POWERFUL NEUTRON SOURCE BASED ON A Z PINCH

V. A. Gribkov, O. N. Krokhin, G. V. Sklizkov, N. V. Filippov, and T. I. Filippova
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 8 August 1973, resubmitted 1 October 1973
ZhETF Pis. Red. 18, No. 9, 541 – 544 (5 November 1973)

We compare the presently existing Z-pinch modifications. A proposed model whereby the thermal fraction of the neutron yield is produced (heating by an electron beam) is used to explain the increase of the neutron yield and of its thermal fraction with decreasing length of collective deceleration of the beam in the Z-pinch. An experimental setup is proposed for increasing the neutron yield, based on a deuterated target at the chamber anode, preheated with a powerful laser prior to development of the relativistic electron beam in the Z-pinch.

Although the Z pinch is one of the first objects investigated for controlled nuclear fusion purposes, many questions remain unanswered. In particular, the mechanisms that produce the neutron and hard x-rays (HX) are still subjects of both experimental [1] and theoretical [2] research. Experiments with different Z-pinch modifications [3 - 6], performed with high-resolution apparatus, have explained many characteristic features of the pinch effect. There exist at present four types of installations in which a Z-pinch is used. Those installations which will be of use to us later are listed in the table. We see that the neutron yield and the fraction of thermal neutrons in it increases with decreasing pinch diameter a at the instant of breakdown and with increasing plasma density. However, the decrease of the pinch diameter prior to the current breakdown leads to large values of the axial electric field [7]:

Parameters \ Type of setup	Classic Z pinch [1]	Plasma focus [3]	Laser induced Z pinch [4]	"Micropinch" (exploding wire)
Capacitor bank voltage U_0	~30 kV	~ 25 kV	~ 15 kV	~600 kV
Current I_0	~400 kA	~1 MA	~250 kA	~1,2 MA
Pinch diameter prior to break of 2-A current	~2 cm	~0,5 cm		~10^{-2}- 10^{-3}cm
Density at neutron pulse maximum, $N_{e_{p\ell}}$	~10^{17}cm^{-3}	~10^{18}÷10^{19}cm^{-3}	~10^{21}cm^{-3}	≳10^{21}cm^{-3}
Temperature from soft x-ray and neut. spectra $T_{e,i\,max}$	< 10^2eV	~10^4 eV	8·10^3 eV	~10^4 eV
Energy of hard x-ray component, W_{0_b}	to 350 keV	200–500 keV	~500 keV	≳ 600 keV
Absolute neutron yield, N_n	~10^7- 10^8	~10^{10}- 10^{11}	—	~10^{11}
Ratio of number of neutrons of thermonuc. and accel. origin, N_n^T/N_n^A	<< 10^{-1}	~10^{-1}- 10	—	> 10

$$E_{z_{max}} \sim H_\phi \sim \frac{2T_0}{ca} \qquad (1)$$

In this field, the deuterons should acquire an energy less than or of the same order as the electron energy. This is confirmed by x-ray [8] and neutron [9] spectral measurements in a plasma focus. On the other hand, when a target of solid CD_2 was placed in the cathode of a micropinch [5], the neutron yield increased by one order of magnitude, and under some conditions of plasma focus with a tube on the cathode along the z axis [9], the neutrons were produced at distances up to 1.5 m from the chamber cathode, thus confirming the presence in the pinch of deuteron beams with velocities ∿ 10^8 cm/sec. Experiments with a longitudinal magnetic field in the plasma focus [10] have revealed a sharp drop in the neutron yield, obviously because the pinch current was not interrupted in this case.

On the other hand, the electron beam produced in the field (1) can heat the pinch plasma [11 - 13]. Such focusing beams, subject to hose instability, were observed and investigated in [6] by high-speed interferometry and by photography in soft x-rays (SX). At the same time, SX photographs of the pinch were obtained in [4] and likewise revealed a conical structure (focusing electron beam).

The beam deceleration length ℓ for the plasma parameters of a dense pinch should exceed by 10 - 10 times [11 - 13] the deceleration length due to two-beam instability:

$$\ell \approx 10^2 - 10^3 \frac{v}{0.7(N_{e_b}/N_{e_{p\ell}})^{1/3}\omega_{p\ell}} \ln\left(\frac{W_{eb}}{W_{th\,p\ell}}\right), \tag{2}$$

where $v \sim c$ is the electron-beam velocity.

The experimental results of [3, 4, 14] demonstrate the following: 1) Electron beams begin to be effectively decelerated in a pinch some 20 - 100 nsec (depending on $N_{e_{p\ell}}$) after their formation, i.e., only after the plasma temperature (which is apparently heated mainly by the reverse current) rises to a value on the order of 10^3 - 10^4 eV. The HX vanish at that instant and the main neutron pulse starts. This is likewise in agreement with the theoretical concepts [11] and with the experimental results of [5], where placement of a cold solid CD_2 target in the chamber anode did not increase the neutron yield. 2) The deceleration length of the electron beam is approximately inversely proportional to $N_{e_{p\ell}}$ (in a classical Z pinch there is practically no deceleration [1], and in a plasma focus we have $\ell \simeq 10^{-1}$ - 1 cm and the deceleration frequently sets in after several focusings of the beam in the plasma [3], while in a micropinch [5] and in a laser-induced pinch [4] we have $\ell \simeq 10^{-3}$ - 10^{-1} cm, which agrees with the theoretical papers [11, 12] and with formula (2). This fact was confirmed also by experts on the effective deceleration of an external electron beam in a plasma focus [16], accompanied by an increased neutron yield.

We can thus conclude on the basis of the foregoing that the main neutron mechanisms in Z pinches are the collisions of deuterium ions, accelerated in electric fields of type (1), with "cold" ($\lesssim$ 1 keV) deuterium of the pinch, and on the other hand plasma heating to $\gtrsim 10^4$ eV as a result of two-stream instability by powerful relativistic electron beams; the role of the second mechanism increases with increasing field $E_z(a)$, density, and temperature of the Z-pinch plasma, for in this case the electron-beam deceleration length decreases sharply, and the per-unit energy input is increased, whereas the cross section of the d-d reaction for accelerator deuterons with energy on the order of several hundred keV is a rather weak function of the energy.

It follows from the foregoing that at the initial instant of time (20 - 100 nsec) the energy of the electron beam is dissipated practically completely but rather inefficiently on the cold anode, since the relatively-low-temperature plasma produced over the anode surface hinders the development of two-stream instability [11]. To increase the neutron yield, it is therefore natural to heat the solid deuterated target placed on the Z-pinch anode, say by using powerful laser radiation, to temperatures on the order of several keV, so that effective plasma heating as a result of two-stream instability development sets in at the instant when the electron beams appear. A micropinch [5] can obviously also become a powerful neutron source if a powerful laser is used to precompress the wire to high density and to produce temperatures on the order of 10^3 eV [17] in the region near the chamber anode.

The authors thank Academician N. G. Basov for interest in the work.

[1] V. V. Aleksandrov, N. G. Koval'skii, S. Yu. Luk'yanov, V. A. Rantsev-Kartinov, and M. M. Stepanenko, Zh. Eksp. Teor. Fiz. 64, 1222 (1973) [Sov. Phys.-JETP 37, No. 4 (1973)].
[2] V. S. Imshennik, S. M. Osovets, and I. V. Otroshchenko, ibid. 64, 2057 (1973) [37, No. 6 (1973)].
[3] V. A. Gribkov, O. N. Krokhin, G. V. Sklizkov, N. V. Filippov, and T. I. Filippova, ZhETF Pis. Red. 18, 11 (1973) [JETP Lett. 18, 5 (1973)].
[4] T. N. Lee, NRL Memorandum Report 2502, NRL, W., D.C., 1972.
[5] D. Mosher, L. S. Levine, S. J. Stephanakis, I. M. Vitkovitsky, and F. Young, 6th European

Conf. on Contr. Fusion and Plasma Physics, Moscow, 1973.
[6] V. A. Gribkov, V. M. Korzhavin, O. N. Krokhin, G. V. Sklizkov, N. V. Filippov, and T. I. Filippova, ZhETF Pis. Red. 15, 329 (1972) [JETP Lett. 15, 232 (1972)].
[7] B. A. Trubnikov, in: Fiz. plazmy i probl. upr. termoyad. reaktsii (Plasma Physics and the Problem of Controllec Thermonuclear Reactions), M. A. Leontovich, ed., AN SSSR, 1958, p. 87.
[8] H. L. van Paasen and R. H. Vandre, Phys. Fluids 13, 2606 (1970).
[9] H. Conrads and P. Cloth, 5th European Conf. on Contr. Fusion and Plasma Physics, 1, No. 67, Grenoble, France, 1972.
[10] D. P. Petrov, N. V. Filippov, T. I. Filippova, and V. A. Khrabrov, op. cit. [7], Vol. IV, AN SSSR, 1958.
[11] L. I. Rudakov, Zh. Eksp. Teor. Fiz. 59, 2091 (1970) [Sov. Phys.-JETP 32, 1134 (1971)].
[12] B. N. Breizman, D. D. Ryutov, and P. Z. Chebotaev, ibid. 62, 1409 (1972) [35, 741 (1972)].
[13] R. L. Morse and C. W. Nelson, Phys. Rev. Lett. 26, 3 (1971).
[14] C. Patou and A. Simonnet, Note C.E.A. No. 1189, 1969.
[15] J. Benford and B. Ecker, Phys. Rev. Lett. 26, 19, 1160 (1971).
[16] D. A. Friewald et al., Phys. Lett. 36A, 297 (1971).
[17] K. A. Brueckner, KMSF-NP5, Ann Arbor, Michigan, 1972.

EFFECT OF PULSED MAGNETIC FIELD ON QUADRUPOLE SPIN ECHO

A. A. Boguslavskii, V. V. Pechenov, and G. K. Semin
Kolomna State University
Submitted 4 September 1973
ZhETF Pis. Red. 18, No. 9, 545 – 546 (5 November 1973)

We investigate the effect of a pulsed magnetic field on quadrupole spin echo. Observing the beats of the spin-echo envelope permits small shifts of the NQR frequencies to be observed against the background of an appreciable inhomogeneous broadening of the spectral line.

The pulsed method of observing NQR signals has made it possible to register small electric-field-induced shifts of the NQR frequency against the back-round of an appreciable inhomogeneous broadening of the spectral line [1, 2].

The effect of a constant magnetic field on quadrupole spin echo is dealt with in [3 - 5]. The beats of the spin-echo envelope (SEE) in a constant magnetic field are determined by the interference effects [6] resulting from mixing of the states $|+1/2\rangle$ and $|-1/2\rangle$, and also of the states $|+m\rangle$ and $|-m\rangle$, if the asymmetry parameter η of the electric field gradient (EFG) is not equal to zero.

If $I \neq 3/2$ and $\eta = 0$, the constant electric field lifts the degeneracy of the states $\pm$ m and leads to an inhomogeneous broadening of the NQR lines. Since the spin-echo amplitude is determined only by homogeneous broadening, no SEE beats are observed for the transitions $\pm m \leftrightarrow \pm(m + 1)$, where $m \neq 1/2$.

We succeeded in observing the effect of a pulsed magnetic field on the SEE. As follows from the general principle of observing external actions that lead to inhomogeneous broadening of the NQR line [1, 2], the external magnetic field should be applied in one of the two intervals $0 - \tau$ and $\tau - 2\tau$, using a two-pulse program for registering the NQR signal.

In single crystals having bonds that are equivalent with respect to the magnetic field and contain quadrupole atoms, the SEE beats are observed in a pulsed magnetic field and are described by the relation

$$A = A_0 \cos[(2\pi\Delta\nu_L \cos\theta)\tau],$$

where A_0 is the SEE in a zero magnetic field, $\Delta\nu_L$ is the Larmor frequency of the investigated quadrupole nucleus in the field H, and θ is the angle between the $\vec{H}$ direction and the EFG axis.

In polycrystals, the SEE is modulated by the Fourier transform of the function $h_H(\nu)$, which describes the shape acquired in a field of intensity H by an NQR resonance line that is monochromatic in a zero field.