

RF breakdown by toroidal helicons

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Abstract. Bounded whistlers are well-known for their efficient plasma production capabilities in thin cylindrical tubes. In this paper we shall present their radio frequency (RF) breakdown and discharge sustaining capabilities in toroidal systems. Pulsed RF power in the electronmagnetohydrodynamic (EMHD) frequency regime is fed to the neutral background medium. After the breakdown stage, discharge is sustained by toroidal bounded whistlers. In these pulsed experiments the behaviour of the time evolution of the discharge could be studied in four distinct phases of RF breakdown, steady state attainment, decay and afterglow. In the steady state average electron density of $\approx 10^{12}$ per cc and average electron temperature of ≈ 20 eV are obtained at 10^{-3} mbar of argon filling pressure. Experimental results on toroidal mode structure, background effects and time evolution of the electron distribution function will be presented and their implications in understanding the breakdown mechanism are discussed.

Keywords. Helicons; radio frequency breakdown; multipactor.

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1. Introduction

Helicon wave is well-known for its extraordinary ionization efficiency [1]. This wave lies in the category of whistler waves. Unlike pure whistlers in free space, helicons are pseudo-electrostatic in nature due to radial boundedness and could be excited to produce and sustain almost fully ionized plasmas with very low input RF power. This particular feature makes them attractive for various plasma processing applications, where high density helicon plasma sources are preferred due to attractive electrical efficiency. Basic studies on dispersive properties of the excited wave, its damping, excited mode structure and ionization capabilities have been conducted for helicons excited in thin cylindrical tubes. The dispersion relation in the whistler wave frequency regime ($\omega_{ci} \ll \omega_{lh} < \omega \ll \omega_{ce}$) is given by

$$\frac{c^2 k^2}{\omega^2} = 1 + \frac{\omega_{pe}^2}{\omega [\omega_{ce} \cos \theta - \omega (1 + \frac{i\mu}{\omega})]},$$

where ω , k , ω_{pe} , ω_{ce} and μ are wave frequency, propagation vector, electron plasma frequency, electron cyclotron frequency and electron collision frequency respectively. In

addition to long wavelength helicon modes, this dispersion relation also allows short wavelength electrostatic Trivelpiece–Gould (TG) waves, that play an important role in power deposition mechanism and resulting radial profiles of plasma parameters. Toroidal helicons are bounded whistler modes of a toroidal plasma cavity and differ in many aspects from cylindrical helicons. In the experiments where RF is used to produce plasma, understanding of the initial breakdown phase is crucial for proper design of the exciter. In most of the low pressure RF plasma sources breakdown mechanism and fast build-up of density is attributed to multipactor effect [2,3]. In this paper we report the time dependent evolution processes in a pulse RF plasma produced by toroidal helicons.

2. Experimental set-up and diagnostics

The experimental system used for results reported here, consists of a toroidal plasma device made of stainless steel chamber without any toroidal electrical break. It has a major radius of 30.0 cm and a minor radius of 10.5 cm. A copper cable is wound on the surface of the vacuum vessel, through which pulsed current of 150 ms duration of full width at half maxima is allowed to flow. This in turn produces a maximum toroidal magnetic field (B_0) of 600 G on the axis. The chamber is evacuated to a base pressure of 10^{-5} mbar with a combination of rotary and diffusion pump system. Discharge is produced using argon gas at 10^{-3} mbar of working pressure. To generate the plasma in the presence of the toroidal magnetic field, RF power is fed to a helical type and a Nagoya type of antennae. It has been observed that production of continuous RF discharge with another exciter and a 100 W continuous source before the main experiment improves the reproducibility of the discharges in our pulsed experiments. During the pulsed experiments, 1.5 kW of RF power for a 50.0 ms duration with $\sim 10 \mu\text{s}$ of rise/fall time is fed to the antenna at 8.16 MHz. This RF pulse excites toroidal helicons to sustain the discharge. Magnetic and electrostatic RF compensated probes, B -dot probes, Rogowskii coil, RF interferometer and retarding field energy analyzer (RFEA) are used for measurements of plasma properties.

3. Results and discussion

In the steady state, plasma discharge with peak electron density $n_e \approx 10^{12}$ per cc and electron temperature $T_e \approx 20$ eV is obtained. Measured phase velocity of the wave using RF interferometer is 10^6 m/sec, while the wave polarization corresponds to right handed circularly polarized wave on the plasma axis. These results indicate the excitation of whistlers during steady state of a self-sustained toroidal plasma.

Figure 1 depicts numerically computed and measured radial variations of wave field components. EMHD regime is used in the numerical model, which computes the variations of these wave field components in the poloidal plane. Detailed description of the numerical analysis will be presented elsewhere. These radial variations of wave field components are measured with B -dot probes. We find close agreement between measured and numerically computed profiles of field components. Strong asymmetry in the radial profile of wave field components for inboard and outboard directions of torus is a result of asymmetric nature of wave field pattern in the poloidal direction. In the parameter regime of our experiment, parallel wavelength of excited whistler (≈ 60 cm) is of the order of the

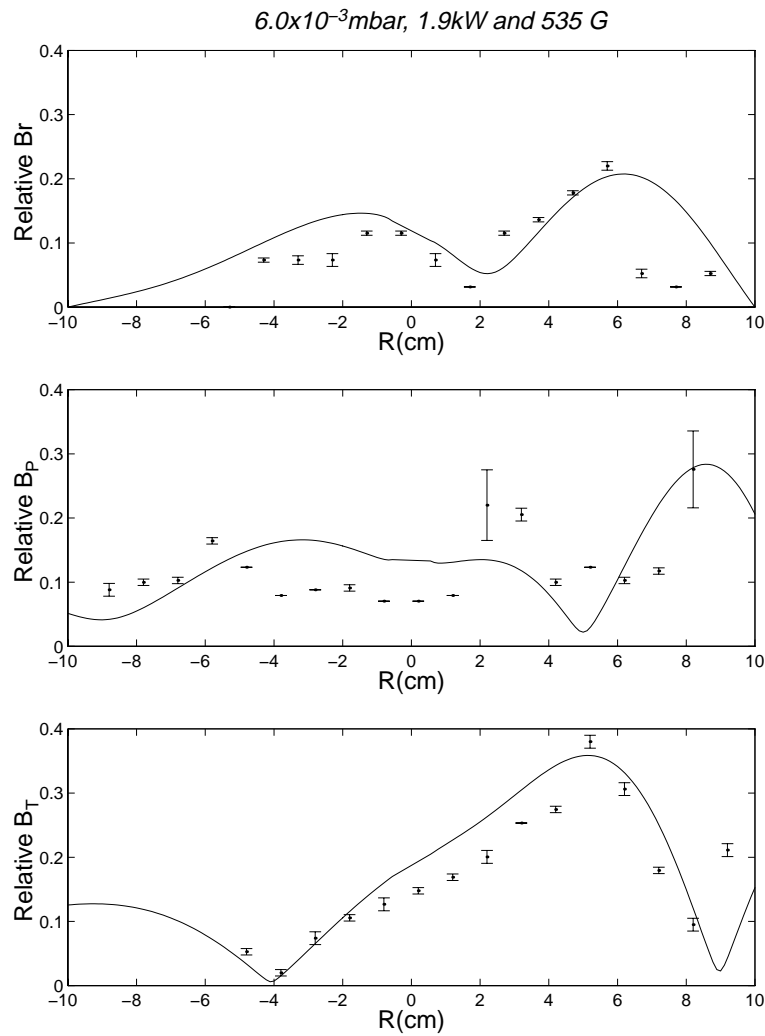


Figure 1. Variation of radial (B_r), poloidal (B_p) and toroidal (B_T) wave field components along plasma diameter are shown here. Positive values are given to all the radial positions in the outboard direction. Solid line represents numerically computed wave field variation. Measured data points for these wave fields are also shown in this graph by discrete points with error bar. Background conditions of pressure, RF power and B_0 are also shown.

system dimension. At the same time due to tight aspect ratio of the torus, inhomogeneity in the ambient toroidal magnetic field is also significant to decide the wave field pattern. These two factors introduce strong poloidal mode coupling in the observed wave fields of the bounded whistler in torus and deviation of the wave field pattern for torus from

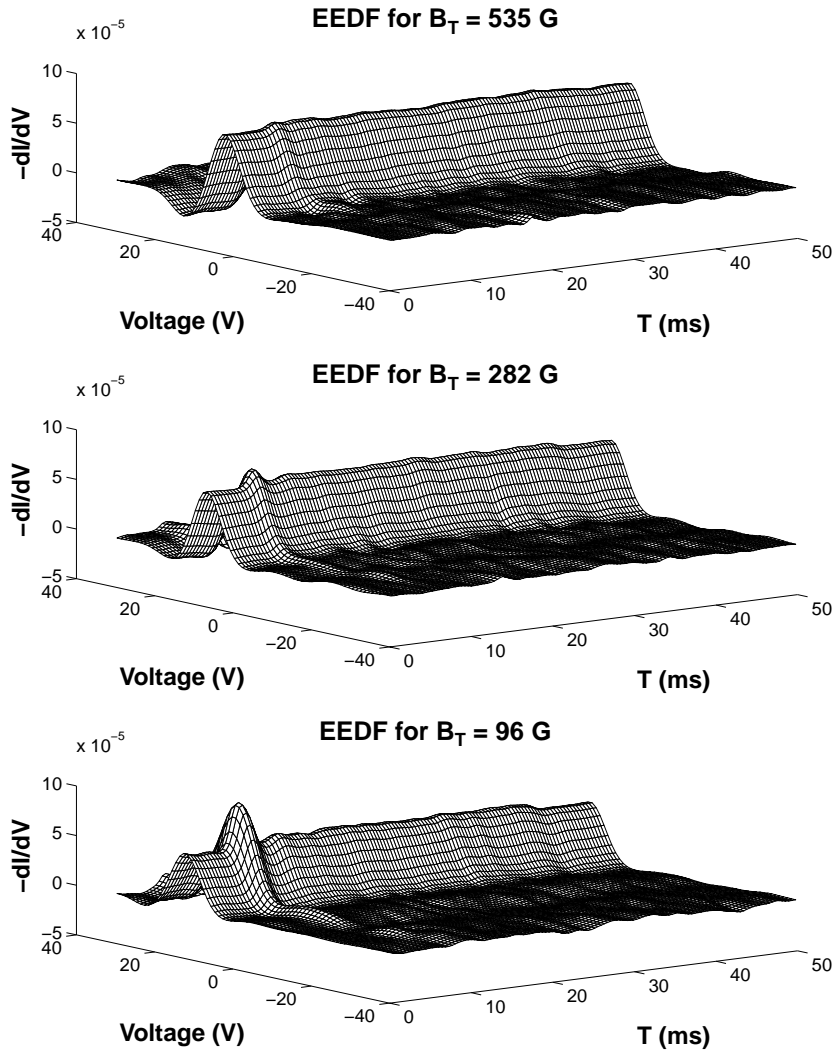


Figure 2. Time evolution of $f_e(v)$ for different values of toroidal magnetic field.

its cylindrical counterpart is observed. This distinct behaviour of wave field shows that normal modes of a tight aspect ratio toroidal plasma, sustained by bounded whistlers, are substantially different than their cylindrical counterparts.

In figure 2 time evolution of $f_e(v)$ for three different magnetic field values are shown. Production of energetic electrons in the initial few microseconds of the breakdown phase is clearly seen in this figure. These energetic electrons are produced due to appearance of over voltage on the antenna due to high Q of the matching network during the initial breakdown phase. These electrons with few keV energy range cause an increase in the avalanche

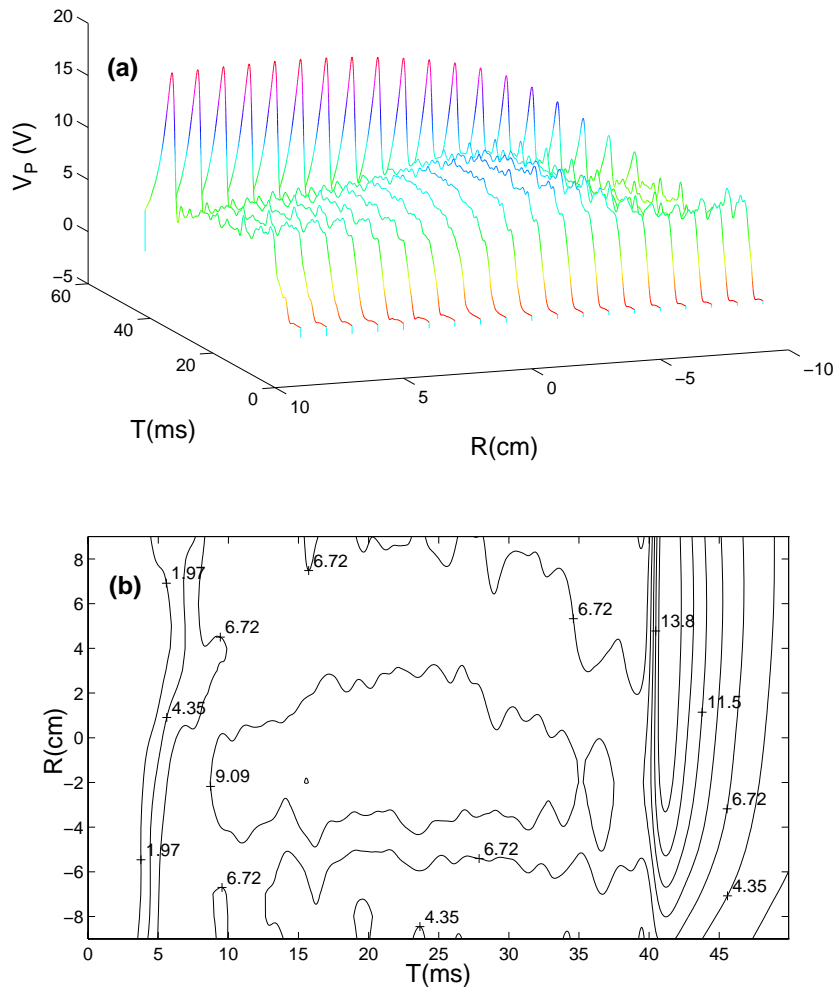
2.0×10^{-3} mbar, 1.6 kW, port2

Figure 3. (a) Time evolution of probe potential at different radial locations are shown here. Ar gas pressure and input RF power are given for these plasma shots. (b) Contours of probe potential to show initial hump and transient nature of sheath at the end of the pulse. It is to check the discharge position and steady state attainment.

process due to multipactor effect [3]. A simple qualitative explanation based on existing ideas of RF breakdown phenomena is given to understand the role of B_0 on RF breakdown. With increasing value of B_0 , trajectories of primary electrons causing secondary emission from antenna and neighbouring surfaces change their nature and required path traveled by them to reach the surface thus increases. In this case, effective momentum transfer to surfaces from electrons reduces with increase in magnetic field B_0 and probability of

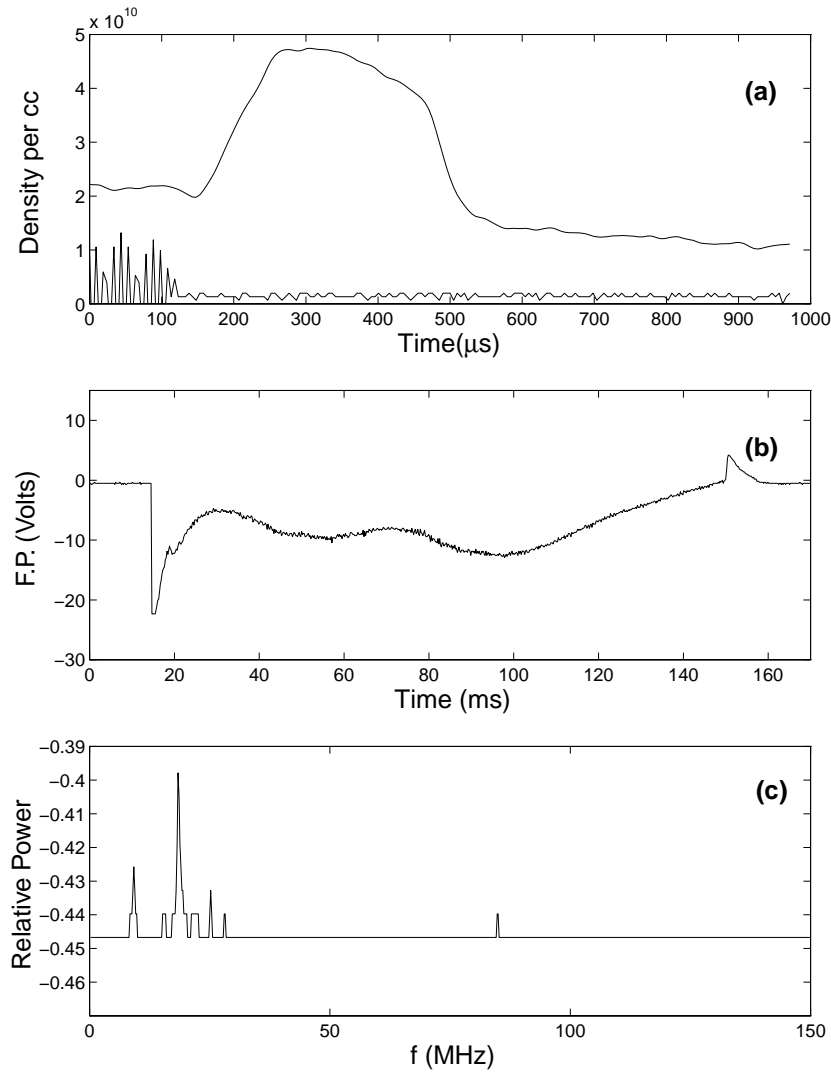


Figure 4. (a) Time evolution of plasma density on the discharge axis after the RF pulse termination, (b) typical time evolution of floating potential and (c) power spectrum of RF signal in the plasma are shown.

proper phase match to initiate multipactor effect is also reduced. Due to these reasons secondary emission from surfaces at larger values of B_0 decreases and subsequently the plasma build-up process becomes slower. Apart from this, we do not get very high density of plasma in the breakdown phase for higher value of B_0 .

In figure 3, movement of the plasma column during the discharge is shown. Steady state plasma for ~ 50 ms is produced. Breakdown and decay phases are shown by open contour lines in this figure. Decay of n_e after RF power termination is shown figure 4. Initial hump

in the trace is caused due to the transient nature of the sheath during the plasma collapse [4]. Floating potential measurement also depicts a similar behaviour. These measurements indicate the transient nature of plasma parameters during initial breakdown phase. Only after few milliseconds steady state phase of the plasma is reached.

4. Conclusion

In the initial breakdown stage, impedance mismatch helps in the breakdown process, whereas the steady state phase is favoured by efficient wave excitation feedback processes. The simple application of these results could be in the development of energy efficient and better particle flux controlled plasma sources. In this low pressure regime, multipactor effect is a deciding factor in the breakdown and plasma build-up processes, therefore the role of antenna surface quality is an important issue of analysis in our future experiments.

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