THEORETICAL AND EXPERIMENTAL STUDY FOR POSSIBILITY OF NUCLEAR BURN WAVE INITIATION IN Z-PINCH DUE TO M=0 INSTABILITY DEVELOPMENT

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Abstract

The development of sausage type (m=0) instabilities in initially homogeneous plasma column leads to the appearance of dense plasma. Temperature of this plasma is substantially higher, than the average plasma temperature in the column. Therefore the reasonable idea might be the using of this high temperature areas for nuclear burn wave initiation. The study for possibility of this phenomenon is presented.

1. INTRODUCTION

Investigation of Z-pinch discharges, compressing itself due to rising magnetic pressure of their currents, shows, that z-pinch plasma column is unstable and the appearance of hot and dense plasma in the neck (the regions of maximal compression) is a reality. Simulation predicts the main part of plasma column has temperature 1-2keV, at the same time the plasma temperature in the neck region may achieve 10keV at 1MA current range. Such the plasma is considered to be perspective for thermonuclear fusion.

With increase of the discharge current confinement parameter $n\tau$ is also increased. If the confinement parameter is enough high, the essential thermonuclear energy in the neck might release and the modelling predict, that under certain conditions burn wave will propagate along z-pinch axis [1-4]. In this case thermonuclear heat release will take place from the all plasma column, not only from the neck region.

2. THEORETICAL RESULTS

Thermonuclear wave initiation in the neck and its further propagation along Z-pinch axis were firstly simulated in [1]. The calculated energy heat release appeared to be essentially larger than, that have been spent to creation of given pinch. Therefore Z-pinch might be the energetically advantageous energy source. Results of MHD modelling of thermonuclear burn wave initiation with its further propagation along plasma column is presented in this paper [3].

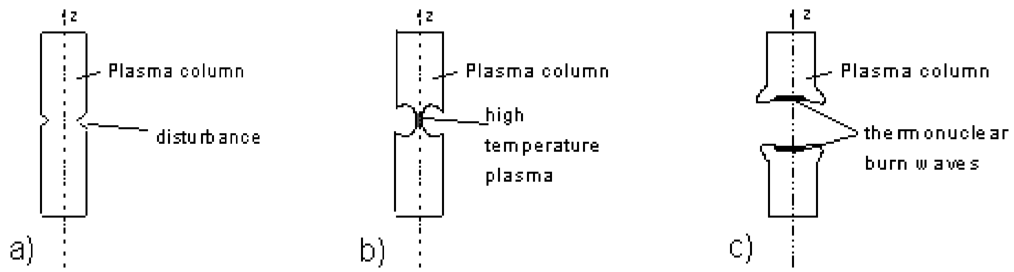

FIG. 1. Dynamics of the discharge with thermonuclear burn wave. a) the initial stage, b) formation of thermonuclear burn wave, c) propagation of the burn waves.

Fig.1 shows distribution of pinch at different stages of the discharge. On the initial stage (during increasing of the current) the z-pinch is cylindrical column with conical perturbed zone (Fig.1a). Such zone is usually formed as a result of m=0 MHD instability. Since the magnetic field pressure in the perturbed zone is somewhat greater than the plasma pressure in the column, the perturbed zone is expended, that result in the emergence of the cavern in the plasma column. The cavern is developed due to the entry of magnetic field into it from the rarefied peripheral plasma (Fig 1b).

In the near axis zone the plasma column is compacting and a gradual increase in its temperature occur. When the temperature > 5keV is attained, an intense fusion heat release, resulting in the emergence of a burn wave, propagating along the pinch axis, starts in dense plasma. In this case, a dense plasma configuration around the axis disappears beyond the propagating wave front, the process of wave propagation is accompanied by an essential plasma temperature rise in near axis zone (Fig.1c).

Thus the appearance m=0 MHD instability plays positive role and leads to creation of hot dense plasma and burn wave. The burn wave in DT mixture will be realized at the current range larger, than 10 MA, if the plasma radius in the neck region will be less, than 10^{-4} cm. At the 100 MA current range thermonuclear wave undoubtedly takes place. Analysis also shows, that to decrease the requirements to energy driver, which must have enough high rate of rise of current, the presence of medium with density for 10-10^4 times less, then solid matter density, is necessary around the DT mixture to achieve the matched regime.

The main state of matched regime is that the initial radius of the handmade neck and the initial fiber density need to be correctly chosen in order to the timescale for development of the neck and the current rise time coincide. Such matched regimes have been thoroughly investigated theoretically by group from Kurchatov Institute, have verified by comparison with experimental results on plasma focus devices and are widely used at present in the design of the new installations.

3. EXPERIMENTAL RESULTS

The 8-module 10TW pulse power generator S-300 was constructed for the development of experimental investigation in this field in RRC Kurchatov Institute. The S-300 installation with output impedance of 0.15 Ohm provides a total current up to 4MA with a rise time of 60ns in Z-pinch load [5]. To examine the desirable theoretical approach and to receive the plasma with thermonuclear parameters fibre with preformed perturbation are used. The initial plasma was produced by an electrical breakdown of profiled carbon filled agar-agar fibres with density of 0.05-1 g/cm^3.

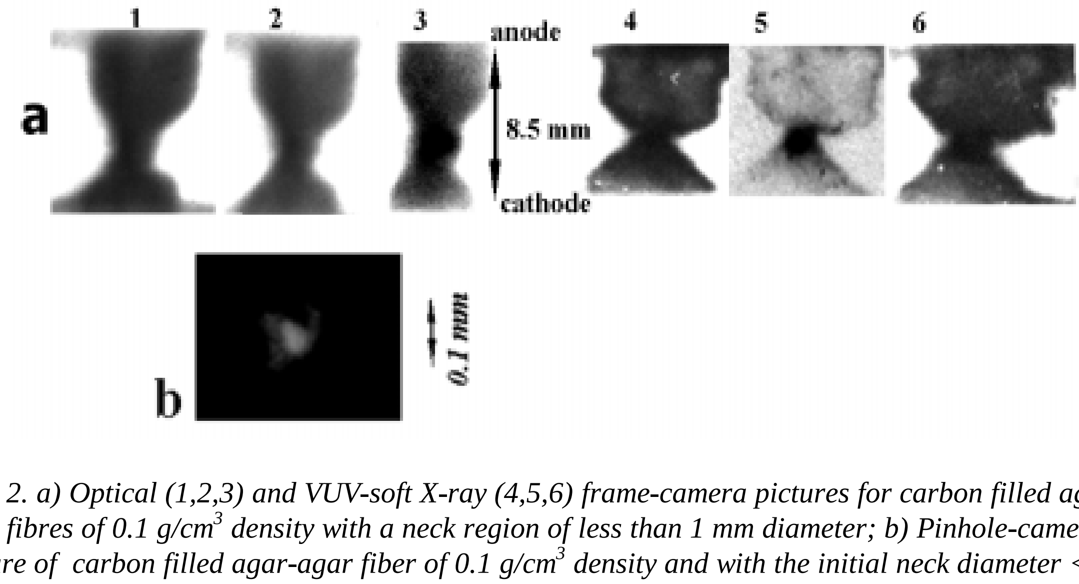

FIG 2. a) Optical (1,2,3) and VUV-soft X-ray (4,5,6) frame-camera pictures for carbon filled agar-agar fibres of 0.1 g/cm^3 density with a neck region of less than 1 mm diameter; b) Pinhole-camera picture of carbon filled agar-agar fiber of 0.1 g/cm^3 density and with the initial neck diameter < 1mm.

The best matching with the load at the level of incident energy wave of 70 kJ, transmitted to the vacuum concentrator unit, occurs for the fibres diameter of 3-5 mm and their length of 7-10 mm. The neck diameter and its mass per unit length were being varied between 0.5-2 mm and 0.1-0.5 mg/cm accordingly. Various X-ray diagnostics were used for plasma parameters measurements: X-ray framing cameras with 5ns exposure time, X-ray pinhole cameras, fast response detectors with filters and crystal Roentgen spectrographs. In addition, optical radial streak photographs with the slit, aligned perpendicular to the pinch axis and framing cameras were used.

It was established that plasma formation essentially depends on the initial density and radius of the neck. At the initial fibre density lower than 0.05 g/cm^3 of the plasma corona was formed with the diameter, exceeding that of the neck diameter [6]. Chaotically arising bright spots were observed in the space occupied by the rare plasma (the corona). At increasing the initial fibre density up to 0.1 g/cm^3 the time integrated pinhole camera and X-ray frame camera pictures show the plasma formation in preliminary made neck (see Fig.2). The mean compression velocity as determined from X-ray frame camera pictures proved to be $5\cdot10^6$m/s. The highest compression for the initial neck diameter of 1 mm corresponded to the moment of current maximum.

Fig.3 shows optical radial streak image in the fibre neck of 1mm initial diameter. The bright region with cross - size dimension of 0.5 mm exists during first 100ns. The continuous expansion of emission comes at least 100ns after the current start. It must be noted that the expansion of bright region is observed on soft X-ray frames. The picture of expansion were taken at about 145ns after the current start. From time-integrated pinhole camera pictures it follows, that as a result of compression the plasma formation occurs with the least diameter dimension of 40-70 μm as observed behind 10-20 μm thick mylar filter (Fig.2b).

Approximately the same dimension values of the hot plasma were obtained in spectroscopic measurements from the width of X-ray penumbra behind the edge of the horizontal slit. The compression was accompanied by the soft X-ray radiation pulses. The moment of the hot plasma appearance determined by soft X-ray radiation burst behind the 10 μm thick mylar filter corresponds to the current's maximum. It should be noted that, the VUV-diode with 10 μm mylar filter is most sensitive to 2keV X-ray radiation. The hot plasma life-time measured by the half intensity of soft X-ray decay is less than 5ns, while the radiation power for > 1keV quanta exceeds $5\cdot10^9$ W and the total irradiated energy is to be 20-50 J.

In some experiments a diagnostic admixture of KCl was used, the luminous region length of helium-like chlorine radiation, measured by a spectrograph proved to be 100-150 μm with its diameter of 200 μm. At the same time measured diameter for helium-like potassium is in one and a half times less. The electron density and temperature, calculated from the spectral lines intensity ratio of hydrogen-like and helium-like ions, proved to be: $n_e = (0.3\text{-}1)\cdot10^{22}$ cm^{-3}, $T_e = (0.8\text{-}1.5)$ keV. The line broadening measurement analysis shows, that there is a significant difference between the ion and electron temperatures. The observed effect is characteristic for fast Z-pinch, compressed by the magnetic field of megaampere current range.

The plasma parameters at the initial density of 0.1 g/cm^3 were depended essentially on the neck profile. The highest parameters were obtained when the load neck was like two truncated cones with their tops directed towards to each other and the cone angle not exceeded 90°. By increasing the initial load density up to 1 g/cm^3 the plasma parameters decreased and became lower than for the density of 0.1 g/cm^3.

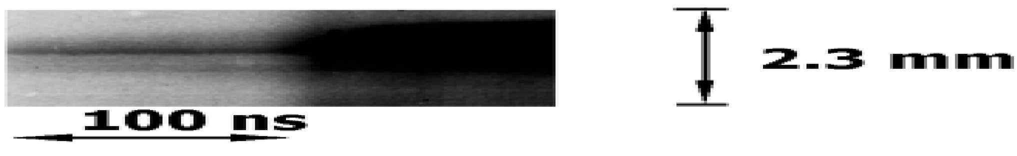

FIG. 3. The radial optical streak photography of a fibre neck

4. DISCUSSION AND CONCLUSIONS

Theoretical and experimental results, presented here, show positive role of m=0 instability. This type of instability leads to creation of hot dense plasma and initiation of burn wave.

The experiments carried out on the S-300 generator at Z-pinch current range from 1 MA [5] to 3 MA, show the reliable effect of deep neck development and hot dense plasma formation. Plasma with typical cross-size dimension of 40-70 μm was formed in the region of a preliminary made neck as a result of electrical breakdown of carbon filled agar-agar fibres. The highest plasma parameters $n_e = 10^{22} cm^{-3}$, T_e = 1-1.5 keV, were obtained by using fibres of 0.1 g/cm^3 density. The hot plasma lifetime proved to be 5 ns. The power and full energy of soft X-ray radiation in the range of quanta energy hν > 1 keV proved to be $5 \cdot 10^9$ W and 20-50 J, correspondingly.

Let we assume, that all the Z-pinch current flows through the neck region. Then for the smallest measured neck diameter values of 40-70 μm, which at the same time correspond to the space resolution of used diagnostics, the magnetic pressure $H^2/8\pi$ round the neck would be about two orders of magnitude higher than the kinetic pressure $(n_eT_e + n_iT_i)$. Thus the experimental investigation, carried out at S-300 device, has shown Bennet equation is not fulfilled at the final stage of neck development.

The probable reasons for such the discrepancy might be because of the following effects have not been accounted:

- generation of axial magnetic field (along z-axes),
- generation of chaotic electromagnetic fields inside plasma,
- transfer of the current by surrounding plasma.

Besides that, it is possibly, that we actually have more deep compression, which is not seen because of inappropriate resolving power of equipment. Probably plasma density is higher, than it is obtained by our methods, x-ray spectroscopy might doesn't show the high density because of possible trapped of corresponding lines.

So, the question about minimal plasma sizes is open and needs more detailed investigation. In this connection one of the most interesting study is that, related to searching the mechanisms, limiting the degree of compression. This might be realized by measuring plasma parameters with high spatial, spectral and time resolutions and by comparison with results corresponding of MHD modelling.

Our results show the perspective of Z-pinch devices for creation of plasma with thermonuclear parameters. To obtain the necessary plasma parameters more careful investigation of the mechanisms, responsible for burn wave initiation is necessary.

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