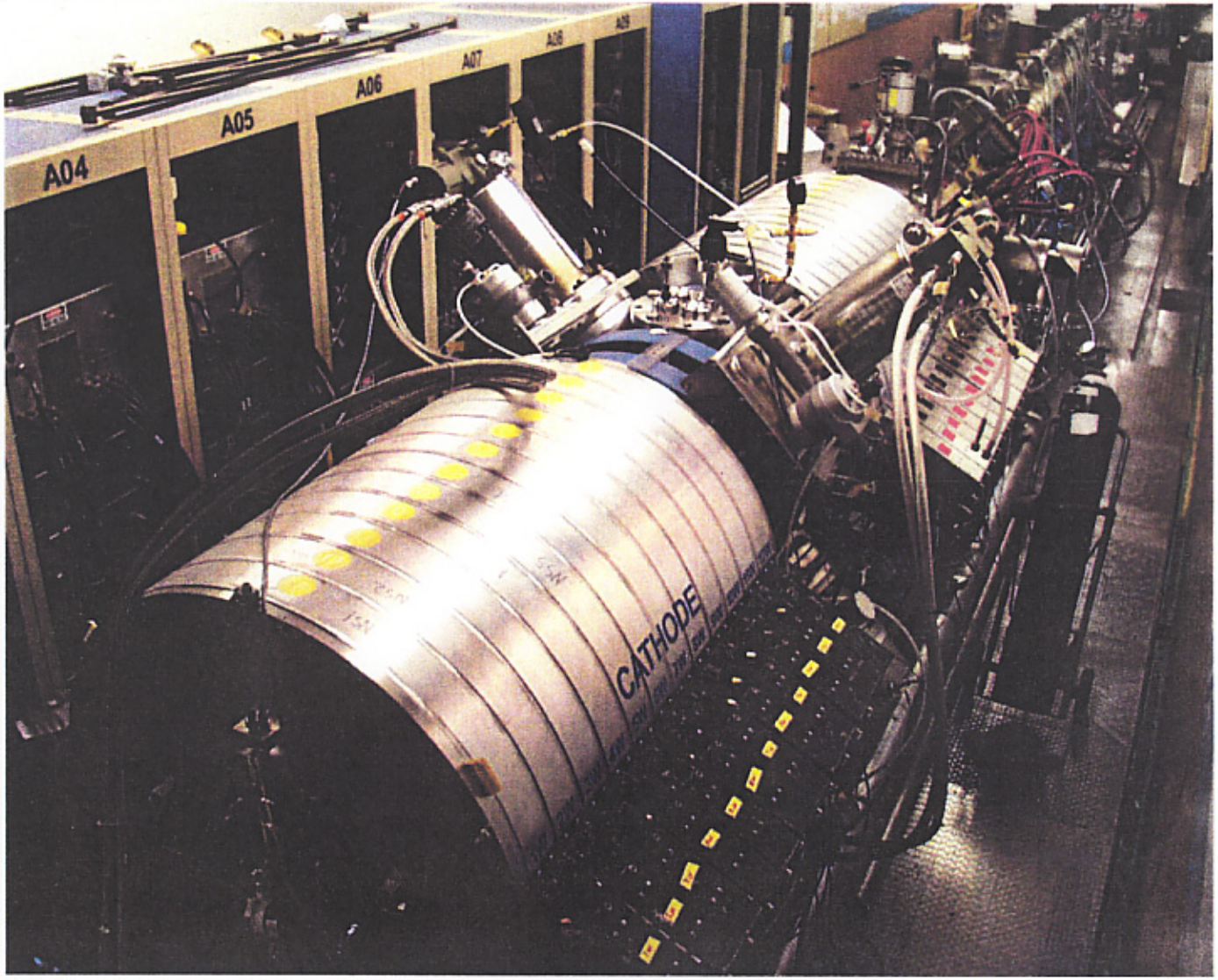
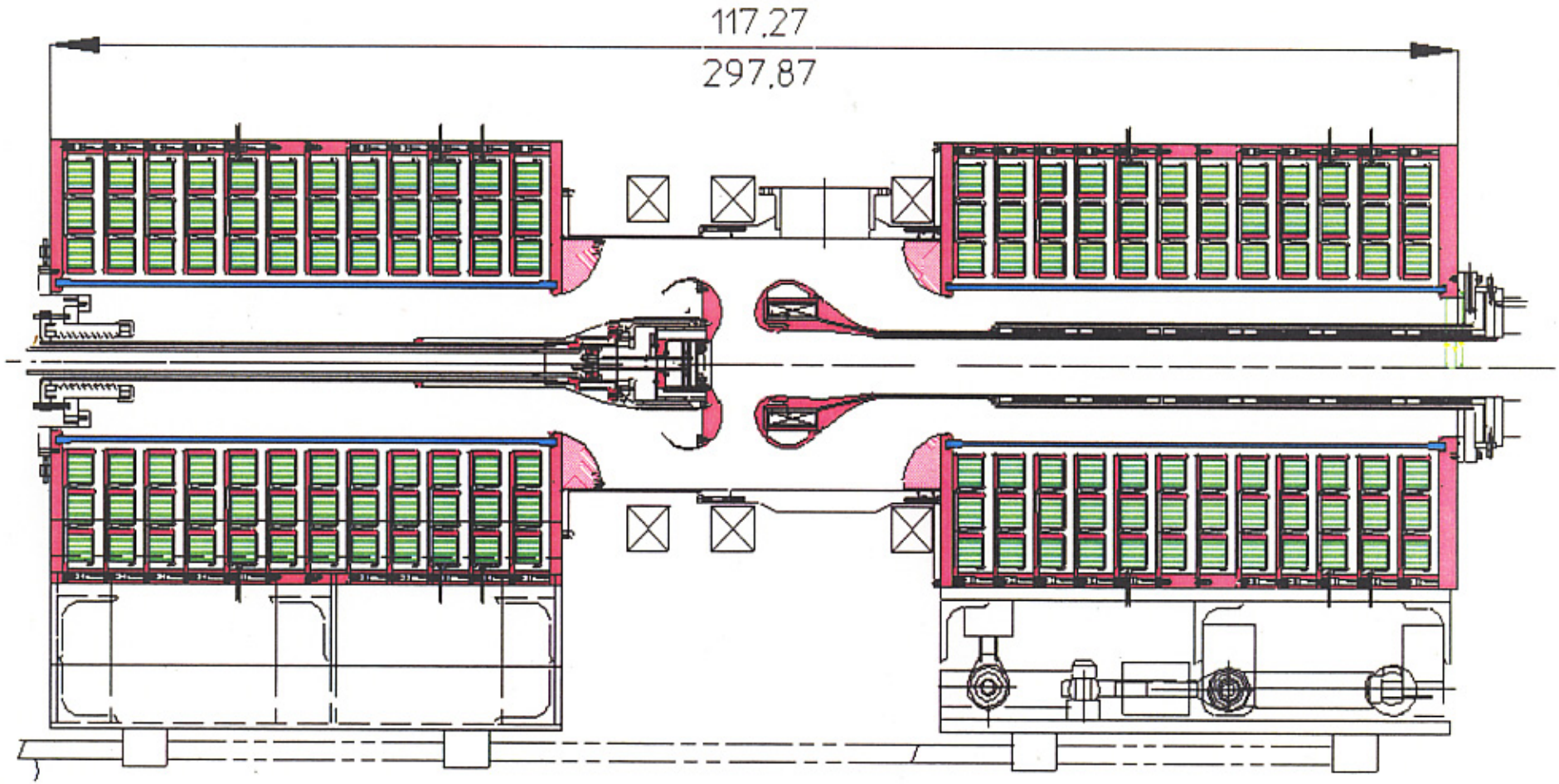
Outline

- Relativistic Klystron Two-Beam Accelerator (RTA) modulators
- DARHT-2 modulators
- Heavy Ion Fusion (HIF) requirements
- First Point Scientific SBIR modulators
- Future development - Integrated Beam Experiment (IBX)

RTA Injector (1 MeV, 600A)



RTA Injector



RTA Injector Pulsed Power System

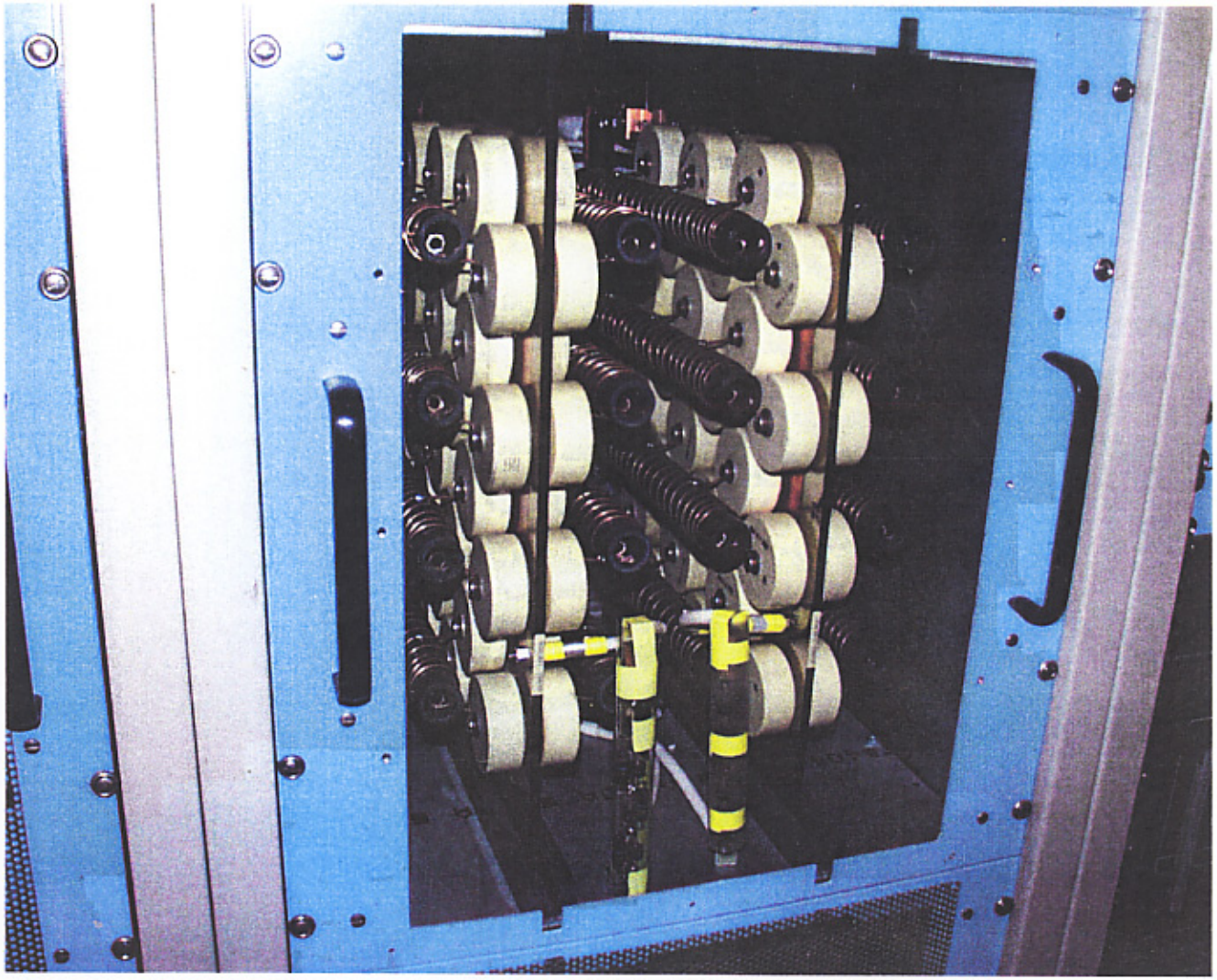
24 thyratron switched PFN's (Z_0 = 1.5Ω)

One PFN per cell which has three Metglas cores in parallel (each driven at 14kV)

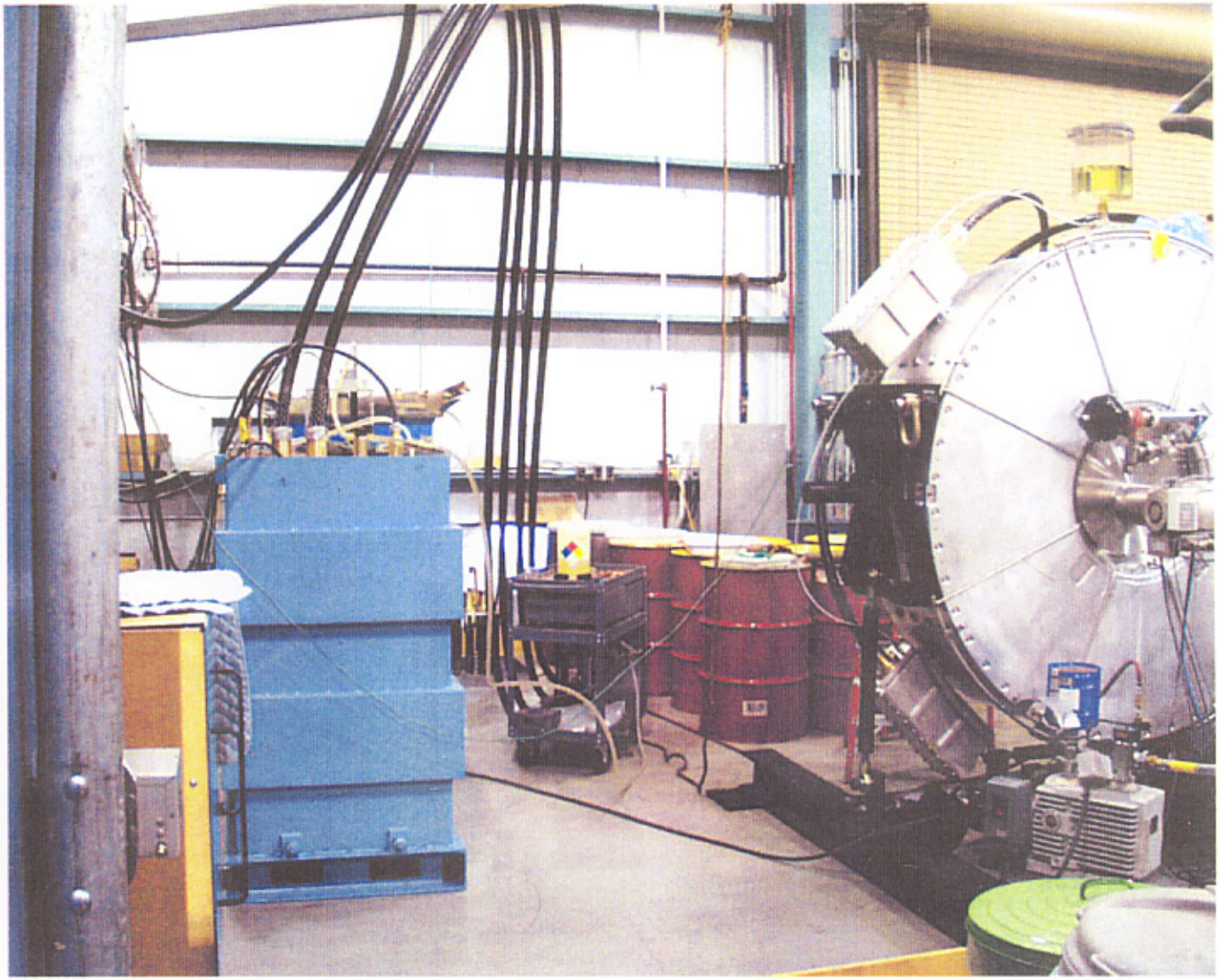
Specifications :

- **1MV on diode**
- **1 Hz repetition rate** **used for testing)**
- **150ns flat-top**

RTA Injector Cell PFN's



DARHT-2 Induction Accelerator Cell Test



DARHT-2 Pulse Forming Network / Marx

Seven section type-E network in a four stage Marx configuration (total $Z_0 = 20\Omega$)

Each Marx stage is a PFN with a tapered impedance to compensate for the nonlinearity of the core magnetization current (provides more current when the cores approach saturation)

Specifications :

- -195kV output pulse
- 2 shot/min. repetition rate (12 shots/min. used for testing)
- 2.02us flat-top with voltage variation $\leq$ +/- 0.5%
- Risetime (10%-90%) $\leq$ 250ns
- Jitter $\leq$ +/- 20ns (3 sigma)
- Minimal voltage reversal on the cell

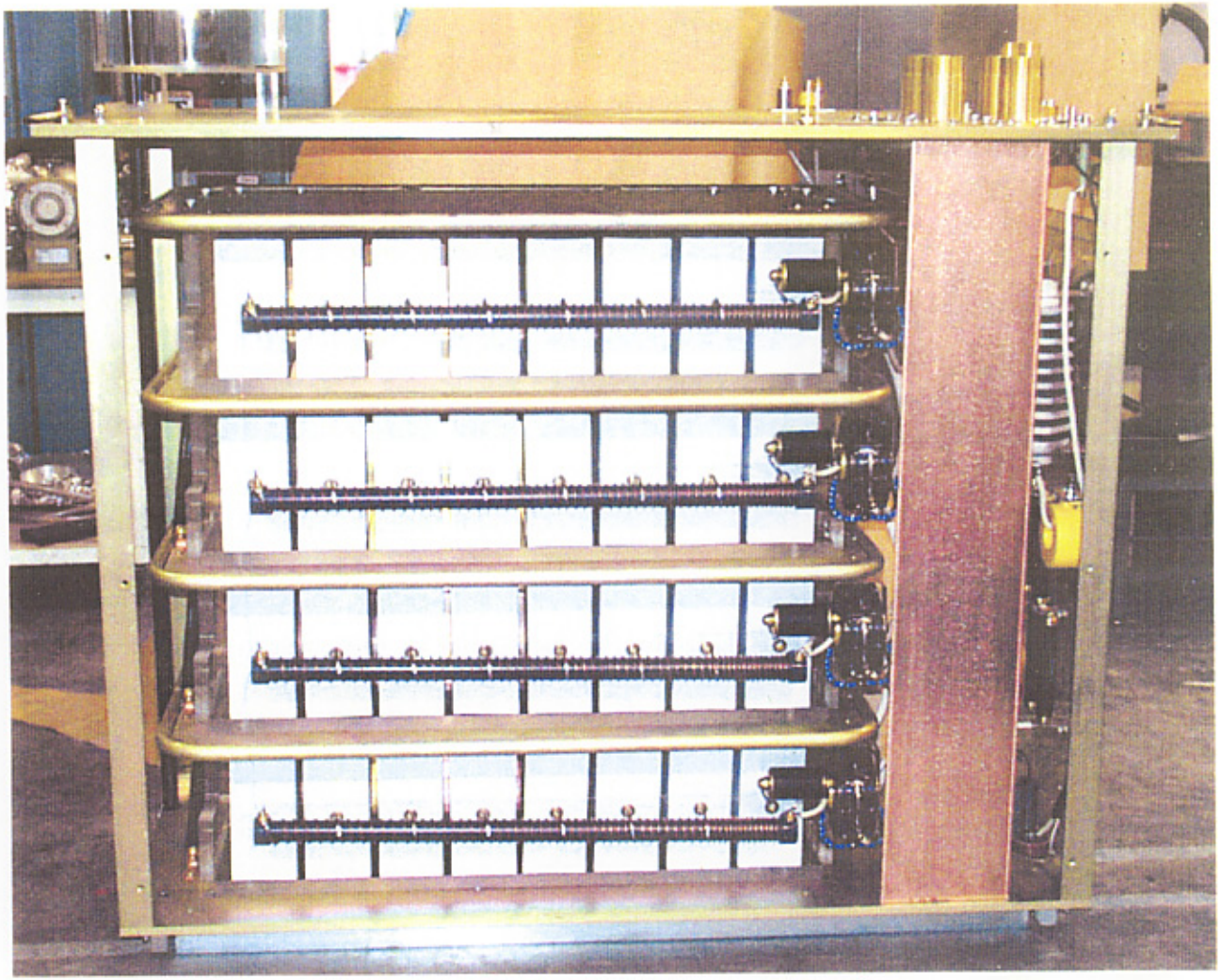
Pulse Forming Network / Marx

200kV

10kA

2us flat top

250ns risetime

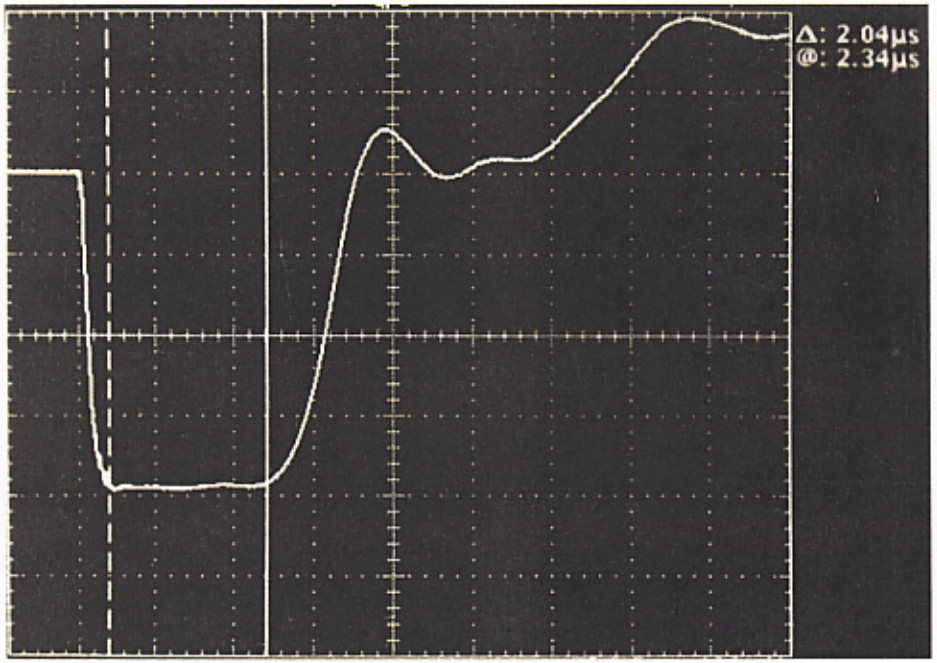


DARHT-2 PFN Spark Gaps and Capacitors

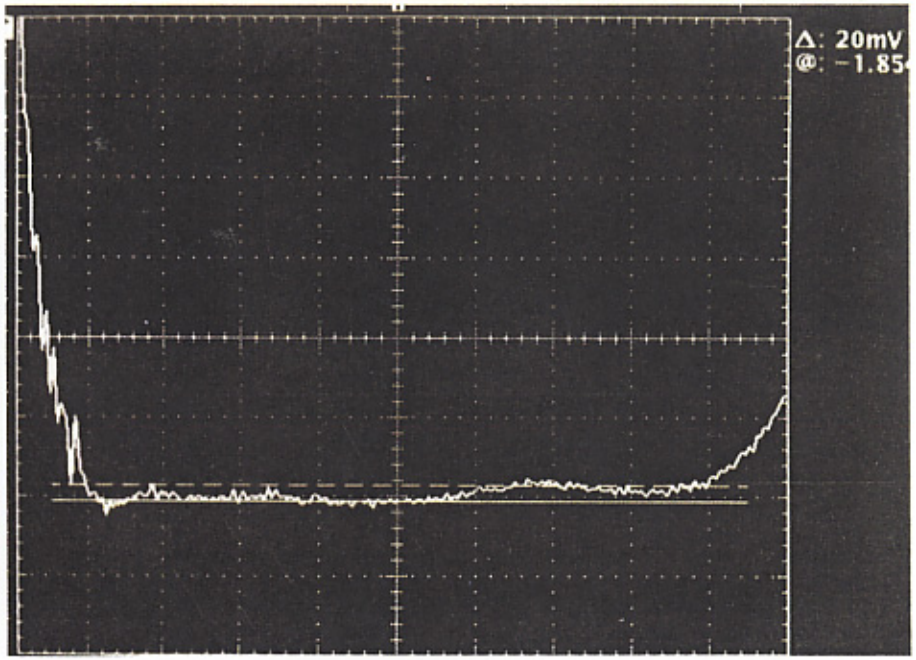
Four spark gaps are triggered simultaneously with a thyratron-switched pulse. These spark gaps are rated at 100 kV and have Schwarzkopf K33S (copper tungsten) electrode material to extend the lifetime to > 10^5 shots before maintenance is required.

The energy storage capacitors are rated at 40nF and 100 kV. Because of an impedance mismatch between the PFN and the cell, the capacitors will be charged to less than –90 kV to get the full –195 kV output, providing some safety margin in the capacitor lifetime (7.5×10^7 shots at 100kV for 90% survival).

Tuning Exercise



50kV/div
1us/div



10kV/div
250ns/div

Adjustments made to the Gibbs resistors and the PFN section impedances to attain +/-0.5% voltage regulation during flattop

Modulators for Heavy Ion Fusion

- The bulk acceleration waveforms can be provided with conventional pulsed power (PFN, PFL, MPC).

- Because precise waveforms are needed to apply longitudinal compression and to offset the effects of space charge on the beam head and tail, additional modulators are required which have agile waveform control based on a programmable input (AWG).

- Solid state modulators can be used for generating these precise waveforms as well as providing voltage regulation for shot-to-shot corrections (iterative feedback) and/or "feed-forward" corrections (slow ions). This method could correct for systematic and random variations in the beam energy.

Modulators for Heavy Ion Fusion

Requirements

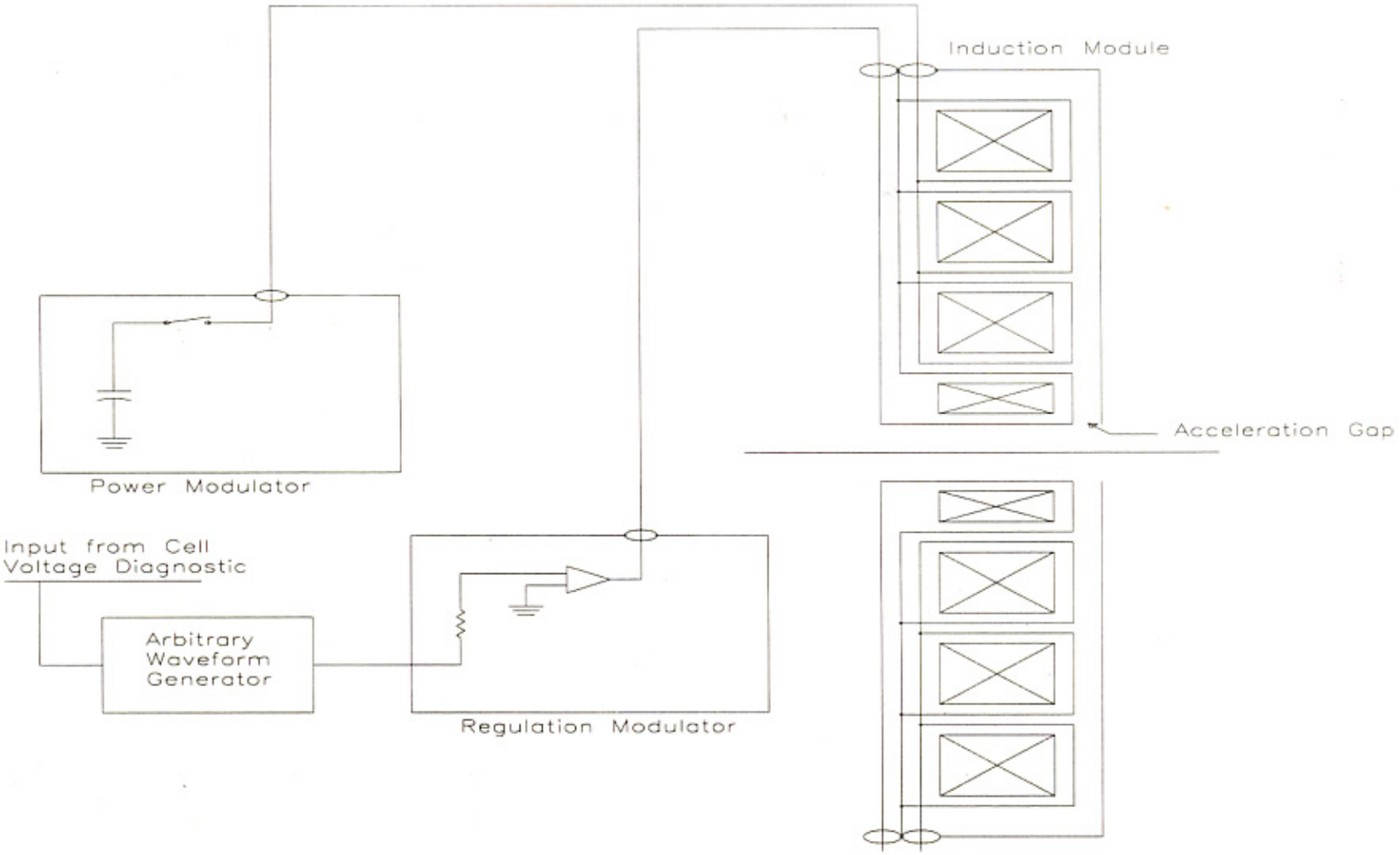
High peak power (driving core losses at up to 10T/us)

5-10 Hz repetition rate (high average power for power plant)

Agile waveform control (regulation and various pulse-shaping schedules)

Production cost $\leq$ 10^{-5}/W, $\leq$ $20/J (competitive cost of electricity)

Induction Module With Multiple Modulators



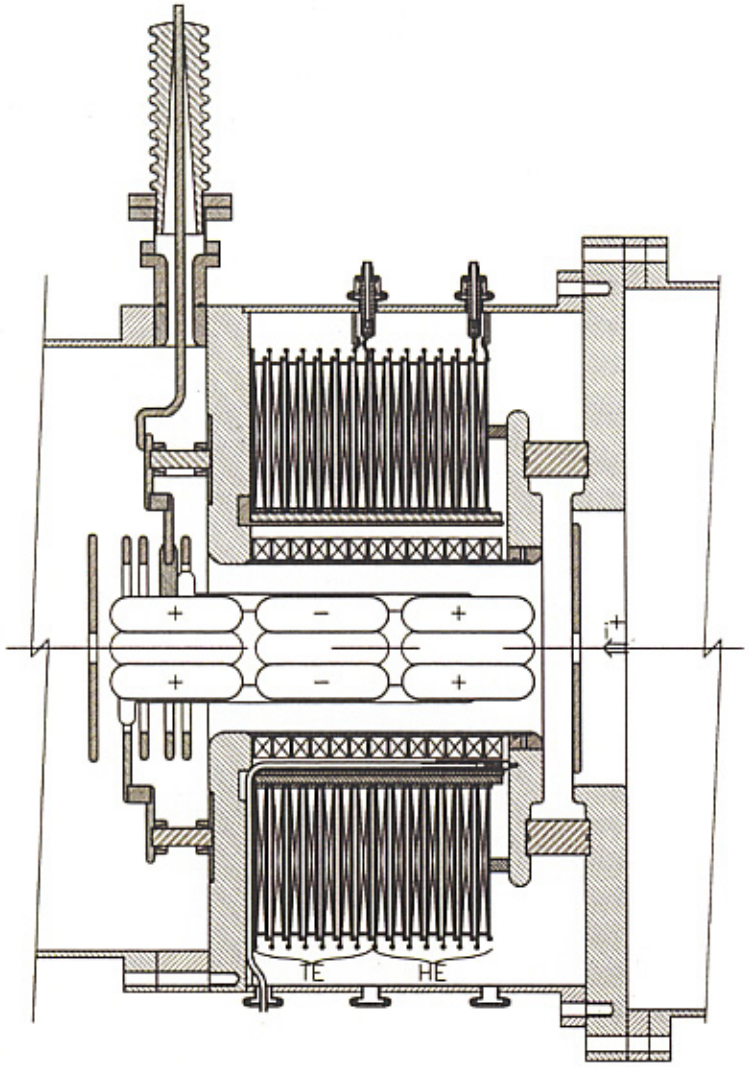
Bunch End Control Module from First Point Scientific (DOE-SBIR II)

Purpose : Apply agile control of the acceleration waveforms to correct for space charge field effects on the head/tail of the beam to provide longitudinal emittance control.

Deliverables : Complete system of induction modules and modulators for use on the 2MV Injector of the High Current Experiment at LBNL

- **Regulate up to 20kV variations during the beam flattop to within +/- 0.1% of the beam energy**
- **Generate +/- 200kV "ear" waveforms which will be actively regulated to within 3%**
- **Demonstrate a fundamental capability which the accelerator pulsed power system must have for a HIF driver**

First Point Scientific SBIR



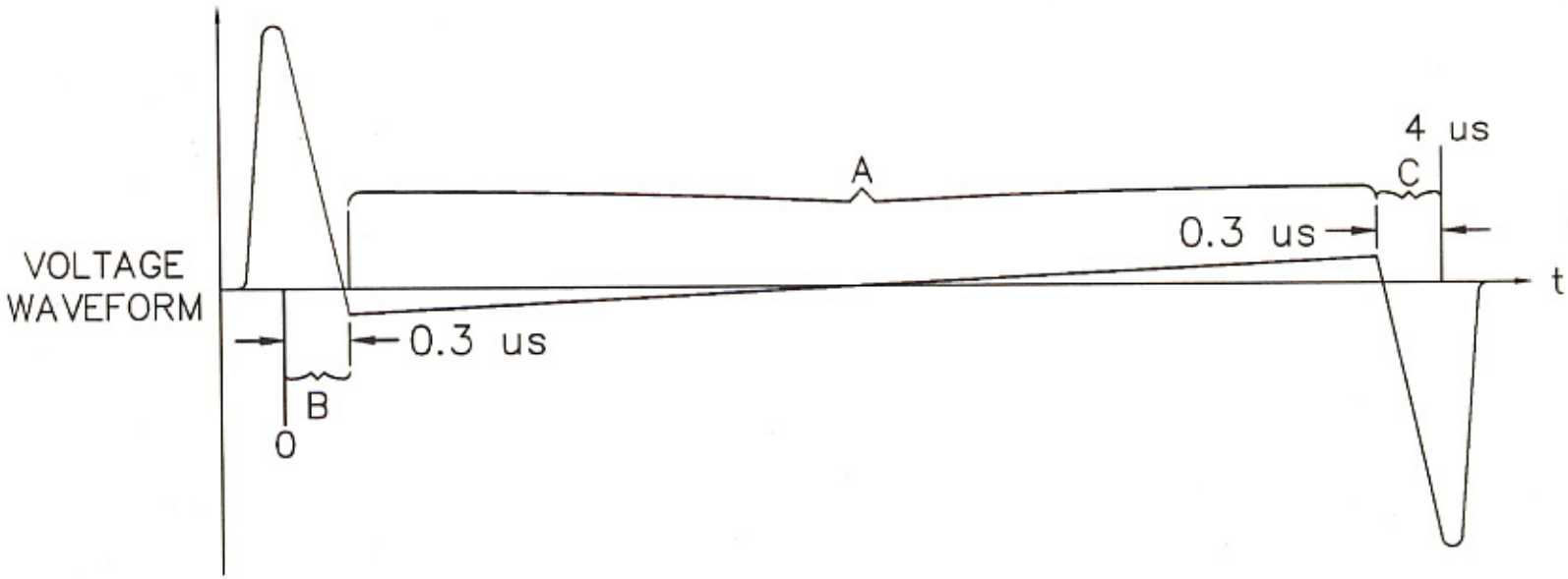
Induction Module

+/- 200kV Ear Modulators
(thyratron-switched lumped elements)

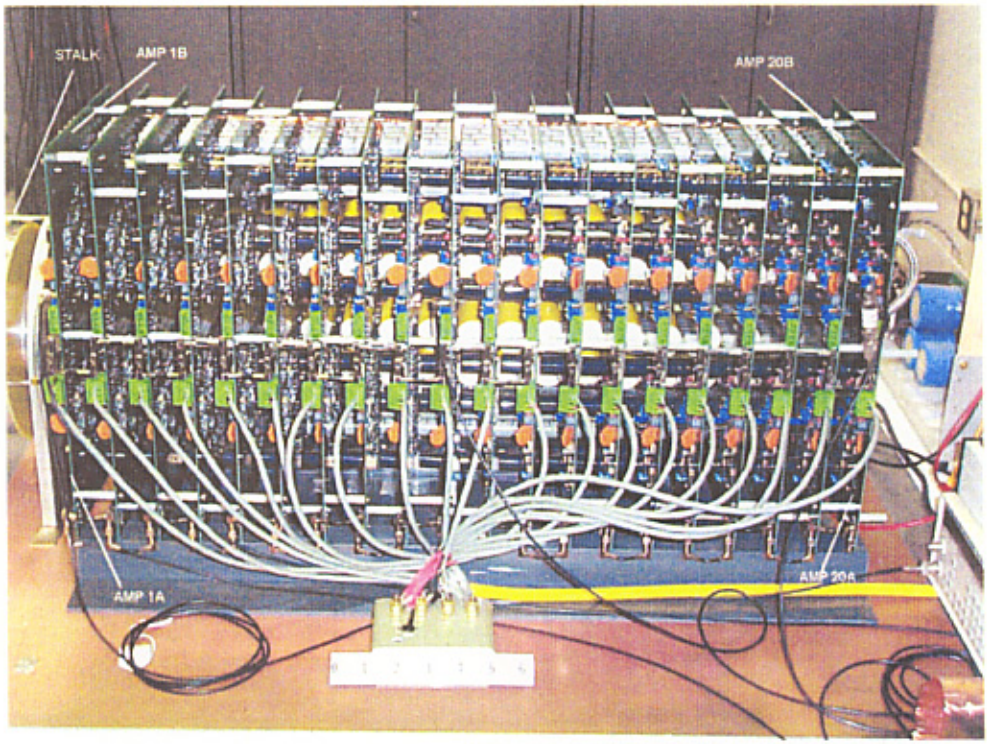
+/- 20kV Regulation Modulator
(MOSFET-based linear solid state amplifier)
400A
10MHz
4×10^{11} V/s

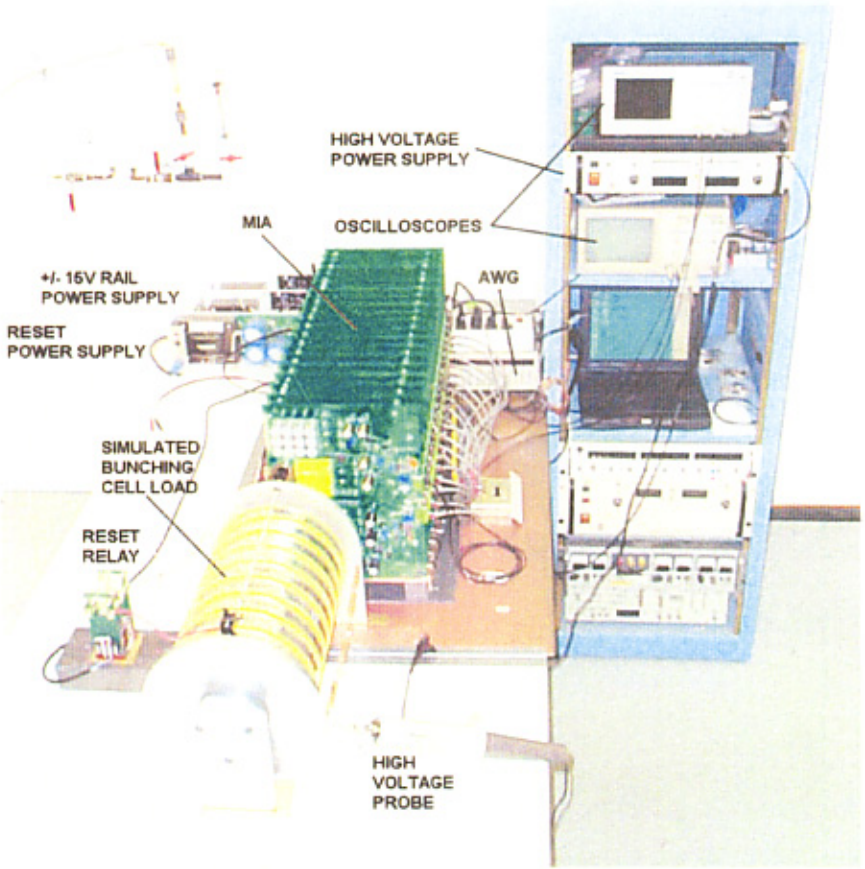
Bunch End Control Waveforms

Apply acceleration waveforms to correct for space charge field effects on the head/tail of the beam to provide longitudinal emittance control



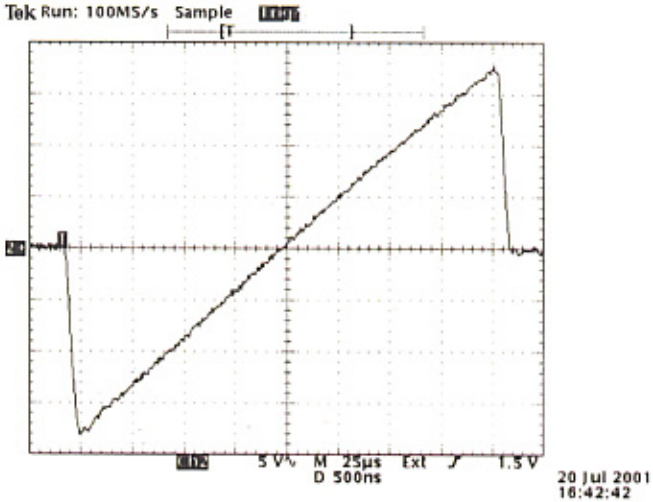
+/- 15kV Bunching Modulator from First Point Scientific

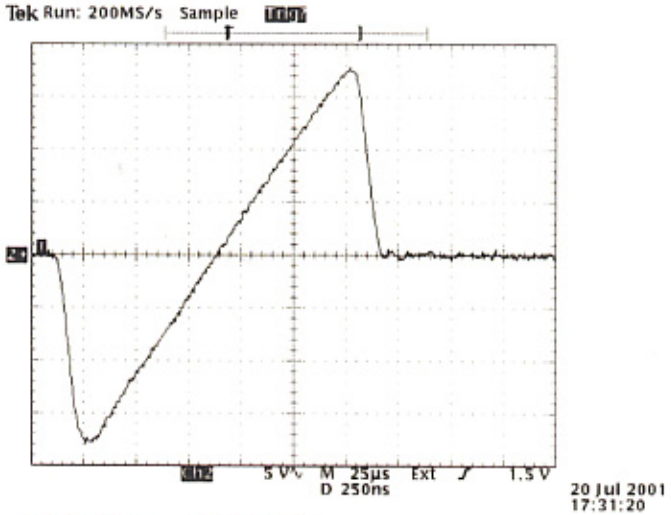


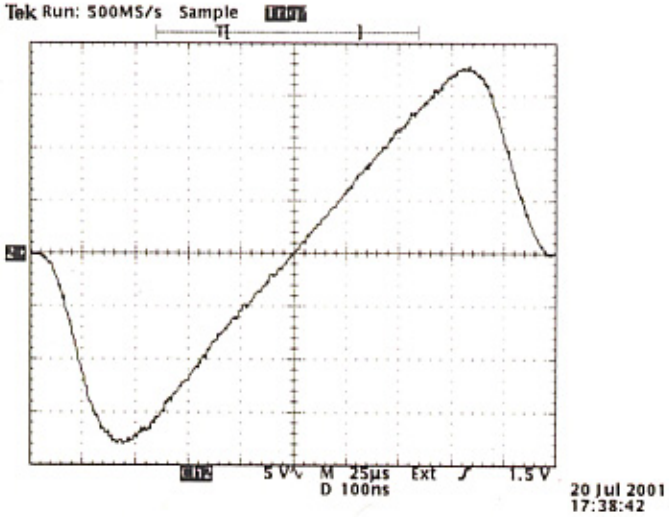


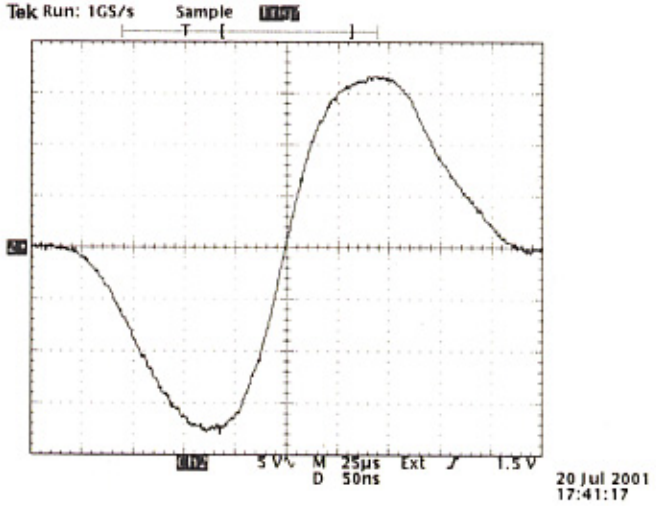
"Miniature Inductive Adder"

+/- 15kV Bunching Modulator from First Point Scientific

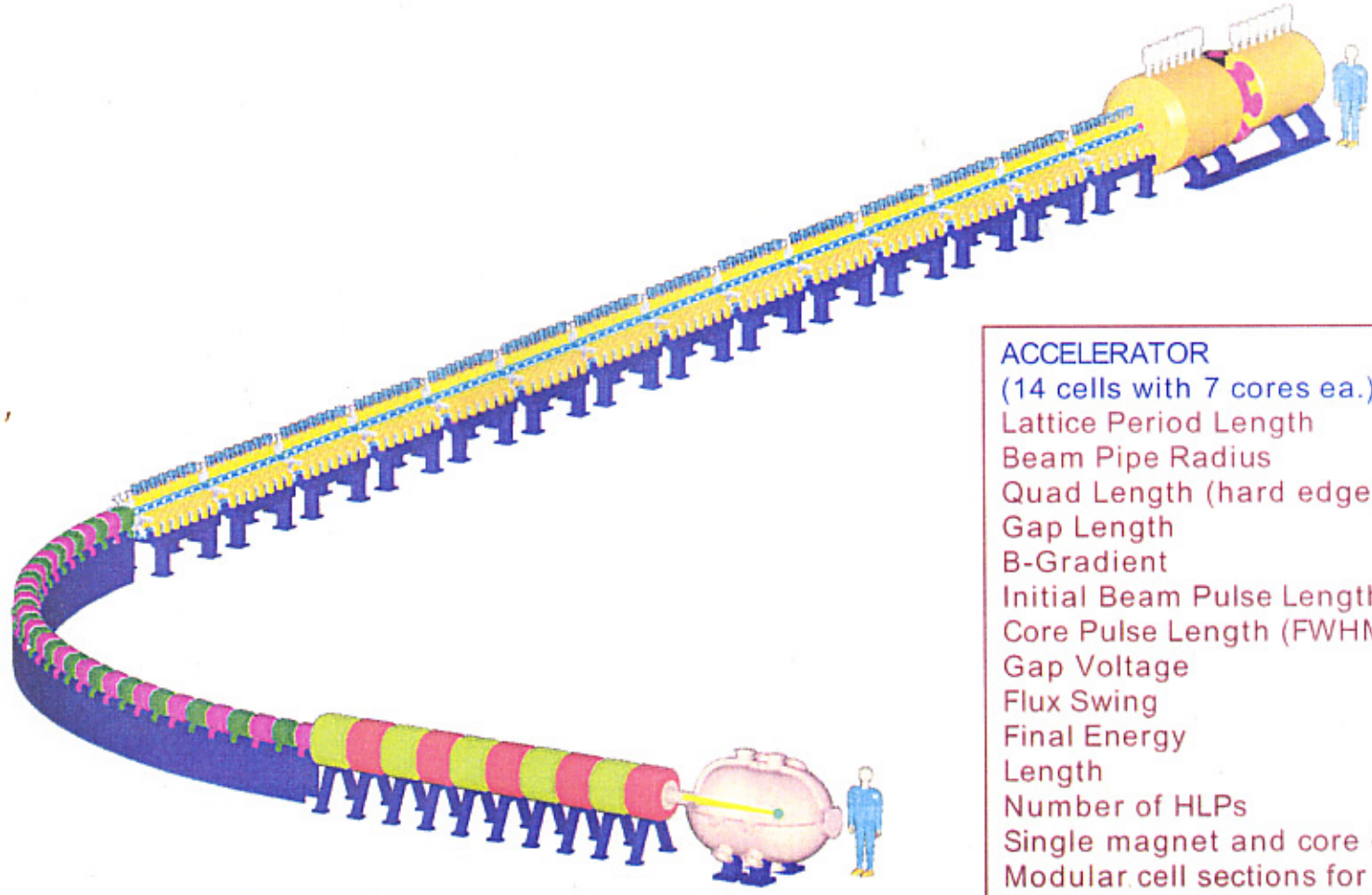








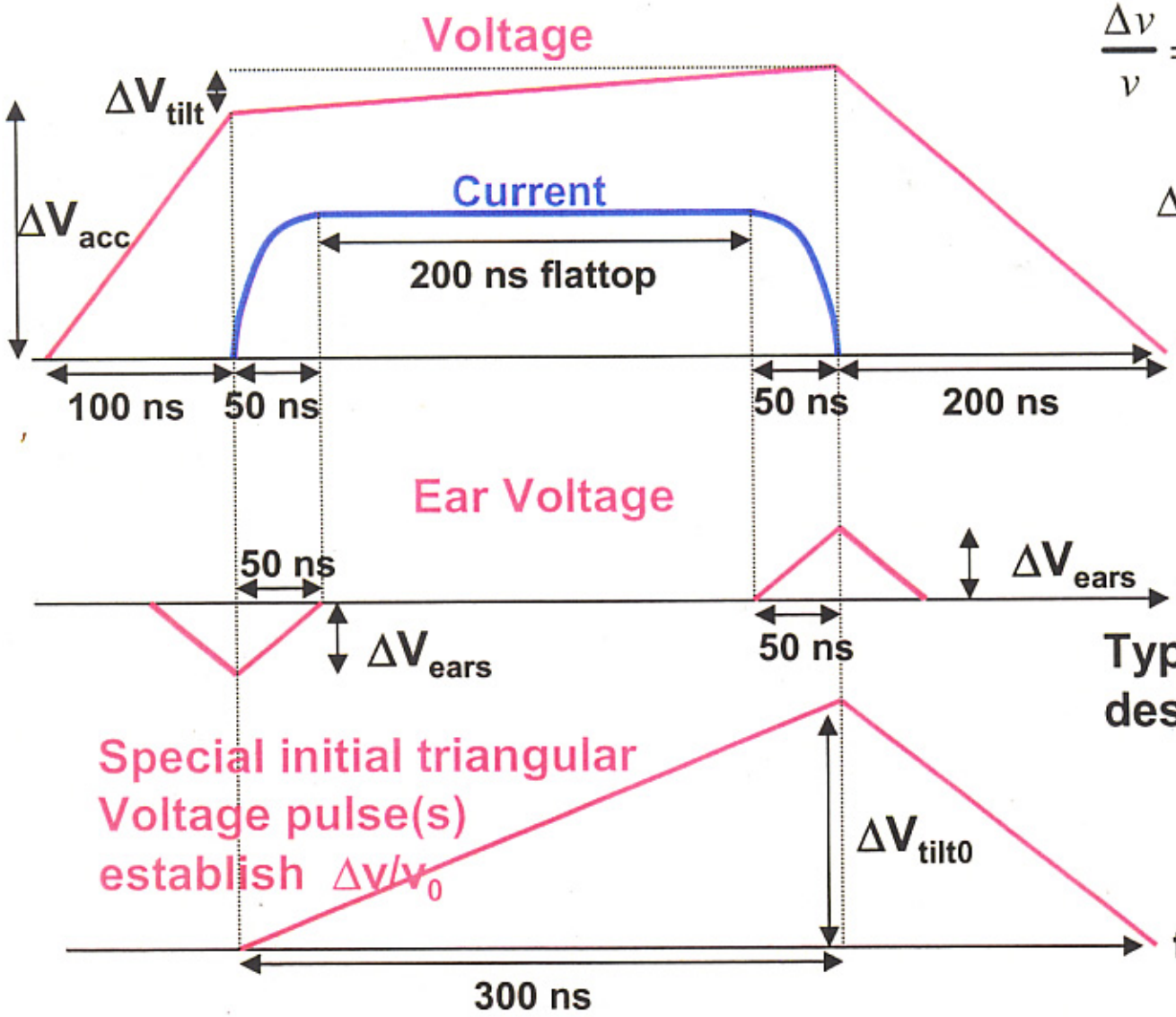
Integrated Beam Experiment



ACCELERATOR (14 cells with 7 cores ea.):	
Lattice Period Length	60 cm
Beam Pipe Radius	4 cm
Quad Length (hard edge)	13.5 cm
Gap Length	16.5 cm
B-Gradient	41 T/m
Initial Beam Pulse Length	250 ns
Core Pulse Length (FWHM)	500 ns
Gap Voltage	100 kV
Flux Swing	2.5 T/m
Final Energy	10 MeV
Length	40 m
Number of HLPs	108

Single magnet and core design
Modular cell sections for removal

Voltage and Current Wave forms



$$\frac{\Delta v}{v} = \frac{dV}{ds}\left(\frac{1}{V}\right)\left(\frac{1}{2} - \frac{V}{1}\frac{dl}{dV}\right)$$

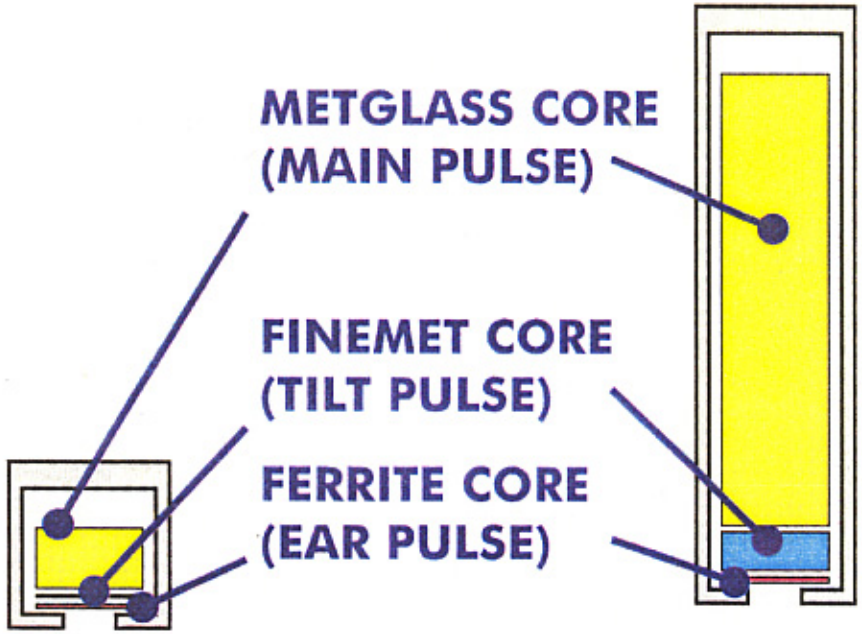
$$\Delta V_{tilt} = \frac{d(2V\Delta v/v)}{ds} L$$

$$\Delta V_{ear} = \frac{2g\lambda_{flat} L}{4\pi\varepsilon_0 \beta c \Delta t}$$

Typical numbers from design:

- ΔV_{tilt0} ~ 100 kV
- ΔV_{tilt} ~ 1 kV
- ΔV_{ears} ~ 14 kV
- ΔV_{acc} ~ 100 kV

IBX Induction Cell Designs



100 kV	200 kV
SC-magnet	SC-magnet
250 ns	1000 ns
Core ID=13.4 in	Core ID=13.4 in
Core OD=25.3 in	Core OD=89.6 in
Core Mass=180 kg	Core Mass=4400 kg

Conclusion

- Modulators for HIF need to be more flexible than the modulators for conventional induction accelerators

- The SBIR hardware from First Point Scientific will demonstrate a significant level of flexibility

- IBX could be the first opportunity to integrate conventional pulsed power and solid state amplifiers in an induction accelerator similar to what would be required for HIF drivers