Important issues in high-current plasma experiments of the Z-pinch type

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Abstract. This paper is based on an invited lecture given at the 10th International Workshop and Summer School "Towards Fusion Energy", which was held in Kudowa Zdrój, Poland, on June 12–18, 2011. A concise review is presented of the known experimental results on various plasma Z-pinch experiments supplied by high-voltage and high-current pulsed power generators. The most important issues and the most valuable results in this domain are highlighted. A broad class of various Z-pinches is considered, including simple inter-electrode discharges, single exploding wires, so-called X-pinches, cylindrical wire-array Z-pinches, radial wire-array discharges, conical wire-array experiments, and gas-puffed Z-pinches. Non-cylindrical Z-pinch discharges (often called plasma focus experiments) are also briefly characterized. The most important characteristics of each category of experiments are outlined. Particular attention is paid to fusion-oriented high-power Z-pinch experiments and the problems encountered in experiments with various sophisticated fusion targets. The main issues in the described Z-pinch experiments are identified. Finally, new trends in the dense Z-pinch research are described.

Key words: Z-pinch • X-pinch • wire-array Z-pinch • gas-puffed Z-pinch • plasma-focus (PF)

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Introduction

The term "linear Z-pinch" is used to denote the effect of a radial compression of the plasma column by an azimuthal magnetic field generated by the current flowing through this column. Unfortunately, the Z-pinch column is prone to various magnetohydrodynamic (MHD) instabilities. In particular, a small local narrowing developes into the so-called sausage instability ($m = 0$), while a small bending leads to the strong "kink instability" ($m = 1$), as shown in Fig. 1.

Linear or *quasi*-linear Z-pinch discharges are observed in nature, e.g. as intense lightnings, as well as in various laboratory experiments, as presented in Fig. 2.

In fact a dense Z-pinch (DZP) was one of the earliest plasma-confinement schemes examined in the quest for controlled thermonuclear fusion. The research on controlled thermonuclear fusion started in early 1950's with experiments involving Z-pinches in deuterium. These experiments were launched almost simultaneously with the effort to construct a thermonuclear weapon (H-bomb), in which self-sustained fusion reactions occurred on a much larger scale. Thermonuclear weapons were tested successfully in the period 1952–1953, but the controlled fusion to be much more difficult to master, despite the fact that apart from the DZP scheme many other approaches were investigated [38, 57]. First observations of the D-D fusion reaction

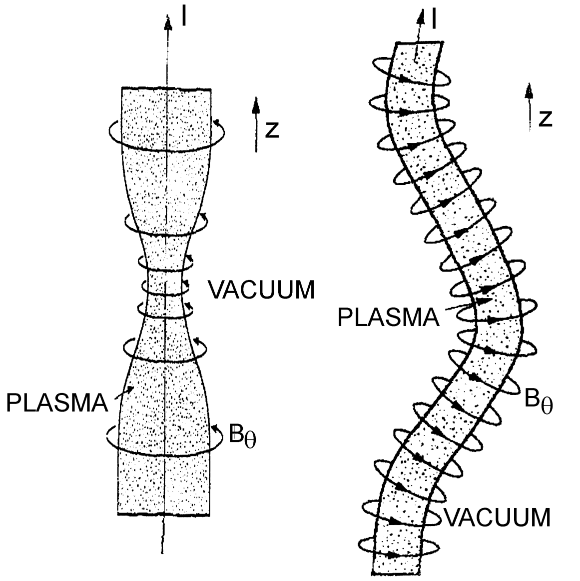

Fig. 1. The most common magnetohydrodynamic instabilities which plague Z-pinch discharges and destroy a dense Z-pinch plasma column.

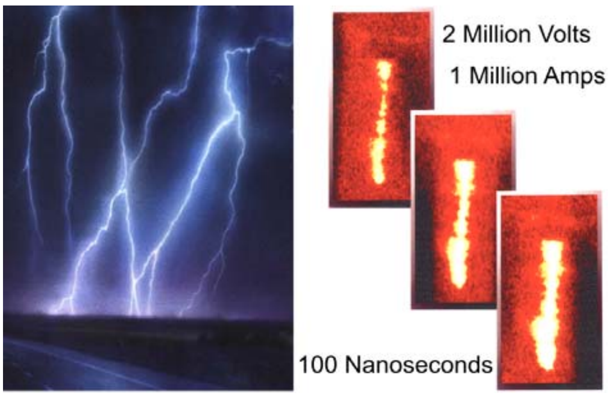

Fig. 2. Examples of Z-pinch type discharges in nature (left) and in the laboratory (right).

neutrons generated in linear Z-pinches were reported by the US, Soviet and some European laboratories in the middle 1950's [4, 10, 12, 29, 44]. However, the optimism connected with Z-pinches did not last long as it was soon understood that the observed neutrons were not of thermonuclear origin. They were produced instead by beams of deuterium ions which were accelerated in Z-pinches to the energies of the order of 50–200 keV and then fused upon impact with other deuterium ions, despite the fact that the plasma temperature remained relatively low [2].

The interest in DZP was revived again in the 1980's when substantial neutron yields were obtained from a Z-pinch of a deuterium fibre heated by a short pulse (< 1 ms) with high current (> 1 MA), but again it turned out that the observed neutrons originated from the beam-plasma interactions [36, 46]. Consequently, the efforts to develop a nuclear fusion reactor based on the direct heating of a fibre Z-pinch plasma were abandoned. Research was focused on wire-array Z-pinches which could produce very intense X-ray pulses, that could then be used for an indirect drive of inertial confinement fusion micro-targets [32]. As an example one can mention a hohlraum system with a fusion micro-target placed between two Z-pinch discharges, which delivered powerful X-ray pulses that ionized and compressed this micro-target [8].

Studies on DZP were continued with a variety of experimental schemes in many laboratories all over the world, and they provided valuable data about dense plasmas at thermonuclear conditions [3, 59]. The main aim of this paper is to present a classification of different Z-pinch experiments, to summarize the important results that had been obtained and to identify most important issues appearing in this approach.

Classification of Z-pinches

The Z-pinch configurations investigated so far may be divided into the following groups:

1. Single-channel Z-pinches:
   a) linear Z-pinch devices with electrodes;
   b) single exploding wire devices;
   c) capillary discharges;
   d) micro-pinches.
2. Wire-array Z-pinches:
   a) cylindrical (classical) wire-array Z-pinches;
   b) nested wire-array Z-pinches;
   c) conical wire-array arrangements;
   d) radial wire-array arrangements;
   e) planar wire-array arrangements.
3. X-pinch configurations:
   a) two-wire X-pinches;
   b) multi-wire X-pinches;
   c) nested X-pinches.
4. Gas-puffed Z-pinches:
   a) single-shell gas-puffed Z-pinches;
   b) multi-shell gas-puffed devices.
5. Non-cylindrical Z-pinches, often called dense plasma focus (DPF) experiments:
   a) DPF devices with classical cylindrical electrodes;
   b) DPF devices with nontrivially shaped electrodes.

We briefly characterize below each of these Z-pinch configurations.

Examples of single channel Z-pinches

As already mentioned, a linear Z-pinch discharge between two metal electrodes placed inside a chamber filled at low pressure with the pure deuterium was one of the earliest and simplest schemes of the plasma heating and confinement in the quest for controlled fusion reactions. The MHD instabilities, along with an impurity influx from the solid electrodes at each end of the linear Z-pinch, forced fusion researchers to use an additional axial magnetic field for stabilization of the $m = 0$ mode, and to eliminate the electrodes altogether by transforming the magnetic field with both the axial and azimuthal components into a toroidal configuration (like a tokamak).

The early modelling of DZP assumed that the pinch current is increased in such a way so as to assure a constant plasma radius and the balance between the magnetic field pressure and the plasma pressure, as well as flat density and temperature profiles. It was deduced that under idealized equilibrium conditions, when the Ohmic heating equals the bremsstrahlung losses, the pinch could operate at the Pease-Braginskii current of I = 1.5–2.0 MA, depending on the plasma temperature and density profiles [21]. In later developments different plasma/current profiles were examined in order to understand possible stability constrains and achieve a better grasp of the overall pinch dynamics and performance. These profiles were assumed to be frozen into the pinch. The analysis of the pinch dynamics was extended to multi-dimensional models, which allowed to take into account the diffusion effects [19, 35].

The research on pulsed DZP was oriented on forming a pinch with a diffuse current by expanding the radial extension of the current sheath, and on applying a high voltage across a fibre made of a metal or frozen deuterium (or frozen D-T mixture). The resulting Z-pinches involved currents in the range of hundreds of kA, passing through a filament of about 10 μm radius, and were shown to be stable for relatively long times, provided that the plasma current was rising quickly enough (> 10^{12} A/s). Preliminary estimates of the DZP neutron emission showed that pinches of the radius a = 15–20 μm and the length of l_p = 5–10 cm, operated with a discharge time τ_D = 50 ns should result in a DT burn-up fraction f_B = 0.05–0.1 and generate a neutron yield Y_n = (0.5–1.0) × 10^{17}, producing W_F = 0.1–0.2 MJ of fusion energy. Such Z-pinches should involve a peak current of 1.5–2.0 MA and for the τ_D = 50 ns they would require voltage gradients V_p/l_p = 5–10 MV/m, which might be delivered, e.g., from a water-filled transmission lines charged by Marx-type generators [21]. Those estimates were the basis for construction of large Z-pinch machines, e.g., a HDZP-II experiment shown in Fig. 3.

It should be noted that the theoretical time needed for a solid fibre pinch to become unstable due to the $m = 0$ and $m = 1$ distortions is of the order of the Alvén transit time $\tau_a = a/v_a$, where a is the pinch radius and v_a is the Alvén speed. The DZP experiments performed in the 1990's have shown stability characterized by the Alfvén time multiplicity $N_A = \int (v_a/a)\, dt$ on the order of hundreds, while for practical applications as a neutron source one would need N_A = 1000. In order to study Z-pinch discharges at very high currents new large pulsed power facilities have been designed and constructed, e.g., the Z-machine at the Sandia National Laboratories in USA [51]. Numerous experiments with a single wire or fibre were performed and it was found that that X-ray images of a single-wire pinch contain numerous micro-regions of enhanced emission (so--called hot-spots), as shown in Fig. 4.

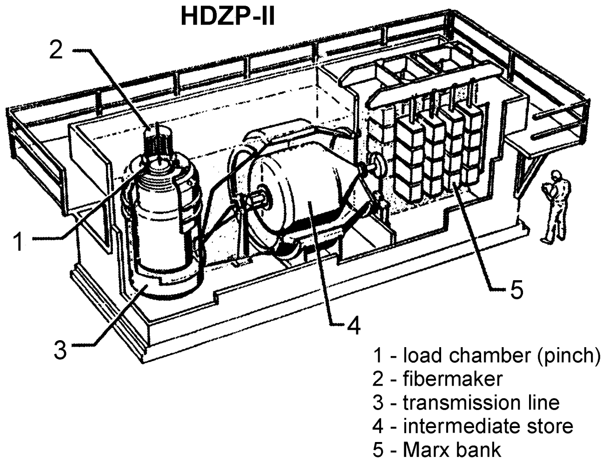

Fig. 3. An outline of a large Z-pinch experiment (HDZP-II) at the Los Alamos National Laboratory in USA [15].

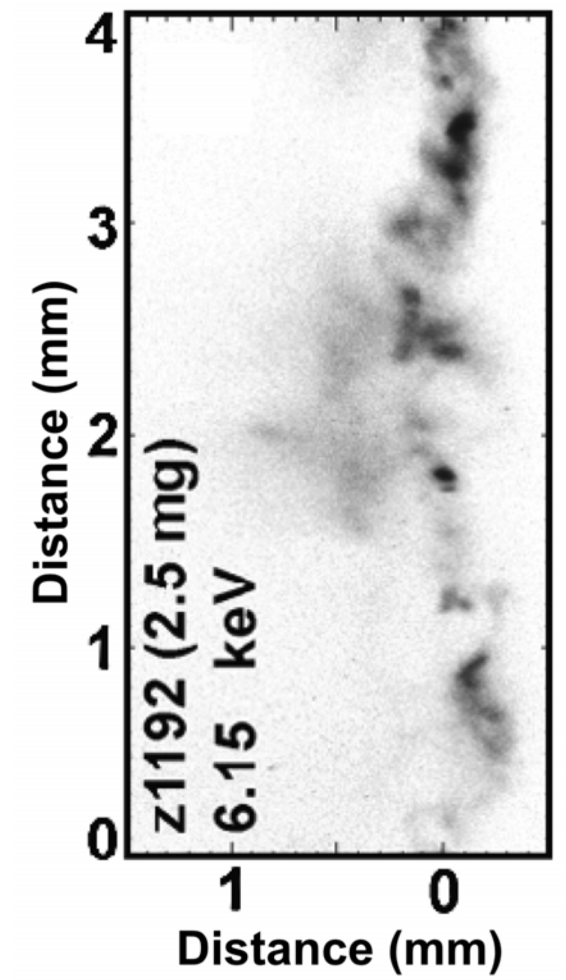

Fig. 4. Image of a tungsten-wire pinch recorded within the Z-machine at Sandia National Laboratories, USA [51].

Spectral distributions of X-rays generated in the Z-pinch were measured and it was found that the averaged electron temperatures T_e are in the range of 150–350 eV. The X-ray energy spectra showed high--energy tails which might be modelled as originating from small but hot and very dense plasma objects (of 50–100 μm in diameter). In fact such hot-spots were recorded in time-integrated images of X-rays in the energy range above 6 keV. These observations provided the motivation for studies of multi-wire loads, which are described further below.

The subgroup (c) of the single-channel Z-pinches category consists of the so-called capillary pinches, which are formed when the discharge is initiated inside a long narrow channel (e.g., 3 mm in diameter and 20 cm in length); in such pinches the plasma column may be stabilized by solid walls [39], as shown in Fig. 5.

Capillary discharges can produce very stable Z-pinches (due to the proximity of cooling channel walls) and are of particular interest for research on X-ray lasing. Contemporary capillary Z-pinches are usually powered by a multi-stage Marx generator capable of supplying 150–300 kV pulse through a 5 Ω, 3 nF water-

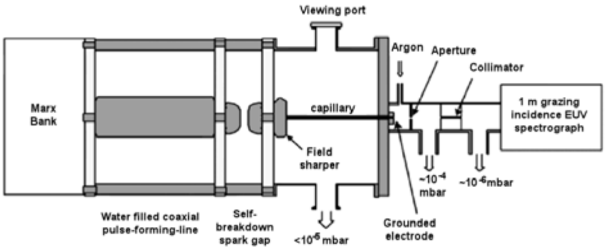

Fig. 5. Schematic diagram of a typical experimental setup for studies of capillary Z-pinches (not to scale). To maintain the pressure in the capillary the filling gas (e.g. argon) is fed through a hole in the grounded electrode, and the X-ray lasing is observed behind a special collimator or filter [39].

-filled coaxial pulse-forming line which, beingswitched by a self-breaking spark gap. To maintain the pressure in the capillary the filling gas, e.g. argon, is fed through a hole in the grounded electrode [11].

It was demonstrated that the capillary Z-pinches are capable of a strong amplification of EUV and soft X-rays, e.g. amplification of the Ne-like Ar line with $\lambda = 46.9$ nm. Unfortunately, the attempts to shorten their operational wavelength have so far been unsuccessful, except in the case of a hydrogen-like carbon line with $\lambda = 18.2$ nm, generated in the discharge channel by the ablation of capillary walls (which is irreproducible). The amplification of shorter wavelengths requires plasma formed from some metal (Pd, Ag, Cd, In, Sn) vapours with the abundance of Ni-like ions. Feeding of such metal vapours into the capillary is difficult because the metal is deposited on capillary wall and shortens its life-time. It was suggested that a wire explosion in the capillary with liquid walls might be a solution to this problem [20].

It should be noted that in accordance with the Saha ionization equation the most stable electron configurations are neon-like ions (with 10 electrons remaining) and nickel-like ions (with 28 electrons remaining). The electron transitions in such highly ionized plasmas usually correspond to energies of the order of hundreds electronvolts (eV).

Another approach to practical table-top X-ray lasers is based on the use of micro-pinches. Such discharges have the form of a high-voltage (HV) breakdown channel with the diameter of approximately 100 μm, formed within a thin insulating foil placed between two HV electrodes. The aim of this approach is to reduce the size and cost of capillary pinch devices, which are influenced mainly by parameters of pulsed power generators. In fact, the contemporary micro-pinch devices, e.g. those developed at the École Polytechnique in France, can play the role of point-like X-ray sources, which are useful for research and various applications.

The most important issues in the research on single--channel Z-pinches described above may be formulated as follows:

1. Although single-wire experiments have been abandoned, single gas-injection Z-pinches still deserve further studies.
2. To explain filamentary structures observed even in the single channel Z-pinches a more refined 3-D (three-dimensional) modelling is needed.
3. The optimization of capillary discharges should be performed by a proper selection of the capillary material, the gas filling system and power supply generators.
4. Diagnostic methods should be further developed to obtain a better picture of Z-pinch characteristics.
5. Optimization of micro-pinch devices should be performed for different research projects and technological applications.

Description of wire-array Z-pinches

As already mentioned above, results obtained from single-wire Z-pinch experiments led to the development of wire-array Z-pinches. The simplest wire array Z-pinch consists of several thin metal wires oriented along the z-axis and distributed symmetrically on a circle, forming a cylindrical structure [14]. Such a structure is then installed between the electrodes of a high pulsed power generator. After a high-voltage and high-current pulse is applied to the wire-array load, the system is subject to compression in the radial direction, as shown in Fig. 6.

One may distinguish several characteristic phases in such a wire-array Z-pinch: 1) the transformation of wire cores into a plasma corona; 2) the development of uncorrelated axial instabilities; 3) an inward flow of metal plasma jets with a low magnetic Reynolds number; 4) the formation of a stable and dynamically confined central plasma column (called the precursor); 5) the radial implosion of metal plasma at almost constant velocity (when gaps occur in the wire cores); and finally 6) the generation of a fast-rising soft X-ray pulse, e.g., 5 ns FWHM pulse emitted at the plasma stagnation phase. These phases can be relatively well modelled with modern computer codes, as shown in Fig. 7.

Advances in the pulsed power technology made it possible to perform Z-pinch experiments of a new type [13]. The new technology allowed to obtain pulses with multi-MA currents. Experiments on the generation of intense electron or proton beams (in PBFA and ANGARA machines) were abandoned, mainly because of difficulties with the focusing of such beams upon nuclear micro-targets. In fact the fusion-oriented re-

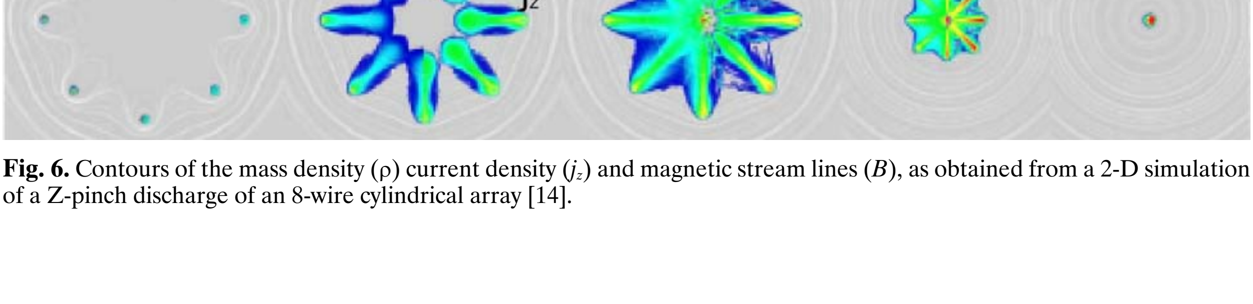

Fig. 6. Contours of the mass density (ρ) current density (j_z) and magnetic stream lines (B), as obtained from a 2-D simulation of a Z-pinch discharge of an 8-wire cylindrical array [14].

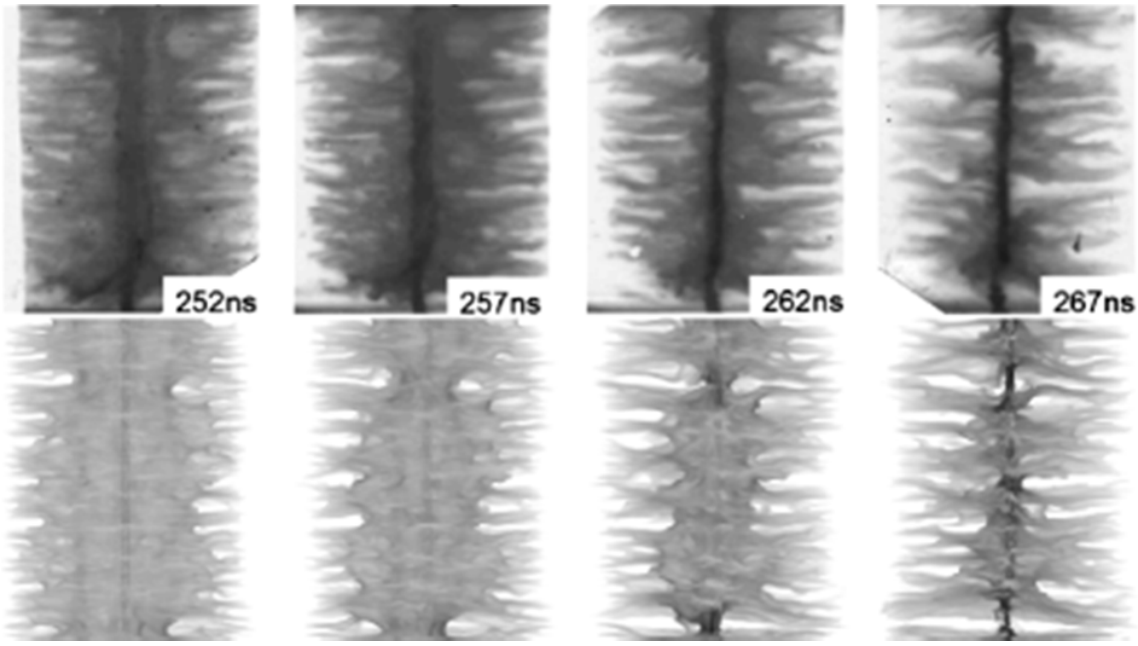

Fig. 7. Experimental (top row) and simulated X-ray images (bottom row) for a cylindrical array of 32 Al-wires investigated at the Imperial College, UK [14].

search based on the use of high-energy heavy ions was never even been started on a larger scale. As a result of the rising interest in discharges with extremely high currents many new Z-pinch facilities were designed and constructed, particularly in the USA and Russia. The modular structure of those facilities allowed them to obtain record discharge power of 10^{14}–10^{16} W, but the fusion neutron yields appeared to be very moderate [13]. A general view of one of the largest facilities of this type is shown in Fig. 8.

Experiments with various wire-array Z-pinches were performed at many large facilities in UK [14], USA [8, 18], France [7] and Russia [22]. The main aim of numerous wire-array Z-pinch experiments was to optimize the power of the X-ray emission, which might be used for inertial confinement fusion (ICF) of micro-targets. Some exemplary results are shown in Fig. 9.

The wire-array Z-pinch experiments in the facilities mentioned above involved implosions of thin cylindrical targets composed of many (from several dozens to several hundreds) very thin metal wires (mostly tungsten). For example, SATURN experiments involved implosions of 12.5 mm i.d. cylinders consisting of 70 tungsten wires with the diameter of 7.5 μm in which X-ray pulses were generated with the energy in the 450–800 kJ range [18]. The large PBFA-II facility at the Sandia Lab [58] initially designed for fusion experiments with the use of particle beams, was converted in the 1990's into the Z-machine which could generate pulsed currents reaching 27 MA [56]. In the experiments with cylindrical targets composed of 480 very thin tungsten wires the record X-ray yields of the total power of 290 TW were obtained. Such X-ray pulses could be used for ICF related experiments, but computer simulations have shown that to achieve fusion one needs X-ray pulses with power in the range of 1000 TW and the total energy of about 16 MJ. Guided by these requirements, researchers at the Sandia Lab designed the X-1 machine which could

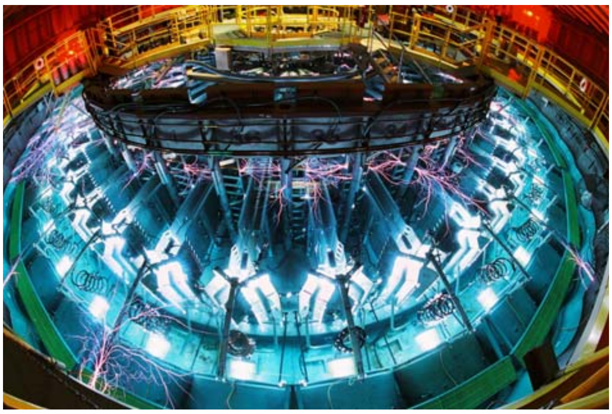

Fig. 8. Photo of the largest SATURN facility at the Sandia National Laboratories, USA, which was later up-graded to the Z-machine, and then to the ZR-machine [13].

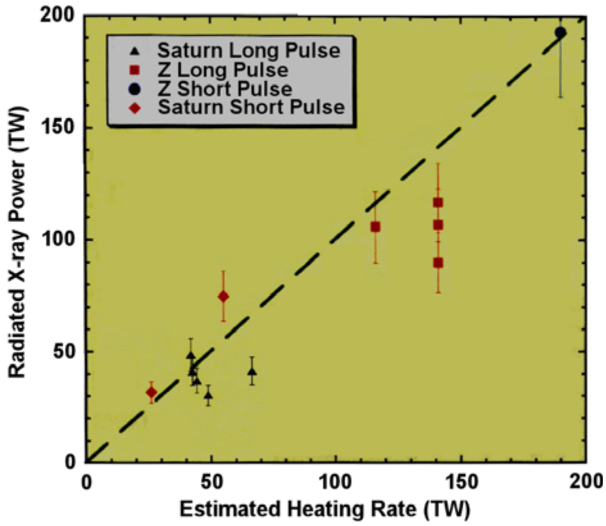

Fig. 9. The power of X-rays emitted in different Z-pinch experiments carried out using SATURN and later the Z-machine at the Sandia National Laboratories, USA [18].

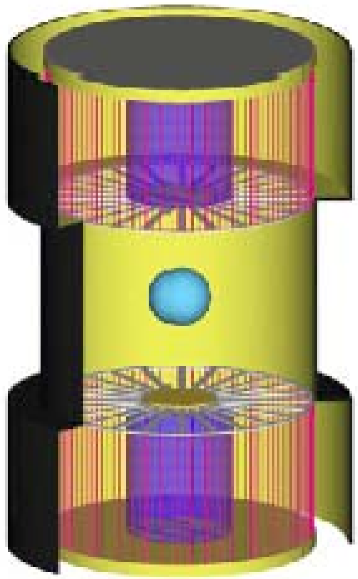

Fig. 10. Triple hohlraum system with a fusion micro-target placed in the centre. Powerful X-ray pulses produced by two Z-pinch discharges (on both sides) ionize and compress the target in order to initiate a controlled thermonuclear explosion [8].

be used for inertial experiments with triple-hohlraum-type loads, as shown in Fig. 10.

Experiments with triple-hohlraum loads in the Z-machine did not achieve very high fusion yields. However, due to its potential as a driver for Z-pinch ICF experiments, the wire-array configurations became one of the most thoroughly developed and intensively studied on pulsed power machines over the world for the next 10 years. Much of the work had been concentrated on the so-called nested wire-array Z-pinches, which consist of two multiple-wire cylinders, one surrounding the other. Such nested wire-array configurations enabled to achieve X-ray pulses with record parameters of 280 TW power and 1.8 MJ energy [9]. The work on optimization of such configurations is still in progress.

Recently there has been some interest in the so-called star-like loads [16], which are shown in Fig. 11.

Simultaneously with the Z-pinch experiments described above, which relied on cylindrical loads, there were some experimental efforts involving other configurations, e.g. conical wire-arrays [1], which are shown in Fig. 12.

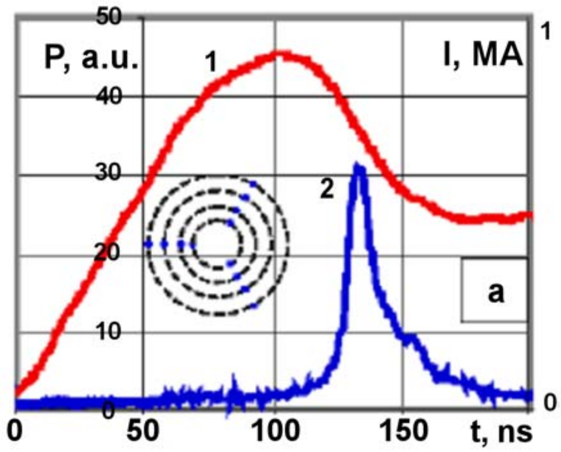

Fig. 11. Star-like loads (points on broken lines denote individual wires) with corresponding current pulses (trace 1) and X-ray signals recorded behind a 2-μm Kimfoil-filter (trace 2) obtained in experiments with copper wires [16].

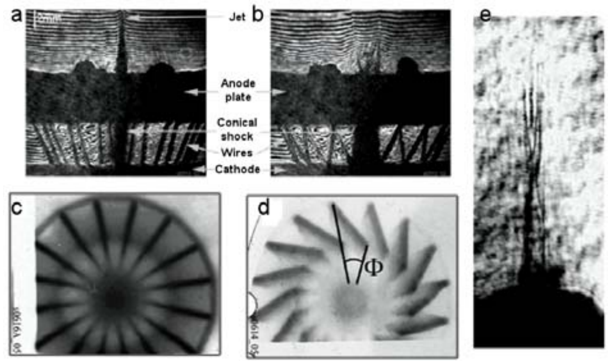

Fig. 12. Side-on interferometric pictures of untwisted (a) and twisted (b) conical wire arrays and end-on images of the self-emission of energy > 30 eV (c and d). A Schlieren image (e) shows the appearance of a rotating plasma jet [1].

It should be noted that the conical wire-array Z-pinches are of particular interest from the point of view of astrophysics, because precursor plasma flows exhibit many effects characteristic of astrophysical phenomena, e.g. super-Alfénic and/or super-sonic flows, radiative cooling effects, high-Beta plasma and fully collisional flows.

Another interesting group of experiments are the radial wire-array Z-pinches, in which wires are extended radially from the centrally located cathode [28]. Such a configuration and the phases of an associated discharge are shown in Fig. 13.

It should be noted that the radial wire-array Z-pinches offer some advantages over standard cylindrical wire-arrays. Such configurations implode in a very stable and orderly way. Therefore they seem to be suitable for coupling with small hohlraum targets. Recent experiments carried out on the MAGPIE (1 MA, 250 ns) machine at the Imperial College in UK, as well as OEDIPE (730 kA, 1.5 μs) and SPHINX (4 MA, 700 ns) facilities at the Centre d'Etudes de Gramat in France, have shown the relatively high scalability of the radial wire-array Z-pinches [27]. Recently also planar wire-array Z-pinch experiments [17] attracted some attention. An example of such a configuration is shown in Fig. 14. The planar wire-array Z-pinches still require an improved modelling and further experimentation.

In authors' opinion the most important issues of research on wire-array Z-pinches can be formulated as follows:

1. The choice of materials, the number wires and their physical dimensions need to be optimized in order to achieve high X-ray yields.
2. Development of appropriate diagnostic methods requires further efforts.
3. Design and manufacturing of sophisticated fusion targets is another task.
4. Development of corresponding physical models and codes is needed.
5. New wire-array Z-pinch experiments at a different scale should be performed.
6. It is important to understand why the K-shell yield varies as $m_k^{1.9}$ (consistent with the K-shell opacity), while for good pinches m_k varies as $I^{1.44}$.

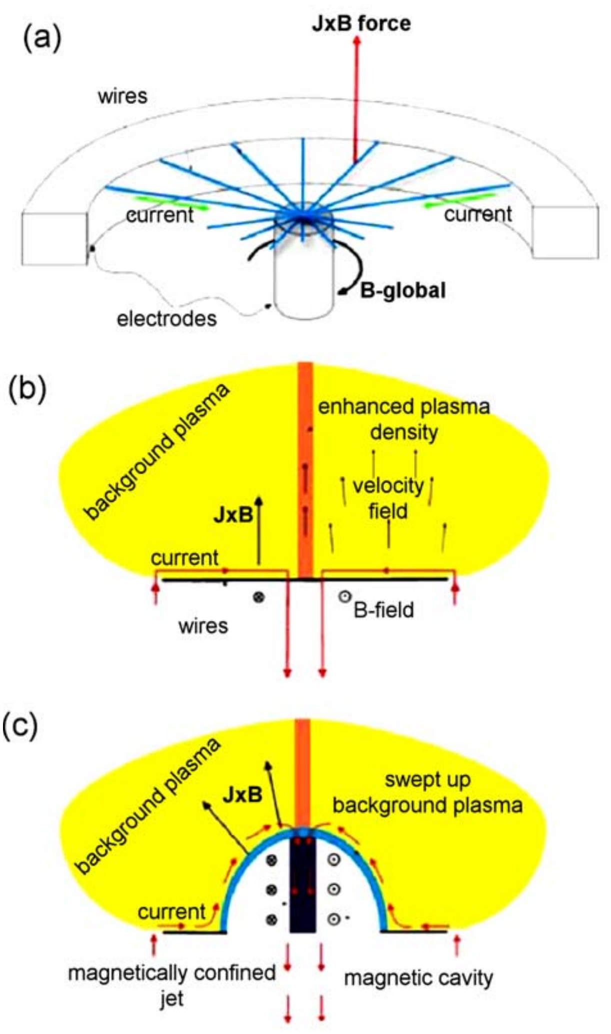

Fig. 13. Phases of the radial wire-array evolution: (a) initial setup, (b) ablation and formation of a precursor, (c) formation of a magnetic cavity, and the collapse phase [28].

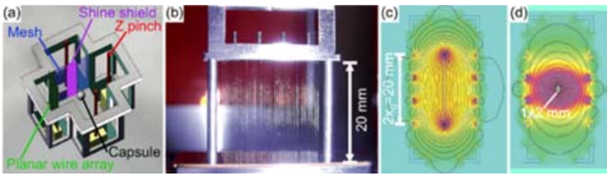

Fig. 14. (a) A 4 planar wire-array Z-pinch used to drive a fusion capsule; (b) a picture of a 20 mm wide system of 40 tungsten wires for the SATURN experiment; and (c) the magnetic field lines computed for a given return current cage and 2 planar wire arrays (c and d) [17].

7. Particular attention should be paid to the explanation of the role of hot-spots in the generation of X-rays with photon energy above 1 keV.

Examples of X-pinch experiments

The X-pinch is an interesting Z-pinch load configuration consisting of two (or more) fine metal wires arranged in such a way that they cross and touch at a single point, forming an "X" shape. Most of the experiments with the X-pinches have been performed with two or four wires driven by high-current pulsed power generators delivering currents in the range of 200–500 kA [33]. In recent years the X-pinches have been also studied on generators with 1 MA or even higher currents. With an increase in the discharge current the initial mass of the X-pinch load also had been increased. Some typical X-pinch configurations are presented in Fig. 15.

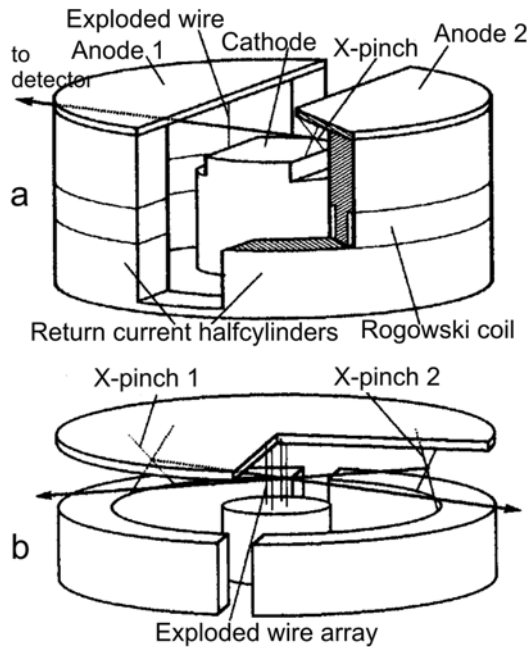

Fig. 15. Examples when X-pinches were used for backlighting of linear pinches: (a) X-pinch and linear Z-pinch in parallel, (b) wire-array in the centre and two X-pinches in return current paths.

It should be noted that in the first approximation the X-pinch mass might be increased according to the formula $m_l = m_{\text{optimum}} I^6$, where I is the discharge current and m_{optimum} is the optimum mass found in the experiments carried out with a lower current, when soft X-ray bursts are emitted at or after the current maximum. It is also worthy to mention that some X-pinch experiments, e.g. XP and COBRA at the Cornell University, USA, showed that X-pinches emit intense electron beams along their symmetry axis [49].

Experimental studies of X-pinch plasma dynamics and plasma parameters have been carried out with different high-current pulsed generators, including the S-300 machine at the Kurchatov Institute (Moscow, Russia), operated with currents up to 2.3 MA and the rising time of 150 ns. The X-pinches with various numbers of crossed wires – between 2 and 20 – and a range of diameters (55–300 μm) made of W, Mo, Ni-chrome and S-S (with linear densities of 3.6–40 mg/cm) were investigated in order to find the configuration ensuring the highest X-ray yield.

A further development of the X-pinch configuration is the so-called nested X-pinch, analogous to the nested cylindrical wire-array, but with all wires crossing in the same place. An example of a nested X-pinch is shown in Fig. 16.

Such nested X-pinches have been investigated on the COBRA generator at the Cornell University [48] and at the Sandia National Laboratories, USA [52]. It turned out that X-pinches are ideal sources for X-ray backlighting, because they produce small bright spots (the so-called hot spots). The hot spots (of about 1.2 μm

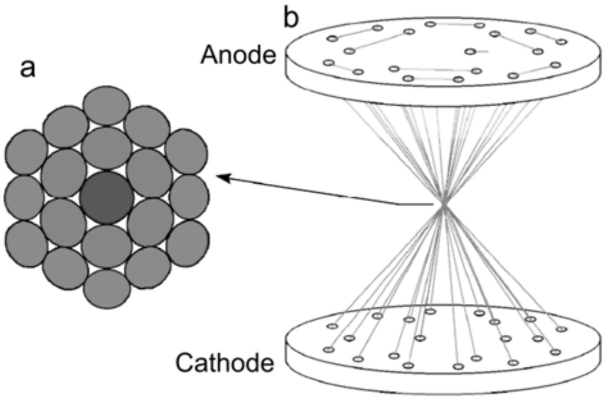

Fig. 16. Scheme of a crossing region and the configuration of a nested (multi-layer) X-ray pinch experiment.

in diameter, lasting 10–100 ps) themselves are interesting plasmas ($n_i \geq 0.1 \times$ solid density, $T_e \sim 1$ keV).

The X-pinches had been investigated for several decades in experiments involving currents in the 0.5–1.0 MA range. These efforts were reviewed by several researchers, e.g. [48]. Studies of the X-pinches at currents above 1 MA were started at the Sandia National Laboratories in 2007 and oriented towards optimization of the mass/length ratio and the scaling vs. current, the optimization of X-pinch configuration (from 2 to 64 wires made of Mo or W), and selection of the best material for wires (Al, Ti, Mo, W). Some examples of the investigated configurations are presented in Fig. 17.

Tests of X-pinches with higher currents (> 6 MA) were performed on the SATURN machine for various loads, e.g. 128 × 75 μm W (108 mg/cm, S3734), 64 × 53 μm W (27 mg/cm, S3735), 32 × 53 μm W (13.6 mg/cm, S3736), 32 × 73 μm Mo (13.7 mg/cm, S3735), but only the 14 mg/cm loads showed pinch near the peak current. The results obtained at SATURN for currents above 6 MA showed that the mass/length does not scale as I^2. These studies have been of primary importance for the HEDP (high energy density physics), e.g. the radiative collapses.

In authors' opinion the most important issues of research on X-pinches can be formulated as follows:

1. Optimization of the X-pinch configuration by selection of materials, number of wires and their physical dimensions.
2. Development of appropriate diagnostic methods.
3. Development of corresponding physical models and codes.

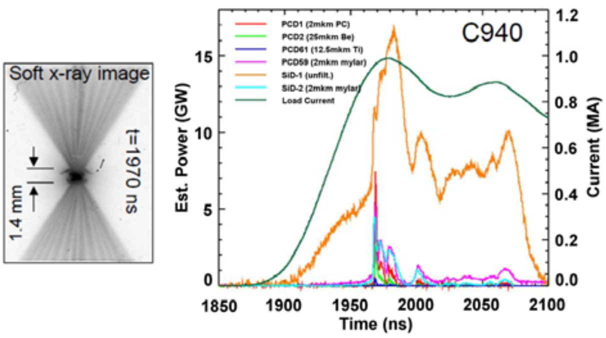

Fig. 17. Soft X-ray framing image and diagram presenting a current waveform and estimated emission power vs. time, which shows multiple X-ray bursts of energy > 1 keV [52].

4. Realisation of new X-pinch experiments of various scales.
5. Explanation on the basis of results obtained from 1 MA X-pinches (with X-ray sources < 16 μm), why the nested 1-MA X-pinches appear to operate more reliably and produce even smaller sources.
6. Continuation of studies of very small X-ray spots, e.g., these of dimensions of about 1 μm [37], in order to produce point-like X-ray sources.

Description of the gas-puffed Z-pinches

A very important direction of research on the Z-pinches is the investigation of gas-puffed Z-pinches, where one of the electrodes is equipped with a system of gas nozzles and fast valves used to produce a gas-curtain load [31]. An example is presented in Fig. 18.

This approach was developed on the basis of intuitive considerations in order to maximize the directed kinetic energy of an implosion, which could be then rapidly thermalized at the stagnation to produce copious X-rays. Another aim was to minimize the growth of the magnetic Rayleigh-Taylor (R-T) instabilities. The main goal of the high-current (1 MA or more), high-Z gas-puffed pinch experiments was to produce plasma of such a temperature and density so as to obtain high yields of the characteristic K-shell radiation.

In fact high-quality implosions originating from gas shells of a large radius, and involving mass profiles with high density near the z-axis, were successfully obtained on Double-EAGLE [31].

Considerations based on fundamental relations for pinch dynamics and plasma energy/mass ratio, together with the experimental data suggested that with the increasing current I_o the optimum mass $m_{optimum}$ scaling is weaker than I_o^2 [50]. The best results have been obtained with a triple-shell nozzle system (see Fig. 18). In these experiments the implosion was started within the outer shell at a large radius, which was stabilized by the inner-shell gas, and subsequently by the central gas jet. Some exemplary results are presented in

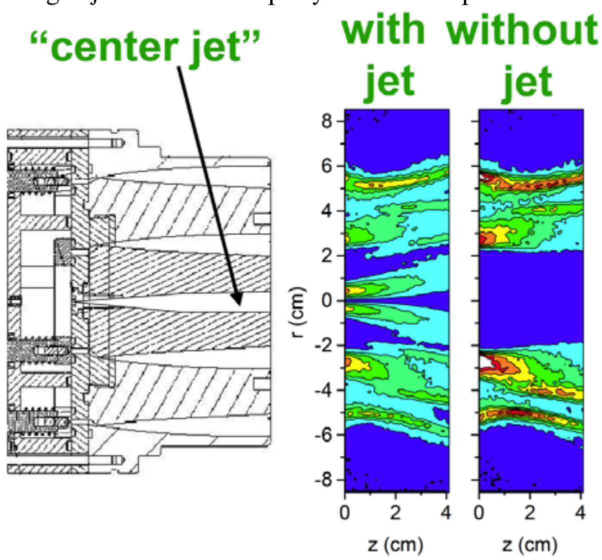

Fig. 18. Scheme of a cathode with coaxial nozzles (left) and gas density distributions obtained with or without the central jet [31].

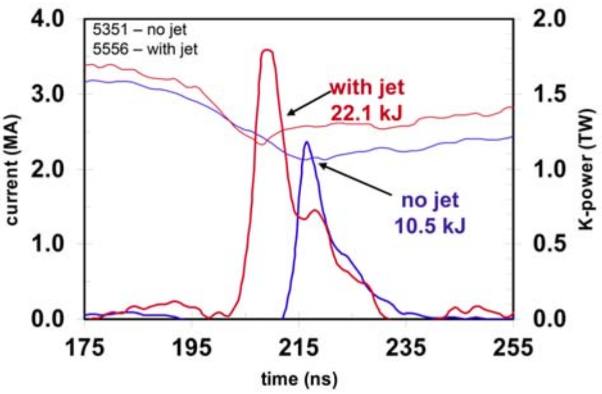

Fig. 19. Current waveforms and power of the recorded X-ray emission from two shots performed with and without the central gas jet [31].

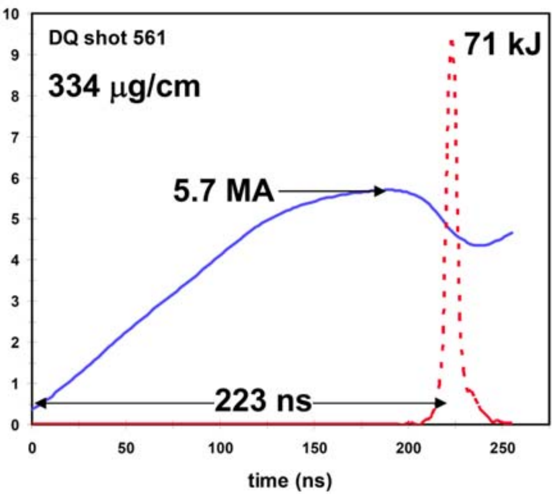

Fig. 20. Discharge current and K-shell radiation vs. time for DQ (5.7 MA, 225 ns) experiment using a triple-shell nozzle gas-puff with the diameter of 12 cm [31].

Fig. 19. The triple-shell nozzle system was successfully used for argon gas-puffed Z-pinch experiments on Double-EAGLE and DQ machines, as shown in Fig. 20.

The same triple-nozzle system was used for gas-puffed experiments on the SATURN machine at $I = 6.5$ MA and $\tau = 200$ ns. About 65 kJ of argon K-shell radiation was obtained, i.e. by a factor of 1.5 higher than obtained previously with a uniform gas-fill introduced through a 4.5 cm diameter nozzle, operated at $I = 7.1$ MA and $\tau = 50$ ns.

In authors' opinion the most important issues in the research on gas-puffed Z-pinches can be formulated as follows:

1. The experimental confirmation that large diameter gas implosions can generate high-energy photons and long implosion times.
2. Optimization of the tailored initial radial mass profiles in order to produce high-quality, large diameter implosions (with mitigated R-T instabilities).
3. Understanding the gas-puffed pinch energetics, i.e. why the kinetic energy stops to increase before K-shell emission, but coupled energy continues to increase.
4. Improving diagnostics in order to explain different results obtained from laser interferometry and other measurements.
5. Continuation of experimental and theoretical studies of combined Z-pinch experiments with wire arrays and gas puffing [34, 50] in order to achieve higher X-ray yields.

Features of non-cylindrical Z-pinch (dense plasma focus)

A non-cylindrical Z-pinch (often called a plasma focus) is formed by a high-current discharge between two co-axial electrodes. In this configuration the initial break-down (at the insulator surface) forms a current sheath, which is accelerated in the inter-electrode region (at appropriate gas pressure) and pushed behind the electrode ends, where it undergoes a radial compression and forms a dense pinch column, as shown in Fig. 21.

It should be noted that although an accurate quantitative model of the breakdown (taking into account all the complexities of the current sheath formation) is still missing, the axial acceleration and radial compression phases can be relatively well described by a 2-D (two-dimensional) MHD model [45]. This model can be applied until the end of the first expansion (and in

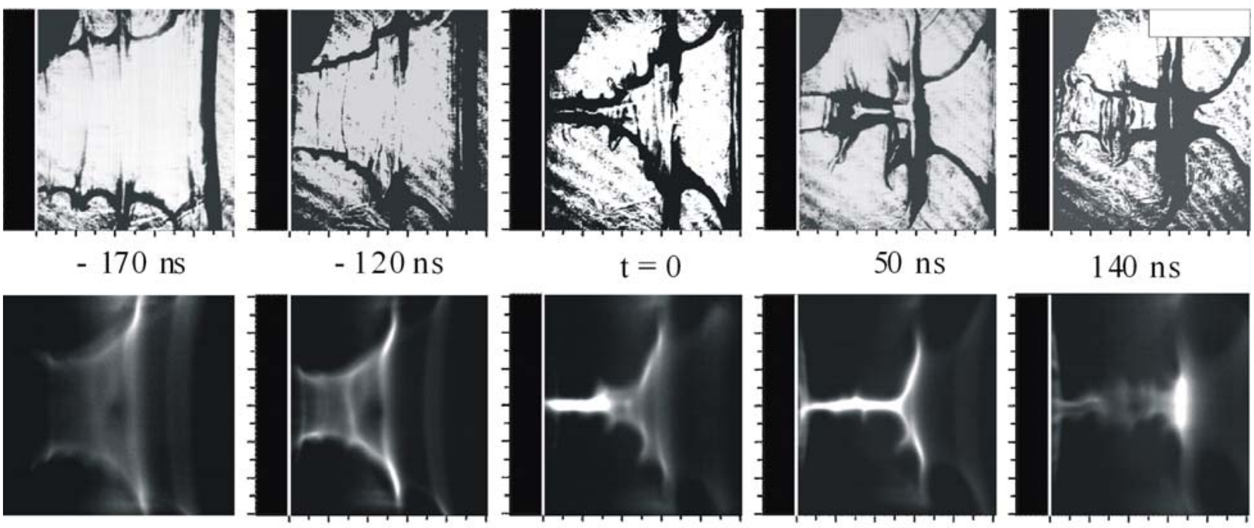

Fig. 21. Schlieren images and visible radiation pictures of the radial compression phase, recorded with a high-speed camera before and after the maximum compression ($t = 0$) in the PF-1000 facility at IPPLM in Warsaw, Poland [45].

the case of large devices even further), but after this phase more sophisticated models are needed.

Discharges of the plasma focus (PF) type have been investigated in many laboratories [5]. It was proved that in the experiments of this type, performed with a deuterium gas filling, a dense magnetized plasma may be obtained, sufficiently hot for the nuclear fusion reactions of D-D and D-T type to occur. In fact, from the very beginning the main aim of the PF experiments was the optimization of fusion-produced neutron yields. The initial scaling $Y_n \propto I^5$ [5] was evidently too optimistic, and eventually a more realistic scaling $Y_n \propto I^4$ [24] was established. The neutron yields obtained from the large PF-1000 facility seem to conform to such scaling, as shown in Fig. 22.

It should be noted, however, that in all the PF experiments performed so far a saturation effect was observed: beyond certain value an increase in the discharge voltage (and discharge energy) does not result in the appropriate increase of the neutron yield. Therefore, the simple scaling law cannot be extrapolated to very high currents (and energies).

Nevertheless, the PF discharges have been and still are investigated in many labs because they are also sources of intense pulses of the electromagnetic radiation (e.g. X-rays) as well as corpuscular emission. In particular, the PF discharges emit intense beams of accelerated primary ions (e.g., deuterons) and fast electrons. Detailed experimental studies of the ion beams in the downstream direction have shown that the primary deuterons are emitted in many narrow micro-beams, with energies reaching 1 MeV [5, 53]. There is some experimental evidence that these deuterons are accelerated by strong electromagnetic fields that are generated inside the dense plasma column. The number of emitted beams is a decreasing function of their energy.

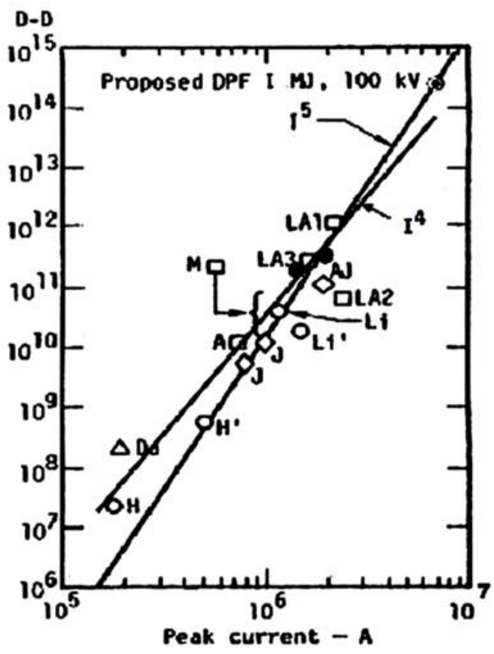

Fig. 22. Optimistic scaling of neutron yields (as I^5) from old PF experiments (J – Julich, Li – Limeil, AJ – Aerojet Lab, M – Moscow, LA – Los Alamos) performed before the 1990's [5], and a more realistic scaling (as I^4) and neutron yields (black circles) obtained in the PF-1000 facility [24].

Recently, it has been demonstrated experimentally that some beams of primary ions are emitted also in the upstream direction (towards the anode) [26, 53].

The experimental studies of the electron beams, which can be accelerated by the same local electromagnetic fields in the direction opposite to that of the ions, have shown that electrons are emitted mostly in the upstream direction (and can be measured behind an axial channel in the anode), but some the electrons are emitted in the downstream direction as well [26].

Unfortunately, the mechanism of the acceleration of the primary ions and electrons in PF discharges have not been so far explained in a satisfactory way. Some researchers suspect that the formation of strong local electromagnetic fields can result from the development of MHD instabilities of current filaments appearing inside the pinch column. Such filaments were observed during the formation of the current sheath in many PF experiments [52]; in some experiments, for example those performed on the POSEIDON facility in Stuttgart University [40], it was observed that such filamentary structures can exist also during the phase of maximum compression. The appearance of the current filaments within the pinch column was also registered on some high-speed camera pictures taken at the IPPLM's PF-1000 facility.

The problem of current filaments and other issues of research on dense magnetized plasmas produced in PF discharges were considered and discussed in a paper published in 2008 [42], but PF studies performed in the past two years provided new data. The investigations performed on PF-1000 were concentrated on two tasks: (a) interferometric measurements of PF-1000 discharges, and (b) studies of the fast (about 3 MeV) protons produced in the second branch of D-D fusion reactions. In regard to the first task, a multi-frame laser interferometry setup was developed at IPPLM, which made it possible to record up to 16 interferometric images during a single discharge [23]. A detailed analysis of the recorded interferometric images was performed by means of an automated system, as shown in Fig. 23.

In these studies a particular attention had been paid to some toroidal, helical and plasmoidal structures formed inside the pinch column, as well as to their correlations with X-ray and neutron pulses [25].

In regard to the second task, the preliminary proton measurements reported in [42] were followed by more detailed studies carried out by means of 16 miniature pinhole cameras equipped with shielded nuclear track detectors (NTD) and distributed around the pinch axis [41]. The proton images obtained in this way showed a distinct azimuthal anisotropy, as shown in Fig. 24.

Had the pinch column been uniform, the emission of the fusion protons would be isotropic in all radial directions. The observed anisotropy of this emission was hypothesized to result from an influence of filamentary structures. The possibility that trajectories of fast charged particles (e.g. fusion protons) might be affected by local magnetic fields arising from current filaments was mentioned in an earlier paper [41], as presented in Fig. 25.

Various possible configurations of the PF pinch column were considered, for example a homogenous column, a configuration of 6 or 12 linear filaments,

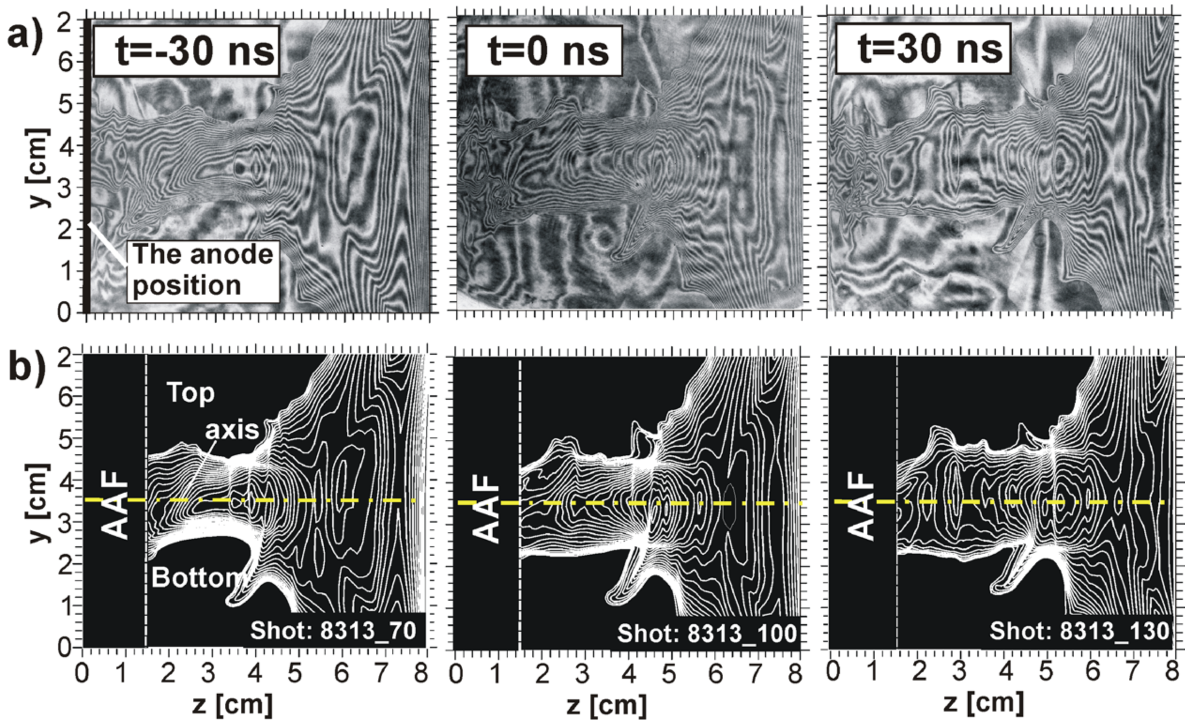

Fig. 23. Examples of interferometric images obtained in PF-1000 at selected discharge stages, and an analysis of the fringes by means of an automatic system [23].

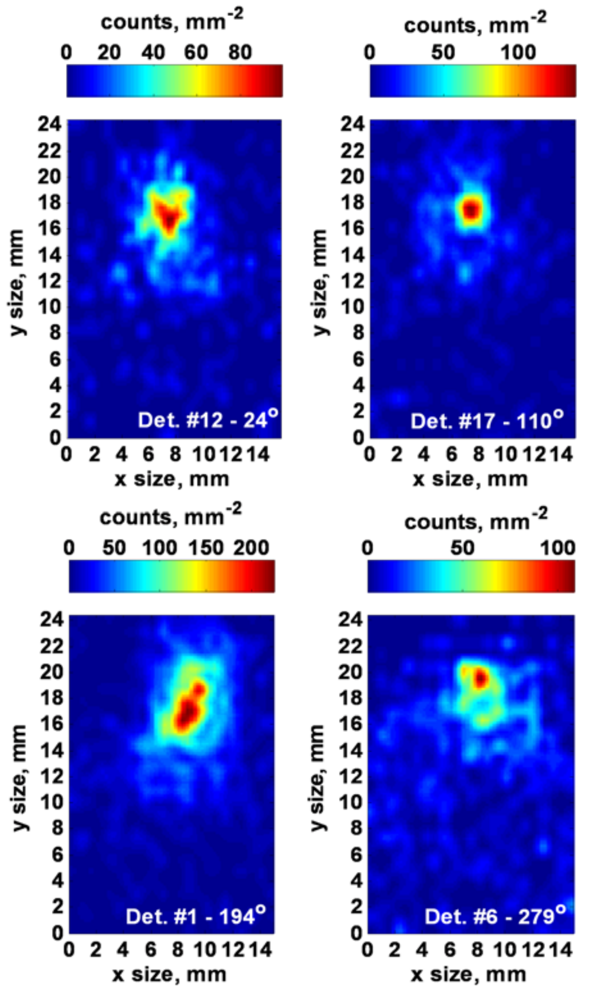

Fig. 24. Examples of fusion-produced proton images recorded at different azimuthal angles around the z-axis in the PF-1000 facility.

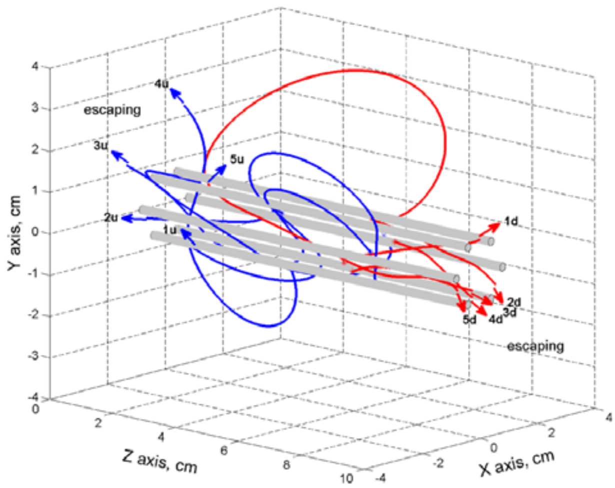

Fig. 25. Computations of trajectories of the fast fusion-produced protons, as performed for 6 current filaments [41].

and a funnel-like configuration. It was shown that for the pinch configuration which contains some linear filaments, fast fusion protons may be deflected close to the pinch column and emitted both in the upstream or downstream direction. Detailed computations of fusion proton trajectories showed that their azimuthal distribution may have a number of distinct peaks, related to the number of current filaments, and the experimental results might be approximated by a multi-peak sinusoidal distribution [43], as shown in Fig. 26.

The proton measurements described above have provided an indirect evidence of an important role played by filamentary structures.

In PF studies carried out in several research centres in the last two years some progress was made in the investigation of small PF facilities designed for different applications [55] an in the measurements of

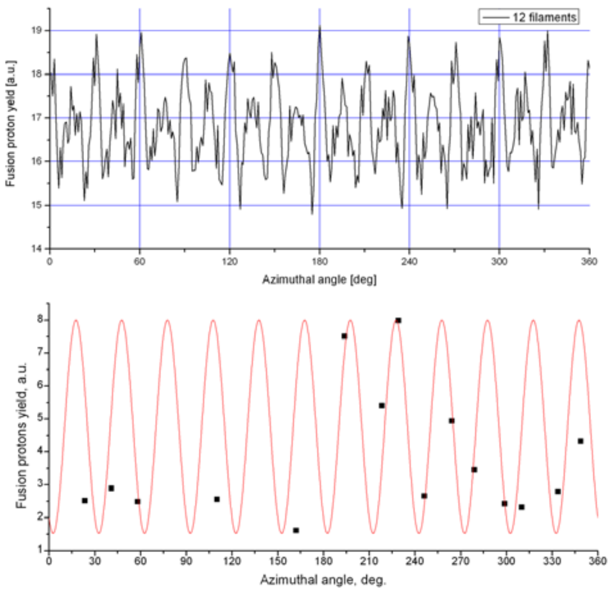

Fig. 26. The distribution of fusion-produced protons, as obtained from the Monte Carlo computations under an assumption of 12-filaments [41], compared with the total yields of fusion-protons recorded around the PF-1000 z-axis for two experiments in PF-1000 and fitted to the 12-peak sinusoidal distribution [43].

high-intensity ion and electron streams emitted from a medium scale PF devices [30].

Taking into consideration the experimental and theoretical studies reported above, the most important issues of research on PF phenomena can be formulated in the authors' opinion as follows:

1. To investigate acceleration of charged particles in plasma by local electromagnetic fields.
2. To study mechanisms by which the fusion neutrons (and protons) are generated during PF discharges.
3. To explain the role of a leakage current and plasma outflow.
4. To determine features of local sources of ion beams and fusion neutrons.
5. To investigate collective acceleration of ions by intense electron beams.
6. To explain the role of dense plasma structures, e.g. hot spots, current filaments, etc.

New trends

After reviewing various Z-pinch experiments done in the past we also want to outline some new trends in the contemporary Z-pinch research. It should be noted that recent efforts, as reported at the DZP-2011 conference [6], have been directed mainly towards hybrid experiments: 1) the magnetized laser inertial fusion (MAGLIF) [54]; 2) hybrid X-pinches [47]; 3) hybrid planar Z-pinches [17]; and 4) micro-pinches for particle acceleration [15].

The MAGLIF experiments are aimed at the investigation of laser-produced plasma magnetized by an axial magnetic field (produced by external coils) and compressed towards the symmetry axis by a liner made of a metal shell with an aspect ratio ($R_0/\Delta R$) equal to about 6 [54]. The hybrid X-pinches are realized with metal electrodes in the form of a cone with the tip cut off to fix very short X-wires [47]. The idea behind the hybrid planar Z-pinches [17] is to use several (6 or 8) small planar arrays placed symmetrically around a cylindrical surface with the central fusion micro-target (analogous to the configuration of 4 planar arrays mentioned in the section devoted to wire-array pinches). Micro-pinches designed for studies of the charged particle acceleration use narrow capillaries (e.g., with diameter less than 100 μm) and very intense laser beams (above 10^{18} W/cm^2), which are tightly focused (e.g., below the spot size of 40 μm) and injected along the capillary axis in order to induce the particle acceleration in very strong wake-fields, generating fields in excess of GV/m [15]. Such an acceleration might eliminate the need to build very long linear RF accelerators, which can only produce fields below 50 MV/m.

Summary and conclusions

The considerations presented above may be summarized as follows:

1. Various types of Z-pinch experiments have been reviewed, in particular single channel Z-pinches, wire-array Z-pinches, X-pinch experiments, gas-puffed Z-pinches and non-cylindrical Z-pinch (DPF) experiments.
2. The most important results and the main aims of theoretical and experimental research on Z-pinches have been presented and discussed.
3. Problems of the optimization of various Z-pinch devices have been characterized, in particular the maximization of the X-ray emission (from multi-wire experiments) and the fusion neutron yield from experiments with sophisticated fusion targets.
4. The main issues of research on non-cylindrical Z-pinches (DPF) have been specified and importance of studies of dense plasma structures, i.e. hot spots, current filaments, etc. had been emphasized.

Our conclusion is that further extensive theoretical and experimental studies of various Z-pinch discharges (including DPF experiments) are needed in order to understand all physical phenomena involved in these processes and to explain voluminous experimental data.

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