Observation of Simple Helical Structure in Low Aspect Ratio RFP Using Fast Camera

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(Received 9 October 2007 / Accepted 22 November 2007)

A fast camera clearly detected a simple helical structure in the visible-light emission region in the reversed field pinch (RFP) configuration. The observed structure is consistent with magnetic field structures deduced from magnetic measurements with the help of equilibrium reconstruction. The observed simple structure is probably an indication of the internally resonant kink mode structure in a low aspect ratio RFP configuration.

Keywords: reversed field pinch, low aspect ratio, fast camera, resistive MHD instabilities, helical structure

DOI: 10.1585/pfr.3.005

Reversed field pinch (RFP) is one of the toroidal magnetic confinement systems for compact, high-beta plasmas for nuclear fusion reactors. The RFP configuration is formed and sustained via magnetohydrodynamics (MHD) relaxation and an RFP dynamo. A nonlinear interaction between resistive MHD instabilities plays important roles in these nonlinear MHD phenomena in RFP plasmas. Recent progress in RFP research has revealed the importance of resistive tearing modes in improving RFP confinement [1].

A low aspect ratio (low-A) RFP configuration is expected to have the advantage of simpler magnetic mode dynamics, because the mode rational surfaces are less densely spaced in the core region than in conventional RFP [2]. Furthermore, it has been pointed out that a simpler magnetic field structure might be self-sustained by the laminar dynamo mechanism without magnetic chaos [3]. With the aim of investigating the advantages of the low-A RFP configuration, we have started a new RFP experiment called "RELAX (REversed field pinch of Low Aspect ratio eXperiment)" [4], whose aspect ratio is 2 (R/a = 0.51 m / 0.25 m), the lowest value ever attempted in RFPs. Typical values of the plasma current are 50-60 kA, with a discharge duration of ~2 ms. Characterization of the initial RFP plasmas will be described elsewhere [5]. A single-chord soft X-ray diagnostic with the absorbing method using two polyethylene filters has provided an estimate of line-averaged electron temperatures higher than 50 eV, thus exceeding the radiation barrier for a hydrogen plasma at least in the core region.

We have installed a fast camera in RELAX to directly observe the plasma images and have obtained a simple helical structure for the first time in the RFP configuration. The fast camera diagnostics has been applied to tokamak, stellarator, and mirror plasmas, providing useful information on edge instabilities or edge turbulence [6–8]. In the present experiments, our attention has been focused on the study of the internal structure of the visible-light emitting area.

As shown in Fig. 1, we have observed tangential images from the initiation to the termination of RFP discharges at a maximum speed of 80,000 frames/s with an image size of 96 × 80 pixels. In the initial phase of a discharge, H_α-line radiation causes strong emission over the minor cross-section. As the discharge evolves to the RFP configuration, the emission decreases and characteristic structures are observed.

Figure 2 shows time evolution of the tangential images of the RELAX plasma from 25 μs before to 25 μs after the transition to the simple helical structure at (c), i.e., 1.4125 ms after start of the discharge.

In Fig. 3, we compare the observed helical structure of the strong emission area (a) with a simulated helical tube

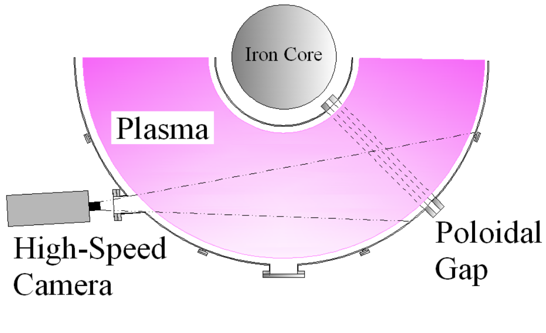

Fig. 1 Experimental setup of the installation of a fast camera in RELAX from a tangential port.

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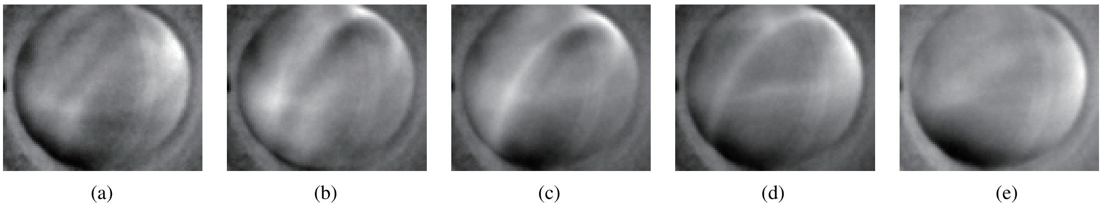

Fig. 2 Time evolution of fast camera images from 25 μs before to 25 μs after the transition to a simple helical structure in (c).

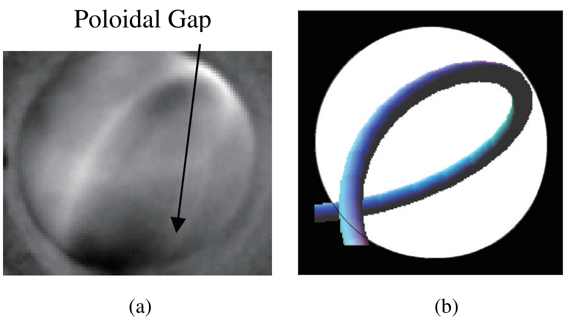

Fig. 3 (a) A simple helical structure observed by the fast camera through the tangential port in RELAX at $t = 1.4125$ ms. (b) Simulated helix on the $(m, n) = (1, 4)$ mode rational surface.

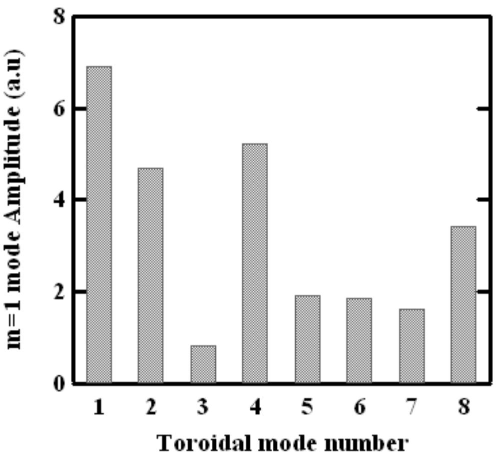

Fig. 4 Toroidal mode spectrum of the $m = 1$ mode when the simple helical structure is observed.

of $m = 1$, $n = 4$ (b). Note that the curved region behind the helical bright structure in (a) is the insulated poloidal gap of the vacuum vessel. In Fig. 3 (b), the helical tube with a 2-cm diameter was located on the $m = 1$, $n = 4$ mode rational surface, whose radial location was estimated from an equilibrium reconstruction code.

Figure 4 shows the toroidal mode spectrum of the simultaneously measured edge B_φ fluctuation with time average over 10 μs centered at 1.4125 ms. The internally resonant $m = 1$, $n = 4$ mode dominates the spectrum with non-resonant $n = 1$ and $n = 2$ components, and the helicity of the observed helical structure in the plasma image agrees with that of the dominant internally resonant mode.

Growth of the non-resonant modes accompanies the deformation of the plasma column, leading to enhanced recycling. In fact, an increase in the brightness of the plasma image (background brightness) with growth of the non-resonant modes has been observed in RELAX. However, in the present experiment, it is difficult to identify the low-n structure in the enhanced background brightness image. One of the reasons for this difficulty may be the low-n nature of the non-resonant modes. Another is that neutral particles might be released from the structured wall surface region characterized by the helicity of the non-resonant mode; however, the source structure fades away at a mean free path distance of 1 unit (for excitation) from the wall into the plasma, because recycling neutrals are released in all directions.

On the other hand, the mean free path of 1-eV atomic hydrogen for electron impact ionization can be estimated from 75 cm (for $n_e = 10^{12}\,\mathrm{cm}^{-3}$ and $kT_e/e = 20\,\mathrm{eV}$) to 4 cm ($n_e = 10^{13}\,\mathrm{cm}^{-3}$ and $kT_e/e = 50\,\mathrm{eV}$) for typical plasma parameters in RELAX, and in reality, the penetration length of the neutrals may be of the order of the plasma minor radius. Therefore, when the electron density and temperature have structures corresponding to the resonant mode at $r/a \sim 0.5$ (12.5 cm into the plasma from the wall), it is likely that the H_α-line radiation exhibits a similar structure. Therefore, in the present experiment, the observed simple helix is probably an indication of the simple structure of electron density and temperature on the $q = 1/4$ mode rational surface. We have observed this kind of simple structure only transiently in the present stage of the RELAX experiment.

This work was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology No. 17360441.

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