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FUSION BURN DYNAMICS IN DENSE Z-PINCHES (DZP)[†]

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ABSTRACT: The fusion burn dynamics and energy yield of the dense Z-pinch (DZP) are examined using a profile-averaged, zero-dimensional, time-dependent model. A range of conditions (fuel, line density, voltage, fusion-product heating, enthalpy endloss, density and temperature profiles, current rise rate, electrode impurities) are examined. Magneto-hydrodynamic stability is assumed, and initial conditions are based on those ideally existing after the melting and ionization of a solid fiber of fusion fuel. Plasma-conditions required of neutron sources for materials testing ($\dot{S}_n \geq 10^{19}$ n/s) and for possible commercial power production are examined.

I. INTRODUCTION

Heating and confinement of high-density plasma by the self magnetic field generated from plasma currents flowing linearly between two electrodes represents one of the earliest plasma confinement schemes.¹ The formation and heating of such a dense Z-pinch (DZP) by a fast-rising current generally relied on a rapid implosion of a cylindrical current sheath onto the axis of the pinch. These early "classical" pinches were found to be highly unstable,¹⁻³ particularly with respect to $m = 0$ (sausage) instabilities. Theoretical predictions using ideal MHD stability theory³⁻⁴ indicate stability to the sausage mode for current profiles that are sufficiently diffuse. The use of frozen deuterium fibers⁵ to initiate a diffuse-current pinch that would be ohmically heated at nearly constant radius was suggested by Hammel, et al.⁶ and achieved experimentally at Los Alamos.⁷ These experiments on the nominally constant-radius, constant-density, diffuse-current pinch, as well as even more recent results,⁸ have shown surprisingly long MHD stable times to both the $m = 0$ sausage and $m = 1$ kink modes. The experiments described in Ref. 5, and subsequently in Refs. 9-11, show no $m = 0$ or $m = 1$ activity during most of the current-rise period, with some indication of an $m = 0$ termination only at the end of the $I \approx 0.25$ -MA ($a = 10$ -20 μ m pinch radius) discharge. Results from the Naval Research Laboratory (NRL)⁸ also show surprisingly long $m = 0$ and $m = 1$ stable times, with the $I \approx 0.55$ -MA ($a = 30$ -125 μ m) discharges terminating in a strong $m = 0$ compression only when $I \approx 0$. In both experiments, the predicted^{3,4} fast-growing $m = 1$ kink was not observed.

In addition to a number of scoping studies of the DZP fusion-reactor embodiment,¹²⁻¹⁴ the potential of this approach as a small but intense source of fusion neutrons for materials testing has recently been evaluated.¹⁵ A simplified analytic model of the DZP has been developed^{13,16} to examine the tradeoffs between physics requirements, fusion-neutron flux, volume available for performing materials tests at a given neutron flux, and, eventually, operational characteristics (i.e., pulse rates, power requirements, heat loads, stresses, erosion, fueling, etc.). The present study revisits and builds on this past work,^{13,16} including recent work by Robson,¹⁷ and identifies optimal burn conditions that maximize the plasma Q-value, (Q_p , ratio of fusion energy to total energy invested) for a range of plasma and (waterline) drive conditions. Specifically, a time-dependent, profile-averaging plasma model is evaluated for equal electron and ion temperatures. Although conditions for radiative collapse¹⁸ of the pinch are sometimes observed computationally, the condition where the pinch becomes optically thick to Bremsstrahlung radiation and where the density increases to the point of electron degeneracy are generally not encountered in the regime of interest to this study and, therefore, are not modeled. Similarly, the assumptions of an inertialess plasma and the electron drift velocity being less than the electron thermal speed (e.g., no current-driven instabilities) are maintained, but relevant diagnostics

are monitored. Lastly, preliminary estimates of the level and time scale for increased electron density from the plasma/electrode interaction are made.

Many of the effects modeled in this study have yet to be achieved in the laboratory and, if achieved, would at best be difficult to measure. The approach adopted by this study is to "turn on" a range of physical processes that may plausibly occur and then to quantify systematically the overall impact on the DZP performance (i.e., Q_p , DT fuel burnup fraction, f_B , discharge time, τ_D). Specifically, this parametric scoping study investigates the impact of energy endloss, density depletion by burnup, fusion-product heating, time-dependence of applied voltage, initial plasma radius and/or line density, fusion fuel, and recycle of fusion reaction products (e.g., T and ³He from the DD reaction), current rise-time constraints, and electrode-originated impurities. After describing in Sec. II the integrated plasma/engineering model used to evaluate the DZP, a DT "point-of-departure" case is developed in Sec. III.A; this point-of-departure case is then used to examine the impact of some of the above-listed effects in Sec. III.B. The impacts of current rise-time constraints ($I > 10^{12}$ A/s) and impurities originating from a low-Z (Li) electrode are also examined in Sec. III.B. Conclusions and main issues are summarized in Sec. IV. A more extensive compilation of parametric results, as well as preliminary reactor prospects, can be found in Ref. 19.

II. MODEL

A single-particle ($T_e = T_i$), profile-averaged energy balance, along with a simplified circuit and mass-balance, constitutes the essential elements of the time-dependent model used herein. Plasma MHD stability is implicitly assumed to be provided by resistive effects ($m = 0$ and at low temperature), viscosity ($m = 0$ at high temperature), skin effects (to enhance the effects of viscosity and/or resistivity), or (possibly) axial flow ($m = 1$ stability at high temperature). Inertial effects are ignored (e.g., the radial Alfvén time, $\tau_A = a/v_A$, is small compared to any time scale on which the pinch/circuit dynamics are measured), and the plasma is assumed to be always optically thin to radiation and electronically non-degenerate. The complexity of the initial melting of the solid DT fiber is circumvented in this study by assuming a low-temperature, low-current pinch of initial radius a_0 has been established at time $t = 0$.

The DZP is described by a filament of radius $a(t)$ and length ℓ_p , with self-similar density and temperature profiles being described parametrically by functions of the form $(1 - x^2)^{\alpha} \cdot \tau$, where $x = r/a$ is the normalized plasma radius. With the exponents α_n and α_T specified, profile factors for the i^{th} plasma power, P_i (i = ohmic, radiation, or fusion powers, designated respectively by the subscripts OHM, BR, and FUS), of the form $g_i = \int p_i dV_p / P_i$, are computed for use in the energy balance and circuit equation, where $p_i(r)$ is the local power density, $V_p = \pi a^2 \ell_p$ is the plasma volume, $dV_p = 2\pi r dr \ell_p$, and P_i is the total power i^{th} kind.

The global energy balance for the DZP takes the following form:

$$\frac{d}{dt}(3f_s N k_B T \ell_p) = P_{OHM} + P_{CF} - P_{RAD} - P_{EL} - P_{PAV} \quad (1)$$

where $N = \pi a^2$ is the ion line density, $f_s \equiv (1 + Z_{AVE})/2$, $Z_{AVE} = \sum_i n_i Z_i / \sum_i n_i$, and the powers P_i are, respectively ohmic heating, charge-particle fusion-product heating, Bremsstrahlung radiation loss, plasma enthalpy endloss (electron-drift and electron parallel-field conductive), and plasma (radial) expansion work.¹⁹ The plasma current is normalized to the Pease-Braginskii^{20,21} current, I_{eq} , the temperature to the corresponding equilibrium temperature, T_{eq} , and the discharge time to the resistive time evaluated of the initial radius and at temperature τ_{eq} , these

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normalizing parameters are dependent on profiles, Z_{eff} , etc. The normalized plasma temperature, $\Theta = T/T_{eq}$, is determined directly from pressure balance and takes the following normalized form

$$\Theta(1 - f_B)f_s = i^2, \quad (2)$$

where $i = I/I_{eq}$ and $f_B \approx 1 - N/N_0$ is the burnup fraction.

Direct plasma heating by fusion charged products is treated parametrically, with ongoing work in this area to be incorporated in the future.^{19,21}

Axial endloss of plasma enthalpy is modelled through the direct electron drift and by electron parallel-field thermal conduction through respective time constants, τ_D and τ_c ; the electrodes are assumed to sustain the plasma pressure. The electron drift current density is taken as a fraction of $j = n u_{A0}$, which is expressed in this study as carrying only the energy of the electron, $\sim \frac{1}{2} k_B T$. Axial thermal conduction is assumed to occur only by electrons in the unmagnetized $(\omega\tau_e \leq 1)$ regions of the pinch. Hence, with the parallel-field electron thermal conductivity given by $\kappa_{||} = C_K T^{5/2}$, an quasi-steady state axial temperature profile of the form $T(x)/T_0 = (1 - x^2)^{2/3}$ results. In order to assure that parallel electron thermal conduction does not exceed the free-streaming limit, the axial enthalpy endloss time used in the energy balance is $\tau_{EL} = \tau_c + \tau_D$. Estimates of the rate of electrode erosion are made under the assumption that all endloss energy is returned to the plasma as electrode ions at temperature T after a delay appropriate to the axial thermal transit time of the electrode impurity ions to within 25% of the pinch length.¹⁹

Particle depletion is assumed to occur only by fusion; radial particle transport is assumed to be small, and the electrodes are assumed to maintain axial pressure balance. The usual fusion reactions are considered (DD_p , DD_n , DT , D^3He). Fusion products generally are assumed to be lost from the plasma without undergoing second-order reactions, although the impact of the catalyzed DD reaction (e.g., in situ burnup of tritium) is considered.¹⁹

Rather than forcing the time dependence of the plasma current, the present model specifies the axial electric field, E_p , applied across the pinch. Generally, the condition $E_p \approx \text{constant}$ accurately reflects the early phase of the co-axial waterline assumed to drive the DZP. The inductance of the waterline front-end neglects the contribution, associated with the inner regions of the pinch, which contains only $\sim 4\text{--}5\%$ of the total stored magnetic energy, but includes a estimate of stray inductances associated with a realistic waterline geometry, which reflects primarily parasitic inductances associated with regions of electrical insulation separating the waterline and the discharge chamber vacuum.^{11,19}

III. PARAMETRIC RESULTS

A "point-of-departure" is first developed and described in the following subsection. Using the plasma Q-value as an "object" function, the performance of the DZP for a range of operating conditions (e.g., profiles, endloss, fusion-product heating, fuel choice, applied voltage, line density, current rise rate, electrode erosion etc.) is evaluated. The point-of-departure case is based on a constant-pinch-voltage, $V_p = E_p L_p$, mode of operation, although other operating modes are reported in Ref. 19. The initial conditions assume the formation of a low-temperature ($\Theta \approx 0.01$), low-current ($i \approx \Theta^{1/2} \approx 0.1$) pinch; the fiber melting and ablation process is not modeled and remains an important area of future work.^{23,24}

A. "Point-of-Departure" Case

Density and temperature profiles characterized by $\alpha_T = \alpha_n = 1.0$ were arbitrarily adopted for the "point-of-departure" case. Parametric studies¹⁹ indicated minimal sensitivity of results (e.g., Q_p) to this assumption. With a constant voltage, V_p , applied to the pinch, the dynamic response of the normalized discharge parameters (e.g., $x = a/a_0$, $\Theta = T/T_{eq}$, and $i = I/I_{eq}$) versus $\xi = t/\tau_0$ is shown in Fig. 1. For this DT-fueled case, density depletion by burnup, endloss of plasma enthalpy, fusion-product heating, and electrodes erosion were not included. The pinch settles into the Pease-Braginskii equilibrium ($di/d\xi = d\Theta/d\xi = 0$; $\Theta = i = 1$) at a normalized radius, x_{eq} , given by $x_{eq} = \sqrt{3/8\epsilon}$, and equal to $x_{eq} \approx 0.40$, where $\epsilon = E_p/E_{eq}$ and $E_{eq} = \mu_0 I_{eq}/2\pi\tau_0$. The dynamics depicted in Fig. 1 change appreciably once fuel burnup, fusion-product heating, endloss, and modification of Z_{eff} and plasma pressure by electrode erosion are taken into account. Since a mechanism for in situ re-fueling cannot be envisaged, fuel burnup

Fig. 1. Plasma transient for constant voltage without burnup, fusion-product heating, and endloss; the case designation used in the more extensive study reported in Ref. 19 are retained in this and other similar figures. For these and other cases reported here, $T_{eq} = 6.4$ keV, $I_{eq} = 1.68$ MA, and $\tau_0 = 29.5$ ns ($\alpha_n = \alpha_T = 1.0$, $Z_{eff} = 1.0$).

is included as part of the point-of-departure case being developed. Figure 2 gives the discharge kinetics when density depletion resulting from DT burnup is included, but fusion-product heating and enthalpy endloss are not; also shown is the burnup fraction, f_B , neutron production, S_N and S_X , and plasma Q-value, Q_p . An optimal value of Q_p is indicated cases, in that once f_B exceeds 0.6-0.9 the cost-benefit of fusing the remaining fuel is not advantageous; the cost in ohmic dissipation exceeds the incremental fusion yield from the $f_B \gtrsim 0.8$, reduced-reactivity plasma. Also noted is the large thermal excursion, since the ohmic dissipation is shared by fewer and fewer particles as burnup proceeds.

The impact of "turning on" plasma enthalpy endloss without electrode erosion was examined, where the endloss is dominated by electron parallel-field thermal conduction for this case where the entire plasma column ($X_L = 1.0$) is assumed to conduct. The combination of density loss by burnup and enthalpy loss by axial conduction accelerates the pinch collapse and fuel burnup, with the simulation being terminated (as in all other cases) when a temperature limit of ~ 200 keV is exceeded. Generally, endloss shrinks the timescale of the burn and causes a diminution of the plasma Q-value.

When both alpha-particle heating (100%) and full ($X_L = 1.0$) plasma enthalpy endloss occurs, the transient given in Fig. 3 results. Generally, the endloss energy sink ameliorates somewhat the adverse effects of the alpha-particle-driven expansion and premature quench that would result without this added energy sink, thereby allowing plasma Q-values near $Q_p \approx 20$ to be achieved. As for the other cases with burnup (Fig. 2) or burnup and endloss, the combination of nominally constant current and diminishing line density, through pressure balance [$\Theta(1 - f_B)f_s = i^2$], rapidly drives the plasma temperature to the ~ 200 -keV computational cut-off value.

The case described in Fig. 3 is selected as the "point-of-departure" case that has been subjected to parametric study. The impact of full fusion-product heating without enthalpy endloss can be dramatic, as is shown in Fig. 4; the achievable value of Q_p decreases by over an order of magnitude, as the re-compressing plasma column undergoes a rapid expansion once a significant fusion rate is achieved. This expansion causes the fusion rate to diminish rapidly, the consequence is a relatively low burnup fraction ($f_B \approx 0.1$) and Q-value ($Q_p \approx 2$). Generally, for the power densities envisaged for DT fusion, the maximum level of enthalpy endloss appears to be well matched with the fusion product heating (Fig.

Fig. 2. Plasma transient for constant pinch voltage, including density depletion from fusion burnup, but no endloss or fusion-product heating.

3) to counter the adverse effects illustrated in Fig. 4 when endloss is "shut off."

B. Parametric Variations about "Point-of-Departure" Cases

1. Performance without Fusion-Product Heating and Plasma Enthalpy Endloss. The dependence of Q_p and r_D on V_p ($a_0 = 20 \mu\text{m}$) and a_0 ($V_p = 2 \text{ MV}$) without fusion-product heating or enthalpy endloss shown on Fig. 5. Generally, the value of Q_p is relatively insensitive to V_p , the applied voltage sets the time scale rather than the Q -value. It is noted that all of the $a_0 = 20 \mu\text{m}$ discharges shown in Fig. 5 achieve the projected Q -value with $I \geq 10^{12} \text{ A/s}$. Unlike V_p , the initial fiber radius has a dramatic impact on the Q -value achieved as well as on that part of Q_p and r_D where $I \geq 10^{12} \text{ A/s}$. This dependence of Q_p on a_0 is examined further for the point-of-departure case, where endloss and fusion-product heating are included (Fig. 3).

2. DT Burn Dynamics with Fusion-Product Heating and Plasma Enthalpy Endloss. Since it seems likely that plasma enthalpy endloss will be a factor in determining the dynamics of an $\ell_p = 0.05\text{--}0.10\text{-m}$ pinch, the point-of-departure case adopted endloss at a maximum value. Endloss without fusion-product heating leads to a rapid collapse of the pinch and an accelerated burn. Inclusion of fusion-product heating without endloss

Fig. 3. Point-of-departure case including 100% fusion-product heating endloss, and burnup for constant pinch voltage.

Fig. 4. Point-of-departure case without axial endloss of plasma enthalpy, but maintaining 100% fusion-product heating.

or an equivalently effective means to drain off the excess heat from the pinch leads to an uncontrolled expansion, a fusion quench, and seriously degraded Q -values (Fig. 4). The parametric dependence on V_p and a_0 for the case is reported in Figs. 6 and 7, respectively. Generally, the sensitivity of Q_p on V_p for the constant- V_p ($a_0 = 20 \mu\text{m}$) mode of operation is greater when endloss and fusion-product heating is included than when these effects are not included (Fig. 5). The point-of-departure case exhibits Q -values in the range 10-12 for discharge times of $r_D = 200 \text{ ns}$ (number of integrated radial Alfvén times $N_A \approx 30,000$), the value of Q_p is approximately halved if the $I > 10^{12} \text{ A/s}$ constraint is imposed, with little impact on r_D (Fig. 6). Most cases in this regime exhibit high burnup, and the decreasing Q_p with increasing V_p is attributed to greater ohmic dissipation in the more restrictive (more compressed) plasma. The dependence of Q_p on a_0 given in Fig. 7 shows an increase in Q_p to values

Fig. 5. Dependence of Q_p and discharge time on initial voltage for the case where fusion-product heating and endloss are not included (Fig. 2).

as high as $Q_p \approx 16$ ($\tau_D = 500$ ns) until a critical initial pinch radius is reached (apparently independent of V_p) where ohmic heating is insufficient to induce a thermal runaway, and a "fizzle" occurs.

Fig. 6. Dependence of Q_p and discharge time on voltage for point-of-departure case (Fig. 3) conditions (constant-voltage, full endloss, full fusion-product heating).

3. DT Burn Dynamics with Full Fusion-Product Heating and Variable Plasma Enthalpy Endloss. The endloss parameter, x_L , describing the fraction of the plasma radius where electron conduction occurs, while in principle dependent on radial field profiles, was equated to unity for the point-of-departure case. The dependence of Q_p on x_L is shown on Fig. 5 for a case where $a_0 = 40$ μm , and $V_p = 2$ kV; values of $x_L \leq 0.5$ are needed to provide a level of energy drain that is sufficient to shed the full ($f_{\alpha} = 1.0$) alpha-particle heating rate to an extent needed to turnaround

the adverse fusion-product-driven expansion. Again, the impact of constraining the system to $\dot{I} > 10^{12}$ A/s more than halves the Q_p value, with little impact on τ_D , which for this larger-radius pinch is in the 400-500 ns range.

Fig. 7. Dependence of Q_p and discharge time on initial plasma radius for the point-of-departure case (Fig. 3).

4. Electrode Impurities. If the electrode material were liquid lithium metal, the ion transit time from the electrode to the pinch midplane at $T_{\alpha} \approx 6$ keV is $\tau_i \sim 120$ ns for $L_p = 0.1$ m; hence, according to Fig. 6, voltages in excess of ~ 5 MV may be desirable to assure that $\tau_D \leq \tau_i$ in order that the ingress of electrode material have minimal impact on the burn. In order to examine this supposition quantitatively, an electrode-material ingress model was developed.¹⁹ In this model, the conduction energy delivered to each electrode in a given time increment is assumed to appear as ionized electrode material in the vicinity of the electrode but at the mean plasma temperature existing at that time. The ionized electrode material created from each electrode at a given time is assumed to join the zero-dimensional plasma and contribute to the Z_{eff} after it has moved one-fourth of the pinch length at the thermal velocity $v_i \approx (2k_B T/m_i)^{1/2}$. Although highly approximate, this electrode-ablation, plasma-contamination model gives an indication of the discharge time scale on which the higher-Z electrode material would move into the central parts of the pinch and, by increasing Z_{eff} and Z_{AVE} , effect pressure and energy balance through the usual terms.

Figure 9 gives time history of Q_p for this constant $V_p = 2$ MV case with and without electrode evaporation and ingestion. The difference between $Q_p(\dot{I} \geq 10^{12}$ A/s) and $Q_p(\text{unconstrained})$ for $V_p = 2.0$ MV is shown; when no electrode effects modeled and $\dot{I} > 10^{12}$ A/s, the value of Q_p is actually improved by the electrode material entering the plasma. The time dependence of Z_{eff} and f_{α} are also shown on Fig. 9. It is not until well into this discharge does the inventory of electrode material in plasma actually begin to match that which is evaporated ($f_{\alpha} \rightarrow 1$), but before this can happen, the pinch collapses, the electrode erosion rate for a brief time dramatically increases, but this material has not had sufficient time to stream into the core plasma. This general improvement of Q_p with electrode evaporation/ingression included is observed¹⁹ for a range of discharge voltage, and is apparently results from a delicate

Fig. 8 Dependence of Q-value and discharge time and degree of endloss (x_L) for large-initial-radius case, but otherwise with point-of-departure (Fig. 6) conditions, but with a_0 increased to $40 \mu\text{m}$.

balance between voltage and pressure balance, with the arrival of electrode impurities into the pinch actually preventing the current from decreasing dramatically. Generally, inclusion of these electrode effects compresses the discharge time while increasing the Q-value significantly, particularly if the $I > 10^{12} \text{ A/s}$ constraint is applied (Fig. 9).

Fig. 9. Time dependence of Z_{eff} , fraction of electrode evaporation entering plasma, and plasma radius with and without electrode evaporation/ingression.

IV. CONCLUSIONS

High-Q DT burns in DZPs should be possible if these $t_p \approx 0.1 \text{ m}$, $a_0 \approx 20 \text{ }\mu\text{m}$ pinches can be held stable for times on the order of 100s of nanosecond ($N_A \approx 10^4$ radial Alfvén transit times) under conditions of

rapidly decreasing line density cause by significant fuel burnup ($f_B \approx 0.9$) and for small, values of I . While fusion-product heating alone may destroy the pinch before significant burnup, yield, and Q_p can be achieved, self-heating in the presence of plasma enthalpy endloss counteracting effects, with little impact of the pinch performance. Ingression of low-Z (Li) electrode material may have a net beneficial effect, which is seen in the context of this simplified model as an extension of the high-Q operating regime where $I > 10^{12} \text{ A/s}$; other more subtle effects of higher-Z impurity influx along the pinch axis during the later, high-temperature phases of the discharge may have positive implications for MHD stability in the fusion-producing phase of the 200-400 ns discharge. Achievement of reactor-relevant Q-values for the DD and D³He fuel cycle¹⁹ will require reversible energy transfer/storage (ETS) with efficiencies in the range. The application of ETS systems to the DT fuel cycle would reduce the requirements on burn time and burnup by a factor 3-4. Lastly, the DT point-of-departure case for $Q_p \approx 1$ generates $S_N \approx 10^{17}$ neutrons (few percent burnup), which if pulsed at a rate $\sim 10\text{-}100 \text{ Hz}$, would provide a DT fusion source with same interact for fusion nuclear materials testing,^{15,25} albeit the pulsed nature and related (neutron) flux-compression effects give some concern to materials scientist.²⁵

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