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Z-Pinch Plasma Neutron Sources

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14. ABSTRACT

A deuterium gas-puff load imploded by a multi-MA current driver from a large initial diameter could be a powerful source of fusion neutrons, a plasma neutron source. Unlike the beam-target neutrons produced in Z-pinch plasmas in the 1950s and deuterium-fiber experiments in the 1980s, the neutrons generated in deuterium gas-puffs, with current levels achieved in recent experiments on the SNL Z facility, could contain a substantial fraction of thermonuclear origin. For recent deuterium gas-puff shots on Z, our analytical estimates and 1-D and 2-D simulations predict thermal neutron yields $\sim 5 \times 10^{13}$, in fair agreement with the yields measured on Z. It is demonstrated that the hypothesis of a beam-target origin of the observed fusion neutrons implies a very high Z-pinch-driver-to-fast-ions energy transfer efficiency, 5 to 10%, which would make a multi-MA deuterium Z-pinch the most efficient light-ion accelerator. No matter what mechanism is eventually determined to be responsible for generating fusion neutrons in deuterium gas-puff shots on Z, the neutron yield is shown to scale as $Y_m \sim I_m^4$ where I_m is the peak current of the pinch. Theoretical estimates and numerical modeling of deuterium gas-puff implosions demonstrate that the yields of thermonuclear fusion neutrons that can be produced on ZR and the next generation machines are sufficiently high to make Plasma Neutron Sources (PNS) the most powerful, cost- and energy-efficient laboratory sources of 2.5 to 14 MeV fusion neutron, just like Plasma Radiation Sources (PRS) are the most powerful sources of soft and keV x-rays. In particular, the predicted neutron-producing capability of PNS driven by ZR and ZX accelerators, from $\sim 6 \times 10^{16}$ to $\sim 10^{18}$ matches the projected capability of the NIF laser at thermonuclear energy gains of 1 and 20, respectively.

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A deuterium gas-puff load imploded by a multi-MA current driver from a large initial diameter could be a powerful source of fusion neutrons, a plasma neutron source. Unlike the beam-target neutrons produced in Z-pinch plasmas in the 1950s and deuterium-fiber experiments in the 1980s, the neutrons generated in deuterium gas-puffs with current levels achieved in recent experiments on the SNL Z facility could contain a substantial fraction of thermonuclear origin. For recent deuterium gas-puff shots on Z, our analytic estimates and 1-D and 2-D simulations predict thermal neutron yields ~5×10^{13}, in fair agreement with the yields measured on Z. It is demonstrated that the hypothesis of a beam-target origin of the observed fusion neutrons implies a very high Z-pinch-driver-to-fast-ions energy transfer efficiency, 5 to 10%, which would make a multi-MA deuterium Z-pinch the most efficient light-ion accelerator. No matter what mechanism is eventually determined to be responsible for generating fusion neutrons in deuterium gas-puff shots on Z, the neutron yield is shown to scale as $Y_n \sim I_m^4$, where I_m is the peak current of the pinch. Theoretical estimates and numerical modeling of

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I. INTRODUCTION

The idea of using deuterium Z-pinch plasmas to generate fusion neutrons is not new. In fact, the quest for controlled thermonuclear fusion started in the early 1950s from experiments with deuterium Z-pinches. This research was launched back then in parallel, almost simultaneously, with the development of thermonuclear weapons, which employ artificial self-sustained fusion reactions on a much larger scale. Such weapons were first successfully tested in 1952-1953. The first nuclear fission weapon was tested shortly before that, in 1945, less than three years after E. Fermi brought on line the first artificial nuclear fission reactor. With nuclear fusion, it was the other way around: The bomb was built first, and the researchers were confident that a controlled fusion reactor was to follow in the not-too-distant future. The first observations of DD fusion neutron yields from linear Z-pinches reported by the U.S., Soviet and European laboratories [1-5] supported this optimistic view. Deuterium Z-pinches were studied then as prototypes of magnetic confinement fusion reactors.

This early optimism, however, did not last long. It was soon understood that the observed fusion neutrons were not thermonuclear. Rather, the neutrons were produced in Z-pinch plasmas by relatively small quantities of "beam" deuterium ions accelerated in the direction of the current, in the strong electric fields accompanying the development of the "sausage" $m = 0$ instability of the pinch, to energies of 50-200 keV. Colliding with the deuterium plasma ions, whose temperature was much lower, the beam ions produced fusion neutrons, which were thereby not thermonuclear [6, 7]. As summarized in Ref. 6, "*The denial of the optimistic conclusion of a thermonuclear yield despite so many favorable results was indeed a sobering experience.*" Since then, linear Z-pinches as magnetic confinement fusion devices have been abandoned for good in favor of toroidal systems, primarily tokamaks.

The next time nuclear fusion reactions in Z-pinches attracted attention was in the late 1980s, when substantial neutron yields were observed from frozen deuterium fiber pinches heated by sub-microsecond long, 1-MA-range current pulses [8-10]. These findings at the time gave rise to some new optimism about the prospects of a linear Z-pinch as an inertial (rather than magnetic) confinement thermonuclear reactor operating at about the 1 MA current level [11-13]. Again, this did not work out as hoped because the neutrons produced in deuterium fiber pinches turned out to be of beam rather than thermonuclear origin [9]. After this fact had been established, all efforts to develop a nuclear fusion device based on the direct heating of a Z-pinch plasma were abandoned. The research of the ICF Z-pinch community since then has focused on the indirect-drive approach to fusion, with the sub-keV, high-atomic-number Z-pinch plasma serving as a source of soft x-rays that heat a hohlraum, see [14] and references therein.

New opportunities for nuclear fusion in Z-pinch plasmas emerged very recently as a result of rapid progress in the development of multi-keV plasma radiation sources (PRS). Record-high radiation yields, ~300 kJ in Ar at 3 keV [15] and ~400 kJ in Al at 1.7 keV [16] have been obtained on the Z accelerator at SNL with aluminum nested wire arrays and argon double shell gas puffs driven by 15-20 MA, 100 ns current pulses. To produce multi-keV photons, plasma electrons are heated to keV temperatures. The primary energy source for heating the electrons is the thermal energy of the plasma ions, which in PRS shots are routinely heated to tens and hundreds of keV at stagnation. PRS plasmas thereby contain the highest-temperature ions, compared to the plasmas heated by any other laboratory devices, including those specifically designed for thermonuclear fusion experiments, like tokamaks or lasers. Recall that a multi-keV temperature of deuterium ions is exactly what is needed for fusion. It is natural to inquire if the existing PRS technology could be applied for this purpose.

The answer to this question appears to be positive. Our theoretical estimates and simulation results indicate that thermonuclear DD neutron yields in the range of $(3-5)\times 10^{13}$ could be obtained on the Z accelerator if argon in the gas-puff load used in [15] was replaced with deuterium. This range is consistent with the neutron yields measured in the first deuterium pinch experiments on Z [17] that used the same gas-puff hardware as in argon shots of [15]. To put these results in perspective, compare them to the highest DD neutron yields from spherical deuterium-filled capsules imploded by laser radiation (2×10^{11} obtained on the OMEGA laser at LLE [18]) and x-rays (3.4×10^{10} obtained in a dynamic hohlraum on Z at Sandia [19]), Fig. 1. The neutron yields measured in the first deuterium shots on Z (for which the origin of neutrons has not yet been established) and our estimates of thermonuclear neutron yields made for Z exceed

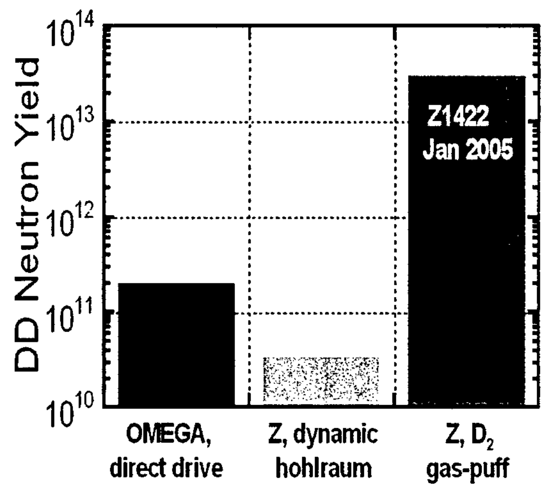

Figure 1. The highest deuterium fusion neutron yields obtained with D_2-filled plastic capsules directly driven by OMEGA laser [18] and indirectly driven by dynamic hohlraum on Z [19] compared to the yield from gas-puff Z-pinch plasma [17]. Capsule neutron yield is thermonuclear; the origin of neutrons from Z-pinch plasma has not yet been established.

these record-high values by two and three orders of magnitude, respectively! Making similar estimates for DT gas-puff implosions on the refurbished ZR accelerator (26 to 30 MA, 100ns [20]), we predict neutron yields of $\sim 6\times10^{16}$, close to the thermonuclear DT neutron yield that could be reasonably expected in the future from indirect-drive implosions on the NIF laser presently under construction at LLNL [21] - a driver, which, when completed, will be incomparable with ZR in terms of complexity and cost.

Z-pinch plasmas are presently the most powerful and energy-efficient laboratory sources of x rays. The new findings show promise that deuterium and deuterium-tritium Z-pinches driven by ZR in the near term, and by the next-generation 40-60 MA machines in the more distant future, can become the most powerful laboratory sources of fusion neutrons. Of course, further study is needed before any definite conclusion can be made. The brief history of Z-pinch fusion in the 1950s and 1980s outlined above serves us as a reminder to be cautious. When discussing fusion neutron generation in the Z-pinch, one has to be sober from the start rather than risking exposure to yet another "*sobering experience.*" If there are, as we believe, new reasons for optimism, then we need to explain why they did not exist previously and elucidate the physics they are based on. This is done in Section II of this report. In Section III we present our numerical predictions for thermonuclear neutron yields that could be obtained now on Z and in the future on ZR, obtained from our 1D and 2D RMHD simulations. In Section IV we conclude with a discussion.

II. THEORY

A. Evidence of beam-target origin of fusion neutrons in quasi-steady Z-pinch plasmas

The conventional mechanism of neutron production in a Z-pinch plasma column is associated with the acceleration of a small number of deuterium ions in the electric field near one or more of the "necks" developing in the pinch plasma due to the $m = 0$ MHD sausage instability, as in the earlier experiments [6, 7, 9]. A beam of these fast ions propagates along the pinch axis, in the direction of the current. Assuming that the average energy of the beam ions E_b is much greater than the ion temperature T_i of the plasma, we note that when the accelerated beam ion hits the thermal "target" ion in the plasma, the average center-of-mass velocity of the two reacting deuterium ions is $v_b / 2$, where $v_b = \sqrt{2E_b / m_D}$ is the average velocity of the beam ion. In this center-of-mass frame of reference, the fusion neutrons are emitted isotropically. Isotropy in the moving frame of reference leads to observable anisotropy of the neutron emission in the laboratory frame of reference.

This anisotropy manifests itself in two ways, both of which have been used to test the origin of the fusion neutrons. One method is based on the observation that the average velocity of the fusion neutrons in the direction of the beam exceeds their velocity in transverse direction by the average center-of-mass velocity, $v_b / 2$. Therefore the time-of-flight delay between the signals registered by two neutron detectors located at the same distance L from the pinch plasma in axial and radial directions is

$$\Delta t = \frac{L}{v_n} - \frac{L}{v_n + \frac{1}{2}v_b} \cong \frac{L}{2v_n^2}\sqrt{\frac{2E_b}{m_D}} = \frac{L\sqrt{E_b m_n}}{4E_n}$$
$$= 10.4 \times L(\mathrm{m}) \times \sqrt{E_b(\mathrm{MeV})}\ \mathrm{ns}, \tag{1}$$

where the initial neutron energy for DD fusion reaction is $E_n = 2.45$ MeV and $v_n = \sqrt{2E_n / m_n}$. For example, the delay of 18 ns measured by neutron detectors located at a distance $L = 6$ m from the pinch corresponds to the measured "center-of-mass energy" of 18 keV [9], which implies the ion beam energy $E_b = 72\,\mathrm{keV}$. This result demonstrated that the 4×10^9 neutrons produced from a Z-pinch plasma at 0.6 MA current in the deuterium fiber experiment [9] were of beam-target origin. A similar conclusion based on time-of-flight neutron measurements had been made about the 2×10^{12} neutron yield obtained at 2 MA on Angara-5-1 facility [22].

Anisotropy of the neutron emission also manifests itself in the dependence of the neutron flux density on the angle θ between the directions of the ion beam and the neutron emission in the laboratory frame of reference. To make an estimate, note that the isotropy of the neutron emission in the center-of-mass frame of reference means that the density of the neutron flux is independent of the angle, $dY_n / d\Omega_0 = Y_n / 4\pi$. Here Y_n is the neutron yield, $d\Omega_0 = 2\pi \sin\theta_0 d\theta_0$ is the element of solid angle, and θ_0 is the angle between the directions of the ion beam and the neutron emission in the center of-mass frame of reference. The angles θ_0 and θ are related by [23]

$$\tan\theta = \frac{v_n \sin\theta_0}{v_n \cos\theta_0 + v_b / 2}. \tag{2}$$

Expressing θ_0 via θ with the aid of (2) and noticing that the element of solid angle in the laboratory frame of reference equals $d\Omega = 2\pi \sin\theta d\theta$, we conclude that

$$\frac{dY_n}{d\Omega} = \frac{Y_n}{4\pi} \times \left[\frac{1 + \left(v_b^2 / 4v_n^2\right)\cos 2\theta}{\sqrt{1 - \left(v_b^2 / 4v_n^2\right)\sin^2\theta}} + \frac{v_b}{v_n}\cos\theta \right]$$
$$\cong \frac{Y_n}{4\pi} \times \left[1 + \sqrt{\frac{E_b}{2E_n}}\cos\theta + \frac{E_b}{32E_n}\left(3\cos 2\theta + 1\right) \right]. \quad (3)$$

In deriving (3), we assumed $v_n > v_b / 2$, $m_n \cong m_D / 2$, $E_b << 2E_n$, and neglected the thermal motion of the plasma ions. From (3) we obtain that the axial emission of fusion neutrons exceeds the radial emission by a factor of

$$\frac{\left(dY_n / d\Omega\right)_{\theta=0^\circ}}{\left(dY_n / d\Omega\right)_{\theta=90^\circ}} \cong 1 + \sqrt{\frac{E_b}{2E_n}} + \frac{3E_b}{16E_n}. \quad (4)$$

For E_b increased from 72 keV, as in [9], to 1 MeV, the right-hand side of (4) increases from 1.13 to 1.53. Therefore, the beam-target origin of the observed fusion neutrons can be established by comparison of the radial and axial emission. It should be noted that requirement for the accuracy of such a measurement is higher than for the time-of-flight measurement. For example, to establish from (4) the beam-target origin of neutrons observed in the Z-pinch plasma deuterium fiber experiment [9] with $E_b = 72$ keV, the neutron emission in each direction needs to be measured with uncertainty much lower than 10%.

Observed anisotropy of the DD fusion neutron emission is direct evidence of its beam-target origin. This observational conclusion is consistent with the theoretical and numerical estimates of thermonuclear neutron yields, which are very low for most of the experiments where neutrons were produced in a Z-pinch plasma. For example, the thermal neutron yield estimated for the conditions of the experiment [9] from the Bennett temperature, $T_i = 53$ eV, is about 2 neutrons per shot. On the other hand, as shown in Section II.D below, the energy and current of the ion beam are very small compared to the energy of the pinch plasma and the current flowing through it, respectively, the fusion neutron yield being the main observable manifestation of the beam. Similar estimates could be made for the experiments [1-8, 22]. The reason why quasi-steady Z-pinch plasmas could never work as thermonuclear fusion systems is that there seems to be no way of heating the bulk of plasma ions to multi-keV temperatures. The current flowing in a steady Z-pinch primarily heats electrons. The electron-ion equilibration time rapidly increases with the electron temperature, so the ions never get heated to keV temperatures this way.

B. Thermonuclear fusion conditions produced in fast Z-pinch plasmas

The above limitation on the ion temperature in Z-pinch plasmas clearly does not apply to the Z-pinch-based plasma radiation sources (PRS). These are dynamic pinches that are imploded at high velocities to produce keV x-rays [15, 16, 24-28]. The goal of heating Z-pinch plasmas to multi-keV temperatures always remained and still is essential for this particular application. It is not possible to generate K-shell emission of Ar, Ti or Fe at $h\nu = 3$, 5 and 7 keV, respectively, from a Z-pinch plasma unless the electrons are heated to the temperature of ~1.5 to 3 keV. The primary energy source for heating the electrons is the thermal energy of the ions. First the kinetic energy of the ions gets rapidly converted into heat at stagnation, and then the ion temperature increases further to tens or hundreds of keV in the adiabatic compression that follows. The implosion velocities needed for it are about 10^8 cm/s, substantially higher than those specified for the ICF capsules, ~3×10^7 cm/s [29]. For example, the Fe ion temperature $T_i = m_i V^2/3$ corresponding to a full thermalization of its kinetic energy $E_i = m_i V^2/2$ equals 193 keV for $V = 10^8$ cm/s. Iron ion temperatures measured in recent experiments from Doppler broadening of their K-lines were found to be in the range 250-400 keV [27], that is, exceeding the value of E_i by a factor of 1.3-2, most likely because of adiabatic heating.

What if the imploded load consists of deuterium? The kinetic energies and temperatures are proportional to the ion mass. Since a D ion is lighter than an Fe ion by a factor of 28, the Fe ion temperature range of 250 to 400 keV translates for deuterium into 9 to 14 keV (around 10 keV), which is well in the fusion energy range we are interested in. To make plasma radiation sources work, we have to transfer the ion thermal energy to the electrons, which is increasingly difficult for higher-atomic-number elements. To produce thermonuclear fusion, heating the ions is sufficient. Is it possible therefore to develop plasma *neutron* sources (PNS) that operate essentially in the same way as PRS?

It is difficult or maybe even impossible to directly reproduce a wire array implosion, as in [16, 25-27], by replacing metal wires with frozen deuterium fibers. First, the technology of extruding high-quality cylindrical fiber arrays from a frozen deuterium is not available. Second, it is not at all certain that such an array, if loaded into a high-current machine, would implode: Recent experiments on MAGPIE with arrays of dielectric deuterated polystyrene (CD) fibers [30] indicate otherwise.

The most promising load for producing hot deuterium ions in a Z-pinch is therefore a gas-puff. Gas-puff loads have proven to be no less efficient in generating K-shell radiation than wire arrays [15]. Stability of gas-puff implosions seems to be even better than that of wire array loads: Multiple-shell gas-puffs were shown to produce tight pinches and considerable K-shell yields when imploded from large outer diameters, from 8-12 cm [15, 28] up to 16 cm [31].

The first experiments in the relevant range of current amplitudes and implosion velocities were performed in late 1990s on the Saturn accelerator at Sandia [32]. Some of these experiments were done with annular, 1.5-cm diameter cylindrical arrays, each consisting of 48 25-μm diameter fibers of deuterated polyethylene, the other - with 2.5 to 3.5-cm diameter single-shell gas-puff deuterium loads. Consistent with the later findings of [30], the CD fiber arrays produced very low neutron yields – they probably did not implode well. On the contrary, the gas-puff loads were accelerated by the 7 MA, 60-ns Saturn current pulses to radial velocities up to $\sim 10^8$ cm/s, producing neutron yields of $\sim 2.5\times 10^{12}$.

Although these neutron yields are very large by today's ICF standards (cf. Fig. 1), the importance of the results of [32] is not mainly determined by the high values of observed neutron yields. After all, yields of this magnitude have been reproduced at much lower currents, 2 MA in the experiments on Angara-5-1 [22], where the beam-target mechanism was responsible for neutron production. Rather, [32] might have been the first experiment to produce a deuterium Z-pinch plasma whose temperature and density, according to their 0-D and 1-D estimates, were high enough to generate a substantial number of thermal fusion neutrons, of the order of the total observed yield. This has never been the case before. Admittedly, the origin of the fusion neutrons has not been unambiguously determined in the experiments [32]. No anisotropy of the neutron yield was seen, which is not inconsistent with the hypothesis of the thermal origin of the neutrons but, given the experimental uncertainty, does not prove it conclusively, as explained in Section II.A.

Thermonuclear neutron yield from a Z-pinch plasma scales with current as I^4, like the K-shell x-ray yield in an "inefficient regime" of implosion [33], and for the same reason, see Section II.C below. The peak current of the Z accelerator exceeds the Saturn current by about a factor of 2 to 2.4, so the thermal neutron yield scaled up to Z conditions from the results of [32] is $(4 \text{ to } 8)\times 10^{13}$. Let us see if the implosion of a gas-puff load on Z can produce stagnated deuterium plasma which is sufficiently hot and dense to generate thermonuclear neutron yields of this order.

C. Estimates of thermonuclear DD neutron yield for Z

The thermonuclear neutron yield from a stagnated Z-pinch column is estimated as

$$Y = \frac{1}{4} n_i^2 \langle \sigma v \rangle \pi R^2 l \tau , \qquad (5)$$

where $n_i = \mu / \left(\pi R^2 m_D\right)$ is the deuterium ion number density in the pinch plasma (μ is the line mass of the load), $\langle \sigma v \rangle$ is the averaged ion-temperature-dependent DD fusion reaction rate, R and l are the compressed pinch radius and length, respectively, τ is the confinement time of the dense pinch, and the factor ¼ is the product of the factor ½, introduced because the colliding ions are identical, and the branching ratio ½ between $D+D \rightarrow He^3+n$ and $D+D \rightarrow T+p$ reactions, of which only the former produces a neutron.

To use (5) for making an estimate of the thermonuclear neutron yield for an implosion of a deuterium gas-puff from a 8 cm initial diameter characteristic of the 1234 nozzle, the same nozzle as successfully used in the Ar gas-puff shots on Z [15], we have first to estimate the parameters of the stagnated plasma column. Imploded deuterium plasma does not lose much of its energy through radiation, and therefore one does not expect a greater than, say, 10-fold radial compression of the pinch; hence we take $R = 4$ mm. For the line mass of the load $\mu = 0.5$ mg/cm roughly corresponding to the conditions of shot Z1422 [17] this final radius corresponds to an ion number density $n_i = 3\times10^{20}$ cm^{-3}. The energy imparted to the plasma in the implosion is estimated as

$$\Delta E = \frac{1}{2}\int I^2 dL \cong a\times\frac{1}{2}I_m^2\Delta L = a\times I_m^2(\text{MA})\ln\frac{R_0}{R}\ \text{kJ/cm}. \tag{6}$$

Here, R_0 is the initial outer radius of the gas puff, I_m is the peak current and $a<1$ is the dimensionless factor accounting for the current pulse shape (obviously, $a=1$ for a constant current $I(t) = I_m = const$; here and below we use the value of $a = 0.6$ accepted for a sine-shaped current waveform [34]). Substituting into (6) the compression ratio $R_0/R = 10$ and the value of $I_m = 17$ MA appropriate for the shot Z1422 [17], we find: $\Delta E = 400$ kJ/cm. Note that this value is slightly larger than the kinetic energy E_k estimated for the above values of line mass $\mu = 0.5$ mg/cm and velocity $V = 10^8$ cm/s, $E_k = 250$ kJ/cm. It indicates that some of the work done by the magnetic field on the plasma is pdV work near stagnation that increases the plasma temperature adiabatically. The confinement time at the high-density stagnated state is conservatively estimated as $\tau = R/V = 4$ ns. Neglecting the radiation losses from deuterium, we estimate the temperature of the plasma from the energy balance equation

$$\frac{3}{2}n_i(T_i+T_e)\times\pi R^2 = \Delta E\,. \tag{7}$$

Substituting $R = 4$ mm, $n_i = 3\times10^{20}$ cm^{-3} and $\Delta E = 400$ kJ/cm into (7), we find: $T_i + T_e = 11$ keV. The ion-electron temperature equilibration time for deuterium is

$\tau_{ei} \cong 2\times10^{12} T_e^{3/2}(\text{keV})/n_i$. For the above value of $n_i = 3\times10^{20}$ cm^{-3}, we obtain: $\tau_{ei} = 6.7$ ns and 19 ns for $T_e = 1$ keV and 2 keV, respectively. Comparing these values with τ, we find that thermal equilibration during the confinement time can only heat electrons to some temperature below 2 keV. In other words, the ions remain at a high temperature, derived from their kinetic energy and subsequent adiabatic compression, during most of the confinement time; they are not confined long enough to cool down to $T_i = T_e$. Therefore our reference value of $T_i = 10$ keV is a reasonable estimate that we will use below. Note that the equilibrium Bennett temperature corresponding to the current $I = I_m = 17$ MA and mass $\mu = 0.5$ mg/cm is lower than the quoted ion temperature: $(T_i + T_e)_B = I_m^2 m_D / 2\mu c^2 = 6$ keV. Stagnated deuterium plasma, due to its low radiation energy losses, is not at steady-state pressure equilibrium with the magnetic field of the current confining it: immediately after stagnation the pinch bounces.

When the ion temperature is increased from 5 to 10 keV, the total DD fusion reaction rate $\langle \sigma v \rangle$ averaged over the Maxwellian distribution of ions increases from 1.8×10^{-19} to 1.2×10^{-18} cm^{3}s^{-1} [35]. Substituting these values and $n_i = 3\times10^{20}$ cm^{-3}, $R = 4$ mm, $l = 2$ cm, $\tau = 4$ ns into (5), we find an estimate for the thermal neutron yield ranging from 1.6×10^{13} to 10^{14}. This estimate is consistent with the I^4-scaling extrapolation from the Saturn results [32], see Section II.B. It is also in fair agreement with the experimental results recently obtained on Z [17]. This estimate indicates that a good fraction if not most of the fusion neutrons produced in the deuterium gas-puff implosions on Z could be of thermonuclear origin.

It should be noted that using the tabulated values of $\langle \sigma v \rangle$ from [34] we can overestimate the predicted thermal fusion yield by assuming a Maxwellian distribution of the plasma ions. The averaging over the Maxwellian distribution implies the existence of its high-energy tail. The cross-section σ of the thermonuclear fusion reaction is a rapidly increasing function of relative kinetic energy of the colliding ions, which is why in plasmas whose ion temperatures T_i are below or of order 10 keV most of the ion collisions resulting in fusion involve ions that belong to this high-energy tail. It takes several collision times to form the Maxwellian distribution of ions; if our confinement time is less than that, then the high-energy tail is not formed. Let us estimate how much the neutron yield from a deuterium gas-puff implosion could be overestimated for Z conditions.

The ion-ion mean free path in deuterium is $l_{ii} = 3\times 10^{18} T_i^2(\text{keV})/n_i$. For $n_i = 3\times 10^{20}$ cm^{-3}, we find $l_{ii} = 0.1$ mm, 1 mm and 1 cm at $T_i = 1$ keV, 3 keV and 10 keV, respectively. The collision time for $T_i = 10$ keV is $\tau_{ii} = l_{ii}/v_{Ti} = 8$ ns. This estimate demonstrates that deuterium ions heated to ~10 keV are not collisional inside the stagnated plasma column whose radius is 4 mm, where they are confined for about 4 ns. Of course, these ions cannot leave the plasma in the radial direction: both the electric field due to the charge separation and the magnetic field of the pinch current (in which the ion Larmor radius is much less than the plasma radius, see below) will prevent it. Adiabatic compression heats the collisionless ions in the same way as collisional ions; in the collisionless situation it is sometimes referred to as the Fermi acceleration mechanism. In our weakly collisional case, however, there is not enough time to form the high-energy tail of the ion Maxwellian distribution.

Radial implosion and adiabatic compression of the pinch accelerate the ions. Ions with higher-than-average kinetic energy are known to make a disproportionally high contribution to the thermal neutron yield; therefore, to make a conservative estimate, we assume that there are no such ions. It means that all the ions have the same kinetic energy $E_0 = m_D v_0^2 / 2$, only the direction of their velocity v_0 is random. Denoting the angle between two colliding ions by θ, we find their relative velocity $v_r = 2v_0 \sin(\theta/2)$; the corresponding kinetic energy of collision (assuming the incident ion hitting the target ion, which is at rest) is $E = m_D v_r^2 / 2 = 4E_0 \sin^2(\theta/2)$.

The collisionless ions are accelerated by the converging plasma shell primarily in the horizontal plane perpendicular to the pinch axis. Supposing the direction of the relative velocity is uniformly distributed over the angle θ between 0 and 2π, we calculate the average reaction rate:

$$\langle \sigma v \rangle_{\text{collisionless2D}} = \frac{1}{\pi}\int_0^{\pi} d\theta \times \sigma(E) v_r(\theta) = \\ = \frac{2}{\pi}\left(\frac{2E_0}{m_D}\right)^{1/2} \int_0^{\pi} d\theta \times \sigma\left(4E_0 \sin^2(\alpha/2)\right) \sin(\theta/2). \tag{8a}$$

Even though the deuterium ions in the absence of collisions are preferentially accelerated in the horizontal plane, we can make another estimate of the averaged reaction rate supposing that the direction of the relative velocity is uniformly distributed over the solid angle 4π, and we thereby calculate the reaction rate averaged over the collision angle θ:

$$\langle \sigma v \rangle_{\text{collisionless3D}} = \frac{1}{4\pi}\int_0^{2\pi} d\phi \int_0^{\pi} \sin\theta d\theta \times \sigma(E) v_r(\theta) = \frac{1}{2}\int_0^{\pi} \sin\theta d\theta \times \sigma(E) v_r(\theta) \\ = \left(\frac{2E_0}{m_D}\right)^{1/2} \int_0^{\pi} d\theta \times \sigma\left(4E_0 \sin^2(\alpha/2)\right) \sin\theta \sin(\theta/2). \tag{8b}$$

Compare this to the conventional averaging over the Maxwellian distribution [36]. Here, the averaging over the angles between the colliding ions is done analytically, and the remaining integration is over the relative kinetic energy:

$$\langle \sigma v \rangle_{\text{collisional}} = \frac{T_i^{-3/2}}{(\pi m_D)^{1/2}} \int_0^\infty dE \times \sigma(E) E \exp(-E/2T_i). \tag{9}$$

The cross-section of the neutron-producing reaction D+D→He^3+n is approximated by the fitting formula

$$\sigma(E) = \frac{A_2}{E\left[\exp\left(A_1 E^{-1/2}\right)-1\right]\left[\left(A_4 - A_3 E\right)^2 + 1\right]} \times 10^{-24} \text{ cm}^2, \tag{10}$$

where the Duane coefficients are $A_1 = 47.88$, $A_2 = 482$, $A_3 = 3.08 \times 10^{-4}$, $A_4 = 1.177$, and E is expressed in keV [35].

Substituting $T_i = 5$ and 10 keV into (9) and performing numerical integration, we obtain reaction rates 9×10^{-20} and 6.3×10^{-19} cm^3s^{-1}, respectively, indeed very close to ½ of the total DD fusion reaction rates for these temperatures quoted above. Assuming the average kinetic energy of the ion to be the same in both the collisional (when $\langle E_i \rangle = 3T_i/2$) and collisionless cases, we substitute into (8a) $E_0 = 7.5$ and 15 keV and perform numerical integration to estimate reaction rates for collisionless ions as 4.9×10^{-20} and 5.3×10^{-19} cm^3s^{-1}, respectively. They are less than the corresponding reaction rates for a Maxwellian distribution of ions by factors of 1.8 and 1.2, respectively. A similar estimate for the averaging (8b) yields the reduction factors of 2.6 and 1.5, respectively. Introducing these larger reduction factors into our estimates of thermal neutron yields, we decrease the predicted values to the range between 6×10^{12} and

7×10^{13}. These estimates of the thermonuclear neutron yields are in same ballpark and still consistent with the results of [17].

For given nozzle dimensions and compression ratio, the ion mean free path is inversely proportional to the line mass μ of the load. Higher-current drivers will be able to accelerate larger masses to the same velocities, $\mu \propto I_m^2$, implying that the ion mean free path at stagnation will decrease as $l_{ii} \sim I_m^{-2}$. For example, peak current on the refurbished ZR accelerator will increase in comparison to Z by a factor of roughly $\sqrt{2}$, which translates into a 2-fold decrease of ion mean free path to about 5 mm. Consequently, the thermonuclear neutron yield from DD gas-puff implosions on ZR will be somewhat reduced due to low collisionality of the hot ions, but by a smaller factor than on Z. For the 40-60 MA next-generation machine, this correction will be negligible.

According to (5), the neutron yield scales as $n_i^2 \propto \mu^2$. For matched implosions, line mass of the load scales as current squared, $\mu \propto I_m^2$, which implies $Y_n \propto I_m^4$. This scaling predicts an increase of the neutron yield by about a factor of 4 for the current increase of 1.4 roughly corresponding to a comparison between Z and ZR. In addition to that, as discussed above, higher density of the stagnated plasma makes the ions more collisional, forming the high-energy tail of Maxwellian distribution. Our hydrodynamic simulations are based on collisional MHD for ions (Section III), hence the resulting predictions of the thermonuclear neutron yield are more reliable in this high-current, high-density limit.

D. Plasma neutron sources can be driven by ion beams

Now consider the mechanism of fusion neutron production in a Z-pinch plasma which is alternative to thermal - the beam-target mechanism, which is responsible for neutrons observed in the experiments [1-7, 9, 22]. Below we estimate the ion beam current required to generate the neutron yield Y_n observed on Z and demonstrate that it is unusually large compared to the driver current, in sharp contrast with the earlier experiments.

The distance traveled by an average beam ion before it produces a neutron in the fusion reaction is

$$l_{bf} = \frac{1}{\sigma(E_b)n_i}, \tag{11}$$

where $\sigma(E_b)$ is the reaction cross-section given by (10). For example, varying E_b between 100 keV and 1 MeV for $n_i = 3\times10^{20}\,\text{cm}^{-3}$ we obtain l_{bf} cm ranging from 1.9 km to 430 m. But the maximum distance that a beam ion can travel inside the pinch plasma in the axial direction is the length of the pinch l. Therefore to produce one neutron, we need l_{bf}/l fast ions in the beam. For the same density as in the above example, with l_{bf} ranging from 1.9 km to 430 m and $l = 2\,\text{cm}$, this translates into 95 to 21 thousand accelerated beam ions per detected neutron. Each ion carries electron charge e, and most of the neutrons are produced by the beam during the time τ while the pinch remains confined near the axis, so we can estimate the beam current as

$$\begin{aligned} I_b &= Y_n \times \frac{l_{bf}}{l} \times \frac{e}{\tau} = \frac{eY_n}{\sigma(E_b)n_i l\tau} = \frac{\pi R^2 m_D e Y_n}{\sigma(E_b)\mu l \tau} \\ &= 1.68\frac{R(\text{mm})^2}{\mu(\text{mg/cm})l(\text{cm})\tau(\text{ns})\left[\sigma(E_b)/10^{-25}\,\text{cm}^2\right]}\left(\frac{Y_n}{10^{13}}\right)\text{MA}. \end{aligned} \tag{12}$$

Since each of the total number of fast non-thermal ions $l_{bf} Y_n / l$ carries energy E_b, the total energy coupled to these ions is estimated as

$$
\begin{aligned}
W_b &= \frac{\pi m_D Y_n E_b R^2}{\sigma(E_b)\mu l} \\
&= 168 \frac{R(\text{mm})^2 \left(E_b / 100\,\text{keV}\right)}{\mu(\text{mg/cm}) l(\text{cm}) \left[\sigma(E_b)/10^{-25}\,\text{cm}^2\right]} \left(\frac{Y_n}{10^{13}}\right) \text{J}.
\end{aligned}
\tag{13}
$$

Let us estimate with the aid of (12)-(13) the ion beam current that produced the neutron yield $Y_n = 4\times10^9$ in the deuterium fiber pinch experiment of [9] and the energy coupled to the non-thermal ions. Substitute into (12) the parameter values corresponding to [9]: μ = 24 μg/cm, l = 5 cm, and the measured values of the pinch radius R = 200 μm, τ = 30 ns, $E_b = 72$ keV (this corresponds to $\sigma(E_b) = 9.4\times10^{-27}\,\text{cm}^2$) and the neutron yield $Y_n = 4\times10^9$. The accelerated ion beam current estimated from (12) is $I_b = 73$ A, less than 0.015% of the pinch current in [9], $I = 600$ kA. The energy of non-thermal ions is 0.16 J, also a tiny fraction of the total energy coupled to the pinch plasma. In other words, in the NRL deuterium fiber experiment [9] the presence of the ion beam did not significantly affect the plasma conditions; in fact, neutron production seems to be the only detectable manifestation of its existence.

Estimates like this lead to very different results for neutron yields above 10^{13}. Both the ion beam currents and the energies coupled to the nonthermal ions are found to be very high. For E_b varied between 100 keV and 1 MeV we find from (10) that $\sigma(E_b)$ varies from 1.7×10^{-26} to $7.7\times10^{-26}\,\text{cm}^2$. Substituting into (12) $n_i = 3\times10^{20}\,\text{cm}^{-3}$, $l = 2$ cm, $\tau = 4$ ns, and $Y_n = 3\times10^{13}$, we find that I_b ranges from 115 to 26 MA. Even the latter value exceeds the peak current 17 MA that imploded deuterium gas-puff load on Z in the experiment [17]. From (13) we find an estimate for the energy W_b coupled to the nonthermal ions that varies in the range between 46 and 104 kJ. With the total energy coupled to a 2-cm long pinch plasma estimated above for the conditions of Z1422 at 800 kJ, this estimate indicates a huge efficiency of magnetic energy conversion into fast ions, from 6 to 13%.

A Z-pinch plasma where the fast ion beam current exceeds the driving current is quite unusual. It is certainly very different from the conditions of earlier Z-pinch experiments with deuterium plasmas, where the opposite inequality $I_b << I$ had been invariably satisfied. Although the inequality $I_b > I$ is not prohibited by any basic law of physics, it seems highly unlikely that such a plasma has really been produced. The return current of thermal electrons of the same magnitude induced in the plasma by such an ion beam would dissipate a significant amount of energy and produce other observable effects, like strong current filamentation.

Of course, the fast ion beam in the pinch plasma could be structured differently. The simple estimates given above assume the beam flowing in the axial direction through the volume of the stagnated plasma, where there is no magnetic field. It corresponds to the conventional scenario of the beam ion acceleration within the "neck" formed by the $m = 0$ instability, after which the fast ion penetrates the plasma and never interacts with other necks. The fast beam ions are effectively confined inside the pinch column by the magnetic field of the pinch, the ratio of their Larmor radius to the pinch radius being estimated as

$$\frac{r_b}{R} = \frac{v_b / \Omega_b}{R} = \frac{v_b m_D c}{eBR} = \frac{c^2}{eI}\sqrt{\frac{E_b m_D}{2}} \cong \frac{\sqrt{E_b(\text{MeV})}}{I(\text{MA})}. \tag{14}$$

What if the above scenario does not hold and the confinement of the accelerated ions is mostly due to their Larmor rotation in the magnetic field of the pinch and their $\mathbf{E}\times\mathbf{B}$ and ∇B drift? This would change the above estimate because the path of an accelerated ion in the pinch plasma is not limited by the plasma length, l; rather, it is estimated as $v_b\tau$. For the relevant range of E_b, this value is of the same order as the pinch length 2 cm in [17]: taking $\tau = 4$ ns and varying E_b from 100 keV to 1 MeV, we find that $v_b\tau$ varies from 1.2 to 3.9 cm. The fast ions in this case, however, do not constitute a directed ion beam carrying a current from anode to cathode. The localized beam only exists in the phase space, whereas in the physical space there is a large number of fast non-thermal ions rotating in their cyclotron orbits. We can estimate how large this number should be to produce the observed neutron yield:

$$n_b = Y_n \times \frac{1}{\sigma(E_b) n_i v_b \tau} \,. \tag{15}$$

The corresponding total energy of all the fast ions is

$$\begin{aligned} W_b &= \frac{Y_n E_b}{\sigma(E_b) n_i v_b \tau} = \frac{\pi m_D Y_n E_b R^2}{\sigma(E_b)\mu v_b \tau} \\ &= 544 \frac{R(\text{mm})^2 (E_b/100\,\text{keV})^{1/2}}{\mu(\text{mg/cm})\tau(\text{ns})\left[\sigma(E_b)/10^{-25}\,\text{cm}^2\right]} \left(\frac{Y_n}{10^{13}}\right) \text{J}. \end{aligned} \tag{16}$$

For the parameters of the above example, with E_b varied from 100 keV to 1 MeV, $R = 4$ mm, $\mu = 0.5$ mg/cm, $\tau = 4$ ns, and $Y_n = 3\times10^{13}$, we obtain W_b varying from 74 to 53 kJ. Again, this indicates an unusually high efficiency of energy conversion into non-thermal ions, 7-9%.

Of course, the origin of the fusion neutrons produced in deuterium gas-puff implosions on Z needs to be (and can only be) established experimentally by time-of-flight measurements and analysis of the spatial anisotropy of neutron emission and of neutron energy spectra, as in [19]. The purpose of the discussion in this Section is not to claim, before these necessary measurements are done in future shots, that the observed neutron yield on Z is thermonuclear because its beam-target origin is questionable. Rather, we wanted to illustrate the following two important points:

1) In all the early experiments [1-7, 9, 22] it was impossible to explain the observed neutron yields by the thermal mechanism without stretching the estimates for Z-pinch plasma temperature and density far beyond reasonable limits. On the other hand, the beam-target mechanism nicely accounted for the observed yields. The estimated fast ion beam current and energy always constituted tiny fractions of the Z-pinch current and total energy, respectively. We have demonstrated here that for the recent experiments on Z with deuterium gas-puff loads, the situation is just the opposite. The estimated thermonuclear neutron yield for Z1422 is quite close to its measured value. Conversely, the conventional explanation based on the beam-target mechanism now requires quite a bit of stretch in estimating the required fast ion beam parameters, i. e. unusually large beam current and/or high efficiency of energy conversion from the pinch plasma to the beam.

2) The above argument does not prove the thermonuclear origin of the observed neutrons on Z. Instead, it demonstrates that if the neutrons are produced by a beam, then the efficiency of the beam-generating mechanism in deuterium Z-pinch plasma exceeds expectations. Therefore, confirmation of the beam origin of the observed neutrons will not be a disappointing, "*sobering experience*" as it was in [6]. Rather, it can well become a pleasant surprise.

Indeed, the hypothesis of a directed multi-MA beam of fast ($E_b = 100\,\text{keV}$ or more) deuterium ions appears too good to be true. Generation of light-ion beams with current and power densities exceeding 40 MA/cm^2 and 20 TW/cm^2, respectively, as our above estimates imply, is far beyond the capabilities of any light-ion accelerators that ever existed or were contemplated for the light-ion ICF program of the 1990s [37]. If such beams were inadvertently created in the gas-puff experiments [17], it would be possible to increase the fusion neutron yields by 2 orders of magnitude or more simply by placing a solid deuterium or DT target at the anode, under the beam.

If there turns out to be no directed fast ion beam in deuterium gas-puff experiments on Z like [17] but rather production of high-energy deuterium ions in very large numbers by some unidentified mechanism, it would be almost as amazing. Indeed, we are talking about 5-10% efficiency of Z-pinch energy conversion into fast ions. To put this number into context, note that it is about the same as the record-high efficiency of Z-pinch energy conversion into the x-rays that reach the capsule imploded in a dynamic hohlraum in experiments on Z like [18]. Hydrodynamic efficiency of the x-ray acceleration is about 10%, which means that out of ~40 kJ of the radiation energy incident upon the capsule [18] only about 4 kJ is converted into its kinetic energy, which, in turn, is the only energy source for heating some deuterium ions to fusion temperature. This difference in efficiency results in a three orders of magnitude difference in the neutron yields, see Fig. 1. The estimated energy in fast ions, 50 to 100 kJ, is very high even if we compare it with what can be obtained on NIF, the 1.8 MJ laser facility under construction [21], which, when completed, will be incomparable with Z and ZR in terms of complexity and cost. The total energy delivered to an indirect-drive NIF ignition target is projected to vary in the range of 75 to 192 kJ ([29], Fig. 2-12), only a small fraction of which can be eventually converted into the thermal energy of fusion-producing deuterium and tritium ions.

Let us assume that the efficiency η_{fi} of Z-pinch energy conversion into fast ions does not increase any further as the pinch current is increased from the Z level: $W_b \sim \eta_{fi} \times I_m^2$, where $\eta_{fi} \sim 5-10\%$. Since for implosions producing the same plasma temperature at stagnation, the load line mass μ also scales as I_m^2 [33], we find from (16) that $Y_n \sim I_m^4$. This is exactly the same scaling as follows from (5) for thermonuclear neutron yield.

III. NUMERICAL SIMULATIONS

A. One-dimensional RMHD simulations

Our simple estimates of neutron yield given in Section II.B are based on some reasonably estimated values of plasma density, temperature, confinement time, etc. It is important to check such estimates with the aid of 1-D numerical simulation that solves the radiation hydro equations self-consistently with a circuit model for the current driver. The 1-D simulations predict the bulk characteristics of the stagnated Z-pinch plasmas, which is exactly what we are looking for. Predictions of the 1-D radiation magnetohydrodynamic (RMHD) simulations are most reliable when the modeled Z-pinch implosions are not too unstable, which is the case for deuterium gas-puffs, as demonstrated below in Section III.B. Moreover, compared to 1-D modeling of K-shell x-ray generating PRS implosions, modeling of deuterium gas-puffs might actually be more accurate because for this case the 1-D RMHD simulations can be carried out from first principles, without introducing any fudge factors to fit the experiments. These fudge factors are routinely used to prevent "radiative collapse," a numerical artifact denoting non-physical unlimited 1-D compression of a strongly radiating plasma. Introduction of the fudge factors is a way to phenomenologically account for the inherently 2- or 3-D properties of the strongly-radiating high-atomic-number Z-pinch plasma flow that limit its radial compression, and thereby to a large extent, determine its radiative output. Deuterium Z-pinch plasmas radiate very weakly: for the conditions of the deuterium gas-puff experiments on Z, the pinch can only lose less than 1% of its thermal energy at stagnation via bremsstrahlung continuum radiation. Immediately after stagnation, the pinch plasma bounces from the pinch axis and starts to expand. This is an essentially 1-D process, reasonably well suited for 1-D RMHD description.

One-dimensional modeling of Z-pinch implosions assumes a perfectly cylindrical shape of the plasma column, ignoring the hydrodynamic instabilities that distort it, in the same way as 1-D modeling of laser capsule implosions assume a perfect spherical symmetry. In laser fusion, the thermonuclear neutron yield of an imploded capsule predicted by 1-D modeling is labeled "clean." The calculated clean neutron yield $Y_n^{(c)}$ is the highest yield that a target is capable of producing in a perfectly symmetric implosion by a given laser or hohlraum drive. The conventional figure of merit of laser target performance is neutron yield-of-clean defined as YOC=$Y_n / Y_n^{(c)}$, where Y_n is the observed yield. Typically, YOC is close to unity for low-yield targets, which are not strongly compressed, whereas the highest observed neutron yields correspond to YOC about 20%. 1-D RMHD simulation without any fudge factors makes it possible to directly evaluate the clean thermonuclear neutron yield that can be produced in a symmetric implosion of a gas-puff load and characterize its neutron-producing performance.

Our 1-D simulations were done using the Lagrangian DZAPP RMHD code developed at Code 6720 NRL on the basis of its earlier version ZPIMP [38]. This code incorporates a comprehensive physics package to describe line and continuum radiation emission and transport (see [39], [40] and references therein). Simulation of deuterium plasma flow only involves modeling of continuum bremsstrahlung emission [40]. It should be noted, however, that emission and transport of line radiation also have to be accurately modeled because in all D_2 gas-puff experiments on Z, small quantities of high-atomic-number tracers, argon and Freon, are added to deuterium for diagnostic purposes. Comparing the observed emission spectra and radiation yields of tracers with the simulation predictions, we can judge how well the simulation reproduces the average parameters of the stagnated deuterium Z-pinch plasma. It is demonstrated below that these parameters are strongly affected by intensive radiation of the tracer ions.

Equations of 1-D magnetohydrodynamics, population kinetics and radiation transport were solved self-consistently with the circuit model for Z. The initial density distribution in the gas puff was taken from the measurements that used a planar laser-induced fluorescence (PLIF) technique [41] to map the absolute cold gas density profile in the radial and axial directions for the nozzle used in the deuterium gas-puff shots on Z. For our 1-D simulations, the density profiles measured at the midsection of the 2 cm long gas jet, 1 cm above the cathode plane, were used. Table I summarizes the results of our simulations done for the three deuterium gas-puff shots on Z reported in [17].

Table I. Comparison of measured and 1-D modeled parameters of deuterium gas-puff shots on Z. Tracer concentration is shown by partial pressure. The calculations for pure D_2 loads were done for the same nominal load masses as in the actual shots but without any tracers.

Shot#	Tracers	Measured peak current BMAVE (BIAVE) (MA)	Calculated peak current (MA)	Measured neutron yield	Calculated 1D neutron yield (as shot)	Calculated 1D neutron yield (pure D_2, same mass)
Z1026	0.5% Ar in inner and outer	13.7 (10.8)	13.0	0.9×10^{13}	0.93×10^{13}	
Z1384	0.5% Ar in inner	13.6 (13.4)	13.0	1.7×10^{13}	1.13×10^{13}	1.28×10^{13}
Z1422	0.5% Ar in inner, 0.5% Freon-12 in outer	17.6 (15.4)	16.6	3.3×10^{13} (ave. 6.34×10^{13})	3.48×10^{13}	3.12×10^{13}

We see that the thermonuclear DD neutron yields found from 1-D modeling are in fair agreement with the results of deuterium gas-puff shots on Z [17]. Yield-of-clean is close to unity, which indicates a very good neutron-producing performance of the deuterium gas-puff loads on Z, and at the same time is not far above unity, which would have been a definite sign of non-thermal origin of the observed neutrons. The plasma conditions obtained in the simulations are consistent with our simple analytical estimates given in Section II.B. This is illustrated by Fig. 2 showing the 1-D dynamics of the pinch plasma implosion, temperature, fusion energy production and deposition for the conditions of shot Z1422. The minimum radius of the hot stagnated plasma is found to be about 5 mm. Its confinement time near peak density is close to 4 ns, after which the pinch bounces. The average ion temperature is about 7 keV. The electrons remain colder than the ions throughout the implosion, reaching the peak temperature about 2 keV. Therefore the 1-D simulations confirm consistency of our basic assumptions, which lead to the conclusion about significant thermonuclear fusion component in the neutron yields measured in the recent deuterium gas-puff shots on Z.

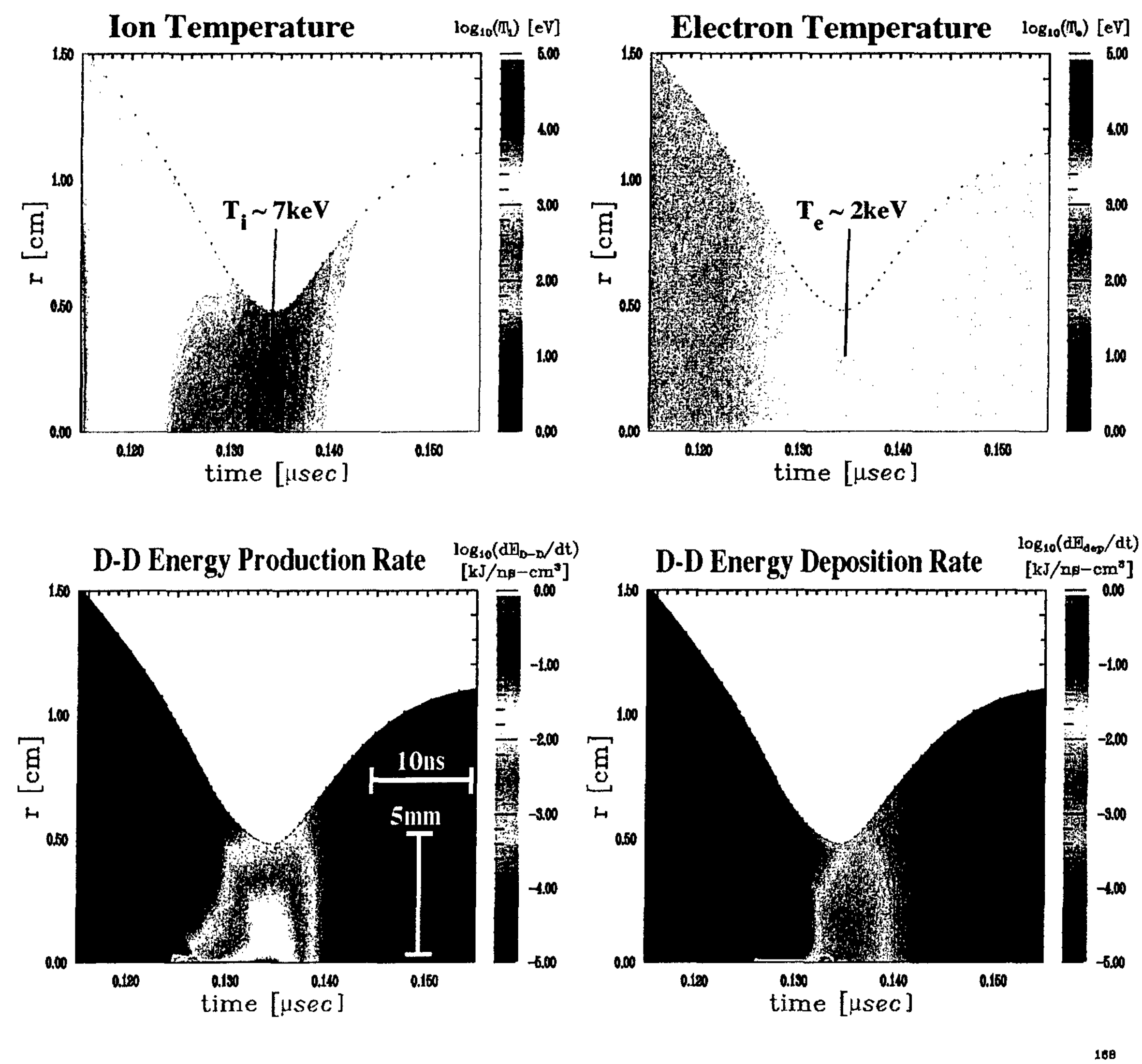

Figure 2. *r-t* diagrams illustrating time histories of ion and electron temperatures, fusion energy production and energy deposition in 1D RMHD run modeling deuterium shot Z1422.

In our simulations, we checked the effect of the Ar and Freon tracers in the deuterium plasma on the thermal neutron yield and found it insignificant. While the electron component of the pinch plasma loses energy due to line emission of the high-atomic-number tracer ions, it does not lead to strong cooling of the deuterium ions because of the long electron-ion temperature equilibration time. Somewhat faster cooling of ions, due to equilibration with tracer – radiation cooled electrons, and a reduced number of deuterium ions, due to the presence of the tracer ions, to some extent reduce the neutron yield. But the presence of tracers also produces a different, opposite effect on the conditions of the Z-pinch plasma: due to radiation cooling, it can be compressed by the magnetic pressure into a tighter, denser stagnated plasma column, which tends to increase the thermal neutron yield. These positive and negative effects are of the same order of magnitude, roughly compensating each other, so the net effect could be either a modest increase or decrease in neutron yield, as demonstrated by comparison of the last two columns of Table I.

Figure 3 compares the observed emission spectra of tracers in shot Z1026 with the simulation predictions. Comparisons with the other shots in the series will be published when they become available. We see that the main spectral features, strong resonant He- and H-like lines of Ar are well reproduced by the simulation. This agreement adds confidence to our above estimates of bulk properties of the stagnated plasma, primarily its density and temperature. The K-shell line ratios, e.g. Ly-α to He-α, are very sensitive to the electron temperature.

It should be noted that the deuterium gas-puff experiments on Z [17] used the same double-shell 8-cm diameter as in earlier the PRS shots, mostly with argon, on Double Eagle, Decade Quad, Saturn and Z, see [15] and references therein. The inner-to-outer shell mass ratio in [17] was fixed at 1:1, same as in [15], whereas the line mass of the load, about 450 μg/cm, was noticeably less than in shot Z663 which produced the

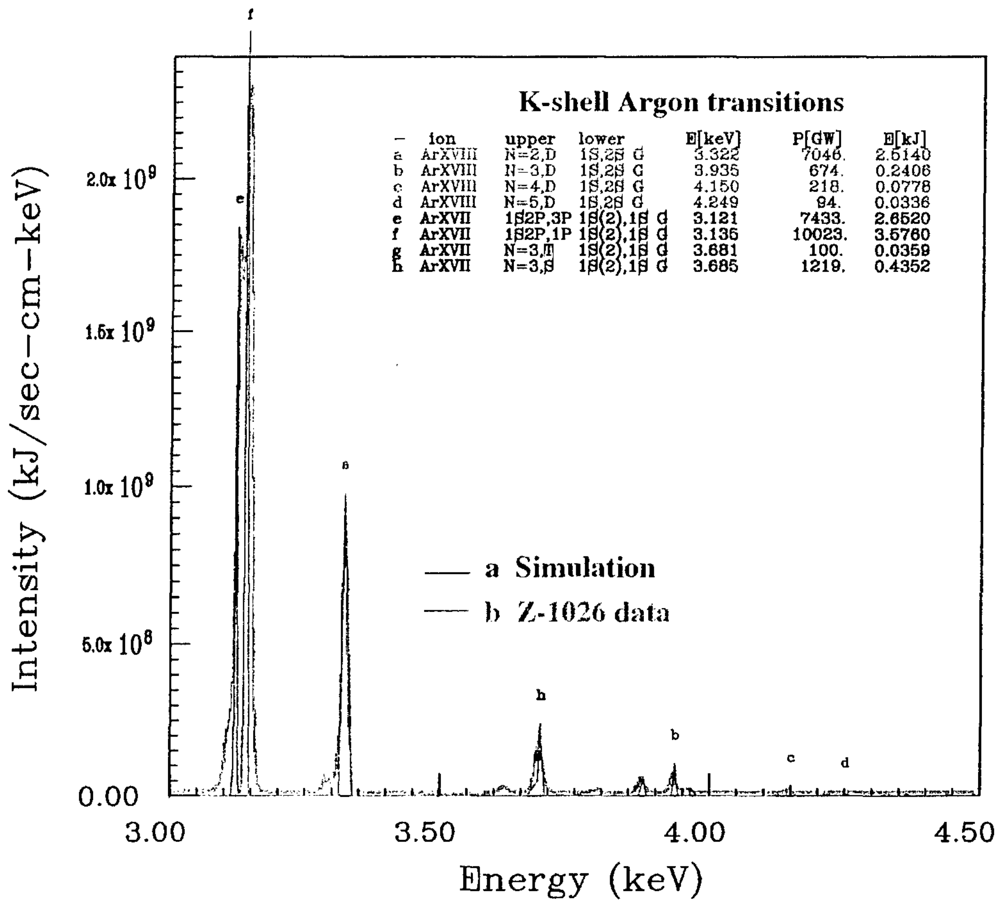

Figure 3. Time-integrated x-ray emission spectrum of Z-pinch observed in shot Z1026 (red curve) and simulated in 1D RMHD modeling of this shot (green curve). Green and blue atomic transition labels refer to H- and He-like argon spectral lines, respectively.

highest Ar K-shell yield, 800 μg/cm [15], still a somewhat under-massed load for Z. Neither the total mass nor the inner-to-outer shell mass ratio has been optimized for increasing the thermonuclear neutron yield of a deuterium gas-puff load. It is well known that optimization of the load parameters can significantly increase performance of a PRS – see the recent results of experiments with argon gas puffs on Double Eagle, *where it was demonstrated that addition of a high-density center jet increases Ar K-shell yield by a factor of 2 or more* [28]. Varying the gas-puff load parameters in our simulations, we have found that thermal neutron yields ~10^{14} are possible on Z with the same nozzle. Our work in progress involves broader variation of the nozzle parameters, including the introduction of a center jet as in [28], which can probably increase the neutron yield on Z even more.

Optimization of a load can improve performance of a Z-pinch neutron source only within some reasonable limits, normally less than one order of magnitude. For deuterium gas puff shots on Z our simulations indicate that this upper limit is about 10^{14}. This is only 1.5-3 times greater than the neutron yield observed in the very first shot on Z at full charge, Z1422. To produce much higher neutron yields, we need to increase the pinch current and to use deuterium-tritium gas-puff loads. We use our simulation results to estimate the performance of plasma neutron sources powered by next-generation drivers, from ZR to ZX. The results of this analysis are presented in Table II.

If on the refurbished ZR machine we will be able to make its full 26 MA peak current pass through a gas-puff load of the same dimensions as that used in [17], then, according to the $Y_n \sim I_m^4$ scaling, the 1.5-fold increase in current amplitude will translate into a 5-fold increase of DD neutron yield to 5×10^{14}, as shown in Table II. Our simulations consistently predict for ZR the neutron yields which are in agreement with this estimate, up to $\sim10^{15}$. Some increase of the yield compared to the $Y_n \sim I_m^4$ scaling prediction at higher current is possible because with a more powerful driver we can increase the ion temperature T_i at stagnation. In the range of T_i between 7 and 20 keV the reaction rate $\langle \sigma v \rangle$ is very sensitive to the ion temperature, and its increase boosts the thermal neutron yield, more than compensating for the reduced ion density.

Table II: Fusion neutron yield from multi-MA Z-pinch plasmas.

Facility	Current (MA)	Load	Neutron yield	Neutron origin	Energy released in fusion reaction (kJ)	Energy in charged particles (kJ)	Source
Angara -5-1	2	DD	2×10^{12}	Beam†	0.00234	0.00155	Ref. 22
Saturn	7	DD	2.5×10^{12}	Beam/thermal*	0.00292	0.00194	Ref. 32
Z	17	DD	3×10^{13}	Beam/thermal*	0.0350	0.0233	Ref. 17
ZR	26	DD	5×10^{14}	Thermal§	0.584	0.388	Extrapolated from Ref. 17 and 1-D simulations using $Y_n \sim I_m^4$ scaling
		DT	6×10^{16}	Thermal§	169	34	1-D simulation, NRL Code 6720
ZX	50	DT	10^{18}	Thermal§	2816	560	Extrapolated from ZR 1-D simulation using $Y_n \sim I_m^4$ scaling

† Determined with time-of-flight diagnostics
* Inferred from experimental data and modeling
§ Predicted

The reaction rate of deuterium-tritium fusion reaction exceeds that of DD by two orders of magnitude. Our simulations for ZR predict a huge DT neutron yield, 6×10^{16}. It corresponds to total released fusion energy of $6\times10^{16}\times17.6$ MeV =169 kJ. This is equal to or greater than the energy which can be realistically coupled to an indirect-drive capsule by the NIF laser [21, 29]. Thus fusion energy release of 169 kJ on NIF would signify the ignition breakeven, inertially confined fusion energy gain exceeding 1, a truly historical milestone for the whole ICF community. Our estimates indicate that the DT neutron yield corresponding to this milestone can be achieved long before NIF is commissioned, on a much less expensive facility, ZR. It is not certain, although possible, that construction and operation of the next-generation Z-pinch facility, a 50 MA ZX machine, will be less expensive and/or easier compared to NIF. Using the $Y_n \sim I_m^4$ scaling to extrapolate our prediction for the ZR result to the current level of the ZX machine, we predict its DT neutron production capability of 10^{18} per pulse, about the same as one can expect from NIF if it proves capable of attaining a fusion energy gain of 20 in its indirect-drive capsule implosions.

B. Two-dimensional MHD simulations

We have demonstrated a fair agreement between the results of our 1-D RMHD modeling and the experimental data. In particular, the observed neutron yields were found to be quite close to the clean 1-D predictions. However, the imploded Z-pinch plasmas are known to be unstable. Rayleigh-Taylor instability of acceleration and/or the MHD sausage instability of stagnated plasma may drastically change the large-scale dynamics of implosion and parameters of the stagnated plasma compared to the perfectly symmetric flow. To find out if this is the case, we need to do two-dimensional modeling of deuterium gas-puff implosions on Z.

In our 2-D simulations we used a version of MACH2 MHD code [42] which incorporates the NRL radiation physics package based on [43]. This code has been most recently used [44] for modeling of innovative PRS loads, including one with a strong central jet [28]. The code has a capability of treating strongly radiating tracers. The runs described below, however, were done for pure deuterium loads.

The two-dimensional profiles of initial gas density for the nozzle used in the deuterium gas-puff shots on Z were taken directly from the PLIF measurements [41]. These initial density distributions are no longer cylindrical, as assumed in our 1-D simulations. The initial radial/axial non-uniformity of the load is amplified by the Rayleigh-Taylor instability of implosion, which leads to further deviation of the imploded plasma column from its approximately cylindrical shape. We did not introduce a random density variation or any other source of load non-uniformity additional to that present in the PLIF data.

Table III summarizes the obtained results in terms of predicted neutron yields. We see that our 2-D simulations predict thermal neutron yields quite close to the 1-D predictions. This might be an indication that 1-D modeling successfully approximates averaged parameters of the stagnated deuterium plasma despite its instability. Somewhat higher yields predicted by 2-D simulations indicate that most of the neutron yield comes from a few dense/hot spots, as typically is the case with K-shell x-ray emission.

Table III. Comparison of measured and calculated parameters of deuterium gas-puff shots on Z. The 1-D and 2-D calculations for pure D_2 loads were done for the same nominal load masses as in the actual shots but without any tracers.

Shot#	Measured neutron yield	Calculated 1D neutron yield (pure D_2, same mass)	Calculated 2D neutron yield (pure D_2, same mass)
Z1384	1.7×10^{13}	1.28×10^{13}	1.64×10^{13}
Z1422	3.3×10^{13} (ave. 6.34×10^{13})	3.12×10^{13}	5.5×10^{13}

To see if the dynamics of implosion and average parameters of the stagnated plasma in 2-D simulations are close to those obtained in 1-D simulations, we present here a sequence of plasma density and pressure maps for a pure D_2 load.

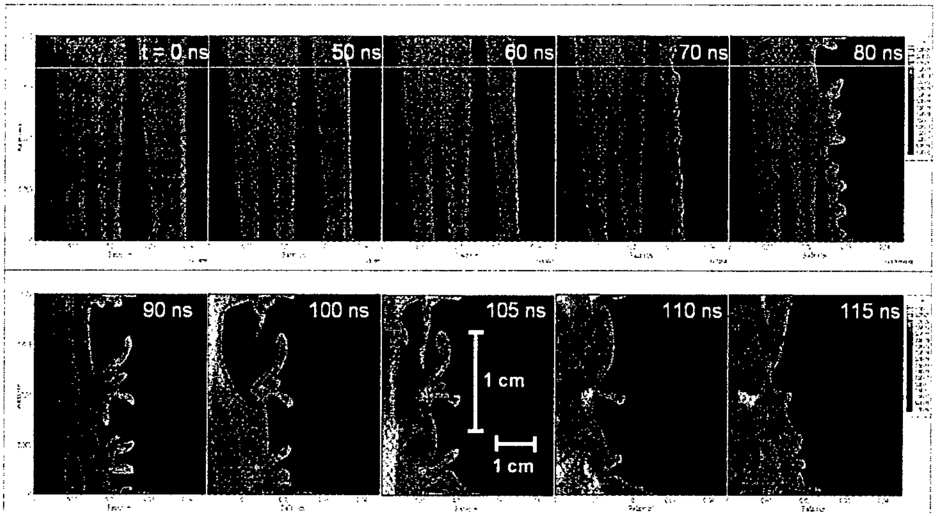

Figure 4. Density maps obtained in a 2-D simulation of the implosion of a pure D_2 load with the same initial density profiles and nominal load mass as in shot Z1422.

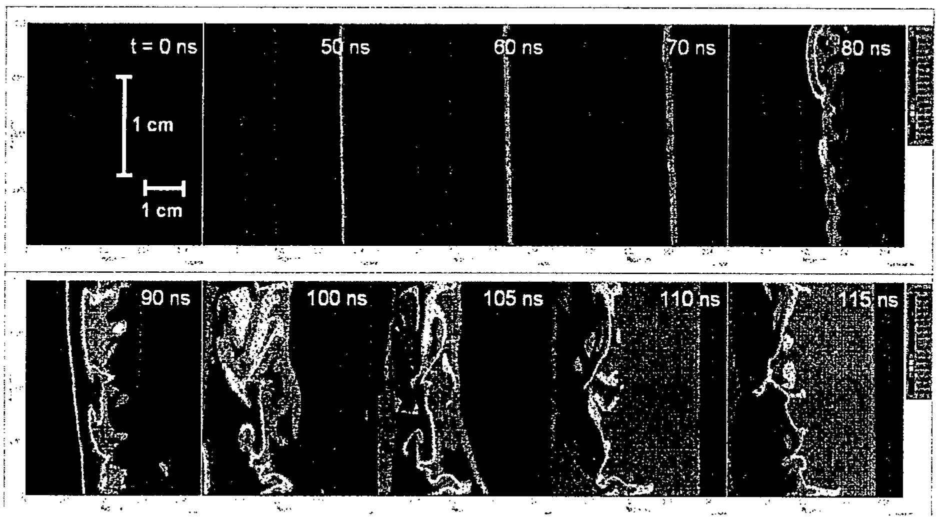

Figure 5. Pressure maps obtained in a 2-D simulation of the implosion of a pure D_2 load with the same initial density profiles and nominal load mass as in shot Z1422.

Figures 4, 5 demonstrate that 2-D simulations predict the implosion history and plasma conditions not far from our simple analytical estimates and 1-D simulation results. In particular, the confinement time of the high density/high pressure plasma near the 105 ns frame is about 5 ns, and the minimum radius of the plasma close to 5 mm. The Rayleigh-Taylor and MHD sausage instability effects redistribute the plasma mass in both axial and radial directions but its average properties are not very far from those found assuming axial uniformity.

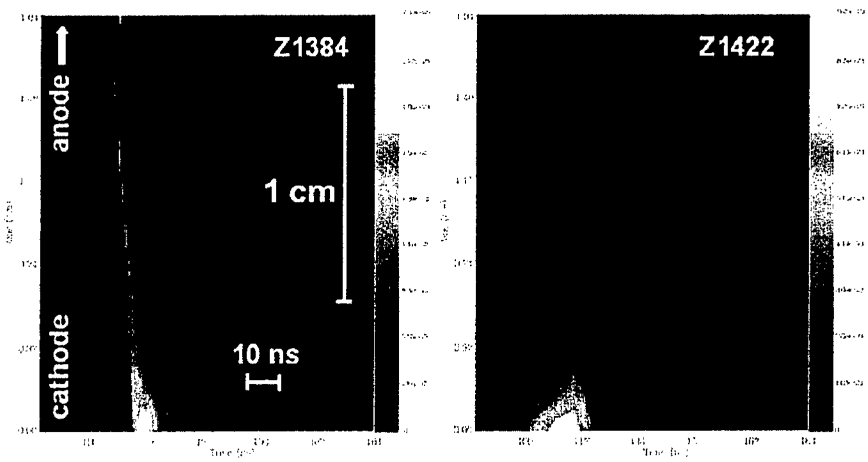

Figure 6. Radially integrated neutron production rates obtained in 2-D simulations of the implosions of a pure D_2 loads with the same initial density profiles and nominal load masses as in shots Z1384 and Z1422.

The main difference between the 1-D and 2-D results is that the neutron production is not axially uniform. Most of the neutrons in the latter case are indeed produced in a bright spot near the cathode, as indicated by the difference between the 1-D and 2-D predictions of the neutron yields. For the 2-D simulations whose results are presented in Figs. 4, 5, this is the area where both density and pressure peak at 105 ns. Non-uniformity of neutron production is illustrated by Figure 6 showing radially integrated contours of the thermonuclear fusion neutron production rate (similar to the PRS "zippering contours" produced by linear sets of x-ray diodes, each observing a fraction of length of the pinch, cf. [28], Fig. 3) for pure D_2 simulation runs imitating conditions of Z1384 and Z1422 shots. Both of these runs generated most of the thermal neutrons from a small hot/dense spot near the cathode. Similar emission patterns are characteristic for PRS implosions producing K-shell radiation. For example, most of the

Ar K-shell emission came in shot Z663 from a tight plasma spot near the anode [15] and for the Double Eagle shot 5560 [28] – from a short segment of the stagnated Z-pinch plasma near its midsection.

Our 2-D estimates of thermal neutron yields in deuterium gas-puff shots on Z are found to be consistent with 2-D simulations of the same Z shots done by Dr. J. P. Chittenden at Imperial College (London) using their GORGON code [45]. For conditions of shot Z1422, the GORGON prediction of the thermal neutron yield is 2×10^{14}, somewhat higher but not inconsistent with ours. Agreement between these results obtained with two very different 2-D MHD codes supports our confidence that both the implosion history and the average parameters of the stagnated plasma are reasonably described by our 1-D and 2-D simulations.

IV. CONCLUSIONS

Our analysis of the recent deuterium gas-puff shots on Z confirms the feasibility of developing Z-pinch plasma neutron sources (PNS). The PNS will operate much like x-ray-producing PRS but employ DD or DT nuclear fusion reaction between plasma ions to produce the neutrons. Theoretical estimates and numerical modeling of deuterium gas-puff implosions demonstrate that the yields of thermonuclear fusion neutrons that can be produced on ZR and the next-generation machines are sufficiently high to make PNS the most powerful, cost- and energy-efficient laboratory sources of 2.5 MeV to 14 MeV fusion neutrons, just like PRS are the most powerful sources of soft and keV x-rays. In particular, the neutron-producing capability of PNS driven by ZR and ZX accelerators is predicted to match that of the NIF laser at thermonuclear energy gains of 1 and 20, respectively.

Our theoretical estimates and modeling results agree with the experimental data obtained in the recent deuterium gas-puff shots on Z [17]. It should be noted that such agreement does not constitute a proof of the thermonuclear origin of the fusion neutrons emitted from the stagnated deuterium plasma on Z. The origin of these neutrons must be established experimentally, with the aid of time-of-flight, neutron energy spectra and other neutron diagnostic techniques. Future deuterium gas-puff shots on Z may reveal that most of these neutrons are produced in a beam-target interaction of plasma deuterium ions. This is possible if the deuterium ions are somehow accelerated in a Z-pinch plasma to energies of the order of or greater than 100 keV with very high Z-pinch-driver-to-fast-ions energy transfer efficiency, 5 to 10%, which would make a multi-MA deuterium Z-pinch the most efficient light-ion accelerator. Discovery of such unexpected high efficiency should stimulate, rather than discourage, development of the PNS because, as demonstrated above, it implies the same scaling of the fusion neutron yield with the peak current, $Y_n \sim I_m^4$, as the thermonuclear mechanism of neutron production. Therefore our projections of PNS performance listed in Table II are likely to remain valid no matter what mechanism is eventually determined to be responsible for generating fusion neutrons in deuterium gas-puff shots on Z.

High thermonuclear neutron yields from PNS are possible because dense Z-pinch plasmas contain the hottest ions compared to all other laboratory plasmas. Does it mean that such plasmas are also best suited to produce a self-sustained fusion reaction, ignition and high energy gain? Not necessarily. High temperatures of deuterium ions come from thermalization of their implosion velocity and subsequent adiabatic heating of the ions while the plasma electrons remain relatively cold. A self-sustained nuclear fusion regime requires that some of the thermal energy released in the fusion reaction heats the plasma ions. Neutrons produced in the DT reaction D+T→n+α escape the Z-pinch plasma, and deceleration of the α-particles carrying 20% of the released fusion energy deposits only about 10-20% to the ions, with most of their energy being spent on heating the electrons. To have the fusion energy feedback to the ions, we cannot keep the electrons cold as in most examples discussed above. Therefore ignition of a DT Z-pinch imposes stricter requirements on the density and temperature of the stagnated plasma, which are much harder to satisfy than those sufficient for successful PNS operation. The latter observation is not supposed to mean that a DT Z-pinch plasma cannot be ignited. Although discussion of this issue is beyond the scope of the present report, we note that ignition conditions for a cylindrical Z-pinch plasma in terms of ρR at stagnation are in fact relaxed compared to those for a laser fusion capsule. This is because the fusion α-particles in a Z-pinch plasma column are confined by the azimuthal magnetic field ($r_\alpha / R = 1.3 / I_m(\mathrm{MA}) << 1$, where r_α is the cyclotron radius of a 3.52-MeV α-particle in the magnetic field of the pinch, and R is the radius of the pinch at stagnation). Hence the ignition does not require achieving $\rho R \sim 0.3$, as in laser fusion, but is possible for ρR between 10^{-3} and 10^{-2}, see [46] for details.

One of the most promising applications of plasma neutron sources involves using a PNS as a trigger in combination with fissionable materials for multiplication of the PNS neutron yields by 2-3 orders of magnitude to produce a safe and reliable neutron source for various testing applications. According to the estimates of [22], if the pulsed power driver could be operated in a high repetition rate regime, then a combination of PNS generating $\sim 10^{16}$ to 10^{17} of DT neutrons (which is the projected capability of ZR, see

Table II) with a properly designed set of uranium composite blankets would make a safe sub-critical fission-fusion reactor that can actually produce energy.

Fusion-like conditions produced in PNS plasmas turn out to be of interest for another application – generation of warm x-rays in the photon energy range 10-20 keV. This opportunity is inferred from the results of experiments [17] where tracer argon ions whose fraction was very small, 5% by mass, produced considerable radiative yields. Comparing the argon gas-puff shot Z663 [15] to the deuterium with Ar tracer gas-puff shot Z1422 [17], we find that in the latter case the number of Ar ions was 35 times less than in the former, the difference being due both to the small percentage of tracer ions in the deuterium load and to the lower line mass of this load compared to that of Z663, 0.8 mg/cm. Nevertheless, the total radiation yield, which in shot Z1422 was almost entirely due to radiation of the argon tracer atoms, was 144 kJ, about 6 times less than in Z663. It means that an isolated argon ion in a thermal reservoir of non-radiating deuterium plasma turned out to be a 6 times more efficient emitter than in an argon plasma, presumably because the energy it loses to radiation is rapidly replenished from the surrounding electron fluid. This leads us to suggestion that a krypton ion emitting strong K-shell lines at 13 keV can also serve as a good radiator in deuterium or deuterium-tritium fusion-like plasma whose electron temperature exceeds 3 keV. The fusion α-particle energy of 34 kJ estimated for a DT gas-puff implosion on ZR (Table II) is rapidly released into the electron fluid, which is not sufficient to approach ignition, but can certainly help to heat Kr ions and thereby boost the Kr K-shell x-ray yield.

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