Review of recent experiments carried out on the 1MJ Plasma-Focus PF-1000U device.

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Outline of the talk:

PF-1000U
Diagnostics
Gas puffing

Experiments:
- experiments with gas-puff
- measurement of the electron temperature
- conical insert in the anode tip
- laboratory astrophysics (jets)
- p + $^{11}\text{B}$ reaction related studies
Plasma-Focus PF-1000

- 2.5 MA: maximum current
- 6 μs: discharge period (1/4)
- <35 kV: charging voltage
- 1.332 mF: bank capacitance
- 1000 kJ: max. energy in the battery
- 12 MA: short-circuit current

anode: 22,6 cm (diam)  
46 cm (length)
katoda: 40 cm (diam0  
(12 rods, diam. 8 cm)
Insulator – alumina, length 8.5 cm

Filling gas: deuterium ~4 hPa

\[ Y_n \propto 10^{11} - 10^{12} \text{ DD neutrons} \]
Plasma-Focus PF-1000
Diagnostics – laser interferometer

\[ \lambda = 527 \text{ nm} \]
\[ E = 450 \text{ mJ} \]
\[ \tau < 1 \text{ ns} \]

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<table>
<thead>
<tr>
<th>Delay between frames [ns]</th>
<th>0</th>
<th>60</th>
<th>120</th>
<th>180</th>
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<td>70</td>
<td>130</td>
<td>190</td>
<td></td>
</tr>
<tr>
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<tr>
<td>40</td>
<td>100</td>
<td>160</td>
<td>220</td>
<td></td>
</tr>
</tbody>
</table>
Diagnostics – 16-frames laser interferometer
Diagnostic laser
Diagnostics: High Speed 4 Frame Soft X-ray Camera
Diagnostics: High Speed 4 Frame Soft X-ray Camera
Diagnostics: High Speed 4 Frame Soft X-ray Camera

XUV spectra range, frame duration -1.8ns, time interval between frames 0-20 ns)
Diagnostics: Soft X-ray Detection Set

Elements, principle of operation and possible arrangement of the Detection Head (DH’s)

The additional elements, improving the DH’s immunity against shock waves and streams of ionized particles.
The DH’s photodetector based on Si P-I-N photodiode S9055 type;

a) photodiode assemble ensures undisturbed high-bandwidth transmission of transient signals;
b) the result of the response time measurement performed with femtosecond laser (7 nJ, 20 fs, 790 nm).
Diagnostics: Soft X-ray Detection Set

a) the SXRDS with accompanied equipment mounted at the experimental chamber of the PF-1000U device;
b) the four Detection Heads installed inside the vacuum chamber of the SXRDS.
The field-of-view and line-of-sight axial points of DHs applied inside the SXRDS.
Diagnostics: Scintillator-photomultiplier Probes for hard X-ray and neutron measurements.
Diagnostics: Ion measurements

nuclear track detector of the CR-39 type

Ion track images, as recorded during angular measurements within PF-1000 facility.

Angular distributions of fast deuteron.

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Additional “degrees of freedom” of the Plasma-Focus operation can be achieved by special gas injecting system. Two solutions of such a system can be used:

- injection of the additional working gas into inter-electrode space (close to insulator) to ensure proper discharge, while keeping low density of ambient gas in the rest of the chamber.

- injection of the additional gas through the hole in front of the central electrode to increase density of the plasma in the pinch.

PF-1000 gas injection system a/ inter-electrode injectors, b/ central injector.
Gas puffing in the PF-1000U

Interferometric pictures of shots # 10064 and # 10080 recorded at the final phase of plasma and current sheath implosion without (left) and with (right) puffing deuterium.

The linear density plasma $7.16 \times 10^{18}$ [cm$^{-1}$] in the imploding plasma sheath was calculated from the left interferogram at a distance $z=1.5$ cm from the anode. Analogous value for the right picture reached $10.6 \times 10^{18}$/cm. One can see that gas puffing result in higher linear density in the created pinch column.

The scheme of the experiment with the use of axial puffing system.
Gas puffing in the PF-1000U

The results of experiments with axial puffing are summarized in the Table below, where basic measured parameters are listed for discharges with and without deuterium puffing.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Without puff</th>
<th>With puff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear density of electrons [x 10^{18} cm(^{-1})]</td>
<td>7.1 ± 0.8</td>
<td>10.6 ± 1</td>
</tr>
<tr>
<td>Length of the column [cm]</td>
<td>6–8</td>
<td>6–8</td>
</tr>
<tr>
<td>Minimal diameter of the pinch [cm]</td>
<td>1.4 ± 0.2</td>
<td>1.5 ± 0.2</td>
</tr>
<tr>
<td>Average (n_e) at minimal diameter [x 10^{24} m(^{-3}) ]</td>
<td>4.5 ± 1.0</td>
<td>5.0 ± 1.0</td>
</tr>
<tr>
<td>Diameter of stagnation [cm]</td>
<td>2.5 ± 0.2</td>
<td>4.0 ± 0.2</td>
</tr>
<tr>
<td>Average (n_e) in stagnation [x 10^{24} cm(^{-3}) ]</td>
<td>1.1 ± 0.1</td>
<td>1.5 ± 0.1</td>
</tr>
<tr>
<td>Average energy of neutrons downstream [MeV]</td>
<td>2.86 ± 0.2</td>
<td>2.80 ± 0.2</td>
</tr>
<tr>
<td>Total neutron yield [x 10^{10}]</td>
<td>4.5 ± 3</td>
<td>5.6 ± 3</td>
</tr>
</tbody>
</table>

This result can be summarized as follows: application of additional gas injected with the use of the axial gas puff system generally leads to increase of plasma density in the pinch, increase of the pinch radius, and decrease of the implosion velocity. Concerning the neutron yield we observed increase of its medium value of about 20\% but this increase is within the statistical error of measurement.
An important qualitative difference can be observed: without gas puffing we can see rapid development of MHD $m=0$ instabilities, while with additional gas injection, the plasma column is stable although the neutron yield in this discharge is high ($3 \times 10^{11}$). This observation contradicts a common opinion that MHD activity is a condition for high neutron yield.
XUV (window 150-300 eV) pictures and interferograms for deuterium puffing in front of deuterium plasma sheath pictures (4 frames, duration of a frame 1 ns, delay between frames $\Delta 10$ ns, pinhole 200 $\mu$m, filtered by polystyrene 5 $\mu$m, four sectors MCP +CCD).
Measurement of the electron temperature in the pinch

Electron temperature – important factor for the neutron emission models.
Stopping power for fast deuterons dominated by ion-electron collisions.

\[ p_0 = 2hP D_2, \quad U_0 = 23kV, \quad I_{max} = 1.8\, M\,A \]
Measurement of the electron temperature in the pinch

for f-f radiation (bremstrahlung):

\[ I_\lambda = \lambda^{-2} (kT_e)^{-1/2} \exp (- E / kT_e - \mu(E)d) \]

for two filters method, after integration:

\[ \frac{I_1}{I_2} = f(kT_e) \]

Using the above diagram and PIN diode signals it was estimated that in the discharge #10071 the electron temperature amounted to 165 eV, during the maximum compression.
The aim of the experiment was to investigate a possibility of steering of the pinch formation process by a change of the anode tip geometry (in view of the neutron yield optimisation).

Inner electrode plate equipped with the conical insert.
Experiments with modified anode tip

What could be expected?

Regular case – flat CE

CE with conical tip
Experiments with modified anode tip

Experimental set-up
Experiments with modified anode tip

It was found that configuration with the conical tip is excellent source of metallic plasm jets, relevant to laboratory astrophysics.
Experiments with modified anode tip

Sequence of interferograms corresponding to the Cu plasma jet development.

Electron density distributions at the plasma cross-sections 0.25 cm distant from the cone tip at different instants of the Cu plasma jet evolution.

The Cu plasma jet at an instant of 65 ns reaches the electron density $n_e = 7 \times 10^{18}$ cm$^{-3}$ at 3 mm (full width at high maximum) in diameter.

The jet velocity progressively increases reaching the maximum value of $5 \times 10^7$ cm/s.
Spatial distribution of the plasma electron temperature for the three successive phases of plasma evolution: motion along the cone surface, pinch formation and jet development (2D MHD code KAROL)

Plasma temperature vs. time at the six points uniformly distributed on the cone side surface (see insert).

Results of modelling using 1D code - temperature inside the thin (1μm) layer of copper subjects to the thermal load (Heviside step function) for $T_e = 10, 25, 50$ eV.
Experiments with modified anode tip (computer simulations)

The set of markers on the cone side surface \((t = 0 \text{ ns})\) and their motion in course of the pinch formation phase \((t = 735 \text{ ns and } t = 779 \text{ ns})\), corresponding to the motion of the copper-deuterium plasma mixture.

Maximum length of the stable copper jets for four values of the cone height \(2, 3, 4, \text{ and } 7 \text{ cm}\).
Experiments with modified anode tip (neutron emission)

two regimes of PF (with modified anode tip) operation have been observed:

- type I with strong erosion of the conical tip and relatively low neutron yield \((Y_n = 10^9 - 10^{10})\).

- type II with low erosion and high neutron yield \((Y_n = 1-2\cdot10^{11})\)

The cone attached to the central electrode tip results in formation of a shorter (1-3 cm instead of 7-8 cm) and thinner (3 mm instead of 16 mm) pinch column.
The longer cone the shorter pinch column is observed.
Experiments with modified anode tip (neutron emission)

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 type I blue
 type II red
Experiments with modified anode tip (neutron emission)

Neutron and hard X-rays waveforms recorded by scintillator-photomultiplier neutron probes. Source – probe distance 7m. Observation angles: 0, 90 i 180 degrees. CE with the conical insert (left) and the classic flat CE (right).
Laboratory Simulations of Astrophysical Jets

In collaboration with Kurchatov Ins. (Moscow)

Scheme of the PF-3 experimental facility and pictures of the plasma stream (jet) during its formation (beneath) and at a distance of 95 cm from the anode surface (upper); the exposition time was 12 ns.

Scheme of the PF-1000U experiment performed with the use of the additional gas injection.
Frame pictures of a plasma stream at a distance of 40 cm from the anode outlet: a) at the stationary initial pressure of 1.2 hPa deuterium; b) at the initial deuterium pressure of 1.2 hPa and the additional injection of a mixture of deuterium (75%) and neon (25%). The pictures show also a magnetic probe which recorded azimuthal magnetic field.

An analysis of the Stark broadening of spectral lines made it possible to estimate the plasma density at a distance of 57 cm from the anode outlet, which had the value of (0.4-3.7) x 10^{17} cm^{-3} and depended on the initial gas distribution and a delay of the spectrum registration in relation to the plasma stream emission. The electron temperature of the plasma stream amounted to about 5 eV, and the density of background plasma was equal to about 1.5 x 10^{15} cm^{-3}.
Plasma-Focus & Proton – Boron reaction

\[ p + ^{11}B \rightarrow 3 \times ^4He + 8.7 \text{ MeV} \]

Successful aneutronic fusion would greatly reduce problems associated with neutron radiation such as ionizing damages, neutron activation and requirements for biological shielding, remote handling and safety.

Figure 4. Total \( p-^{11}B \) fusion cross-section plotted versus the centre of mass energy. The fit described in the text is shown as the solid curve.
Plasma-Focus & Proton – Boron reaction
Plasma-Focus & Proton – Boron reaction

\( ^4\text{He} \) tracks identified in the irradiated CRN-39 detector

To be continued …
Thank you for attention

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The two equations describing dynamics of the plasma sheath elements are solved together with equation of the external electric circuit:

\[ U_B - \frac{1}{c} t \int_0^t \! I \, dt = R_\Omega + \frac{1}{c^2} \frac{d[(L_0 + L)I]}{dt} \]

where:
- \( U_B \) - charging voltage of the battery
- \( I \) - current
- \( R_\Omega \) - total ohmic resistance in the circuit
- \( L_0 \) - inductance of the external circuit
- \( L \) - inductance of the plasma sheath

Sequence of successive shapes of the plasma sheath as modeled by the SP code.

**PF-1000, influence of the working gas pressure on max. current.** \((L_0=15\ \text{nh}, U_b=23\ \text{kV}, R_{\text{inner}}=11.6\ \text{cm}, R_{\text{out}}=22\ \text{cm}, Z_e=56\ \text{cm})\).
The 10 MJ case (1):

Fig. II.7 PF-10MJC, influence of the working gas pressure of the current waveform ($L_0=15$ nh, $U_b=35$ kV, $Z_{el}=80$ cm, $R_{in}=24$ cm, $\Delta R = 12$ cm).

Fig. II.8 PF-10MJC, high voltage case $U_b=50$ kV, $Z_{el}=70$ cm, $\Delta R = 12$ cm,
a) $R_{in}=18$, $p=25$ Torr,  
b) $R_{in}=24$, $p=20$ Torr,  
c) $R_{in}=30$, $p=15$ Torr.
The 10 MJ case (2):

Fig.II.9. PF-10 MJ, $Z_{el} = 60$ cm, $R_{in} = 12$, $p=10$ Torr, variable charging voltage.

Fig.II.10. PF-10 MJ, $Z_{el} = 60$ cm, $R_{in} = 12$, $p=25$ Torr, variable charging voltage.
Search for optimum configuration

The system consists of three basic components:

1/ set of initial assumptions (e.g. energy stored, charging voltage) and range of variable parameters (e.g. radi of inner and outer electrodes, working gas pressures, insulator lengths, etc).

2/ solver that will deliver resulting parameters to be analysed (SP code)

3/ set of selecting criteria (e.g. pinch current, max. current/pinch current ratio, efficiency of capacitor energy usage etc.).

For given energy stored in the capacitor bank and high voltage applied (these parameters depend on general assumption on the available funds and technology to be applied) the following parameters of the Plasma Focus configuration are varied during the optimum configuration search for exemplary 10 MJ - 90 kV solution:

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>From - To</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Filling gas (DT) pressure $p_0$</td>
<td>3 – 30 Torr</td>
</tr>
<tr>
<td>2.</td>
<td>Inner electrode radius $R_i$</td>
<td>10 -50 cm</td>
</tr>
<tr>
<td>3.</td>
<td>Inner electrode length $l_0$</td>
<td>30-150 cm</td>
</tr>
<tr>
<td>4.</td>
<td>External inductance $L_e$</td>
<td>20 -100 nH</td>
</tr>
</tbody>
</table>
Criteria for selecting the best configuration have been proposed basing on experience collected by the community operating Plasma-Focus machines with energy of the capacitors bank > 50 - 100 KJ, various theoretical models and numerical simulations.

Table II.2 The selection criteria:

<table>
<thead>
<tr>
<th>Level</th>
<th>Name of parameter</th>
<th>Definition</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Maximum current at the pinch phase</td>
<td>Current for the pinch length equal to $R_0/2$</td>
<td>All temporary models of neutron emission from Plasma Focus treat $I_{pinc h}$ as key parameter for neutron yield (vide scaling laws)</td>
</tr>
<tr>
<td>Secondary</td>
<td>Minimum difference between:</td>
<td>$\Delta I = I_{max} - I_{pinc h}$</td>
<td>Maximum of the $I_{pinc h}$ can be achieved in various ways. Some of them by very high value of $I_{max}$ (strong erosion of electrodes, high values of the EM stresses) and then significant drop of the current during collapse phase.</td>
</tr>
<tr>
<td>Secondary</td>
<td>Minimum energy left at the capacitor bank</td>
<td>$\eta = \frac{E_{final}}{E_{Initial}}$</td>
<td>Natural parameter – energetic efficiency of the generator.</td>
</tr>
<tr>
<td>Secondary</td>
<td>Maximum energy stored in magnetic field</td>
<td>$E_{mag} = 0.5 \cdot L_{pinc h} I_{pinc h}^2$</td>
<td>Available magnetic energy stored around the pinch is a source of energy used for generation of fast deuterons.</td>
</tr>
</tbody>
</table>
Output:

Solutions of the 2D SP for 15x15x15x15 = 50625 sets of configuration parameters.

Ipitch – pinch current in descending order selected for Vz – axial velocity > 8 \cdot 10^6 \text{ cm/s}

<table>
<thead>
<tr>
<th>M</th>
<th>Ipinch</th>
<th>Imax</th>
<th>IMAXMAX</th>
<th>VZMAX</th>
<th>DI</th>
<th>RO</th>
<th>ZO</th>
<th>LO</th>
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<td>5.29D+00</td>
<td>5.41D+03</td>
<td>8.01D+06</td>
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<td>10898</td>
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<td>1.33D+01</td>
<td>1.20D+01</td>
<td>3.90D+01</td>
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</tbody>
</table>
Fig. II.11. PF-10MJ, $U_b=90$ kV, $R_i/R_o=1.6$

1/ $p=15$ Torr, $R_{in}=15$ cm, $Z_{in}=86$ cm, $L_0=27$ nH
2/ $p=21$ Torr, $R_{in}=10$ cm, $Z_{in}=102$ cm, $L_0=57$ nH
3/ $p=17$ Torr, $R_{in}=13$ cm, $Z_{in}=110$ cm, $L_0=39$ nH
4/ $p=17$ Torr, $R_{in}=13$ cm, $Z_{in}=102$ cm, $L_0=69$ nH

$I_{\text{pinch}} = 4.65$ MA

Fig. II.12. PF-10MJ, $U_b=90$ kV, $R_i/R_o=1.6$

$p = 31$ Torr, $R_{in} = 10$ cm, $Z_{in}=166$ cm
$L_0=27$ nH

$I_{\text{pinch}} = 4.91$ MA
$I = 5.71$ MA
Assuming neutron yield scaling of the form:

\[ Y_n \approx 0.6 \cdot 10^{14} I_{\text{pinch}}^4 \]

Thus 4.65 MA pinch current corresponds to \( Y_n \approx 3 \cdot 10^{16} \) neutrons per discharge.
Conclusions:

Realization of the Project goals established a basis for preparation of a more detailed design of an intense (at least $10^{16}$ per discharge), relatively compact, pulsed, 14 MeV neutron source for various applications. There is a permanent need for such a source in many areas of science and technology (material science, fusion material technology, detection of illicit materials, neutron diagnostic testing, etc.).

Various experiments carried out within the Project broadened knowledge on mechanisms of neutron emission, current carrying plasma dynamics, nonlinear effects etc. in dense magnetized plasmas.

In our opinion the Project should have a follow-up devoted to more technical aspects of the neutron generator construction (e.g. alternative methods of power supply, thermal and radiation loads of the generator, detailed analysis of the nuclear safety aspects, etc.).