Mechanism for deuteron acceleration at a plasma focus

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The mechanism by which deuterons are accelerated in the induced electric field at a plasma focus has been studied by numerical simulation. The group of accelerated deuterons consists of particles outside the pinch, which are not captured by the current shell as it converges on the axis of the plasma system. The calculated deuteron energy spectra agree well with experimental data.

1. We have carried out numerical simulations to determine those physical conditions for the acceleration of deuterons which correspond to the experimental results on the energy spectrum of the particles, their energy range, and their acceleration direction (from the anode toward the cathode) obtained from plasma-focus devices at various energies. The model is constructed from the experimental facts established in research on the Z pinch and the plasma focus, supplemented with the assumption that the gas is not completely captured by the current shell as this shell converges on the axis of the plasma system.

This assumption means that the initial coordinates of the accelerated particles are outside the pinch.

2. At the time in which the plasma focus (the pinch) is formed, the discharge current $J(t)$ and its magnetic field

$$H_\varphi = 2J(t)/cR \tag{1}$$

change rapidly (they decrease), leading to the production of an induced accelerating electric field E_z. The conditions for the production of megavolt fields in a Z pinch and a plasma focus, associated with a partial or complete interruption of the current, were studied first in Ref. 1 and later in Refs. 2 and 3.

Let us assume that the discharge current decreases linearly over the time interval (τ) of its change:

$$J(t) = J_1 - (J_1 - J_2)\frac{t}{\tau}, \qquad 0 \leqslant t \leqslant \tau. \tag{2}$$

The accelerating electric field is then found from (1) and (2) to be

$$E_z = \frac{2}{c^2}\,\frac{J_2 - J_1}{\tau}\,\ln\frac{R}{R_{\text{eff}}}, \qquad 0 < R \leqslant R_{\text{eff}} \tag{3}$$

where R_{eff} is the radius of the external conducting wall of the discharge chamber.

For all the present calculations we use $J_1 = 1$ MA and $J_2 = 0.7$ MA.

A lower limit is set on the deuteron acceleration zone by the plane of the anode

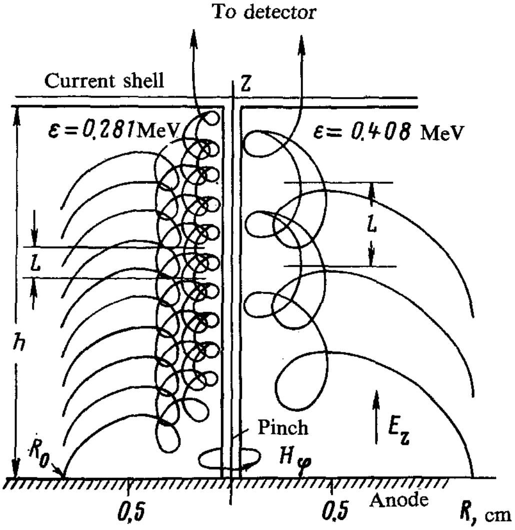

FIG. 1. Layout of the pinch and paths traced out by two energy groups of deuterons (the intensity of the monoenergetic line in the spectrum is proportional to the number of entrances onto a path leading to the detector).

($Z = 0$), while an upper limit is set by the current shell, which is a dynamic continuation of the pinch, as shown in Fig. 1. Shown in the same figure are the paths traced out by deuterons according to the solution of the equation of motion with fields (1) and (3). As the accelerated deuterons interact with the target deuterons in the plasma focus (the pinch) and the current shell, they cause (in particular) an emission of neutrons. Some of the deuterons which have not undergone collisions reach the detector.

3. The initial coordinates of the accelerated deuterons form the sites of a coordinate grid constructed along the R and Z axes. The sequence of initial coordinates of the deuterons along the radius is specified as a function of the particle index N:

$$R_0(N) = (2{,}5 - 0{,}002N)\ \text{cm}$$

$$N = 1, 2, 3, \ldots, 1200.$$

Each N-th particle is multiplied by a corresponding weight factor $R_0(N)$ to reflect the cylindrical geometry of the system.

For comparison with the observed spectrum, we consider only those initial coordinates along the Z axis which correspond to deuterons that reach the detector. We are thereby discarding those particles whose direction at the height $Z = h$ deviates from the vertical by an angle greater than $\Delta\varphi = 1'$.

Figure 1 shows two groups of deuterons, with final energies $\epsilon = 0.281$ MeV and $\epsilon = 0.408$ MeV, which reach the detector. We see from this figure that in the acceleration zone ($0 \leqslant Z \leqslant h$) the density of initial coordinates Z_0 and thus the density of paths increase with decreasing final energy of the deuterons and with decreasing size (L) of the loop in the path. For this dependence of the density of initial coordinates on the

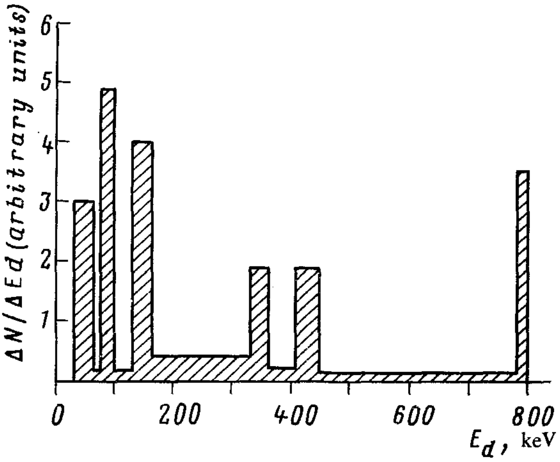

FIG. 2. Experimental deuteron spectrum (from an apparatus with $W = 100$ kJ and $U_0 = 40$ kV).

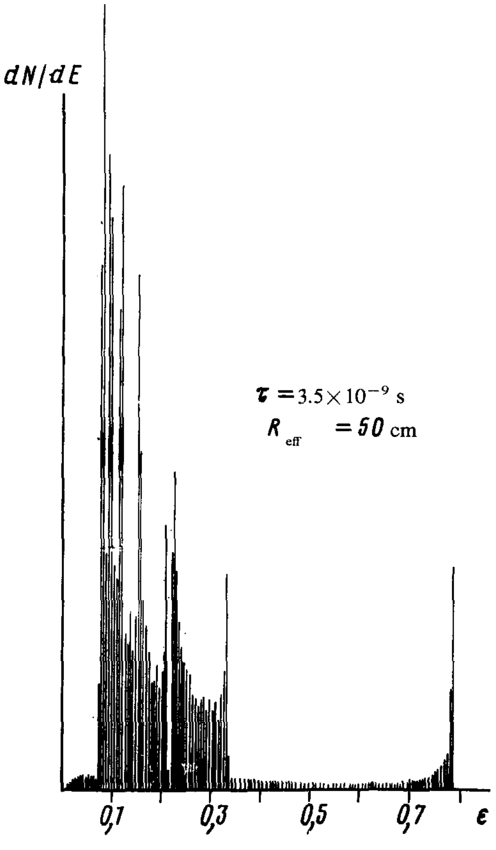

FIG. 3. Model spectrum.

energy or loop size L we would expect the intensity of a monoenergetic line to increase with decreasing energy ϵ.

Figure 2 shows an experimental spectrum of deuterons from Ref. 4. This spectrum is distinguished by an isolated large peak at its upper boundary. In the low-energy part of the spectrum, there are several groups of closely spaced peaks, whose heights and repetition frequency increase with decreasing energy ϵ down to a certain limit.

A similar spectrum was reported in Ref. 5. Spectra with fewer characteristic features have also been observed; for example, the high-energy peak may be missing.[6,7]

The spectrum in Fig. 3 is a model analog of the spectrum in Fig. 2. This spectrum reproduces quite well the isolated high-energy peak and the increase in the density and heights of the peaks in the low-energy part of the spectrum.

According to this model, a transition can be made from the spectrum in Fig. 3 to a spectrum without the high-energy peak by varying the parameters τ and R_{eff}.

The calculations show that the line of the interaction of the accelerated deuterons with the target deuterons generally does not coincide with the direction of the field E_z. This general case characterizes an acceleration regime of the plasma focus with a nearly isotropic emission of neutrons. As the height of the current shell is reduced (as certain experimental conditions are varied), the paths of the deuterons are curved to a lesser extent by the magnetic field H_φ and correspond better to a motion along the Z axis. In this case, we are dealing with the classical acceleration mechanism for the production of neutrons which was discovered in Z pinches, with a preferred direction of the accelerated deuterons and thus an anisotropic neutron emission.

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