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ORIGINAL PAPER

# Pinch modes in the SPEED2 plasma focus

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**Abstract** Deuterium discharges in the SPEED2 plasma focus (80 kJ, 200 kV, 2 MA, 400 ns) have been found unexpectedly stable within the operational regime as a neutron source. Only at higher filling pressures (above 6 mbar) sometimes m=0 instabilities appeared in the pinch column, especially in discharges of lower efficiency (moderate dynamics and neutron yield). Enhancing the electromagnetic radiation by doping these discharges with heavy gases (e.g. neon, argon) distinctly two pinch modes are produced, the micropinch mode (MPM) or the stable column mode (SCM), with a transition regime where the initial SCM is followed by the MPM. Micropinches are local radiative collapses initiated by m=0 instabilities of low-energy-density pinch plasmas. These instabilities and the successive micropinches can be suppressed by kinetic deuterons produced during dynamical compression of high-energy-density deuterium plasma sheaths. Depending on the relaxation of this fast deuteron component the pinch column can be stabilized for several tens of nanoseconds. While the short-lived (appr. 1 ns) micropinches erratically appear as point-like successive flashes along the pinch axis with temperatures about 1 keV and about solid density the reproducible SCM, optimized with respect to the compression ratio, forms a powerful linear radiation source of temperatures and densities similar to the MPM. The SCM needs powerful (fast) drivers in order to use the kinetic ion stabilization, but not necessarily MA currents as available from the SPEED2 driver. This opens the possibility to establish the SCM also in compact experiments like SPEED3 (8 kJ, 80 kV, 0.8 MA, 300 ns) or even SPEED4 (2 kJ, 40 kV, 250 kA, 300 ns).

**Key words** pinch plasma • pinch stability • plasma focus • plasma radiation • radiation source

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## Introduction

It has been found [12, 13] in the past of pinch physics research that plasma focus experiments essentially behave alike concerning sheath and pinch structure and stability. Independent of driver energy and electrode configuration plasma sheaths seemed of filamentary structure merging into an m=0 unstable pinch finally exhibiting a variety of physical phenomena like anomalous enhanced resistivity, particle acceleration and neutron production mechanisms.

The operation of high voltage and fast experiments in the past two decades [2, 5] then revealed that this similarity was the result of a limited range of discharge parameters (e.g. reduced breakdown field $E/n_0$, initial current density rise rate $j_{dot}$) determining sheath and pinch energy density. Extending this parameter range to higher values sheaths and pinches lost their filamentary structure and even the notorious m=0 instability could be either delayed [8] or totally suppressed [15]. Since also these pinches produced neutrons of beam-target origin deuteron acceleration could not longer be exclusively attributed to these instabilities and the subsequent pinch disruptions. In case of stable pinch columns the neutron production starts prior (up to 50 ns) to pinch formation (sheath stagnation) lasting for more than 100 ns, while the neutron signal shows a single pulse without substructures (spikes) known from unstable pinches. Also the neutron energy distribution (spectra) and anisotropy (believed to be characteristic of all plasma *foci* [14]) completely changed in these high power experiments.

In this paper we present results from our high performance experiment SPEED2 [3] operated up to a voltage of 200 kV (80 kJ), a discharge current of 2 MA with a current rise time of 400 ns. This experiment has not only been investigated as a neutron source but also as a soft X-ray (SXR) radiation source when various heavy gases were injected into deuterium discharges.

## SPEED2 experiments

Because of the high breakdown voltage (>100 kV) and the high initial current rise rate ($\approx 10^{13}$ A/s) SPEED2 produces thin deuterium plasma sheaths within a filling pressure range of 2 to 6 mbar. Because of the high run-down and compression dynamics, this plasma sheath forms a reactive load (inductance derivative $L_{dot}$ and resistance R) impedance that tends to determine and damp the discharge current. For this reason SPEED2 is designed as a high impedance ($\approx 70$ m$\Omega$) driver dominating the load impedance up to final compression when the load impedance becomes so high that the current is damped (dip) for a few tens of ns only. In view of the current scaling for the neutron yield ($Y \propto I^4$) this is an important feature of this experiment. Around the filling pressure optimum (4 mbar) a few $10^{11}$ neutrons are produced if the insulator is properly conditioned. Enhancing the power input to the discharge in increasing the voltage above 200 kV the reproducibility of the discharges becomes poor due to higher sensitivity against impurity so that the mean neutron yield drops despite record yields ($\geq 10^{12}$) produced in a few shots.

Unfortunately, it has also been found that the neutron production due to the beam-target mechanism inherently saturates [10] so that the scaling laws are only valid in a limited range of energy or discharge current.

Fig. 1 schematically shows the electrode configuration, the gas injection system and the phases of SPEED2 discharges. The plasma sheath is always initiated in pure deuterium on the alumina surface of a cylindrical glass insulator. Without gas injection the deuterium plasma forms a pinch as shown by typical Schlieren pictures, published already in 1985 (e.g. Fig. 4a,b in Ref. [1]). Since these pictures visualize the electron density gradients of the sheath and the pinch, the separation of the line-pairs (<1 mm) roughly give the thickness of the sheath. Three features are especially remarkable:

i. Except for the contours of the sheath no substructures are visible, which means there are no filaments or vortices.
ii. The sheath stops (stagnation) at a much larger radius ($\approx 2$ mm) than the sheath thickness (<1 mm).
iii. The forming pinch appears stable within the 15 ns window of the picture. Even pictures taken about 50 ns after stagnation show neither m=0 instabilities nor pinch disruptions.

It has been found [6, 9] (i) that a fast deuteron component produced by ion runaway and gyro-reflection acceleration (GRAM) during sheath compression adds to the pressure of the thermal plasma so that equilibrium is reached at larger pinch radius and (ii) that these fast deuterons ($\geq 100$ keV) stabilize the pinch during relaxation ($\geq 100$ ns).

In order to enhance the SXR radiation yield many different heavy gases were injected into the deuterium discharges, the effects of two of them (neon, argon) are shown and discussed here.

The deuterium plasma sheath runs into a stream of the doping gas that is formed above the anode by gas injection through a hole in the copper electrode via a fast electric valve (primary pressure 3–4 bar) triggered a few milliseconds before discharge initiation. The deuterium filling density is typically $10^{23}$ m$^{-3}$ (a pressure of a few millibar) and comparable to the density of the injected gas. This gas injected a few ms before discharge initiation forms a conical stream above the hole in the anode with radial dimensions of 1 cm near the anode surface and a neutral line density of a few $10^{19}$ m$^{-1}$ that only slightly decreases along the z-axis. The compressing deuterium plasma sheath hits this

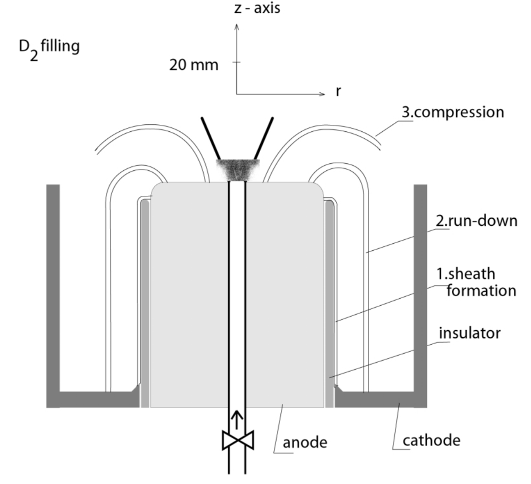


Fig. 1. Schematic diagram of the SPEED2 plasma focus configuration, the gas injection system and the phases of a typical focus discharge. The gas stream shown above the anode is a replica of a picture taken by an X-ray backlighting system and gives roughly the cone angle of the gas distribution.

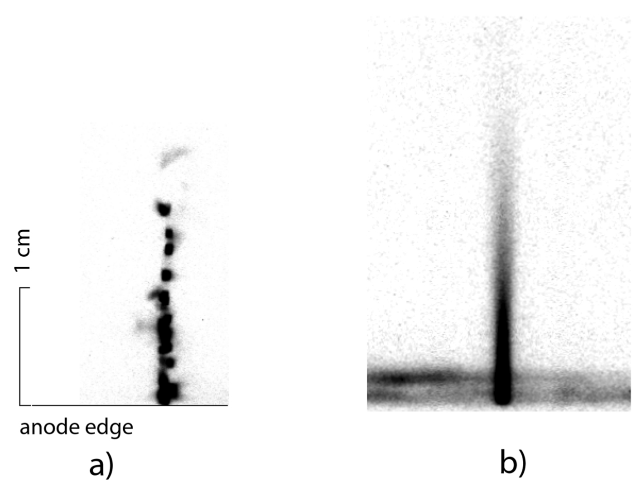


Fig. 2. Filtered ($\lambda$ < 1 nm) time-integrated pinhole pictures:
a) MPM, in a deuterium-argon plasma showing structures around 10 $\mu$m (determined by means of a square pinhole and the penumbra method). b) SCM, in a deuterium-neon plasma (column radius $\leq$ 0.5 mm).

stream typically 50 ns before stagnation on-axis depending on the delay time between valve opening and discharge initiation. Delay times that are too short (<5 ms) result in pure deuterium pinches producing intensive neutron pulses but only weak soft X-radiation. Too long delay times (>20 ms) prevent plasma sheath formation because the heavy gases as well as other impurities on the insulator surface lead to sheath break-up and decay and no pinch is formed. These cases are easily realized from the neutron yield that almost vanishes if no proper sheath is formed. This sensitivity against impurity, well known from high-performance dynamical pinches [9], makes discharge initiation with premixed or pure heavy gas fillings impossible in SPEED2. On the other hand, neutron pulse traces and yields serve as sensitive indicators of sheath and pinch conditions.

Fig. 2 shows typical filtered time-integrated pinhole pictures of argon and neon pinches depicting the so-called micropinch mode (MPM) [4] and the stable column mode (SCM) [11]. How do these different pinch structures come about?

Using argon as doping gas in SPEED2 (60–70 kJ, 180 kV, 1.5 MA) and a delay of 7 ms necks appear a few ns before sheath stagnation on-axis from which micropinches develop. Fig. 3 shows a sequence of MCP (microchannelplate camera with 3 ns exposure) pictures and a time-integrated filtered ($\lambda$ < 1 nm) pinhole picture. The necks in the inhomogeneous plasma appear first near the anode and later on higher z-positions of the pinch. The growth times (r, in seconds) agree well with the ratio of the pinch radius (r, in meters) and the Alfven velocity ($v_A$, in meters per second):

$$\tau = \frac{r}{v_A} = \left(10^7 m_i N \frac{\mathrm{Am}}{\mathrm{Vs}}\right)^{\frac{1}{2}} \left(\frac{r}{I}\right) \quad (1)$$

with the ion mass $m_i$ in kilograms, the line density N in $m^{-1}$ and I in amps, which gives about 8 ns for argon and 5.6 ns for neon, assuming a line density of $10^{20}$ $m^{-1}$ and a radius-current ratio of $10^{-9}$ $mA^{-1}$.

Surprisingly, injecting the lighter neon and applying the same electrical parameters of SPEED2 no instabilities but stable pinch columns develop, as shown in Fig. 4. MCP pictures stem from radiation with wavelengths less than 20 nm, so that not only the plasma surface but also the inner column is depicted, showing remarkable homogeneity of the pinch (see Fig. 3 for comparison).

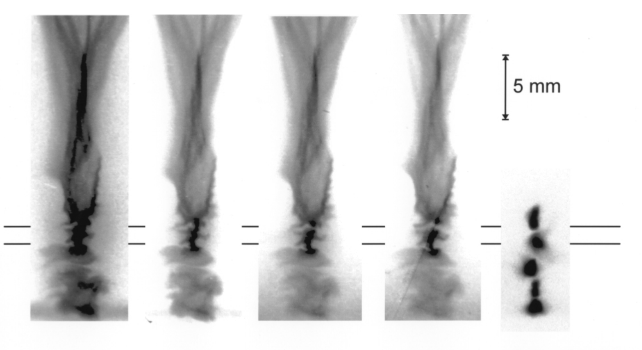


Fig. 3. MCP pictures (3 ns exposure) and a filtered ($\lambda$ < 1 nm) pinhole picture showing instability development and micropinch actuation in deuterium-argon plasma (the z-positions are marked).

Since the radius and the line density of the gas stream, as well as current and compression velocity, are comparable, the main difference is the ionization energy between argon and neon (14.4 keV and 3.5 keV, respectively for full ionization) so that the energy density differs by more than a factor of 4 at the end of compression if both gases were fully ionized. From the MPM it is known that argon is ionized to the lithium-like stage before the radiative collapse, so that neon atoms should be completely stripped by sheath stagnation on-axis. How are the instabilities suppressed and what makes the pinch stagnate at a radius of 1 mm or so as the example of Fig. 4 (t = 0 ns) shows? In a number of time-integrated pinhole pictures very thin (radius < 0.2 mm) stable columns are to be seen. Since these pinches appear in discharges with a moderate neutron yield it is suspected that the energy density of the sheath and its dynamics are reduced so that the pinch column can be more deeply compressed by the magnetic field.

In order to further elucidate this SCM behavior, efficient diagnostic tools were additionally and simultaneously used at SPEED2: an X-ray streak camera with temporal resolution of about 100 ps, a compact spectrometer for the spectral range of 0.9 nm to 1.5 nm with a spectral resolution of $10^4$ and a multilayer mirror (MLM) optics for the spectral range of 0.5–1.5 nm for wavelength selective imaging. The spectrometer and the MLM optics can be combined with a MCP camera and the spectrometer with the addition of an entrance slit, so that spectra and images can be obtained with temporal and spatial resolution.

Fig. 5 shows a typical axially integrated spectrum of a neon plasma on-axis. The temporal resolution of 10 ns was achieved by using MCP detectors for spectral recording. Already 20 ns before sheath stagnation on-axis, only line radiation from hydrogen-like neon ions is detected vanishing at stagnation (t = 0) and only continuum radiation around 1 nm is observed. From the slope of the recombination continuum ($\lambda$ < 0.9 nm) an electron temperature of several 100 eV is determined which is corroborated determining the intensity ratios of the resonance Lyman a transition 1s-2p of hydrogen-like neon and a dielectronic satellite $1s2p(^1P_1)$-$2p^2(^1D_2)$. We assume that optical thickness does not play any role for dielectronic satellite transitions, which terminate on very low populated excited levels of He-like ions. On the other hand, it was measured that Lyman alpha transition has no significant additional line broadening (compared with satellites) which shows that intensity of this

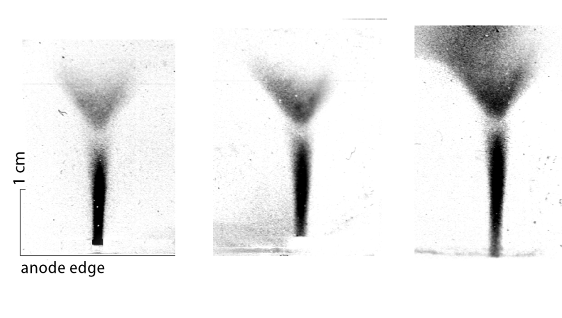


Fig. 4. MCP pictures (3 ns exposure) of a deuterium-neon pinch column (SCM).

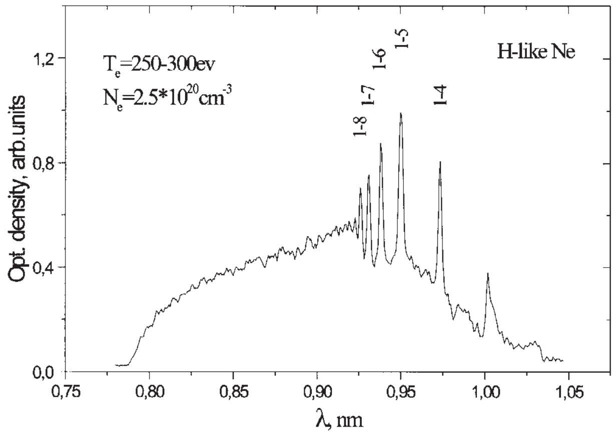


Fig. 5. Axially integrated, radially resolved (1 mm) and time resolved (10 ns) spectrum of the SCM in a deuterium-neon pinch plasma on-axis about 20 ns before sheath stagnation.

line was not affected by any possible optical thickness. Considering Stark broadening of high-level transitions in the hydrogen-like series electron densities up to several $10^{26}$ $m^{-3}$ are determined even for moderate discharge efficiency.

Since the lines vanish at stagnation, temperature and density of the SCM seem to be similar to the MPM especially in the optimized SCM where very small pinch radii (≤0.2 mm) are achieved. Increasing the neon injection, a tendency for second compressions and m=0 structures is observed in MLM and MCP pictures. On the other hand, increasing the energy input to the discharge this tendency vanishes, which means that the SCM is favored by high-energy-density sheaths and pinches. Fig. 6, showing a pinhole picture from a discharge with argon injection but increased energy input (80 kJ), proves that the SCM can also be established in heavier gases than neon. This is very promising because the energy density can also be increased in small experiments using thinner gas streams and smaller anode radii.

Fig. 7 shows typical signal traces of the current derivative and the neutron pulse for the MPM and the SCM, respectively. Analyzing a series of 80 plots the following characteristics can be summarized:

(1) Compression dynamics (spike onset and amplitude of the current derivative) of the SCM is stronger than that of the MPM.
(2) The onset of neutron production is earlier for the SCM than for the MPM (up to several tens of nanoseconds).
(3) FWHM of the neutron pulse of the SCM is more than twice that of the MPM.
(4) The neutron yield of the SCM is always higher (more than by a factor of two) than that of the MPM.
(5) The neutron pulse of the MPM is always more structured than that of the SCM.

## Discussion and conclusions

According to an ionizing shock wave model [7] the thermal energy per neutral particle (filling density $n_0$) provided by the magnetic field B is $\frac{B^2}{32\mu_0 n_0}$ ($\mu_0 = 4\pi\cdot10^{-7}(V\cdot s\cdot A^{-1}\cdot m^{-1})$ so that the thermal energy density e of the plasma sheath

Table 1. Ionization times T in nanoseconds for an electron density of $2\times10^{24}$ $m^{-3}$.

| Ion | $T_e$=300 eV | $T_e$=1000 eV |
|---|---|---|
| $Ne^{6+}$ | 0.85 | 0.53 |
| $Ne^{9+}$ | 2300 | 64 |
| $Ar^{14+}$ | 83 | 9 |

with a density $n_S$ running into the fill gas with a Mach number of the order of 100 ($n_S/n_0 \approx 8$) is

$$\varepsilon = \frac{\mu_0}{128\pi^2}\frac{n_s}{n_0}\left(\frac{I}{r}\right)^2 = \frac{\mu_0}{16\pi^2}\left(\frac{I}{r}\right)^2 \tag{2}$$

At the beginning of the dynamical radial compression the thermal energy density of the deuterium sheath depends only on the ratio of sheath current I and the radius r of the anode. For SPEED2 with I=1.5 MA, r=5 cm and a filling density of about n=$10^{23}$ $m^{-3}$ this gives a thermal energy per neutral particle of around 56 eV and a sheath energy density of several $10^6$ $Jm^{-3}$ which is more than enough to fully dissociate and ionize deuterium and heat the deuterium plasma.

Assuming constant current, filling and sheath densities until the shock front reaches the axis the magnetic piston has reached the gas stream at a position of about 8 mm from axis. Because of a compression ratio of about seven the energy per neutral particle now is about 2.8 keV, which is still not enough for full ionization of neon or argon. The line density of the forming pinch column ($10^{21}$ $m^{-1}$) increases about 10% for neon and 20% per cent for argon, depending on the ionization degree $N_S = (Z_{eff} + 1)N_i$ where $Z_{eff}$ is the effective charge number and $N_i$ is the ion line density. The relatively low electron temperatures (>300 eV) derived from spectra show that much of the energy is consumed by ionization. Using the ionization rate coefficients $<v\sigma>$ of Voronov [16] the ionization times $T = (<v\sigma>n_e)^{-1}$ for the lithium-like and fully stripped ions are given in Table 1.

For reasonable pinch times (several tens of nanoseconds) full ionization can only be expected for neon whereas argon hardly reaches the lithium-like stage. Since the stagnation radius of the SCM is less than 2 mm, a final pinch electron density of up to $10^{26}$ $m^{-3}$ can be reached so that full ionization for neon and lithium-like argon ions can also be expected for lower electron temperatures. Nevertheless, fully stripped argon ions as produced in the MPM during radiative collapse need higher compression ratios than mostly observed in the SCM.

However, the magnetic field energy is not only converted into ionization and thermal energy, but also into the kinetic energy of the moving ions. Taking measured compression velocities of $3\times10^5$ m $s^{-1}$ for deuterium and about $10^5$ m $s^{-1}$ in neon or argon into account, kinetic ion energies around 1 keV are thermalized at sheath stagnation on-axis. Moreover, runaway deuterons produced during compression by the so called gyro-reflection acceleration mechanism GRAM [6] and by high electric fields, because of anomalous enhanced plasma resistivity and/or disruptive instabilities, gain much higher kinetic energies, eventually producing neutrons via fusion reactions with one another (beam-beam reactions) or with thermal deuterons (beam-target reactions). Hence, three species of particles (electrons and two sorts of ions) have to be dealt with in dynamical pinches, thermal ones with a radial kinetic component (radially drifting Maxwellian) and fast ions (primarily deuterons since runaway of highly charged ions is less probable because of their high collision probability ($\sim Z^2$)) with the azimuthal and axial components. While the kiloelectronvolt ions are rapidly thermalized (nanosecond time scale) upon sheath stagnation, the fast deuterons generated and accelerated within the sheath where the density is comparatively low and the temperature high, the relaxation can be several tens of nanoseconds, as realized from the neutron pulse decay.

The equilibrium of the pinch can be described by an extended Bennett relation

$$\frac{\mu_0 I^2}{8\pi} = (Z_{eff}+1) N_i kT + N_d W_d \tag{3}$$

with $Z_{eff}$ $N_i$, $N_d$, and $W_d$ denoting the effective charge number, the line density of thermal ions and fast deuterons and the fast deuteron energy, respectively.

A line density of $N_i = 10^{21}$ m$^{-1}$ and an electron temperature of 300 eV gives a line energy (or a force) of the thermal component around 50 kJ·m$^{-1}$ (50 kN) that is more than a factor of two less than that of the current (1.5 MA) term. Using the stagnation radius from MCP pictures (2 mm) the energy density of the thermal component in the pinch (nkT) is less than 5–10$^9$ J·m$^{-3}$ (5 kJ·cm$^{-3}$) whereas the energy density of the magnetic field is also more than twice this value. This means that the energy density of the fast ions is comparable to that of the thermal ions. Since these estimates neglect particle loss (outflow) from the pinch region the numbers given are the upper limits of the thermal energy density. Assuming a mean energy ($W_d$=50 keV) the line density of the fast ions is about 1% of the total pinch line density.

In SPEED2 this fast deuteron component is initiated prior to the sheath contact with the doping gas so that the neon or argon pinch is confined by a “tube” of fast deuterons surrounding and stabilizing the column. In cases where runaway deuterons are either hindered by collisions or rapidly thermalized (e.g. in a “cold” argon plasma) instabilities develop.

High sheath dynamics and temperature lead to the effective GRAM of deuterons. High line densities of the injected gas stream and high atomic numbers Z of the gas lead to a low energy density of the column and GRAM and the relaxation time of the fast component is reduced so that, locally, further compression becomes probable. In cases where the GRAM is totally suppressed instabilities and local collapses inevitably develop; in other words, the MPM occurs. This means that dynamic compression is always stabilized if GRAM is active (runaway radius > stagnation radius) and that the pinch column is stable until the fast ions are thermalized.

The number of fast deuterons per length, the line density $N_d$, recruits itself from deuterons that have the highest probability to run away, that is those with the highest velocity relative to the magnetic piston velocity and the highest angular momentum. Only deuterons in the “left” tail of the radial velocity distribution of the sheath and tail deuterons of the azimuthal velocity distribution have a chance to escape the bulk of collision-dominated deuterons. Since the mean free path is of the order of tenths of a millimeter, only deuterons, in the vicinity of the piston, that is, deuterons within the current sheath manage to escape. Requiring,

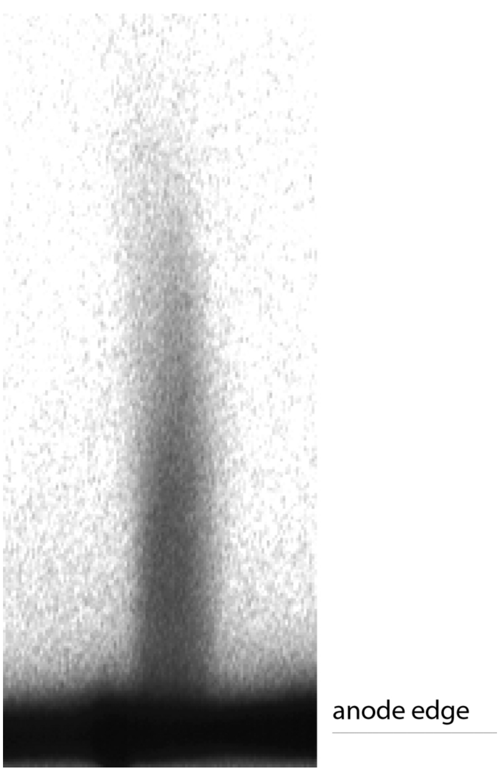


Fig. 6. Time-integrated pinhole picture ($\lambda$ < 1 nm) of a SCM formation in a deuterium-argon pinch plasma with enhanced bank energy (80 kJ).

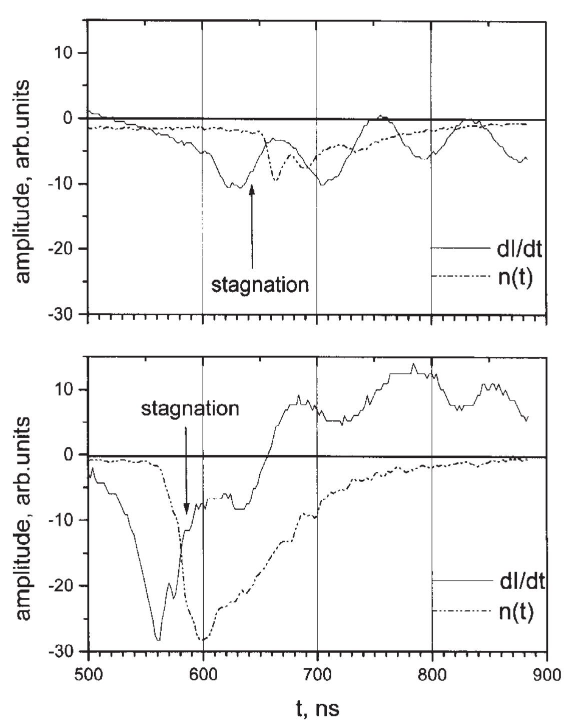


Fig. 7. Typical signal traces of the current derivative and the neutron flux of MPM (upper) and SCM (lower) formation showing different compression dynamics and neutron production (onset, flux and pulse structure) in either case.

arbitrarily, their velocity $v_d$ is greater than the mean thermal velocity, $v_d = (kT/m_d)^{1/2}$, the number of runaway deuterons is of the order of a few per cent of $N_i$. Since the temperature rises towards the axis, the chance to run away increases during compression and vanishes upon stagnation on-axis. This estimate gives an upper limit for $N_d$ of a few $10^{19}m^{-1}$ the final energy of which depends on the ratio of their runaway radius $r_{ra}$ to the stagnation radius $r_{st}$ ($W_d \sim (r_{ra}/r_{st})^2$). It also makes it plain that detectable neutron production due to this mechanism (SCM) starts before stagnation whereas that due to instabilities (MPM) should start after stagnation (see Fig. 7).

The narrow pinch columns (<200 µm) first observed in time-integrated pinhole pictures are presumably due to the fact that thinner gas streams (lower line density) were injected and thinner deuterium sheaths were produced. Thus, even discharges with relatively high filling pressures (thin sheaths) can produce high neutron yields via small stagnation radii. Therefore, these discharges seem first realizations of optimized SCMs. An optimized SCM is something like a collapse by itself that needs no further initiation because the energy loss within the column is maximized (ionization, line and continuous radiation) and local as well as possible global collapses are sufficiently long suppressed by the stabilizing fast ions. This line source of SXR needs powerful (fast) drivers in order to use GRAM for stabilization, but not necessarily MA currents, since high-energy-density plasma sheaths and pinches can also be generated in smaller experiments with reduced radial dimensions of the electrode configuration and the doping gas stream.

With the free parameters filling density, electrode radius, line density and atomic number of the gas stream runaway radius, the number of runaway deuterons and compression ratio can be predetermined for SCM optimization. As a first step this optimization procedure is in preparation in SPEED2 with reduced electrode and stream dimensions. This activity is accompanied by similar experiments using the compact Z-pinch SPEEDS (8 kJ, 80 kV, 800 kA and 300 ns) or even SPEED4 (2 kJ, 40 kV, 250 kA, 300 ns).

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