Exploration of spontaneous vortex formation and intermittent behaviour in ECR plasmas: the HYPER-I experiments

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HYPER-I is a linear device that combines a wide operation range of plasma production with flexible diagnostics. The plasmas are produced by the electron cyclotron resonance heating with parallel injection of right-handed circularly polarized microwaves of 2.45 GHz from the high-field side. The maximum attainable electron density is more than two orders of magnitude higher than the cutoff density of ordinary waves. Spontaneous formation of a variety of large-scale flow structures, or vortices, has been observed in the HYPER-I plasmas. Flow-velocity field measurements using directional Langmuir probes and laser induced fluorescence method have clarified the physical processes behind such vortex formations. Recently, a new intermittent behaviour of local electron temperature has also been observed. Statistical analysis of the floating potential changes has revealed that the phenomenon is characterized by a stationary Poisson process.

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1. The HYPER-I experiments

1.1. *The HYPER-I device*

HYPER-I (High Density Plasma Experiment-I) is a linear plasma device with adjustable magnetic fields designed for various basic plasma experiments at the National Institute for Fusion Science, Japan (Tanaka *et al.* 1998). The HYPER-I device consists of a cylindrical vacuum chamber whose dimensions are 0.3 m in inner diameter and 2.0 m in axial length surrounded by a set of ten magnetic coils that produce a weakly-diverging magnetic field, which is shown in Fig. 1. The vacuum chamber is a double-pipe type one which made of stainless steel and water-cooled. The base pressure achieved by evacuating the chamber with a turbomolecular pump is less than 1×10^{-6} Torr. The operating gases are introduced by mass flow controllers from the top of the vacuum pump system and distributed to the main chamber by diffusion. The filling gas pressure is typically in the

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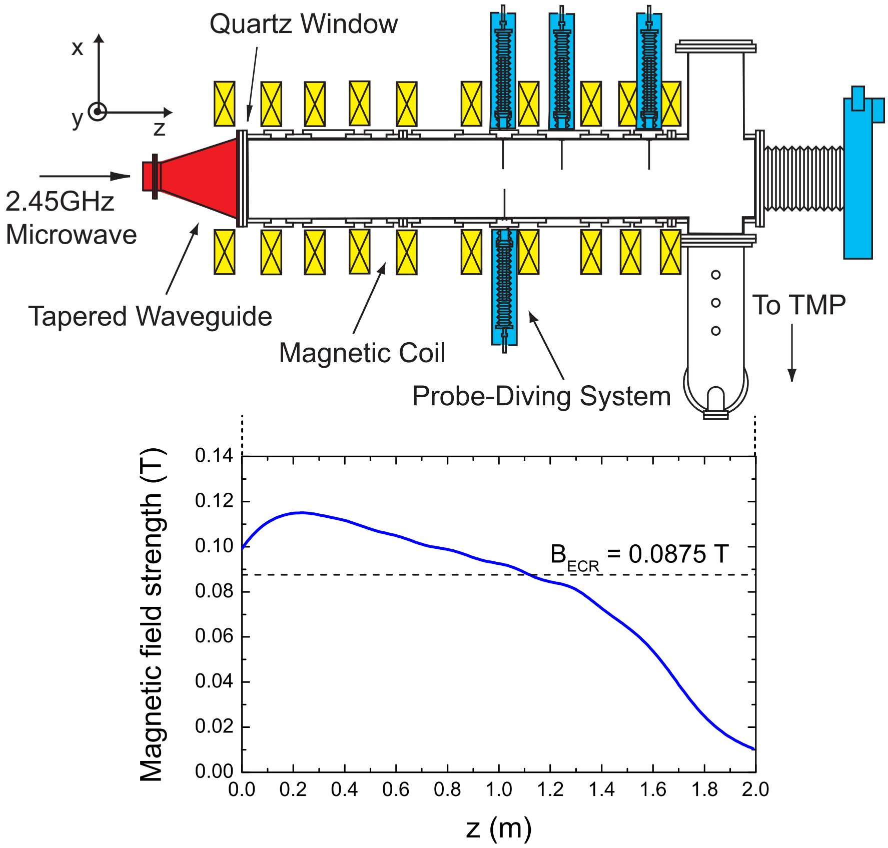

FIGURE 1. Schematic of the HYPER-I device and typical magnetic field configuration (so-called magnetic beach, where the coil current $I_{\rm coil} = 120$ A). We use a Cartesian coordinate system of which origin is at the centre of the microwave injection window; the z-axis is along the axis of the chamber and points toward the right end of the chamber, and the x-axis (y-axis) lies in the horizontal (vertical) plane and points rightward (upward) as viewed from the end of the chamber.

range of $1 \times 10^{-4} - 2 \times 10^{-2}$ Torr. The magnetic field configuration can be changed by the positions of magnetic coils and the coil current of a dc power supply. The HYPER-I plasmas are produced by electron cyclotron resonance (ECR) heating with a microwave of frequency 2.45 GHz. The details of plasma production using electron cyclotron wave are described in section 1.3. A high power klystron amplifier (80 kW CW max.) is available for the microwave source. When the microwave power is relatively low ($\leqslant 5$ kW), the plasma duration time more than 360 s can be attainable. By setting three external parameters (gas pressure, magnetic field, and microwave power), the HYPER-I device is capable of producing a variety of plasmas to explore various plasma phenomena. Plasma operations are controlled by a programmable touch-screen logic sequencer. The typical parameters of HYPER-I device is listed in table 1.

1.2. *Diagnostics systems of the HYPER-I device*

The HYPER-I device offers flexible and easy-to-use diagnostic facilities. Five radial probe-driving systems, which can be readily relocated to different ports, are available to conduct probe measurements; two of them are shown in Fig. 2 (left). The flanges are designed to provide flexibility in probe measurements, some of which are custom-made

Vacuum chamber	0.3 m (inner diameter) × 2.0 m (axial length)
Microwave	2.45 GHz ($\leqslant$ 80 kW, CW, continuously variable)
Magnetic field strength	$<$ 0.2 T (ECR point: 0.0875 T)
Gas species	H_2, He, Ne, N_2, Ar, O_2, and Xe
Operating pressure	$1 \times 10^{-4} - 2 \times 10^{-2}$ Torr
Plasma density	$\leqslant 10^{19}$ m^{-3} (depending on gas species)
Electron temperature	$2 - 30$ eV
Plasma duration time	$3 - 360$ s (depending on microwave power)

Table 1. Parameters of the HYPER-I device.

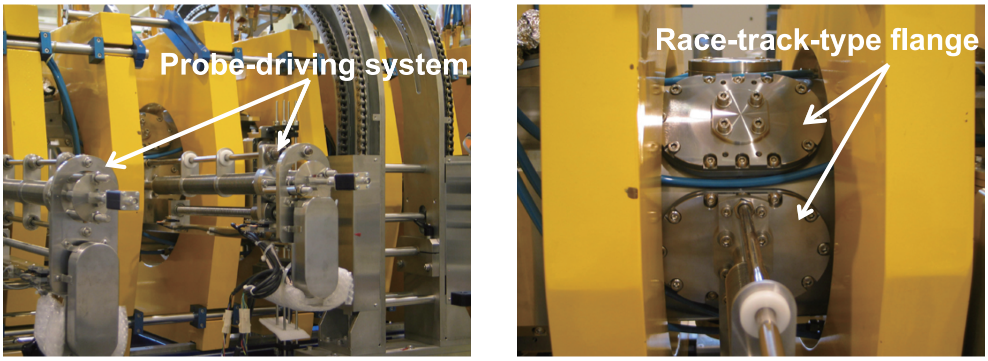

Figure 2. Radial probe-driving systems and race-track-type flanges.

race-track shaped ones that ensure enough room to equip probe-driving systems for different magnetic coil arrangements (See Fig. 2 (right)). The positions of measurement ports are $z = 0.128$, 0.414, 0.500, 0.740, 0.950, 1.175, 1.400, 1.555, and 1.828 m. Four rectangular ports (54 mm × 155 mm) at $z = 0.950$ m (right, left, top, and bottom), are sealed by quartz windows for laser measurements. The axial-end flange is also exchangeable to a large-diameter quartz window for optical imaging.

A variety of electrical probes are available in the HYPER-I experiments. A Langmuir probe which consists of a 1.5 mm diam tungsten rod covered with a 3.0 mm diam ceramic insulator tube is used to measure electron temperature and electron density. Floating potential fluctuation is also measured with a Langmuir probe connected to a 1 MΩ termination resistance. To ensure sufficient frequency response, a voltage follower circuit using a precision high-speed operational amplifier (OPA627, Burr-Brown) is connected to the probe. An emissive probe which consists of a 0.7 mm diam tungsten wire loop heated by dc power supply is used to measure plasma potential. A directional Langmuir probe (DLP) is used to measure ion flow velocity (ion Mach number), where a simple formula based on symmetry property between the directional ion current and the probe angle with respect to the flow direction is used (Nagaoka *et al.* 2001). A magnetic probe is used to measure magnetic field fluctuations. All probes mentioned above can be mounted in the probe-driving systems, which enable us to obtain radial profiles of various plasma quantities. In addition, a pair of probe insertion-angle adjusters by which the insertion angle can be changed up to ±34° are installed at $z = 0.740$ m (see Okamoto *et al.* 2003, Fig. 2); the ion flow velocity field over 80% of the whole plasma cross section can be measured with this system.

Since the ion flow velocity field is essential to investigate plasma vortices, a laser-induced fluorescence (LIF) is used as a complementary measurement tool. Two tunable

Diagnostic	Measured quantity
Langmuir probe (LP)	Electron temperature, density, and floating potential
Emissive probe (EP)	Plasma potential
Magnetic probe (MP)	Magnetic fluctuation
Directional Langmuir probe (DLP)	Ion flow velocity
Laser induced fluorescence (LIF)	Ion and neutral velocity distribution function
Spectrometer and ICCD camera	Optical emission intensity

TABLE 2. Diagnostics in the HYPER-I experiments.

external cavity diode laser (ECDL) systems and a 30 Hz tunable pulsed dye laser system are available to perform the LIF measurements. The LIF spectrum measured by tuning the laser frequency gives the velocity distribution function of metastable excited target particles; the absolute flow velocity and the temperature of ions and neutrals can also be obtained. The information on neutrals is crucial especially for high pressure discharges, where the interaction between ions and neutrals may play an important role in structure formation of weakly ionized plasmas. Very high accuracy in neutral flow velocity determination has been achieved by combining a saturated absorption spectroscopy with the LIF method (Aramaki *et al.* 2009, 2010), where the minimum detectable flow velocity is ± 2 m/s.

For optical emission spectroscopy, a portable spectrometer (EPP2000, StellarNet) and an ICCD camera (ICCD 576 MG/1, Princeton Instruments) with optical bandpass filters for several line emissions (helium, argon, and neon) are available. The latter is used to measure the time development of optical emission with high temporal resolution. Diagnostics systems installed in the HYPER-I device are summarized in table 2.

1.3. *High density plasma production using electron cyclotron wave*

The maximum attainable density of microwave discharge plasmas is limited to rather low values when the ordinary waves are responsible for the plasma production. However, it has been shown (Tanaka *et al.* 1991) that the density limit posed by ordinary mode cutoff is overcome by using electron cyclotron waves (ECW), which is the whistler mode in the electron cyclotron range of frequency. This mode can be accessible to the ECR point for any high-density plasmas, provided that the high-field-side injection condition: $\omega/\omega_{\rm ce} < 1$ is satisfied, where ω and $\omega_{\rm ce}$ are the wave frequency and the electron cyclotron frequency, respectively. This mode also has an advantage to make experiments with various gas species, since the propagation characteristics of ECW are determined only by the electron dynamics.

In the HYPER-I experiments, a microwave generated by a klystron amplifier is transferred with a rectangular $\rm TE_{10}$ mode, which is transformed into a right-handed circularly polarized $\rm TE_{11}$ mode by a dielectric-plate polarizer. As shown in Fig. 1 (top), the circular waveguide is directly connected to an open end of the chamber with a quartz window through a tapered waveguide of which opening diameter is commensurate with that of the chamber. When the microwave is launched in parallel to the magnetic field line from the high-field side, the reflected power is typically lower than 10%.

Figure 3(a) shows the dispersion relation of excited waves measured with a one-turn loop antenna using the interferometric method, where the filling pressure of helium gas was 7.1×10^{-4} Torr and the microwave power 6.5 kW. The experimental results show a very good agreement with the theoretical dispersion curve for ECW derived under the

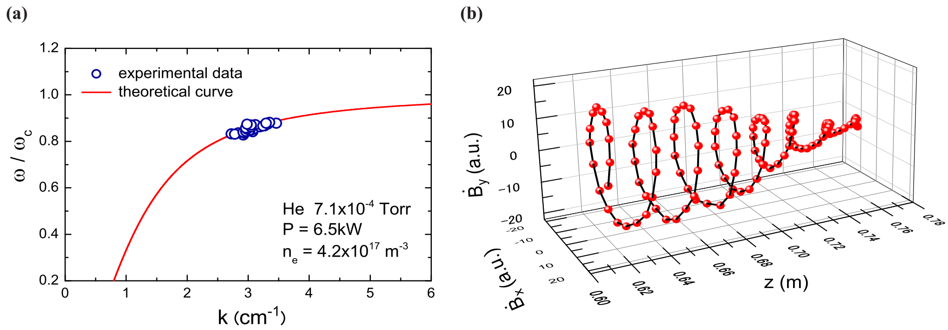

FIGURE 3. (a) Dispersion relation for ECW, where k is the wave number of propagating ECW. Open circles are experimental data. Solid line shows a theoretical dispersion curve, where the cold plasma approximation is used. (b) Polarization of ECW reconstructed from interferometric wave patterns measured with a one-turn loop antenna and a double balanced mixer.

cold plasma approximation (see Chen 1984, chap. 4). Figure 3(b) shows a snapshot of the polarization and attenuation of excited ECW as a function of axial position. A right-handed circularly polarization of ECW is clearly seen. In addition, the energy absorption estimated from the variation of Poynting flux shows that the maximum absorption takes place at $\omega/\omega_{\rm ce} \simeq 0.85$ ($z \sim 0.7$ m), i.e. before reaching the ECR point. This result indicates that energetic electrons may play an important role in the high-field side plasma production through the Doppler-shifted cyclotron resonance. It should be noted that a good single-path absorption of ECW is achieved in the HYPER-I device. General theories of ECR discharges and resonant wave absorption are found in many text books, e.g. Lieberman & Lichtenberg (2005, chap. 13).

2. Spontaneous vortex formation and intermittent behavior in ECR plasmas

Vortex formation has been a topic of interest in plasma physics because of its potential impacts on turbulence and transport in magnetically confined plasmas. It can be said that the magnetized plasma is a treasure trove of vortices. It is because any laboratory plasmas inevitably have inhomogeneities in electric potential, density, temperature, etc. across the magnetic field line, resulting in rotating motion of plasma particles by $\boldsymbol{F}\times\boldsymbol{B}$ drifts. A localized potential structure in the magnetized plasma is equivalent to a vortex; the relation between drift wave vortices and transport of particle, energy and momentum has been studied intensively (e.g. Horton 1999).

A variety of inhomogeneity scale lengths give rise to vortices with various sizes. The formation mechanism of such vortices may also be varied for plasmas of different parameters. When the vortex is driven by $\boldsymbol{E}\times\boldsymbol{B}$ drift, its vorticity can be determined from the plasma potential measurement, which is substituted by the floating potential measurement in many cases. However, a direct measurement of flow-velocity field is indispensable for the vortex driven by other than $\boldsymbol{E}\times\boldsymbol{B}$ drift. The HYPER-I device is ideal to study such vortex formation in magnetized plasmas due to the wide range plasma-production controllability as well as the flexible and tractable flow-velocity measurement capability. It should be noted that the dynamics of neutral particles and interactions between ions and neutrals may have nonnegligible effects on vortex formation in a weakly-ionized plasma.

Intermittency has also been one of the important topics in plasma physics. Intermittent transport of coherent filamental structures called *blobs* is ubiquitous in the edge of many magnetically confined plasmas (e.g. D'Ippolito *et al.* 2011). The convection of blobs significantly enhances cross-field transport and may lead to deterioration in edge confinement. Intermittent transport of similar turbulent structures has also been studied by linear devices (Carter 2006; Windisch *et al.* 2011).

In contrast to those studies, an intermittent behaviour of local electron temperature in an ECR plasma has recently been observed in the HYPER-I device. In the case of helium plasmas, this phenomenon appears for relatively high microwave power ($\geqslant$ 15 kW) discharges. Our previous study has shown that the intermittency appears in the limited operation-parameter space which is different for the different gas species. Since the HYPER-I device is capable of exploring wide parameter space because of the continuous control of microwave power and variety of gas species, the dependence of atomic species on the intermittency can be studied.

3. Experimental results

The experimental results on vortex formation in the HYPER-I plasma are reviewed. Overview of each plasma structure is briefly described in the following subsections. Intermittent behaviour of floating potential due to electron temperature changes, which has recently been found, is also described shortly.

3.1. *Spiral structure*

Figure 4(a) shows an end-view CCD image of a spiral structure in an ECR plasma, where the argon gas pressure is 1×10^{-2} Torr and the microwave power $\leqslant$ 1 kW. The electron temperature and the electron density are 5 eV and 1×10^{18} m^{-3}, respectively. A two-arm spiral can be seen, where the arms are stretched in the counter-clockwise direction. The observed spiral is a density modulation pattern in an azimuthally rotating plasma. It should be emphasized that the spiral pattern is stationary for the entire discharge time. Kono & Tanaka (2000*a*,*b*) have formulated a theory of spiral structure formation in magnetized rotating plasmas subjected to various types of instabilities. The low frequency perturbations are described using two-fluid approximation, and the eigenvalue problem is numerically solved in their work. The instability responsible for the spiral formation in our experiment was identified as the collisional drift wave instability. The density perturbations in the rotating magnetized plasma may develop into spiral structures, which may be stationary in particular cases. Although the theory also predicts a circulating plasma flow that has the similar spiral pattern, experimental verification has not been done yet. This may be attributable to that the structure is not robust against the disturbance induced by probe insertion.

3.2. *Plasma hole*

Spontaneous formation of a density hole structure has been observed in the HYPER-I plasma, which is shown in Fig. 4(b). The helium gas pressure is $< 1 \times 10^{-3}$ Torr and the microwave power 10 kW. The electron temperature and the electron density are 10 - 20 eV and $10^{16} - 10^{18}$ m^{-3}, respectively. The structure is called as *plasma hole* (Nagaoka *et al.* 2002; Tanaka *et al.* 2004, 2005). The electron density of the dark (hole) region is about 1/10 of that of the ambient plasma, and the density transition takes place at a thin layer of the order of several ion Larmor radii.

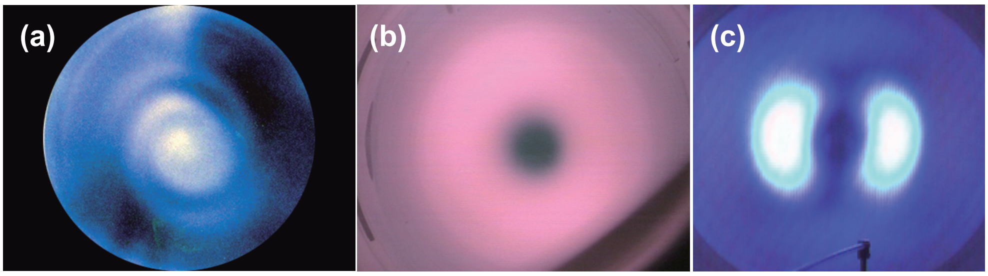

FIGURE 4. (a) Spiral structure. (b) Plasma hole. (c) Tripolar vortex.

The ion flow velocity field associated with the plasma hole has been measured with a directional Langmuir probe. The flow pattern exhibits a monopole vortex with a transonic rotation velocity. Plasma potential measurement using an emissive probe has revealed that the bell-shaped high positive potential ($\sim 5\ T_e$) is localized in the hole; it produces a strong radially outward electric field that drives high speed azimuthal rotation due to $\boldsymbol{E}\times\boldsymbol{B}$ drift. Moreover, the radially inward ion flow also exists, which is attributable to the anomalous viscosity of the plasma. The plasma hole resembles a typhoon not only in the appearance but in the flow field that is a monopole vortex with a sink in its centre. The plasma hole has also been observed in Ar plasmas (Yoshimura *et al.* 2004, 2009), where the subsonic azimuthal rotation has been measured by LIF method.

3.3. *Tripolar vortex*

Two bean-shaped bright regions appear in the HYPER-I plasma as shown in Fig. 4(c). The argon gas pressure is 2.5×10^{-2} Torr and the microwave power $\leqslant 6.5$ kW. The electron temperature and the electron density are 3 eV and $\sim 10^{19}$ m^{-3}, respectively. The electron densities of the bright regions are about three times higher than that of the ambient plasma. Okamoto *et al.* (2003) has measured the ion flow velocity field in a plasma cross section using two directional Langmuir probes mounted in the insertion-angle adjuster of the HYPER-I device. Contour plot of the axial-component of vorticity calculated from the flow field shows the existence of three vortices: two vortices with the same polarity corresponding to clockwise rotation is located in the bright regions in Fig. 4(c), whereas a vortex with the opposite polarity in the slightly dark region at the centre. Hence this structure is called as a *tripolar vortex*. This vortex pattern is also stationary in the laboratory frame. The existence of a stationary tripolar vortex in a cylindrical plasma has been derived analytically by Vrangĕs *et al.* (2002), where the distribution of neutrals in a weakly-ionized plasma plays an important role.

One of the remarkable properties of the tripolar vortex is that each vortex rotates in opposite to the direction of $\boldsymbol{E}\times\boldsymbol{B}$ rotation. Vrangĕs *et al.* (2006) have shown that the counter-$\boldsymbol{E}\times\boldsymbol{B}$ rotation is attributable to the concave neutral density distribution. The neutral distribution affects the dynamics of plasma ions through the charge exchange interactions, resulting in effective pressure of which direction is opposite to that of the electric field. Therefore, when the effective pressure exceeds the electric field, the counter-$\boldsymbol{E}\times\boldsymbol{B}$ rotation can be observed. This theory motivated us to develop the accurate neutral flow measurement using LIF spectroscopy. The inward flow of the neutrals have indeed been observed for a monopole vortex that rotates in the counter-$\boldsymbol{E}\times\boldsymbol{B}$ direction (Aramaki *et al.* 2010).

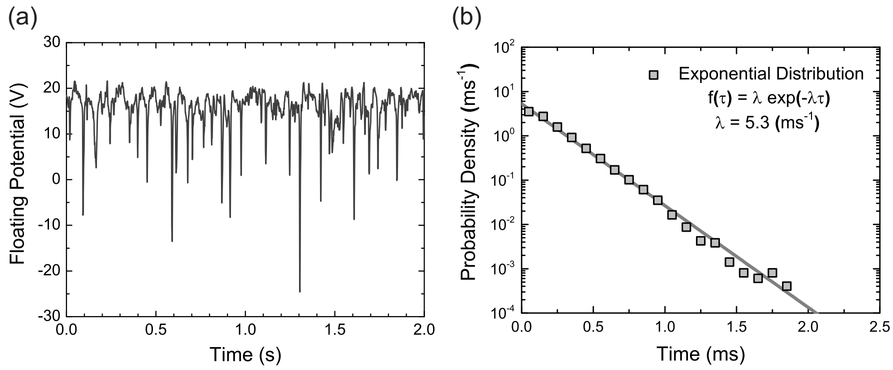

FIGURE 5. (a) Typical time series of intermittent floating potential variation in a helium plasma. (b) Probability density function (PDF) for waiting time with an exponential distribution fitting.

3.4. *Intermittency in electron temperature*

The occurrence of electron temperature intermittency has been first observed as sporadic large-amplitude negative spikes of floating potential measured with a Langmuir probe, as shown in Fig. 5(a) (Yoshimura *et al.* 2014). These negative spikes are attributable to intermittent enhancement of electron energy (temperature), because the floating potential is determined by the balance between influxes of electrons and ions. The electron temperature in the large negative spiky events is, indeed, approximately three times higher than that of equilibrium phase, which has been derived from the current-voltage characteristics obtained by the conditional averaging technique.

To investigate such intermittent phenomenon, the statistics of *waiting-time* (see Aschwanden 2011, chap. 5) provides important information on the mean occurrence rate and the randomness of the events. For example, the probability density function (PDF) of solar flare events gives a power-law distribution that comes from a time-dependent Poisson process (Wheatland & Litvinenko 2002). The waiting time PDF of the floating potential spikes is shown in 5(b). The probability density shows a very good agreement with a exponential distribution fitting, showing that the stationary Poisson process is underlying.

As for the spatial distribution of the phenomenon, two-dimensional measurement of floating potential and ICCD imaging of a line emission from excited neutrals have shown a circular high-temperature region of which size is about 30-40 mm. The position of occurrence is randomly distributed in the plasma cross section. Spatial properties of this phenomenon will be reported elsewhere.

4. Conclusion

The main features of the HYPER-I device are its capability of the wide range of plasma production control and the flexible diagnostics. The former is realized by the parallel injection of right-handed circularly polarized microwaves that couples to the electron cyclotron wave (ECW) in a plasma. Since this mode is not subjected to any density cutoff, the HYPER-I can produce overdense plasmas ($\sim 10^{19}$ m^{-3}) without difficulty. As for the latter, many types of probes are available and able to readily install with the relocatable probe-driving systems. The laser induced fluorescence (LIF) systems provide accurate measurement of the velocity distribution functions, i.e. temperature and flow velocity, for both ions and neutrals. This combination makes HYPER-I an ideal experimental environment for fundamental plasma physics.

The HYPER-I device can be used as a testbed for developing new diagnostics. A fine multihole directional Langmuir probe (FM-DLP, Terasaka *et al.* 2010) has been developed to measure ion flow Mach number. Operation tests of an ultrashort-pulse reflectometer and a helium beam probe for magnetically confined plasmas have also been conducted with the HYPER-I device. Comparison with the existing diagnostics is essential to verify the validity of such work. The development of a novel laser diagnostics using the Laguerre-Gaussian beams, or *optical vortex* (e.g. Allen *et al.* 1994), has recently been started as a collaboration research. It is expected that the new diagnostics will serve as a useful tool to explore a variety of plasma phenomena that take place in the HYPER-I device.

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