MHD stability of plasma with supercritical current density at the axis

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I. INTRODUCTION

The MHD stability of current-carrying magnetized plasmas is an important problem that influences fusion research for a long time. In many configurations, it limits the achievable plasma parameters. The most-widely-used numerical criterion for the stability of plasma with electric current is the Kruskal-Shafranov (KS) condition.

In this paper, we discuss magnetic perturbations in the GOL-3 experiment [1], where plasma is collectively heated in a multiple-mirror trap by a high-power electron beam - see Fig. 1. The start plasma is created with a discharge between a biased annular electrode and the opposite camera end [2]. Then, the electron beam is injected through the opposite end of the device. The beam current is much higher than the discharge one and exceeds the KS limit. An exit beam receiver is grounded with a resistor R_g that provides near-to floating potential; the return current (that brings the beam charge back to a beam source) flows mainly through the plasma. The net plasma current stays therefore below the KS limit.

Due to the high kinetic energy of relativistic electrons, the exit receiver potential does not influence their movement thus enabling co-existence of two counter-propagating electron flows in the same elementary plasma volume, namely the beam current of relativistic electrons and the combined return and discharge currents of thermal electrons. The beam-plasma interaction maintains a high-level turbulence during the beam injection. The resistivity of the turbulent beam-heated plasma core is high and this leads to depletion of the plasma current in the core despite the fact that formal electron temperature in this zone reaches keV-level values. All the mentioned features of GOL-3 provide an unusual magnetic configuration with the strong magnetic shear [3]. This magnetic configuration is stable if operation regime of GOL-3 is set properly. In some cases, the plasma loses its stability and disruption occurs.

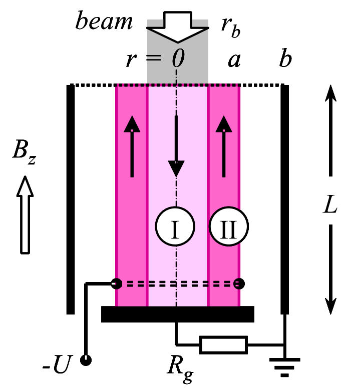

Fig. 1. Schematics of the GOL-3 experiment. Thin arrows show directions of movement of electrons. The beam heats the core plasma (zone I); the edge plasma (zone II) remains cold; a is the plasma radius, b is the wall radius, r_b is the beam radius, and L is the plasma length.

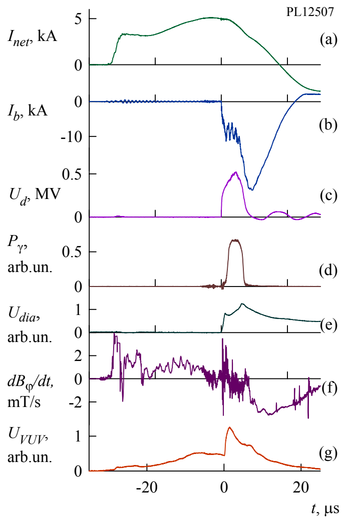

Fig. 2. Typical waveforms: (a) the net plasma current, (b) the beam current, (c) the diode voltage, (d) bremsstrahlung, (e) diamagnetic signal, (f) one of magnetic signals, (g) VUV signal. The preliminary discharge started at t = -30 μs, the beam injection started at $t = 0$.

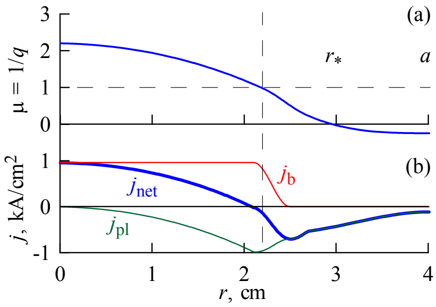

Fig. 3. Radial profile of $\mu = 1/q$ (a), and corresponding densities of the net current j_{net}, of the beam current j_{b} and of the plasma current j_{pl} (b). Position of the helicity inversion radius r_* is also shown. Dashed lines indicate $q(r) < 1$ core.

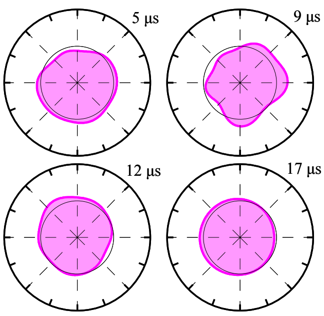

Fig. 4. Shape of the magnetic boundary in the shot PL10647 for different moments since the beam start. The beam duration was 9 μs. Thick outer lines correspond to the limiter at a = 4 cm. Thin lines indicate the surface r = 2 cm.

II. GOL-3 EXPERIMENT

The main part of GOL-3 is the multiple-mirror solenoid with 52 corrugation cells of 22 cm period. The mean magnetic field in the experiments was 4 T. The mirror ratio is $R = B_{\max}/B_{\min} \approx 1.4$. The solenoid ends with magnetic mirrors with a field of 6 – 8 T.

The scenario was as follows. The required longitudinal density distribution was created by pulsed valves. Then, the start plasma with the length-average density in the range of (0.1 – 3)×10^{21} m^{-3} and temperature of ~2 eV was created. After that, the relativistic electron beam was injected into the plasma. The ion temperature reached 2 – 3 keV in the hottest section of the plasma column with the energy confinement time up to 1 ms in best regimes (see [1]). If all the experimental conditions are set properly, the net plasma current changes insignificantly compared to the case of preliminary discharge only – see Fig. 2.

III. MODE EVOLUTION IN NORMAL REGIMES

The typical radial profile of the inverse value to the KS safety facto q is shown in Fig. 3 for this regime [3]. At the axis, $q(0) \approx 0.35 – 0.5$; this means that the current there is provided by the beam electrons only. The turbulent resistivity prevents other currents from flowing here. At some radius r_*, the field lines are non-twisted and $q(r_*) = \infty$. At the edge, $q(a)$ = -4 with different twist of the magnetic field lines comparing with the core.

The mode m = 1 was the largest one throughout the beam injection and after it. Higher modes grew during the beam injection, this followed by a steady growth of the mode number with the second-highest amplitude (after the m = 1) up to m = 5 – 6 at the beam end [4]. After the beam injection stops, the m = 1 mode usually

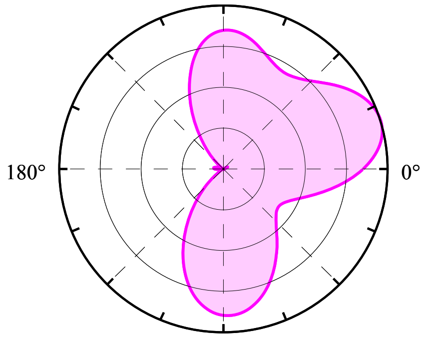

Fig. 5. Reconstructed magnetic boundary in the disrupted shot PL11188 at t = 10 µs after the beam injection start. Thick outer line corresponds to the limiter at a = 4 cm. Distances between thin circles are of 1 cm.

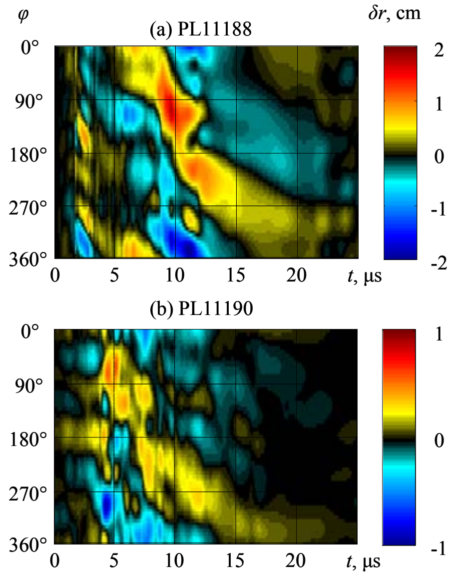

Fig. 6. Comparison of "slow" dynamics of magnetic perturbations in the disrupted shot PL11188 (a) with the stable shot PL11190 (b). The beam injection started at t = 0. Color scales are different.

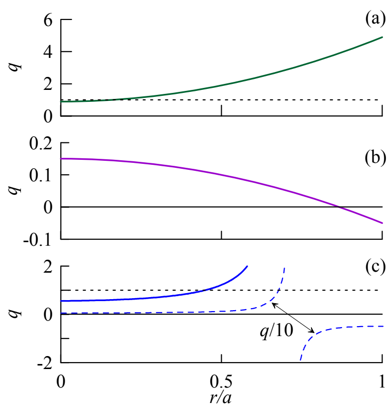

Fig. 7. Typical radial profiles of safety factor q for different configurations: (a) tokamak, (b) reversed-field pinch, (c) GOL-3.

became dominant with higher modes being rapidly decreasing. The plasma rotated; the direction and frequency of the rotation depended on the conditions and the time moment relatively to the beam injection [4]. Typical evolution of the magnetic plasma surface is shown in Fig. 4. The plasma boundary stayed far from the limiter.

After subtraction of the m = 0 mode, magnetic signals had good correlations with the m = 1 mode assuming regular twist of the plasma. Correlation coefficients reached $c \approx 0.8$. There is no delay of perturbations measured by different coils. Correlation of higher azimuthal modes was worse with typical $c < 0.25$. The plasma twist corresponds to 2π rotation at the length of 11 m. Therefore we can conclude that the most intense observed magnetic perturbations mode is $n = 1$, $m = 1$.

IV. MODE EVOLUTION IN DISRUPTED SHOTS

In GOL-3, disruptions are rare events that not only terminate the plasma but also damage the facility. In all cases, the reason for disruptions was insufficient conductivity of the start plasma. We identified four disruptions in a large series of experiments. The low-m perturbations were 4 – 8 times larger than those in stable shots. The calculated plasma boundary reached a limiter at r = 4.0 cm shortly after the beam injection started - see Fig. 5. If one considers only low-frequency components of the magnetic signals, then evolution of the magnetic surface will be similar with the exception of different scales of the distortions, see Fig. 6. The helicity of the m = 1 mode stayed the same in both stable and disrupted shots. Most probably, that we observed the classical m = 1, n = 1 mode that became saturated when the plasma reached the limiter.

V. DISCUSSION

Figure 7 shows typical q profiles for three configurations. In classical tokamaks, gradual inward diffusion of current provokes periodic sawtooth crashes. In classical RFPs, plasma is MHD unstable with $q < 1$ everywhere in the plasma; the turbulence defines properties of the confinement. In GOL-3, configuration with $q < 1$ in the plasma center exists during the full beam duration. The magnetic shear does not eliminate interchange modes [5] but decreases the growth rates down to values typical for Mercier modes in tokamaks. Unlike Mercier modes, growth rates for interchanges in GOL-3 are positive for all pressure gradients. Therefore one can expect that stability will degrade with the increase in the pulse duration.

VI. SUMMARY

Spatial structure of magnetic perturbations in the GOL-3 experiment was studied. The system uses the high-current relativistic electron beam for collective heating of plasma in the multiple-mirror trap. Non-trivial configuration of azimuthal magnetic field was formed by the beam current and the counter-directed plasma current. The beam-excited turbulence suppresses electric conductivity in the core and therefore expels the return current to the edge. The combined magnetic field had strong shear; it provided stability of the plasma with $q(0) \approx 0.3 - 0.5$. Cold plasma shell outside the beam-heated turbulent zone was necessary for MHD stability. In stable regimes, the most pronounced perturbation is the $n = 1$, $m = 1$ mode that is most probably localized near the $q = 1$ surface. Shorter perturbations with $n = 2$ and 3 were expected but such modes were not identified with our current experimental procedures. Disruptions were analyzed for the first time in GOL-3. Such events occurred when current of the preliminary discharge was zero or too low. During a disruptive shot, fast simultaneous growth of modes with $n = 1$ and $m = 1 - 4$ was observed up to plasma contact with a limiter. After that the plasma decayed. New experimental data is in a good agreement with the existing understanding of GOL-3 physics. More information is available in [6].

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