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BEAM REQUIREMENTS FOR LIGHT-ION-DRIVEN INERTIAL-CONFINEMENT FUS--ETC(U)
NOV 80 D MOSHER, D G COLOMBANT, S A GOLDSTEIN
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Pulsed-power and ion-beam production and handling techniques are available to assemble a break-even ICF experiment. In this report, simple scaling laws for beam focusing, transport, bunching and packing are combined to define an acceptable range of parameters for ignition-system modules delivering low-atomic-number (≤ 6) ion beams to a pellet. Techniques for increasing the deliverable beam intensity are then discussed.

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BEAM REQUIREMENTS FOR LIGHT-ION-DRIVEN INERTIAL-CONFINEMENT FUSION

Proof-of-principal and scaling experiments for light-ion-driven inertial-confinement fusion are in progress with generators appropriate for use as ignition-system modules.[1,2] Megampere currents of 2 MeV protons and deuterons have recently been extracted in 100 ns pulses from 100 cm^2 pinch-reflex diodes (PRDs) operating at 3-TW diode electric powers.[3] Experiments at the 1-TW level have recorded focused proton-current densities approaching 1 MA/cm^2 with cylindrical magnetically-insulated diodes.[4] Deuterons extracted from PRDs have been focused to over 300 kA/cm^2 in a geometry appropriate for injection into transport channels.[3] Proton beams extracted from pinch-reflex diodes have been transported meter distances in the focused state through 50 kA wall-stabilized z-discharges established in 1 Torr gas backgrounds.[5] Experiments utilizing laser-initiated discharges are in progress.[6] Several-meter channel transport provides a means to deliver beams extracted from a large number of generators to the vicinity of the pellet. These lengths are sufficient to achieve beam power multiplication by axial bunching.[7] Computational MHD research[8] and microinstability calculations[9] indicate that individual proton beams with currents approaching 1 MA can be transported.

The cited work indicates that the pulsed-power and ion-beam production and handling techniques are available to assemble a break-even ICF experiment. In this comment, simple scaling laws for beam focusing, transport, bunching

Manuscript submitted October 6, 1980.

and packing are combined to define an acceptable range of parameters for ignition-system modules delivering low-atomic-number ($\lesssim 6$) ion beams to a pellet. Techniques for increasing the deliverable beam intensity are then discussed.

Figure 1 illustrates schematically one module for extraction, focusing and transport of an intense ion beam. Ions are accelerated axially across the diode vacuum gap by the applied electric field and are accelerated radially inward by their azimuthal self-magnetic field. The transmission cathode separates the diode region from a low-pressure, gas-filled drift section. Beam-induced breakdown of the gas reduces the self-magnetic field by about two orders of magnitude so that ion orbits in the drift section are nearly ballistic.[3] The anode and cathode structures are shaped so that ions exiting the diode converge to a focus at the entrance of the transport section. Beam ions are magnetically confined in the centimeter-diameter discharge channel and are transported to within a few centimeters of the pellet. The maximum injection angle of ions into the channel must be $\lesssim .2$ radian so that modest discharge currents ($\lesssim 50$ kA) suffice for beam confinement[2,7] and excessive expansion between the channel exit and pellet does not occur. For such injection and channel current conditions, ions of a few MeV/nucleon (which couple efficiently to the pellet[10]) can propagate in a range of channel-plasma densities limited from below by channel expansion during beam transit and from above by excessive collisional beam-energy loss.[8] Increasing the diode accelerating voltage during the ~ 50 ns injected ion pulse permits power multiplication during transport by axial bunching down to the ~ 10 ns required to drive the pellet.[10] Substantial power-multiplication can be achieved only when the dispersion in axial ion velocities during transport is small.[7] This condition is also satisfied by small ion-injection angles.

The accelerating-voltage waveform appropriate for beam bunching during transport produces ions which exit the diode with an axial velocity[2,7]

$$v_i(t) = \frac{v_i(0)}{1-t/T} \quad ; \qquad 0 \leq t \leq \tau < T \tag{1}$$

where τ is the ion pulse duration at the diode and T determines the voltage-ramp steepness. As the beam propagates in z, the beam duration is reduced according to

$$\Delta t = \tau\left[1 - \frac{z}{v_i(\tau)(T-\tau)}\right] \tag{2}$$

In order to reduce Δt to τ/α, propagation a distance

$$\ell = 1.3\times10^9(1-\alpha^{-1})(T-\tau)\sqrt{E/A} \quad \text{cm} \tag{3}$$

is required where E(MeV) is the ion energy at $t = \tau$ and A is the atomic weight and α is the power multiplication factor.

The accelerating-voltage ramp required for bunching produces a similarly-varying ion current. These time variations cause the magnetic pinch force in the diode to increase with time. In order to minimize defocusing with time at the entrance aperture of the transport section, the diode vacuum gap should decrease with time. With optimal gap-closure velocity,[11] residual time variations produce a focal-spot radius

$$r_s \simeq \frac{.15Z_D I}{\sqrt{AE}} \frac{(1-\tau/T)v\tau}{(R/F)} \quad \text{cm} \tag{4}$$

In Eq. (4), Z_D is the ion charge state in the diode, I(MA) is the ion current in the diode, v (cm/s) is the electrode-plasma velocity for cathode or anode, R is the diode radius and F is the focusing distance from diode to transport entrance aperture. The quantity R/F defines the maximum injection angle of ions into the focus.

The magnetic field produced by the channel current I_{ch}(MA) must confine these ions within the channel radius $r_{ch} > r_s$. From conservation of canonical momentum[2,7]

$$I_{ch} \gtrsim 1.3 \frac{\sqrt{AE}}{Z_T} (R/F)^2 \tag{5}$$

where $r_s^2 = r_{ch}^2/2$ has been assumed, and Z_T is the beam charge state in the discharge. Collisions with discharge-plasma electrons can produce a charge state different from that in diode.[12] The transporting beam current $I_T = (Z_T/Z_D)I$ produces a plasma-return current of nearly-equal magnitude. The channel expands under the influence of the resulting $j_z B_\theta$ force. MHD calculations demonstrate acceptable channel expansion when[2,8]

$$I_T I_{ch} \lesssim 3\times10^{-10} \frac{\rho r_{ch}^4}{\tau^2} \tag{6}$$

where ρ(g/cm^3) is the channel-plasma mass density.

The channel-response calculations[8] determine the $V_r B_\theta$ electric field which removes energy from the beam as well as collisional energy losses. Minimum beam energy loss occurs at the plasma density where these two loss rates are equal since the former is proportional to ρ while the latter is proportional to ρ^{-1}. For a fully-ionized deuterium plasma,[13] this optimum density is given by

$$\rho_{opt} = \frac{.12 I_{ch}}{r_{ch}^2} \sqrt{\frac{IE\tau}{AZ_D}} \tag{7}$$

and the corresponding total beam-energy loss rate in the channel is

$$\frac{dE}{dz} \approx \frac{2\times10^3 A Z_T^2 \rho_{opt}}{E} \quad \text{MeV/cm} . \tag{8}$$

Substituting the optimum density into Eq. (6) leads to

$$\frac{Z_T \tau^{3/2}}{r_{ch}^2} \sqrt{\frac{AI}{Z_D E}} \le 3.5\times10^{-11} \quad . \tag{9}$$

An estimate of the minimum total energy loss experienced during transport is

$$\Delta E = \ell \frac{dE}{dz} \quad . \tag{10}$$

Requiring that ΔE be no more than a quarter of E leads to the condition

$$\frac{Z_T \tau^{3/2}}{r_{ch}^2} \sqrt{\frac{AI}{Z_D E}} \le \frac{7\times10^{-13}}{(1-\alpha^{-1})(T/\tau-1)(R/F)^2} \quad . \tag{11}$$

A larger energy loss at $t=\tau$ is unacceptable because lower-energy ions emitted earlier already experience greater losses.

Equation (9) must be satisfied when $(R/F) \le (R/F)_c$ while Eq. (11) must be satisfied otherwise where

$$(R/F)_c^2 = \frac{.02}{(1-\alpha^{-1})(T/\tau-1)} \quad . \tag{12}$$

For the purpose of discussion, the above relations can be simplified by assuming that $Z_D = Z_T = Z$. Also, the beam-energy can be eliminated by adjusting E with species to maintain a constant deposition length in the target.[14] Since the stopping power scales roughly like AZ^2/E, constant range results when

$$E^2 = AZ^2E_0^2 \quad . \tag{13}$$

In Eq. (13), E_0 is the proton energy of equivalent range. With this energy scaling, a particularly simple form results when Eqs. (9) and (11) are written in terms of beam power $P(TW) = IE/Z$.

$$P \leq \frac{1.2\times10^{-21}E_0^2 r_{ch}^4}{\tau^3} \begin{cases} 1 & (R/F) \leq (R/F)_c \\ \frac{(R/F)_c^4}{(R/F)^4} & (R/F) > (R/F)_c \end{cases} \tag{14}$$

It is noteworthy that Eq. (14) is species independent. Note also that P refers to the power extracted from the diode. As the beam bunches, $P\tau$ remains constant so that Eq. (14) becomes easier to satisfy.

Applying the considerations of the previous paragraph to Eq. (4) with $r_s \leq r_{ch}/\sqrt{2}$ leads to

$$P \leq \frac{4.6E_0^{3/2}A^{5/4}}{Z^{\frac{1}{2}}} \; \frac{(R/F)r_{ch}}{(1-\tau/T)v\tau} \tag{15}$$

Equations (14) and (15) are plotted in Fig. 2 for E_0 = 2 MeV, r_{ch} = .5 cm, τ = 50 ns, v = 1×10^7 cm/s, α = 5 and τ/T = .2. The velocity is consistent with observed electrode-plasma expansion.[15] The τ/T value corresponds to a voltage which rises 50% during the pulse. These results suggest that limits to focusability constrain deliverable modular beam power for protons while lack of beam confinement and energy loss during transport limit beam power for heavier ions. In either case, very long focal lengths (R/F ≤ .1) are required for transport of maximum beam power. Since focusability may be limited by a number of factors not considered here (electrode-plasma instabilities, asymmetric diode fields, beam-plasma interaction in the focusing drift region or effects peculiar to advanced focusing diode designs not yet discovered), operation at the largest R/F values possible would be desirable. However, increasing R/F increases beam expansion between the channel exit and pellet. Therefore, beam overlap on target must be considered to determine optimum power and injection angle regimes of operation.

For channel exits located a distance d from the pellet, each beam expands to a radius $r_{ch} + d(R/F)$ before impacting on target. The average power density on target can then be approximated by

$$p = \frac{NP\alpha}{4\pi\left[r_{ch}+d(R/F)\right]^2} \tag{16}$$

where N is the total number of transported beams. Assuming that no more than 25% of 4π steradians is subtended by the channel-exit aperture area, the maximum number of beams is given by $(d/r_{ch})^2$. The power density on target therefore satisfies

$$p \leq \frac{NP\alpha}{4\pi r_{ch}^2\left[1+N^{\frac{1}{2}}(R/F)\right]^2} \quad . \tag{17}$$

Since the pellet design specifies p and the facility configuration determines N, Eq. (17) represents an additional constraint which P must satisfy. This constraint is plotted in Fig. (3) for N = 36 and 72 modules and two values of p. Other parameters are as in Fig. 2. The lower p value corresponds to the incident power density required to drive a 1 cm diameter break-even pellet of recent design.[16] Acceptable operating ranges are defined by the regions above these curves and below the expansion/energy-loss curve. Thus, operation appears to be limited to the below .1 radian regime unless techniques can be employed to relieve the expansion/energy-loss constraints. Various options to achieve this are now considered.

Slight increases in $(R/F)_c$ are achieved when the voltage-ramp steepness is increased. This may not be beneficial since low energy ions emitted at early times suffer strong energy losses during transport.[8] Low energy ions do not penetrate deeply enough into the pellet to efficiently couple energy to the fuel. Thus, propagation of several-TW beams at R/F values in excess of .1 may require substantial increases in $E_0^2 r_{ch}^4/\tau^3$. A 2 TW beam could be propagated at R/F = .15 by increasing E_0 to 3 MeV, decreasing τ to 40 ns and increasing r_{ch} to .6 cm. The increase in E_0 requires pellets designed for longer deposition lengths. The Sandia National Laboratories PBFA facility is designed with $\tau \leq 40$ ns so that the decrease in τ presents no difficulty. The channel radius can be increased provided a final-focusing stage can be added at the channel exit.[7,17] Limitations to deliverable beam power can also be relaxed by employing a discharge channel which is imploding rather than static at the time of beam injection.[18] The MHD expansion constraint is relaxed since an imploding channel must experience stronger radial acceleration for a longer time before reaching an expanded state. Such dynamic channels have imbedded electric fields which tend to accelerate the beam,[18] thus reducing energy loss as well.

Scale-up of $E_0^2 r_{ch}^4/\tau^3$, dynamic channels or a combination of both techniques can be used to extend allowable R/F values or increase beam power in the transport section. For low pellet irradiance, these techniques may permit delivery of few TW beams with R/F values as large as .15. Proton-beam focusability precludes their use in high-irradiance configurations. When the same focusing constraint is applied to higher-atomic-number beams, high-irradiance operation with a standard, static channel is permitted with R/F ≈ .05. For reasons discussed in the paragraph following Eq. (15), focusing with such small R/F values is, at best, uncertain. Thus, application of advanced techniques to transport of non-hydrogenic beams is desirable in order to permit high pellet irradiance at R/F ≈ .1.

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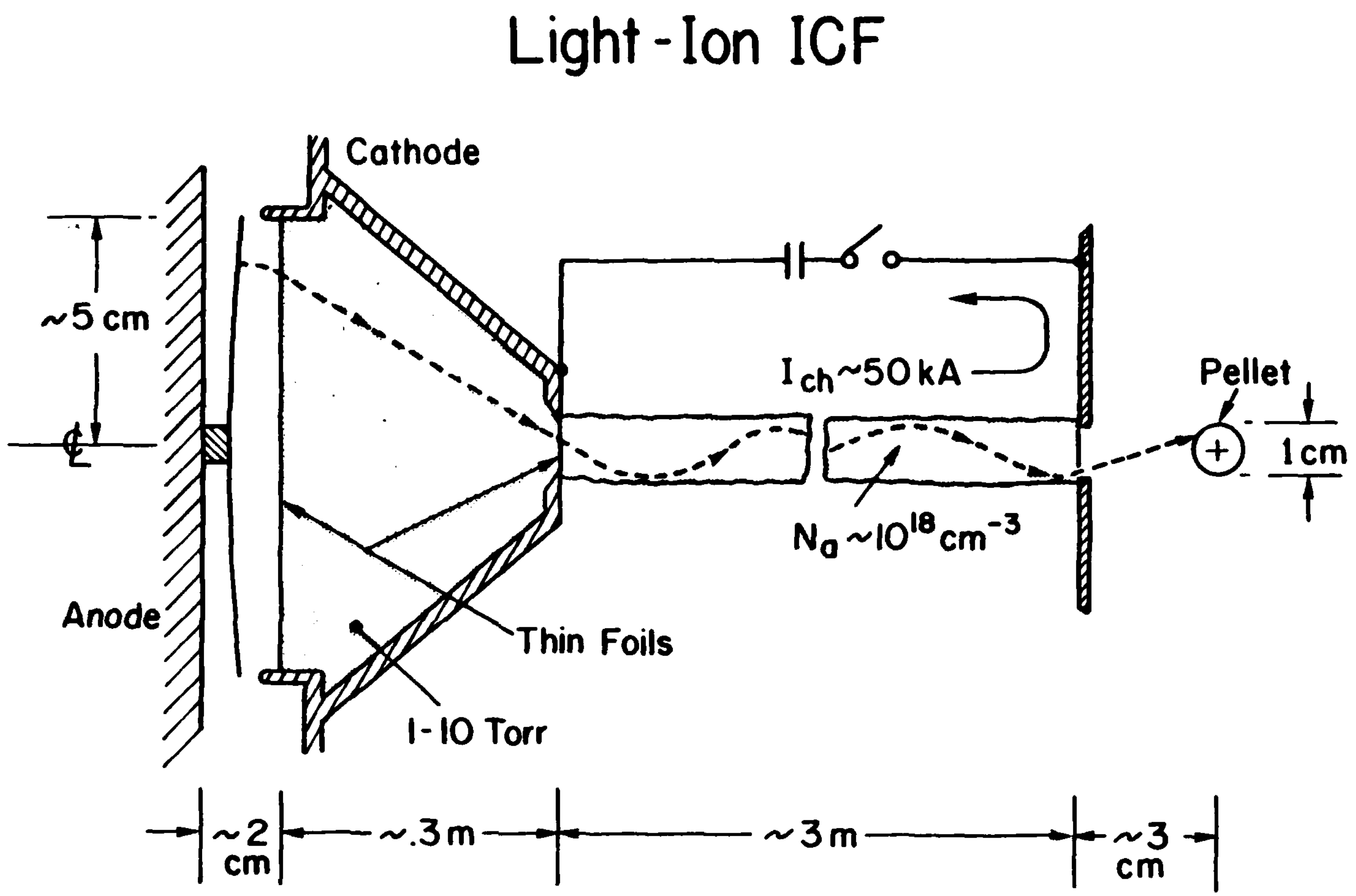

Fig. 1 — Conceptual schematic of one light-ion ICF module showing a pinch-reflex diode, focusing-drift region, and transport channel

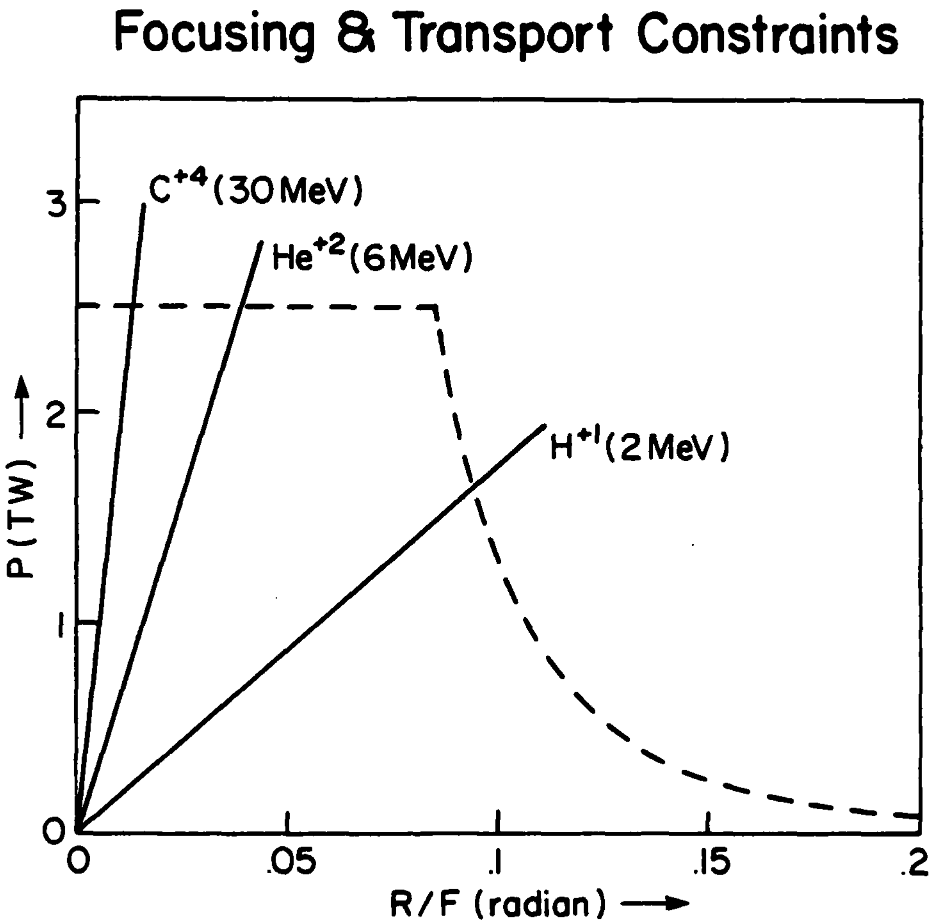

Fig. 2 — Beam power constraints as a function of the maximum injection angle of ions into the channel. The solid lines represent the maximum focusable power for the species and energies shown. The dashed line represents the maximum transportable power for all species.

Beam Packing Constraint

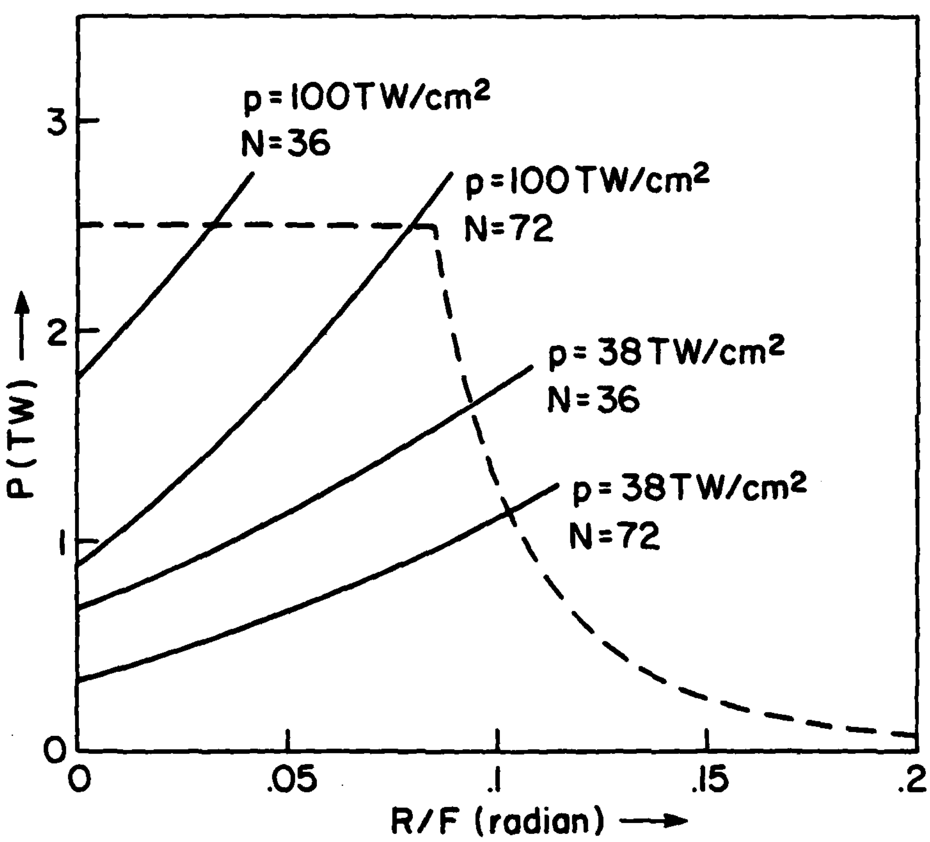

Fig. 3 — Beam packing constraints for two pellet-irradiance requirements and two ion-module-number values. Acceptable operation is associated with beam powers above the curves but subject to the maximum power displayed in Fig. 2.

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