Estimation of the Neutron Generation from Gas Puff Z-Pinch on Qiangguang Facility

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Abstract. Z-pinch using a deuterium gas-puff load has been validated as a plasma neutron source (PNS) on many accelerators such as Saturn, Z, Angara-5 and S-300. The experimental results on these accelerators show that the production of the neutron can be scaled as $Y_n \propto I_m^4$, where Y_n is the yield and I_m is the peak current of the accelerator, no matter what mechanism is eventually determined to be responsible for generating fusion neutrons. The neutron production on Qiangguang generator (1.5 MA, 100 ns) is analytically estimated that approximately 4×10^{10} D-D neutrons would be produced, among which the thermonuclear neutrons are only 7×10^{7}. The gas puff construction used on Qiangguang is introduced and the optimum line mass of the D_2 gas is given. The results show that the optimum line mass is approximately 50 μg/cm for Qiangguang's driving current. The mass density distribution obtained with the classical ballistic-transport model demonstrates that the gas puff forms a hollow gas shell with the length of 2 cm. For D_2 to produce a gas flow with the line mass 50 μg/cm, the firing time of Qiangguang changes to 250 μs and the absolute pressure of the chamber increases to 4.2 atm.

I. INTRODUCTION

Z-pinches can be used not only as a powerful X-ray radiation[1-3] source, but also a very powerful plasma neutron source (PNS)[4-6], which can be applied to radiation material science, detector calibration, nuclear medicine and illicit material detection. In fact using the deuterium Z-pinch plasmas to generate fusion neutrons is not a new idea. The main purpose of the Z-pinch researches on last century is looking for controlled thermonuclear fusion neutrons however it was soon found the observed neutrons were not produced by thermonuclear fusion but beam-target reaction[7]. In recent years with the rapid development of the gas puff load the Z-pinch plasma has become the most powerful neutron source with the record of 4×10^{13} on Z (15 MA, 100 ns) facility[8]. Velikovich has induced that half of the neutron yield on Z is produced by thermonuclear fusion and the others come from beam-target mechanism, and he also predicted that the neutrons would be all produced by thermonuclear fusion when the current of the accelerator is big than 26 MA[4]. These inspiring results evoke again the researchers' interesting in inertial controlled fusion through Z-pinch and a new concept is proposed as the magnetized liner inertial fusion (MAGLIF)[9,10].

In the present paper, The D-D neutron yield by a D_2 gas puff on Qiangguang is predicted through analytical estimation as well as the scaling relationship given by neutron yields on other generators; this is done in Section II. The construction of the gas puff load is shown in Section III, and in this section the optimum line mass of the gas puff is also obtained by analyzed the Krypton pinch experimental results performed before. In Section IV the density profile of the gas flow is obtained by the classical Ballistic-Transport model and Section V will give a brief summary.

II. ESTIMATION OF THE D-D NEUTRONS YIELD ON QIANGGUANG GENERATOR

Qiangguang[11] is a facility that includes a linear transformer driver (LTD), an intermediate storage, a pulse compression line, a pulse output line and a vacuum chamber. The facility will send a pulse with 2 MV to the vacuum chamber and the typical load current has a peak of 1.5 MA with the rise time of about 100~120 ns.

A. Estimates of the thermal D-D neutron yield

The thermonuclear neutron yield Y from stagnated Z-pinch plasma is estimated as[4]

$$Y_{\mathrm{n}} = \frac{1}{4} n_i^2 \langle \sigma \upsilon \rangle \pi R^2 l \tau \,, \tag{1}$$

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, m_D is the mass of the deuterium ion), R and l are the compressed pinch radius and length, respectively, $\langle \sigma \upsilon \rangle$ is the average ion-temperature-dependent rate of the DD fusion reaction, τ is the confinement time of the dense pinch, and the factor 1/4 is the product of the factor 1/2, introduced because the colliding ions are identical, and the branching ration 1/2 between D+D→He^3+n and D+D→T+p, of which only the former produces a neutron.

First we estimate the parameters of the stagnated pinch plasma. The outer diameter of the gas puff used on Qiangguang is 20 mm, and therefore the final radius of the stagnated column R=1 mm given the 10-fold radial compression of the pinch. For the line mass of the gas puff load μ=50 μg/cm the ion number density for the stagnated plasma column $n_i \approx 5 \times 10^{20}$ cm^{-3}. The energy imparted to the plasma during the implosion phase can be valued as

$$E = \frac{1}{2} \int I^2 dL \cong \alpha I_m^2 (\mathrm{MA}) \ln \frac{R_0}{R} \,\mathrm{kJ/cm} \,. \tag{2}$$

Here, R_0 is the initial outer radius of the gas puff, α is the dimensionless factor accounting for the current pulse shape and for Qiangguang's current the typical value of α is 0.7,[12] and I_m is the peak current. Substituting into (2) the compression ratio we find $E \approx 4 \mathrm{kJ/cm}$. Neglecting the radiation losses from deuterium, the temperature of the plasma from the energy balance can be expressed as

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

Taking R=1 mm, $n_i \approx 4 \times 10^{20} \mathrm{cm}^{-3}$, and $E \approx 4 \mathrm{kJ/cm}$ in (3) we get (T + T_e) = 1.3 keV. The ion-electron temperature equilibration time for the deuterium is $\tau_{ei} \approx 2 \times 10^{12} T_e^{3/2} \left(\mathrm{keV} \right) / n_i$ and for the density $n_i \approx 4 \times 10^{20}$ it is 3 ns for T_e= 0.7 keV. The confinement time is estimated as $\tau = R/V$ where V is the implosion velocity, for μ= 50 μg/cm and $E \approx 4 \mathrm{kJ/cm}$ the velocity is ~4 × 10^7cm/s. Given R=1 mm and $V = 4 \times 10^7 \mathrm{cm/s}$ we get τ ~3 ns, which means the ion-electron equilibration time is compared to the confinement time and the temperature equilibration nearly arrives between electrons and ions, so the temperature of the ion on Qiangguang's experiments is below 1 keV.

When the temperature of the deuterium ion is 1 keV the total D-D fusion reaction $\langle \sigma \upsilon \rangle$ averaged over the Maxwellian distribution of ions is 7×10^{-23}cm^3/s. Substituting these values of the parameters into the formula (1) we can obtain an estimation for the thermal neutron yield on Qiangguang is 7×10^7. According to (1), the neutron yield scales as $n_i^2 \propto \mu^2$. From the Z-pinch implosion physics the line mass of the load scales as current squared $\mu \propto I_m^2$, which implies the yield from the thermonuclear $Y_{\mathrm{n}} \propto I_m^4$.

B. Estimates for beam-target neutron yield

Now consider the alternative mechanism of fusion neutron production in Z-pinch plasma, the beam-target mechanism, which is mainly responsible for neutrons produced by the lower current driving Z-pinch plasma below 7 MA according Velikovich's calculation[4].

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

$$l_{bf} = \frac{1}{\sigma(E_b)n_i}. \tag{4}$$

For the ions with the energy E_b = 100 keV we can obtain the length l_{bf}= 1.5 km with the parameters $n_i \approx 4 \times 10^{20}$ and $\sigma(E_b) = 1.7 \times 10^{-26}\mathrm{cm}^2$ [13], while the maximum distance that a beam ion can travel inside the pinch plasma in the axial direction is the length of the pinch l. So, to produce one neutron l_{bf}/l fast ions is needed in the deuterium beam. For the load with l = 2 cm the number of the fast ions is 75 thousand.

Because most of the neutrons are produced by the beams during the time τ while the pinch remains confined near the axis, we can express the beam current needed to produce the neutron yield Y_n as

$$I_b = Y_n \frac{l_{bf}}{l}\frac{e}{\tau} = \frac{\pi R^2 m_D e Y_n}{\sigma(E_b)\mu l \tau}. \tag{5}$$

Using this formula we can estimate the upper limit of the neutron yield supposing that all the load current is carried by the accelerated ions. For Qiangguang's current 1.5 MA the limiting yield is 5×10^{11}.

It is obvious that not all the load current flow through the accelerated ions. The experiments on S-300 facility[14] show that the D-D neutron yield is about 6×10^{10} under the driving current 1.6 MA, which means that the beam current is 180 kA by formula (5) with the parameters on S-300 ($\mu = 20 \mu g/cm$, R=1 mm, l = 2 cm, and E_b = 150 keV), and the beam current occupies 11% of the total load current. Assuming that the percent is almost the same for Qiangguang and S-300, we estimate that the D-D neutron yield produced by the beam-target mechanism is about 5×10^{10} for Qiangguang facility.

The energy coupled to the accelerated ions is expressed as

$$W_b = \frac{\pi m_D E_b Y_n R^2}{\sigma(E_b)\mu l}. \tag{6}$$

For the parameters of the experiment on S-300, we obtain W_b = 140 J, while the magnetic energy coupled to the Z-pinch plasma during the implosion phase is 10 kJ, this means an efficiency of 1.4% for the magnetic energy converting into fast ions. Given the same efficiency for Qiangguang we can also obtain an estimate of neutron yield for Qiangguang. Substituting $\mu = 50\,\mu g/cm$, R=1 mm, l = 2 cm, and E_b = 150 keV into the formula (6) we obtain the neutron yield is 4×10^{10}. From formula (6) it can be seen that $Y_{\mathrm{n}} \propto \mu W_b$, which implies that the yield scales as $Y_{\mathrm{n}} \propto I_m^4$ with $\mu \propto I_m^2$ and $W_b \propto I_m^2$.

Formulas (5) and (6) give different neutron yield estimations, 4×10^{10} and 9×10^{10} respectively, and it is difficult to say which value is more accurate by now. For a conservative estimate we select 4×10^{10} as the neutron yield from the beam-target mechanism on Qiangguang.

III. THE CONSTRUCTION AND THE OPTIMUM LINE MASS OF THE GAS PUFF

A kind of annular-shell gas puff adopted on Qiangguang[15] is shown in Fig.3. The throat has a 0.25 mm-width in radial direction and its area 18 mm^2. The outer and the inner radius of the gas exit are 9 mm and 7.5 mm respectively.

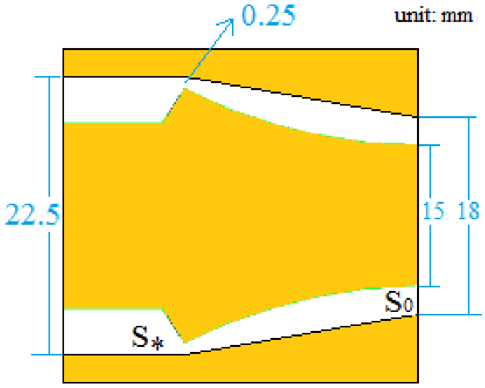

Fig.1. The sketch of the gas puff on Qiangguang (unit: mm).

Based on the aerodynamic analysis we can know that the line mass of the gas-puff is directly proportional to the product of the gas pressure P in the chamber, the atomic weight A, and the area of the throat $S_{\square}$. The relation is expressed as[16]

$$\mu = kPAS_* \,. \tag{7}$$

Here k is the scaling factor.

From the snow-plow model the implosion time t_{imp} of the gas puff is expressed as[17]

$$t_{imp} = C_t \frac{\mu^{1/2} R_0}{I_m} \,, \tag{8}$$

Where R_0 is the initial radius, I_m is the peak current, C_t is a constant related to the shape of the current waveform. The line mass deduced from formula (8) is expressed as

$$\mu = C_m \left[\frac{t_{imp}(us)\, I_m(MA)}{\langle R\rangle (cm)} \right]^2 \ \mu\mathrm{g/cm}\,, \tag{9}$$

Where <R> is the average radius of the shell[17]

$$\langle R\rangle = \int n(r) r^2 dr \Big/ \int n(r) r dr = \frac{2R_{\mathrm{O}}}{3} \frac{1-\left(R_{\mathrm{I}}/R_{\mathrm{O}}\right)^3}{1-\left(R_{\mathrm{I}}/R_{\mathrm{O}}\right)^2}, \tag{10}$$

R_{I} and R_{O} are the inner and the outer radius of the gas puff. For $R_{\mathrm{I}} = 7.5$ mm and $R_{\mathrm{O}} = 9$ mm the average radius $<R>$ is 8.3 mm by formula (10). C_m is a constant which is related to the shape of the current and the width of the gas shell $\Delta = R_{\mathrm{O}} - R_{\mathrm{I}}$. Mosher given the expression of the constant C_m in reference [17] as the following formula

$$C_m = 10^3 \left[12 + 1.3 \frac{\Delta}{R_{\mathrm{O}}} + 10 \left(\frac{t_c}{t_{imp}} \right) + 8 \left(\frac{t_c}{t_{imp}} \right)^3 \right]^{-2}, \tag{11}$$

where t_c is the rising time of the current. For most of the gas-puff Z-pinch experiments on Qianguang the ratios t_c/t_{imp} are 0.8~0.9, and the corresponding values of C_m are 1.66 ~ 1.35.

The optimum line mass of the gas puff can be deduced from the krypton experiments that had been performed on Qiangguang.

Table 1. Results of 15 shots of Kr experiments.

Shot	load current (MA)	t_c (ns)	t_{imp} (ns)	line mass (μg/cm)
03081	1.4	90	100	36.5
03082	1.4	88	101	39.6
03083	1.5	97	113	58.5
03084	1.5	95	110	54.8
03086	1.5	92	101	41.7
03087	1.4	100	120	60.6
03089	1.4	96	106	40.5
03091	1.4	110	136	81.9
03092	1.5	94	110	55.9
03093	1.4	88	101	39.6
03094	1.5	94	110	55.9
03095	1.4	90	105	44.1
03096	1.5	92	110	58.1
03098	1.5	97	115	62.5
03099	1.5	97	124	82.5

The line-mass data calculated by the formula (9) for fifteen shots of Kr Z-pinch are listed in the Table 1, as well as the load current, the rising time of the current and the implosion time. We take the average line mass of the fifteen shots as the optimum line mass which is 50 μg/cm.

IV. THE PROFILES OF THE GAS DENSITY

The density profiles can be determined by the classic ballistic-transport model (BFM)[18]. The BFM treats the gas flow as emerging from a thin annulus with a Gaussian distribution in angle about the nozzle tilt angle, and this distribution is the propagated forward ballistically along the axial direction of the nozzle. The BTM is illustrated as the following formula[18]

$$n(r,z)=\frac{N}{\pi\delta^2}\exp\left[-\frac{r^2+\left(R_C-z\theta_t\right)^2}{\delta^2}\right]I_0\left[\frac{2r\left(R_C-z\theta_t\right)}{\delta^2}\right] \tag{12}$$

where $\delta(z)=(z+z_0)\theta_d$, z is the distance from the nozzle, z_0 is the gas-source offset from the nozzle plane, θ_d is the divergence angle of gas escaping from the nozzle, θ_t is the nozzle tilt angle, N is the line density, R_C is the nozzle radius and I_0 is the Bessel function. The parameters θ_t and R_C can be determined from the nozzle geometry while θ_d and z_0 are chosen to simultaneously provide the best fit to the measured density profile. For Qiangguang's gas puff the parameters are set as $\theta_d \approx 11^\circ$, $\theta_t \approx 0.17\text{rad}$, $z_0 = 5$ mm, R_C=8.3 mm, and $N = 4\times10^{17}/\text{cm}$, respectively.

The calculated density contour lines for axis distance z in the range from 0 to 4 cm are shown in Fig. 2. The gas density in the main district is $10^{16}\sim10^{17}/\text{cm}^3$, which two orders of magnitude lower than that of the gas at normal pressure and room temperature. Gas flowing from the nozzle forms a hollow shell within the length 2 cm and will assembles on the axis to form a solid column when the length is beyond 2 cm, so the anode of the gas puff should be assembled on the position z = 2 cm.

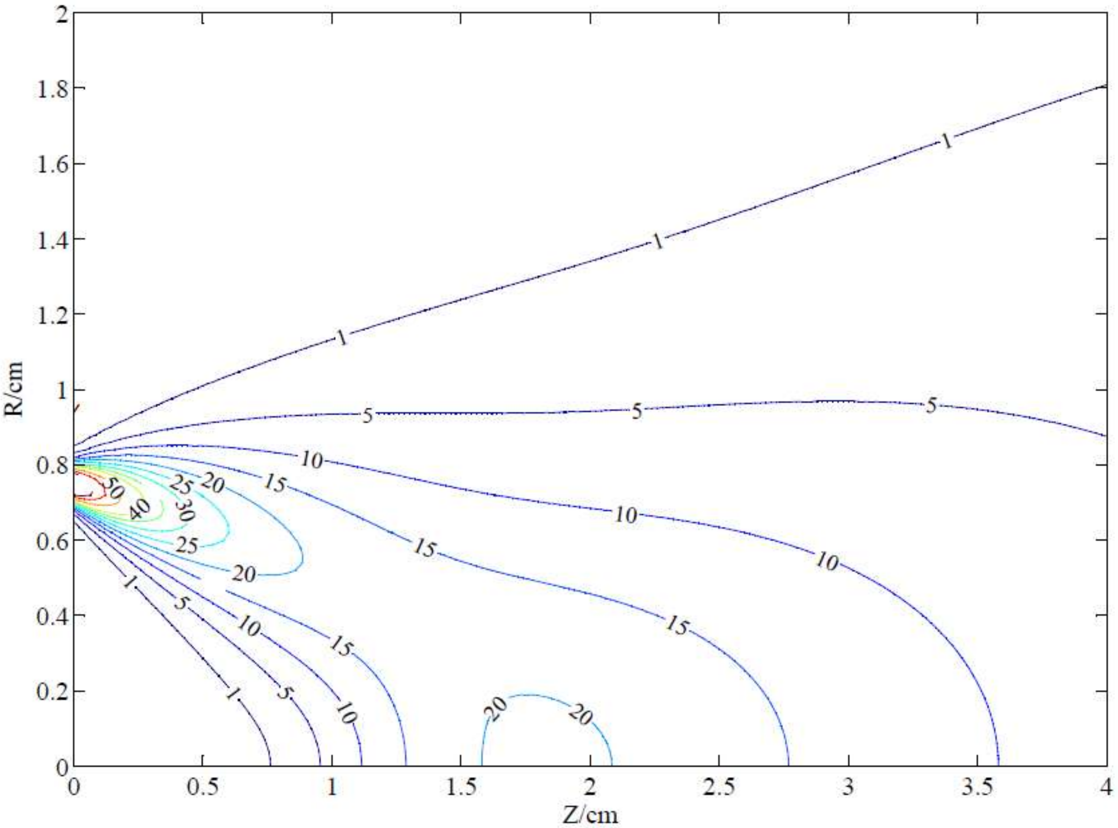

Fig. 2. The contour line of the gas density (the unit for the number density is $10^{16}\,\text{cm}^{-3}$).

As mentioned above, the optimum line mass 50 μg/cm is obtained from the data of the Kr Z-pinch experiments, where the gas pressure of the chamber is 2.5 atm (absolute pressure). This means by the formula (7) that the chamber pressure is nearly 50 atm in the D_2

experiments if other conditions are the same while the mass of the krypton atomic is nearly 20 times that of the D_2 molecule. Obviously, it is too difficult to keep the chamber from gas leakage in such a high pressure. In fact the line mass in the gas puff z-pinch experiments can be adjusted by changing the firing time of the generator. For the Kr experiments on Qiangguang the generator is fired 60 μs after the breakdown signal of the pin located in the anode of the gas puff, while the krypton gas flow from the nozzle achieves the quasi steady state after ~250 μs when the line mass is 600 μg/cm or so[19]. The line mass for D_2 will arrive 50 μg/cm when the delay time is adjusted to 250μs and the chamber pressure is 4.2 atm.

V. SUMMARY

In conclusion, we have estimated the D-D neutron yield on Qiangguang generator. Nearly 4×10^{10} D-D neutrons will be produced from the beam-target mechanism, while the thermonuclear neutrons are only 7×10^{7}. The means the percent of the thermonuclear neutron is less than 1% of the total neutron yield. The optimum lines mass is 50 μg/cm analyzed from the krypton experimental data on Qiangguang and the corresponding density profile is illustrated by the classical ballistic- transport model. The density profile shows that a hollow gas shell is formed whose length is not beyond 2 cm. This result may imply that the interval between the nozzle and the anode net should be not beyond 2cm. For D_2 to produce a gas flow with the line mass 50 μg/cm the firing time of Qiangguang is needed to adjust to 250 μs and the absolute pressure of the chamber is increased to 4.2 atm.

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