Main Issues of High-Current Plasma-Focus Experiments

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Abstract – The paper concerns the main problems of contemporary Plasma-Focus experiments and particularly these run with MAJA-PF, PF-360 and PF-1000 facilities in Poland. Some theoretical models of the initial breakdown, which occurs at the insulator surface, are compared. It is pointed out that modeling of the breakdown is sensitive to kinetics of ionization processes and transport coefficients. Progress in experimental studies of the axial acceleration phase is un-satisfactory. Important experimental data have been collected, but new measurements are still needed. For the radial collapse phase it was shown that the MHD modeling is efficient until the maximum compression, but plasma instabilities require more sophisticated approaches. The pinch phase was investigated by means of different diagnostics. Differences in the polarization of X-ray spectral lines have been explained as a result of directed e-beams generated within hot-spots. The emission of accelerated primary ions was also considered and their angular distributions and energy spectra have been compared. Fusion neutron yields were measured in different experiments, but some discrepancies in scaling must still be explained. Attention has been paid to neutron anisotropy and fusion-produced protons. The conclusions concern directions of further studies and the optimization of large-scale high-current PF facilities.

1. Introduction

During the recent years numerous Plasma-Focus (PF) facilities of different energy have been investigated in Poland, e.g., PF-1000, PF-360, and MAJA-PF [1–12].

The largest mega-joule PF-1000 facility, equipped with a 3.5-m long experimental chamber, is shown in Fig. 1.

The PF-1000 facility was equipped with various diagnostic tools: equipment for measurements of voltage- and current-waveforms, high-speed cameras recording VR and X-ray images of plasma, X-ray pinhole cameras and crystal spectrometers, ion pinhole cameras and sets of nuclear track detectors (NTDs) for measurements of fast primary ions (mostly deuterons), as well as scintillation- and activation- detectors for measurements of fusion-produced neutrons, etc. [12–13]. All these tools were used for numerous experimental studies, which have been performed by international-teams within the frame of the International Center for Dense Magnetized Plasmas (ICDMP) operated at IPPLM in Warsaw.

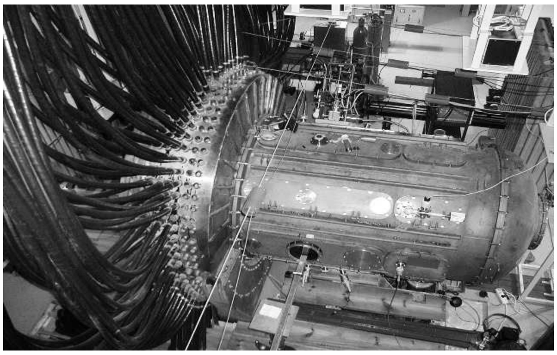

Fig. 1. Top view of the present experimental arrangement with the large PF-1000 chamber

Numerous PF experiments were also carried out at IPJ in Swierk [6–7]. A general view of the PF-360 machine [6], which was constructed as a 1:4 scale prototype for the PF-1000 facility many years ago and after that modified several times, has been presented in Fig. 2.

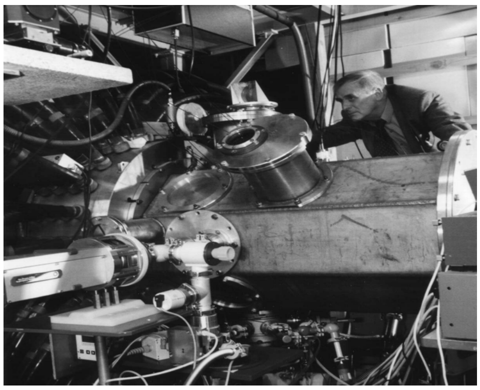

Fig. 2. General view of the PF-360 experimental chamber with the diagnostic equipment used during recent experiments

The PF-360 machine was also equipped with diagnostic tools similar to those used in PF-1000 facility. The third MAJA-PF device [7] was equipped with special Cerenkov-type detectors and magnetic analyzers for measurements of fast electron beams, and two crystal spectrometers for studies of the polarization of X-ray lines [7–9]. Unfortunately, the experimental data from these facilities, and even those gathered from the same PF machine with different diagnostic techniques, could hardly be compared due to different measuring techniques and a lack of good storage and synchronization. The main phases of the PF discharges, however, have been well defined and they can easily be identified in all the experiments, as shown in Fig. 3.

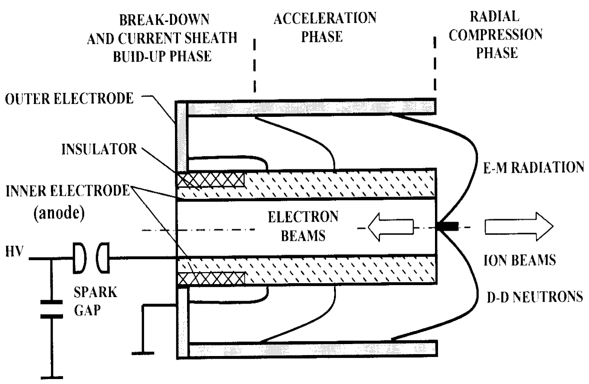

Fig. 3. Scheme of an experimental setup, showing the location of a current sheath during the three main phases of the PF-discharge

Stochastic character and complexity of PF phenomena require a detailed qualitative and quantitative analysis. For this purpose the data obtained with a given diagnostic technique should easily be related to those obtained with other methods (even after a long time). Therefore, all the PF discharge phases should still be studied in more details and more systematically.

2. Progress in Studies of Breakdown

The initial breakdown occurs at the insulator surface, and the final PF pinch-column is formed at the electrode outlet. These two stages, which are separated by the axial acceleration and radial collapse phases, can in fact be optimized in different ways. A current-sheath layer, as formed at the insulator, cannot be accelerated within the inter-electrode gap effectively at a very low gas pressure. An appropriate amount of gas must be delivered to enable effective "snow-plough" process. Numerical simulation of the breakdown phase was performed by different researchers [1–3] and the results of such computations agree relatively well with results of experimental observations, as shown in Fig. 4.

Other theoretical approaches of the breakdown phase have been reported recently [14]. Unfortunately, an accurate quantitative model, taking into account complexity of the current sheath formation phase, is still missing. In particular, influence of a status of the insulator surface should be taken into consideration. Active experiments with planned modifications of the insulator surface have not been performed so far, although they were proposed during the IWDMP in 2002. A localized gas puffing has also been under consideration only.

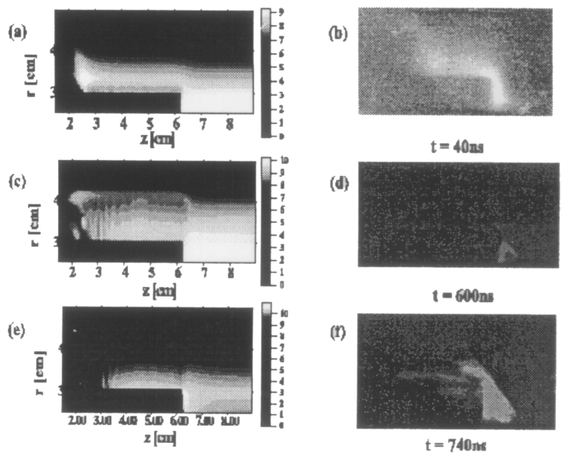

Fig. 4. Comparison of computed density distributions with high-speed camera pictures showing a relatively good agreement

The well known difficulties in the operation of PF facilities at large energy are probably connected with a lack of the optimization of different parts and/or procedures. It should be reminded that in the POSEIDON facility [15] the replacement of a glass insulator by a ceramic one shifted the so-called „neutron saturation limit" and it made possible the operation at higher energy and higher neutron yields. As regards the breakdown phase in the PF-1000 facility, it is a pity that no experimental optimization of the main insulator material and configuration has been made so far.

3. Status of Research on Axial Acceleration Phase

To perform modeling of the axial acceleration phase different approaches were applied. The most popular and effective appeared to be the 2-fluid MHD model using plasma continuity, momentum and energy equations, Maxwell equations and the electrical circuit equation. In general, the modeling is very sensitive to kinetics of the ionization and transport coefficients. The computer simulation must of course be specified for the chosen electrode configuration and gas conditions. For the PF-1000 experiment simulation the use was made of the Braginski transport coefficients [14]. The ionization process was described by the known formula $dn_e/dt = n_e(n_o - n_e)\, S - \alpha_r\, n_e^2 - \beta_{3B}\, n_e^3$, where values of coefficients S, α_r and β_{3B} were assumed according to the Braginski theory. Anomalous resistivity of plasma was also taken into account. Some results of the performed computations are presented in Fig. 5.

Unfortunately, there are is no progress in experimental studies of the axial acceleration phase, although new probe and spectroscopy measurements are under preparation. In authors opinion attention should be paid to effects of non-uniformities and quasi-radial filaments during the axial motion of the current sheath, as shown in Fig. 6.

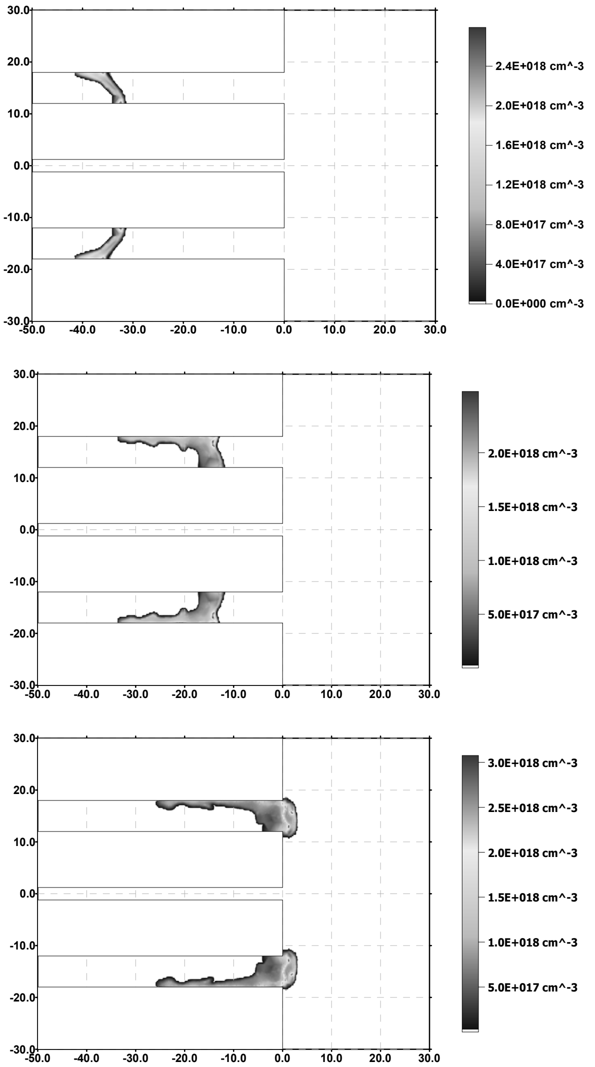

Fig. 5. Plasma density distribution in the accelerated current-sheath, as computed for the PF-1000 experiment [12] and different instants: 3 μs, 5 μs and 7 μs after the discharge beginning

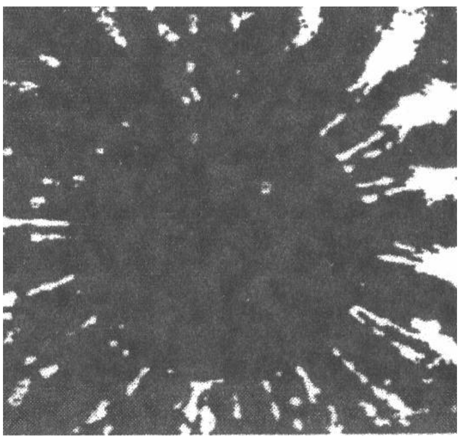

Fig. 6. Quasi-radial filaments in the CS layer during the axial acceleration, as recorded end-on with a high-speed camera [16]. A role of such filaments has not been explained so far

4. Status of Research on Radial Collapse Phase

The performed computations have proved that the MHD modeling of the collapse phase is efficient until the maximum compression occurs. After that the development of different plasma instabilities requires more sophisticated approaches. Nevertheless, using an extended MHD model described above, some valuable computer simulations of the collapse phase were carried out. Some examples are shown in Fig. 7.

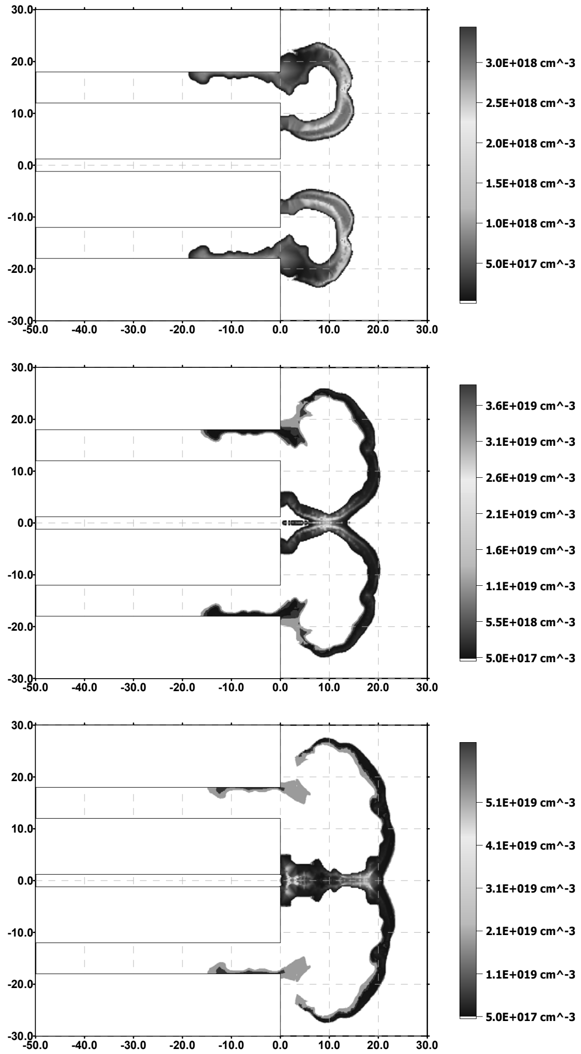

Fig. 7. Plasma density distribution during the radial collapse, as computed for the PF-1000 experiment [12] and different instants: 9 μs, 9.7 μs and 10 μs after the discharge beginning

The dynamics of the radial collapse phase has been extensively investigated with high-speed cameras. Numerous VR pictures were collected and analyzed by a comparison with some model computations. Those calculations were performed simultaneously on the basis of the extended MHD model described above. In general, the ecorded VR pictures are in a good qualitative agreement with results of the performed simulations, as shown in Fig. 8.

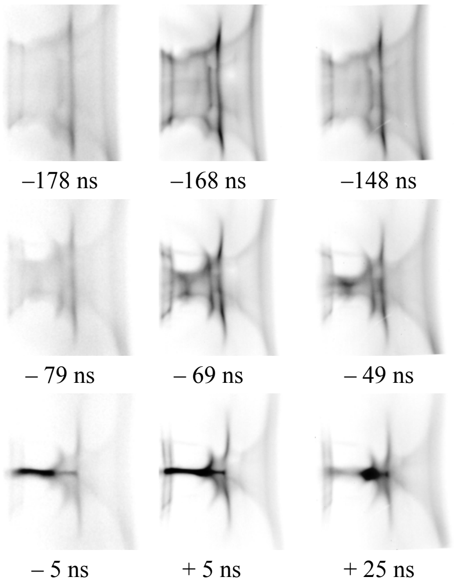

Fig. 8. High-speed frame camera pictures of the radial collapse phase, as taken in the PF-1000 experiment performed at $p_0 = 4$ hPa, $U_0 = 33$ kV and $I_{max} = 1.7$ MA (2002). Time is expressed in relation to the maximum compression

One can easily see that the development of local MHD instabilities can be simulated, but their location in the real experiment cannot be indicated synonymously, due to their stochastic character. Another problem is some disagreement between the computed and recorded current waveforms, as shown in Fig. 9.

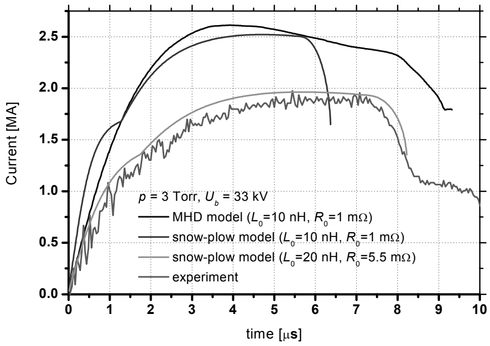

Fig. 9. Discrepancies between computed current-waveforms and experimental traces, as observed in the PF-1000 experiment [14]

These differences could be induced by wrong values of the circuit parameters, which were taken for the modeling of PF-1000 discharges, but one cannot exclude the case that the applied model does not work sufficiently. This question must still be investigated experimentally and theoretically.

5. Progress in Studies of the Pinch Phase

The pinch phase of PF discharges has also been investigated extensively. The use was made mostly of high-speed smear- and frame-cameras and the other diagnostic tools described above. Some examples of the recorded traces and high-speed VR pictures are shown in Fig. 10.

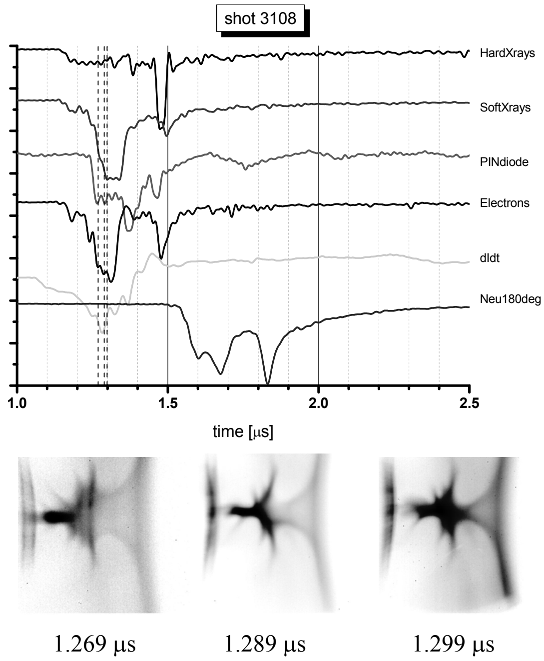

Fig. 10. Time-resolved traces and high-speed pictures of the pinch phase in the PF-1000 experiment performed at $p_0 = 4$ hPa, $W_0 = 734$ kJ and $I_{max} = 1.66$ MA [14]. The images correspond to instants indicated by broken lines

6. PF Emission Characteristics

The emission of X-rays from PF discharges was investigated with different techniques: pinhole cameras, scintillation detectors and crystal spectrometers. Numerous data were collected and reported. Differences in the polarization of various X-ray spectral lines have been discovered (in MAJA-PF experiments) and explained as a result of the appearance of directed e-beams, which are generated within hot spots [6–7]. The polarization effects should be studied in more details, also in large-scale PF experiments. Correlations between pulsed e-beams (emitted mainly in the upstream direction), the formation of so-called "hot-spots" (observed in X-rays pinhole images) and pulsed beams of high-energy deuterons (emitted mostly in the downstream direction) have been observed in several MAJA-PF experiments (2001). Some examples are shown in Fig. 11.

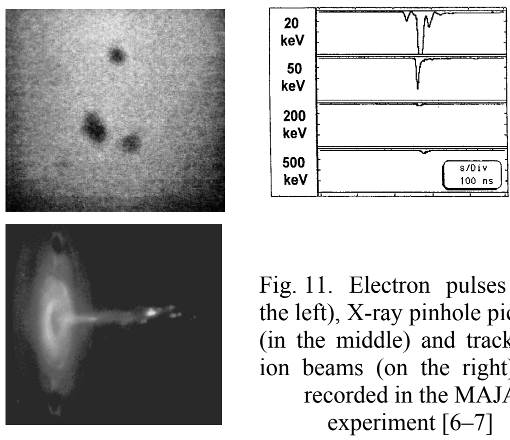

Fig. 11. Electron pulses (on the left), X-ray pinhole picture (in the middle) and tracks of ion beams (on the right), as recorded in the MAJA-PF experiment [6–7]

The emission of accelerated primary ions (mainly deuterons) was investigated with different techniques, as described above. Angular distributions of the emitted ions have been measured by means of NTD samples placed at various angles and fixed upon the semi-circular support, as shown in Fig. 12.

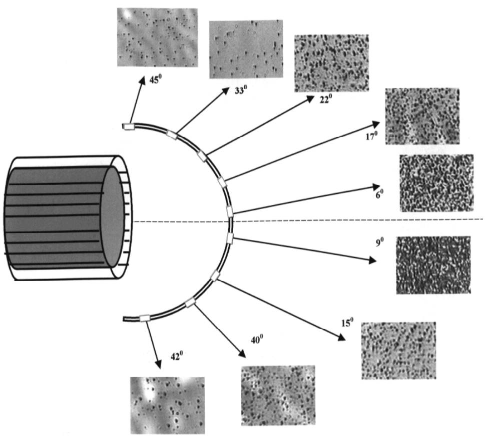

Fig.12. Ion angular distribution in the PF-1000 facility, as measured by means of NTDs placed at different angles to the z-axis [3]

Energy spectra of these fast ions have also been investigated, but they are not of importance for the D-D fusion reactions occurring mostly within a dense magnetized plasma column. During recent PF experiments particular attention has just been paid to the emission of fast neutrons produced by the D-D fusion reactions. The total fusion neutron yield was measured within the PF-1000 facility at different experimental conditions, as shown in Figs. 13 and 14.

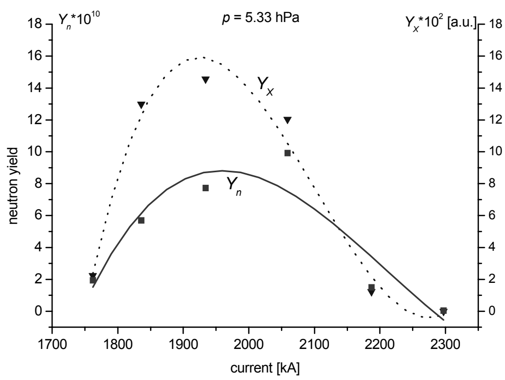

Fig.13. Neutron and X-ray yields from the preliminary experiments performed at constant initial pressure and different discharge currents in the PF-1000 machine equipped with an old set (version I) of electrodes [3]

Recent neutron measurements, performed for PF-1000 machine with new electrodes, have shown some discrepancy in absolute values (by factor of 2), as determined by means of different measuring techniques [14]. This effect must still be investigated and explained. Recently, particular attention has also been paid to measurements of neutron anisotropy and fusion-produced fast protons. These experiments must be continued.

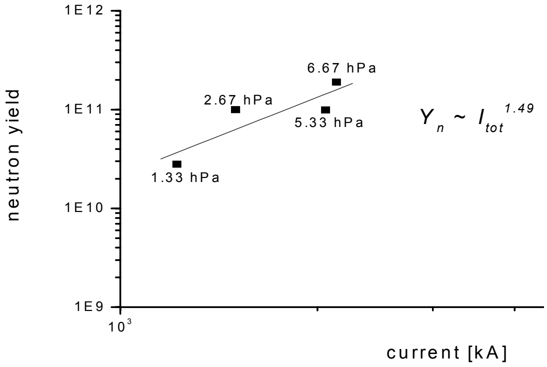

Fig.14. Neutron yield from the PF-1000 experiments performed with another set (version II) of Mather-type coaxial electrodes in order to determine the scaling law [11]

In general, PF discharges with the highest neutron yields are not necessarily the ones with the strongest anisotropy. High neutron yields were observed in some large-scale PF experiments, when the first predominant neutron pulse was characterized by a reduced anisotropy. One should also study temporal changes in the neutron emission anisotropy, as it was done in the PF-360 machine [17].

In order to optimize the operation of the chosen PF facility and to estimate possibilities for an increase in the fusion neutron yield, one should analyze the whole circuit of the PF discharge. For this purpose one should consider energy (W_{in}) supplied to the system, energy cumulated within the pinch ($W_{\mathrm{pinch\text{-}internal}}$) which can be divided into two components: thermal (W_{th}) and fast beam ($W_{\mathrm{fast\text{-}ion}}$). The final neutron yield is in fact determined both by the thermo-nuclear processes and beam-target interactions, as shown in Fig. 15.

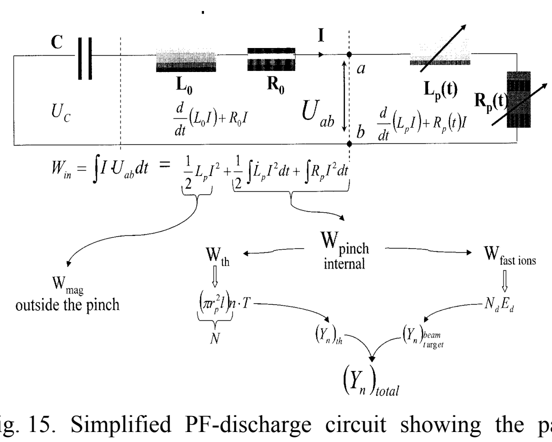

Fig. 15. Simplified PF-discharge circuit showing the parameters which determine the total neutron yield from D-D fusion reactions

Such an analysis, which should be performed for realistic experimental parameters, may deliver valuable information how to increase the total neutron production.

7. Summary and Conclusions

The most important conclusions from this review paper can be formulated as follows:

1. Further theoretical and experimental PF studies are necessary. The main aims remain: optimization of PF machines operation, analysis and optimization of the fusion yield.

2. To study the breakdown phase an improved model should be developed and the dedicated experiments should be run with special pre-formed insulators or localized gas puffing.

3. The axial acceleration phase should be modified by the use of active segmented electrodes or additional gas puffing. A role of the current-sheath filamentation should be explained.

4. The radial collapse phase should be optimized by modifications of electrode ends and gas conditions. A role of current-sheath symmetry and uniformity must be investigated.

5. Behavior of a pinch column must be studied in more details. Time-resolved X-ray, optical and corpuscular measurements should be carried out simultaneously and systematically.

6. The obtained data should be stored and analyzed by different researchers. This is needed to explain PF phenomena, (e.g. hot-spots) and to optimize PF emission characteristics.

7. The fusion yield might be increased by use of special targets. One might apply special gas- or solid-targets.

Acknowledgements

The authors wish to express their thanks o all the colleagues and coworkers who helped to perform numerous PF experiments at IPPLM and IPJ.

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