EXPERIMENTAL EVIDENCES AND ROLE OF CURRENT FILAMENTS APPEARING INSIDE DMP DISCHARGES

Marek J. Sadowski[1-2)]

[1)] The Andrzej Soltan Institute for Nuclear Studies (IPJ), Swierk n. Warsaw
[2)] Institute of Plasma Physics and Laser Microfusion (IFPiLM), Warsaw
E-mail: msadowski@ipj.gov.pl

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5. Formation of local sources of fast e-beams and accelerated ions
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    - Energy spectra of electrons (in upstream direction) and ions along z-axis
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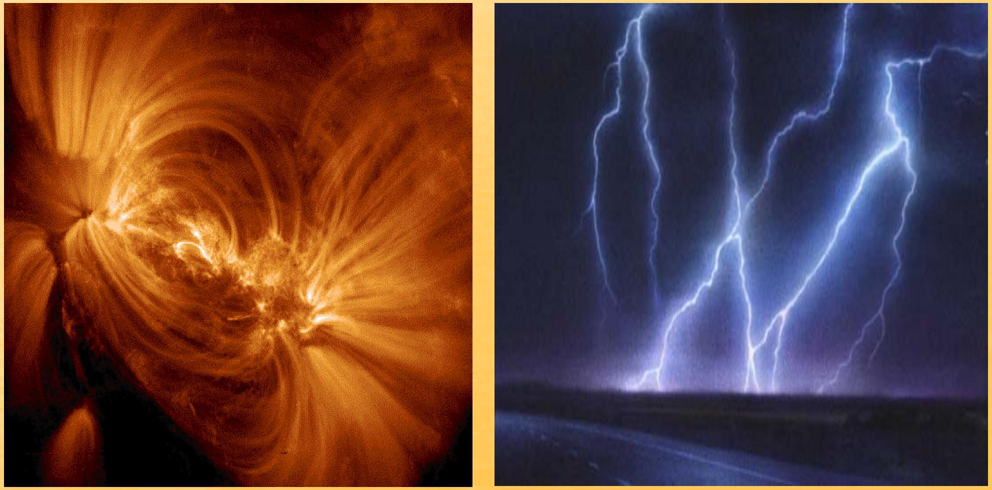
7. Summary and conclusions

Introduction

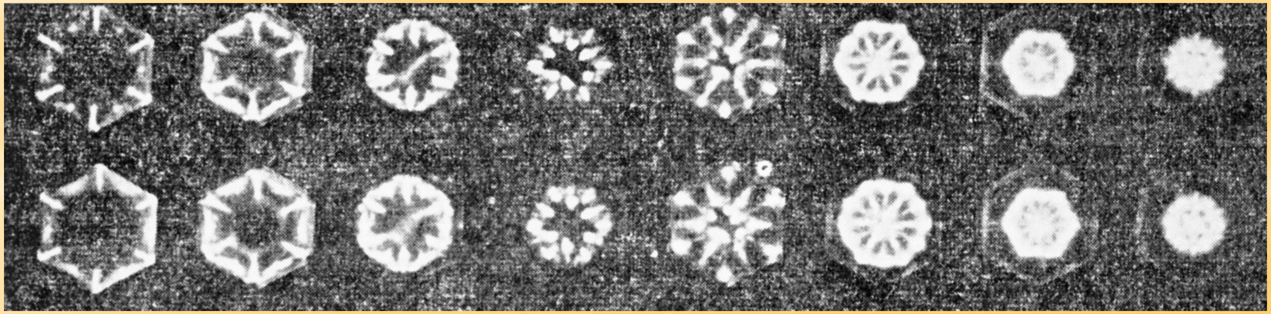
Dense magnetized plasmas (DMP) can be observed in nature and in various laboratory experiments of the Z-pinch or PF type.



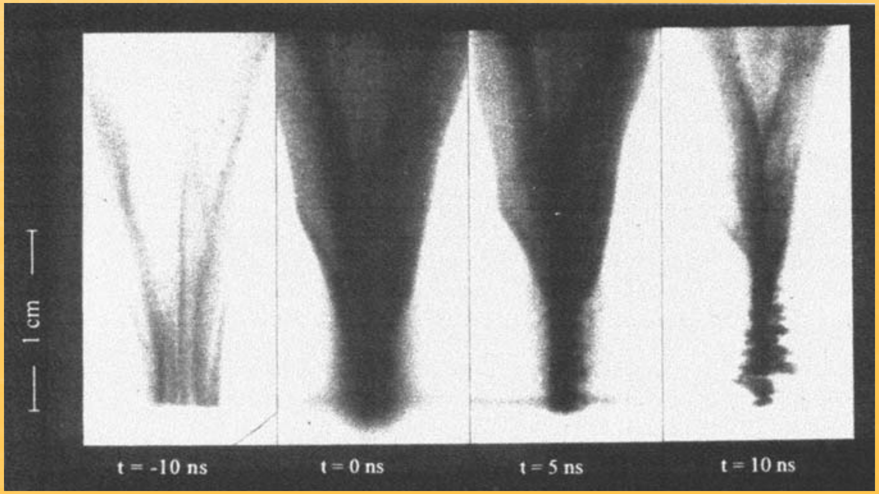
Solar flares emitted from the Sun surface and the intense lighting in atmosphere, in which discharge channels contain dense (10^{16}-10^{19} cm^{-3}) plasma, which is influenced by strong magnetic fields produced by high-intensity currents.

Intensively emitting DMP channels are evidently inhomogeneous ones, and they can have a complex internal structure.

Observation of current filaments in Z-pinch experiments

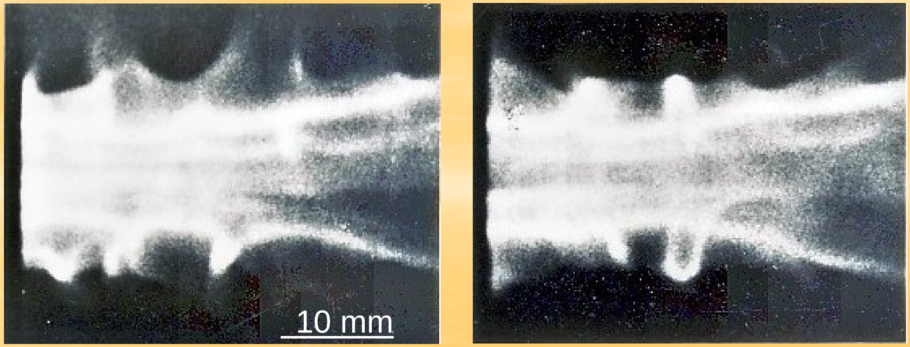


Examples of current filaments observed end-on in Z-pinch type experiments (performed by I.F. Kvartsava et al. in 1965) within a hexagonal vacuum chamber.

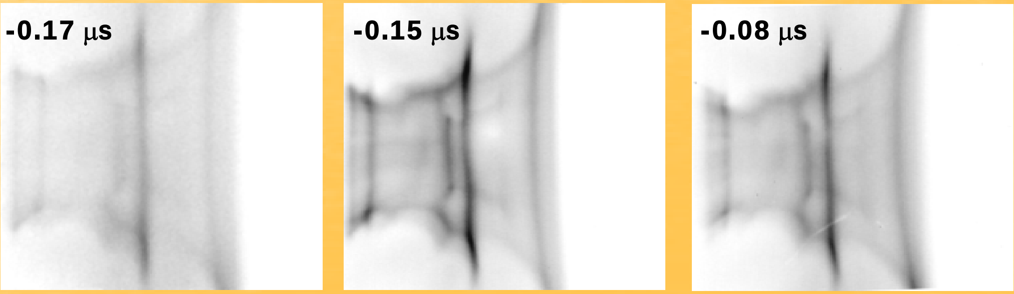


High-speed pictures of a high-current Z-pinch in an US laboratory, which show quasi-axial filaments in the DMP column. The VR emission of current filaments are coated by intense radiation of plasma.

Observation of current filaments in PF-type experiments



X-ray pinhole pictures, as taken in the POSEIDON (by M.J. Sadowski et al.) at p_o = 6.7 hPa, 500 kJ, which show current filaments inside a DMP column of about 15 mm in diameter.

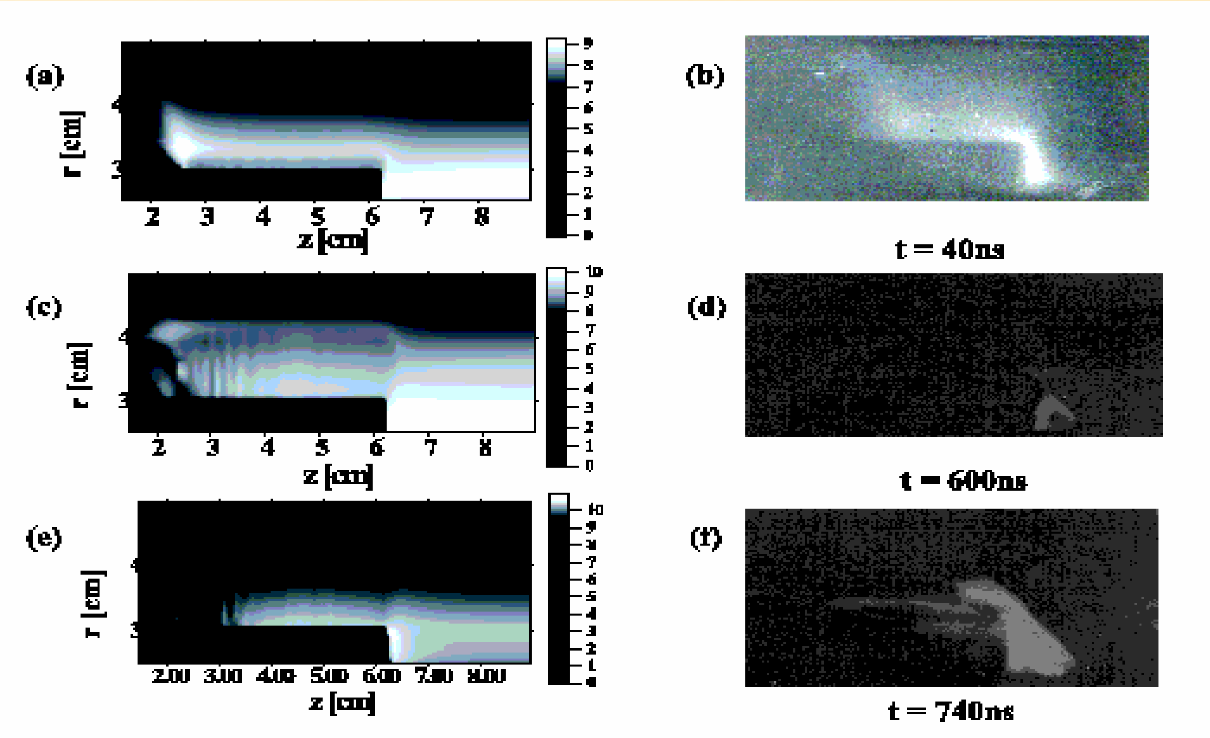


High-speed pictures taken (by K. Tomaszewski et al.) during the radial collapse phase in the PF-1000 experiment, which was performed at p_o = 4 hPa, U_0 = 33 kV and I_{max} = 1.7 MA.

It is of interest to observe and analyze filamentation phenomena, which seem to be common for different DMP experiments.

Breakdown phase and formation of CS layer

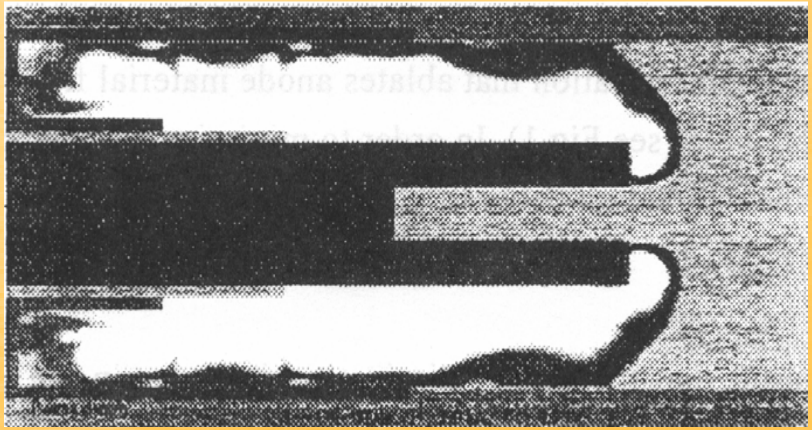
The initial breakdown occurs at the insulator surface, where a current sheath (CS) layer is formed. The breakdown depends on: 1. The configuration of electrodes near the main insulator, 2. The initial gas conditions inside the system, 3. A voltage pulse applied to electrodes.



Monte-Carlo computations of plasma density at different instants of the breakdown, and VR pictures taken with a high-speed camera (M. Scholz et al., PLASMA-2005).

Axial acceleration phase

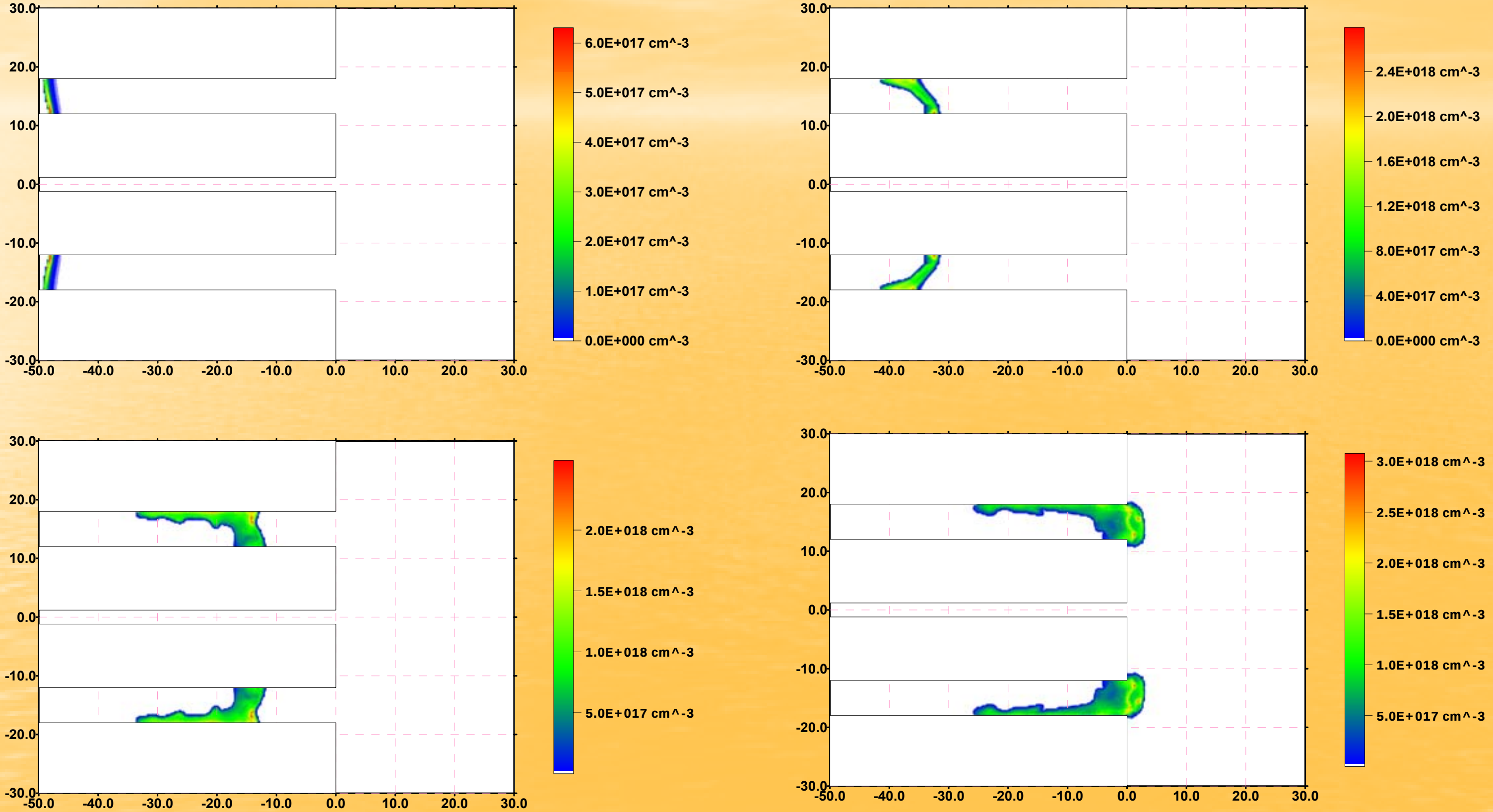
The CS layer can be accelerated along the tubular electrodes. To describe its motion the most popular and effective is a 2-fluid MHD model using equations of plasma continuity, momentum and energy balance, and Maxwell- and circuit-equations.



MHD simulation of the acceleration phase, as performed by M. Kashani et al., shows that the CS layer is pressed towards the inner surface of the outer electrode at its whole length.

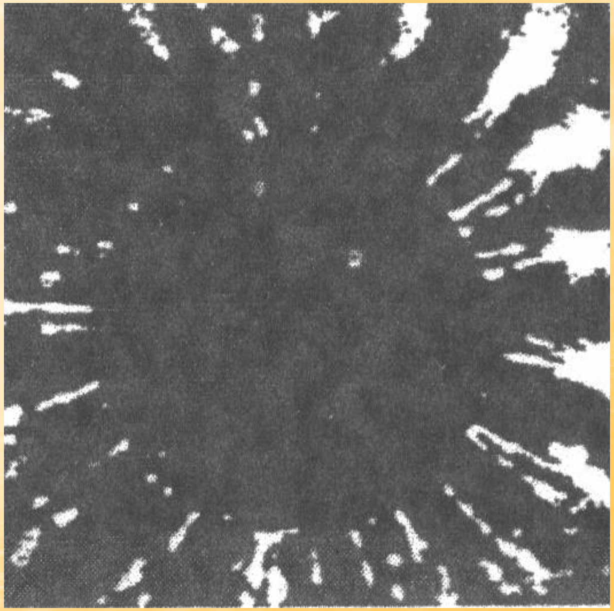
An appropriate amount of working gas must be delivered to enable the effective „snow-plough” motion to be achieved.

2D-MHD modeling of the axial acceleration phase

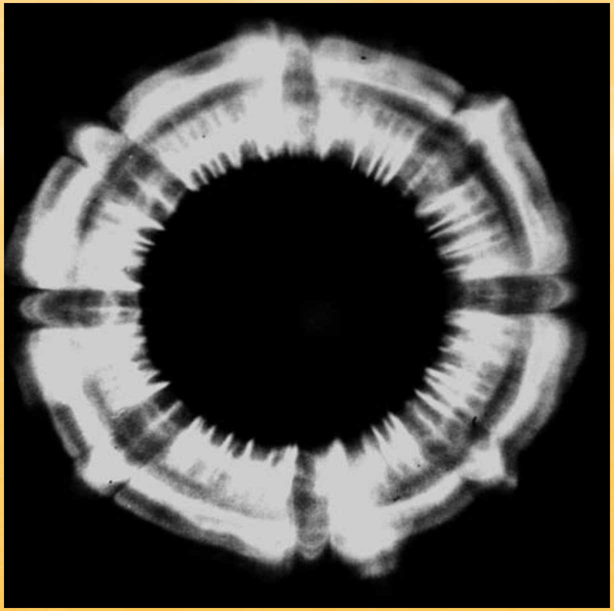


Plasma density distribution in the accelerated current-sheath, as computed by M. Scholz et al. for PF-1000 system (1 μs, 3 μs, 5 μs and 7 μs after the discharge start).

Current filaments in the axial acceleration phase



High-speed picture taken (by W.H. Bostick) end-on the coaxial electrodes, which shows quasi-radial filaments in the CS layer during its axial motion.

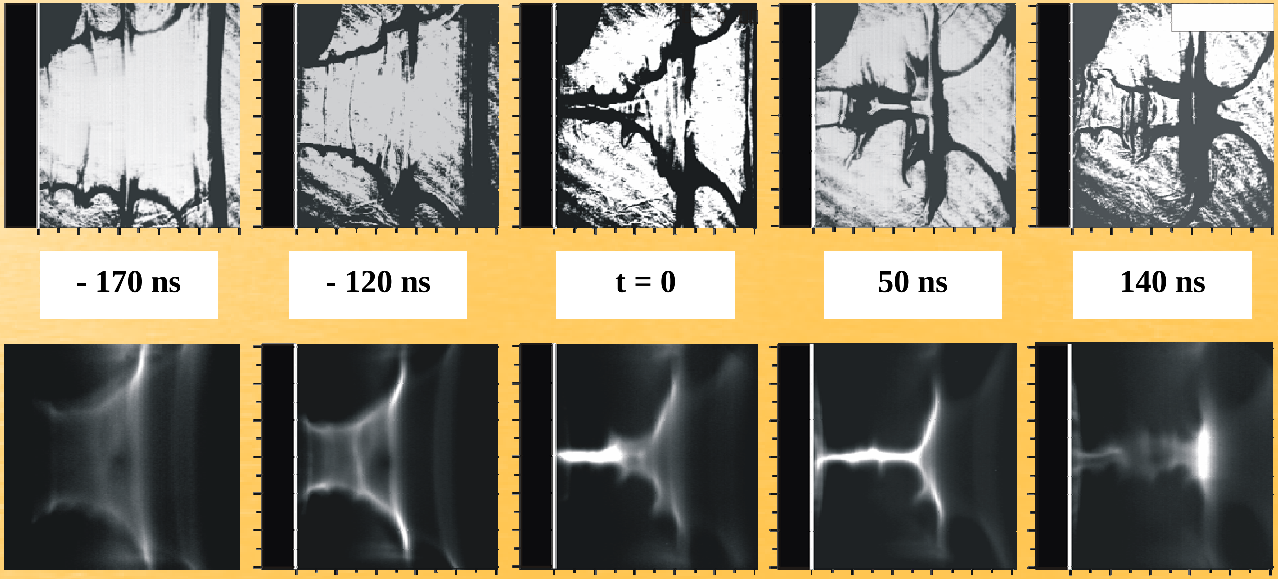


High-speed picture, which was taken by K. Tomaszewski in a PF-20 experiment, which also shows distinct filaments in the moving CS layer.

The main issue of this phase are effects of non-uniformities and quasi- radial filaments, which might be formed and preserved during the CS motion.

Radial collapse phase

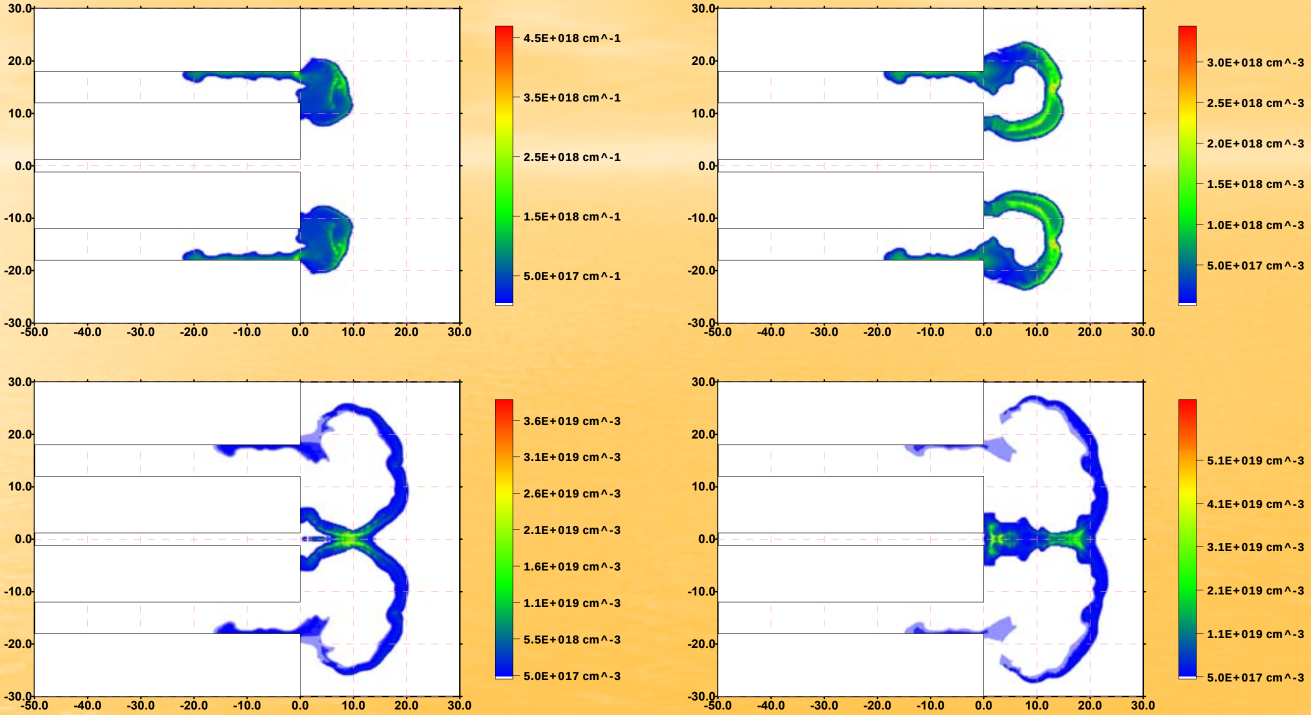
This 3rd phase occurs when the CS layer reaches electrode ends and undergoes the radial collapse leading to the formation of a DMP column.



Schlieren images and VR pictures, which were taken with a high-speed camera before and after the maximum compression (t = 0) within the PF-1000 facility .

The applied diagnostic techniques are often unable to deliver information about the internal structure of the collapsing CS layer.

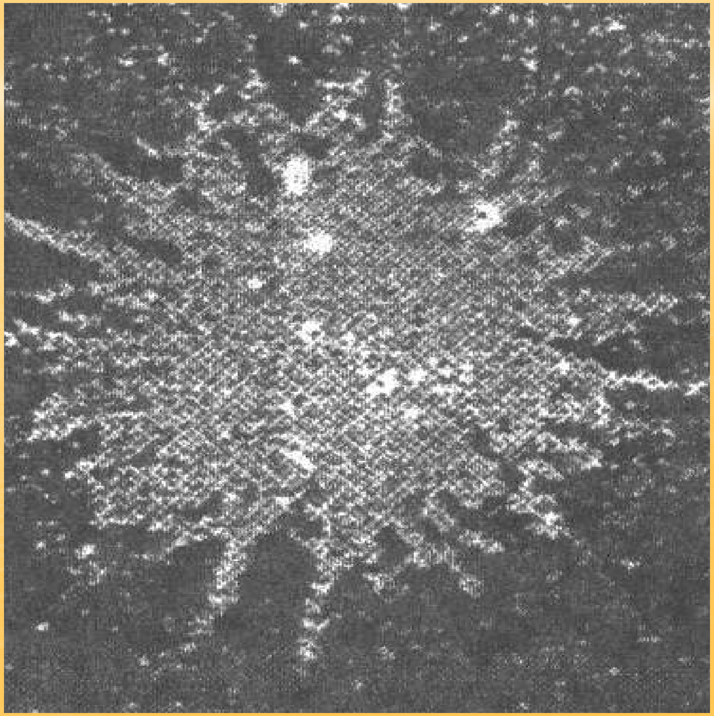
2D-MHD modeling of the radial collapse phase



Plasma density distribution during the radial collapse phase, as computed by M. Scholz et al. for PF-1000 system (8 μs, 9 μs, 9.7 μs and 10 μs after the discharge start).

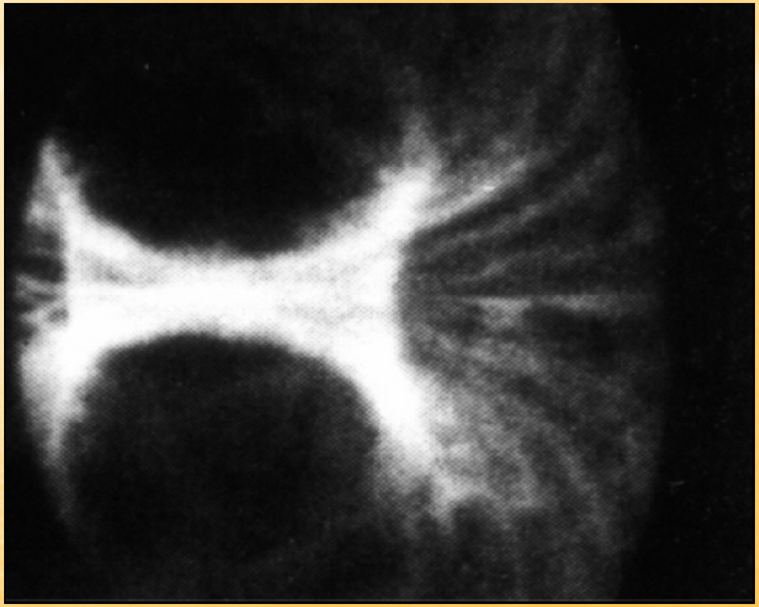
An extended MHD modeling of the collapse phase is efficient until the maximum compression occurs. In the later phase the development of different plasma instabilities requires more sophisticated approaches.

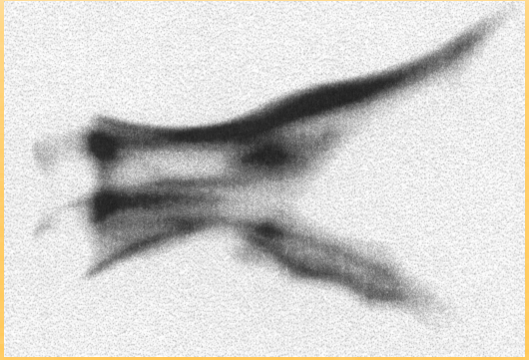
Current filaments in the radial collapse phase



High-speed camera pictures, as taken (by W.H. Bostick et al.) end-on a PF discharge, which show quasi-radial filaments in a CS layer during the radial collapse phase.

Plasma filaments can also exist when the CS layer is blown out the inter-electrode gap and it undergoes the radial compression

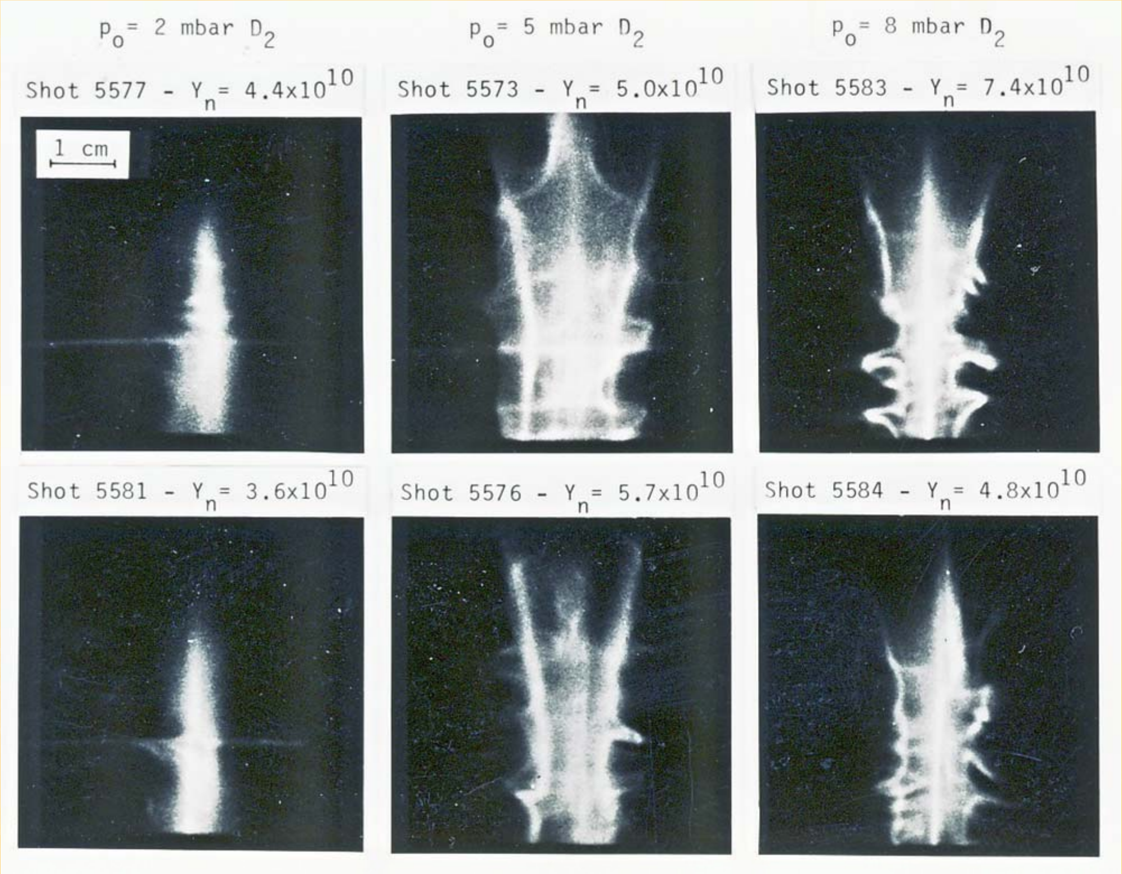




High-speed camera VR pictures, as taken in different PF-type experiments, which show distinct plasma filaments during the radial collapse phase and quasi-axial filaments inside the DMP column.

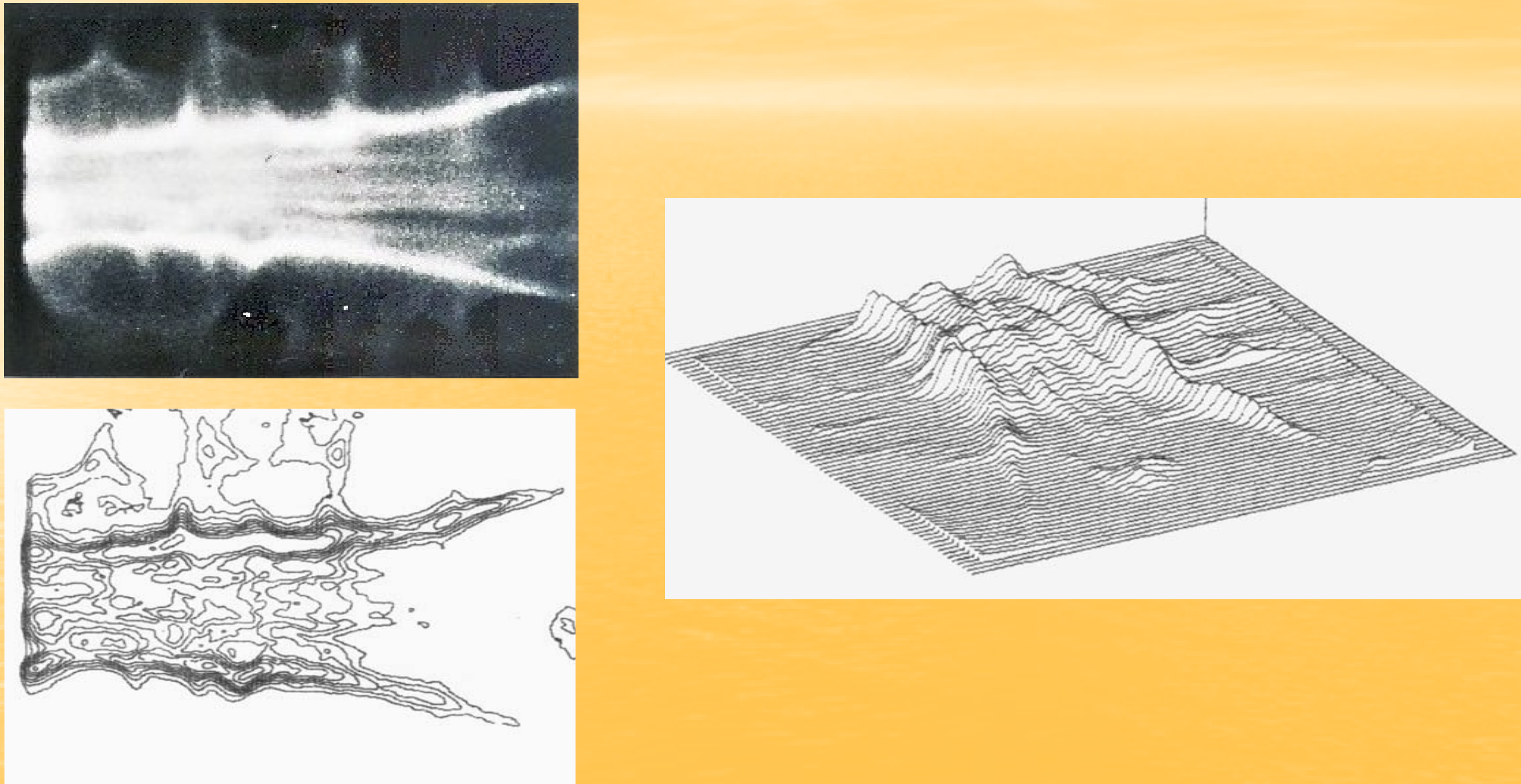
Current in a single filament can amount to several hundreds kA, and the local plasma density can reach even 10^{17}–10^{19} cm^{-3}.

Experimental evidence of current filaments in PF column



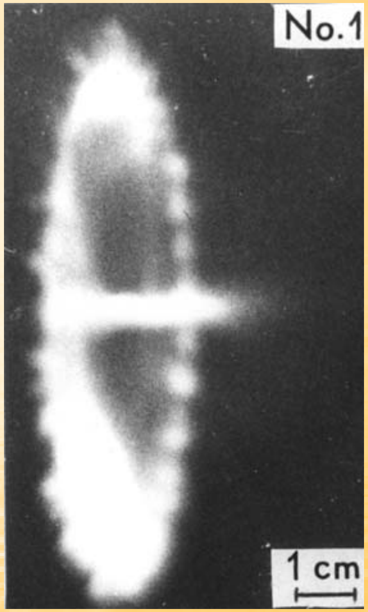
X-ray pinhole pictures, as taken (by M.J. Sadowski et al. in 1984) within POSEIDON experiments performed at different experimental conditions, which show various filamentary structures.

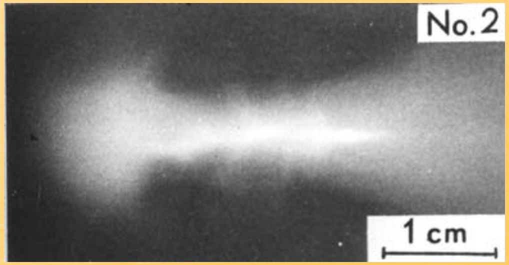
Visualization of current filaments in the pinch column



X-ray pinhole picture, isodensity lines (on the left) and the corresponding 3D diagram of the filamentary structure (on the right).

Other experimental evidences of the current filaments



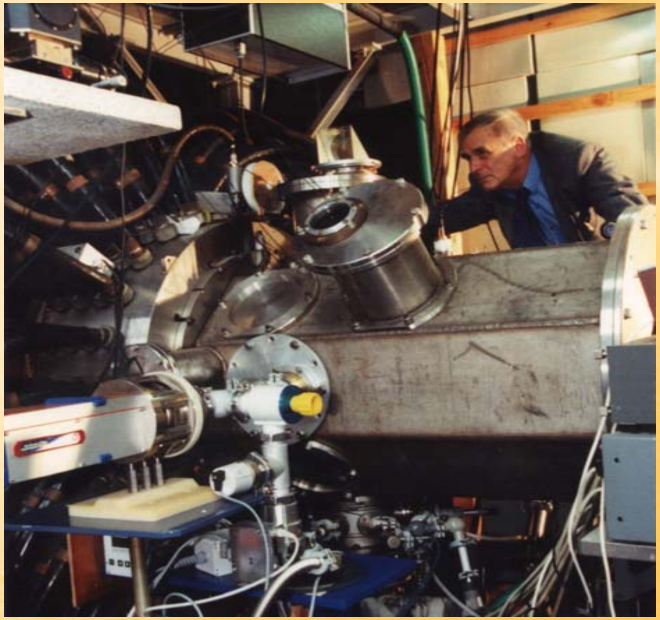


X-ray pinhole pictures taken during a PF-360 discharge, which show spots of current filaments on the edge of the inner electrode and microstructure of the pinch column.

X-ray pinhole picture from another shot, which show very distinct spots of current filaments on the electrode edge.

Existence of current filaments in PF discharges is also confirmed by the appearance of intensively emitting spots upon edges of the coaxial electrodes.

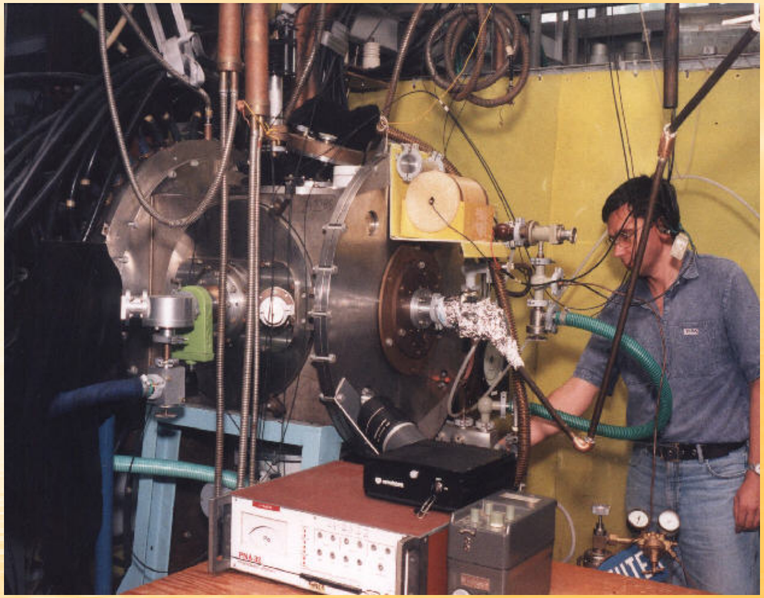
Plasma hot-spots in PF-360 experiment



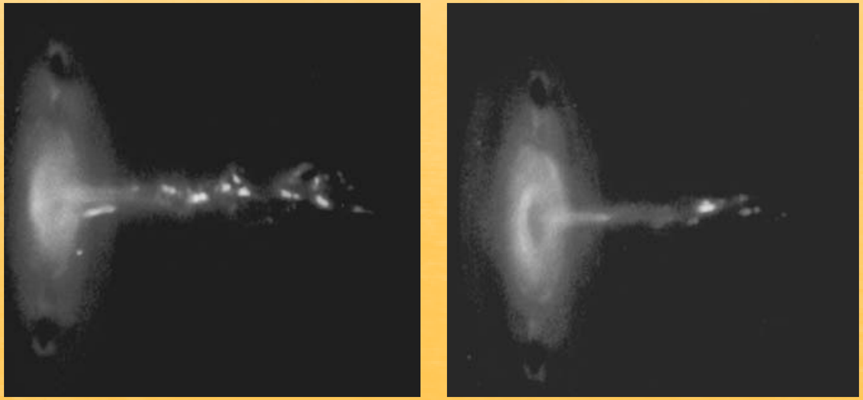
PF-360 experimental chamber surrounded with some diagnostic equipment used for optical and X-ray measurements

Hot-spots in PF-360 discharges. VR pictures (left) were taken with 1-ns exposition, at 31 ns and 41 ns after the maximum pinch, and the X-ray image (right) - at 28 ns.

Plasma hot-spots in MAJA-PF experiment



MAJA-PF experimental chamber with some diagnostic equipment used for X-ray and e-beam studies.

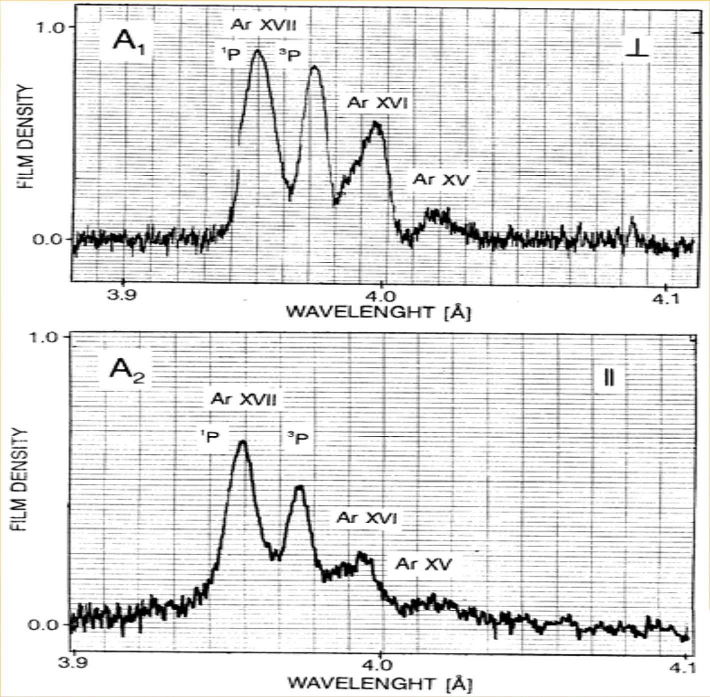


X-ray pinhole camera pictures, which show miniature hot spots in MAJA-PF experiment.

Mechanism of the formation of hot spots remain an open issue, but one can suspect that they are produced by splitting of current filaments.

Polarization of X-ray lines emitted from hot-spots

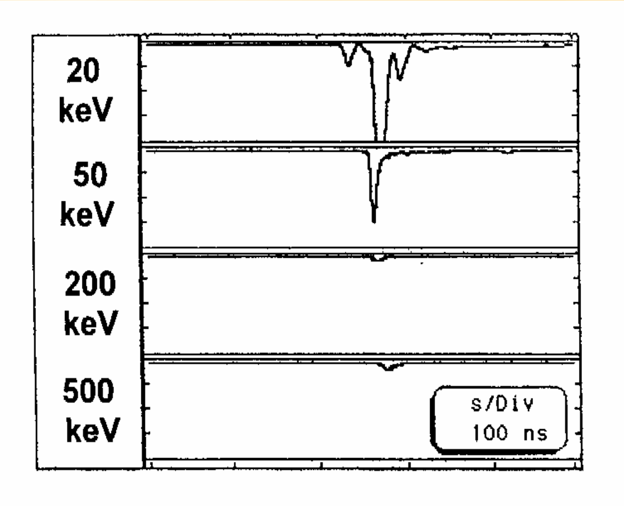
Studies of X-ray lines polarization were performed by means of two identical crystal spectrometers placed side-on MAJA-PF chamber, but with mutually perpendicular dispersion planes.

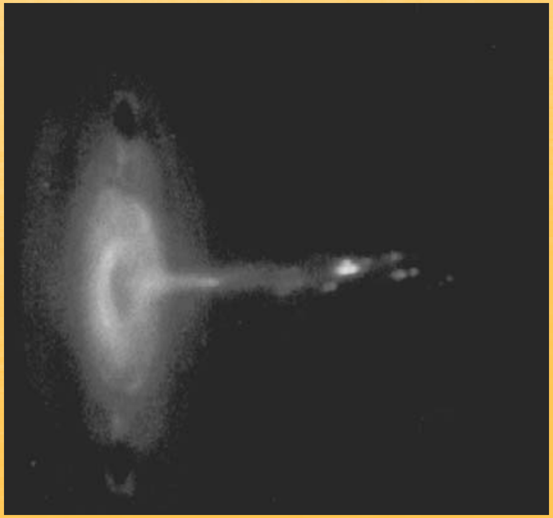


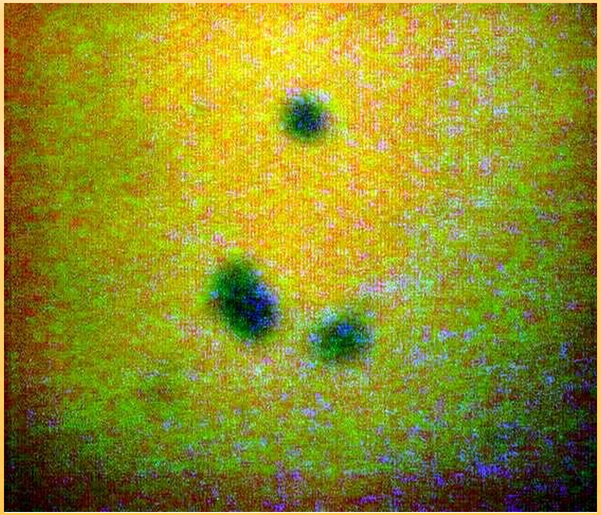
The measurements of X-ray spectra showed that the polarization of the highly-ionized Ar-lines is evidently different and it changes in time.

It suggests that the X-ray emission is induced by directed e-beams, which are emitted from different parts of current filaments (hot-spots).

Pulsed e-beams, hot-spots and beams of deuterons

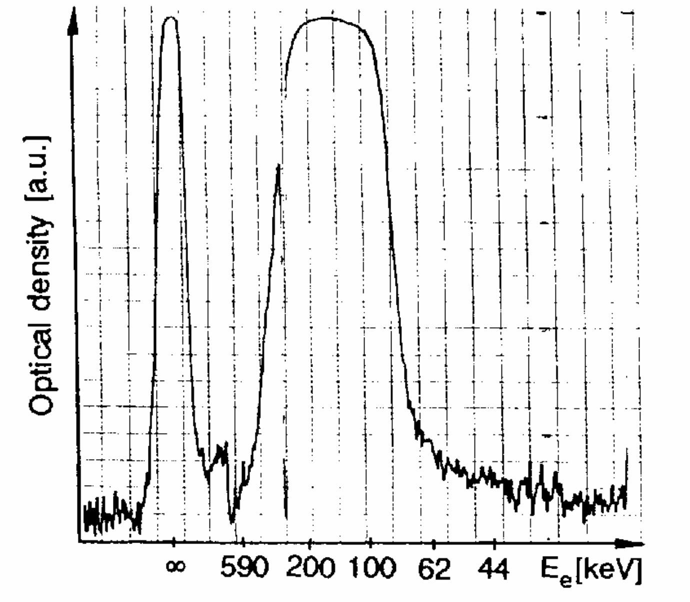




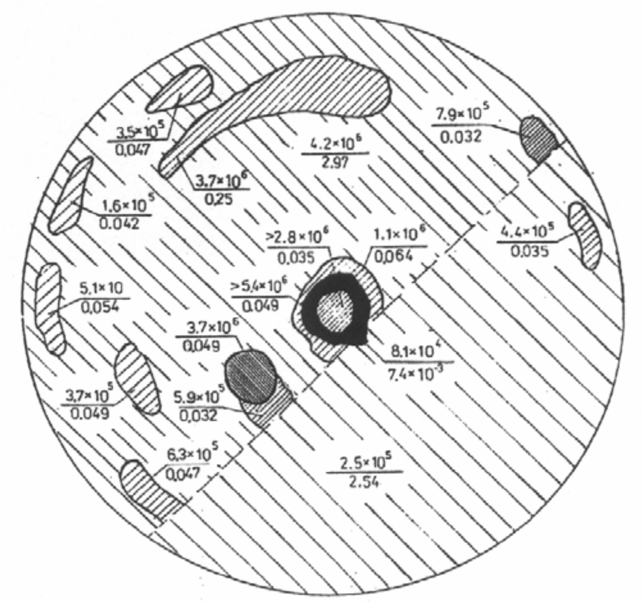


Signals of pulsed e-beams (measured in the upstream direction), images of hot-spots (observed in side-on X-ray pinhole images) and tracks of high-energy deuterons (recorded in the downstream direction) in MAJA-PF experiments.

Study of electrons and ions emitted from PF discharges



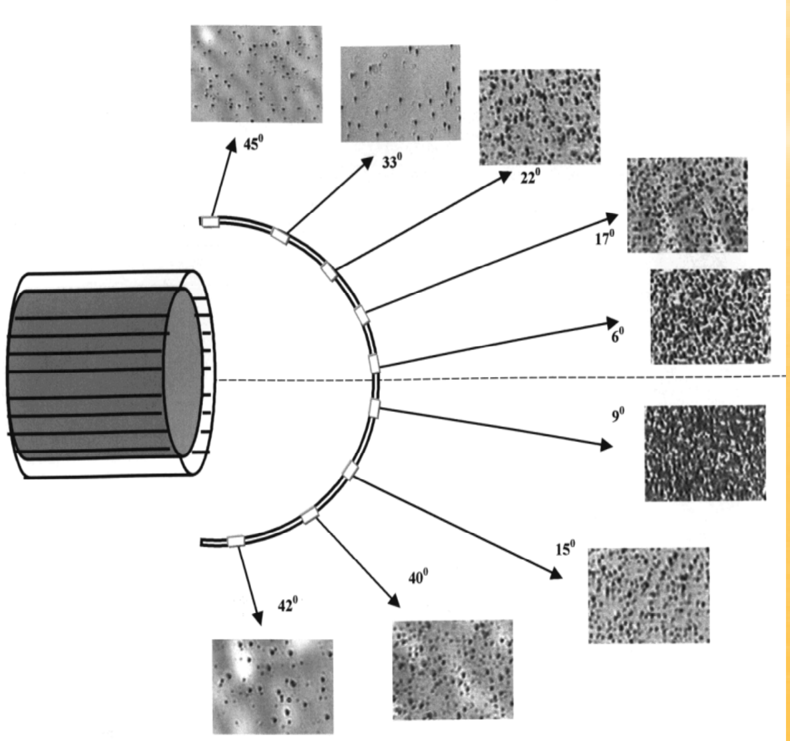
Energy spectrum of pulsed e-beams of energy ranging from about 50 keV up to about 800 keV, as measured with a magnetic analyzer in PF-360 facility operated at 154 kJ / 35 kV.



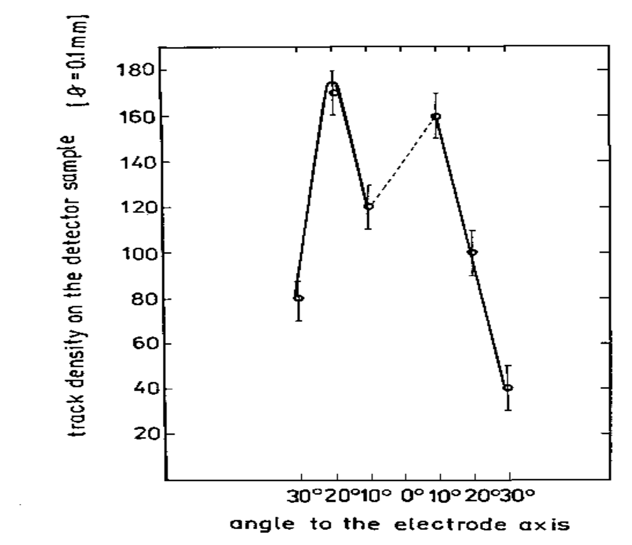
Fluxes of deuterons emitted from PF-360 facility, as measured with NTD shielded with different Al filters; the upper part recorded deuterons > 80 keV, while the lower part >220 keV only.

Fast electrons and ions are emitted (in opposite directions) from many miniature sources formed from current filaments, and they are deflected by magnetic fields.

Study of an angular distribution of the ion emission



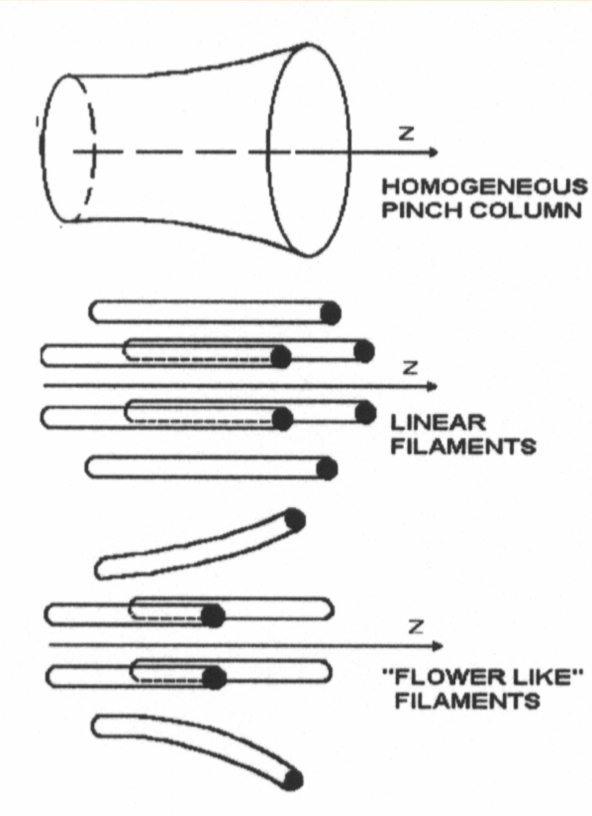
Measurements of fast ions at different angles to the z-axis in the large PF-1000 experiment (by A. Malinowska et al.)



Angular distribution of fast deuterons emitted from the PF-1000 facility, as measured earlier by M.J. Sadowski et al.

The observed angular distribution of fast deuterons, which show a local minimum at the z-axis, might be explained by the filamentary structure of the pinch column.

Theoretical analysis of an influence of current filaments



Modeling of a PF pinch column structure (by A. Pasternak et al.)

For a single linear-current column

$$B_r = 0,\ B_z = 0 \text{ and } B_\varphi = 2I\, r/c \quad \text{for } r < R$$

$$B_\varphi = 2I/r\,c \quad \text{for } r > R$$

Filamentary column can be described as a superposition of separate cylindrical currents

$$B_r \neq 0,\ B_z = 0 \text{ and } B_\varphi = \Sigma\, B_\varphi^{\,i}$$

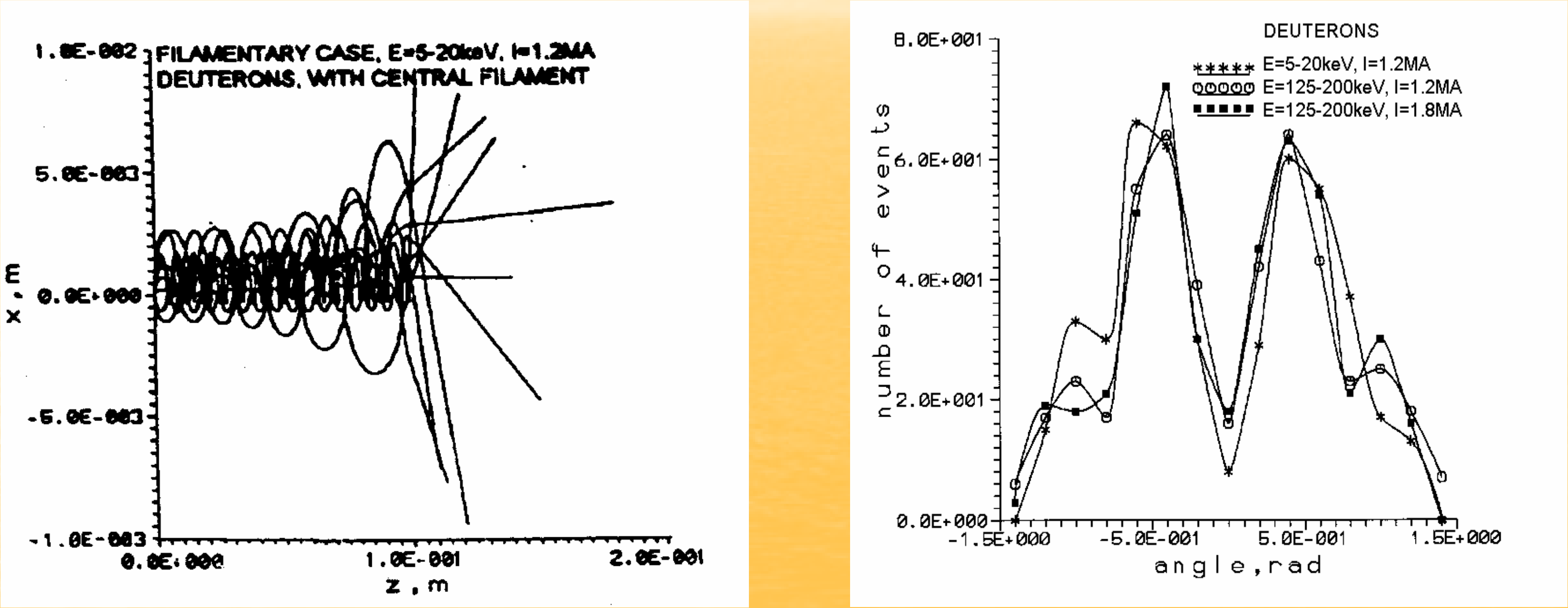
Ion motions can be analyzed by solving the known equations

$$m_i\, d\vec{v}_i/dt = Z_i e\, (\vec{v}_i \times \vec{B}) - \nu_{coll} \cdot \vec{v}_i$$

where $\vec{v}_i\, (v_r, v_\varphi, v_z)$ **denotes the particle velocity,**
$Z_i e$ **– electrical charge,** m_i **- mass of the particle,**
$\vec{B}\,(r, \varphi, z)$ **– local magnetic field, and** ν_{coll} **– collisional term.**

The system of equations can be solved numerically for different initial and boundary conditions.

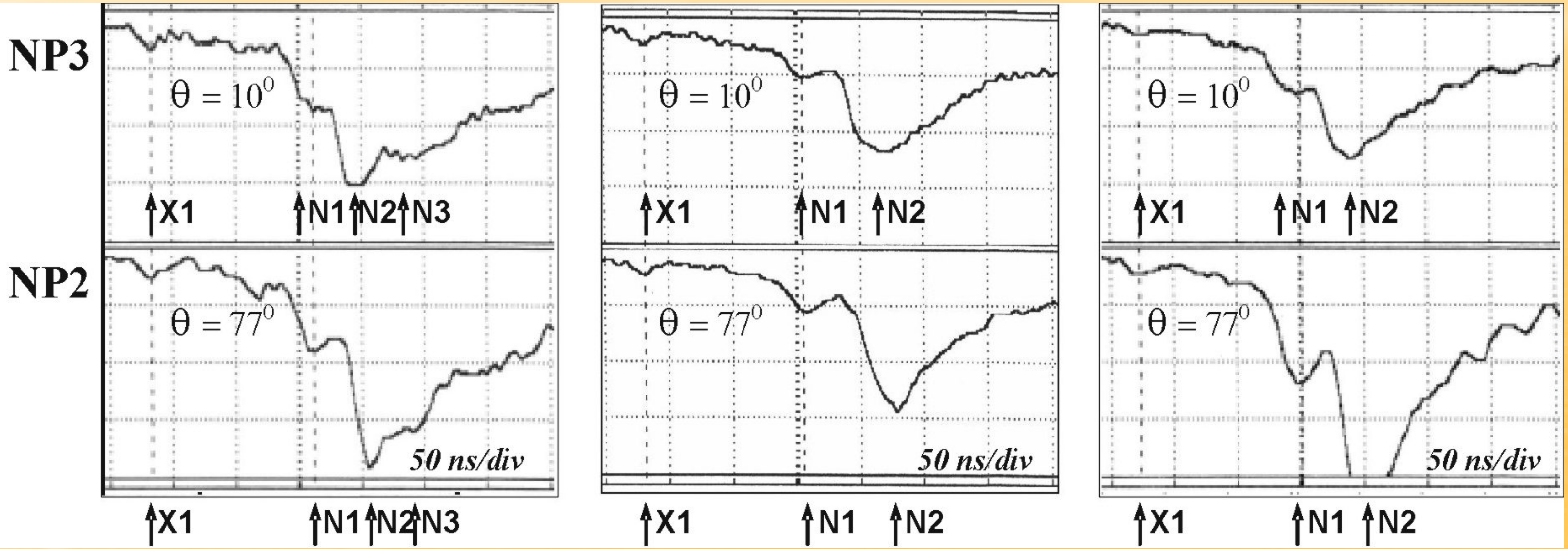
Influence of current filaments on ion trajectories



2D projection of ion trajectories within the PF column, as computed (by A. Pasternak et al.) for 7 linear current filaments (on the left), and the ion angular distribution - computed for 6 flower- like current filaments (on the right).

Anisotropy of the fusion neutron emission

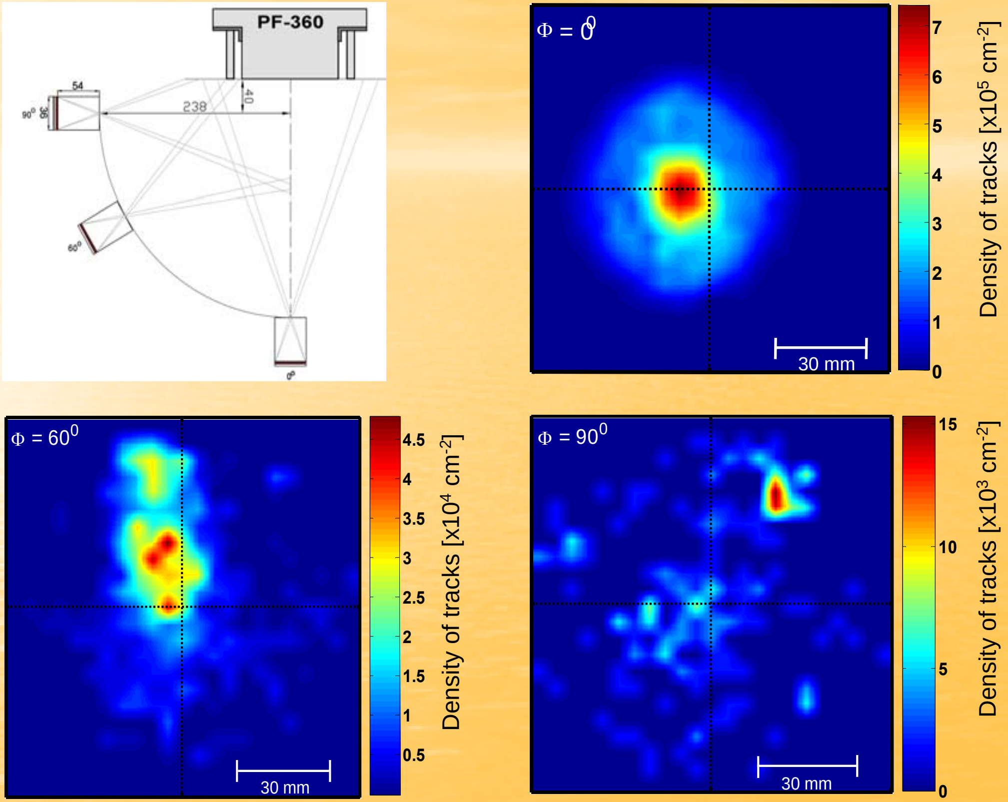
The neutron anisotropy is probably a result of different fusion mechanisms, e.g. beam-target interactions, thermonuclear reactions etc. (an open issue).



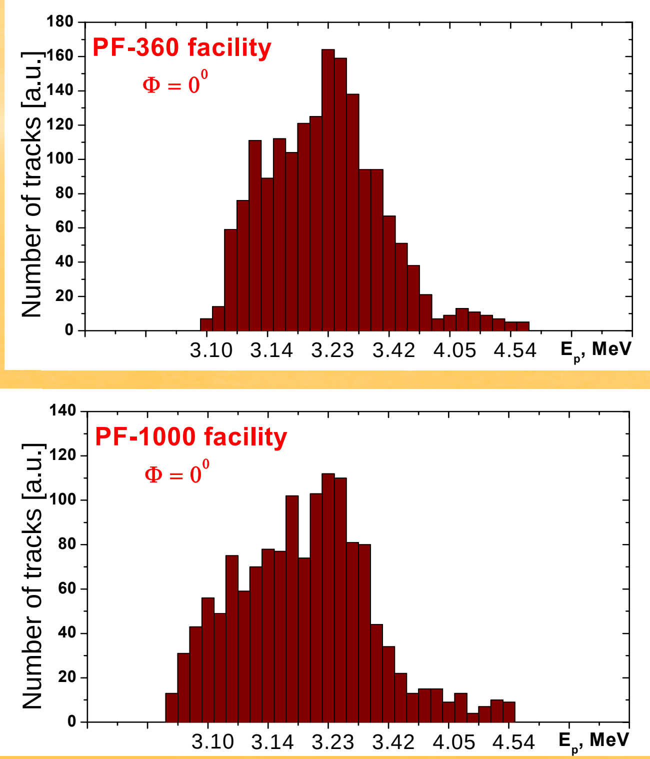
Neutron signals from scintillation probes placed at a distance of 3 m from the electrode outlet at different angles, as recorded in PF-360: a) at U_o = 29 kV, E_o = 106 kJ, p_0 = 6.25 hPa, $Y_n = 2.16 \times 10^{10}$; b) at U_o = 30 kV, E_o = 113 kJ, p_0 = 7.95 hPa, $Y_n = 1.41 \times 10^{10}$; c) at U_o = 30 kV, E_o = 113 kJ, p_0 = 7.8 hPa, $Y_n = 1.54 \times 10^{10}$.

Current filaments (i.e. their magnetic fields) do not deflect neutrons, but they influence motion of primary deuterons, which undergo the fusion.

Studies of fusion-produced protons

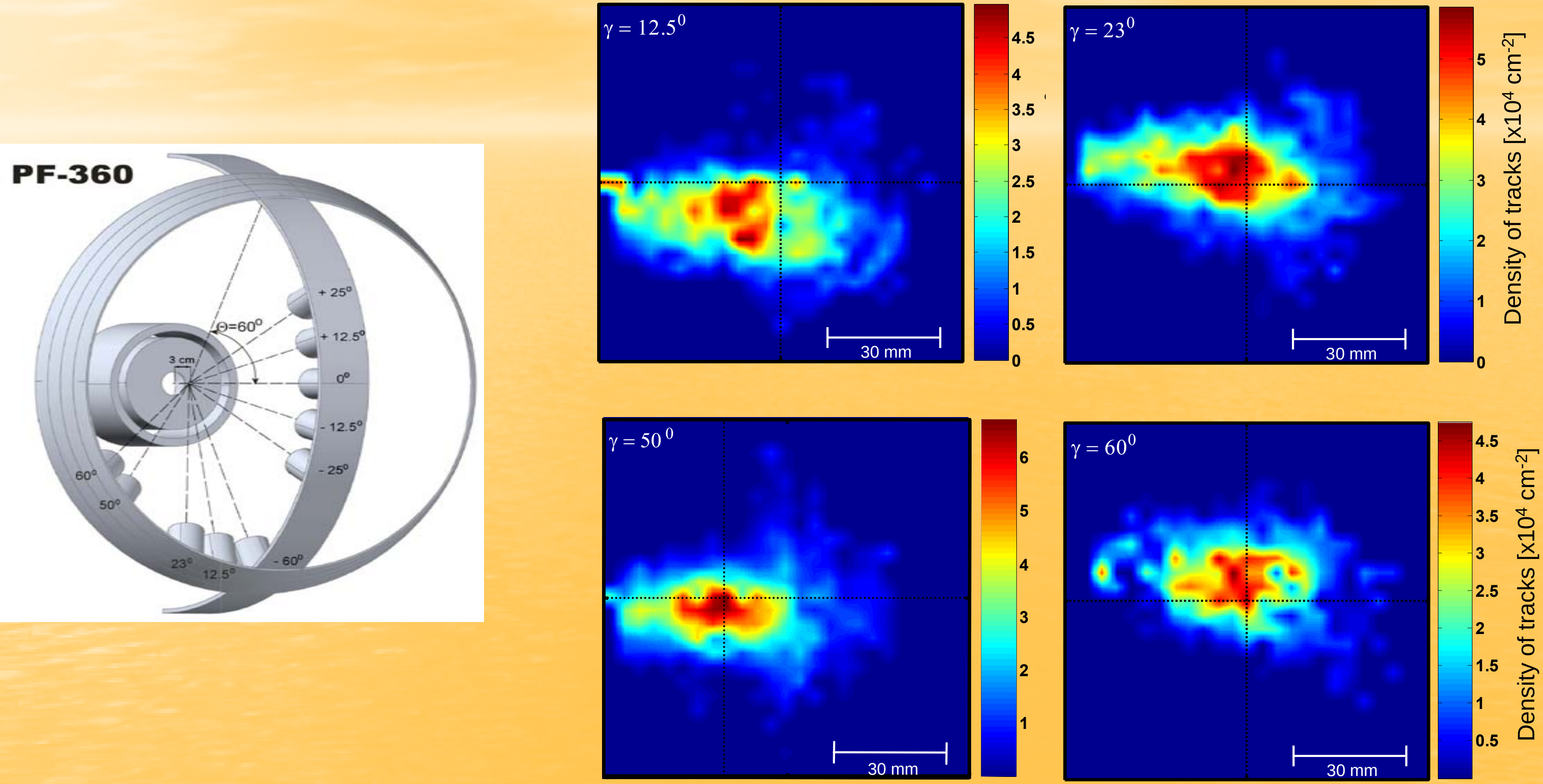


Arrangement of pinhole cameras in the horizontal plane of PF-360 facility, and images of tracks of fusion protons (recorded by A. Malinowska et al.) at different angles to z-axis.



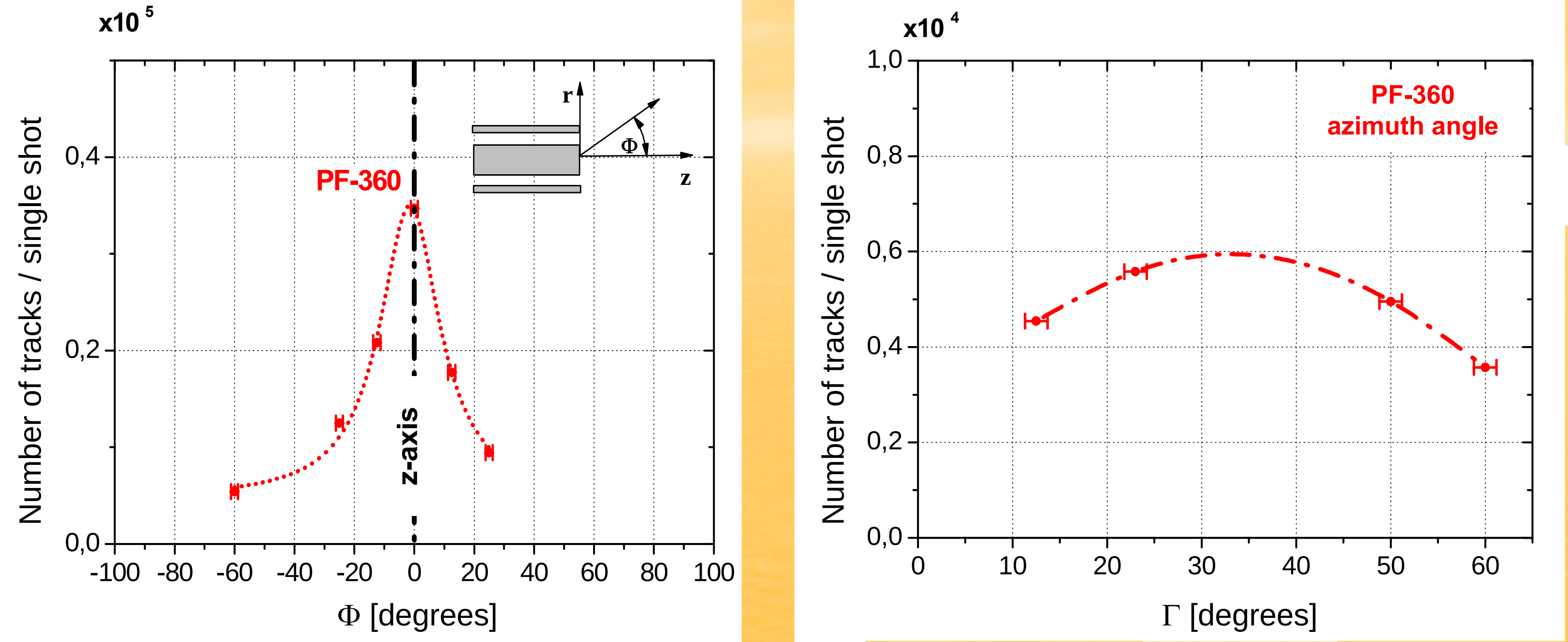
Histograms of the recorded tracks, which show that energy distributions of fusion protons in both experiments were very similar.

Studies of fusion-produced protons



Arrangement of ion-pinhole cameras and proton images, as recorded by A. Malinowska et al. at different angles in the plane vertical to the z-axis.

Studies of fusion-produced protons



Angular distribution of the fusion protons in the horizontal plane (on the left) and that in the plane vertical to the z-axis (on the right), as measured by A. Malinowska et al. in the PF-360 facility.

Considerable difference in numbers of the fusion-proton tracks recorded at different Γ angles (around the z-axis) shows a role magnetic fields of current filaments.

Summary and conclusions - I

1. **The breakdown and formation of a current sheath layer can be described by an improved 2D-MHD model, but the appearance of current filaments cannot be analyzed in this approach.**

   The formation and role of such filaments is still an issue.

2. **The axial acceleration phase is well described by 2D-MHD models, but new more-detailed studies of 3D phenomena (e.g. current filaments) are needed.**

   An influence of plasma non-uniformities and quasi-radial filaments is still a problem.

3. **The radial collapse phase can be described by an extended MHD model, but plasma instabilities and their roles require sophisticated models and detailed experimental studies of electromagnetic- and corpuscular-emissions.**

   The role of the current filaments in the radial compression phase is not clear.

4. **Research on dynamics of the PF column and its internal structure delivered information about current filaments and hot spots, but more accurate space- and time-resolved measurements are needed.**

   Mechanisms of the formation of quasi-axial filaments and hot spots remain open issues.

Summary and conclusions - II

5. Studies of fast electron beams and ion streams delivered information about their spatial- and energetic-characteristics. Correlation measurements and further theoretical analysis of electron- and ion-behavior in the a PF column, are needed.

   Mechanisms of the electron- and ion-acceleration as well as their motions inside the DMP region remain important issues.

6. The emission of fusion-produced neutrons was investigated in different PF experiments and many efforts were undertaken to optimize the neutron yield.

   The issue is still the optimization of the fusion-neutron yield and understanding of a role played by current filaments in this process.

7. The emission of fusion-produced protons has recently been studied, and valuable information about an influence of filamentary currents and magnetic fields appearing in the PF columns has been obtained.

   The influence of current filaments and local magnetic fields on trajectories of fusion-protons seems to be evident one.

Many experimental evidences of the appearance of current filaments in DMP discharges have been presented and it has been shown that such filaments play an important role.