Neutron production mechanism at constrictions in plasma pinches

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Electric fields are induced at the constrictions in plasma pinches because of a current redistribution over the discharge cross section. The deuteron spectrum $dN/dv \sim \exp(-v/v_*)$ and the neutron yield $V = 2\times 10^{12}\cdot I_{\rm MA}^{5/4} \times \exp(-3.33/\sqrt{I_{\rm MA}})$ are calculated. The results agree well with experiment.

1. The emission of neutrons during discharges in deuterium, which was discovered in 1952 in the USSR and the USA, is caused by nuclear reactions $d + d \rightarrow {}^3{\rm He} + n$. A question which has not been finally resolved is whether the fast deuterons appear as a result of plasma heating (the "fusion" mechanism) or as a result of acceleration in electric fields (the "accelerator mechanism"). In Ref. 1, I suggested an induction mechanism for the appearance of the electric fields, as a result of a decrease in the current in the main discharge channel during the onset of a sausage instability there (the "$m = 0$ mode"). This instability was first studied in my 1952 paper.[2] According to the mechanism of Ref. 1, if the current $\delta I' = j' dx' dy'$ vanishes on the line x', y' at the time t', a cylindrical wave is excited in the surrounding space with a field

$$\delta E_z(x, y, t\,;\, x', y', t') = 2\delta I'/c\sqrt{c^2\tau^2 - R^2}\,;\quad \tau = t - t';\quad \mathbf{R} = \mathbf{r}_\perp - \mathbf{r}'_\perp, \tag{1}$$

if there is no external plasma (the "vacuum model"). Various versions of the initial distribution of the current j' were examined in Ref. 1: a δ-function distribution of the current at the axis (this version was also studied in Ref. 3), a uniform distribution over the cross-sectional area of the pinch, πa^2, a Gaussian distribution, and a current concentrated in an infinitely thin skin or shell of the pinch. All these versions can be obtained from Green's function (1). In connection with the plane pinch, this mechanism is known as the "Bulanov-Syrovatskiĭ mechanism," and it was studied in Ref. 4 for the model of an infinitely thin plane current i_z^0, in which an expanding zone $|x'| = vt'$ of vanishing current arises at the time $t = 0$. At the point x, y, t we then have a field which can be written as follows,[4] where we are using Green's function (1):

$$E = \int \delta E = \int \frac{2i^0 dx'}{c\sqrt{c^2\tau^2 - R^2}} = \frac{B_0}{2\pi}\,\beta\gamma \ln \frac{G_+ + 1}{G_+ - 1}\,\frac{G_- + 1}{G_- - 1}\,, \tag{2}$$

where $\beta = v/c$, $\gamma = 1/\sqrt{1-\beta^2}$, and $G_\pm = \gamma(ct \pm \beta x)/\sqrt{c^2t^2 - x^2 - y^2}$. It has been suggested that this mechanism accelerates particles in "giant" solar flares. The vacuum models in (1) and (2) need to be refined, however, to incorporate the peripheral plasma. This refinement was made in Refs. 5 and 6, by Zhdanov and the present author. In the present letter it is shown that a more detailed calculation on the basis of the qualitative picture in Refs. 1, 5, and 6 leads to equations which agree even quantitatively with experimental data on cylindrical pinches, in particular, on the neutron yield.

2. We assume that the total current (I_0) in the pinch is constant but consists of two components: $I_0 = I_1 + I_2$, where $I_1(t)$ is the decreasing current in the main pinch, and $I_2(t)$ is the increasing current in the magnetized peripheral plasma outside the main pinch. We can use the approximation that the current $I_1(t)$ creates fields $B = 2 \cdot I_1/cr$ and $E = \dot{I}_1(t)c^{-2}\ln(r/R)^2$, outside the pinch, where R is a scale length. If the current $I_1(t)$ falls off so rapidly that the ions (deuterons) are not turned by the magnetic field B, these ions must acquire a momentum

$$Mv = e\int_0^\infty E\,dt = Mv_*\ln(R/r)^2 \qquad (3)$$

in a pulsed fashion, where $v_* = eI_0/Mc^2$ is a scale velocity. We thus have $r^2 = R^2\exp(-v/v_*)$, and if we assume that the density of the peripheral plasma is constant ($n_1 = \text{const}$) outside the pinch over the length of a constriction, $\delta_z = L$, we find the number of accelerated ions to be

$$dN = n_1 L\, 2\pi r\,dr = (N_*/v_*)\exp(-v/v_*)\,dv\,, \qquad (4)$$

where $N_* = n_1 L\pi R^2$. It can be shown,[6] however, that under the condition $\omega \gg \omega_{Bi}$ ("unmagnetized ions") the peripheral plasma screens the rapidly varying field $E \sim \dot{I}_1(t)$ roughly over the "electron" distance $R = \sqrt{I_0/2\pi n_1 ce}$. As a result, expression (4) should be replaced by the following description of the spectrum:

$$dN/dv = F(v, t=0) = (N_*/v)\exp(-v/v_*)\,. \qquad (5)$$

Furthermore, we should take into account the fact that after the pulse the deuterons are turned by the magnetic field and subsequently penetrate into the "target" plasma of density n_0—into the thicker regions between the constrictions and into the "residual" central pinch. Here the deuterons lose energy and velocity exponentially through Coulomb collisions, primarily with electrons[7]:

$$\epsilon = \epsilon_0\exp\left(-\frac{t}{\tau_0}\right);\quad v = v_0\exp\left(-\frac{t}{2\tau_0}\right);\quad \tau_0 = 54{,}5\,T_{\text{keV}}^{3/2}\,(10^{-20}\cdot n_0\ \text{cm}^{-3})^{-1}. \qquad (6)$$

Spectrum (5) therefore evolves over time in accordance with

$$F(v,t) = (N_*/v)\exp\left[-(v/v_*)\exp(t/2\tau_0)\right], \qquad (7)$$

where $\tau_0 \sim T_0^{3/2}/n_0$ can be assumed conserved even during an adiabatic expansion of the target plasma.

3. We can use (7) to find the neutron production rate:

$$\dot{Y} = \int n_0\sigma v F(v,t)\,dv\ ;\qquad \sigma = c_1 v^{-2}\exp(-c_2/v)\,, \qquad (8)$$

where σ is the cross section for the nuclear reaction $d + d \rightarrow {}^3\text{He} + n$, and the $c_{1,2}$ are the "Gamow parameters." Assuming $n_0 = \text{const}$, and integrating over v and t, we find the total neutron yield to be

TABLE I.

I_{MA}	1/8	1/4	1/2	1	2
Y	1.2×10^{7}	4.5×10^{8}	7.6×10^{9}	7.2×10^{10}	$4,5\times10^{11}$

$$Y = \alpha x_0^{-2} K_0(x_0) \approx \tilde{\alpha} I_{\mathrm{MA}}^{5/4} e^{-x_0}\ ;\quad x_0 = 3,33/\sqrt{I_{\mathrm{MA}}}\,, \tag{9}$$

where I_{MA} is the current in megamperes, and $\tilde{\alpha} = 10^{11}\cdot L_{\mathrm{cm}}\cdot T_{\mathrm{keV}}^{3/2}$. Curiously, the value of Y in our model depends on neither the density of the peripheral plasma (n_1) nor that of the target plasma (n_0); it actually depends on only the current at the time of the "singularity." If we use the approximation $\tilde{\alpha} = 2\times10^{12}$ (neutrons), we find the behavior $Y(I)$ demonstrated in Table I. This behavior agrees well with observations in all plasma-focus devices that are optimized for neutron yield.

Spectrum (7) is also satisfactory. If we assume that as a result of the stopping in (6), a certain time t determined by the expression $\exp(t/2\tau_0) = (1 - l/2v_0\tau_0)^{-1}$, is required for an ion to travel a certain distance l, we can rewrite spectrum (7) for the ions which escape from the chamber as a distribution in the energy $\epsilon = Mv^2/2$:

$$\frac{dN}{d\epsilon} \doteq \frac{N_*}{\epsilon}\exp\left[-\sqrt{\frac{\epsilon}{\epsilon_*}}\left(1-\sqrt{\frac{\epsilon_{min}}{\epsilon}}\right)^{-1}\right]. \tag{10}$$

This result also agrees quite well with the observed spectra of accelerated ions outside the chamber.

We believe that the approximate agreement of the picture assumed here with the generally accepted Bulanov-Syrovatskiĭ mechanism, on the one hand, and the agreement of expressions (9) and (10) with experimental data, on the other, are evidence for the accelerator mechanism instead of the fusion mechanism for the production of neutrons in pinch experiments.

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