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On the influence of gas puff loads on plasma focus dynamics

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Abstract The plasma focus is a source of pulsed radiation, which is of interest in various fields of physics and technology. Applications include soft X-ray microscopy, soft X-ray and electron beam lithography. The plasma focus is also a highly efficient source of fast neutrons. If one applies gas puffing instead of static filling, decoupling of plasma conditions in the breakdown and compression phases can be achieved. Results of experiments with a fast valve and accompanying 2D modelling of the dynamic gas target are presented. Among other advantages of gas puffing, neutron yield could be increased up to a factor of three in appropriate experiments. The concept of gas puffing has been extensively investigated in many Z-pinch experiments including multiple gas puffs. It seems desirable to increase the efforts to understand and optimise the gas puffing option for small and large plasma focus devices.

Key words computer modelling • gas puffing • nuclear fusion • nuclear reactions • plasma focus • Z-pinch

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Introduction

Plasma focus devices are known as sources of soft and hard X-rays, of high-energy electrons and ions as well as intense sources of fast neutrons. They belong to the family of high density Z-pinches, earlier also being called non-cylindrical Z-pinches. Two main classes of Z-pinches are the equilibrium Z-pinches (exploding wire, fibre pinch, gas-embedded pinch, vacuum spark, capillary discharge) and dynamic Z-pinches. In dynamic Z-pinches the converging current (plasma) sheet may propagate in a medium of homogeneous density (classical Z-pinch) or into a gas of non-homogeneous density distribution (e.g. gas puff pinch, wire-array pinch, or cylindrical liner [6]).

Gas puffing in Z-pinch or plasma focus devices has not only the advantage of shaping the density distribution in the discharge region, but one may also use different gases, which helps in diagnosing (using characteristic line emission) the physical behaviour of the various stages in the plasma compression. In some plasma focus devices (predominantly those in the energy range above 100 kJ) hot (or bright) X-ray emitting spots in heavy gases can only be generated when gas puffing in front of the anode is applied and the breakdown and running down phases occur in light gases, e.g. hydrogen [21]. The application of gas puffing in a plasma focus can be manifold: 1) In the breakdown region, 2) in the region of the final compression or 3) in between, i.e. above the insulator in the run down region in order to avoid impurities from breakdown on the insulator surface to be swept down to the pinch region. (There were also attempts to use laser beams in this region).

In a more general sense, wire arrays can also be regarded as gas puffing. Here the particles are not injected from outside but are released locally from solid state to gas phase when the current (plasma) sheet arrives. The result in both cases (gas puffing and insertion of wire arrays) is shaping of the density distribution. In the case of wire arrays and foam targets the density distributions can be tailored more exactly than in gas puffing where properties of fast valves play an important role. The highest X-ray yields were attained with wire-array Z-pinches [7, 9, 10]. Research activity in optimising the emission characteristics of a plasma focus has predominantly been performed in the experimental field during the last decades. Applications include soft X-ray microscopy, soft X-ray and electron lithography, and metal coating by ion sputtering.

The following paper first describes some of the main characteristics of plasma focus discharges (with or without gas puffing). Then possibilities and motivation of gas puffing are discussed. The paper also presents some details of experiments performed in Stuttgart (Germany) in the frame of a collaboration with the Soltan Institute in Swierk (Poland) and includes results of modelling the gas puffs from the nozzles of the fast valve used for the experiments. The main aim of those experiments was to investigate the modified plasma pinch dynamics and its influence on the emission characteristics of electrons, X-rays and neutrons. Special emphasis was put on the influence of gas puffing on neutron yield.

Plasma focus characteristics

In a plasma focus discharge one should distinguish three main phases: the breakdown phase, the running down (or acceleration) phase and the compression phase. Homogeneous breakdown is of importance for a successful radial compression of the plasma. In any case Rayleigh-Taylor instabilities will occur [11, 12, 19, 20]. Axial magnetic fields [4] and thin plasma (current) sheets increase the stability behaviour of the compressed plasma column. In the final compression phase the plasma current decreases rapidly, predominantly due to microinstabilities causing anomalous resistivity. Increasing inductance (of geometrical origin due to the shrinking plasma and current tube) in this phase has a minor influence on the observed current dip.

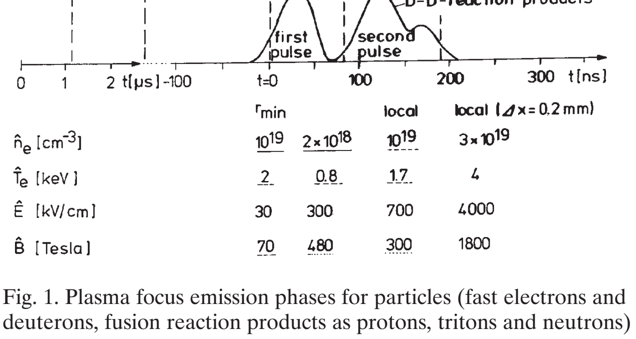

Fig. 1. Plasma focus emission phases for particles (fast electrons and deuterons, fusion reaction products as protons, tritons and neutrons) and radiation. Neutron emission shows two distinct phases of totally about 200 ns in the case of a 280 kJ shot with a 131 mm diameter anode. Figures for maximum electron densities, temperatures, electric and magnetic fields in the various phases are also given. The time scale refers to the maximum compression (minimum radius of the plasma column $r = r_{min}$ at t=0).

The plasma focus is a source of pulsed radiation, which is of interest in various fields of physics and technology. Relatively slow current rise time of the (usually capacitive) generator (in the range of one to a few microseconds) leads to intensive short bursts (in the one to several hundred nanosecond range) of soft hard X-rays, collimated electrons and ions. The final pinch phase is characterised by flash emission of radiation (from the microwave up to the hard X-ray region) and directed high-energy particles: Ions and electrons are accelerated in the high amplitude transient electromagnetic fields [8] and are emitted downstream and upstream (i.e. away from and towards the anode, which is usually the inner electrode of the coaxial accelerator). The temporal emission often manifests itself in two consecutive phases, as shown in Fig. 1. The neutron emission (in the case of operating the device with deuterium filling) is anisotropic in space in both emission phases [8, 13].

For optimisation of the emission characteristics of a plasma focus the following parameters are usually varied: electrode and insulator geometries, operating voltage, impedance and energy of the generator, filling pressure. The electric characteristics of the discharge have to be matched with the geometry and gas filling density in such a way that current maximum is reached around the final compression phase. Variation of the energy input is therefore rather limited for a given accelerator geometry and/or filling density.

A new degree of freedom in the choice of parameters can be accomplished if one applies gas puffing instead of static filling. In former experiments gas puffing was used either in the "breakdown region", i.e. near the insulator at the back end of a Mather-type plasma focus [1] or in the "focus region" [14] where the final compression to a magnetized plasma of

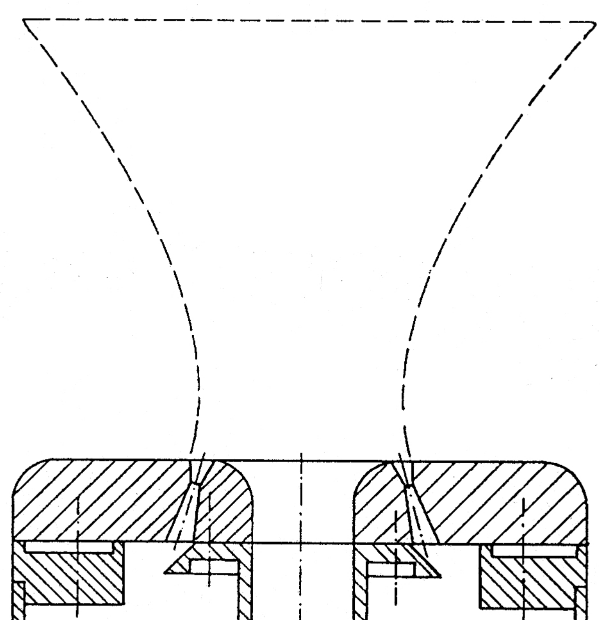

Fig. 2. Cross-section of the inner electrode (anode, 131 mm diameter) with nozzles (diameter 2 mm, tilted by 15° to the axis). The pinch region is marked by the dotted lines.

high particle and energy density with strongly anomalous resistivity takes place. Gas puffing allows a certain degree of decoupling of plasma conditions in the breakdown phase to that of the final compression phase. This concept has extensively been investigated in many gas-puff Z-pinch experiments [2, 3, 7] whereas only few experiments have been performed with plasma focus devices [1, 15].

Gas puff loads and their mathematical modelling

"Z-pinch experiments with gas puff loads are difficult to compare qualitatively to theoretical predictions since the mass distribution varies both radially and axially, is time dependent, often suffers from fluid turbulence, and is difficult to quantify" [9].

Experiments with a fast valve for gas puffing [14, 15] were performed in POSEIDON, a large 80 kV, 500 kJ Mather-type plasma focus. The fast valve was inserted in the anode and gas puffing was applied in the downstream direction. A coaxial array of 24 miniature nozzles, 2 mm in diameter, tilted by 15° to the axis, formed a convergent conical gas target at the end of the inner electrode, see Fig. 2. The interaction of the radially converging current carrying plasma sheath with the injected gas target was investigated via various diagnostic methods, including a pulsed image converter (planar diode) camera for pictures in the visible range with exposure of less than 3 ns, image converter streak pictures, Schlieren frames with exposure of 1 ns, and voltage and current signals of the discharge, which were modified in various degrees by the strength and timing of the gas puffing [15]. The discharge vessel was filled with deuterium to pressures between 1 and 5 hPa, the input energy ranged from 135 to 210 kJ at an operating voltage of up to 51.5 kV. Taking into account the time interval needed for the injected gas to expand through the nozzles and to form a gas cloud, the plasma focus discharge was initiated with a time delay between 300 and 800 μs in relation to the triggering of the valve. The trigger of the valve was determined by monitoring the current in the valve coil with a Rogowski coil. Analysing the main discharge current, the measured time interval between the beginning of the dI/dt peculiarity (which corresponds to the moment when the current sheath hits the dense gas-puffed target) and the first distinct dI/dt peak, can be regarded as the compression time of the gas-puffed target. This compression time depends strongly on the application of the gas puffing. If one applies higher pressures inside the valve plenum (5 cm^3), the compression time is increased.

There has been an attempt to model the gas target being ejected from the fast valve by Semushin [5]. In the 2D simulations of the nozzles used in the POSEIDON device, shown in Fig. 2, all the holes are represented as annular gaps with equivalent cross section areas. As there are a large number of holes, the 2D simulation should give adequate results. In the computation, it is assumed that the valve is opened with infinite speed. According to the mathematical simulation, the flow is supersonic (Mach number M=2) at the exit of the nozzle, and the flow is quasi stationary after 100 μs. At later times the density decreases. Distribution of gas speed, density, pressure and Mach number at 400 μs after the opening of the valve are presented in Figs. 3 and 4. The presented results are only the first step in the simulation. Semushin concluded that a favourable mass distribution for a Z-pinch is not formed by the spreading jet itself but by complex pattern of mutually interacting shock and other waves. The supply system design can strongly affect the mass load, i.e. the supersonic flow from the nozzle is very sensitive to details in the design of the valve. In the next step one should try performing a MHD calculation taking into account the gas target as produced by the gas puffing. This is a large field for comparing the theoretical [17] and well diagnosed experimental results. Recently experiments were performed with multiple gas puffing in order to further decrease the instabilities of the Z-pinch column [16, 18].

Influence of gas puff loads on neutron and X-ray emission

In experiments without gas puffing usually two main neutron pulses and two groups of fast electron beams are registered. These electrons (as registered with Cerenkov detectors) are well correlated with the hard X-ray pulses and the

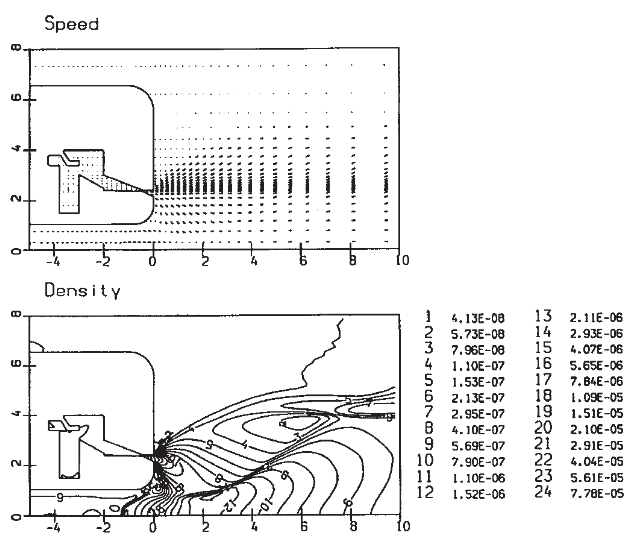

Fig. 3. Plots of distributions of flowing speed and gas density at 400 μs after the opening of the valve. Radial and axial scales are given in cm.

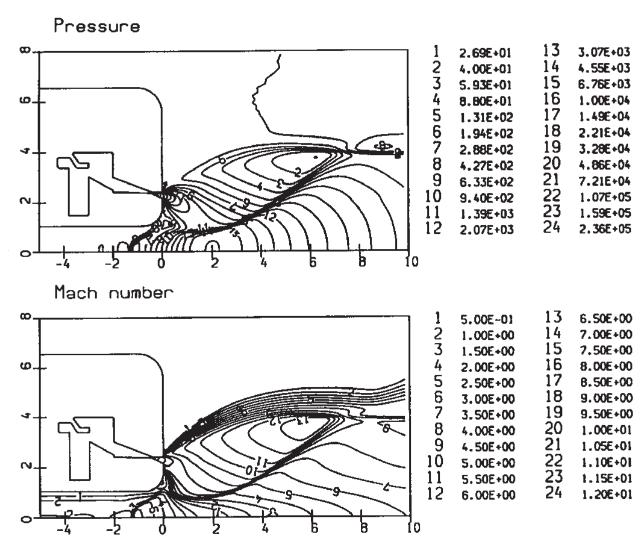

Fig. 4. Contour plots as in Fig. 3 for gas pressure and Mach number, also at 400 μs after the opening of the valve.

first dI/dt peak. Sometimes they show a multi-spike structure, however.

In experiments with gas puffing the first of the two neutron pulses (as well as the total neutron yield, up to 80%, see Fig. 5) can be increased. The first group of fast electron beams is emitted simultaneously with the corresponding hard X-ray pulses, but the second group of neutron and electron pulses is usually decreased. With a further increase of the injected gas, the second group of neutron and electron pulses usually completely disappears.

It seems that with gas puffing of sufficient intensity the dynamics of the final pinch phase are profoundly changed: The absence of the second pulse of accelerated electrons and ions is an indication that the temporal behaviour of instabilities and electromagnetic field distributions has quite different characteristics than in the case of experiments without gas puffing. Only careful diagnostic observations including e.g. time resolved interferometry, time resolved neutron anisotropy measurements and neutron spectrometry allows definite conclusions on the prevailing processes taking place.

As to the observed increased neutron yield for gas puff experiments, there were applied two different ways of gas puffing during the last decades. Whereas in the experiments described so far, performed in Stuttgart, where gas puffing was applied in front of the anode in the final pinch region [15], there were experiments performed in Limeil [1] with the motivation not to disturb the possibility for the formation of micro-instabilities and as a consequence anomalous resistivity in the final pinch phase by keeping the density low. Gas puffing was applied in those experiments using fast valves in the breakdown region. The measured increase in neutron yield was even higher (up to a factor of three, see Fig. 6) [1] than in the case of gas puffing in the final pinch region.

When we want to compare the results of experiments with different gas puffing, we should take into account that they were performed in different laboratories where additional experimental parameters may have had an influence. Therefore one should try to develop an experiment where gas puffing in both regions is possible and can be applied separately or simultaneously.

Conclusions

1. It has been found that gas puff loads allow to increase the neutron yield up to a factor of three. Neutron and fast electron pulse shapes can also be strongly modified.

Gas puffing favours the hot (bright) spot formation in plasma focus devices. Gas puffing (with various gases at various positions) is useful for diagnosing the pinch development taking advantage of the characteristic X-ray emission of the various atoms.

2. Future experiments could prove a higher stability of the pinch obtained by multiple (coaxial) gas puff analogous to multiple wire arrays [18].

One should expect optimal neutron (or X-ray) emission for "simultaneous" (with the appropriate time delay) gas puffing in the breakdown and in the pinch region of a plasma focus. Combinations of fibre or wire arrays with gas puffing should be considered.

3. Mathematical modelling of gas puffs should be continued and extended to MHD calculations of the pinch phase with inhomogeneous density distributions (as invoked by gas puffing) prior to the arrival of the current sheath.

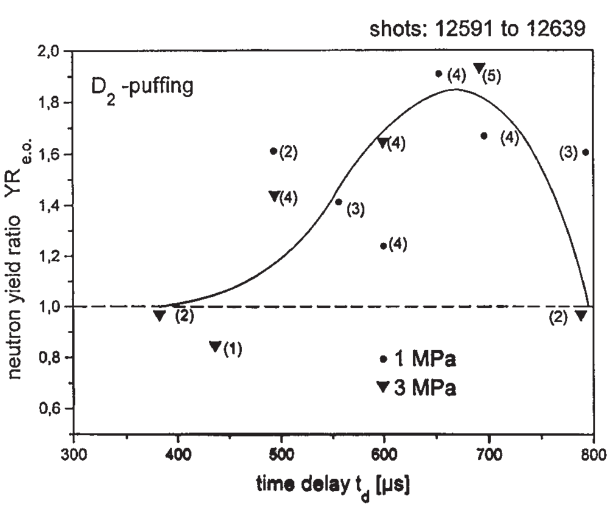

Fig. 5. Neutron yield ratio YR (yield with gas puffing/yield without gas puffing), as registered end-on for 135 kJ plasma focus shots with additional deuterium gas targets (for fast valve plenum pressures 1 MPa and 3 MPa, resp.) at an initial chamber filling pressure of 1 hPa deuterium. Numbers of averaged shots are given in brackets. The average neutron yield without gas puffing was 1.86×10^{10}. Maximum neutron yield was measured for a time delay of about 680 µs between the triggering of the valve and the plasma focus discharge.

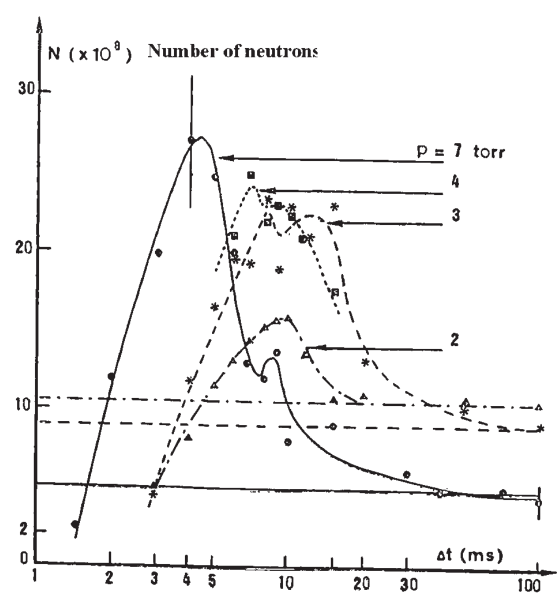

Fig. 6. Neutron yields for shots with various equilibrium chamber filling pressures (reached after about 100 ms) from 2 to 7 Torr deuterium, accomplished with gas puffing in the breakdown region. The valve opened 4 times for 1 ms about every 10 ms. Plotted results are averaged over 10 shots [1]. Neutron yield with static filling amounts to 10^9 for p = 3 Torr, as indicated by the broken horizontal line.

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