United Nations, Educational Scientific and Cultural Organization and
International Atomic Energy Agency

THE ABDUS SALAM INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

TRANSIENT PHENOMENA IN THE FINAL IMPLOSION STAGE
AT THE PF-1000 FACILITY

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MIRAMARE – TRIESTE
December 2006

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Preface

This paper consists of two parts, which are essentially constituted as a single whole. Dense Plasma Focus device (DPF), which is known from the early 50’s, is the oldest machine which has survived since the very beginning of thermonuclear researches. This is a high-voltage high-current pulsed discharge, which is produced usually by a discharge of a capacitor bank in various gases. It consists of two coaxial electrodes with the central one (anode) spanned by a ring insulator.

The device is known in two configurations of electrodes named by their creators – the Filippov type (in year 1954) and the Mather one (1961). The first configuration, elaborated in the Kurchatov Institute for Atomic Energy, Moscow, Russia, has a flat anode of disc shape lying directly on the upper edge of an insulator and a cathode (“liner”) looks like a pan turned up-side down and covers the anode from the top. This is a relatively infrequent modification used at the present time in two or three centres. The second one was elaborated in the Los Alamos scientific laboratory, USA, and this has an anode in the shape of a tube with a flat lid on the top of it. Cathode is usually made in the form of a squirrel cage, i.e. containing a number of rods placed along the circumference around the anode tube.

These devices on the low level of the energy stored in the bank are important due to their numerous applications. The upper level of the bank energy reached at present is interesting because of its perspectives as a unique neutron source for use in nuclear physics and radiation material sciences.

The main processes taking place during a development of the discharge is described in this paper. Here we shall mention that the paper is devoted to investigations of physical processes taking place in the PF-1000 facility. This device was put into operation with full energy stored in the bank at the Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland, about two years ago. The energy in the bank is equal to 1 MJ so it makes this device one of the few where one can investigate an effect of the “neutron saturation” phenomenon. It was found about 20 years ago and is still under discussion up to now. During these experiments we concentrated our efforts in an investigation of very fast non-equilibrium phenomena taking place in the final stage of plasma implosion, i.e. namely in the period of time, when neutron pulse is generated.
PART I

PLASMA DYNAMICS IN PF-1000 DEVICE UNDER THE FULL-SCALE ENERGY STORAGE: PINCH DYNAMICS, SHOCK-WAVE DIFFRACTION, AND INERTIAL ELECTRODE

Summary

This paper (part I) presents the first part of results obtained with the PF-1000 facility for the first time at its upper energy limit (≈ 1 MJ). Special attention was paid here to plasma (“pinch”) dynamics, which was investigated in relationship to its electro-technical and radiation (especially neutron) characteristics with the help of a number of diagnostics both time-integrated and with nanosecond temporal resolution. In these methods we utilized Rogowski coil for the routine electro-technical measurements, visual multi-frame and streak cameras, soft X-Ray pin-hole multi-frame cameras, PIN-diode assembly, and PM tubes with scintillators for soft and hard X-Rays as well as for neutron investigations together with a set of activation counters. In particular, the temporal cross correlation of different phenomena taking place during the discharge was investigated. The pinch’s longevity appears to be 10-15 times larger than the ideal magnetohydrodynamic growth time (ratio of the pinch radius to the ion thermal velocity). It is demonstrated how the “target” dynamics (pinch plasma of the DPF) depends and may be controlled by the electrodes size and geometry of the chamber in this large-scale device. Diffraction of a shock wave together with a current sheath on an obstacle made at the DPF anode cap opens an opportunity for an inertial electrode to be used in future at larger DPF devices.

1. Introduction

Dense Plasma-Focus (DPF) [1] is a gas-discharge installation with two cylinder metallic coaxial electrodes. It belongs to the Z-pinch class and operates with a cylindrical insulator positioned at the lower part of the internal electrode (anode). Initial pressure of the working gas is equal to a few Torr. Temporal evolution of the discharge undergoes, as a rule, the following several phases.
The first phase is a gas breakdown developing along the exterior of a cylindrical insulator. This surface discharge [2a] takes from a few through to a hundred ns and bears non-equilibrium kinetic (K) character (acceleration of initial charged particles, streamers, avalanche, etc. [2b]).

The second one is of a magneto-hydrodynamic (MHD) nature. It is an inverse pinch, when the plasma sheath expands from the insulator to the cathode bars, being stable all the time.

The third one, being relatively long (several microseconds for medium- and large-scale facilities), is also mainly of an MHD nature [3]. It starts after the second phase with supersonic plasma acceleration by an azimuth magnetic field of the discharge current and matures with implosion of the plasma onto the Z-axis of the chamber. There are two types of electrodes systems of DPF – the Filippov’s configuration, where plasma accelerates to the chamber’s Z-axis radially along flat anode immediately after the second stage, and the Mather one where plasma accelerates first next to the anode tube elongated up to Z-axis and only after this stage it turns around the edge of the tube and implodes radially. The speeding up plasma (plasma-current sheath – PCS) is contained during its movement to the chamber’s axis between a shock wave (SW) in front of it and a current sheath (CS) behind the SW. The discharge current at this time is subdivided inside the DPF chamber into four non-equal parts [4-6]:

1) Current flowing along the front of the SW.
2) Skin-layer current at the back side of the PCS (constituting the main part of the current, which is established in this device during the so-called “working regime of DPF operation” after passing through a set of conditioning shots); it pushes PCS to the chamber axis.
3) Residual current flowing behind the PCS throughout low-density plasma, which has not-completely been captured by the PCS; this current turbulizes the residual plasma and produces the “third type of insulation” – isolation of the main part of current flowing within the PCS and later on through a pinch (dense plasma column) from the surrounding residual plasma.
4) Remanent current on the insulator surface (which is not present in some DPF devices).

However this phase also bears an evidence of some kinetic phenomena [5, 6], viz. micro-turbulence within the skin-layer of PCS, making the sheath more rigid in relation to the flute instability from the side of short wavelengths, runaway electrons accelerated both at the front of the converging quasi-cylindrical shock wave and within the PCS, and turbulence of residual plasma.
This stage is completed first by a convergence of the SW on Z-axis (singularity line for the azimuth magnetic field) accompanied (in the case when deuterium is used as a working gas) by runaway of its part of the current. These fast runaway electrons ("runaways") form a thin filament near Z-axis (of a diameter equal to circa SW front) and produce medium-energy X-Rays (with energy of photons about 30…50-keV) (see e.g. [5, 7]). Then, some tens of ns later, this phase finishes by the maximum plasma compression on the chamber axis Z, with confinement of this pinch plasma during circa 100 ns. This phase is accompanied with plasma cooling due to radiant and electron conductivity. Soft X-Ray radiation (of about 1-keV photon energy) is produced during this process. It is clear that during this period, known in literature as a so-called “first compression” stage, three “pinches” in fact exist [7]:

1) “current pinch” occupying the biggest diameter (~ 10 cm) and including in itself almost total discharge current (seen by magnetic probes and due to Faraday rotation measurements);

2) “dense plasma pinch” (~ 1 cm) containing dense plasma imploded about the chamber axis (seen by interferometry) and carrying circa 70% of the discharge current; and

3) “bright plasma pinch” (a few mm of diameter), which is positioned about the Z-axis and usually related to current/plasma filamentation (runaways) taking place near this line of the magnetic field singularity and seen by soft X-Ray pin-hole camera.

The main aim of the present paper is to describe a specificity of plasma dynamics under the full-scale energy storage of the PF-1000 facility.

The next stage is a short-lasting event of a kinetic (K) character (a few tens/hundreds nanoseconds) [5 – 9], which will be discussed in detail in part II. It starts from the so-called “current abruption” phenomenon when the pinch is disturbed by Rayleigh-Taylor instability provoking in turn various micro-instabilities. These non-linearly coupled instabilities, practically instant (during a time period much less than 1 ns), substitute the classical collisional current within the pinch by the collisionless stream of fast electrons having characteristic energy of several hundred keV. The latter fast electron beam generates hard X-Ray radiation on the anode [3, 6, 7, 10, and 11]. Then these fast electrons are magnetized and the whole current is carried mainly by fast ions [12] having spectrum extended to several MeV.
The first MHD phase forms a “target” – hot (≤ 1 keV) compressed (≤ 10^{19} \text{ cm}^{-3}) plasma, whereas during the second one (K) the powerful beams of fast electrons and ions are generated and start to interact with plasma and electrodes. A noticeable part of the fast ion stream composed of “medium” energy particles (usually in the range 50…150 keV) is captured by a magnetic field of the pinch and confined within the plasma “target” for a period of about 10 drift times of them [13]. Interactions of these ions – both Coulomb and direct fusion ones – with the above-mentioned plasma target (at the operation of DPF with deuterium or deuterium-tritium – DT – mixture as a working gas) results in neutron emission [13, 14]. Energy \( E_c \), released from capacitors to the discharge, is in the range from just a few Joules to circa 1 Mega Joule (MJ).

At the present time there is a rapidly increasing field which includes various applications of small- and medium-size DPF installations. The new high-current technology [15] introduced in these devices provides an opportunity for reliable exploitation with a high repetition rate (up to ten cps) and ensures its long life-time (circa \( 10^7 \) discharges) [16]. According to our experience at least 3 modern elements have to be introduced in any new DPF device of a small or large scale: capacitors of the assembly similar to KMK type, pseudo-sparks as a main switches, and DPF chambers manufactured by means of e-beam or laser welding having no rubber o-rings [15, 16]. Such a device may be used as a source of radiation of various types for goals of semiconductor industry (projection and proximity X-Ray lithography, micromachining), biology and medicine, in material sciences, etc. [16-20], and it will have a reliable operation during a million-shot run with a repetition rate of ten cps (if the proper cooling will be organized).

As to the fame of the big DPF facilities, it is based on the fact that the large-scale DPF might be a very intense and efficient neutron-producing device. The scaling law for the neutron yield has been formulated at the beginning of the plasma focus investigations: \( Y_n \approx E_c^2 \), where \( Y_n \) is the DPF absolute neutron yield per shot and \( E_c \) – its bank energy. It is a very promising one for the efficiency of neutron production namely of large facilities having a high value of \( E_c \). However, later on, the investigations carried out with the biggest devices of that time revealed that a certain limit existed for bank energy, above which the scaling law with those installations was not fulfilled [21]. Apart from the failure of fusion perspectives, even now this experimental fact is a serious preclusion for a particular use of a big DPF. We mean its possible exploitation as a powerful source namely of fusion neutrons for material sciences, viz. as the source for testing of materials perspective for the first wall components.
and construction elements in the magnetic confinement fusion and, especially, in the inertial
confinement fusion reactors (where the neutron interaction with materials will be of the
“explosive-like” type – the same as within a DPF).

Indeed, the present day expectations in this field related to the IFMIF facility [22] are
based on a powerful high energy deuteron accelerator (about 40 MeV, 0.5 A). It is thought
that it will be able to ensure, during a one-year irradiation term, the neutron fluence on the
levels from 0.01 till 50 displacements per atom (dpa) in various zones positioned near a target
having the area $5 \times 20 \text{ cm}^2$. The value of 1 dpa corresponds to the irradiation e.g. of iron-based
specimens (counted as the perspective ones for a fusion reactor [23]) with the mean
neutron flux $4.5 \times 10^{16} \text{ n/m}^2\text{s}$ during a year. 1 dpa is approximately equal to a total fluence of $10^{21}$
neutrons per $\text{sm}^2$ for Be- and C-based materials. The total cost of the IFMIF is estimated to be
above the level of $10^9 \text{ US$}$ with the operating cost of circa $6 \times 10^7 \text{ US$}$ per year. Projected
construction time of this notable facility is about 10 years.

However the above new run-up operational DPF technology might be fit for a
construction of an effective 0.5-1.0 MJ DPF facility (thus on the level of present-day devices)
working on DT mixture with a current of the order of 5.5...6 MA and in a high repetition
mode. The cylindrical shape of the plasma neutron source in this device will be characterized
by a diameter of 1 cm with a length of 10 cm. In this case such a device could ensure, during
the one-year run, an overall fluence of the order of 0.1-1.0 dpa with its total and operational
costs two orders of magnitude less compared with the above-mentioned. And what’s more
this kind of facility can be constructed and put into operation in a 3-year period of time. Thus
this device might easily fill the niche between fission reactors (having no proper neutron spectrum), used at the moment for the above purpose, and IFMIF. But to reach this aim the
neutron yield of the DPF of a few hundred kJ must follow the above scaling law
$Y_n = 10^{10} I_p^4$
for deuterium as a working gas (where $I_p$ is the current flowing through the pinch, measured
in MA).

It means that if in the facility of the PF-1000 type [24] the pinch current would be
about 6 MA its neutron yield will exceed $10^{13}$ of 2.5-MeV neutrons/pulse. It will give $>10^{15}$
for the 14-MeV neutrons at the operation of the DPF with the deuterium-tritium mixture as a
working gas. Taking into consideration a possible geometry of the near-pinch anode part of
the DPF of this energy level it is easy to estimate that 1 dpa can be succeeded during an
operational year in a volume of about 1 litre with the irradiation area ~ 0.1 $\text{ m}^2$. For all that a
PF must work with a repetition rate of 3-4 cps with the irradiating zone positioned 0.1 m
apart from specimens. During a one-year run main parts of the device (capacitors and switches) will be changed 10-20 times. These figures for a facility, designed with the use of the above-mentioned new technology, look feasible since for several years we have already DPF devices working with a repetition rate 3-16 cps [16] whereas with our recent PF-6 device [25] we reached current circa 760 kA and neutron yield \( Y_n \) about \( 10^9 \) neutrons per pulse with deuterium as a working gas with 4 capacitors having the overall energy bank \( E_c = 7 \) kJ only. According to our experience in scaling law for bank parameters the above-mentioned figures might be expected for the same type of DPF-based neutron test facility on the level of a few hundred kJ.

As for the above-mentioned saturation of the DPF neutron yield several phenomena, responsible for the effect, were found during the last two decades. We shall discuss the physics of them elsewhere, but here we would just like to mention that in our point of view it is possible to get over these difficulties, and here we shall analyze some of them, which are intrinsic to the PF-1000 device.

But there is something more in this sphere. This project in the field of radiation physics and chemistry of material science (in the case of a success in the above scaling) could be aimed to develop a new field within the area. Namely, it might ensure radiation tests at *heightened* conditions thus *shortening* the test periods of candidate radiation resistive materials (e.g. berillium, tungsten, ceramic composites, austenitic and ferritic steels, lithium, etc.), being designed to meet the needs of fission and fusion power engineering, space industry and accelerator technology.

In fact, in the field of radiation tests of materials there is a unique opportunity to shorten the period of testing session. Indeed such a device enables to ensure a *peak* power flux density of neutron radiation in the range \( 10^{23} \) n/cm\(^2\)s (or its energy density up to \( 10^{10} \) J/cm\(^3\)). It is even much higher for \( e^- \) and \( i^- \)-beams as well as for plasma streams generated by DPF. Thus it seems to be tempting in such experiments to produce, just during a few shots, the same effects as under exploitation of classical radiation devices *for years* when operated at the much lower working power flux density. And what’s more, many major problems can be investigated here – atoms displacements, blistering, erosion, redeposition and material migration, fuel recycling and retention, etc., possibly during a very short period of time. It seems that it would also generate material-specific activation and radiological property data, and support the analysis of materials for use in safety, maintenance, recycling, decommissioning, and waste disposal operations.
Thus potentially it can give an opportunity to sustain a rate of the materials’ investigation and their selection (e.g. for space vehicles and fusion devices like ITER, NIF or Z-machine) in a proper time regime in relation to fusion program development. But of course for this aim a so-called “damage factor” should be established, i.e. a dependence of both damage degree and its nature (side by side with other interaction effects) on power flux density, i.e. on energy and pulse duration of penetrating radiation. A dependence of the damage factor on elemental contents of materials should also be investigated as well.

However another point becomes an issue for such a big, powerful device, having high repetition rate. Viz. simple estimations show that in the above DPF facility working as a repetitively pulsed neutron source an average heat power released onto the metallic surface in the center of its anode could reach circa 1 MW/cm². It implies serious (if resolved at all) problems for a material of the central anode’s part of a DPF chamber.

We shall present in this paper our recent results taken from the investigation of the operation of the PF-1000 facility, which exploits deuterium as a working gas in a single-shot mode on the energy level close to the maximal one between all other devices of this type (0.6…1.0 MJ). We intend to discuss these data in view of the above-mentioned problems and means for their possible solving.

2. The apparatus

The PF-1000 facility [24], manufactured on the base of the corresponding technology of the 70’s of the previous century, has nevertheless the largest bank operating on the energy level about 1 MJ, and it operates with deuterium as a working gas (Fig. 1).

It consists of the following main units:

• vacuum and gas assembly which includes vacuum chamber (right-hand side of Fig. 1) with coaxial electrodes and vacuum/gas handling systems
• condenser bank positioned on two other levels of the building ($E_c \approx 1.056$ MJ at initial charging voltage up to $U_0 = 40$ kV) and pulsed electrical power circuit with high-pressure spark-gaps, low-inductance coaxial cables, a collector (left-hand side of Fig. 1) and a control room.
After the engaging of the spark-gaps, energy, which has been stored in the bank, is transferred by means of coaxial cables through the collector to electrodes of DPF chamber. The vacuum chamber, which contains the electrodes, has a large volume (1400 mm in diameter and 2500 mm in length).

Two families of electrode geometries differing essentially by their inter-electrode gaps, lengths and shape were used in this set of experiments. The copper anode has a diameter 230 mm with a length of 600 mm. This anode had on the top of it a cap, which in two dissimilar types of experiments had a diameter equal to or slightly larger than the anode tube itself (Fig. 2a). In the second case the protrusion of the cap outside of the anode tube was manufactured as a circular hat-shaped “tooth” on its end (in fact the anode cap was of a radius 1 cm larger than the anode cylinder itself). Its primary destination was to grasp excessive metallic debris possibly produced and entrained by the current sheath from the anode on its way to the Z-axis of the DPF chamber. But it constitutes a small obstacle for a shock wave (SW) pushed by a magnetic field of a current sheath (CS). This SW stumbles on the obstacle when arriving to the edge of the anode.

Fig. 2b) is an example of the first type of the cathode electrode system. It is made as a squirrel cage which consists of 12 stainless-steel rods each of 40 mm in diameter and of an 800-mm in length, distributed around a 400 mm diameter circumference. In Fig. 2c we show a second type of a squirrel cage cathode – 24 stainless steel rods 32 mm in diameter and with a length of 600 mm. They were distributed also around a 400 mm diameter perimeter with the same anode and insulator. As it may be seen from Fig. 2a (left side), b the cathode rods in the
first case are much longer than the anode. In the second configuration (Fig. 2a – right side, c) some of them are equal to the anode’s length with the others being slightly longer (by a value of 2 times less than the pinch’s length). The cylindrical alumina insulator sits on the lower part of the anode. The main part of the insulator extends 113 mm along the anode into the vacuum chamber. The condenser bank of capacitance 1320 µF (264 capacitors having 5 µF capacitance and 40 nH inductance each) was charged in these experiments to the voltage \( U_0 \) varying between 20 to 40 kV, which corresponded to discharge energies \( E_c \) ranging from 264 kJ to 1056 kJ. Usually the bank was exploited on the level of 810 kJ and 35 kV respectively.

In this set of experiments with PF-1000 compared with previous researches [26-29] the energy increase was made by the bank capacitance increase (not by a voltage rise as was made previously with those devices). And, as circuit/chamber matching demands, the electrodes dimensions were increased in relation to the previous ones in an attempt of harmonizing external and internal inductances of the gun and equalizing the current quarter of the period with the plasma collapse time. This device operates with a rate not higher than 1 “shot” per 10 minutes.

![Fig. 2 Electrodes set up (a – scheme of two variants – left and right – of cathode roads and a cap of the anode, and their pictures – b and c)](image)

3. **Experimental arrangement**

The overall scheme of the experimental set-up is shown in Fig. 3. To study the MHD evolution of plasma, a three/four frame optical camera with exposure time of about 1 ns was employed (see Fig. 4). The delay between the subsequent frames is in the range of 10 – 20 ns. An interference filter (\( \lambda_{\text{max}} = 593 \) nm, FWHM = 6 nm) recording only continuum radiation
far from spectral lines was put into the optical path of the passive optical diagnostic subsystem. In addition to this diagnostics visible streak camera was also used. In this camera its slit was positioned perpendicular to Z-axis of the chamber. It ensures measurements of the radial plasma CS and SW speeds and gives information on the implosion symmetry.

![Fig. 3 Scheme of the experimental set-up](image)

Two types of the four-frame soft X-Ray (SXR) cameras have been applied in order to obtain plasma images in soft X-Ray range – one based on an open microchannel plate (MCP) device (Fig. 5) and another just a time-integrated pin-hole camera with an X-Ray film registration. Regardless of construction details the first camera has an MCP and phosphor screen, divided into four electrically independent sectors. The screen is attached to a fiber optics plane-plate separating the vacuum inside the camera from the atmospheric pressure outside. Each sector is gated by a single (positive) electrical pulse with an amplitude of 5-6 kV applied between a phosphor screen and the input side of MCP, which is connected to a common ground. Its activation is produced for a time interval 1 ns with a delay of 10…20 ns with regard to others.

The MCP is charged automatically through capacitor divider formed by a gap between MCP and MCP-screen. After applying a voltage pulse to any sector, SXR radiation
is converted into an electron flow, which is amplified inside MCP and converted by a phosphor screen into visible light outgoing from a fiber optic plate. Both SXR cameras were used side-on to Z-axis.

![Diagram of passive optical diagnostics subsystem](image)

**Fig. 4** General layout of the passive optical diagnostics subsystem

![Diagram of four-frame soft X-Ray camera setup](image)

**Fig. 5** The schematic diagram of the set up of the four-frame soft X-Ray camera

Time-resolved measurements of soft X-Ray (SXR) radiation was also made by means of PIN diodes covered with different filters. One of these signals from a PIN diode was used for synchronization purposes and for the determination of temporal relation between the SXR radiation of the plasma and the frame images recorded by means of optical and X-Ray diagnostics.
We investigated the neutron production process by measuring its time evolution, the anisotropy and the absolute neutron yield on the basis of both time-integrated methods and time-resolved registration of neutron pulses at different angles to the electrode axis, as well as by their comparison with time-resolved and time-integrated measurements of the soft, hard X-Ray radiation and the fast electron and ion beams. The total neutron yield \( Y_{\text{tot}} \), i.e. the number of neutrons produced during a single discharge (“shot”) and emitted in various directions, was measured taking into consideration the data received by means of five silver-activation counters (SC) placed on equal distances at different angles around the PF-1000 experimental chamber.

Three scintillation-photomultiplier detectors (SPD), located at different angles – head-on \( (0^\circ, \text{SPD1}) \), side-on \( (90^\circ, \text{not shown in Fig. 6}) \), and back-on \( (180^\circ, \text{SPD2}) \) – all of them 7-m distant from the electrode outlet – were used to perform time-resolved measurements of the hard X-Ray radiation and neutron emission, pulses of which were separated on the oscilloscope traces due to the corresponding time of flight. An investigation of electron and ion beams generated in the facility was done by a number of diagnostics using Cerenkov detectors and special track detectors. These means of fast particle investigation, as well as results received from them, are described in the following paper II. Special electrical and optical synchronization arrangements allowed the synchronizing of all diagnostics with the PF phenomenon with a temporal precision of 5 ns.

4. Experimental results and discussions

The first series of observations was carried out at the PF-1000 facility in the operational regime with a deuterium pressure range of \( \approx 2 \div 4 \) Torr and with a discharge energy level up to 850 kJ. In these series the chamber had long cathode rods as is shown in Fig. 2a (left) and 2b, the anode’s cylinder was smooth and even with its flush-mounted head. In these conditions a discharge current was 2.5-3 MA. Neutron emission \( Y_n \) was of the order of \( 5 \cdot 10^{10} \div 2 \cdot 10^{11} \) n/shot with the maximum neutron yield of \( 6 \cdot 10^{11} \) measured by 5 silver and 3 indium activation counters taking into consideration the neutron yields anisotropy. Each shot with the highest neutron yield was preceded by the two so-called “conditioning” discharges, made with a lower charging voltage and a relatively higher initial pressure of gas. Such a procedure noticeably increases reproducibility of all “working” shots and the absolute value of the best
ones. The results obtained during these series in relation to the pinched plasma can be summarized as follows.

1. It was found that for each initial filling pressure value ($p_0$) the neutron yield ($Y_n$) increases as a function of the charging voltage ($U_0$) up to a certain maximum and after that it decreases in spite of a further increase of $U_0$.

2. The same behavior of neutron yield was found for the situation when for a given charging voltage $U_0$ we increased the initial deuterium pressure – after a certain maximum it decreases in spite of a further increase of $p_0$.

3. Charging voltage increase produced in parallel with the initial pressure rise (provided that for each initial pressure we used the above optimal charging voltage) resulted in a further increase of neutron yield. No saturation in neutron yield was found up to 35 kV.

4. Two neutron pulses were observed in most of the discharges, as usual for these devices having about the same pulse duration and interval between the two peaks ($\approx 150$ ns FWHM for all of them), and typically in our case the second pulse was four to six times larger by its amplitudes than the first one (see however discussion on this point about an impact of scattered neutrons in the following paper).

Our investigations of the current sheath (CS) collapse dynamics performed by means of a streak camera for the shots with low and high neutron yield are presented in Fig. 6a and 6b respectively. One may see very different implosion velocities of CS and the degree of their symmetry. Both are much better in the case of high neutron yield (Fig. 6b). In good shots for the speed $v_{im}$ we have received usually a value equal to $2\cdot5\cdot10^7$ cm/s.

![Fig. 6 Streak-camera pictures made for shots with low (a) and high (b) neutron yield](image)

Five typical sequences, consisting of the 3-frame pictures, each taken during one shot in visual wavelength range, are put together in Fig. 7 in a single set according to the time synchronization. These sequences were selected for the operation of the device in the same
conditions and with similar neutron yield. From this figure we determine the CS speed also on the level $\geq 2-5 \cdot 10^7$ cm/s changing from shot to shot. One may observe a collapsing process of the CS preceded by a SW (double structure of the converging plasma shell – images 1 and 2a, b, c plus 3a of Fig. 7), then a formation of a straight and bright column (filament) with a “halo” of lower luminosity (3b through 5b and an enlarged picture d on the same figure) all having a height of its cylindrical part approximately $8 \rightarrow 10$ cm. The average diameter of the filament during the period of its luminescence is less than 0.2 cm whereas the “halo” is of 0.9-cm diameter (see a separate picture 7d and also Fig. 8). Maximal plasma compression precedes the current dip by $\approx 100$ ns and takes place about 2 $\mu$s after the current maximum.

Implosion speed measured by the above three methods gave us a lower estimate of the plasma temperature $T$ in the dense plasma pinch provided that the ordered kinetic energy of the PCS is converted into the chaotic plasma particle motion: $(m_d v_{im}^2)/2 = 3/2(kT)$, and that additional plasma heating takes place because the final adiabatic plasma squeezing (see [3], [7] and references therein). It appears to be in the range from $T \approx 0.5$ to 2.5 keV. Let’s take $T \approx 0.9$ keV as an average one for the most typical implosion velocity $3.5 \cdot 10^7$ cm/s and eventually $T = 1.3$ keV taking into consideration the ultimate adiabatic compression. Then taking into consideration the Bennett’s equation $H^2/8\pi = 2nkT$ (where $H$ – magnetic field about the pinch border) and supposing that the whole current measured flows through the pinch, density will be circa $2 \cdot 10^{19}$ cm$^{-3}$. If we shall take into account a current decrease to the moment of maximal plasma compression and suppose that the part of only 70% of the total current flows through the dense pinch column [1] the average density for this value of 2 MA during first neutron pulse will be around $0.8 \cdot 10^{19}$ cm$^3$.

After this period the plasma column is disturbed by instabilities (Fig. 7: 2c, 3a, b). Local disc-like plasma inrush into magnetic field (Fig. 7: 3a, 4b and d – on “plasma diode” see part II) and strong luminescence of filament and copper vapor are seen (Fig. 7: 3b, c, 4a, d). Later on (approximately by 50 ns) copper vapors near the anode centre disappear (Fig. 7: 4b), and the bright region of the picture starts to move to the upper part. At this stage the second pulses of HXR and neutron emissions (the 3rd and 4th pulses in traces of Fig. 9 a, b) starts. In all our regimes they were higher compared with the first ones by 4 through 10 times.
Fig. 7 Set of visible frame camera pictures of pinching dynamics (time sequence develops from the left to the right: a), b), c) and from the top to the bottom of the picture 1 through 5 with “A” – anode position) and d) – an enlarged example of the pinch with “filament”, “halo”, “plasma diode” and copper vapors at the anode surface.

Similar images were obtained as a result of the photographing of a plasma with the help of a pin-hole SXR camera with ns time resolution (Fig. 8 – three-frame picture taken in a single discharge). Measurements of the height of the bright part of a plasma column gave us here approximately the same value as in the visible range. But its diameter – circa 1 cm – is larger than the filament in Fig. 7, and it coincides with the “halo” around it.
Fig. 8  Three-frame time-resolved X-Ray pictures made for the case of long cathode rods (1, 2, and 3-rd frames in the clock-wise direction as shown by digits) with anode positions (⏐A) seen as vertical dark lines on the left-hand side of each image.

In the absence of interferometric pictures of the pinch we attribute the brightest structure of the pinch to the current filamentation (i.e. with runaways – see above) whereas we consider the halo as the dense plasma part of it (thus the volume of the dense plasma column is 6.4 cm³). The characteristic “confinement” time $\Delta t$ of the pinch lasts about 150 ns as seen from frame and streak pictures. This time interval coincides with the duration of the first HXR and neutron pulses (Fig. 9 – the 1st and 3rd pulses on a and b traces). However in comparison with the ideal magnetohydrodynamic (MHD) growth time $\tau_i$ (a ratio of the pinch radius to the ion thermal velocity) this real time interval $\Delta t$ is much longer. In fact measurements gave us $\Delta t = n \times \tau_i = n \frac{r}{v_i} = n \frac{r}{(3kT/m_D)^{1/2}}$ (where $n$ – coefficient, $\tau_i$ – inertial confinement time or ideal MHD growth time, $r$ – pinch radius, $v_i$ – ion thermal velocity, $k$ – Boltzmann constant, $T$ – plasma temperature, and $m_D$ – deuteron ion mass) with $n$ changed within the limits 10…15 from shot to shot (compared to $\tau_i \sim \frac{r}{v_i} \sim 10^{-8}$ s).

Fig. 9 Hard X-Ray (1st and 2nd pulses) and neutron signals (3rd and 4th pulses) taken in the same shot by SPD positioned at 0°, i.e. for neutron emission propagating along the direction of Z-axis (head-on – a) and at 90° (side-on – b) to Z-axis accordingly.
This large pinch’s longevity can very likely be explained by a longitudinal component of magnetic field generated during the implosion phase, considered in a combination with the inverse pinch effect. Indeed the reason for the $H_z$-component is very simple. Viz. because a coefficient of symmetrical compression of PCS on its way to Z-axis by “an effective radius” (i.e. the ratio of the length of its way from the upper part of insulator to the final pinch radius) is equal to $\sim 100$, the surface compression is about $10^4$. Any initial random magnetic field (earth magnetic field, remnant magnetic fields from DPF constructions, initial magnetic field components of vortex structures of PCS at its formation, etc.) will be captured by a highly conductive PCS and increased in this namely degree. A presence of this field (of the magnitude $|H_z| \sim 0.1|H_\phi|$, a comparable value with the external azimuth one) was experimentally ascertained in two independent experiments and by dissimilar techniques [8, 30a]. This field has produced a stabilizing effect on the pinch [30b]. Another possible mechanism of the pinch stabilization has a dynamic nature. It is a plasma flow along the axis (a cumulative stream, which produces above the pinch a shock wave). When the deuterium shots were fired in the Z machine at Sandia, calculations were performed that indicated that this is indeed the operable mechanism for the temporary stabilization [31]. If we take into account the length of the pinch (10 cm) and the maximum measured speed of this jet ($5 \cdot 10^7$ cm/s) the time duration of this effect would be 200 ns, which is close to our figures. On the other hand, as it was mentioned above, maximal plasma density (so-called “first compression”) is reached at the moment following the current maximum by about 2 $\mu$s, i.e. during the droop of the current pulse. It means that stabilization by the inverse skin effect [32], i.e. by a force produced during the phase when current aimed to leave a skin layer for the centre of the pinch, must contribute to the confinement time. With this characteristic – $\Delta t$ – we have a full collection of data on the pinch’s plasma – future hot dense “target” to be bombarded by a fast ion beam.

After the investigation of the above described (let say “usual”) regime we have examined other operational modes of the PF-1000 facility. As it was found, these regimes appear when the anode has the above described mushroom-like cap on its top. We have found two different types of plasma behavior that take place for the dissimilar cathode configurations of the DPF chamber, namely with short and long rods of the cathode. Current and current derivative oscilloscope traces look rather similar for both these regimes as well as in the previous “normal” case. Yet many other discharge characteristics differ strongly for these two diverse cathode configurations.
In the first regime we had the cathode rods much longer compared with the anode length as shown in Fig. 2a, b. In this case the shock wave (SW) and the plasma current sheath (CS) after traveling along the whole anode tube length (so-called “run-down phase”) can move easily in two directions – upward along the cathode rods and radially towards Z-axis upon the cap of the anode (implosion of the plasma shell). Contrarily in the second regime both anode and cathode electrodes have almost equal sizes (the geometry is in Fig. 2c). In the latter situation the external contact of the CS rests connected to the top of the cathode rods after the run-down phase during the whole time of the implosion of the sheath on the Z-axis thus implying certain restrictions on the plasma expansion in Z direction.

![Fig. 10 Time sequence of the SW bifurcation at the short cathode rods](image)

In these experiments we have found by three-frame or four-frame visual-light cameras and by SXR pin-hole cameras (both time resolved and time integrated) that the above-mentioned anodic hat-shaped obstacle (its radius is 1 cm larger than the anode radius) produces a bifurcation of the SW. Because of this the final pinch consists of two parts by its height (Fig. 10).

Namely the SW at its collision with the cap’s protrusion (barrier) in a course of its turning around the anode edge was divided into two SWs. They become equal by their height to the end of their implosion (together with subsequent CSs). And what’s more these two parts were compressed to the axis in different moments of time depending on the cathode geometry.

Videlicet in the first case of the long cathode configuration (Fig. 2a, b) usually the part, which is closer to the anode surface (to the line “anode” in Fig. 11a – the “lower” or left part) is compressed later than the more distant (“upper” – right) part of the column. Just contrarily to it in the second situation with the short cathode rods (Fig. 2a, c) the upper part is tardy (as in Fig. 11b) compared with the lower one. It may also be seen in Fig. 10, where a sequence of 1 ns-exposure pictures for short cathode rods is presented. Fig. 11c and d – time-integrated X-Ray pictures for long and short cathode rods respectively.
However in both situations the highest compression of plasma is reached in those “half-pinch”, which is compressed earlier. From Fig. 11c, d it is clearly seen – the brightest SXR luminosity relates to the “first compression” (in the Fig. 11c this is the upper part corresponding to the upper pinch of Fig. 11a and vice versa with Figures 11d, b). We have found that neutron yield is distinctly higher in the case of the long cathode rods when the highest mentioned plasma compression takes place at the “upper” half-pinch and earlier.

![Fig. 11 Visible (a, b, 1-ns time exposure) and soft X-ray (c, d, time-integrated) frame pictures for long (a, c) and short (b, d) cathode rods correspondingly](image)

This phenomenon of the SW decay can find its explanation on the bases of a simplified model based on an optical analogy, namely on the shock wave diffraction at the above-mentioned obstacle (in fact we have to discuss the diffraction of the dynamical SW+CS structure – “plasma shell”). Indeed the diffracted wave must propagate at a certain angle $\vartheta$ to the primary wave:

$$\vartheta \approx \frac{\lambda}{d}$$  \hspace{1cm} (1)

where $\lambda$ - is the “wave-length” of SW that can be estimated from Figs. 8 and 11 as a zone of the density (pressure) gradient at the front of SW, and $d$ is the characteristic size of the obstacle (protrusion) at the end of the cylindrical part of the anode (the push-through head of
the cylinder). Substituting to the above equation \( \lambda \cong 0.5 \text{ cm} \) and \( d \cong 1 \text{ cm} \) we shall receive an estimation for the height of the diffracted part of SW in the centre of the anode of the radius \( R \cong 10 \text{ cm} \):

\[
h \cong R \times \vartheta \cong R \times (\lambda / d) \cong 5 \text{ cm}
\]  

(2)

This value coincides with the experimental one (approximately one half of the total pinch size). However, the discussed reason for the bifurcation of SW at the obstacle does not explain the speeds’ differences of the two pinches in the above two dissimilar cases. Its understanding can be found in a more refine examination of the phenomenon as follows.

As learned from many experiments and 2-D numerical simulations, the plasma shell (SW+CS) during its run-down phase travels as a slanting structure. The angle in respect to the generatrix of the anode cylinder is equal to about 45° and the shell is almost flat im kleinen. As it is well known [33] a slanting shock wave in principle has a possibility to bifurcate into two upon an obstacle. Because, in our case, the diameter of the anode is much larger than the distance between our SW and CS, and we may count this SW in each point of the obstacle’s circumference as a plane one (having as a matter of fact a cylindrical shape of a relatively large diameter). Then because the characteristic sizes of the pressure (density) gradient in front of SW and of the cap’s edge are much smaller than the characteristic size of the task (e.g. the diameter of the anode) we may neglect both of these sizes and treat, in particular, the obstacle as a point-like one.

With these assumptions the problem can be examined as a 2-dimensional one in each plane of the cross-section cutting the chamber through Z-axis and with a point of bifurcation at the edge of the anode cap. In this case (see the scheme in Fig. 12) our slanting SW \( aO \) being initially single one will decay into \( Ob \) and \( Oc \).

It is easy to see that, side by side with these shock waves, the tangential discontinuity \( Od \) must exist which divides two plasma streams propagating through \( Ob \) and \( Oc \). As it is shown in literature [33] this line of discontinuity divides the flow into two regions (3 and 4), in which only two conditions must be fulfilled, namely the same velocity directions:

\[
v_3 \parallel v_4
\]  

(3)

and the same pressure:

\[
\rho_3 v_3^2 = \rho_4 v_4^2
\]  

(4)
where $v_3$, $v_4$ and $\rho_3$, $\rho_4$ are velocities and densities in plasma streams of regions 3 and 4.

![Fig. 12 Scheme of the SW bifurcation](image)

It means that in both regions (3 and 4 in the scheme of Fig. 12 or in the upper and lower pinches of Figs. 10 and 11) we shall have the same directions of SW+CS propagation. But in the case of long cathode rods when CS can freely expand in Z direction the density inside the upper part of the pinch (or in the region 4) $\rho_4$ becomes lower thus increasing the velocity $v_4$ according to the relationship (4). Contrarily, in the case of short cathode rods the upper part of the plasma stream (SW+CS) is compressed relatively to a higher degree because CS is now locked to the cathode end and restricted in its movement in Z direction. That is why in this case the lower pinch (or the region 3) has now lower density $\rho_3$ and higher velocity $v_3$.

In our real DPF situation the scheme of Fig. 12 should be modified taking into consideration the fact that after a so-called “run-down” phase of SW+CS acceleration between anode (A) and cathode (C) in a direction parallel with Z, our magnetic field of current turns the plasma shell by 90° thus changing the above main acceleration direction into a radial collapse to Z-axis. Thus the above picture in the DPF configuration will look like as shown in Fig. 13 where one has to turn the upper part of the flow by 90° around point $O$ along the circular arrow.

In connection with the above presented model we have to make four remarks. The first one is connected with the fact that because we deal with the collision of a relatively strong SW in plasma with a solid surface a more accurate examination of the problem has to take into account a boundary layer and thermo-conductivity as well.
Fig. 13 Real bifurcation of $SW_1$ (a) in DPF on the obstacle $O$ with subsequent turning of the streams (SWs c and b) by 90° towards $Z$ axis following the circular arrow

Secondly, generally speaking there is a principal difference between a front of a linear wave (as at diffraction of light or acoustic waves) and an SW front. Namely SW velocity in a given point depends on its intensity thus the geometry of a task is determined additionally by the particular SW intensity (e.g. SW angle of reflection is not simply equal to the angle of incidence). The third point is related to the fact that in our case the whole process is ruled by a current flowing along CS (namely its magnetic field pressure is the piston producing SW) thus the problem is related to magneto-hydrodynamics. Moreover, as it is stated in monographs on these issues (see e.g. [34]), the problem of interaction of a strong slanting shock wave with a solid barrier can be described at present time only by a simplified theory whereas a rigorous analytical one is absent. The majority of non-trivial cases here are investigated experimentally.

Thus the above remarks mean that the next steps in understanding the phenomenon can be reached by a more detailed experimental examination of the observed event done in a close vicinity to the obstacle and by a numerical simulation of the problem.

The fourth note is connected with the well known fact that usually any line (or surface) of tangential discontinuity diffuses sooner or later into a turbulent layer. In our case it has an important consequence. Indeed the current disruption phenomenon, which is intrinsic to a DPF (see part II), can usually take place randomly in various cross-sections of the pinch column. On the contrary, it finds in this situation its particular predominant place: namely near the border between the two pinches and usually in the lower part of the column (see Fig. 14a, b).
Fig. 14 Frame pictures of the final implosion stage of pinch in case of optimal (a) and higher (b) initial gas density with arrows showing plasma column disruption (gap), shown in relation to corresponding temporal evolution of neutron emission (arbitrary units) (c) at the double-pinch (firm line) and cusp-like plasma (dashed-line curve) structures (a vertical scale of the neutron pulse for the cusp is increased by about 3 times for demonstrational purposes).

Interesting results in the described regime with short cathode rods have been received when increasing the initial pressure of the working gas. In this case the velocity of the lower part of SW+CS has been decreased and become equal to the upper one. The resulting dynamics of plasma may be seen in the three-frame sequence of Fig. 15. One may see that in this case on the border between the above-mentioned two (“upper” and “lower” or left and right in this picture) pinches a plasma blob is created, which has a long life-time: \( \Delta t \geq 10 \tau_i \), where \( \tau_i = R_p/v_i \) with \( R_p \) – pinch radius and \( v_i \) – ion thermal velocity.

Fig. 15 Three-frame picture of pinch dynamics taken in one shot at the conditions of short cathode rods and high initial pressure (time interval between frames – 20 ns)
It is evident that this relatively long confinement of the plasma formation is ruled by a naturally formed cusp-like magnetic field configuration, produced by Rayleigh-Tailor instability, which is developed on both pinches simultaneously.

In comparison with the previous cases the confinement time $\Delta t$ is increased by a factor of circa 2.5. It also reflects in neutron emission: the second neutron pulse for optimal initial gas pressure of Fig. 14c (firm line) has a duration of approximately 175 ns (FWHM), whereas the same neutron pulse for high initial pressure, see Fig. 14c (dashed line), lasts 450 ns when measured on the FWHM level (both curves are normalized in arbitrary units here). However, the volume of the plasma blob $V_b$ having characteristic size circa 2.5 cm is $V_b = \frac{4}{3}(\pi R^3) \leq 10$ cm$^3$, i.e. about 3-4 times smaller compared with the pinch volume in the first regime of the PF-1000 operation (25 cm$^3$). So it is not surprising that the absolute neutron yield in this very case hasn’t increased (in fact it was about the same like in the case reflected in Figs. 6-10) comparing with the previous regimes, as it might be expected, because of the plasma confinement time increase. Additional analysis has also shown that too high initial gas pressure reduces plasma shell velocity, and as a whole that results in time mismatching of its arrival to the Z-axis in relation to the current maximum. Because of this fact the moment of neutron production shifts to the later time when we have, accordingly, the lower absolute value of current.

As a whole the described phenomenon of SW+CS bifurcation might give an optimistic opportunity for the future of large DPF devices. Indeed, as mentioned at the beginning of the paper, an expected thermal load on the central part of the DPF anode in these big devices operating with a high repetition rate may be of the order of 1 MW/cm$^2$. We shall have sputtering of the material here in any case. In fact, even at the proper cooling of the anode by e.g. water, it will be vaporized because of the powerful relativistic electron beam, which self-focuses along the Z-axis and strikes the central part of the anode. To prevent the damage of it the only foreseen way is to create here a plasma layer (so-called “inertial electrode” – IE) instead of the anode cap (or at least its central part).

E.g. this plasma IE can be produced by an independent SW formation inside the anode tube, which will be pushed from the bottom to the upper part of it (see Fig. 2a) to substitute the anode lid (the cap of the cylinder) in a proper moment of time. Viz. its arrival to the anode upper section should be synchronized with the DPF pinch formation at the anode centre. In this case this complimentary SW plasma will accomplish an electrical contact with
the anode tube along a circumference of a big diameter. The electron beams will go inside the anode tube through this plasma layer and spread upon a much larger surface of it.

However our present experiment has shown that instead of producing this “plasma anode” by external means, we may use the above described phenomena of the SW bifurcation upon an upper anode widening. It can help us to produce automatically the “inertial plasma electrode” during the discharge in the proper place and time. It seems quite clear that this plasma ‘inertial electrode’, which appeared in these experiments, may resolve a foreseeable risk of future difficulties with the high repetition rate DPF, but in particular with their next generation (above 10 MJ). Indeed the most loaded part of such a device – centre of the anode – may be changed routinely by plasma of such a kind. This plasma sheath has to have a much larger circumference of contact with the anode, which can now be done with a big hole in its center. Consequently, the heat energy would spread onto a much larger surface of metal, from which it can be removed much easier by water cooling.

We shall discuss radiation characteristics of PF-1000 in the second paper. But at the present time, according to the results described, it is seen that at the available configuration of the PF-1000 facility namely the parameters of the “target” constitute the main feature influencing the neutron emission. And we can control the neutron emission of the PF-1000 facility by changing these characteristics. Indeed with the present geometrical configuration we may change only charging voltage and filling gas pressure. Within a small range of their optimal values we cannot change formidably the total current and consequently the parameters of the beam. But by these $U_0$ and $p_0$ changes, as well as by the anode geometry, we can control the final pinch plasma parameters.

As for the electrode shape changes there are several promising possibilities to be checked in future. The simplest one is to make the central electrode shorter. In this case PCS will arrive much earlier to the Z-axis provided that the same initial pressure $p_0$ will be used. Thus it may give a possibility to further increase the initial gas pressure provided that the proper surface breakdown conditions will be preserved on the insulator. In turn it gives a possibility to match electrical circuit parameters with the PCS dynamics and to reach higher final plasma density of the pinch. Another opportunity is connected with the anode shape. It is known that the spherical shape of electrodes gives better pinch parameters than the rectangular ones [35]. In this case contrarily to the cylindrical (rectangular in its cross-section) Mather’s geometry the magneto-hydrodynamic flow of PCS proceeds smoothly and results in higher plasma compression. But there is probably even a better opportunity.
Fig. 16 presents two results of the interaction of electromagnetic waves with an obstacle – uniform input function and apodized one versus their resulting instrument functions (see e.g. [36]). It is clearly seen how the apodization procedure can suppress all diffraction oscillations at the edges. Such an effect can be produced either by an obstacle with a tailored wave penetration or by a special shape of an obstacle. It has to be mentioned however that in some cases for our goals just opposite procedure producing cumulation of the plasma on the Z-axis (of the type of compression force profiling as in the super-compression of pellets in Laser Fusion) could be useful.

Another interesting opportunity might be provided by the above-described double-pinch and cusp formations in a case when DPF would operate with noble gases filling its chamber (e.g. with neon). In this case it is possible to reach efficiency of soft X-Ray generation of circa 10% with a radiation being almost monochromatic (concentrated mainly in a resonance line of H-like neon ~ 1keV) and having a pulse duration of a few ns. Repetition rate of the device can be of about 10 cps [16]. It’s interesting to check whether such a scheme could be used for a hohlraum target irradiation scheme as it is discussed for wire arrays [37, 38]. Evident twofold benefits of a DPF over the wires might be an automatic formation of two pinches one above another as it is proposed in [37] and a high repetition rate with about the same soft X-Ray production efficiency.

It is a well-known fact that the main neutron yield is generated always namely during the second pulse at each shot, i.e. in the pulse, which appears after the phenomenon of the current abruption. Our PF-1000 device is not an exclusion from this rule.
This last event takes place somewhere in the middle of the plasma column, in particular, near the border between the two above-described pinches when we have an anode obstacle for PCS. Ions produced in this place have a predominant drift directed to the cathode side of the chamber, i.e. to the upper part of the pinch. We have seen that in the regimes with two pinches the highest compression (i.e. the highest density of the hot plasma target) is produced within the pinch, which is compressed earlier. That is why it seems not surprising that namely in the case of the long cathode rods (i.e. when the highest density is reached in the pinch produced further from the anode as in Fig. 11 a and c) we have received the highest neutron yield. And it should be marked here that the neutron pulse duration in these experiments coincides namely with the plasma “target” confinement time.

5. Conclusions

The results of the experimental study presented in this paper gave the main parameters of dense plasma column – dense pinch, which is produced in the PF-1000 facility on its upper energy limit and with its present-day configuration. The column of dense plasma at the moment of its maximal pinching has a diameter of about 1 cm with its height of about 10 cm. Temperature estimations related to this “first compression” stage give us values in the range of 1.2…1.4 keV. Plasma density evaluation results in figures within the limits of 0.7-0.9 $10^{19}$ cm$^3$. Confinement time of the pinch is about 150 ns in usual regimes, which is several times larger than the ideal magnetohydrodynamic growth times of plasma. These data constitute the initial characteristics of the future “target” parameters to be “exploited” in a subsequent self-irradiation of the pinch by ion beam generated during the last phase of the kinetic stage of the DPF processes evolution.

These data give evidence also for the possibility to control plasma pinch parameters (such as its confinement time, plasma dynamics, etc.) by several methods, not only by changes of initial gas pressure, battery charging voltage, but by geometry of the electrodes as well. The last one can formidably change pinch configuration.

The PF-1000 device characteristics, which can be changed (and improved) in the frame of the present (unchanged) chamber configuration, are the pinch plasma characteristics (i.e. “hot target” ones – not ion beams). It also opens perspectives for construction of future high-power devices by use of a so-called “inertial electrode”. When it will operate with noble gases it might be used probably in a hohlraum scheme of irradiation of a solid target, i.e.
applied for the inertial confinement fusion systems. Hopefully these facilities will be used in
the nearest future as a powerful neutron source for radiation material science.

However based on the results of this and following papers further improvement of the
PF-1000 facility becomes clear. First of all we need to change its geometry, which will be
discussed in details in part II. In particular it is obvious that the length of the device’s anode
has to be cut down. Then the circuit/chamber matching conditions will immediately demand a
further increase of the initial pressure of working gas that, in turn, might improve the final
“target” characteristics together with the neutron production efficiency. But as it will be seen
from the second paper a geometry change, both of the chamber and of the collector, might
also result in beam characteristics improvement.

Physical data received in the course of these experiments, which are connected with
the diffraction/bifurcation/reflection of SW upon the obstacle at the anode edge, also result in
the specific important conclusion: the best configuration of a DPF anode is might be not a
cylinder one. It has to be found on the way taking into consideration these bifurcation
phenomena, e.g. with the *apodized* shape of the anode as it is used in optics to eliminate
diffraction pattern or *vice versa* to use special measure to stress SW+CS *diffraction effects.*

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PART II

BEAMS DYNAMICS IN PF-1000 DEVICE UNDER THE FULL-SCALE ENERGY STORAGE: FAST ELECTRONS AND IONS CHARACTERISTICS VERSUS NEUTRON EMISSION PARAMETERS, AND THE GUN OPTIMIZATION PERSPECTIVES

Summary

Electron and ion beams dynamics of the PF-1000 facility was investigated for the first time at its upper energy limit (≈ 1 MJ) in relationship with neutron emission, pinch’s plasma (“target”) characteristics and some other parameters with the help of a number of diagnostics with ns temporal resolution. Special attention was paid to the temporal and spatial cross correlations of different phenomena. Results of these experiments are in favor of neutron emission model based on ion beam-plasma interaction with three important features: 1) plasma target is hot and confined during a few “inertial confinement times”; 2) ions of the main part of the beam are magnetized and entrapped around the pinch plasma target for a period longer than the characteristic time of the plasma inductive storage system; and 3) ion-ion collisions and fusion ones, due to head-on impacts and Coulomb ones, are both responsible for neutron emission. Analysis has shown that one of the ways for future improvement of neutron yield of the PF-1000 facility may be foreseen on the device’s geometry changes. It may ensure an increase both the discharge current and initial working gas pressure eventually resulting in the neutron yield boost.

1. Introduction

Dense Plasma Focus (DPF) [1] is a gas-discharge installation of a Z-pinch class. It has two coaxial electrodes with the internal one spanned by an insulator. After applying voltage between the electrodes and a breakdown of a filling gas along the insulator’s surface such a discharge undergoes two general phases [1, 2]:

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1) A relatively long magneto-hydrodynamic (MHD) stage (several microseconds), during which a plasma-current sheath (PCS) is accelerated to the chamber axis and imploded on it thus forming a “pinch”; after this implosion (so-called “first compression”) the plasma column is confined during a time interval $\Delta t$ equal to several $(n)$ inertial periods of time $\Delta t = n\tau = nr/v_i = nr/(3kT/m)^{1/2}$ (where $r$ is the pinch radius, $v_i$ is the thermal ion velocity, $k$ is the Boltzmann constant, $T$ is the plasma temperature, and $m_D$ is the deuteron ion mass) and eventually it is disturbed by MHD instabilities (mainly by the Rayleigh-Taylor one) having an increment of about $10^8$ s$^{-1}$.

2) A short kinetic (K) stage (with an assortment of characteristic times of micro-instabilities ranged within the interval of $10^{-13}...10^{-10}$ seconds) when the pinch, already MHD-perturbed, is destroyed by micro- and macro-instabilities during the above period $\Delta t$.

As it was measured by many researchers right from the start of the DPF phenomenon investigations (50 years ago, see references in [1]) a consequence of the perturbation of a plasma column (pinch) is a generation of powerful beams of fast electrons ($e^-$) and ions ($i^-$) having particle’s energy in the range extending to hundreds of keV and a few MeV (for electrons and deuterons respectively). After generation of these $e^-$ and $i^-$beams the intense emissions of hard X-Rays (HXR) and fusion neutrons (N) are produced. The latter type of radiation takes place at the operation of a DPF with deuterium (DD) as in our case of PF-1000 or deuterium-tritium (DT) mixture used for the filling of its chamber as a working gas under the initial pressure of a few Torr.

Energy $E_c$, stored in capacitors for a subsequent release to the discharge, occupies a range from just a few Joules [2] to about 1 Mega Joule (MJ) [1b, c, d, e, f, g]. The main interest to the installation on its highest energy level operation is connected with a favorable scaling law for neutron production yield -- $Y_n \sim E_c^2$ or $Y_n \approx 10^{10} I_p^4$ (sometimes $Y_n \sim I^5$ [1], in particular for the same device [2e]). The scaling type is valid for deuterium as a working gas, where $I$ is a discharge current, and $I_p$ is the part of a total current, which flows through the dense plasma pinch, measured in MA. The operation of a DPF with the deuterium-tritium mixture produces an increase in the neutron yield by a factor of circa 100 [3]. This means that on a level of a 10-MA current a DPF might produce the same neutron yield as modern pulsed fission reactors differing from them however by much shorter neutron pulse duration – few hundreds of ns – and by almost monochromatic spectrum centered near 14 MeV. This would open opportunities for many applications in science (e.g. in neutron spectrometry due to a
very high “quality” of the source, \( q \geq 10^{37} \) [neutrons per second\(^3\)] and technology (e.g. in radiation material sciences – see part I).

As it was shown in many publications (see first of all [4] and also the references in [1]) the major mechanism responsible for neutron emission in DPF is the interaction of deuterons of “medium” energy (50-150 keV) with a “target” (pinch), which is a hot (\( \leq 1 \) keV) and relatively dense (\( \leq 10^{19} \) cm\(^{-3}\)) plasma (so-called “Gyrating Particle Model” – GRM). Here the term “medium energy” we use for the ion energy of a magnitude well above the thermal one for ions of the pinched plasma (\( \sim 1 \) keV) but much lower than the upper limit of the accelerated deuterons registered (\( \sim \) a few MeV). Larmor radius of these medium-energy deuterons in the magnetic field of the pinch is much less compared with the size of the pinch itself thus providing an opportunity to entrap them for a period longer than a simple direct fly-out time.

Part I presented our recent results taken during the investigation of the PF-1000 facility on the energy level close to the maximal one (\( \sim 0.85 \) MJ). In that paper we paid special attention to different scenarios of the dynamics of the pinch’s plasma (target) depending on various modes of the device operation. Here we shall concentrate our attention on a generation of charged particle beams and their interaction the above mentioned plasma and with the anode. Conception of the fast particle generation mechanism in DPF has been developed in [2]. It is based on the electron magneto-hydrodynamics (EMH) theory [5] and uses the model of a “virtual plasma diode”, which appears due to anomalous resistivity, sprang up in the pinch and constituted the current abruption phenomenon. Within this diode, at first fast electrons are accelerated towards the anode, and then they are magnetized and substituted by fast ions. Magnitudes of both beams’ currents are of the order of the total discharge current. The ion beam aimed to the direction opposite to the electron stream way – towards the cathode. Processes of interaction of both \( e^- \) and \( i^- \)beams with targets also have non-trivial character, and they were the subject matter of the above cited works. In this paper we shall examine the \( e^- \) and \( i^- \)beams dynamics on the upper level of the DPF energy in its relation to the target evolution (part I) and neutron emission in view of the above-mentioned models. So the issue is whether the same physics are true at an energy level of the device, an order of magnitude higher than at the previously exploited ones.
2. **The apparatus**

The PF-1000 device [6] is the Dense Plasma Focus of the Mather type [1] operating with deuterium as a working gas at the energy level up to 1 MJ. It was designed about 30 years ago and manufactured on the basis of the technology used in those days. However this is the only kind facility of being used at the present time, with which one can investigate mechanisms of neutron generation within a DPF on an MJ energy level.

Yet its neutron yield at the present time is quite far from those deduced from the above-mentioned law of the neutron yield dependence on energy, stored in the bank (it should be on the level of $10^{13}$ neutrons per shot whereas the yield actually is equal to $6 \times 10^{11}$ for the best shot and $2 \times 10^{11}$ for the typical “good” ones as will be seen in this paper). The PF-1000 construction (described in [6] and in part I) consists of the following main units (positioned in three different floors of the IPPLM building):

- Condenser bank, coaxial cables and a collector of a diameter 3 m (Fig. 1 a and the left-hand side of the Fig. 1 b), charger and pulsed electrical circuit with high-pressure spark-gaps,
- Vacuum chamber (Fig. 1 b) with coaxial electrodes of the Mather-type geometry [1] (see also Fig. 2 of part I) and vacuum/gas handling systems.

Fig. 1 PF-1000 – current collector with cables (a) and vacuum chamber with the collector (b)
Cylindrical copper anode ($\varnothing = 230$ mm, $l = 600$ mm) is closed by a lid, having the same, or slightly larger diameter, i.e. a circular hat-shaped “cap” on its end. If the anode had this cap of larger diameter, it represented an obstacle for a PCS, which will be bifurcated into two parts (see part I). Two modifications of cathode electrode geometry of a squirrel cage type differing essentially by their inter-electrode gaps, as well as by lengths and shape of rods were used in this set of experiments. The cathode stainless-steel bars were much longer than the anode in the first case whereas both electrodes are equal by length in the second configuration. Their modes of operation, resulting mainly in different MHD plasma dynamics, are also discussed in part I.

Alumina insulator envelops the anode at its lower part. Its main fraction is extended by 113 mm along the anode into the vacuum chamber. The condenser bank of total capacitance 1320 $\mu$F (264 capacitors of 5 $\mu$F capacitance and 40 nHn inductance each) was charged in these experiments to the voltage $U_0$ ranging between 27 to 36 kV. It corresponds to discharge energies $E_c$ within the limits from 480 kJ through 850 kJ. Usually its energy and voltage were equal to 810 kJ and 35 kV respectively. The energy increase in this set of experiments with PF-1000 compared with previous ones (see e.g. [7]) was made by the bank capacitance increase (not by the voltage change as in many previous experiments made in Frascati, Stuttgart and Düsseldorf). And as usual the electrodes’ sizes were increased in comparison with previous experiments to match the external and internal inductances of the gun and to equalize the current quarter of the period with the plasma collapse time at this energy magnitude. Typical oscilloscope traces of current and voltage taken at the charging voltage of the battery equal to 27 kV are presented in Fig. 2 a and b correspondingly. They look similar in all cases of electrodes geometries.

![Fig. 2 Current (a) and voltage (b) waveforms of the PF-1000 taken at $U_0 = 27$ kV](image-url)
3. **Experimental arrangement**

To study the MHD evolution of plasma a *streak* camera with a slit parallel to the anode surface and a three/four *frame optical* camera with exposure time of about 1 ns were employed (see their description in part I). Two types of the three/four *frame soft X-Ray* cameras – one based on an open microchannel plate (MCP) device in conjunction with a pin-hole camera and another just time-integrated pin-hole camera with an X-Ray film registration – have been applied in order to obtain plasma images in soft X-Ray (SXR) range (see details in part I).

Fast electron beams generated in the DPF were investigated registering Hard X-Ray (HXR) radiation produced by them on the anode. This was done with the help of photomultiplier (PM) tubes plus scintillators (PM+S). These beams were also registered directly by means of Cerenkov-type detectors (Fig. 3) positioned down-stream *in a relation to the principal e-beam direction of propagation* (i.e. at the back side of the anode). These detectors were composed of rutile crystals covered with Cu foils of different thicknesses, and they were coupled with fast photomultipliers through optical cables. Energy of fast electrons, which can be registered by this method are: without filters – >35 keV, with foils either above 80 keV or above 120 keV. Signals from them were observed with a fast oscilloscope in correlation with signals from other diagnostic tools.

![Fig. 3 Cerenkov detectors](image)

In order to define the emission characteristics of fast ions (deuterons) in relation to the neutron production process (i.e. ion fluxes, ion angular distributions, ion source location etc.) direct ion measurements of fast deuteron beams have been performed within the PF-1000 device. An angular distribution of fast deuterons has been measured with nuclear track detectors (of the PM-355 type), placed at a distance of 550 mm from the inner electrode. The
semi ring, where the number of the ion tracks detectors is located, can be seen in Fig. 4. Each of these detector samples was covered with different Al-foil filters. Ions have been registered at various angles to the electrode axis. To investigate a spatial distribution of fast ions and their trajectories beyond the pinch, the miniature ion pinhole cameras have been used. They were positioned at a number of angles to the anode’s axis. Those cameras were also equipped with the same nuclear track detectors. In order to estimate the energy of the observed deuterons, the detector samples were shielded with Al-foils of different thickness. Some temporal and spatial characteristics of the ion beam and its dynamics have been received by means of optical multi-frame camera.

![Image](image.png)

**Fig. 4 Scheme of track detectors mounting**

Time-resolved SXR signals were measured by means of PIN diodes covered with different filters and by PM tubes also shielded by different foils. Signals from these two types of SXR measuring techniques were compared with other oscilloscope traces (voltage waveforms, dI/dt signals, Cerenkov-detector signals, and neutron/hard X-Ray pulses) in order to determine their cross correlation. The SXR signal detected by the PIN diodes was also used for synchronization purposes and the determination of the temporal relation between the maximum of SXR radiation of the plasma and the frame images recorded by means of optical and X-Ray diagnostics. Special electrical and optical synchronization arrangements allowed synchronizing the optical diagnostics and other DPF time-resolved diagnostics with a precision of 5 ns.

We investigated the neutron production process by measuring its time evolution, absolute neutron yield and its anisotropy on the basis of both time-integrated methods and
time-resolved registration of neutron pulses at different angles to the electrode axis, as well as by their comparison with time-resolved and time-integrated measurements of the soft, hard X-Ray radiation and the fast electron and ion beams. Total neutron yield \( Y_{\text{tot}} \), i.e. the number of neutrons produced during a single discharge ("shot") and emitted in various directions, was measured taking into consideration the data received by means of five silver-activation counters (SC) placed at equal distances (3.396 m) in the head-on direction for ions propagation, i.e. in the direction of Z-axis (SC4) as well as at different angles to it (30°, 60°, 90°, and 150° for SC1, SC2, SC3, and SC5 respectively) around the PF-1000 experimental chamber (Fig. 5).

![Fig. 5 Electrodes set-up showing also the positions of the neutron activation counters (SC) and the fast probe (photomultiplier + scintillator) detectors (SPD) in relation to Z-axis of the facility](image)

Independently these measurements were verified by the use of indium-activated counters and so-called “bubble detectors”. Calibration of all detector types was made simultaneously by placing the AmBe isotope neutron source inside the DPF chamber in the position of the plasma pinch. Three scintillation-photomultiplier detectors (SPD), located at different angles (all of them in a 7-m distance from the electrode outlet), were used to perform time-resolved measurements of the HXR radiation and N emission with their pulses being separated on the oscilloscope traces due to the corresponding time of flight.
4. Experimental results

Our main series of observations at the PF-1000 facility devoted to the beam generation investigation were carried out in the operational regime with the deuterium pressure $\approx 2 \div 4$ Torr and with a discharge energy 810 kJ. In these series the chamber had long cathode rods. The anode’s cylinder was smooth and even with its flush-mounted head (i.e. without a protrusion).

The obtained results, in relation to the discharge current, can be summarized as follows:

1. Amplitude of the total discharge current measured by Rogowski coil, positioned in close vicinity to the cathode rods inside the DPF chamber, in typical discharges was 2.5-2.6 MA being sometimes close to 3 MA for the best DPF shots. However, it is much less than the expected one for such an energy of the bank according to the following experimental scaling law valid for DPF devices within the above-mentioned energy range (increasing a bank, one has to pay attention that an inductance magnitude will be decreased not simply linearly with the number of capacitors, but in a root-square dependence on them because of cables’ length and adding of pre-collectors [2]):

$$I_{tot} \approx U_0 \times (N)^{1/2} \times (C/L)^{1/2} \approx 3.3 \times 10^4 \times 16.3 \times (C [\mu F]/L [\text{Hn}])^{1/2} \approx 6.0 \text{ MA} \quad (1)$$

where $U_0 = 33$ kV – initial charging voltage of the bank, $N = 264$ – a number of capacitors constituting the bank, $C = 5 \mu F$ and $L = 40 \text{ nHn}$ – are capacitance and inductance of a single capacitor of the bank. Unfortunately any attempts to increase this magnitude by a maximization game with initial pressure and charging voltage of the device were not crowned with success.

2. No any attempts to measure the pinch current $I_p$ were made during these experiments, i.e. there are no experimental data on the part of the total current flow actually through the dense plasma column (see part I). However, substitution the total measured current value into the neutron scaling law gives the following figure expected of the PF-1000 operation:

$$Y_n = 10^{10} \times I_{tot}^4 = 10^{10} \times (3 \text{ [MA]})^4 = 8.1 \times 10^{11} \quad (2)$$
that is, only 35% more than the best experimental magnitude, and 4 times more than the mean one. The latter result signifies that the estimated *average pinch current* was about 1.4 times less compared with the total one. This is a reasonable value: \( I_p \cong 2 \text{ MA} \), which is consistent with the data known from literature [1] and deduced from the other results in part I.

3. Plasma dynamics was investigated in part I. Here we present four frame-by-frame pictures taken in a visible range in one shot (Fig. 6). They demonstrate a plasma pinch formation (“first compression” – (1), (2)), a filament creation (3), i.e. a process of free-streaming of run-away electrons along the Z-axis in its opposite direction, and a start of MHD perturbation of the boundary of a pinch (4). Exposure time – 1 ns, time intervals between frames ~ 10…20 ns.

![Fig. 6 Time sequence of plasma compression stages](image)

4. A diagram of the angular distribution of neutron emission is presented in Fig. 7. It was measured by the above-mentioned 5 silver activation counters for the shot No. 3121 produced at the initial pressure of 465 Pa and charging voltage 35 kV (thus the total energy in the bank was about 0.810 MJ). One can see that at these conditions the anisotropy of the emission measured in the laboratory coordinate frame has a so-called “normal” character (i.e. it is characterized by a preferential direction of neutron irradiation at 0° to Z-axis) and its magnitudes are equal to circa 1.8 for the ratio \( Y_{0^\circ}/Y_{90^\circ} \) and to \( \cong 0.65 \) for the ratio \( Y_{180^\circ}/Y_{90^\circ} \).

![Fig. 7 Angular distribution of the PF-1000 neutron yield](image)
5. At these conditions the total neutron emission yield calculated by integrating the data over all 5 silver counters was of the order of \(5 \cdot 10^{10} \ldots 2 \cdot 10^{11}\) neutron/shot with the maximum neutron yield of \(6 \cdot 10^{11}\) neutron/shot measured by silver and supported by indium activation counters. Bubble detectors (positioned only at the angle of 90° in these experiments) gave us, in these discharges, 30% less value.

6. Two neutron pulses were observed in most cases. The second pulse was higher by amplitude from four through ten times compared with the first one (Fig. 8). Durations of each pulse (FWHM) as well as the interval between them at their registration in the “head-on” direction were circa 150 ns (except the case of a “cusp geometry” – see part I). Comparing with smaller devices the first pulse is relatively much larger (usually it was 1 through 5% of the second one in small DPF whereas here it is 10…25%) and they both have larger longevity (thus in the range of the DPF bank energy from 0.1 through 800.0 kJ the neutron pulse duration increases from 4-5 ns till 150 ns, i.e. it is roughly proportional to the current value).

Fig. 8 Hard X-Ray pulses (a and c) versus neutron pulses (b and d) taken at 0° and 90° to Z-axis after moving them forward according to their real (HXR) and assumed (N) time-of-flight
However one can see the difference in neutron pulse shape (and their duration) for two dissimilar directions of investigation. Namely at the 90°-observation (“side-on”) both two pulses are longer and look smoother compared with the “head-on” measurements (0°).

It should be mentioned here that the data in Figs. 7 and 8 have a rather rude character. Indeed the environment, walls, columns, ceiling and floor, made by concrete, elements of the DPF construction and capacitors of the main bank in particular, are positioned in distances of 1.5 through 10 meters apart from the chamber or from the counters. It means that the time of flight of primary scattered streams of 2.45-MeV neutrons along the paths from these elements till the counters (1.5…30 m) is circa 75…1,000 ns that makes the absolute measurements position-dependent and problematic. Moreover our analysis has shown inequality of the two directions. Viz. PM tube situated in Z-direction has almost nothing in the hall for single-reflected neutrons to it (a hatch beneath the chamber as well as a door and a window behind the detector are wide) whereas the side-on PM tube has a wall and columns just near it. These “obstacles” scatter neutrons and thus give additional primary streams onto the scintillators. Taking into consideration the particular time of flight of scattered neutrons it should be admitted that the real shapes of the neutron pulses are distorted especially after their maxima (i.e. in their “tails”). However it is evident that such an environment cannot influence a position of the N-pulse summit in both cases. That is why the rise-time of pulses in both directions is almost similar (see Fig. 8) whereas the pulse decay time is much longer at the side-on observation.

At the same time our activation counters summarize the total yield over a long period (1 min) (Fig. 7). So they are irradiated by repeatedly scattered neutron streams (low-intensity but long-lasting radiation). That is why the data on the neutron yield anisotropy seem to be exaggerated in the normal direction to the Z-axis.

In any case these results gave us an important and correct qualitatively as well as some quantitative information. In future they have to be verified by a computer simulation of the neutron field evolution in this particular environment, which would give a possibility of better interpretation of the numerical results received in such an experiment.

7. As we mentioned in part I it was found that for each value \( p_0 \) of an initial filling pressure there is an optimal charging voltage \( U_0 \), which ensures the maximal neutron yield \( Y_n \). Thus the initial pressure increase produced in parallel with the charging voltage rise during the operation of the facility (provided that for each initial pressure we used the above
optimal initial charging voltage) resulted in a further increase of neutron yield. No saturation in neutron yield was found at this strategy till 4 Torr and 35 kV.

8. HXR and neutron signals presented in Fig. 8 are essentially the same as given in Fig. 9 of part I. But in this case we have moved forward both HXR pulses of each oscilloscope traces (a, 0° and c, 90°) by their time-of-flight (TOF) at the 7-m distance (23.3 ns). At the same time for both neutron emission pulses we’ve done the same procedure for their TOF (b, 0° and d, 90°) as if these neutron pulses consist exactly of 2.45-MeV neutrons, namely by 323 ns. It is clearly seen that the first pulses of both HXR and N emissions almost coincide in both cases (0° and 90°) after their correction by TOF. This means that in the PF-1000 device runaway electrons are accelerated during or slightly earlier in comparison with a so-called first compression phase as in other devices [2], and neutron emission produced during this period of time (i.e. in the first pulse) has an energy spectrum centered at 2.45 MeV.

On the contrary, second N pulses in the two directions start and have their peaks at later moments compared with the second HXR pulses. Namely, they have their maximal value during a decay time (droop) of the HXR pulses. Moreover the second pulse maximum in the head-on case comes earlier than those in the side-on case and “runs over” the HXR pulse. It means (and we might expect it from our anisotropy measurement and literature) that the spectrum of neutrons irradiated at 0° has higher energy than the neutrons propagating at 90°. Comparing these data with Fig. 7 one can really see that with the angle variation higher neutron yield corresponds to higher energy of neutrons. It supports results usually being received in smaller devices. We shall discuss it in more details later in correlation with other diagnostics data.

Two special features of these oscilloscope traces in correlation with frame pictures and with fast particle and neutron generation mechanisms are:

1) The start moment of the second pulse of the hard X-Rays (t = 0) being very sharp (in fact it is out of temporal resolution of our diagnostics) precisely coincides with the appearance of the disruption at plasma column as it was described above. It is seen in Fig. 6 (4) and is shown in Fig. 9 by a “↔”-mark. The sequence of pictures shows the column break with plasma streaming along the circumference and having a meniscus shape (see discussion of this phenomenon later in this paper). Pictures are taken for the anode with an obstacle and short cathode rods – see part I.

2) Second neutron pulse starting at the same time or a bit later compared with the second HXR pulse reaches its peak when HXR pulse is over already.
1. \( t_1 = +5 \text{ ns} \)
2. \( t_2 = +15 \text{ ns} \)
3. \( t_3 = +35 \text{ ns} \)
4. \( t_4 = +87 \text{ ns} \)

Fig. 9 Experimental images of the current cutoff phenomenon (marked by a sign: “↔”) taken by the optical image camera with 1-ns time resolution.

Fig. 10 Typical set of registered signals illustrating correlation of various signals versus temporal evolution of neutron emission with its anisotropy data.

9. The group of traces (Fig. 10) taken in a single shot with the whole set of diagnostics presents examples of typical waveforms displaying from top to bottom: a) hard X-rays from PMT (8 – 30 keV), b) soft X-rays from PMT (3 – 8 keV), c) soft X-rays from PIN diode (0.8 – 4 keV), d) fast electrons from Cerenkov detectors, e) the Rogowski \( \frac{dI}{dt} \) signal, and finally neutrons plus very hard X-Rays (> 80 keV) taken at \( 90^\circ \) (f) and \( 0^\circ \) (g) by PM tubes + scintillators.
All traces are moved according to the time of flight of the corresponding type of radiation, as well as the delay times of related detecting systems (dead time of PM tubes, cables, oscilloscopes, etc.) except neutron pulses which moved with their HXR pulses synchronously (i.e. by TOF of HXR).

From these traces, in correlation with Figs. 6 and 9, one can observe the following features:

a) Soft X-Ray pulses from PMT practically coincide with the same from PIN diodes (b, c) and with maximal plasma compression.

b) Hard X-Rays (a) in the range 8 – 30 keV (presumably produced by run-aways) reflects correctly fast electron signals (d) taken by Cerenkov detectors (pulses 1, 2, and 3) with one exception: the first and most intense pulse from Cerenkov detectors does not correlate with the above HXR trace; probably it is related to HXR of higher energy than the range 8…30 keV, because it is correlated with the beginning of the very hard X-Rays seen on the two bottom traces.

c) 1-st maximum of the neutron signal $Y(t)$ (f, g) appears 323 ns after SXR pulse maximum (PIN, PMT); this time interval is exactly equal to the time-of-flight of 2.45 MeV neutrons from the pinch to the PMT; these maxima of both first neutron pulses delayed by 323 ns practically coincide with their first HXR maxima, and it is so for both ($0^\circ$ and $90^\circ$) directions again as for the shot reflected in Fig. 8; synchronization with Fig. 6 gives that the 1-st neutron pulse coincides with maximal plasma compression and heating of at least its electron component.

d) The second maxima of the neutron signals registered in both directions correlates with the second, relatively small SXR pulse as well as with the hard X-Ray signals and the electron beam pulse. And again, as in the case of Fig. 8, the side-on N pulse is late to the start of its HXR pulse by 323 ns. However the head-on N pulse delayed only by 300 ns in relation to the moment when the side-on pulse appears inside the chamber; it means that the head-on neutrons have higher energy. Thus if one moves this head-on pulse to its real place on the trace (the start should coincide with the start of the N pulse seen at $0^\circ$) it should be delayed by 23 ns in comparison with the side-on N pulse. After this procedure one can see that both second N pulses registered in two directions ($0^\circ$ and $90^\circ$) start with the beginning of HXR pulses, as in Fig. 8. Again, as in Fig. 8, both second pulses reach their maxima at the decay of their HXR pulses.
10. The samples of nuclear track detectors were irradiated by fast deuterons emitted from a single PF-1000 shot, the same as in Fig. 10. After the irradiation these samples were etched under standard conditions and scanned with an optical microscope. The optical analysis has shown the ion crater densities ranging from $10^3$ – $10^5$ craters/mm$^2$ with this number increased to the Z-axis up to a saturation level. To understand the results received we have to take into account the energy losses of D$^+$-ions in Al foils (D$^+$-ions of energy > 250 keV can penetrate through about 1.5-µm Al-foil, and 500-keV ions – through 4-µm Al-foil), and the detection characteristics of the used detector [8, 9]. Thus one could estimate that the uncovered detector samples recorded D$^+$-ions of energy above 80 keV, samples covered with 1.5 µ-Al foil registered D$^+$-ions more energetic than 330 keV, and samples masked with 4 µ-Al foil revealed tracks of ions of energy > 580 keV. It was, however, observed that this fast ion emission is not reproducible from shot to shot (at least less reproducible than the neutron yield), but its absolute yield as usual decreases with an increase in the filling pressure. Angular distributions of primary deuterons, having different energy and obtained in the above-mentioned shot, are presented in Fig. 11. In fact the area of our track detector near Z-axis was damaged in spite of its distant position from the pinch.

Fig. 11 Angular distributions of fast deuterons deduced from track detectors samples subjected by direct ion irradiation

11. Our miniature ion pin-hole cameras have shown the tracks distribution as presented in Fig. 12. It is clearly seen that the image ("autograph" of the fast ion beam) has a tubular structure with an additional very bright maximum on the Z-axis.

12. In the frame pictures (see Fig. 13) taken in visible range with a 1-ns time resolution we found some structure within a zone above the pinch (on the right-hand side of the frames b and c) which looked very correlative with the above Fig. 12. This tubular-conical formation
with a central stem (also of a conical shape) appears always after the pinching period. (The pinching process is always accompanied by a characteristic hemispherical shock wave – see Fig. 13a).

![Image of tracks and shock wave](image)

Fig. 12 Spatial distribution of tracks received by 3 ion’s pin-hole cameras placed at different angles to the Z-axis of the chamber.

![Image of 1-ns frame pictures](image)

Fig. 13 1-ns frame pictures taken in visible range for 3 different shots and demonstrating a shock wave produced by a cumulative stream during the plasma pinching (a) and an ion beam structure as it appears after the current abruption phenomenon (b) and (c).

These structures become visible right after the moment of current abruption. They changed from shot to shot by cone angle (e.g. the half-angle on the picture b is 20° whereas on c it is about 35°) and by their transverse “layers” (bright discs). E.g. in both pictures the thickness of these discs are less than 3 mm. But in the picture b one may see just two of them.
separated by a distance of 10 mm whereas in picture c there are three discs with distances between them of 5 and 8 mm from left to right respectively.

5. Discussion

In part I we presented results on the main parameters of pinch’s plasma measurements as well as on their evolution during the period of generation of hard radiations. If the Gyrating Particle Model [4] is valid this pinch is presumably a target, which would be irradiated by fast ion beam generated within a DPF after current abruption phenomenon. The Bennett equation being possibly correct during the period of plasma confinement time (so-called “first compression”) can help in the estimation of plasma density during the first neutron pulse (see part I): \(0.8 \times 10^{19} \text{ cm}^{-3}\). Pinch radius also determines the maximum value of the azimuth magnetic field at the pinch’s border:

\[
B_{\text{max}} = 0.2 \frac{I}{r^2} = 2 \text{ MG}
\]

(3)

where \(I = 2 \text{ MA}\) and \(r = 0.45 \text{ cm}\). This means that Larmor radii of fast (100 keV) electrons and deuterons, widely presented in the discharge, are accordingly [10]:

\[
r_{\text{Be}} \geq 3.37(W_\perp)^{1/2}/B_\phi \quad \text{and} \quad r_{\text{Bd}} \geq 204(W_\perp)^{1/2}/B_\phi
\]

(4)

where transverse energy \(W_\perp\) is in eV, \(B_\phi\) is in Gauss, and \(r\) is in cm. It gives estimations for the minimal values of \(r_{\text{Be}} \geq 5 \times 10^{-4} \text{ cm}\) and of \(r_{\text{Bd}} \geq 3 \times 10^{-2} \text{ cm}\). They both appear to be much less than the pinch diameter. As for the compressed \(B_z\) component being of the order of \(10^5\) Gauss (see part I), these values are correspondingly 100 \(\mu\text{m}\) and 0.6 cm.

As it was found in part I the pinch’s column during the first neutron pulse is straight and has a height of 10 cm with a radius of \(~0.45\text{ cm}\). Later on this plasma column is widened and disturbed by instabilities. All pinch’s parameters start to fall down with the characteristic time of the order of the above plasma confinement time (\(~150\text{ ns}\)). As it was shown in part I the coefficient of the pinch longevity is 10 to 15 times larger in comparison with the ideal MHD confinement time. And as a consequence its effective expansion velocity \(v_{\text{exp}}\) is also 10 to 15 times lower compared with the implosion one \(v_{\text{im}}\), i.e. \(v_{\text{exp}} \leq 0.5 \times 10^7 \text{ cm/s}\). It is supported
by the frame-by-frame pictures showing that to the moment of the maximum of the second neutron pulse the radius of the pinch is 1 cm.

Strong perturbations of plasma sheath surface can be found after the confinement period in all frame images of it. The pinch breaks usually in two (or sometimes several) cylinder regions along the column. It looks like a fast penetration (emission) of plasma into the surrounding magnetic field at the periphery of the pinch in the form of a meniscus, i.e. a disk centered in a certain point on the pinch axis and slightly concaved up to the cathode. For a pinch column it gives the impression to be like a gap creation, which “breaks” the column in a transverse direction to its length. Examples are shown both in Figs. 9 and 13 of this paper and in some pictures of part I, but in particular in the pictures 7d and 14 of part I. It is seen that plasma does not push away (disappear) from this gap, but becomes of a lower density compared with the adjacent parts of the pinch above and below this “gap”. A typical size of this zone along Z-axis (the gap’s width) seen in the pictures is circa a mm, which is much larger than the electron Larmor radius, but it is comparable with the ion one for the $B_\phi$ field, which is becoming lower than its above-mentioned maximum during the process of its diffusion into pinch’s plasma (see equation (4)).

We shall start our discussions concerning fusion events taking place in PF-1000 with estimations of a possibility of thermonuclear mechanism for neutron generation during first and second pulses. We shall assume that the first pulse is produced by a compression of fast moving ($3.5 \cdot 10^7$ cm/s) plasma-current sheath (PCS) with transformation of the energy of its direct movement (quasi-cylinder shock wave) into heat with additional subsequent adiabatic compression (temperature increase factor is about 1.4 [11]). As for the second neutron pulse we shall propose at first that it is generated by the second subsequent plasma compression.

Taking into consideration plasma parameters during the first period of the plasma confinement (see part I) – its ion density $n_i \approx 0.8 \cdot 10^{19}$ cm$^{-3}$, ion temperature $T_i \approx 1.3$ keV, pinch dimensions $R_p \approx 0.45$ cm and $h_p \approx 10$ cm, and pinch longevity $\tau \approx 1.5 \cdot 10^{-7}$ s, we have [10]:

$$Y = \left(\frac{n_i^2}{4}\right) <\sigma \nu>_{DD} \pi R_p^2 h_p \tau \approx 1.5 \cdot 10^{10} \text{ n/pulse}$$

(5)

This amount is 10 times less than the total neutron yield of the device ($1-2 \cdot 10^{11}$ n/pulse), and it coincides with the results of measurements made by PM tubes (Figs. 8 and 10).
As for the more hypothetical “second compression” (see e.g. at Fig. 9 the 4-th frame taken at the moment \( t = +87 \text{ ns} \); the picture looks as it should for this event being however 100 ns earlier than one can expect according to the second neutron pulse maximum) we have nevertheless to substitute figures really seen for the moment of the 2-nd neutron pulse maximum \((t \cong +180 \text{ ns})\): for the pinch radius \( R_p \cong 1 \text{ cm}, \) ion density \( n_i \cong 2 \cdot 10^{18} \text{ cm}^{-3} \) (calculated due to pinch radius change) with other parameters having the same value. In this case in order to receive from formula (5) an experimentally measured real neutron yield \( 2 \cdot 10^{11} \text{ n/pulse} \) we have to assume that the ion temperature during this interval of time should be increased to the level of \( T_{i,e} \cong 4 \text{ keV}. \)

The most doubtable data in both cases are ion temperatures, which were not measured here directly (and haven’t been reliably measured even in all previous experiments). Let’s check a possibility of existence of these temperatures in our real situation. We can estimate the mean-free path of ions in our plasmas by using the following equation [12]:

\[
l_{ii} = 3 \cdot 10^{18} \frac{T_i^2}{n_i} \tag{6}
\]

where \( l_{ii} \) in cm, \( T_i \) in keV and \( n_i \) in \( \text{cm}^{-3} \). The results are shown in Table 1.

<table>
<thead>
<tr>
<th>No. of neutron pulse</th>
<th>Time of pulse maximum ns</th>
<th>( T_{i,e} ) keV</th>
<th>( n_i ) ( \text{cm}^{-3} )</th>
<th>( R_p ) cm</th>
<th>( h_p ) cm</th>
<th>( l_{ii} ) cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.3</td>
<td>( 8 \cdot 10^{18} )</td>
<td>0.45</td>
<td>10</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>+180</td>
<td>4</td>
<td>( 2 \cdot 10^{18} )</td>
<td>1</td>
<td>10</td>
<td>24</td>
</tr>
</tbody>
</table>

It’s clearly seen that if for the first compression the mean-free path of ions is less compared with the pinch’s dimensions, plasma of the “second one” should be collisionless.

Estimations of the characteristic collision rates can be made using equations [12, 13]:

\[
\nu_e = 2.9 \times 10^{-6} n \lambda T_e^{-3/2} \tag{7}
\]
\[
\nu_i = 3.4 \times 10^{-8} n \lambda T_i^{-3/2} \tag{8}
\]

These estimations have supported the above conclusion: for the first compression stage equilibrium for electrons and for ions is established during less than 0.2 ns and 20 ns correspondingly, which is short compared with the duration of this phase (150 ns). Time to
achieve thermal equilibrium between ions and electrons (here we have presumably ion heating by SW and adiabatic compression) would be by \((m_i/m_e)^{1/2} \approx 60\) times longer. It would mean that even here electrons might not have enough time to reach the level of ion temperature. On the contrary, the above time intervals for the hypothetical “second compression” (20 ns and 2 \(\mu\)s for electrons and ions separately and even larger for their mutual equilibrium) are substantially longer than the duration of the second neutron pulse.

One can now see that the first pulse can be explained in principle on the base of the shock wave/adiabatic plasma compression and heating. Conversely for an explanation of a generation mechanism of the second neutron pulse we have to attract other ideas.

According to our analysis of the data received here we have an evidence of the virtual plasma diode creation at the PF-1000 facility. That is we have here the same phenomena, which was investigated in the FLORA device [2, 11] and proved in those experiments by almost the same set of diagnostics as here but additionally supported there by a 1-ns multi-frame laser interferometry.

Indeed to the moment of the current maximum the main part of electric energy accumulated previously in the bank is concentrated as magnetic energy near the pinch column, i.e. in the “plasma inductive storage”. Then we have an abruption of current and a formation of a plasma diode on the pinch. The effects in the diode have an evolution following the scenario (compare experimental sequence of frames at Fig. 9 presented in a lower part of the double-pinch structure – see part I – with schematic drawing of Fig. 14a made for this lower pinch and with the Fig. 14b, where the region of the EMH effects [5] is shown in an enlarged scale):

1. Rayleigh-Taylor instability development on the surface of the pinch (with an increment of the unstable state development of the order of \(10^8\) s\(^{-1}\)).

2. Formation in a certain pinch region along a perimeter of the pinch column (above plasma neck, but below plasma widening – i.e. in a region shown by a symbol “\(\leftrightarrow\)”) of the right-hand-triple of vectors \(\{H_\phi, \text{grad } n, V_h\}\), where the vector \(H_\phi\) – an azimuth magnetic field of current, \(\text{grad } n\) – a plasma density gradient, and \(V_h\) – a vector of the magnetic field penetration direction.

3. Fast increase of anomalous resistivity \(R_{an}\) in this ring-like region of a skin-layer because of a number of micro-instabilities (with their increments of the order of \(10^{13...11}\) s\(^{-1}\)) provoked by the EMH field effects, which resulted in plasma disk-like release in the outwards from the pinch (practically with the gas-dynamic velocity of the penetration into the “confining”
magnetic field $H_\phi$) as well as in the fast *meniscus-like convective penetration of the magnetic field* into plasma (anomalous resistivity $R_{an}$ can be deduced from the electro-technical measurements of current and voltage across the pinch column and also evaluated from EMH theory [5]).

![Model pictures of the plasma diode evolution](image)

Fig. 14 Model pictures of the plasma diode evolution a) and b) based on [2, 5, 11]

4. **Current cutoff** within the skin-layer due to $R_{an}$ followed by an induction of a high vortex electric field $E_{ind}$ according to the Maxwell’s equation: $\partial H/\partial t \sim \text{rot } E_{ind}$ inside the gap of the magnetic field penetration; thus this process forms a virtual “plasma diode” with the “anode” width of the order of pinch diameter and the “anode-cathode” separation determined by a subsequent process of the $e$-beam formation based on a parapotential model [13, 14], which permits to carry, through the gap, the $e$-beam $I_b$ of circa the same current magnitude as the previous collisional current $I_c$:

$$I_b \approx 8500 \beta \gamma r/d [A] \approx I_c \quad (9)$$
where $\beta$ and $\gamma$ are relativistic factors, $r/d$ – a so-called aspect ratio, i.e. a ratio of radius of the diode $r \approx r_p$ to the distance $d$ between virtual anode and cathode, $I_b$ and $I_c$ are in Amperes.

5. **Acceleration of electrons** by the above field ($E_{ind} \sim (\Delta H/\Delta t) \times d$), generated during the cutoff process, where $\Delta H \sim 0.2I_p/r_p$, $\Delta t$ is the current’s cutoff time ruled by increments of micro-instabilities and measured by a rise-time of the second HXR pulse, and $d$ is the diode separation, defined from equation (5) and estimated from Fig. 9 or from Figs. 7d and 14a of part I.

6. **Self-focusing of the e-beam** inside the pinch and the propagating of it right up to the anode (see, in Fig. 9, images related to the moment $t_1 = +5$ ns and $t_2 = +15$ ns and the schematic drawing in Figure 14a in a sequence 1, 2, 3).

7. **Interaction of fast electrons** with the anode surface, resulted in production of hard X-Rays and vapors of anode material glowing in visible and SXR range (Fig. 9, frames 2 and 3).

8. **Magnetizing of the fast electrons** after penetration of magnetic field up to the center of the virtual diode; it descends from the fact that the Larmor radius of electrons is short compared with the diode gap $d$ – see disappearance of the filament luminescence between the diode and the anode in Fig. 9 ($t_3 = +35$ ns and $t_4 = +87$ ns) and the corresponding explanation in Fig. 14a,b.

9. **Substitution of the e-beam by i-beam**, taking place *simultaneously* with the above process; it becomes possible because the Larmor radius of the accelerated ions is larger than $d$; the currents of fast electron and ion beams carry approximately the total pinch current $I_p$ during the time interval $\tau$, for the period of which the plasma inductive storage releases its magnetic energy onto an anomalous resistivity of the virtual diode:

$$\tau = \frac{L_{int}}{R_{an}}$$  \hfill (10)

where $L_{int}$ is the internal inductance of the discharge chamber (probably with some part of the external one related to the part of the electrical circuit adjoining to the DPF chamber).

Later on those parts of the fast ions, which were accelerated to the *medium* energy (i.e. to the energy, at which their Larmor radius in the magnetic field inside the pinch is of the order, or less, compared with the pinch radius), should be magnetized. It takes place mainly above the virtual diode gap, i.e. inside the upper part of the pinch [2]. They gyrate during time interval determined by their confinement time, which could be, in principle, longer than
that given by (10) and even longer than the plasma diode existence time. During this confinement time of fast ions they interact with the pinch plasma (“hot target”) [2, 3].

To “fill” the whole pinch volume by these medium-energy ions, to confine them there and to give them a possibility to go eventually away from the pinch we have to suppose an existence of a longitudinal component of magnetic field (along Z-axis) $\mathbf{H}_z$. Its origin, magnitude measurements ($|H_z| \sim 0.1 |\mathbf{H}_\varphi|$), and stabilizing effect on the pinch were discussed in part I (see also the corresponding references there).

Now let’s see how this overall physical picture is reflected in our full-scale experiment at PF-1000 facility fulfilled with a number of different diagnostics and what are the magnitudes of the parameters appearing in the above-mentioned model. In these discussions we shall widely use the results of part I giving us temporal behavior of dense plasma (“pinch”, “target”) parameters.

Let’s examine a possibility of applying to our case the above-mentioned model based on the virtual plasma diode, direct production of neutrons by fast ions, and ion beam heating of pinch’s plasma. First check the validity of the parameters measured here to the model’s variables.

1. Diode geometry

To be in conformity with formula (9), assuming the current of fast electrons (for $E_e \approx 100$ keV, $\beta = 0.62$, $\gamma = 1.28$) of the order of pinch current, we shall have for our virtual diode ($r \approx 0.45$ cm): $d \approx 0.15$ mm, i.e. for 100-keV particles we have to have a vortex field $E \approx 10^7$ V/cm; at the same time by these estimations it is established the validity of the demands on the magnetizing of electrons and free-streaming of ions within this diode (see equations (4)):

$$r_{Be} \sim 5 \cdot 10^{-3} \text{ cm} < d < r_{Bd} \sim 3 \cdot 10^{-2} \text{ cm}$$

2. Current abruptions time

Estimations using the Maxwell equation: $E \approx \nabla \times \mathbf{H} \times \mathbf{H}/\Delta t$ (where dimensions are in V/cm, Gauss, cm and s respectively) gave us for the above $E \approx 10^7$ V/cm: $\Delta t \approx 10^{-11}$ s, which is short compared with resolution time of our PMT channels (pulse rise-time) for the hard X-Ray pulse (the fact supported by experiments) and is of the order of ion-sound instability increment.
3. **Beams existence time**

Now we can estimate the diode impedance: 
\[
R \equiv \frac{U}{I} \cong \frac{10^5}{2 \cdot 10^6} = 5 \cdot 10^{-2} \Omega \quad (U \sim E \times d).
\]
This is a rather poor value – in the best devices the impedance can be up to 0.3...0.5 Ω [1].

According to equation (10) with the inductance of our “plasma magnetic storage” equal to \(\sim 10^{-8} \, \text{H}\) we shall have for the energy release time \(\tau_L\) from the plasma inductive storage:

\[
\tau_L \cong \frac{L_{\text{int}}}{R} = 200 \, \text{ns} \quad (12)
\]

Real time of the ion beam existence should be at least 2 times shorter (ions substitute electrons), i.e. \(\tau_i = 100 \, \text{ns}\). In fact, as it is seen from the oscilloscope traces of Fig. 10, HXR pulse at its FWHM is 50 ns. The same should be evenly right for the ion beam. Thus let’s count \(\tau_i = 50 \, \text{ns}\). It is noticeably shorter than the neutron emission duration in normal regime, and in particular for the case of the “cusp-like” plasma configuration (see part I). Together with the fact of vanishing plasma diode after the moment circa +250 ns in the frame pictures it means that the **confinement time of fast ions** within the plasma cloud is large compared with the diode existence time and in particular with the time of the energy release from the plasma inductive storage.

4. **Energy of the beam**

Now we can estimate the overall energy of the \(e-\) and \(i-\)beams together:

\[
W = I \times U \times \tau \cong 2 \cdot 10^6 \times 10^5 \times 10^{-7} = 20 \, \text{kJ} \quad (13)
\]

It gives the efficiency of the beam generation on the level of about 2.5% from the mains. Taking into consideration figures for the highest beam efficiency reported by the Kurchatov Institute team (20%), the Limeil Laboratory (20%), and the Lebedev Institute team (10%) measured by different methods, the figure received must be considered as a very modest one.

Let’s examine a possibility of the above containment of the fast ion beam inside the pinch. As it was shown the *minimal* ion Larmor radius in the azimuth field is much smaller than the size of the pinch. We can estimate now the *minimal* average magnetic field magnitude (for both \(H_\phi\) and \(H_z\)) inside the pinch provided that the ion Larmor radius is about the pinch radius:
\[ B \geq 204 \left( W_\perp \right)^{1/2}/r_{Bd} \cong 3 \cdot 10^4 \text{ G} \quad (14) \]

It is close to the above estimate. To have a rough figure for the coefficient of the fast ions “magnetization” we must compare their direct-flight time through the pinch’s length \( l_p \) with the duration of the second neutron pulse \( \tau_n \). We shall have for the group of ions having energy \( E_i = 100 \text{ keV} \):

\[
k = \frac{\tau_n}{(l_p/v_i)} = 1.5 \cdot 10^{-7}[\text{s}] / \{10[\text{cm}] / 3 \cdot 10^8[\text{cm/s}]\} = 4.5 \quad (15)
\]

Now we can estimate the concentration of the 100-keV ions inside the pinch during their confinement period provided that the pinch radius is 1 cm, its height is 10 cm, and that all other parameters are the same. Then the length of the fast ion bunch in a free space should be: \( l_b = v_i \times \tau_i = 15 \text{ cm} \); the cross-section of the bunch inside the pinch is 3.14 cm²; the effective volume of the bunch (provided that it is not widened, which is true inside the pinch): \( V_b = l_b \times S_b \cong 50 \text{ cm}^3 \); the full energy in the bunch: \( E_b = 10^4 \text{ J} = 6 \cdot 10^{22} \text{ eV} \); the total number of ions in the bunch: \( N_{tot} = E_b/E_i = 6 \cdot 10^{17} \) particles; the concentration in the bunch: \( N_i = N_{tot} /V_b \cong 5 \cdot 10^{16} \text{ cm}^{-3} \), and taking into consideration the above coefficient of magnetization we shall have the fast ions concentration inside the pinch:

\[
N_i = N_{\theta0} \times k \cong 5 \cdot 10^{16} \text{ cm}^{-3} \quad (16)
\]

According to the track detector measurements (see above) the main part of our fast ions abandoning the pinch is concentrated approximately within the energy range below 200 keV. Unfortunately it is difficult to say how representative this measured part of fast ions is. Viz. the surface covered by fast ions at a distance of about 0.5 m and giving a possibility to investigate these fast ions (if the ion beam preserves its contents within the cone of about 20…30 degrees with a stem of just a few degrees at this distance) should be, in our case, of the order of 0.1 m². I.e. this area could collect, in the unsaturated regime, only the amount of ions \( N \), which escaped the pinch:

\[ N \sim 10^5 [d/mm^2] \times 10^5 [mm^2] \cong 10^{10} \text{ ions} \]

This is about \( 10^8 \) from the overall number of the generated fast ions. Moreover, it seems that our high-current ion beam can exist as a beam only from the rear side (behind) of the SW front, where it can be compensated by an electron back-current inside the cloud of
compressed ionized plasma. After penetrating the SW front (which has gone to about 30 cm from the anode to this moment) and injecting into neutral gas of low density, where the mfp of fast ions is long compared with the geometry the main part of it, the ion beam has to be disintegrated. But even the remaining part of the ion beam will still be of much higher concentration compared to a saturation level of the track detectors. Thus all measured ions are distributed at a distance of 0.55 m from the anode upon the periphery to the near-axis zone in an arbitrary manner. However in spite of the facts described here it is reasonable to suppose that the energy range of our “acting” fast ions (i.e. those ones mainly captured inside the pinch and producing neutrons – not those, which escaped the pinch) falls within the energy spectrum interval circa 10-100 keV.

Neutron spectra, depending on the energy of the fast deuterons $E_d$ bombarding the deuterium gas/plasma target and the angle of their registration $\Theta$, will have a peak at an energy $E_n$, which can be deduced from the equation [16]:

$$E_n = (3.269 [\text{MeV}]) + E_d + 2\sqrt{2(E_nE_d)^{1/2}} \cos \Theta$$  (17)

For $E_d = 0$ and $\Theta = 90^\circ$ we shall have, as well known, $E_n = 2.45$ MeV. At the same time for our data on a side-on spectrum of DPF, which demonstrates the same peak position, it only means that the energy (and velocity) distribution of fast ions is peaked at 0 MeV, i.e. we might have rotations of fast ions in both directions around $Z$-axis – clock-wise and counter-clock-wise – equally possible. It is so in particular because estimations of the probable plasma temperature deduced from the FWHM $\Delta E$ of the spectra in this very direction ($\Delta E = 72.5(T_{pl})^{1/2}$) usually gave us a value about 3-4 keV, which is impossible as we have shown above. However it should be marked that neutron spectral measurements have not been provided in these series of experiments.

The head-on neutron spectra for the energy of fast ions of $E_d = 100$ keV moving along $Z$-axis and producing these neutrons gave us the following data for its peak: $E_n = 2.85$ MeV. It reflects in the anisotropy factor, which is connected with the energy of fast ions (neutron energy spectrum shift) according to the kinematics of the reciprocal fusion reaction [16].

Neutron yield distribution in different directions to the path of the beam of fast deuterons in the case of 100-keV deuterons will look as shown in Fig. 15. Angular distribution of the cross-section in the centre-of inertia system is described by the formula:
\[\sigma(\Theta) = \sigma(\pi/2)(1 + A\cos^2 \Theta)\]  \hspace{1cm} (18)

We compare the data for the experimental coefficient \(A\) measured by many authors in the 50’s and 60’s for different energy ranges of deuterons and in various geometries of experiments and took its value for our case equal to 0.8.

Comparison of the experimental data of Fig. 7 with the computed ones according to equation 17 demonstrates fairly good agreement one with another. One has to take into account that because our chamber has made of steel with thick walls we put our activation counters in positions where its thickness is the same for all directions except 180°. But our estimations have shown that an influence of the materials in this direction (copper anode lid and stainless steel flange) on the neutron penetration is about the same as in all other directions. However the experimental curve has two distinctions: the absence of the yield’s decrease (“neck”, “waist”) on the distribution at 90° and slightly lower values of the yield along the Z-axis (0° and 180°). However if one will take into account rotations of the entrapped fast ions inside the pinch contrary to the parallel beam they both vanish first by disappearance of the distribution valley and subsequently the ratio of yields.

Fig. 15 Theoretical angular distribution of neutron intensity produced in a thin gas target by a low-intensity parallel beam of 100-keV deuterium ions as test particles:

- \(a\) – in a center-of-mass system,
- \(b\) – in a laboratory coordinate frame
We can now estimate two things – direct neutron production by fusion collisions of these magnetized ions with plasma as well as plasma heating because of Coulomb interaction of these fast magnetized ions with the pinch’s plasma.

Let’s examine first a relaxation of the ion beam inside the pinch. We shall be interested whether our ion beam can lose its energy and add it to the bulk plasma in a comparable degree in relation to the pinch’s own energy contents.

It is a well-known fact [12, 13, and 15] that fast ions of energy $E_i$ lose their energy to the bulk plasma via Coulomb collisions with field electrons and/or ions depending on the plasma temperature $T_{pl}$. When $E_i > (m_i / m_e) T_i$ the ions are cooled by Coulomb drag on electrons and undergo little angular scattering. Within the range $T_i < E_i < (m_i / m_e) T_i$ most collisions happen with field ions and strong scattering of ions occur. In our case the above latter energy interval lies in the range between 10 and 400 keV.

We shall use for these estimations the following equation valid for the so-called “slowing-down” time $\tau^{i/e}_s$ of the deuterium i-beam relaxation on field ions (the energy loss time for this beam is longer correspondingly by a factor of $(m_i/m_e)^{1/2}$) [12, 13]:

$$\tau^{i/e}_s = (2)^{1/2} E_i^{3/2} / 9 \cdot 10^{-8} n_i \lambda$$

where $\lambda$ is Coulomb logarithm, $e$ is electron charge, and $E_i$ is energy of fast deuteron in $eV$. This formula is true if $m_i V_i^2 / 2kT_i << 1$ as in our case. Taking into account pinch’s radius, its height (1 and 10 cm respectively) and its ion density $2 \cdot 10^{18}$ cm$^{-3}$ one can see that the “slowing-down” time of 100-keV ions is $2.4 \cdot 10^{-8}$ s (i.e. less compared to the neutron pulse duration time). It gives mean-free path for the slowing-down time 7 cm (strong scattering ions on ions), whereas to establish the Maxwell distribution function the time will be circa $1.5 \cdot 10^{-6}$ s. For ions within the energy interval 10…100 keV it will be noticeably shorter. On the other hand, ions of the above energy range (velocities 1…3$\cdot10^8$ cm/s) being magnetized should make 2-10 rotations inside the pinch during the neutron pulse duration (150 ns) thus increasing their trajectory length to ~ 50-200 cm during the plasma confinement time.

Now let’s check a slowing-down time of these ions on field electrons for our case $m_e V_i^2 / 2kT_e << 1$ (where $T_e$ is the field electron temperature):

$$\tau^{i/e}_s = (2)^{1/2} T_e^{3/2} / 1.6 \cdot 10^{-9} n_e \lambda = 5 \cdot 10^{-8} s$$
The result is close to that obtained by equation (19). It is not surprising. The scattering process is greater for particles with smaller velocity differentials. In our case the velocity of fast ions \((3 \cdot 10^8 \text{ cm/s})\) is about 5 times higher than the field-ion velocities \((\leq 5 \cdot 10^7 \text{ cm/s})\) and also about 5 times less than the field-electron ones \((\geq 1.5 \cdot 10^9 \text{ cm/s})\). However the ion slowing-down time interval is determined by two-three collisions with ions and about 100 collisions with electrons. This fact explains our estimations made using equations (19) and (20). It means that our fast ions interact with both plasma components in almost a comparable degree with a certain preference to field ions and with one important feature – scattering character is strong for the ion component changing the direction of decelerated fast ions, which was mentioned above. Thus, between the two parts of fast ions (approximately equal quantitatively but both small compared with the total number of them generated in the PF) the group slowed-down on field ions is isotropic contrary to those stopped by field electrons.

Later on, because of the fact that our pinch has its confinement time shorter compared with the ions energy loss time (time of establishment of the new Maxwellian distribution) namely the first group of decelerated ions will be magnetized and namely this group will produce the main part of fusion neutrons.

It means that about ~1/4-1/8 part of the fast ions will lose their energy inside the plasma. Thus \(\equiv 2 \text{ kJ}\) of the beam energy will be deposited inside the pinch within the field particles (mainly on the ion component). As a result, each particle of the ion component of plasma will acquire an additional portion of energy: \(\sim 2 \text{ kJ} / n_i V_{pl} \geq 0.5 \text{ keV}\). It is comparable with the initial thermal one \((\sim 1.3 \text{ keV})\). At this increased temperature \(T_i = 1.8 \text{ keV}\) a mean-free path for ions (equation (6)) is < 5 cm – still less compared to the pinch height. It can explain a partial neutron yield increase during the second pulse: according to equation (5) with an increase of volume by 4 times (radius by 2 times), a decrease of plasma density by 4 times, but with an increase of a cross-section of fusion reactions [13] by about 10 times:

\[
Y = \left( \frac{n_i^2}{4} \right) <\sigma \nu>_{DD} \pi R_p^2 h_p \tau \equiv 4 \cdot 10^{10} \text{ n/pulse} \tag{21}
\]

On the other hand a 10-kJ beam of 100-keV ions contains \(6 \cdot 10^{17}\) particles. For these particles equation (5) will look as follows:

\[
Y = \left( n_{ipl} N_{i, \text{fast}} / 4 \right) \sigma \nu_{i, \text{fast}} \pi R_p^2 h_p \tau \tag{22}
\]
where \( n_{\text{pl}} = 2 \cdot 10^{18} \text{ cm}^{-3} \) – plasma density, \( N_{\text{i fast}} \) – concentration of fast ions within the pinch, and \( v_{\text{i fast}}, \sigma \) – velocity of fast ions and fusion cross-section respectively.

Taking into consideration the concentration of these fast (100 keV) ions in the bunch, their magnetization inside the pinch, and using fusion cross-section for 100-keV deuterium ions equal to \( 1.5 \cdot 10^{-26} \text{ cm}^2 \) [16] one will receive a figure for the total neutron yield \( 10^{12} \) neutrons per shot, which is a bit higher compared with the best experimental one. But this exaggeration can be easily explained by lower real concentration of fast ions within the pinch plasma.

The overall result for the fast ion interaction with the hot dense pinch’s plasma can be reformulated now in the following manner: the situation for the primary (“thermonuclear”) model of neutron production presented in the first guess is remarkably improved by the second mode described here. Viz. the above inductive (rapid in comparison with the collisional one!) mechanism of generation of fast ions within DPF’s plasma will form the overall distribution function with an enriched high-energy tail that usually produces most fusion reactions.

Now we have to link these results to our data on the ion beams observations made for the outside part of the pinch (Figs. 11, 12, and 13). First let’s propose that the conical structures seen in Fig. 13b and c are produced by a beam of fast ions, which escape the pinch and heat/ionize the residual gas/plasma in this zone on the rear side of the SW, thus becoming visible itself. Indeed this explanation of the cone-tubular structure type is quite reasonable. In fact, inside the pinch we have a superposition of longitudinal (captured by PCS and compressed) and azimuth (compressing and diffusing) magnetic fields. And in the centre, as well as outside of the pinch (above it), the \( H_z \) prevails whereas on the periphery inside of the pinch the situation is in favor of \( H_\phi \). Above the pinch the force lines of the longitudinal (mainly presented here) magnetic field should fan (diverge by a cone structure).

Because of this in a close vicinity to Z-axis fast ions are accelerated along the singularity line of the azimuth magnetic field (so without any influence from it) thus forming the above-mentioned stem with slight divergence. We believe that this stem is reflected in the pictures of Fig. 13. At the same time the conical tubular structure of the ions leaving the pinch can be formed by those higher energy ions, which made only a few (or just one incomplete) gyrations inside the pinch and were collected near its generatrix. And because the cone-like shape is specific for the upper part of the pinch (and for the longitudinal
magnetic field connected with it) their stream acquires this shape. It is seen both in the direct-
irradiated track detectors of Fig. 11 and in the pictures of Fig. 13.

Because the generatrix of the cone outside the pinch at a distance of about 10 cm has
a regular cone shape it is clear that the external magnetic field (outside the pinch) cannot
change an orbit of 100-keV ions. It means that its magnitude is $10^{-2}$ MGauss or less. This is
the upper limit for $H_{ext}$ having mainly longitudinal components and produced by compression
of an initial small field as it was mentioned above. The smallest extreme of the field, at a
distance ~ 10 cm from the pinch, can be roughly estimated by the inverse quadratic distance
law $H_{ext} \sim 1/r^2 \sim 10^3$ Gauss.

The situation written above and connected with a disintegration of the ion beam after
penetrating it the SW front could explain why we cannot see this “centered ring” in Fig. 11
but can see it with the ion pin-whole chambers in Fig. 12. Indeed, because this scattering of
the ion beam has a random character any pin-hole positioned at certain distances from the
SW front will form an image of a source of the ions similar to the optical case of an image
produced due to light scattering by an object. At the same time in the above weak fields
Larmor radius of ions of energy above 100 keV will be ~ 100 cm – i.e. large compared with
the value for our distance from the pinch to the SW front and the two copper semi-rings with
track detectors. This means that the ions, which travel first along the conical generatrix, later
on scatters randomly. That is why we do not see them in Fig. 11.

But there is something more. Those “discs” (layers) seen in Fig. 12 and taken with a
1-ns time exposure reflect the temporal structure of the ion beam. Viz. the velocity of ions is
above $3 \cdot 10^8$ cm/s. During 1 ns they pass a way having the length less than 3 mm. Namely this
width of the discs we saw in the picture (it should be mentioned here that only a small
fraction of these fast ions interact with and heat plasma in this rear part of SW because a
collisional cross-section for these ions is low). Verification of the plasma cooling rate (and
photo- and triple-particle recombination processes in deuterium gas [17] if it became already
neutral) showed that their time is short compared with 1 ns (our exposure time of the frame
camera). It means that the ion beam consists in fact of a sequence of multiple pulses having
duration $\leq 1$ ns each and separated from one another by distances 5 to 10 mm, i.e. by time
intervals 2…3 ns.

In connection with all the above estimations we have to make three notes. First,
examining the virtual diode configuration one can notice a very small effective separation
between virtual anode and cathode – only 150 µm with a large diode’s aspect ratio. It seems
that such geometry of the diode should be unstable during this unsteady-state plasma phenomenon. Probably it bears an oscillating character, what is reflected in those short bunches seen in Fig. 13.

Secondly, one can see that estimations made by using equations (5) and (21) are very sensitive to plasma/beam parameters. In particular it relates to equation (5) where density is presented in the second power. Moreover, a thermonuclear reaction rate averaged over Maxwellian distribution depends on this formula on plasma temperature in the power 4.5 within the range of 1 through 5 keV (below 1 keV even faster). So, in this situation a real astonishing fact is not the large neutron yield variations in a DPF from shot to shot (usual reproach to this device), but its relatively stable average behavior (within a factor 2 in good facilities)! Probably this fairly fine performance is an additional argument in favor of the second neutron production mechanism: still fusion head-on impact cross-section on the level of fast ion’s energy near 100 keV follows to the ion energy change even slower than by a linear law. And very likely this remark relates not only to the second neutron pulse, but also to the first one: this yield looks more stable than PCS velocity changes. And we know that usually when we have fast electrons (“run-aways” during the first compression of plasma) we can also expect fast ions.

Our third remark is connected to the ions escaping the pinch in a Z-axis direction. According to our measurements and analysis they have a slightly higher energy compared to the “working ones”. Leaving the pinch they interact inside our large chamber (2 meters to the chamber wall) with residual gas having density \( \sim 2 \times 10^{17} \text{ cm}^{-3} \) (4 Torr D\(_2\)). Suppose here an effective distance of interaction to be equal to: \( l_{\text{int}} = v_i \times \tau_n = 3 \times 4 \times 10^8 \times 1.5 \times 10^{-7} \approx 50 \text{ cm} \).

We have to take into account also that the duration of the ion beam (and consequently the volume occupied by it) is 3 times shorter than the neutron pulse duration (i.e. 50 ns instead of 150 ns) and there is no appreciable magnetization effect. Thus the ratio of the external neutron yield to the internal one will be:

\[
\frac{N_n(\text{ext})}{N_n(\text{int})} \sim \frac{\{N_i(n) V\}_{\text{ext}}}{\{N_i(n) V\}_{\text{int}}} < 1/20 \tag{23}
\]

It means that the neutron yield from the space above the pinch is less compared to the yield from the pinch during first neutron pulse. For simplicity we neglect here ionization loss, which is not low (!) thus the received figure has even a certain exaggeration. Our preliminary measurements with collimation of the neutron emission from PF-1000 chamber support the
result of equation (23). This is a beneficial consequence of a plasma density increase, its heating and confinement (*hot compressed target*) as well as a *magnetization* of fast ions.

Being guided by these results let’s now discuss possible ways for the PF-1000 facility optimization. As it was mentioned above during our experiments we found that a *simultaneous* increase of charging voltage and initial gas pressure raises the device neutron yield. We observed that in the ranges of pressure 1.0…3.6 Torr and of voltage 30…36 kV the current of the device was increased linearly with both parameters. Thus, in the course we have reached practically the upper limit of operational regime of our device. At the same time, as seen from the oscilloscope traces in Fig. 2, the current is not changed during the formidable part of the 1st quarter of the discharge period (after the first 3.5 µs). In fact it demonstrates that at the end of this time interval the current has a character of the plateau with a tendency to a certain decrease (beginning from the 5-th microsecond till the peculiarity occurring at the 8-th microsecond). It means that the internal dynamical inductance of the device (its PCS) increases approximately with the same rate as the quasi-cosinusoid current *should be* increased thus compensating it. So the first step for the device optimization could be done as a decrease of the *internal* variable inductance of the DPF chamber executed by the anode tube shortening. Indeed because of a coaxial configuration the overall internal inductance of the gun is expressed by formula:

\[ L_{int} = 2l_\sim \times \ln (R/r_\sim) \]  

(24)

where \( l_\sim \) is the length of a part of the anode tube being included into the electrical circuit during PCS traveling *along* it, \( R \) is the radius of cathode rods circumference, and \( r_\sim \) is the radius of the pinch, which is included into the electrical circuit as the variable internal conductor of the coaxial part of the circuit’s inductance during PCS traveling *radially* to its implosion. It is seen that during the run-down phase internal inductance increases linearly with \( l_\sim \) whereas at the implosion stage its enlargement proceeds much slower following the logarithmic law with radius \( r_\sim \). Thus it is seen that this re-design of the anode will give an opportunity to eliminate a “plateau” on the current waveform and to increase the amplitude of the discharge current as it is approximated from the current waveform at least circa by 30%.

Another opportunity becomes clear from the total *external* inductance measurements. It appears that it is of the order of 20 nH at the present moment. At the same time it is known that an increase of a number of capacitors \( N \) in a battery should result in a decrease of its
inductance according to a practical law valid for large batteries: \( L_{\text{ext}} \sim N^{1/2} \) (an increase of the battery size and consequently its inductance must be partially compensated by the parallel operation of the increased number of capacitors). It means that in our case the external inductance for our bank must really be on the level:

\[
L_{\text{ext}} \cong \{(40 \text{ nH}) : (264)^{1/2}\} \cong 6 \text{ nH} \quad (25)
\]
i.e. 3 times lower in comparison with the actual one. According to our estimations the main impact in our present external inductance is produced by our current collector. Its new design might improve the situation tremendously. We may expect an increase of our current in this situation by a few times. This hope is based on our previous experience with the PLAMYA facility [1f] where we had a total current 2.5 MA and neutron yield (not yet completely optimized due to restrictions implied by the outer diameter of the DPF chamber used) of the level of 2 \( \times 10^{11} \) n/pulse (i.e. practically the same figures as in PF-1000). And it was done on the device with energy storage of only 250 kJ based on the same type of capacitors but with a much more compact collector system (\( \varnothing \cong 50 \text{ cm} \)) and at the DPF chamber having relatively shorter anode tube.

One specific detail was very important in our experiments with the PLAMYA device [1f]. Namely, we used inside the chamber a disk positioned 10 cm apart from the upper anode plate, which restricted PCS from moving it in an upward direction. The same measure made recently and investigated in more detail with the support of numerical calculations was performed with an optimization of the PF-3 facility at Kurchatov Institute [18, 19]. In these experiments it was found that the upper disk not only decreases the overall inductance giving rise to the current maximum by 10%, but what is more important it moves current peculiarity (dip) forward in time ensuring an increase of the pinch current at the plasma maximal compression at identical conditions by two times.

6. Conclusions

According to the results of the whole set of the experiments one may see that the main neutron pulse (the second one as usual) is irradiated after the phenomenon of current abruption. This event bears many features inherent to a plasma diode formed in accordance with the electron magneto-hydrodynamic model. The main mechanism of neutron generation
is in chime with a gyrating particle model whereas three groups of temporal parameters rule the neutron yield:

1) Time of the energy release from the plasma inductive storage system (magnetic field store around the pinch) after the moment of current abruption, when this energy is converted into the streams of fast electrons and ions, as well as the efficiency of this conversion.

2) Confinement time of fast deuterons having medium energy (10-100 keV), which are produced at the above current abruption and gyrated in the magnetic field within the pinch.

3) Confinement time of pinch plasma (the “hot plasma target” bombarded by the above stream of the medium-energy ions), as well as its density and volume.

The analyses of these results are in favor of the neutron emission model based on ion beam-plasma interaction with three important features: 1) plasma target is hot and confined during more than 10 “inertial confinement times”; 2) ions of the main part of the beam are magnetized and entrapped about the pinch plasma target for a longer period than the characteristic time of the plasma inductive storage system; and 3) ion-ion collisions - fusion ones due to head-on impacts and Coulomb ones by an increase of the effective temperature of the ion component of the bulk plasma – are both responsible for neutron emission.

Fast ions are generated as a sequence of pulses having duration less than 1 ns and separated in time by intervals about 2…3 ns. The part of ions leaving the pinch in the direction of Z-axis has conical-tubular structure. They produce neutrons in a certain volume of residual gas next to the pinch with total yield much less compared with the main neutron pulses.

An analysis of the results has shown that one of the ways for future improvement of neutron yield of the PF-1000 facility may be foreseen on device geometry changes. We believe that the experiments are in favor of the construction of new larger DPF devices, in particular if based on a modern high-current technology. In this case an increase of plasma volume, energy of fast ions as well as longevity of the “target” and beams will give additional advantages.

Acknowledgments

The work was supported in part by the International Atomic Energy Agency grants No. 11940, 11941 and 11942 and by the Federal Agency on Atomic Energy of Russian Federation.
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