CONF-9006176--4

THE COMPACT LINEAR ACCELERATOR PROGRAM AT SANDIA NATIONAL LABORATORIES*

SAND--90-0333C

DE90 013061

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Introduction

Sandia National Laboratories is currently investigating methods of producing long (several microseconds), high voltage (tens of megavolts), kiloampere electron beam pulse trains using compact linear accelerators. These machines will consist of many ferrite- or air-core cavities sized for operation at 200-250 kV with pulsewidths of 5-25 nanoseconds. A bipolar voltage waveform of 20-100 MHz frequency is required for each accelerator cavity. The electron beam is generated and accelerated during the negative half-cycle of the input waveform, while the positive half-cycle between accelerating pulses is used to reset the ferrite cores. The electron beam generated and accelerated using such a device, therefore, is actually a long train of very short beams.

At present, each cavity of our prototype accelerator (PTO) is driven by a ringing transmission line system of 5-10 ohm impedance. The core impedance (approximately 200 ohms/cavity) and the beam impedance (200 ohms during the negative half-cycle) combine to reduce the driving voltage by approximately ten percent each half-cycle. Also, cavity capacitance and the inductance of the cavity, feeds, and gas switches used in the transmission lines result in degradation of the input waveshape over successive pulses. These effects limit the number of 25 ns beamlets that can be effectively generated and transported through the PTO accelerator to two. Subsequent, lower-voltage, beams generated in the machine injector are outside the range of the accelerator focussing system and are lost to the beampipe walls.

In an effort to produce more, higher-fidelity drive pulses for a compact linear accelerator, we are now pursuing several modulator options that require fast (nanosecond), high-voltage (200-250 kV), kiloampere toggling switches. The switches or switching schemes under study include (a) photoconductive semiconductor switches, (b) the PULSATRON switch produced by Quantum Diagnostics of Hauppauge, NY, (c) a gated vacuum triode, and (d) a swept electron beam oscillator. We are also proceeding with a next-generation cavity design, that addresses many of the problems encountered with the PTO cavity (eg. gap capacitance, insulator flashover, focussing geometry, beam-breakup modes, etc.).

This paper will describe the original PTO design and results, the modulator experiments and results, and the next-generation cavity design.

*This work supported by the U. S. Department of Energy under contract DE-AC04-76DP0789, and SDIO.

The PTO Accelerator

The PTO accelerator[1], shown in Figure 1, is the first compact linear accelerator developed at Sandia to investigate the production of multiple electron beams with sub-microsecond separation between pulses. The accelerator consists of a four-stage injector and two post-injector accelerating stages. Each cavity is designed for operation at 200-250 kV, and uses ferrite cores for inductive isolation. The cavities are energized, from two feeds located 170 degrees apart in azimuth, through vacuum feedthroughs that use conical ceramic or plastic insulators as the barrier between vacuum and SF_6 gas.

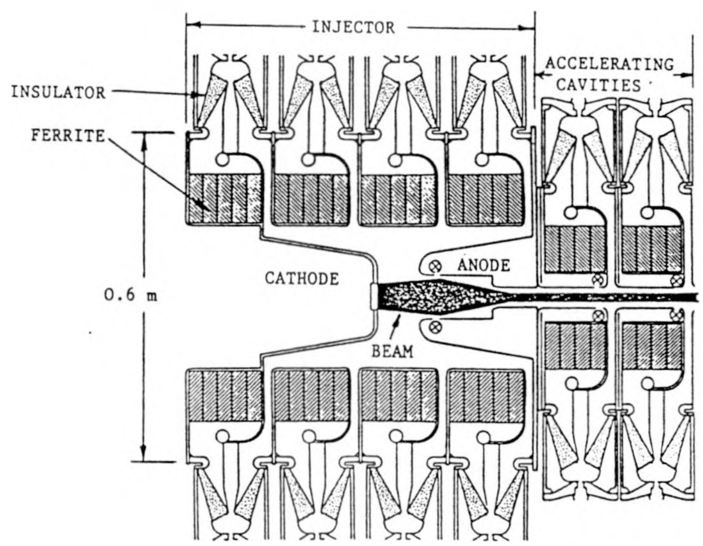

Figure 1. Cross-Sectional View of the PTO Accelerator

The accelerator is driven by a ringing transmission line circuit that uses pulse-charged water lines and self-breaking gas switches. This scheme, shown schematically in Figure 2, produces a short train of bipolar pulses that is used to generate up to four sequential electron beams in the accelerator injector. A four-stage 250-300 kV Marx generator is used in the PTO design to drive the twelve transmission line circuits, two for each accelerator cavity. The Marx generator is capable of charging the 40 ns transmission lines to 200 kV in approximately 200 ns. A self-breaking gas switch in each line then closes and launches a voltage wave (V/2 in amplitude) into the shorter, 12 ns long transmission line that connects to the cavity vacuum interface. At the cavity, this voltage wave doubles in amplitude and reflects due to the large mismatch between the 11 ohm transmission line and the parallel combination of the beam and ferrite impedances (> 100 ohms). The reflected wave returns to the gas switch area and overvolts two small gas gaps located between the high voltage center conductor and the

grounded outer conductor of the 12 ns transmission line, thus trapping the voltage wave between a high impedance (100 ohm cavity) and a short circuit. This results in reversal of the cavity voltage every 25 ns.

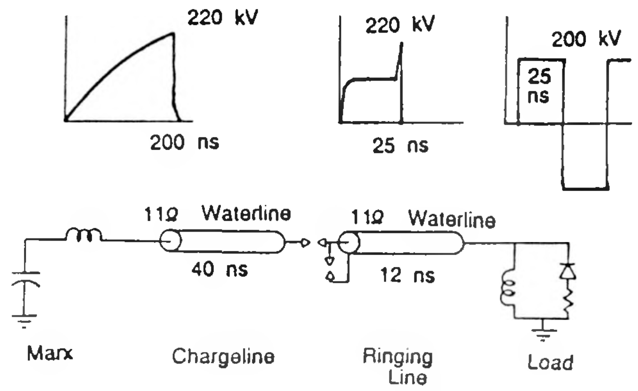

Figure 2. Schematic Representation of the PTO Ringing Transmission Line System

A typical voltage waveform on a single injector cavity is shown in Figure 3. Two non-optimum features of the waveform are immediately apparent: (1) the ratio of the peak voltage of the second and subsequent pulses to the peak voltage of the previous pulse is approximately 0.75, and (2) the rise- and fall-time of each successive pulse increases and the waveshape approaches that of a sinewave. The drop in peak voltage with each succeeding pulse is a result of the ratio of source (11 ohms) to load (133 ohms) impedance for each transmission line circuit; with each half-cycle of the ringing waveform, the absolute value of the peak voltage is reduced by approximately ten percent. The gradual smoothing of successive pulses is a result of switch and feed inductance, as well as the capacitance of the cavity. These two effects result in the rapid falloff of the accelerating pulse voltage, with the third pulse being only half the amplitude of the first.

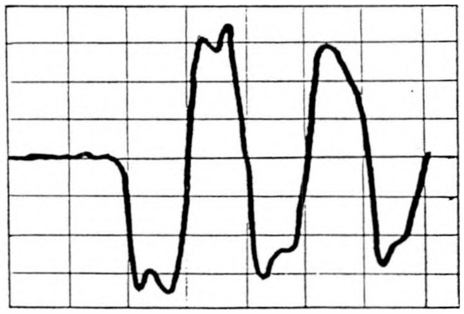

Figure 3. Typical Voltage Waveform for a Single PTO Cavity.

The e-beam generation and transport system consists of a Pierce-geometry velvet cathode and a group of solenoidal focussing coils located within the anode throat and along the beampipe in the accelerating cavities. This system has been shown both computationally and experimentally to result in 100 percent beam transport over a voltage range of 0.65 to 1.00 V_0, where V_0 is the nominal peak voltage of 0.8 MV in the injector. In Figure 4, the injector and accelerating cavities' voltages, as well as the injected and transported currents, are shown. It can be seen that all of the current in the first beam, and the current in the second beam corresponding to voltage above 0.5 MV, is transported through the entire accelerator length. Current generated at voltages below 0.5 MV is overfocussed and lost to the beampipe walls.

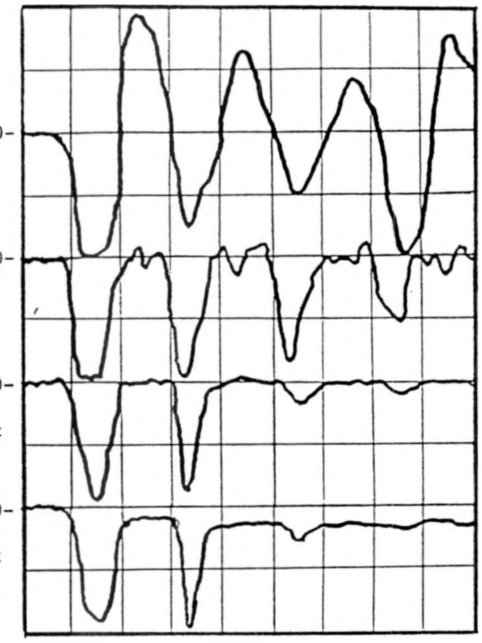

Figure 4. Summary of PTO Accelerator Voltages and Electron Beam Currents.

A crossed array of Faraday cups is used to measure the beam current density, in the first pulse, as functions of radius and axial position in the beampipe. Figure 5 summarizes these measurements and reveals a well focussed beam centered within 0.4 cm, with the beam radius varying between 0.5 and 1.5 cm while inside the beampipe. These results match well with theoretical calculations using trajectory codes such as EGUN and TRAJ.

DISCLAIMER

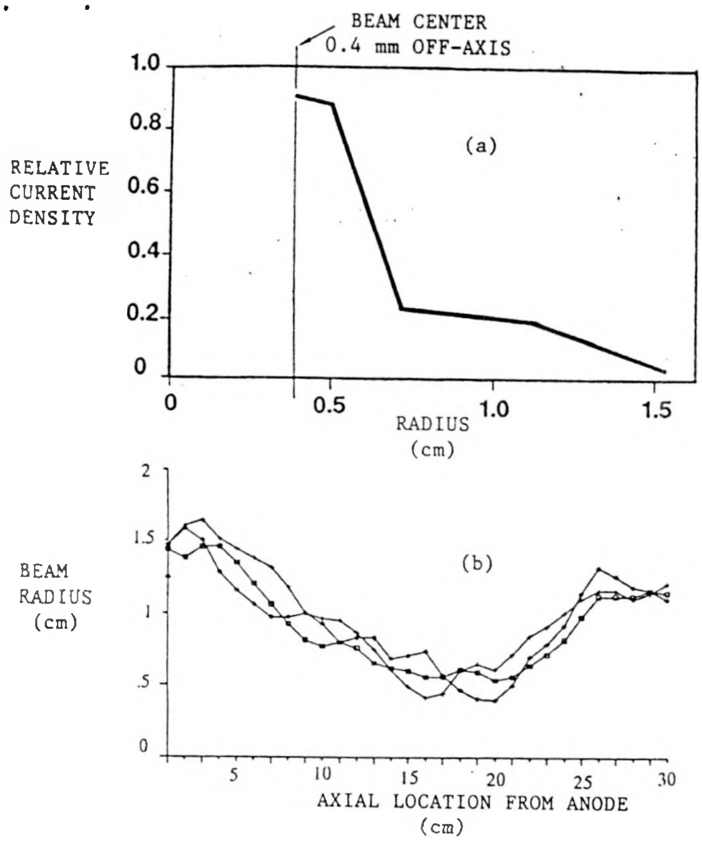

Figure 5. Radial (a) and Axial (b) Beam Profiles within PTO. The Radial Profile is Taken at a Focal Minimum.

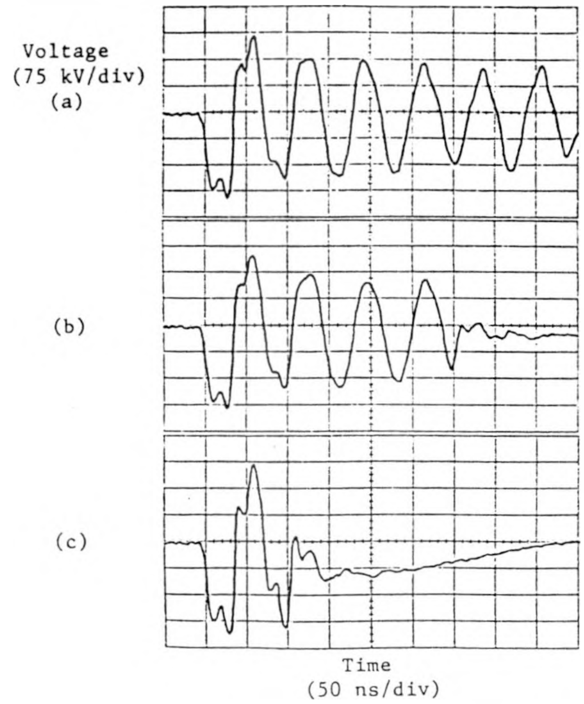

Figure 6. Cavity Voltages with 5 Ohm Transmission Line Feeds. (a)-No Breakdowns; (b) Insulator Flashover after Four Pulses; (c) Insulator Flashover after Two Pulses.

Attempts to increase the number of beams with energy in the 0.65-1.00 V_0 transportable voltage window of PTO have been unsuccessful. The approach taken to increase the number of pulses was to decrease the source impedance of the ringing transmission lines, from 11 to 5 ohms. The resulting waveform for a single cavity is shown in Figure 6(a), where four pulses are produced within the range of the accelerator's focussing system. However, the increase in the number of high voltage pulses amplified the frequency of flashover on the conical vacuum insulators. Figures 6(b) and 6(c) show insulator breakdown after four and two negative pulses, respectively. In 50-shot series on single insulators, the probability of a breakdown on one of the first three pulses was shown to be approximately 4 percent; this implies a probability of breaking down one of the twelve PTO insulators on a given shot of approximately 30-40 percent. Adding to the reliability problem is the fact that the self-breaking gas switches, used for synchronization of the twelve ringing transmission line circuits, have jitters of 3-5 ns, meaning that only one in five PTO shot attempts results in useful injector and accelerating cavity waveform synchrony. These two factors - insulator flashover and high switch jitter - combined to make PTO unreliable in producing more than two transportable beams. In May 1990, PTO was dismantled, and the emphasis of the Sandia effort shifted to developing a modulator for the next-generation accelerator.

MODULATOR INVESTIGATIONS

In order to generate multi-microsecond pulsetrains, a high-fidelity 20-100 MHz squarewave oscillator is required to drive the accelerator cavities. Concepts for generating the required waveshapes in a small package require toggling (i.e. opening and closing) switches that operate at a multi-megahertz frequency. The simplest circuits call for a multi-microsecond PFN that is switched on and off at the required frequency, and a voltage reversing system (typically a shorted PFN or cable) that provides the core reset action while the toggling switch is open. Sandia's compact accelerator program is currently investigating four potential switching technologies to meet the modulator requirements. These switch options are (1) the photoconductive semiconductor switch, which is discussed by Zutavern, et. al. at this conference[2], (2) a vacuum triode switch[3], (3) a scanned electron-beam oscillator[4], and (4) the PULSATRON, a travelling wave tube manufactured by Quantum Diagnostics of Huappauge, NY.

The photoconductive semiconductor switch (PCSS), as currently envisioned, consists of an array of Si or GaAs wafers stacked in series to allow voltage holdoff of up to 500 kV. In addition, wafer stacks would be paralleled to handle currents of several kA, allowing a single switch array to drive several accelerator cavities. Gold-doped silicon has been operated at electric fields of up to 35 kV/cm in the linear photoconductive mode, and switched the required kiloampere currents with approximately 30 ns recovery times. The amount of laser energy required to provide the carriers in these switches, however, is too high (1-10 kJ) to be practical in an accelerator system.

Investigations of GaAs have identified a mode of triggering (lock-on) which uses substantially less laser energy to close a switch, but requires reduction of the switch voltage, below a characteristic 'lock-on' threshold, to induce recovery. Such lock-on switches have been operated at up to 70 kV per centimeter of length, at current levels up to 1600 A per centimeter of width. In order to recover to a fully-insulating state, though, the voltage on the semiconductor must be reduced below the lock-on threshold for tens of ns. Methods of providing this voltage reduction, by generating circuit transients, as well as progress in measuring the recovery time, are subjects of Zutavern's paper presented at this Conference.[2]

One possible alternative to the PCSS is the vacuum triode switch, in which a modulated, bipolar grid voltage is used to turn a thermionic cathode on and off at the required 20-100 MHz frequency. The electron beam drawn from the cathode is accelerated through a vacuum gap and used to drive an accelerator cavity. Operating conventional cathodes at higher-than-rated temperature (corresponding to higher current density), and sacrificing the barium lifetime, is expected to result in a compact assembly that can meet the size requirements of the accelerator modulator. An experiment is in progress that will address the feasibility of this concept; major issues to be studied include plasma generation, grid spacing and transparency, anode heating, and maximum current density.

Another concept for producing the bipolar cavity waveforms is the scanned electron-beam switch, depicted in Figure 7. The approach to produce a bipolar voltage involves generating a multi-microsecond e-beam, accelerating the beam to the desired voltage (plus the diode voltage drop), and alternately deflecting the beam at the desired frequency onto two inverse diodes that direct the current in opposite directions through the load. Sandia is procuring hardware to test the concept using a rectangular, 2.5 cm X 15.0 cm thermionic cathode as the electron source. A 5 μs, 250 kV PFN will be used to drive the cathode. Again, the beam will be accelerated through a 200 kV potential, then electrostatically deflected onto inverse diodes connected to resistive loads. Issues to be studied in depth include collector heating, breakdown potential, and inverse diode efficiency.

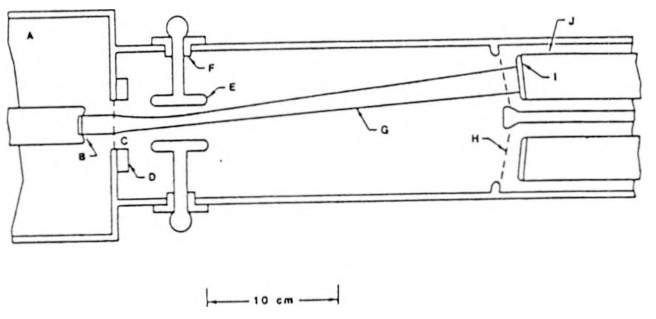

Figure 7. The Scanned Electron Beam Oscillator Concept. A-Vacuum Housing; B-Cathode; C-Anode; D-Tuning Lens; E-Deflector Plate; F-Signal Input; G-Sheet E-Beam; H-Inverse Diode Grid; I-Collector; J-Output Transmission Line.

The PULSATRON switch is a commercially available travelling wave vacuum tube advertised at 0.5 MV, 0.5 MA, with opening and closing times of approximately 1.0 ns. Sandia is currently investigating the performance of the switch in a test stand; the test setup utilizes a 20 MHz cable oscillator to drive the grid, and a 50-100 kV charged cable as the main source connected across the anode/cathode terminals. After demonstration of the required on/off performance is completed, the voltage and current switched by the tube will be increased to test the limits of the device.

NEXT-GENERATION ACCELERATOR DESIGN

The PTO accelerator was successful in identifying several design areas where improvement can be made in the next-generation machine. These include (a) the vacuum insulator, where the electric fields must be substantially reduced, (b) the cavity capacitance, which must be lowered in order to reduce the current-handling requirements of the switching arrays, (c) the injector voltage should be increased if possible, (d) the use of single or staggered feeds for cavities is possible, especially at beam voltages above 5 MV, and (e) more axial coverage of the beampipe with magnetic field coils is desirable. Several other features of PTO worked well and will be incorporated in the new accelerator. These include (a) the use of the Pierce geometry cathode, (b) the placement of the ferrite cores within the vacuum vessel, and (c) dual feeds for the injector.

The next-generation accelerator, called CASSANDRA, is depicted in Figure 8. Of note in the injector is the addition of another cavity, thus raising the injector voltage to 1.0 MV, while increasing the injector length by only 2.5 cm. This is accomplished by using four 2.5 cm thick ferrite slabs for each cavity, whereas PTO used five slabs. A larger diameter cathode and more field coils in the anode throat will be required to guide the beam into the beampipe. TRAJ code simulations of the CASSANDRA optics system are shown in Figure 9. The required 1 kA current is generated at 1 MV by using a Pierce cathode with a 3 mm indention, a 2.4 cm radius emitting area, and an 7 cm AK gap spacing. Also shown in Figure 9 is the B-field profile required to capture and guide the beam into the 1.9 cm beampipe. Further code runs are required to design the coils to produce the necessary field profile.

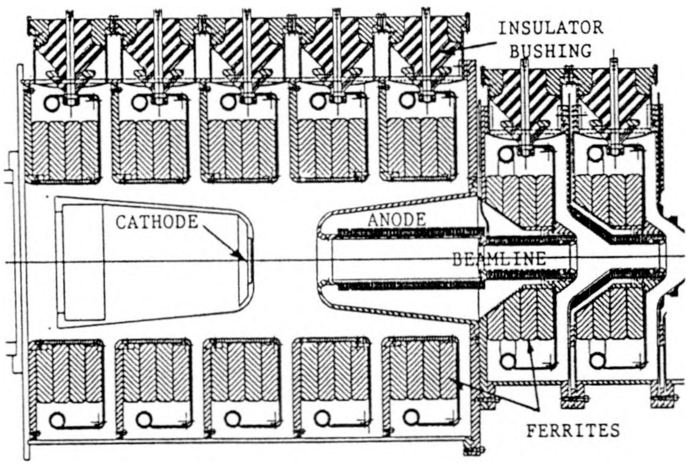

Figure 8. Cross-Sectional View of the CASSANDRA Accelerator.

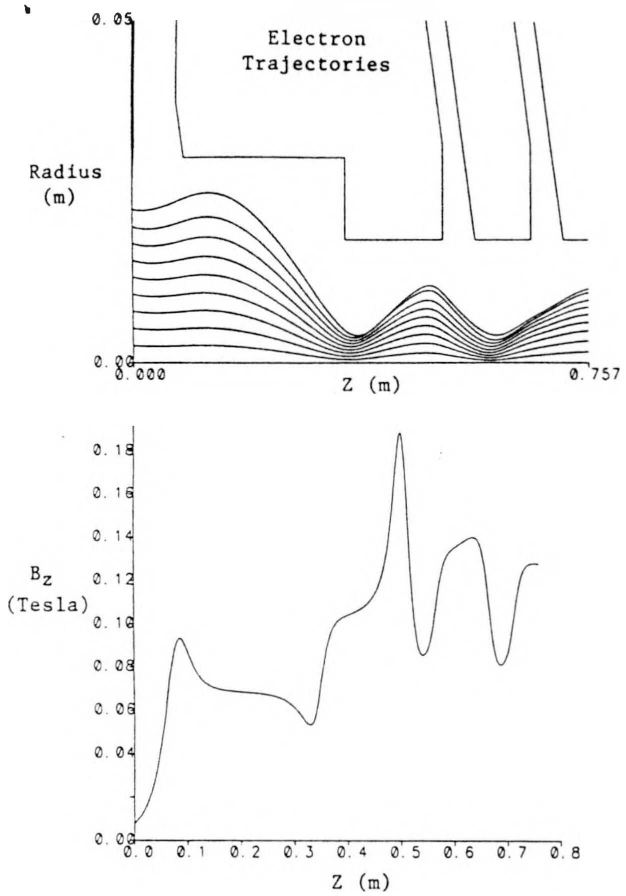

Figure 9. TRAJ Simulations of the CASSANDRA Injector and First Two Accelerating Stages. (a) Electron Trajectories; (b) Required Focussing B-Field.

The CASSANDRA accelerating cavities will incorporate an angled gap that allows the placement of B-field coils across the accelerating gap. In order to make room for the additional coils, the core size will be reduced approximately 20 percent, resulting in a maximum 200 kV pulsewidth for CASSANDRA of 20 ns. In addition, the angled gap is intended to direct BBU-inducing waves onto exposed microwave absorbing ferrite in the radial feed. Beam break-up calculations on the CASSANDRA accelerating cavity, using the AMOS computer code[5], are being conducted by G. Craig and J. Deford of LLNL. A single prototype cavity is being procured and will be used to (a) test the insulator bushing design, (b) measure and quantify the RF content (BBU) of the cavity, as verification of the AMOS calculations, and (c) investigate methods of reducing the Q of the BBU modes found.

Summary

Sandia's compact linear accelerator program is in a period of transition, shifting from experiments on the PTO accelerator to investigations of switch/modulator options for the next-generation accelerator (CASSANDRA). Information gathered from the PTO accelerator will be combined with prototype cavity experiments before completing the CASSANDRA design. Switch options for the 20-50 MHz modulator required for CASSANDRA have been identified; these include the photoconductive semiconductor switch, a gated vacuum triode, the scanned E-beam oscillator, and the commercially available PULSATRON.

References

1. K. T. Lancaster, et. al., Proc. 6th IEEE Pulsed Power Conference, pp. 374-377, June, 1987.

2. R. J. Adler, North Star Research Corp. Tech. Report TR-040002, November, 1988.

3. S. Humphries, Jr., IEEE Trans. Plasma Science, PS-15, p. 772, 1987.

4. F. J. Zutavern, et. al. 'Recovery of High Field GaAs Photoconductive Semiconductor Switches', 1990 Power Modulator Symposium, to be published in Proceedings.

5. J. F. DeFord, et. al., Proc. 1989 IEEE Particle Accelerator Conf., pp. 1181-1183, March, 1989.