DESIGN AND OPTIMIZATION OF THE PBFA II VACUUM INTERFACE AND TRANSMISSION LINES FOR LIGHT ION FUSION*

D. H. McDaniel, R. W. Stinnett, and E. W. Gray
Sandia National Laboratories, Albuquerque, NM
and R. E. Mattis, Cornell University, Ithaca, NY

Abstract

The PBFA II vacuum insulator was originally designed for optimum coupling to a proton ion diode with minimum inductance. In July 1983 it was decided that lithium ions at 30 MeV would be the baseline for PBFA II. This requires the use of Plasma Opening Switches (POS) and vacuum inductor to reach 30 MV. To achieve this, the vacuum magnetically insulated transmission lines had to be redesigned as an inductive energy store. To gain optimum coupling to this vacuum inductor, the output impedance of the water section was increased by the use of a water-dielectric transformer. The calculations leading to the final design will be discussed.

Introduction

The PBFA II project began in July 1981.[1] The baseline configuration was for an accelerator that would deliver 100 TW to a proton ion diode at 7.5 MV. Flexibility had to be maintained in the design since the optimum ion for driving ICF targets with PBFA II was not known. Due to the long lead time needed to procure the Vacuum Insulator Stack (VIS), the design of this component and the Magnetically Insulated Transmission Lines (MITLs) began in October 1982. In July 1983 it was decided that lithium ions at 30 MeV were the optimum ions for driving ICF targets with PBFA II.[2,3]

Initial Configuration

The PBFA II accelerator consists of 36 coaxial modules arranged in four layers of nine modules each. Each of these modules divides into two parallel plate transmission lines. This provides flexibility in the output configuration of the accelerator. Alternate parallel plate lines have a voltage inverter, which allows the output of a pair of lines to be added in series. Each layer of this series arrangement was combined in parallel with another layer to drive a single ion diode. This was the configuration for both the top and bottom half of the accelerator. Figure 1 illustrates the intial design. This resulted in an effective output impedance of .23 ohms driving a 25 nH diode at an equivalent matched load voltage of 6 MV. The VIS configuration for one layer of the accelerator is shown in electrostatic field plot in Fig. 2.

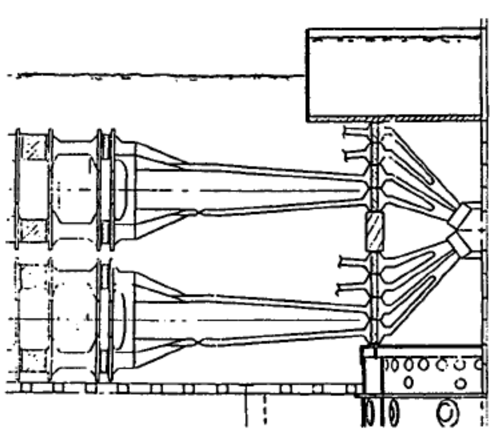

Figure 1. Initial configuration of the PBFA II accelerator.

*This work supported by the Unites States Department of Energy under Contract number DE-AC04-DP00789.

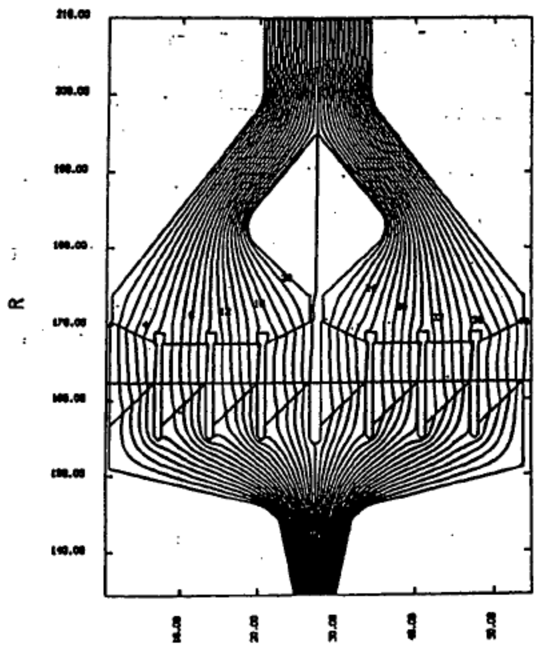

Figure 2. Electrostatic field plot of the vacuum insulator region for the initial configuration of the PBFA II accelerator.

Optimization of Accelerator Coupling

In July of 1983 the choice of Lithium as the optimum ion for ICF meant that the water insulated voltage adding section had to be changed and another stage of voltage gain and pulse compression was needed. The approach taken to achieve this was to store the accelerator energy in a vacuum inductor and use a Plasma Opening Switch (POS) as a means of transferring the energy to the diode load. The POS is being developed in a joint program between Naval Research Laboratories and Sandia National Laboratories.[4,5] It is desired that the ion diode load operate at five ohms. Criteria for the design of the MITL feeding the load set the free space impedance of the feed at 7.4 ohms.[6] To be more conservative, since the interaction between the POS and the MITL at these voltages is not understood, we chose 10 ohms to be the free space impedance of the MITL. The mean transit time from the POS to the transition of the MITL with the VIS is 5.5 ns. Hence the inductance of the MITL section is 55 nH. The transition from the MITL to the VIS adds an additional 16 nH. Hence the total vacuum inductance is 71 nH. There existed, at this time, a strong desire to make the minimum amount of change to the VIS design as it coupled to the MITL and the water section. Using the original design for the VIS there was 12 nH in the plastic insulators and approximately 32 nH in the water section. Hence the total inductance was 104 nH with 68% in the vacuum.

To gain the greatest benefit from the final pulse compression stage with the POS, we would like to begin with the maximum amount of energy stored in the vacuum inductor. A simple analysis using of a square wave, of duration τ, charging a vacuum inductor L through a transmission line, of impedance Z, shows that 83% of the forward going energy can be stored in the inductor when $L/Z\tau = 0.78$. A similar analysis can be done for

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1985	**N/A**	-

4. TITLE AND SUBTITLE
Design And Optimization Of The Pbfa II Vacuum Interface And Transmission Lines For Light Ion Fusion

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Sandia National Laboratories, Albuquerque, NM

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
The PBFA II vacuum insulator was originally designed for optimum coupling to a proton ion diode with minimum inductance. In July 1983 it was decided that lithium ions at 30 MeV would be the baseline for PBFA II. This requires the use of Plasma Opening Switches (POS) and vacuum inductor to reach 30 MV. To achieve this, the vacuum magnetically insulated transmission lines had to be redesigned as an inductive energy store. To gain optimum coupling to this vacuum inductor, the output impedance of the water section was increased by the use of a water-dielectric transformer. The calculations leading to the final design will be discussed.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT	b ABSTRACT	c THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

an arbitrary wave shape. To define τ the following equation is used:

$$\tau = [\frac{V_2 dt]^2}{V^2 dt}$$

For the PBFA II waveshape, Fig. 3, τ = 75.68 ns. The curves for the coupling efficiency of a pulse-forming line charging an inductor for the case of the actual waveshape of PBFA II is shown in Fig. 4. For the PBFA II waveshape the voltage across the inductor normalized to the matched load voltage can also be calculated. Referred to as the overshoot factor, this has the value of two for inductors that are equivalent to an open circuit and it is also shown in Fig. 4. The value of $L/Z\tau$ for our intial configuration was 1.43. Hence using the simple circuit analysis we see that only 64.5% of the forward-going energy would be coupled to the inductor and the overshoot would be 1.62 .

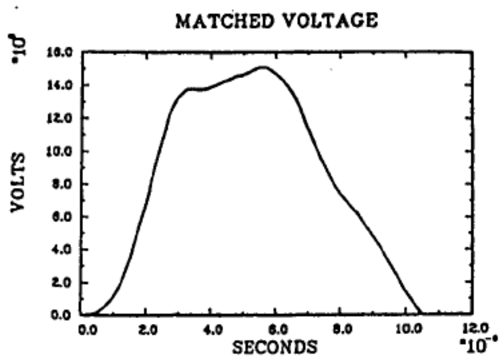

Figure 3. PBFA II forward-going voltage waveshape.

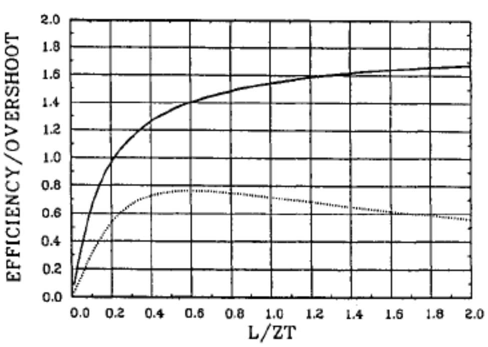

Figure 4. Coupling efficiency and Overshoot factor for charging a vacuum inductor with the PBFA II waveshape.

For PBFA II the pulse shape of the initial configuration is fixed. Because of MITL criteria, the amount of inductance within the VIS is also fixed. Hence the only free parameter that is available for optimization is the effective impedance of the accelerator. As we increase the output impedance, which can be done by a transformer in the water section, the value of $L/Z\tau$ is decreased. This results in a higher coupling efficiency and reduces the overshoot factor. The reduction in the overshoot factor helps to offset the increase in voltage that would arise with an impedance transformer. By increasing the gap in the water lines to the full height of an insulator section, the output impedance of the accelerator is increased by a factor of three. Since the voltage at the output of the transformer increases as the square root of the ratio of the gap spacing and the electric field is proportional to voltage divided by the gap spacing, the electric field on the water side of the VIS decreases by the square root of the ratio of gap spacings. The amount of inductance that is effectively on the water side of the VIS also decreases. This further lowers the value of L and at the same time improve the fraction of the inductance inside the VIS. This all helps to maximize the energy stored in the vacuum inductor.

To model PBFA II adequately, a circuit code was developed which includes the effects of the water section as transmission lines, electron losses in the MITL, vacuum insulator flashover, the POS, and the ion diode load. The effects on the insulator voltage and energy into the vacuum inductor are shown in Figs. 5 and 6. As can be seen the peak insulator voltage is increased only slightly while the energy in the vacuum inductor increases by 30%. Other code runs show that the A-K power increases by 55%. Hence it was decided to incorporate a transformer between the voltage conditioning network and the VIS in PBFA II.

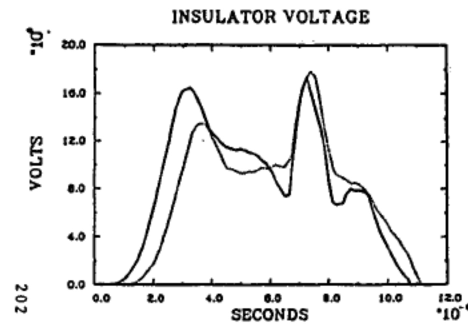

Figure 5. The voltage across the vacuum insulator.

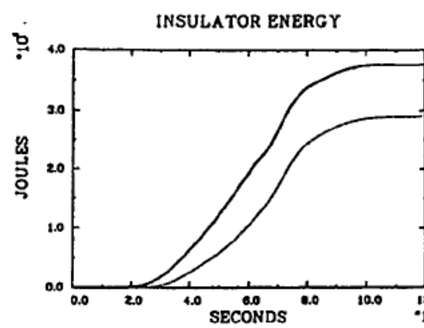

Figure 6. Energy into the vacuum inductor.

The final configuration for the VIS is shown in the electrostatic field plot of Fig. 7. This configuration reduces the total inductance to 96 nH with 73% in the vacuum and lowers the $L/Z\tau$ to 0.542 . Figure 8 also shows that we have greatly simplified the structure around the VIS. These simplifications will allow us to inspect the water side of the VIS for air bubbles and facilitate their removal prior to an experiment. The overall configuration of the accelerator is shown in Fig. 8.

<u>Sensitivity to Performance of POS</u>

Good performance of the POS is crucial to achieving the goals of the ICF program on PBFA II. A detailed model of the POS has been developed by the Naval Research Laboratories.[7] For this study, we have used a model that simply sets the time and rate of opening. Figures 9 and 10 show the power and energy delivered to the A-K gap as functions of the time that the POS begins to open. We see that for times earlier than optimum the power is down but the energy delivered is relatively constant. The power and energy are both reduced sharply after the optimum switch opening time. Hence the power and energy delivered to the A-K gap are very sensitive to POS timing.

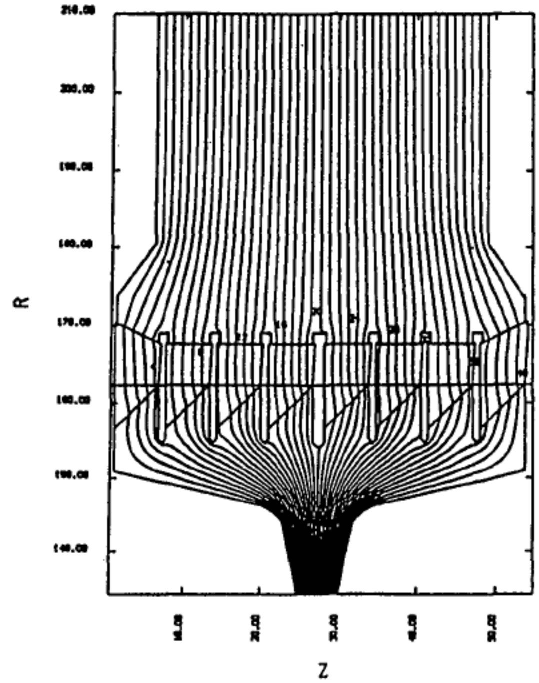

Figure 7. Electrostatic field plot for the final configuration of the VIS.

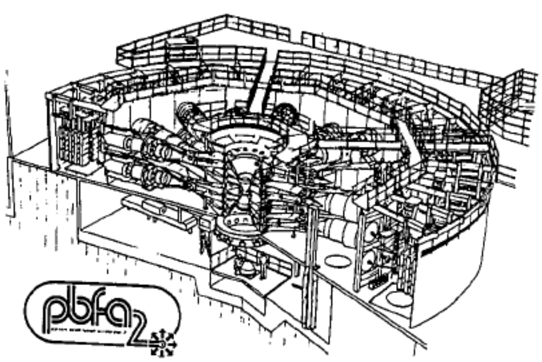

Figure 8. The overall accelerator configuration for PBFA II.

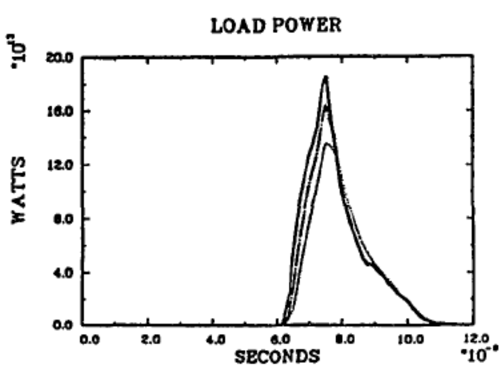

Figure 9. Power delivered to the A-K gap for various rates of opening of the POS.

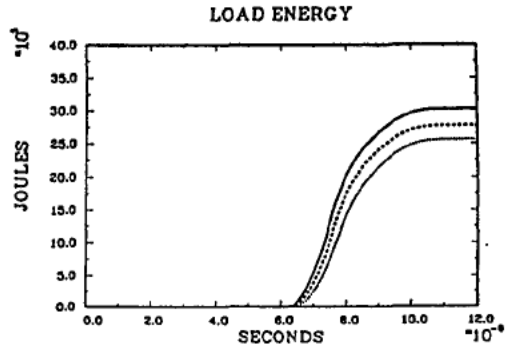

Figure 10. Energy delivered to the A-K gap for various rates of opening of the POS.

Figure 11 shows the sensitivity of the power delivered to the load as a function of the opening time of the POS. The maximum power that we can expect to deliver at the A-K gap is 160 TW. We expect to deliver 148 TW for reasonable attainable opening times. We see that improved switch performance will only increase energy by 14% and the opening time of the switch would have to be 46% poorer to decrease the power by the same amount. Hence the system is not as sensitive to switch performance as it is compared to the timing of the switch opening.

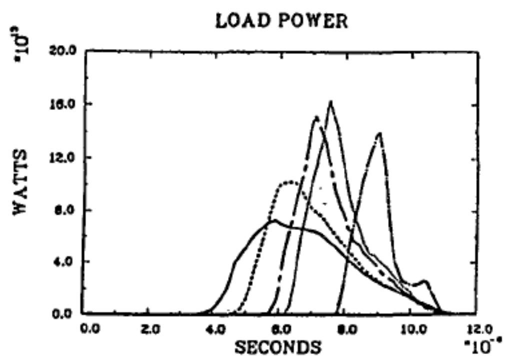

Figure 11. Power delivered to the A-K gap for various opening times of the POS.

Initial Ion Beam Parameters

To predict the expected ion beam parameters a ion Child-Langmuir diode model with 10 cm/us gap closure was used. Eighty percent of the anode-cathode gap energy is assumed to be coupled to Li^+. The energy that is available at the output of the transformer was adjusted to be 120 kJ/module, or 4.32 MJ total from 36 modules, which is consistent with the performance of the demonstration module.[8] Models for the losses in the MITL and flashover of the vacuum insulator interface were included. The "reasonable parameters" for the plasma opening switch discussed above were used. The results for the ion beam voltage, power, and energy are shown in Figs. 12 to 14. The peak voltage at the diode 24 MV with a power of 120 TW and an energy of 2.25 MJ.

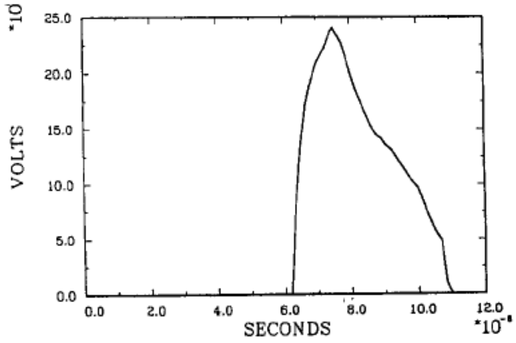

Figure 12. Ion beam voltage.

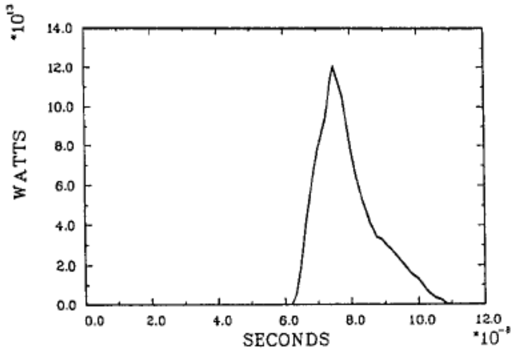

Figure 13. Ion beam power.

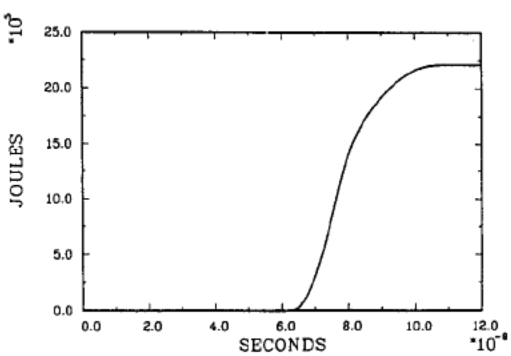

Figure 14. Ion beam energy.

The power in the ion beam is lower than we desire. As discussed in a previous section improvement in the switch performance will only make a 14% increase in the power avaliable at the anode-cathode gap. The most effective way to increase the power in the ion beam is to increase the avaliable energy in the accelerator. Figure 15 illustrates this. With a 40% increase in the avaliable energy the power at the anode-cathode gap would be in excess of 200 TW.

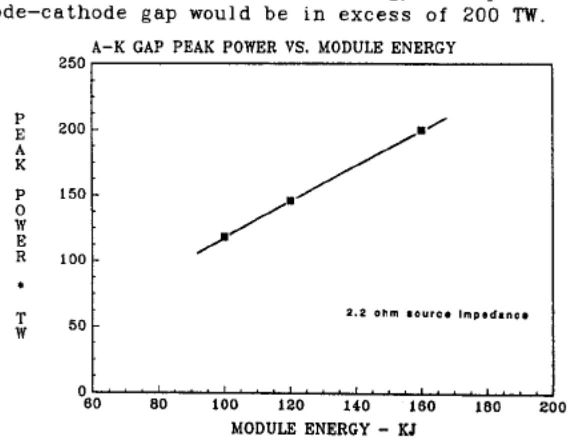

Figure 15. Power delivered to A-K gap as a function of module energy.

Conclusions

The inclusion of the transformer in the water section has several advantages. The energy coupled to the load has increased by 30% and the power by 55%. The electric stress in the water section has decreased by 70%. Accessibility to the vacuum insulator stack has been greatly improved. The vacuum insulator interface and the magnetically insulated transmission lines are conservatively designed and electrical breakdowns in these regions should not occur.

The main uncertainties in the PBFA II accelerator are in the plasma opening switch, the ion beam source and the scaling of the ion beam diode to the 30 MeV level. Research is actively being pursued on these subjects to minimize these concerns prior to the first operation of the PBFA II accelerator in January 1986. At this time PBFA II will deliver three times as much power and energy to the vacuum section of the accelerator as has previously been delivered in any other accelerator system.

References

1. G. W. Barr, J. P. Furaus, and D. L. Cook, "A Status Report on the PBFA II Construction Project," to be presented at 5th IEEE Pulsed Power Conference", Arlington, VA, June 10-12, 1985.
2. J. P. VanDevender, "Light Ion Beam Fusion," Proc. of the 5th Int'l Topical Conf. on High-Power Particle Beams, San Francisco, CA, September 12-14, 1983.
3. J. P. VanDevender, et al, "Decreased Beam Divergence in Proof-of-Principle Experiment for the Light Ion Beam Fusion Facility PBFA II," Lasers and Particle Beams, Vol. 3, Part 1, pp. 93-105, 1985.
4. R. A. Meger, et al, "Pulsed Power Application of the Plasma Erosion Opening Switch," to be presented at 5th IEEE Pulsed Power Conference, Arlington, VA, June 10-12, 1985.
5. B. V. Weber, et al, "Progress in Plasma Erosion Opening Switch Research at NRL," to be presented at 5th IEEE Pulsed Power Conference Arlington VA, June 10-12, 1985.
6. S. Shope, J. W. Poukey, K. D. Bergeron, D. H. McDaniel, A. J. Toepfer, and J. P. VanDevender, J. Appl. Phys. Vol. 49, p. 3675 (1978).
7. P. F. Ottinger, S. A. Goldstein, and R. A. Meger, "Theoretical Modeling of the Plasma Erosion Opening Switch for Inductive Storage Applications," J. Appl. Phys. Vol. 56, p. 774 (1984).
8. B. N. Turman, et al, "PBFA II, A 100 TW Pulsed Power Driver for the Inertial Confinement Fusion Program," to be presented at 5th IEEE Pulsed Power Conference, Arlington, VA, June 10-12, 1985.