PRELIMINARY PBFA II DESIGN*

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Abstract

The upgrade of Sandia National Laboratories particle beam fusion accelerator, PBFA 1, to PBFA II presents several interesting and challenging pulsed power design problems. PBFA II requires increasing the PBFA I output parameters from 2 MV, 30 TW, 1 MJ to 4 MV, 100 TW, 3.5 MJ with the constraint of using much of the same PBFA I hardware. The increased PBFA II output will be obtained by doubling the number of modules (from 36 to 72), increasing the primary energy storage (from 4 MJ to 15 MJ), lowering the pulse forming line (PFL) output impedance, and adding a voltage doubling network.

A prototype accelerator, called Supermite, is being fabricated for use in the development and testing of PBFA II components. Supermite tankage will accommodate four PBFA II modules. However, only one is initially used for research and development. In Supermite, a 208 kJ Marx generator charges a water insulated transfer capacitor which in turn charges four water insulated pulse forming lines through a triggered gas switch. The self closing PFL output switches feed the 1.25 MV power pulse into a pulse conditioner which increases the voltage to 4 MV at 400 kA.

Details and data from the module development program and an analysis of the effects of component and module jitters on PBFA II output parameters will be presented.

Introduction

Sandia National Laboratories particle beam fusion accelerator, PBFA I, shown in Fig. 1 will be operational in July 1980. The 2 MV, 30 TW, 1 MJ accelerator consists of 36 modules housed in a 100 foot diameter tank. The 16 foot wide outer section is oil insulated and contains the Marx generators. The 14 foot wide water insulated section contains the intermediate storage capacitor, SF_6 trigatron switch, pulse forming network, and vacuum interface. The final inner section of the machine contains the magnetically insulated vacuum transmission lines and the diodes.

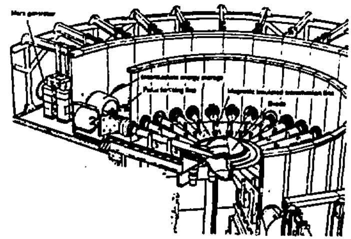

Fig. 1. PBFA 1 accelerator.

Originally the upgrade of PBFA I to PBFA II was to have been the simple addition of 36 more PBFA I modules to the accelerator. These were to be included as a second layer of modules, above the existing modules. The output parameters would just be twice those of PBFA I or 2 MV, 60 TW, 2 MJ.

The rapid progress that has been made in exploring the ion option[1] for PBFA has shifted the emphasis from having an electron output to an ion output. The decision to make PBFA II a light ion accelerator allows a more powerful accelerator to be produced. Target and ion focusing requirements make increasing the output voltage from 2 MV to 4 MV advantageous. This increased voltage allows the accelerator output to be increased from 60 TW to 100 TW with the same reliability from the pulsed power and power flow technologies that we have in PBFA I.

In addition to doubling the number of modules, the upgrade to 4 MV, 100 TW will require increased energy storage in the Marx generators, twice the number of pulse forming lines per module, and the development of a voltage multiplying transition between the output switch and the vacuum insulator. Constraints imposed by size and space limitations and in self breakdown water switching prevent the formation of the 4 MV pulse at earlier stages in the machine. The upgrade must be accomplished within the PBFA I tankage and, to reduce cost, as much as possible of the PBFA I hardware should be utilized. Low system jitter with high reliability must also be maintained.

To facilitate the necessary research, development, and testing for PBFA II, a machine called Supermite, shown in Fig. 2, has been constructed. The Supermite tankage is a 20° sector of the PBFA tank which can house up to four accelerator modules. Development and testing of PBFA II designs and components will be performed on one or more of the Supermite modules. The full four module capability will later be used as a demonstration of the engineering design of the PBFA II system.

Marx Generators

The present Marx generators used on PBFA I store insufficient energy for the PBFA II upgrade. Capacitors with energy greater than the presently used 0.7 µF, 100 kV, 3.5 kJ units are required. Commercial suppliers are able to produce capacitors with an increased energy, 6.5 kJ, and similar voltage in the same size can as the PBFA I capacitors. Use of these capacitors increases the Marx generator energy by 86 percent from 112 kJ to 208 kJ or 15 MJ total for the 72 PBFA II Marxes.

Tests of two Marx generators using the 6.5 kJ capacitors have begun on the Mite[2] and Supermite facilities. While lifetime and reliability data have not been obtained, the Marx generators have passed full power and voltage tests. Figure 3 gives the equivalent circuit obtained during the Marx generator tests.

Figure 4 shows a cross sectional view of the PBFA tank with two levels of Marx generators installed. The inductances of the high voltage connections from the Marx generators to the oil/water interfaces are different for the two positions. This will cause different charging times of the two intermediate storage capacitors. A compensating inductor must be

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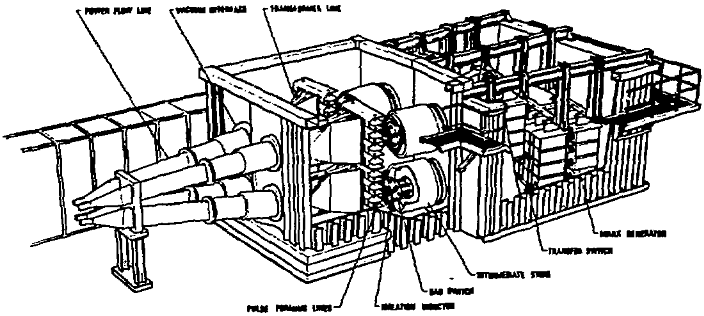


Fig. 2. Supermite, PBFA II research and demonstration module.

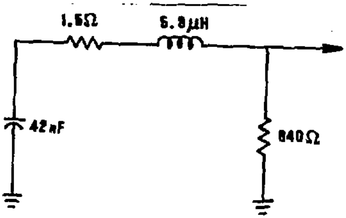


Fig. 3. PBFA II Marx generator equivalent circuit.

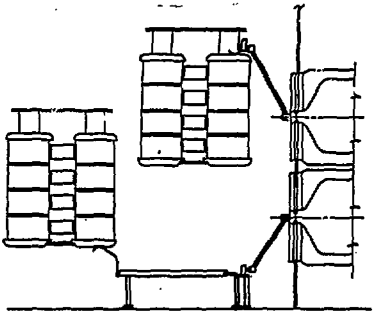


Fig. 4. Cross section of PBFA II Marx tank.

inserted in the upper charge feed to equalize the charging times. This overall increased charge time due to the added inductance and increased Marx generator capacitance is expected to reduce the hold off strength of the interface and water capacitor to 93 percent of the PBFA I value.

Circuit Calculations

Circuit calculations of the Marx to intermediate store to pulse forming lines charging circuit were made using the SCEPTRE[3] circuit analysis program. The circuit used is shown in Fig. 5. A 1.5 μH inductance was used for the Marx generator high voltage feed and a 0.6 μH inductor represented the inductance of the gas trigatron and feed to the pulse forming lines. The shunt resistances across the water capacitor and pulse forming line capacities are consistent with 2 MΩ-cm water.

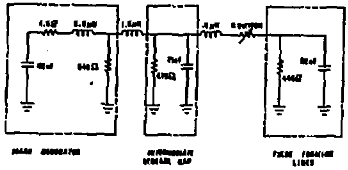


Fig. 5. Circuit used in SCEPTRE simulation.

Table I shows the results of the circuit calculations for various switching times of the trigatron switch. The peak voltages and energies on the pulse forming lines are relatively insensitive to switching times from 0.7 to 1.0 μs. Early switching times would be advantageous to reduce the time the voltage is across the intermediate storage capacitor.

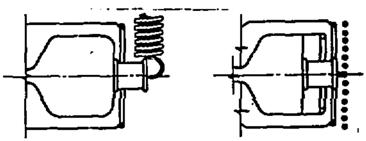
TABLE I

Results of SCEPTRE Circuit Calculations

Switching Time (µs)	Voltage on Intermediate Store (MV)	Voltage on Pulse Forming Lines (MV)	Charging Time of Pulse Forming Lines (ns)	Current thru Gas Switch (kA)
0.6	2.59	3.65	300	452
0.7	2.33	2.93	275	510
0.8	2.55	3.06	265	549
0.9	2.8	2.96	256	555
1.0	2.89	2.93	264	552

4 MV Pulse Forming Network

To provide as much room as possible in the 14 foot long water section to achieve the required 4 MV, a modification to the PBFA I intermediate storage capacitor was designed and fabricated. Figure 6a shows the original (PBFA I) capacitor/trigatron/inductor geometry and Fig. 6b shows the new geometry. The inductor which provides the trigger pulse to the trigatron switch was changed from a helical coil to a flat spiral. Equipotential field plots from the Jason[4] computer code show only slight differences in the voltage grading across the trigatron switch for the two geometries. An additional 2 feet of length was gained by this modification.



(a) (b)

Fig. 6. Water capacitor and gas switch.
a. PBFA I
b. PBFA II

Convoluted, water dielectric transmission lines have reduced prepulses, provided pulse-forming-line stacking in parallel, and reversed the output polarity in high current accelerators.[5] A new convolute design stacks lines in series to provide the accelerator voltage gain required for PBFA II. Experiments on a scale model have demonstrated the feasibility of the concept.

Flat plate pulse forming lines provide equal and oppositely directed fields when switched into two back-to-back transmission lines. If one side of the line has a polarity reversal convolute, as shown in Fig. 7, the electric fields of the two waves (top and bottom) will be in the same direction and a traveling voltage wave of twice the amplitude and impedance will be transmitted from the convolute.

An experiment was designed for Mite to check the efficiency of wave additions with triplate, water-dielectric lines. The initial pulse forming lines provide a two sided, 1.5 MV, 0.8 TW, 40 ns output into the transmission lines. One side of this output was inverted and both sides were transformed to higher voltage and impedance and then added. The convolute, Fig. 7, was one meter long. Resistive loads were connected directly across the high voltage terminals

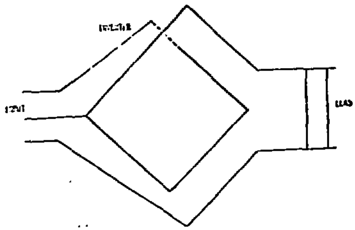


Fig. 7. Convolute for reversing polarity and stacking transmission lines.

and the accelerator load line, shown in Fig. 8, was determined. The output impedance of the pulse forming network was 10-Ω.

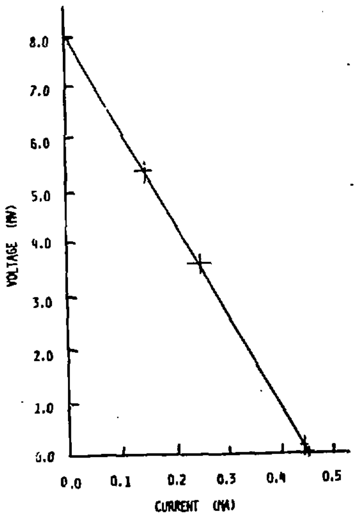


Fig. 8. Load line from convolute.

The voltage multiplication from 1.5 MV to 4 MV was accomplished with nearly a 100 percent peak power efficiency. This concept of inverting and stacking and introducing impedance mismatches has been incorporated into an experimental pulse conditioner. Low voltage, model tests of a similar pulse conditioning network for application to PBFA II have been completed. Figure 9 shows the geometry of the network. The transmission lines are vertical flat parallel plates driven by horizontal triplate pulse forming lines at the input end with the output ends connected in series. The output voltage is thus the sum of the voltage in each of the transmission lines. The series lines were terminated in a 2:1 impedance mismatch to achieve an additional voltage gain. Test results have shown an energy transfer efficiency of 61 percent, which is 86 percent of the efficiency calculated from a simple transmission line model that ignores parasitic, back impedance effects. The impedance mismatches in a PBFA II design are less than those in the low voltage tests so that energy efficiency is expected to be 71 percent in the PBFA II design.

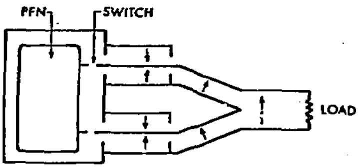


Fig. 9. Model of PBFA II pulse conditioning network.

Gas Switch Program

PBFA II places greater demands on gas switch performance than does PBFA I. Increased current and charge transfer capabilities with low jitter and greater reliability are required. While the present trigatron switch performance is adequate for initial PBFA I tests, this switch is not satisfactory for long term PBFA I or for PBFA II use. Proto II switching data show that after 30 to 100 shots, PBFA I type trigatrons degrade to unacceptable *simultaneity*. A gas switch research program has been initiated to develop a reliable, low jitter, long lifetime switch for the PBFA accelerators. The program includes material studies, investigations of breakdown processes in SF_6, *small and full scale testing of improved trigatron* switches and alternatives to trigatron switches. Two alternative switches are being investigated at Sandia. They are a laser triggered switch and an x-ray triggered switch.[6] In addition, switches under development by industry are being considered as alternatives to the trigatron.

The trigatron experiments are directed towards improving the reliability and lifetime of the trigatrons and, hence improving the performance of Proto II and PBFA I. Towards this goal, experiments on Hydramite, Supermite, and Proto II are planned. Erosion of *electrodes and degradation of switch jitter will be* measured using several different electrode materials. The trigatron geometry (e.g., hole and trigger pin sizes and shapes) will be varied in an attempt to reduce the increase in switch jitter caused by electrode erosion.

A 1 MV, transformer driven test stand will provide voltage to study the breakdown physics in SF_6 insulated trigatrons. A basic understanding of the breakdown processes should lead to improved trigatron design.

Successful experiments[7] by LLL on laser triggered switching of a SF_6 insulated gap using a few mJ KrF laser has prompted an investigation by Sandia into laser triggered switching for the PBFA Program. Studies of U.V. absorption, laser induced excitation, ionization, and their effects on the dielectric properties of pure SF_6, commercial grade SF_6, and SF_6 with selected trace additives are underway. In addition large scale testing on Supermite of a KrF triggered switch is also scheduled.

Vacuum Insulator and Power Flow Lines

The 4 MV, 10 Ω power pulse requires a new vacuum insulator section and modified power flow lines. A conceptual design for the vacuum insulator is complete and detailed field plots for determining the final design are underway.[8] Magnetic insulation at the higher voltage should be more efficient than it was at 2 MV because the vacuum gap between the electron flow and the positive conductor in a self-magnetically insulated transmission line increases with increasing voltage.[9]

Jitter Effect on Output Power

A statistical analysis of PBFA module simultaneity was performed and measured values of gas and water switch jitter were used to predict the output power from a 72 module system. Data from Mite[10] showed that the rms standard deviation in breakdown time of a single water dielectric switch was 6 ns. Each PBFA II module will have 16 of these water switches in parallel. The mean time to closure of the 16 switches was selected as the random variable to be used as the water switch closure time. The rationale for this *selection was that significant power would not begin* to flow from that module until half of the switches had closed. Each of the 16 switches were assumed to be *independent and normally distributed*. This assumption, while not entirely correct, is probably acceptable since the switches are transient time isolated from one another. The standard deviation of the mean time is then

$$\sigma_{mean} = \frac{\sigma_{one\ switch}}{\sqrt{16}}$$

The module output time is equal to the sum of the times to closure of the gas and water switches plus a fixed delay.

$$T_{out} = t_{gas\ switch} + t_{water\ switch} + t_{delay}$$

Measurements of the trigatron switch timing on Hydramite yielded ≈ 2 ns standard deviation for the gas switch time. *The standard deviation of T_{out} is then*

$$\sigma_{out} = \sqrt{\sigma_{gas}^2 + \frac{\sigma_{water}^2}{16}} = 2.5 \text{ ns}$$

The expected value of the range of firing time ($R = T_{last} - T_{first}$) for all 72 PBFA II modules is

$$E\{R\} = 4.78\ \sigma_{out} = 12 \text{ ns}$$

The effect of the module jitter was estimated using order statistics for 72 normally distributed random variables. A $\sin^2 \theta$ pulse with 40 ns FWHM was assumed for the output pulse from each module. Figure 10 shows the normalized output pulse. The amplitude was reduced by 1 percent and the pulse width increased by less than 1 ns.

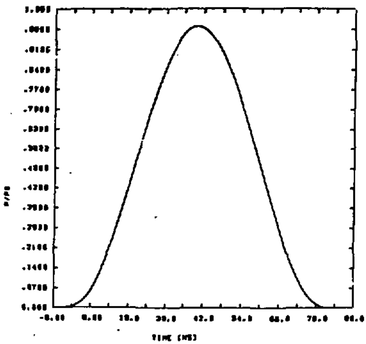


Fig. 10. Output of PBFA II with and without module jitter.

Summary

The conceptual design for the 4 MV, 100 TW PBFA II accelerator has been completed. The critical issues in the design have been identified and research programs are underway to address these issues. The results of these programs indicate that the conceptual design is a sound one and the project is currently on schedule.

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