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INTENSE PARTICLE BEAMS*

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Abstract

Substantial progress has been made recently in generation, focusing, and transport of intense electron and light ion beams. The impetus for this work has been to develop a 1 MJ, 10^{14}W particle beam device for inertial confinement ignition experiments and to create a practical technology base for application to future commercial power reactors.

Introduction

The demonstrated low cost and high efficiency of pulsed power driven intense beam accelerators make them particularly attractive for both the initial scientific feasibility demonstration as well as the ultimate application of inertial fusion. Several difficult problems were identified at an early stage in the evolution of this program and others have been recognized since sizable activities began in 1973:[1-3]

a. Synchronized multichannel (low inductance) megavolt switching was needed to obtain multimegampere pulses with rise times of tens of nanoseconds or less.

b. Methods had to be developed to overcome the limitations in power concentration due to the breakdown of the electrically weak solid dielectric-vacuum interface.

c. Electron beam diodes required further improvement in order to operate efficiently, reliably, and reproducibly in the 1 TW range with beam current densities > 10 MA/cm^2.

d. Techniques to suppress electron flow and provide an anode plasma to supply a high current density, low divergence ion beam were needed for target and beam transport experiments.

e. Methods were needed to transport and concentrate beams onto several cm^2 targets with sufficient "standoff" to protect the diode from the damaging effect of repetitive explosions.

f. Concepts, components, and materials had to be developed to extend this "one shot" technology to the high average power levels needed for an experimental power reactor (∿ 1 MW) and beyond to commercialization.

Since that time, extensive programs in the U.S. (primarily at Sandia Laboratories with support from N.R.L., Physics International Company, Maxwell Labs., Inc., Cornell Univ., and MIT) and the Soviet Union (Kurchatov Institute with support from the Efremov and Lebedev Institutes) have either fully satisfied these requirements or made important progress toward the needed parameters. The Sandia program has adopted as its timetable to complete the 30 TW, 1 MJ accelerator EBFA[4] by 1980 and to upgrade the device to 100 TW by 1984 and the Kurchatov program is based on the 100 TW Angara V accelerator[5] to be completed in the early 1980's. The Sandia program is investigating both electrons and light ions with a common beam transport approach, that of beam confinement in a narrow, preformed discharge channel[6] and the Kurchatov group is emphasizing an "in-diode" electron beam method which involves the direct connection of multiple, magnetically insulated transmission lines directly to the target.[7]

Reactor Considerations

Simple economic analysis shows that the efficiency with which electrical energy can be converted to driver energy, is delivered to, and absorbed by the pellet is one of the dominant factors in defining the reactor approach. Gas lasers with an overall efficiency $\gtrsim$ 1 percent are being considered[8] for pure fusion reactors necessitating pellet gains of ∿ 1000, a complex liquid curtain reactor wall protection concept, and an energy storage device as large as 100 MJ. Ironically, two of the leading ICF laser candidates, HF and KrF, require high efficiency, relatively short pulse electron beam excitation sources with KrF demanding an order of magnitude larger driver system because of its low electrical efficiency. Overall electron beam efficiencies, including beam generation and deposition in the laser volume, greater than 50 percent are envisioned. The implications of using the required beam accelerator directly to produce either electron or light ions for pellet ignition would mean that the same recirculating power fraction could be derived from a 40 percent efficient driver with a pellet gain of 25 and an energy store of 2.5 MJ as compared with the 100 MJ energy store in the above laser example. Such a smaller energy store and lower yield explosion would permit a modular system with reduced capital investment in the high risk demonstration phase and thus would more readily lend itself to early commercialization.[9]

An additional advantage of direct use of intense beams instead of their application to laser excitation is the prospect of extremely low cost. Single shot driver costs are currently ∿ \$10/J and repetitively firing high average power drivers may cost as little as \$20/J[10] (to be contrasted with costs of the present day high power single shot lasers which are in the range of several hundred \$/J). These potential advantages of cost and efficiency were recognized long ago but the question of obtaining sufficient "standoff" to protect accelerator components from the repetitive fluxes of neutrons, x-rays, and pellet debris prevented these devices from being considered seriously for reactor applications. Recent emphasis, however, on use of a buffer gas-filled reactor chamber[11] and beam propagation in plasma channels[12] have led to more detailed conceptual reactor studies.[13,14] The background gas density can be sufficiently high to absorb and thus convert the x-rays and debris into a blast wave which decays as it spreads and applies an overpressure to the chamber wall. This overpressure can be supported by various mechanical configurations, and the gas acts as a thermal reservoir reaching a high equilibrium temperature (possibly permitting in-situ synthetic fuel production[15]). Although reactor conceptualization has not as yet received a great deal of emphasis, the results to date indicate fruitful avenues for further work.

Pulse Forming and Power Concentration

The nominal conditions needed for a 1 GW fusion power plant are thought to be 1 MJ, 100 TW of 5 MeV protons or 10 MJ, 1000 TW of < 3 MeV electrons.[16] Reduction in the requirements for electron may be attainable because of electron beam deposition enhancement[17,18] or use of magnetically insulated targets to reduce power requirements[19] and in this way we may reach ignition conditions at the 1 MJ, 100 TW level for either particle. The primary goal of the Sandia Particle Beam Fusion Program is to investigate the threshold for

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ignition at the > 1 MJ level and such an experiment is planned for an upgraded version of EBFA to be completed by 1984. EBFA,[20] a 1 MJ, 30 TW device now in construction and to be complete in 1980 (shown in Fig. 1 and Fig. 2) is based on a series of developments in pulsed power technology which span the last several years involving Proto I, Proto II, MITE, and Hydramite. One module of EBFA has been tested in MITE and the first complete module of the 36 modules in EBFA is being tested in Hydramite (Fig. 3). Line charging and output wave forms from MITE are shown in Fig. 4 with typical output conditions of ∿ 0.8 TW peak power and ∿ 30 kJ delivered to the vacuum interface. An important feature of the pulse line output switch is a prepulse suppressing ground plane which also serves to improve the switch transfer efficiency and to prevent waves reflected from the load from reaching the P.F.L. and Marx.[21] Another important feature in MITE is an optional convolute in the water transition section between the output switch and the vacuum interface which also permits operation with a positive output pulse (as needed for certain ion diode configurations) with > 90 percent transfer efficiency.[22] In order to further concentrate the power from 10^8W/cm^2 at the solid dielectric vacuum interface to > 10^{10}W/cm^2 level needed to generate a beam within 1 m of the target, a magnetically insulated triplate transmission line has been used to transport power over 6 m with 90 percent energy transport efficiency and losses only due to erosion of the propagating pulse front. Experiments and theory have provided a criterion for allowable geometrical transitions in such lines and a geometry now exists for efficient propagation with the inner conductor charged either negative or positive.[22] A 20° sector of the upgraded version of EBFA is now in design and this device will be used to study increased energy storage, higher power pulse forming lines, and various output configurations. Tests on this device in 1980-1981 should provide the basis for the upgrade in 1982-1984. The dramatic advances in pulsed power technology (Fig. 5) have justified our projections of five years ago[23] and indicate that the question of the scalability of the technology has been answered affirmatively.

Electron and Ion Beam Generation and Focusing

High current electron beam diodes begin to self-focus when their current exceeds the critical value at which the outermost electron trajectories are self-magnetically turned through a substantial angle. The focusing process is complete when a stable bipolar flow is reached with the ions emitted from the electron beam produced anode plasma. Because of the longer electron path relative to that of the ions, the ratio of the ion to electron current greatly exceeds the normal value for bipolar flow.[24-26]

Parallel Bipolar Flow

$$\frac{I_i}{I_e} = \sqrt{\frac{ZM_e}{M_i}}$$

Self-Focused Flow

$$\frac{I_i}{I_e} = \frac{0.033}{A^{\frac{1}{2}}} \frac{\gamma}{(\gamma+1)^{\frac{1}{2}}} \frac{R}{d}$$

where Z, A are the ion charge and atomic weight, R is the cathode radius and d is the accelerating gap. The total diode current can be described by the "parapotential formula"[27] and as the diode aspect ratio, R/d, is increased both the total current and the fraction of ion current increase until a maximum electron current is reached.[26]

$$I_e^{\max}(\mathrm{kA}) = 258 \sqrt{A/Z} \sqrt{\gamma + 1} \; \ln\left[\gamma + \sqrt{\gamma^2 - 1}\right]$$

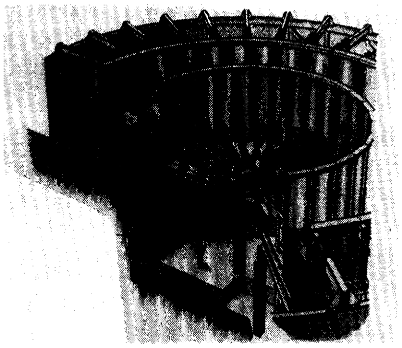


Fig. 1. EBFA I.

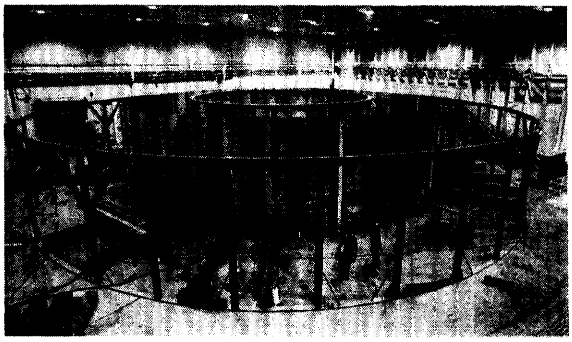


Fig. 2. EBFA I under construction, January 1979.

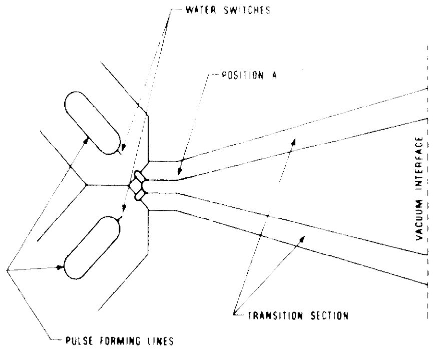


Fig. 3. Top view of EBFA pulse forming section. An optional prepulse switch can be installed at position A.

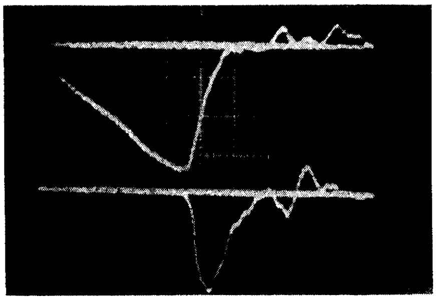


Fig. 4. (a) Pulse forming line charging voltage 0.74 MV/div, 50 ns/div.
(b) Pulse forming line output voltage 0.63 MV/div, 50 ns/div.

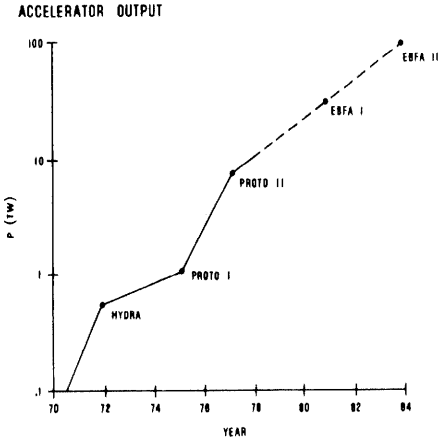
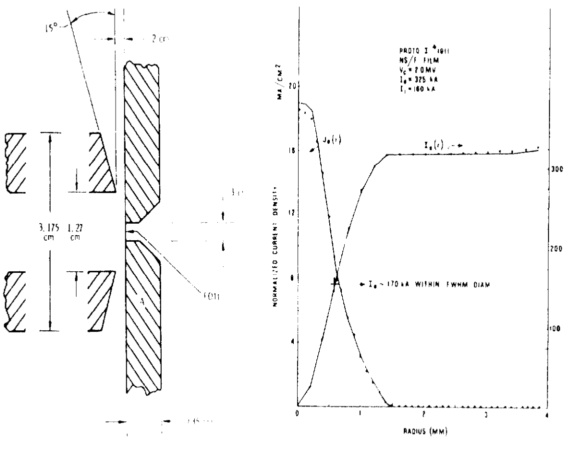


Fig. 5. Sandia Laboratories accelerator development.



(a) (b)

Fig. 6. (a) Proto I electron beam diode configuration.
(b) Current density profile.

In order to self-focus electron beams efficiently it is thus desirable to utilize multiple beams, each with an impedance > 1 Ω, which are then transported to a common target. For instance a 2 MV, 1 TW diode, using an Argon anode plasma would be 95 percent efficient. Although experiments with externally injected low Z anode plasmas have shown beam self-focusing,[28] such an experiment has yet to be carried out with a high atomic number plasma.

Electron beam experiments with self-generated anode plasmas have been carried out with diode impedances of a few ohms. The absolute minimization of prepulse was essential to the behavior of this diode (Fig. 6) yielding a beam diameter of 3 mm.[29] Utilizing a lower bound estimate of the fractional electron current one finds a peak current density close to 20 MA/cm^2. Beams with a factor of two lower current density have already shown a deposition enhancement factor of 3 to 5 due to "magnetic stopping" in agreement with theory and future deposition experiments are planned with this more tightly focused and higher current beam.[29] We conclude that diodes of a few ohm impedance useful for beam focusing onto targets or for transport studies are readily available and well understood. Other diodes which appear to involve an electron-ion feedback mechanism to achieve rather low impedances with small aspect ratio are in an early stage of understanding,[30] but also may give the needed efficiency and high current density.

Although ion beam driven inertial fusion had been proposed in a patent disclosure by Gale submitted in 1960,[31] further interest did not arise until 1968.[32-34] Experimental and theoretical activity concerning high current ion diodes began to increase in 1975 as a reaction to the fact that enhanced electron deposition had not yet been demonstrated at that time and the realization that target designs based on only classical deposition were more compelling with ions than electrons.[35] It was also realized that an efficient high current ion diode would require: (a) the generation of a dense anode plasma capable of supplying space charge limited ion flow, and (b) the suppression of the electron current. The first question was solved by Drieke, et al.[36] who demonstrated that a surface flashover plasma source would satisfy plasma requirements. The second question has been dealt with in two ways.

It has been now shown that the electron flow can be largely eliminated by applying a magnetic field parallel to the cathode surface so that the electron Larmor radius is smaller than the accelerating gap.[37] The resultant ion current density is a multiple of that given by the Child Lagmuir (C.L.) value because the effective accelerating gap is determined by the potential distribution modified by the electron cloud[38]

$$J(A/cm^2) = K \cdot 55 \times 10^{-9} V^{3/2}/d^2$$

with V in volts and d in cm. If K is unity, then for energies up to 10 MeV ion current densities up to 10^3 A/cm^2 can be obtained. In order to reach the power densities thought to be needed for pellet ignition, a further beam concentration of 10^3 to 10^4 is needed implying a beam divergence angle < 1° if simple ballistic focusing of a force free beam is utilized. Thus far, experiments have shown divergences of 2 to 3° with ∿ 1 MV diodes and higher voltages together with greater care taken in providing uniform anode plasmas should yield smaller inherent divergence angles. Another possible cause of beam divergence is ion trajectory deflection due to the external magnetic field which extends beyond the extraction cathode into the ion drift space and prevents the current neutralizing flow of low energy electrons along the beam. Further beam concentration is thus likely to be needed but fortunately this appears to be consistent with the empirically determined C.L. constant, $K \approx 10$,[39] and the need for adequate standoff[40] to insure diode survival. By propagating multiple, magnetically confined beams which are bunched by space time compression and then overlapped at the target it should be possible to reach power densities in the 10^{13}-10^{14}W/cm^2 range.

In recent experiments, Johnson and Kuswa used an annular external field insulated diode producing a beam with 80 percent efficiency at current densities ten times the C.L. value. The beam was geometrically focused to current densities of ∿ 40 kA/cm^2 (Fig. 7)[39] and recently an improved cathode geometry has indicated current densities of ∿ 100 kA/cm^2.[40]

The other method for electron current suppression followed from the fact noted earlier that high current electron beam diodes tend to be self-magnetically insulated. The potential advantage of this approach over the external field method is that there is no applied field to prevent current neutralization in the beam drift region. At first it was thought that very low impedance, high aspect ratio diodes would be needed for efficient ion behavior, but work at NRL now indicates that the "reflex pinch" geometry can be 50 percent efficient at one ohm with peak focused current densities of 70 kA/cm^2.[41] Recently, ion beam currents of

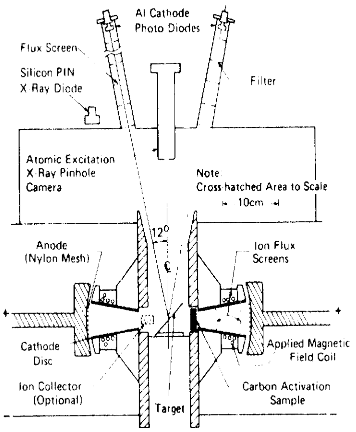


Fig. 7. External field magnetically insulated diode.

∿ 500 kA have been generated and current densities of 150 kA/cm^2 have been obtained with curved diode geometries.[42]

Another external field approach subdivides the accelerator into successive gaps separated by charge neutralized drift regions[43] (Fig. 8) in order to reach the higher voltage (several hundred MeV) needed for heavier ions such as oxygen.[44] Questions of ion sources, multi-kiloampere beam stability, and ion dynamics in accelerating and focusing gaps are under investigation.[45] Thus far a 500 A proton beam and a 2 kA carbon ion beam have been successfully post-accelerated through a single 200 keV gap. The carbon ion source was an independent carbon plasma gun array[46] and this type of plasma source may be important to long life single and multiple gap ion accelerators.

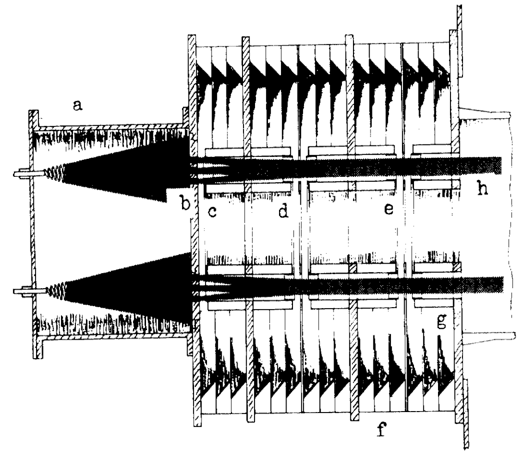


Fig. 8. Pulselac B experiment. (a) Plasma gun housing. (b) Extraction electrode. (c) Gap 1. (d) Gaps 2 and 3. (e) Gaps 4 and 5. (f) Insulators. (g) Cast drift tube and coil structure. (h) Ion beam envelope.

Another pulsed power approach to heavy ion acceleration is the use of the collective electrostatic field at the head of an unneutralized electron beam. If the beam current produced potential barrier exceeds the beam kinetic energy the beam will be self-stopped near the anode. It has been shown that by transversely sweeping a low power photoionizing source through a pre-excited low pressure background gas, the acceleration of the beam head and its potential well can be controlled.[47] Ion loading and acceleration are now under investigation using this device.

Beam Transport and Combination

Although reactor concepts have been suggested for "in-diode" pellet ignition[48] it has become increasingly clear that limitations on pellet yield or the complexity of diode replacement, may prevent this implementation. Even though such techniques may play an important role in initial pellet ignition experiments, it is extremely desirable to develop means for transporting beams over sufficient distances to allow for repetitive pellet ignition without damage to nearby walls or diodes. One can see that we are considering beams with relatively high "temperatures" due to the beam self-magnetic field if no current neutralization is provided. For example, if we adopt as the needed condition for ignition 10^{14}W, 3 MeV beam energy, and 4 ohm individual diode impedance then, we will have 40 beams each with a $\nu/\gamma = 6$ and 0.3 for electrons and protons, respectively. Either particle beam would expand rapidly in vacuum so that a background plasma is needed for space charge neutralization. If the background plasma has a conductivity σ, then the beam will be fully current neutralized with an inductive electric field $E = J_b/\sigma$, and a characteristic magnetic diffusion time $\tau_0 = \mu_0 r_b^2 \sigma$. With air at 3 eV and $\rho/\rho_0 = 0.3$, $\sigma \approx 2 \times 10^4$ mho/m and $\tau_0 \sim 1$ μsec. Such a beam would be force free and will expand following its initial divergence at injection into the drift region. Thus a confining magnetic field is needed and both longitudinal[18] and azimuthal fields[6] have been proposed. The longitudinal field technique is being implemented in the form of a disc beam injected along a ring cusp with the beam to be trapped in the low field region forming a cloud of electrons.[18] Wright[49] has shown that particle angular momentum may prevent efficient target irradiation in the cusp geometry and this configuration is under study at the Kurchatov Institute. The azimuthal field approach has been demonstrated using a 200 kA, 1 MeV electron beam which was propagated efficiently using a 70 kA preformed discharge in air at one atmosphere.[50] The discharge joule heats a narrow channel which expands leaving a low density core surrounded by a cold high density layer. This layer inertially confines the discharge channel and thus the beam which is confined by the discharge magnetic field. Miller, et al.[51] also showed that although the uniform discharge was initiated with a fine tungsten wire, the channel properties were independent of the wire after a short time and thus it is assumed that a laser initiated discharge will behave similarly. Initial experiments using ion beams have begun at NRL using a 40 kA low pressure discharge in a quartz tube and transport at a few kA/cm^2 over 1 m is under investigation.[52] With a propagating beam current density of 10^6 A/cm^2 the inductive electric field is ∿ 0.5 MV/m and the beam energy loss over the 25-50 cm transport envisioned for EBFA is negligible but would constitute an important energy loss for a reactor. For this reason, a lower atomic weight background gas which relies on return current heating to reach temperatures of several tens of eV and $\sigma > 10^5$ mho/m is postulated.[53] The final order of magnitude needed in additional beam concentration may be achieved by beam overlap in the case of electrons[54] and a combination of beam bunching and overlap in the case of ions.[55]

Multiple electron beam transport and overlap is envisioned for use on EBFA and a 12 beam test of this concept on Proto II is underway. In initial experiments, 6 of the 12 beams were propagated with the other 6 used for diagnosis of injection. Energy transport over 46 cm to a target radius equal to 0.6 of the channel overlap radius has been accomplished with 90 percent efficiency and a peak power density of $5 \times 10^{11} W/cm^2$ (Fig. 9).[54] Experiments with smaller targets and the full 12 beam array are continuing. Both electron and ion beam focusing, transport, and combination have made substantial progress over the last five years with the most rapid advances being made with ions. In fact, the progress with ion beam concentration has been so great that ions are likely to overtake electrons as the leading contender for the first pellet ignition experiments if the past trend continues.

High Average Power Drivers

Various functions which are readily provided in the single shot pulsed power devices of today will have to be modified for repetitive pulse, high average power operation. Although the output switching in EBFA, which is of the self-breaking water variety, is suitable for initial, single shot experiments, gas switching will have to be introduced. The electrode housings will have to be cooled by flowing liquid or gas and the dielectric itself flowed to provide cooling, debris removal, and to provide a high dielectric strength medium for each successive shot. In addition, it is necessary to either employ inductors rather than resistors in the Marx generator or replace the Marx with a transformer. Both the Marx and transformer approaches require cooled, flowing gas spark gaps. The diodes themselves may present the most formidable challenge to repetitive operation. Both electron and ion beam diodes will require injected plasma rather than solid anodes and cathodes, which will erode due to plasma formation, will have to be adjustable to maintain a constant accelerating gap, and will have to be designed to avoid ion bombardment.

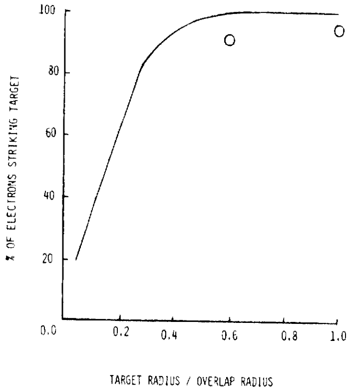


Fig. 9. Beam transport and overlap efficiency as compared with theoretical prediction[49] (solid curve). Transported energy = 50 kJ.[54]

Economic analysis[56] indicates that yearly replacement (2×10^8 shots) of the relatively low cost pulsed power components would have little impact on the power cost if the recirculating power fraction is 0.1. This implies a gain-driver efficiency product of 25 or a pellet gain of 62.5 for a driver efficiency of 40 percent. At a lower gain value, the component lifetime would have to be increased (3 years at a pellet gain of 25). Thus, component lifetime of 10^8-10^9 shots is thought to be necessary and the preliminary steps toward achieving this goal are underway.

One of the goals of the Sandia Particle Beam Fusion Program is to demonstrate a single 100 kJ, 10 Hz module of EBFA on the same time scale as an ignition experiment. These two milestones carried out simultaneously would provide the basis to proceed with an experimental test facility which would ignite pellets on a repetitive basis. The first step toward this long term goal is embodied in the RTF-1 device, a 200 kV, 100 Hz 30 kW average power test facility.[57] The output switch for RTF-1 was tested in a 10^6 shot run to test system reliability and electrode erosion rate. Extrapolating from the measured erosion rate of 5.4×10^{-4} g/C one predicts a lifetime of $\sim 10^9$ shots. The higher charge transfer switch on the primary side of the transformer experienced more severe erosion and other designs are being tested. It has been found that high velocity gas flow tends to distribute the arc location uniformly over large area electrodes thus reducing erosion.[58] A 3 MV transformer of spiral strip design has been tested in the dual resonance mode with a 45 kV primary capacitor bank and with 92 percent energy transfer capacity.[58] This type of transformer is to be compared with a Marx generator as an alternate high voltage supply to the pulse forming line. A 1 MV, 10 kJ per pulse, 10 100 Hz inductively isolated Marx is being constructed and will be tested shortly.[59]

Operation of RTF-1 with an electron beam diode has begun with a diode impedance of 10 ohms (200 kV, 20 kA).[60] A single run of 17,000 shots varying in rate from 2 to 30 Hz showed stable diode operation with no cathode erosion at an average cathode current density of ~ 2 kA/cm^2. This is still an order of magnitude lower current density then that needed for multiple electron diodes but is likely to be adequate for efficient ion diodes. These results are promising but are still only initial steps toward what may be one of our most difficult technical challenges.

Conclusion

Although substantial progress has been made in the last few years in developing the technology of intense particle beam drivers, there are still several unanswered questions which will determine their ultimate feasibility as fusion ignition systems. The question of efficiency, cost, and single pulse scalability appear to have been answered affirmatively but repetitive pulse technology is still in its infancy. The allowable relatively low pellet gains and high available beam energies should greatly ease questions of pellet implosion physics. Insofar as beam target coupling is concerned ion deposition is thus far well understood and our measurements of enhanced electron coupling agree with theory. With the development of beam guiding plasma discharges, it appears that small reactors can be designed, but ion beam transport and concentration is still incompletely demonstrated.

Acknowledgment

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