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# Electron density inversed by plasma lines induced by suprathermal electron in the ionospheric modification experiment

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**Abstract**

Incoherent scatter radar (ISR) is the most powerful ground-based measurement facility to study the ionosphere. The plasma lines are not routinely detected by the incoherent scatter radar due to the low intensity, which falls below the measured spectral noise level of the incoherent scatter radar. The plasma lines are occasionally enhanced by suprathermal electrons through the Landau damping process and detectable to the incoherent scatter radar. In this study, by using the European Incoherent Scatter Association (EISCAT) UHF incoherent scatter radar, the experiment observation presents that the enhanced plasma lines were observed. These plasma lines were considered as manifest of the suprathermal electrons generated by the high-frequency heating wave during the ionospheric modification. The electron density profile is also obtained from the enhanced plasma lines. This study can be a promising technique for obtaining the accurate electron density during ionospheric modification experiment.


*Keywords:* Suprathermal electron; Plasma lines; Ionosphere heating experiment; Incoherent scatter radar; Electron density

## 1. Introduction

Incoherent scatter radar is the most powerful ground-based facility for measuring the ionospheric plasma parameters, such as electron density, electron temperature, ion temperature, ion velocity, ion composition and ion-neutral collision frequency (Evans, 1969; Kelley, 2009). In the standard incoherent scatter radar analysis, the ion lines, which are the radar echoes from the ion acoustic waves in the plasma, have been exploited to estimate the plasma parameters in the ionosphere (Evans, 1969). Generally, a double humped spectra shape of the ion lines is observed in the F region echoes of ISR. The power under the double humped spectra of the ion lines is proportional to the electron density (Kelley, 2009). The plasma lines measured by the incoherent scatter radar are associated with the Langmuir waves in the plasma (Perkins et al., 1965). Most ISRs cannot routinely measure the plasma lines because the power of the plasma line often below the detectable spectral noise level. However, plasma lines are occasionally enhanced and measured in the presence of electron non-thermal feature – such as photoelectrons (Perkins et al., 1965; Yngvesson and Perkins, 1968; Evans and Gastman, 1970), secondary electron (Kirkwood et al., 1995; Carlson et al., 2015), electron beams (Akbari et al., 2012; Isham et al., 2012) and in the ionospheric modification experiments (DuBois et al., 2001).

Perkins and Salpeter (1965) predicted that the plasma lines would be enhanced by the photoelectrons produced by solar UV radiation in the theory. Perkins et al. (1965) first observed the enhanced plasma lines from the daytime ionosphere with the Arecibo incoherent scatter radar, in which the suprathermal electrons were locally generated by photoelectrons. Later, both Arecibo incoherent scatter radar and Millstone Hill incoherent scatter radar were

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utilized to observe the enhanced plasma lines during local darkness (Yngvesson and Perkins, 1968; Evans and Gastman, 1970).

Wickwar (1978) first observed the enhanced plasma lines in E-region of the high-latitude ionosphere during intense auroral activity by using the Sondrestrom incoherent scatter radar. The observations showed that the plasma lines intensities increased up to 30 times above the thermal level between the altitudes 98–134 km and in the frequency range 3.8–6 MHz. Kofman and Wickwar (1980) used Sondrestrom incoherent scatter radar to detect the similar observations and calculated the enhanced Langmuir waves were in resonance with electrons in the range 0.5–1.5 eV. Recently, Vierinen et al. (2016) reported the high temporal resolution plasma lines enhanced by the auroral electron precipitation with the Sondrestrom incoherent scatter radar.

It was suggested that the Langmuir waves generated by the electron-beam resulted in the anomalous and intensive incoherent scatter radar echoes, which can be directly observed (Akbari et al., 2012; Isham et al., 2012). The simultaneous enhanced downshifted and upshifted plasma lines and ions lines provided the direct evidence of the Langmuir turbulence generated by the electron beams (Akbari et al., 2012). Isham et al. (2012) observed the zero-frequency peak, which were considered as results of the stationary density cavities.

During ionospheric modification experiment, the high-powerful high-frequency (HF) electromagnetic (EM) waves injected into the ionosphere from the ground-based heating facility (Utlaut and Cohen, 1971). Near the reflection altitude, the HF O-mode EM wave decayed to the Langmuir wave and the ion acoustic wave through the parametric decay instability (Fejer, 1979), or decayed to the two Langmuir waves propagating to the opposite directions and a purely growing mode though the oscillating two-stream instability (Kuo, 2002). The X-mode heating wave also excites the Langmuir wave near its reflection height through the parametric instability under certain scenario (Blagoveshchenskaya et al., 2014; Wang et al., 2016). The Langmuir waves generated by the heating wave enhanced the plasma lines which were observed by the incoherent scatter radar at Arecibo, Puerto Rico (Muldrew and Showen, 1977) and Tromsø, Norway (Rietveld et al., 2000). Carlson et al. (2017) reported that the plasma lines were enhanced by both the HF-accelerated suprathermal electrons and the photoelectrons from conjugate hemisphere after the heater turned on with the Arecibo incoherent scatter radar.

There exists a great number of publications with the goal of exploring potential applications of plasma lines in estimation of the ionospheric plasma parameters, such as electron density. Showen (1979) detected daytime plasma lines at the peak of F region with Arecibo incoherent scatter radar and measured electron density fluctuations from slight variations in the frequency offset. Hagfors (1982) theoretically introduced a high spatiotemporal resolution measurements of electron density with the chirped plasma-line technique. Using Sondrestrom incoherent scatter radar, Vierinen et al. (2016) made the high temporal resolution measurements of the electron density with advanced digital receiver technology during auroral precipitation events

The high-powerful HF EM waves that propagates in the ionosphere undergoes the collisional damping and therefore heats the plasma. In addition, the sufficiently powerful EM waves as pump waves excite various nonlinear phenomena of plasma waves and generate changes in the ambient conditions with a large spatial and temporal scales. When the heating wave injects into the upper F-region (higher than 200 km), the electron density depletes near the heating wave reflection height, due to the diffusion process (Rietveld et al., 1993), parametric instability (Kuo, 2015), and Langmuir turbulence (DuBois et al., 2001). Meanwhile, the electron temperature significantly increases (Hansen et al., 1992), leading to the change of the electron velocity distribution function. Owing to the parametric instability, the ion lines considerably distort during the heating experiments (Kohl et al., 1993). The ionospheric parameters strongly dependent on the shape of the ion line spectra (Kelley, 2009), which is affects by the distribution function. Consequently, the electron density sometimes is hard to accurately estimate in the ionospheric heating.

In this study, the enhanced plasma lines by the suprathermal electrons above the heating region are utilized to accurately estimate the electron density in the ionosphere heating experiment. The outline of this paper is as follows. In Section 2, the experiment facilities are briefly introduced, as well as the experimental observations. The further discussion is shown in Section 3. The electron density estimation from the plasma lines is presented and compared with the electron density calculated from the ion lines in Section 3. The principal conclusions are summarized in Section 4.

## 2. Instrumentation and experimental observations

The ground-based high-frequency ionosphere heating facility is located at Ramfjordmoen near Tromsø, Norway (69.59°N, 19.21°E), which is run and operated by the EISCAT (Rietveld et al., 1993, 2016). We report the experiment observation of the plasma lines in the ionosphere heating experiment, which is performed in 14:11–14:26 UT on October 22, 2012 by the Russian team led by Dr. Blagoveshchenskaya (Wang and Zhou, 2017). In the experiment, the facility operated on 7.953 MHz using the high-gain array with the beam inclination of 6°. The polarization is set as the extraordinary EM wave, with the effective radiated power (ERP) of 530 MW. The facility operated a 15 min transmission cycle of 10 min on/5 min off, i.e., the heater turned on at 14:16 UT and off at 14:26 UT.

During the experiment described here, the EISCAT UHF incoherent scatter radar (Rishbeth and Eyken, 1993), collocated with the HF heating facility, measured

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