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EBFA - Pulsed Power for Fusion*

T. H. Martin, J. P. VanDevender, G. W. Barr and D. L. Johnson
Sandia Laboratories, Albuquerque, New Mexico 87185, USA

ABSTRACT

This paper will describe the EBFA I accelerator under construction for inertial confinement fusion studies with particle beams and will update previous publications concerning particle beam fusion accelerators.[1] Previous information included Proto I,[2] a triggered oil insulated 1 TW accelerator; Proto II,[3] a water insulated 10 TW accelerator; and EBFA I, a 30 TW, 1 MJ accelerator.[1] Some modifications to the original design[1] have occurred. A new pulse-forming-line concept has been developed which increases the flexibility of the accelerator. The major problem of vacuum interface flashover has been solved by the use of long, magnetically-insulated, transmission lines. The first production module of EBFA I has been received, assembled, and is now undergoing extensive testing. The technology is extendable to at least a factor of ten above the projected EBFA capabilities of 30 TW and 1 MJ output. Progress on facilities associated with the Sandia Particle Beam fusion program is reported.

INTRODUCTION

The state-of-the-art pellet designs for achieving scientific breakeven through inertial confinement fusion (ICF) with electron or ion beams require a power of $\approx 10^{14}$ watts at a density of 10^{17} to 10^{18} W/m^2 or 0.2 to 2 TW/sr incident upon the pellet surface.[4] The development of an accelerator technology that can produce the necessary power and power density for ICF has been the goal of the Sandia Laboratories accelerator development program since 1970. The program has evolved through a series of accelerator programs as shown in Fig. 1. Hydra[5] is water insulated with two single line outputs and has a 1 MV, 500 kA, 50 kJ output per line. Proto I[2] has a two-sided output and uses triggered, oil-dielectric switching. It is a 2 MV, 500 kA, 20 kJ accelerator. Proto II[3] produces 1.5 MV, 6 MA, and 250 kJ pulses and employs self-breaking water dielectric switching. EBFA I consists of 36 modules

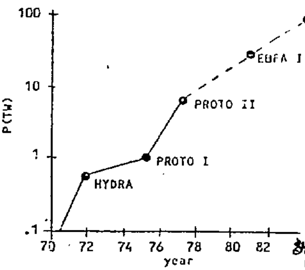

Fig. 1. ICF accelerator progress at Sandia.

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and is designed to generate a 2 MV, 15 MA, 1 MJ output. EBFA II will be a 100 TW upgrade of EBFA I. The Sandia development program has resulted in an accelerator technology that delivers electro-magnetic power at 34 TW/sr and is scalable to $> 10^{14}$ watts. The elements of the accelerator technology are the basic energy storage; module synchronization through gas dielectric switching; high-energy-density pulse-forming lines; short-pulse, water-dielectric switching; and long, self-magnetically insulated transmission lines for power transport to the diode. The system is reliable and is sufficiently flexible to accommodate both electron and ion beam generation for ICF experiments. The operation of the EBFA I accelerator will be outlined and then the EBFA I technology will be described in this paper.

EBFA I OPERATION

The EBFA I accelerator under construction at Sandia is shown schematically in Fig. 2. The energy flows from the Marx generator into the intermediate store capacitor in ≈ 600 ns. A gas insulated, triggered switch is then actuated to transfer the energy from the intermediate store capacitor to the water insulated pulse forming line (PFL) in ≈ 250 ns. Untriggered multichannel switching in the PFL then provides a 20 ns 10-90 percent risetime, 50 ns duration pulse into the output pulse transformer and to the vacuum insulator. After passage through the vacuum insulator, one of the most inductive components in the accelerator, the power per unit area is increased during transport through magnetically insulated transmission lines to the diode. The energy in the electromagnetic wave is then converted to particle beam energy by either an electron or ion diode. The particle beam is either guided to the target by a magnetized plasma column, which prevents beam dispersion, or ballistically focused to the target. Many beams are formed and then are overlapped on the target to provide further power concentration.

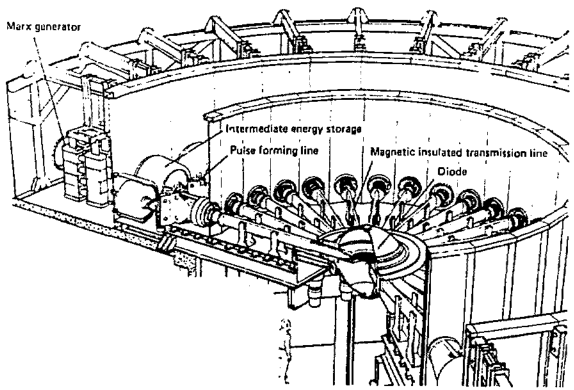

Fig. 2. EBFA I.

PRIMARY PULSED POWER SYSTEM

The primary pulsed power system stores 4 MJ of energy, then simultaneously transfers that energy to the pulse forming lines in the 250 ns time scale that is compatible with untriggered, water-dielectric switching. Since jitter in initiating the transfer, results in a reduced power density at the target, the jitter must be small compared to the implosion time of the target. Typically, a 5 ns rms jitter is required for a 35 ns pulse duration and implosion time. Consequently, the key questions for the primary pulsed power system are rapid energy transfer, simultaneity, and reliability. The requirements have been met by using a compact Marx generator with 200 kV across each spark gap and a water-insulated intermediate store capacitor to obtain the rapid energy transfer. The required simultaneity is obtained by synchronizing the energy transfer from the intermediate store to the PFL of each module with a 3 MV SF_6 trigatron spark gap which has 1.8 ns jitter. The reliability is obtained by employing diverting resistors during charging of the Marx, and by a full charge pre-shot, pulsed power test into this divertor load immediately before each shot. The operation and reliability of the primary pulsed power system has been extensively tested with eight modules on the Proto II accelerator and the design parameters have been verified.

In EBFA, 36 Marx generators are contained in a 4.8 m x 4.5 m outer annulus and provide a maximum stored energy of 4 MJ. Each Marx generator[6] consists of 32-0.7 ufd 100 kV capacitors, 16-200 kV triggered spark gaps, and the appropriate mounting hardware and electrical connections. Each Marx unit is supported by twin I beams and can be easily removed by an overhead crane to facilitate maintenance. All Marx module outputs will be recorded on the automated data recording system and automatically examined for signs of potential malfunction. Any Marx modules needing maintenance can be conveniently replaced with spare units.

WATER DIELECTRIC PULSE FORMING NETWORK

The pulse forming network required the following developments: a higher average-power-density pulse forming line, an effective means of reducing prepulse, a method for crowbarring the pulse forming lines for protection from reflected energy, and a polarity inverter for the ion accelerator option. The final design that accomplishes these requirements is shown schematically in Fig. 3.

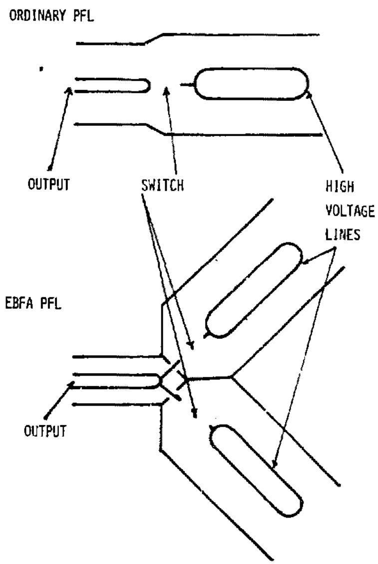

Fig. 3. Schematic diagram of EBFA I PFL.

The fast charge from the primary pulsed power section allows the mean operating electric field in the pulse forming lines to be 1.8 x 10^7 V/m and, hence, the average energy density is 10^5 J/m^3. Since a module stores 50 kJ, each module requires 0.5 m^3 of stressed volume. A 40 ns output pulse requires the length of the line to be ~ 0.6 m. The dielectric stress limits the conductor separation to 0.14 m for V = 2.5 MV so the required width of the line is 6 m of parallel plate line or 3 m of triplate transmission line. The most scalable and cost effective accelerator configuration is to package each stage at a constant power per unit solid angle. The three meter length is twice as large as it should be for optimum packaging. The solution[8] was to use two 1.5 m wide triplates in parallel and mix the waves into a single triplate line. The mixing is accomplished by a special convolute devised for EBFA I and shown in Fig. 3.

A prepulse voltage preceding the main power pulse is coupled to the load through the switch capacity between the pulse forming line (PFL) and the transmission line (TL). The large dielectric constant of the water and the fast charge time needed for untriggered switching can cause this prepulse voltage to be 20 percent of the PFL charge voltage. The prepulse causes premature shorting of the diode and limits the particle beam power density. The ground plane inserted between the PFL and TL reduces the capacity and the prepulse by ~ 80 percent. A second water dielectric prepulse switch in the transmission line further reduces the prepulse to 6 kV for a 2.5 MV charge. In addition, the PFL capacity to ground is increased and more efficient energy storage results. After the main pulse is transmitted down the transmission line, the breakdown streamers continue to grow from the ground plane holes to the switch electrode and crowbar the entire system, thus protecting the PFL, water capacitor and Marx generator from further transients. The PFL configuration adapts the self-breaking, water dielectric switching developed for Proto II to the EBFA I requirements. The system has been fired over 400 times at full power on Mite, an EBFA I test module, without any problems.

The pulse forming line should be designed so that the spacing between plates is small compared to the short wavelength components in the output pulse. Under such conditions, transverse modes are not excited and the energy can be extracted efficiently. Since the spacing is proportional to the charge voltage, this criterion becomes important for ICF accelerator pulses at approximately 2 to 3 MV. Consequently, the PFL is charged to 2.4 MV and discharged into a transformer at 1.2 MV. The 2 MV EBFA I output voltage is obtained by means of a short pulse transformer and impedance mismatch at the vacuum insulator with 90 percent efficiency.

EBFA I can be used with either electron or ion beams. The output can to be either positive or negative. Since water breakdown is strongly polarity dependent,[7] the polarity change can not be simply obtained at full power by reversing the Marx charge voltage. The pulse is inverted by a cross over network in the output transmission line as shown schematically in Fig. 4. The network is simple to install, is cost effective, and was more than 95 percent efficient in full power tests on

Mite. The first criterion for the ion accelerator option is the positive polarity operation and has been achieved.

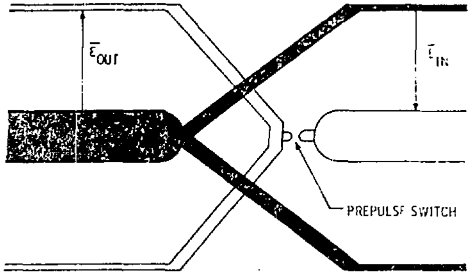

Fig. 4. Schematic of polarity inverting convolute.

POWER FLOW SECTION

The weakest element in the power flow chain is the vacuum interface, which flashes over at $\sim 10^7$ V/m. The power density through the vacuum insulator is limited to 0.5 to 0.8 TW/m^2. The module design of 34 TW/sr, therefore, requires the vacuum insulator to be ~ 7 m from the target. The power transport between the vacuum insulator and the diode is accomplished by self-magnetically insulated transmission lines (MITL).

A Mite module MITL is shown in Fig. 5. The overall line is 6.3 m long. The 0.8 TW flows through the 0.4 m^2 of the vacuum interface into the .005 m^2 cross sectional area of the magnetically insulated line. The power density in the line is 160 TW/m^2. The power density is further increased to 500 TW/m^2 by tapering the line at the diode. The triplate geometry was adopted for its mechanical strength and allows the line to be cantilevered from the vacuum insulator stack while maintaining the necessary mechanical tolerances.

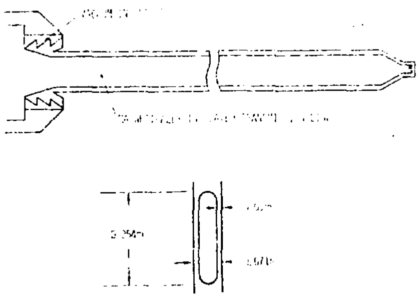

Fig. 5. Mite power flow line.

The MITL's must have efficient power transport and very low maintenance requirements. The efficiency of the power flow is strongly dependent on voltage and improves rapidly above ~ 1.8 MV, because the electron flow is separated from the anode by a substantial vacuum gap[9] for V > 1.8 MV. The efficiency is also determined by the geometry of the transition region between the vacuum insulator and the power flow line.[10] The geometry determines the canonical momentum distribution of the electrons in the power flow line, which determines the stability of the flow and the power transport efficiency.[9] The details of the magnetically insulated flow from these transition sections are still under investigation.[11] However, the present understanding has already led to the development of a transition section that gives ≈ 100 percent power transport and 90 percent energy transport at 2 MV through the 5.8 m long EBFA I MITL triplate section. The reliability of these lines has been demonstrated in over 200 shots at full power on the Mite accelerator without maintenance and without a failure of self-magnetic insulation.

DIODE

The conversion of the electromagnetic energy into electrons or ions and the focusing and transport of the resulting particle beams to the target are currently under investigation on the Proto I, Proto II, and Mite accelerators. The first EBFA I diode configuration will be selected in January 1980 in time to be procured for accelerator operation in the summer of 1980. Experiments with electron beam diodes at the end of the Mite magnetically-insulated transmission line have demonstrated reliable 3 mm diameter pinches that produce a 1 cm diameter hole through a 1.27 cm thick Al witness plate as shown in Fig. 6.

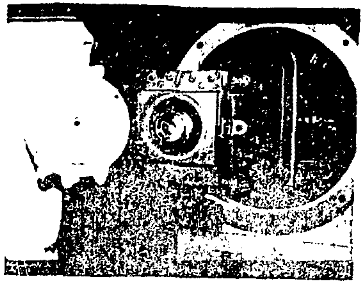

Fig. 6. Mite electron beam diode at the end of the 5.8 m long power flow line.

CONTROL AND MONITOR SYSTEM

The successful integration of the multiple modules into a single, reliable accelerator required extensive control and monitor system development. The EBFA control/monitor system is a distributed microprocessor system controlled by a minicomputer. The control system is divided into three main sections, i.e., EBFA, EBFA support, and personnel safety. The EBFA controls consist of Marx generator charging and firing, energy transfer switching, gas switch firing, event timing, and experimental control. The last few seconds before a shot the accelerator is controlled by the final event timing and firing unit. The EBFA support controls consist of liquid transfer (oil and deionized water between storage and accelerator), SF_6 and other insulating gases, and the vacuum system. The personnel safety controls consist of high bay access control, firing-interlocks, TV monitors, public address system, tritium monitors and pit ventilation, emergency generators, etc. All slowly varying functions throughout the accelerator, i.e., the charging voltage, the oil and water temperature, the vacuum status, etc. are monitored and recorded several times per second. This information is stored on a floppy disc and forms a permanent record of the accelerator condition for every shot.

EBFA I SCHEDULE

The assembly of EBFA began in August 1978 with the start of the on-site erection of the main tank structure to house the 36 modules. This tank structure has undergone final acceptance testing and installation of the energy storage section will start mid July 1979. The Marx generator assembly began in August 1978 and was completed February 1979. The first complete set of EBFA hardware was assembled into a demonstration experiment, Hydramite, for verification of the engineering design. Hydramite pulse power testing started in March 1979 and the power flow testing started in May 1979. Acceptance testing of the Marx generator charging and firing systems was completed in May 1979. EBFA is scheduled to begin pulsed power testing of the entire energy storage section in October 1979 with all 36 accelerator modules operational by June 1980.

EXTENDING THE TECHNOLOGY TO HIGHER POWERS

If the EBFA I modules are packaged into 4π sterradians instead of just a plane, then very large outputs are obtainable. An extrapolated level of 400 TW and 16 MJ is possible. The present device can be upgraded with modest alterations and higher total powers may be achieved as shown in Fig. 7.

INCREASING ENGINEERING → / CONSTANT COST/OUTPUT

INCREASING SCIENCE ↓ / DECREASING COST/OUTPUT

	EBFA I		EBFA II		FULL SPACE	
	TW	MJ	TW	MJ	TW	MJ
PRESENT MODULE 112 KJ	50	1	60	2	400	16
PRESENT TEST 160 KJ	42	1.4	85	2.8	[illegible]70	22
SUPERLITE 208 KJ MARX	50	1.8	100	3.7	600	26
SUPERLITE UPGRADE 530 KJ MARX	140	4.7	280	9.4	>1000	>40

Fig. 7. Present and possible accelerator outputs.

SUMMARY AND CONCLUSIONS

A short pulse accelerator technology suitable for ICF accelerators with electrons or light ions has been developed. The technology is bounded by the low output voltage < 1.5 MV requirement for short pulse water switching and the high, > 1.8 MV voltage requirement for efficient transport through long, magnetically-insulated transmission lines. The two voltage requirements are readily satisfied by the use of a transformer between the PFL and the MITL. The technology is extendable to > 400 TW and total energies in excess of 30 MJ.

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