České vysoké učení technické v Praze
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Z-pinč a jaderná fúze

Z-pinch and nuclear fusion

Summary

A z-pinch may be defined as a cylindrically symmetric plasma column in which the plasma carrying an axial current is confined, owing to the Lorentz force, by its own magnetic field. Deuterium z-pinches have produced a large number of fast neutrons from the very beginning of fusion research. Even though the thermonuclear origin of neutrons was not confirmed in the first compressional z-pinch experiments, a high efficiency of neutron production led to the study of z-pinches as neutron sources. In order to produce a significant number of fusion reactions, various z-pinch configurations have been tested. The most promising configuration seemed to be a dense plasma focus and a deuterium gas puff z-pinch. Z-pinches as pulsed neutron sources can be useful tools in radiation material science, radiobiology, nuclear medicine, cargo inspection, improvised-explosive-device detection and controlled thermonuclear fusion research.

This habilitation lecture introduces the results of neutron measurements carried out on the fast (100 ns) S-300 z-pinch at the Kurchatov Institute of Atomic Energy in Moscow, on the powerful (terawatt) GIT-12 generator at the Institute of High Current Electronics in Tomsk, and on the energetic (megajoule) PF-1000 plasma focus at the Institute of Plasma Physics and Laser Microfusion in Warsaw. The main aim of these experiments was to study neutron production mechanisms. Among other results, the first experimental evidence of thermonuclear neutrons in z-pinches and the efficient neutron production by fast, magnetized deuterons in deuterium gas puffs are presented.

Souhrn

Silnoproudý výboj typu z-pinče je založen na principu, při kterém proud protékající plazmatem ve směru jedné z os generuje (na základě Ampérova zákona) azimutální magnetické pole, jež působením Lorenzovy síly komprimuje či udržuje plazmatický kanál. Když byl na začátku výzkumu řízené termojaderné syntézy zkonstruován první z-pinč s plynným deuteriem, bylo detekováno velké množství rychlých neutronů. Přestože tyto neutrony nebyly termonukleárního původu, vysoká účinnost produkce neutronů byla hlavním důvodem pro další studium pinčů jako neutronových zdrojů. Za účelem vysokých neutronových zisků byla na principu z-pinče vyzkoušena celá řada konfigurací. Jako nejúčinnější se zatím osvědčily především tzv. plazmatické fokusy a z-pinče s impulzním napouštěním plynu do vakua. Z-pinče jako neutronové zdroje mohou mít široké uplatnění nejen ve fúzním výzkumu, ale také v materiálových vědách, radiobiologii, nukleární medicíně nebo při kontrole nákladů či detekci výbušnin.

V této habilitační přednášce jsou prezentovány výsledky měření neutronů na rychlém (100 ns) z-pinči S-300 v Kurčatově ústavu pro atomovou energii v Moskvě, na výkonném (terawatovém) generátoru GIT-12 v Ústavu silnoproudé elektroniky v Tomsku a na megajouleovém plazmatickém fokusu PF-1000 v Ústavu fyziky plazmatu a laserové mikrofúze ve Varšavě. Hlavním cílem těchto experimentů bylo studium mechanizmu, kterým jsou produkovány fúzní neutrony. Mezi nejdůležitější výsledky patří především experimentální ověření termonukleárních neutronů v z-pinčích a také účinná produkce neutronů pomocí rychlých iontů urychlených a zachycených v z-pinči s impulzním napouštěním deuteria.

Klíčová slova:	Z-pinč, plazmatický fokus, jaderná fúze, neutrony, deuterium, napouštění plynu, diagnostika plazmatu
Keywords:	Z-pinch, plasma focus, nuclear fusion, neutrons, deuterium, gas puff, plasma diagnostics

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Contents

1 Brief survey of z–pinch fusion research

1.1 Z-pinch effect

The z-pinch may be defined as a cylindrically symmetric plasma column in which the plasma carrying an axial current is confined, owing to the Lorentz force, by its own magnetic field. The term ‘pinch’ originated in the 20th century, when also the first systematic research of z-pinches began. The prefix ‘z’ was added in the 1950s to denote the confinement driven by the axial (z) current.

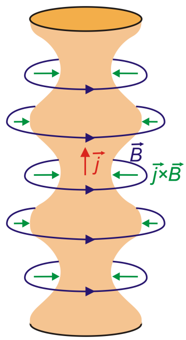

Figure 1.1: Z-pinch being susceptible to $m = 0$ instabilities.

The fluid dynamics of z-pinches can be described by the Euler equation of motion as

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}\right) = -\nabla p + \mathbf{j}\times\mathbf{B} \tag{1.1}$$

where the pressure gradient $-\nabla p$ and the magnetic force density $\mathbf{j}\times\mathbf{B}$ are included, whereas the viscous force $\eta\Delta\mathbf{v}$ and other terms are neglected.

Z-pinches belong to the most fascinating objects in plasma physics because of their simple principle, natural occurrence including lightings and current channels in galactic scales as well as variety of applications.

1.2 Beginning of the controlled thermonuclear fusion research

It was the simple principle and geometry in particular why magnetic pinches enjoyed great attention in the early 1950s in conjunction with controlled thermonuclear fusion research [1]. The idea behind this research was to heat a fusion mixture by Joule heating and by adiabatic or shock compression, and then to confine the plasma by the pinch effect until a sufficient amount of fusion energy was released. One of the first experiments was performed with compressional z-pinches. In this configuration, the electric current started at an insulating wall and when the magnetic pressure exceeded the gas pressure, a current carrying plasma shell together with the preceding shock wave radially collapsed (see Fig. 1.2). Characteristic parameters of compressional z-pinches were 50 cm long and 5 cm diameter vessels, 0.1 Torr initial pressures of a D_2 gas, 20 kV charging voltages, μF capacitor banks and μs implosion times [2].

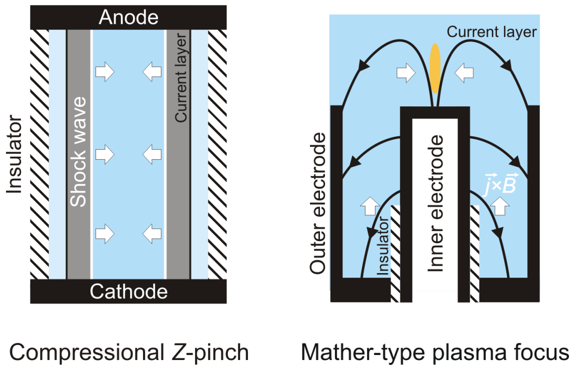

Figure 1.2: Compressional z-pinch and plasma focus configuration.

The compressional z-pinches produced a high number of neutrons, above 10^8 per one pulse on a 100 kA current level. However, S. Colgate with his colleagues showed that the neutrons were not produced by a Maxwellian plasma. They proposed that deuterons were accelerated by axial electric fields created by the growth of magnetohydrodynamic instabilities [2]. This was consistent with Kurchatov's explanation [3] and Kruskal's and Schwarzschild's theoretical work [4]. All these facts together, particularly the conclusion that neutrons were not of thermal origin, led to the abandonment of a straight z-pinch as a fusion power source. As a result, more complex schemes of magnetically confined plasma devices, such as tokamaks and stellarators that are also free from electrode phenomena and end-losses, were suggested and researched in an attempt to reduce MHD instabilities.

During the research of one of more stable schemes, namely the Scylla-θ pinch at Los Alamos, a plasma gun was used to inject a plasma into the device. When the plasma gun was studied, it was found that a large number of neutrons were generated from this plasma gun itself. This was the main reason why a so-called Mather-type plasma focus was researched from that time on [5]. The plasma focus is a device also based on the pinch effect as shown in Fig. 1.2. At the end of this axial phase, a radial collapse occurs in the way similar to z-pinches. The maximum yield on sub-MJ devices approached the value of 10^{12} DD neutrons per pulse.

1.3 Rebirth of z–pinch research

The interest in z-pinches was renewed in the 1970s when high voltage, > 100 kV pulsed power technology was developed and used to drive a z-pinch load. Using the pulsed power technology, it has become possible to deliver an electrical power of ≈50 TW and an energy of ≈10 MJ to a load. The compression of an electrical energy in time and space is enabled by a Marx generator, (water) pulse forming line and magnetically insulated (vacuum) transmission line. When the pinch effect is used as a final stage of these devices, the energy stored in capacitors can be deposited into a small volume of ≈cm^3 within several nanoseconds with a high efficiency of about 30%. Due to a low impedance of these current generators, the implosion of a low inductance cylindrical plasma onto its axis is a more effective way to generate radiation than resistive heating of an exploding wire with an initial low diameter. For this reason, cylindrical arrays of wires and annular gas puffs have been used. With these loads, the stored electrical energy is converted into a kinetic energy of magnetically confined, imploding plasmas. At stagnation, the kinetic energy is thermalized. In the case of high atomic number material, the significant part of the energy is radiated in sub-keV and keV radiation.

By using nested arrays of ≈μm diameter wires, z-pinches have become the world's most powerful (350 TW power, 2.8 MJ radiated energy) and most efficient (15%) laboratory X-ray sources [6]. From other significant parameters of the most powerful Z-machine in Sandia, we can mention magnetic and kinetic pressures of the order of 10 Mbar, electron temperatures of about 1 keV, radiated powers of 100 TW, magnetic fields of 1000 T, and the energy density of about 10 MJ/cm^3. Matter with these parameters fulfills the conditions required for high energy density physics.

1.4 Z-pinch as driver for ICF

At present, z-pinches are being intensively researched as the most powerful and efficient laboratory sources of soft X-rays. The refurbished *Z* machine in the Sandia National Laboratories is now capable of producing 5 ns X-ray pulses with 350 TW peak powers and 2.8 MJ radiated energies. Such a large volume, near–Planckian X-ray source provides a well–characterised indirect driver for experiments relevant to the *Inertial Confinement Fusion* programme. The high X-ray production efficiency ranked z-pinch among three major drivers for *Inertial Fusion Energy* (IFE). In one of the most perspective concepts, the z-pinch radiation is produced during the collision of an imploding liner (high–*Z* wire–array) with an inner shell (a low density foam "convertor"). The inward travelling shock–wave generates radiation that is trapped by the outer imploding high–*Z* shell. Therefore, the shell acts as a hohlraum wall and becomes a high temperature blackbody radiator. Later, the generated blackbody radiation drives a spherically symmetric DT capsule in very similar way as in ICF indirectly driven by lasers. Since the shell is moving, we call it "dynamic hohlraum" or "flying radiation case".

Dynamic hohlraum ICF experiments on *Z* accelerator were created from two annular tungsten wire–arrays (a 240–wire 40–mm diameter outer array and a 120–wire 20–mm diameter inner array, see e.g. [7]). This way, a deuterium–filled capsule absorbed $\approx$ 24 kJ of X-rays from a $\approx$ 220 eV dynamic hohlraum. The thermonuclear neutron yield from the D–D reaction was up to 8×10^{10} which was the highest D–D neutron yield reached with X-ray drivers those days.

1.5 Magnetized Liner Inertial Fusion

Recently, the ICF programme in the U.S. has been redirected to the National Ignition Facility at the LLNL. Therefore other approaches have been considered for the refurbished *Z*-machine at the SNL. There are two principal reasons for novel fusion approaches. The first one is the idea to employ the effect of inertial as well as magnetic confinement in a large space of plasma densities between 10^{20} and 10^{29} m^{-3} (so-called Magneto-Inertial Fusion or Magnetized-Target Fusion). This density region has not been investigated in such details as ICF and MCF (Magnetic Confinement Fusion) concepts but it seems worthwhile to do so. The second reason follows from basic principles of particle diffusion which show that alternative approaches based on the z-pinch effect could provide much smaller fusion reactors than tokamaks and ICF drivers [8]. This is an important fact because it means cheaper way of fusion research which has not been finished yet. In this respect we can mention the MagLIF concept (Magnetized Liner Inertial Fusion, [9; 10]) which is a very promising even though there are many technological challenges that need to be overcome.

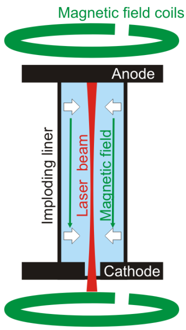

Figure 1.3: Imploding liner heated by laser in the MagLIF concept.

The basic idea of the MagLIF project is based on magnetically driven compression of a solid liner that contains a fuel preheated by a powerful laser and magnetized by an embedded axial magnetic field, as shown in Fig. 1.3. In comparison with gas puffs, solid metal liners provide higher initial conductivity and they enable us to use a DT mixture with much higher initial pressure of about 100 Mbar. Due to the preheating by a laser to ≈500 eV temperatures, a relatively low implosion velocity of the order of 10^5 m/s is required to obtain the ignition temperature. The axial magnetic field of ≈10 T is expected to stabilize the implosion, to suppress thermal conduction losses, and to enhance the energy deposition by alpha particles. When a 100 ns current generator is used, a modest laser energy is required and a purely axial magnetic field is sufficient to confine α particles within a 2 cm long cylindrical column. According to numerical predictions, conditions sufficient for breakeven might be reached even with the Z-machine and Z-beamlet at the Sandia National Laboratories. But even if the issue of controlled fusion is not solved in the near future, z-pinches might be applied as efficient neutron sources in fusion-fission reactors [11; 12].

1.6 Deuterium gas-puff z-pinch

At the end of the previous section, we mentioned the application of efficient neutron sources. It is reasonable to research deuterium z-pinches as compact sources of fast neutrons since they produced a large number of DD fusion neutrons already in the 1950s at the very beginning of the fusion research.

To achieve high neutron yields, various configurations based on the z-pinch effect have been suggested and tested from that time on. The most promising configuration seemed to be a dense plasma focus (DPF) with a deuterium gas filling and a deuterium gas puff z-pinch. In comparison with plasma foci, deuterium gas puffs are much more variable. To be more precise, deuterium gas puffs allow us to study the influence of various gas density profiles, various implosion velocities and shorter current rise times. They also allow to research the influence of different gases and admixtures inside an inner and/or outer shell. They possess the advantage of causing no difficulties with an insulator, namely with its conditioning and re-strikes during the pinch phase.

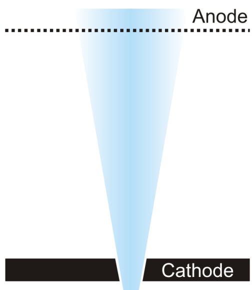

Figure 1.4: Solid fill deuterium gas puff z-pinch.

A growing interest in deuterium gas puff z-pinches is also motivated by a high DD neutron yield of 4×10^{13} in a 15 MA deuterium gas puff on the *Z* machine [13; 14; 15]. In addition to that, MHD and particle-in-cell simulations showed that there is a hope of a large thermonuclear component [14; 15]. In the case of the 29 *ZR* machine, up to 6×10^{16} DT neutrons are expected which was a lower estimate for ICF (Inertial Confinement Fusion) capsules on the National Ignition Facility.

2 Purpose and methods used in our research

2.1 Applications of plasma-based neutron sources

Recently, there has been a growing interest in neutron production in z-pinches. There are three main reasons for this renewed attention: (i) the MAGLIF project [10]; (ii) high DD neutron yield of 4×10^{13} in a 15 MA deuterium gas puff on the *Z* machine [13; 14; 15]; and (iii) a need for pulsed sources of fast neutrons. Small repetitive portable neutron sources could be useful in radiation material science, radiobiology, nuclear medicine, cargo inspection, improvised-explosive-device detection, whereas large devices could be effective for the recycling of nuclear waste into low-radioactive waste and for a fusion–fission hybrid reactor.

2.2 Aims of our research

In the previous section, we pointed out the importance of applications of z-pinches as neutron sources. Before z-pinches are used in these applications, however, it is necessary to address all issues which are specific for the implosion of deuterium plasma. In this respect, more experimental data are needed to benchmark numerical codes. At the most powerful z-pinches in Sandia National Laboratories, only a few shots per one year are devoted to fusion research. For instance, the latest deuterium gas puff experiments were carried out in 2005 and new experiments are scheduled on 2013/2014. Therefore, in order to acquire more details on neutron production, experiments on a MA current level with advanced neutron diagnostics are required. The research of high-current discharges at the Department of Physics of the Faculty of Electrical Engineering (Czech Technical University in Prague) has a 50 year tradition. Therefore our team was asked to support the fusion research of deuterium gas puffs at the Sandia National Laboratories.

The last but not least reason for being interested in experiments with deuterium is related to plasma diagnostics. As far as the fusion of two deuterons is concerned, there are four products of two main branches of the DD reaction, one of them is a neutron. Because neutrons are influenced neither by magnetic nor by electric fields, neutron detection is a favourable diagnostic tool of fast deuterons in plasma. While a large number of scientific papers in the last years were devoted to studies of X-ray radiation, the information about fast ions was rather rare. Therefore fusion neutron measurements could provide invaluable data about fast ions for plasma physics and for a large variety of modern applications.

2.3 Methods used in our research

Z-pinch discharges showed specific experimental results in each shot and shot-to-shot variations were large. Therefore it was important to use simultaneously comprehensive set of diagnostic tools with temporal, spatial, and spectral resolution. In our fusion experiments, the emphasis was put on finding information about (i) neutron yields, (ii) energy distributions of fusion neutrons, (iii) anisotropy of neutron emission, (iv) a spatial region of neutron generation, and (v) a time and duration of neutron production with respect to general plasma dynamics. In what follows, we will restrict ourselves to the description of the measurement of time resolved neutron energy distribution function.

An important piece of information about colliding deuterons is carried by a neutron energy spectrum. If we assume the binary reaction of a fast deuteron with a stationary target deuteron, the neutron energy E_n depends on the deuteron energy E_d and on the laboratory angle θ between the colliding fast deuteron and the outgoing neutron as

$$\begin{aligned} E_\mathrm{n}(E_\mathrm{d},\theta) &= E_\mathrm{d}\frac{m_\mathrm{n}m_\mathrm{d}}{(m_\mathrm{n}+m_\mathrm{He})^2}\cdot \\ &\cdot\left(\cos\theta + \sqrt{\frac{m_\mathrm{He}(m_\mathrm{n}+m_\mathrm{He}-m_\mathrm{d})E_\mathrm{d}+m_\mathrm{He}(m_\mathrm{He}+m_\mathrm{n})Q}{m_\mathrm{n}m_\mathrm{d}E_\mathrm{d}}-\sin^2\theta}\right)^2 \end{aligned} \tag{2.1}$$

where $Q \doteq 3.27$ MeV represents the energy released from the D(d,n)^{3}He fusion reaction, m_n is the neutron mass, and m_He is the mass of helium $^3_2$He.

One of the most accurate methods of measuring energy spectra of fast neutrons which are produced by the D(d,n)^{3}He fusion reactions is time-of-flight (ToF) diagnostics. This is why the ToF analysis was applied to diagnose fusion processes in our experiments.

A significant part of our diagnostic instruments and methods was prepared and tested on a small plasma focus PFZ-200 at the Faculty of Electrical Engineering, Czech Technical University in Prague [16]. This device with DD neutron yields of 10^7-10^8/shot could be easily modified with respect to applied diagnostic techniques and methods. When diagnostic instruments had been successfully tested, it was possible to use them abroad at larger facilities.

3 Results gained on S-300, PF-1000 and GIT-12

One of the main aims of our research is to discuss various mechanisms of deuteron acceleration and fusion neutron production, and to specify suitable usage of z-pinch neutron sources in various applications and fusion research. In the previous chapter we showed that neutron energies carry important information about colliding deuterons. Therefore, if the space and time resolved information together with the anisotropy of neutron production are known, it is possible to study the generation of fast deuterons.

In our case, neutron measurements were performed on the large z-pinches S-300 in Moscow and GIT-12 in Tomsk, and on the PF-1000 plasma focus in Warsaw. The most important results are presented in the following sections.

3.1 Efficient production of 100 keV deuterons in deuterium gas puff z-pinches at 2 MA current

On the S-300 generator, various z-pinch loads containing deuterium were explored, e.g. a deuterated polyethylene fibre [17], cylindrical and conical wire arrays imploding onto a deuterated fibre [18], deuterated cylindrical foams [19] or X-pinch from deuterated fibres [20]. We found that the most efficient configuration with respect to the neutron yield was a deuterium gas puff (see Fig. 3.1).

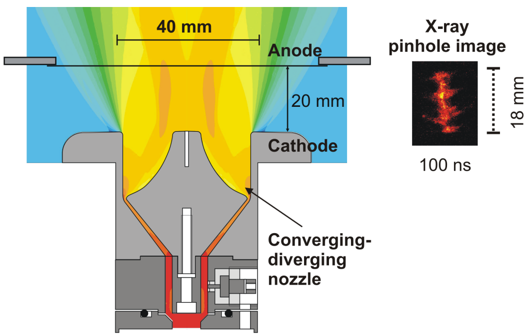

Figure 3.1: Deuterium gas puff, electromagnetic valve and X-ray pinhole image at the S-300 generator.

For our first experiments, we constructed a solid fill deuterium gas puff driven by burning gun powder similarly as on the Angara at Troitsk [21]. With such a gas puff, the peak neutron yield of 10^{10} was achieved on the current level of 2 MA. The main contribution of this experiment was the result from neutron TOF diagnostics. It was for the first time in z-pinch research when 12 nTOF detectors were used and the radial isotropy of neutron emission was studied by TOF signals [22].

In our first gas puff experiment on the S-300, the injection of gas into vacuum was not reproducible. In addition to that, the deuterium gas was likely interfused with the burning gun powder and thus a linear mass density was higher than expected (above 200 μg/cm). It resulted in a low implosion velocity and lower neutron yields. Therefore we prepared a new electromagnetic valve to drive a gas puff in the following experiments (see Fig. 3.1). The gas flow simulation confirmed our expectation that the maximum achievable linear mass density was about 20 μg/cm. Such a low mass proved to be suitable for a higher neutron yield. For 20 μg/cm, we increased the neutron yield up to 6×10^{10} neutrons in one shot.

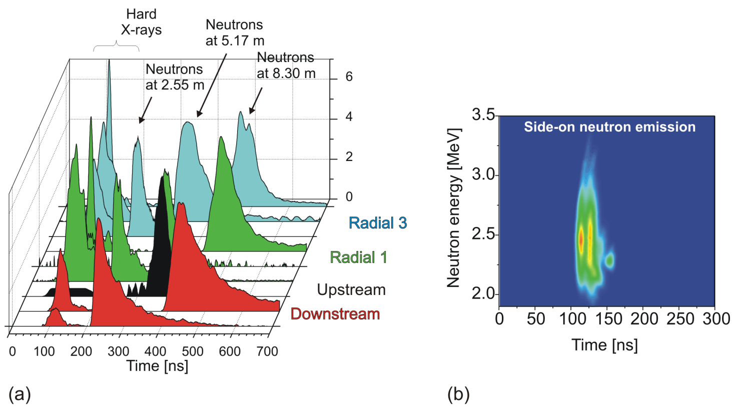

Figure 3.2: (a) Signals measured by neutron time-of-flight detectors. (b) Reconstructed neutron energy distribution function in the side-on direction. Shot No. 090922, the neutron yield of 3×10^{10}.

Another important conclusion was related to the efficiency of ion acceleration. The estimation of the total energy of deuterons accelerated to fusion energies was enabled by the simultaneous measurement of the energy input into a plasma, the plasma diameter, the neutron yield and neutron TOF signals in the radial and axial direction (c.f. Fig. 3.2). The total energy of fast deuterons was 1.5 kJ. This represented more than 15% of the energy input into a plasma. Therefore gas puff z-pinches seem to be not only powerful sources of X-ray radiation but also efficient sources of 100 keV deuterons. These results were published in the article that was awarded as one of the most frequently downloaded articles in *Plasma Physics and Controlled Fusion* in 2010 [23].

3.2 Experimental evidence of thermonuclear neutrons in a modified plasma focus

Most of the neutrons observed in z-pinch experiments were beam-target in origin. However, the characteristic feature of our deuterium gas puff experiments was the observation of multiple neutron pulses. As a result, neutron production seems to be a multiphase process in which more than one mechanism occurs during the implosion, stagnation, expansion and disruption of the plasma column. The first neutron pulse usually occurs during stagnation. It is therefore natural to ask whether a fraction of neutrons in the first pulse may be explained by thermonuclear mechanism, i.e. whether deuterons are accelerated to fusion energies by multiple elastic collisions in a high-temperature plasma. To prove the thermonuclear mechanism experimentally has been the challenging issue for fifty years of the z-pinch research. For example, at the end of the well diagnosed experiment at Limeil, Dr. Bernard wrote that he had never seen any piece of evidence indicating that neutrons have thermonuclear origin [24]. On other devices, researchers arrived at similar conclusions. Despite these results, it is important to search for thermonuclear neutrons from two main reasons. The first being the uniqueness of the thermonuclear mechanism which offers the possibility of energy gain. The second reason is promising scaling of a fusion yield with a current $Y_\mathrm{n} \propto I^4$.

From these reasons, we wanted to continue with D_2 gas puff experiments on the S-300. However, the S-300 generator at the Kurchatov Institute of Atomic Energy had to be closed due to fire safety regulations in 2010 and our research had to be transferred to the the Institute of Plasma Physics and Laser Microfusion in Warsaw where the PF-1000 plasma focus was built (2.0 MA peak current, 24 kV charging voltage, 400 kJ stored energy, 25). The PF-1000 plasma focus demonstrated similar behaviour as the MA deuterium gas puff z-pinch, particularly the first neutron pulse was observed during the quiet phase. There was one significant advantage of PF-1000 after all, and that was the interferometry diagnostics which enables to provide 16 interferograms from each shot.

In order to search for thermonuclear neutrons, we modified the plasma focus discharge. Firstly, we used a relatively low deuterium pressure between 160 and 240 Pa, i.e. lower than is usual because we wanted to increase the

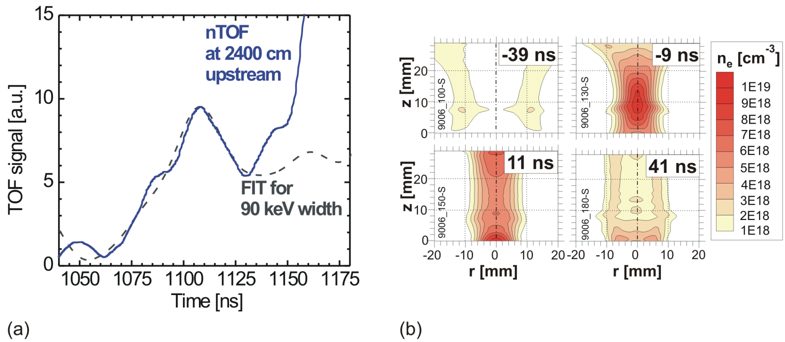

Figure 3.3: (a) The first neutron pulse at 24 m and the fit for the energy spectrum with the 2.46 MeV peak and 90 keV width. (b) The sequence of electron density distributions. Shot No. 9006, the neutron yield of 2×10^{10}.

implosion velocity and the ion temperature. Secondly, we placed the cathode disk 3 cm in front of the anode to localize the region where deuterons are accelerated. There were two great advantages of such a modification, namely (i) a higher current during the stagnation and (ii) more straightforward interpretation of plasma dynamics. Despite these changes, however, the evaluation of the neutron energy spectrum of the first, small pulse was still rather complicated. Nevertheless, there was one more advantage of the PF-1000 – its horizontal position of a discharge axis. The horizontal orientation of the PF-1000 enabled us to place neutron TOF detectors on the axis in an upstream direction. In the upstream direction, 2.45 MeV neutrons were one of the fastest and they could be distinguished from scattered and beam-target neutrons which were emitted after the first compression.

After the preparation of neutron and interferometric diagnostics mentioned above, we proved that (i) the time, (ii) the energy spectrum, (iii) the emission isotropy and (iv) the neutron yield of 10^9 during the first neutron pulse corresponded to theoretical predictions for thermonuclear neutrons. The author believes that we provided the first unambiguous experimental evidence of thermonuclear neutrons in z-pinches after 60 years of the research. In addition to that, an ion temperature of 1.2 keV was calculated from the width of the neutron energy spectrum. These achievements were published in *Applied Physics Letters* in 2011 [26].

3.3 Controlled thermonuclear fusion in z-pinches

The occurrence of the thermonuclear mechanism was the most evident during the plasma stagnation. Nevertheless, it was still a very small fraction of the total neutron yield on a mega-ampere current level. Therefore we can now derive parameters of a current generator and a load which are suitable for higher thermonuclear yields during the pinch phase [27]. The following derivation will be somewhat simplified, nevertheless it may be useful for the discussion of the thermonuclear mechanism in fast, dynamic z-pinches.

We start the derivation from the Lawson criterion [28]. If we assume the optimal ion temperature during the stagnation T_{D}, the thermonuclear mechanism requires a high product $n_{\mathrm{D}}\tau$. Here, n_{D} represents the ion density, and τ stands for the confinement time.

As far as the final plasma density is concerned, it can be expressed as

$$\bar{n}_{\mathrm{D}} = \frac{\hat{m}}{m_{\mathrm{D}}}\frac{1}{\pi R_{\mathrm{final}}^2} = \frac{\hat{m}}{m_{\mathrm{D}}}\frac{C^2}{\pi R_0^2}, \tag{3.1}$$

where $\hat{m}$ is the linear mass density, m_{D} is the mass of one deuteron, R_{final} is the final radius, R_0 is the initial radius, and $C = R_0/R_{\mathrm{final}}$ is the compression ratio. The linear mass density $\hat{m}$ is connected with the dimensionless parameter Π, the peak current I and the rise time to current maximum t_{MAX} as

$$\hat{m} = \frac{\mu I^2 t_{\mathrm{MAX}}^2}{4\pi\Pi R_0^2}. \tag{3.2}$$

This equation with the parameter Π was derived for the implosion of a thin shell (see Ref. [29]). Similar equations can be derived for other configurations. For instance, the optimal parameters for dense plasma foci with comparable implosion velocities are given by the constant value of I^2/pR_0^2, where p is the initial filling pressure [30].

By inserting Eq. (3.2) into (3.1), we have

$$\bar{n}_{\mathrm{D}} = \frac{\mu I^2 t_{\mathrm{MAX}}^2}{4\pi\Pi R_0^2 m_{\mathrm{D}}}\frac{C^2}{\pi R_0^2} = \frac{\mu\beta^2 C^2}{4\pi^2\Pi m_{\mathrm{D}}}\frac{I^2}{R_0^2 v_{\mathrm{imp}}^2}, \tag{3.3}$$

where we considered the matching of the current rise time with the implosion time which depends on the initial radius, the implosion time, and the dimensionless constant β as $t_{\mathrm{MAX}} = t_{\mathrm{imp}} = \beta R_0/v_{\mathrm{imp}}$.

As for the confinement time τ, it depends on the final radius R_{final}, the ion thermal velocity $v_{T_{\mathrm{D}}} = \sqrt{kT_{\mathrm{D}}/m_{\mathrm{D}}}$ and the coefficient α as follows

$$\tau = \alpha\frac{R_{\mathrm{final}}}{v_{T_{\mathrm{D}}}} = \alpha\frac{R_0}{C\sqrt{kT_{\mathrm{D}}/m_{\mathrm{D}}}}. \tag{3.4}$$

From (3.3) and (3.4), we obtain the product

$$\bar{n}_{\mathrm{D}}\tau = \left(\frac{\alpha\beta^2 C^2 \mu}{4 m_{\mathrm{D}}^{1/2} \Pi \pi^2}\right) \frac{I^2}{v_{\mathrm{imp}}^2 R_0 \sqrt{kT_{\mathrm{D}}}}. \tag{3.5}$$

If we consider the same character of implosion, i.e. the coefficients α, β, C and Π are constant, we can write

$$\bar{n}_{\mathrm{D}}\tau \propto \frac{I^2}{v_{\mathrm{imp}}^2 R_0 \sqrt{kT_{\mathrm{D}}}} \propto \frac{I^2}{v_{\mathrm{imp}}^3 t_{\mathrm{MAX}} \sqrt{kT_{\mathrm{D}}}}. \tag{3.6}$$

On the basis of this formula, we are able to make the following conclusions:

Firstly, it should be emphasized that the thermonuclear yield is important mainly for higher current machines. The fusion yield scales as $Y \propto \hat{m}^2 \propto I^4$ assuming the constant ion temperature. Because the energy input into a plasma also increases with the rising current, the product $\bar{n}_{\mathrm{D}}\tau$ depends on the second power of the current as I^2.

Secondly, at higher currents and higher plasma densities, the thermonuclear mechanism can be improved by significant plasma heating with alpha particles and/or by higher plasma stability. On the other hand, however, the energy transfer from ions to electrons reduces the ion temperature and consequently it reduces the neutron yield. In addition to that, at high currents, there is a question of how to achieve enough high mass densities. To use gas puffs may not be sufficient. Deuterium fibre z-pinches can provide higher densities but experiments have not been very successful so far.

Thirdly, a high implosion velocity means a shorter confinement time as well as a large initial diameter and a lower plasma density. As a result, the product $\bar{n}_{\mathrm{D}}\tau$ strongly decreases with an increasing implosion velocity. Also at high velocities, the implosion can become unstable. If the final ion temperature is proportional to the kinetic energy $T_{\mathrm{D}} \propto v_{\mathrm{imp}}^2$, then it is always a trade-off between a high ion temperature T_{D} and a high product $\bar{n}_{\mathrm{D}}\tau \propto (kT_{\mathrm{D}})^{-2}$. In addition to that, at high plasma temperatures and low ion densities, the frequency of ion–ion collisions could be too low to produce the Maxwellian tail during the stagnation.

Fourthly, provided that the compression ratio C and the final ion temperature T_{D} are kept constant, it is better to use a high current generator with a shorter rise time t_{MAX}, and to start with a higher initial density and smaller diameter R_0. It follows that the thermonuclear yield of 100 ns deuterium solid gas puffs should be higher than with 1 μs plasma foci, if currents are the same. To start with the initial small diameter was also the idea of gas embedded and fibre z-pinches. However, since the compression ratio cannot be considered as fully independent on the initial radius and on the early development of instabilities, this idea proved to be wrong (see [18] for more details).

Finally, we may use relation (3.6) to discuss the MagLIF concept [10]. This concept is a modification of magnetized target fusion [29] to a faster current generator. It is based on the laser preheating, the implosion of a heavy metal liner, and the usage of an axial magnetic field. Because of the laser preheating, a high implosion velocity $v_{\mathrm{imp}} \sim 10^6$ m/s is not required in order to achieve a high plasma temperature $T_{\mathrm{D}} \sim 10$ keV. An enough high temperature can be reached by an adiabatic compression with a moderate ($\sim 10^5$ m/s) implosion velocity of the metal liner. The heavy metal liner with a moderate velocity is suitable for a longer confinement time $\tau \propto R_{\mathrm{final}}/v_{\mathrm{imp}} > R_{\mathrm{final}}/\sqrt{kT_{\mathrm{D}}/M_{\mathrm{D}}}$. In addition to that, the metal liner and the fast current generator enable to start from a small initial radius $R_0 \sim 3$ mm and from the initial DT gas density of $\sim 10^{21}$ cm^{-3} which is substantially higher than contemporary possibilities of deuterium gas puffs and plasma foci. Another advantage of the heavy metal liner is the sufficient electrical conductivity which has been the serious issue in the case of deuterium frozen fibres. All these facts strongly support the reasonableness of the MagLIF concept.

3.4 Efficient neutron production by high energy deuterons accelerated in a megaampere deuterium z-pinch

A dense plasma focus produced 10^{11} DD neutrons/shot at stored energy of 100 kJ. Plasma foci demonstrated the dependence of a neutron yield per length on a current as $Y_{\mathrm{n}}/l \propto I^4$ up to $I = 1$ MA [31]. Unfortunately, this favorable scaling law was not extended above 1 MA. The successful experiment on the DPF 6-1/2 plasma focus at the LANL in 1973 was not confirmed and the 'saturation' of a neutron yield between 10^{11} and 10^{12} was observed on the megaampere plasma foci in Frascati, Limeil, Stuttgart, Warsaw and Moscow. The lack of scaling beyond 10^{12} was one of the most important arguments for shutting down the largest plasma focus facilities in Europe in the 1980s. In the 1990s, neutron yields above 10^{12}, namely up to 2.8×10^{12}, were reached with a deuterium gas puff z-pinch on Saturn, however, at much higher currents of ≈ 8 MA [32].

In order to understand better the process of the neutron yield 'saturation' and to investigate neutron production mechanisms, we decided to carry out z-pinch experiments on the GIT-12 generator at megaampere current level. Neutron measurements at this current level are also of a high importance considering the development of rep-rated megaampere current generators.

During two experimental campaigns in 2013, 37 shots were performed with the plasma shell on the deuterium gas puff. For the total linear mass

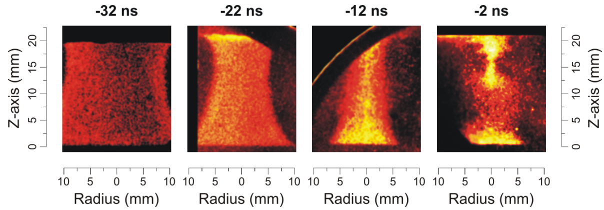

Figure 3.4: Gated soft x-ray images of the deuterium gas puff z-pinch. The time $t = 0$ corresponds to the sharp onset of > 2 MeV bremsstrahlung radiation and the start of main neutron emission.

density of $\approx 100\ \mu$g/cm, the implosion from the 350 mm diameter lasted 700 ± 50 ns and seemed to be stable. Fig. 3.4 shows a typical example of soft x-ray images of the final stage of the snowplough implosion when the current rose to 2.7 MA. The implosion driven by the $\mathbf{J} \times \mathbf{B}$ force reached the radial velocity of 4.5×10^5 m/s. During the stagnation, $m = 0$ instabilities became more pronounced. When a disruption of necks occurred, high energy (> 2 MeV) bremsstrahlung radiation and a main neutron pulse were observed.

In order to achieve neutron yields above 10^{12}, we had to optimize deuterium gas puffs. Using the optimized parameters, the peak neutron yield from DD reactions reached $Y_n = (2.9 \pm 0.3) \times 10^{12}$. Taking into account the scaling law in Krishnan's review paper [31], the yield of 2×10^{12} at 2.7 MA means that the I^4 scaling law of the neutron yield was extended to the current of $I \doteq 3$ MA. As for published z-pinch and dense plasma focus experiments, DD neutron yields higher than 2.9×10^{12} were achieved only on Z, however, at very high currents of about 15 MA. Calculating with the 60 kJ energy input and the 3×10^{12} DD neutron yield on the GIT-12, the number of DD neutrons per one joule of stored plasma energy approached the value of 5×10^7. A higher efficiency of DD neutron production above 10^8 neutrons/J was obtained at the National Ignition Facility and the largest tokamaks (such as JET and JT-60U), however, at much higher input energies. An implication of this is that deuterium gas puff z-pinches belong to the most efficient plasma-based sources of fusion neutrons.

Probably a more important result than the neutron yield itself is a substantial difference between neutron spectra in low yield (2×10^{11}) and high yield (2×10^{12}) shots. Fig. 3.5 shows radial nToF signals measured at 10.13 m. In high yield shots, the maximum neutron energies in the radial direction were 15.5 ± 0.5 MeV. The flux of > 10 MeV neutrons in the radial direction reached the value of $(3 \pm 1) \times 10^9$ n/sr. Most of the neutrons originated from $D(d,n)^3He$ reactions but a certain number of neutrons could be produced also

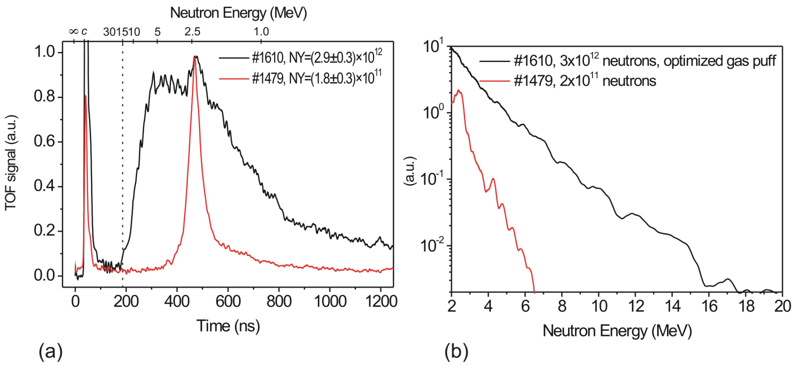

Figure 3.5: (a) Neutron ToF signals at 10.13 m and (b) neutron spectrum in a high yield shot (#1610) and a low yield shot (#1479, without using plasma guns).

by secondary D(t,n)^{4}He reactions, deuteron break-up (d,np), deuteron electro-disintegration d(e,e'n)p, photonuclear (γ,n) and other endothermic reactions. In any case, it follows from Fig. 3.5 that the high yield regime was achieved mainly by a large number of deuterons with higher ($\approx$ MeV) energies. Due to the fact that fast neutrons were observed with the radial ToF detectors, the radial component of deuteron kinetic energy was significant.

Neutron energies even higher than 15 MeV were measured by the axial nToF detector at 475 cm. Downstream, i.e. in the axial direction towards the cathode, the peak neutron energy reached 22 ± 1 MeV. We believe that this is a record value for DD neutrons in a plasma. Assuming stationary target deuterons, such a high energy means that a large number of deuterons were moving with 20 MeV kinetic energy in the axial direction. In order to verify high energy deuterons on the axis directly, we placed a stack of five CR-39 track detectors at 18 cm below the cathode mesh. The CR-39 detectors confirmed the presence of high energy ions on the axis: The first CR-39 layer at 19 cm was saturated, implying more than 10^{10} of > 15 MeV hydrogen ions per steradian. For the energies E above 12 MeV, the number of hydrogen ions $N(E)$ decreased rapidly according to a power law distribution as $dN/dE \propto E^{-5}$. Nevertheless, there were still protons or deuterons with kinetic energies above 38 or 51 MeV, respectively, since the number of tracks at the rear side of the last layer was still significantly above 'neutron background'. 30 MeV is an impressively high energy considering that modern pulsed power technology was not required.

4 Summary and conclusion

In conclusion, it is possible to summarize that deuterium z-pinches belong to the most efficient plasma-based sources of fusion neutrons. One of the principal advantages of z-pinches is a high conversion efficiency of stored electrical energy into fast, magnetized ions. At this point, it seems useful to compare the neutron production efficiency of the most powerful z-pinch with high energy lasers and tokamaks. The JT-60U tokamak with the total energy input of about 4 GJ and 8×10^{16} DD neutrons provides the efficiency 2×10^{7} neutrons/joule [33]. Direct drive capsules at the Omega laser produced much lower DD neutron yields of about 4×10^{11} at a 40 MJ stored energy and at an efficiency of 10^{4} neutrons/J [34]. In our experiments, the peak neutron efficiency was 6×10^{5} DD neutrons per one joule of stored energy with a gas puff z-pinch on the S-300. The neutron yield of 4×10^{13} neutrons on the 10 MJ *Z*-machine implies almost 4×10^{6} neutrons/J. Such a value is comparable with the JT-60U and JET tokamaks (cf. Fig. 4.1). In addition to that, even higher neutron yields are expected on future higher current generators and for the MagLIF project on the refurbished *Z*. Of course, a lot of technological and material issues have to be solved in order to use z-pinches in the controlled thermonuclear fusion research. Nevertheless, it is evident that z-pinches are efficient sources of fusion neutrons that might be useful for hybrid fusion-fission concepts or for other applications.

As for other applications, smaller repetitive devices are usually more suitable. In this respect, a small dense plasma focus in the range of 100 – 1000 J reaches the efficiency of about 10^{5} neutrons/J [35]. It seems to be lower than 10^{5}–10^{6} neutrons/J which is the typical value of femtosecond laser systems [36; 37]. However, here 1 J represents the energy of a laser beam whereas the stored electrical energy is higher. As a result, on the one hand, the efficiency of a small DPF is higher than the efficiency of ultra-short laser systems. On the other hand, laser-based neutron source is more localized and the properties of neutron emission can be modified by parameters of laser beams and targets more easily.

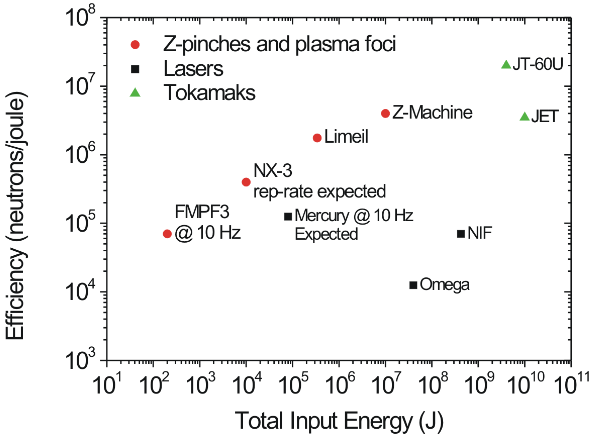

Figure 4.1: Wall-plug efficiency of DD neutron production in various plasma-based sources: JET [38] and JT-60U [33] tokamaks; FMPF-3 [35], NX-3 [39] and Limeil [40] plasma foci; Omega [34], and Mercury [41] lasers; gas puff z-pinch on *Z* [13].

Prospects

Z-pinches and plasma foci are now being researched as efficient sources of X-rays and neutrons. Nevertheless, several technological issues need to be solved before they are put into practice more extensively. For instance, the usefulness of small plasma foci as neutron sources depends on the development of a higher repetition device with a long lifetime (>10^7 shots). As far as z-pinches are concerned, we suppose that their future will be strongly influenced either by the success or failure of the MagLIF project. Next, we believe that the further progress of z-pinches is dependent on the construction of petawatt class generators. Always, when a new machine with a higher current is constructed, the significant progress and breakthroughs might be expected. Now, the most powerful current generator provides the >50 TW peak power and the current of 25 MA. To concentrate a twofold current into a small volume is not as simple as to reach a twofold laser energy by increasing the number of beams. Since it is difficult to concentrate the charge into a small volume, the construction of 50 MA devices requires a new technology. Such a challenging project has been solved in [42]. The construction of 50 MA device is now in the preparatory phase at TRINITY in Troitsk as well as at the Sandia National Laboratories in Albuquerque, New Mexico.

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Selected publications over the last 3 years

2013	Klir, D. and Shishlov, A.V. and Kubes, P., *et al.* “Search for drive parameter of neutron optimized z-pinches and dense plasma foci” *IEEE Transactions on Plasma Science* **41**, No. 11, 2013.
	Klir, D. and Shishlov, A.V. and Kokshenev, V.A., *et al.* “Characterization of neutron emission from megaampere deuterium gas puff z-pinch at microsecond implosion times” *Plasma Physics and Controlled Fusion* **55**, art. no. 085012, 2013.
2012	Klir, D. and Soto, L. “Drive Parameter of Neutron-Optimized Dense Plasma Foci” *IEEE Transactions on Plasma Science* **40**, pp. 3273-3279, 2012.
	Klir, D. and Kubes, P. and Paduch, M., *et al.* “Search for thermonuclear neutrons in a mega-ampere plasma focus” *Plasma Physics and Controlled Fusion* **54**, art. no. 015001, 2012.
	Klir, D. and Shishlov, A.V. and Kokshenev, V.A., *et al.* “Deuterium gas puff z-pinch at currents of 2 to 3 mega-ampere” *Physics of Plasmas* **19**, art. no. 032706, 2012.
2011	Klir, D. and Kubes, P. and Paduch, M., *et al.* “Experimental evidence of thermonuclear neutrons in a modified plasma focus” *Applied Physics Letters* **98**, art. no. 071501, 2011. *Applied Physics Letters* **100**, art. no. 016102, 2012. (Response)
	Klir, D. and Kravarik, J. and Kubes, P., *et al.* “Fusion neutron detector for time-of-flight measurements in z-pinch and plasma focus experiments” *Review of Scientific Instruments* **82**, art. no. 033505, 2011.

Awards

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