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Retarding field energy analyzers for the ion temperature measurements in the SOL plasmas of the tokamak ISTTOK and the TJ-II stellarator

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Measurements of the ion temperature in the plasma boundary of fusion devices typically employs the Retarding Field Analyzer (RFA) that is based on selective rejecting or retarding the plasma ions by a varying braking electric field. Normally, the RFA comprises an input slit and collector electrode with two or more separately biased fine grids placed in front of it. With an assumption of Maxwellian ion distribution, the exponential decay of the RFA collector current-voltage characteristic is determined by the ion temperature. This contribution describes 1- and 3-channels RFAs for the ion temperature measurements in the scrape-off-layer of the tokamak ISTTOK and the TJ-II stellarator. Selected results of the ion temperature measurements on the ISTTOK and the TJ-II are presented. In addition, limitations related to the RFA operation (including the alignment along magnetic field direction and plasma loading) are considered.

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1 Introduction

The retarding field analyzer (RFA) is one of the mostly used diagnostic tools for the ion temperature measurements in the scrape-off-layer (SOL) and edge plasmas of fusion devices (see, for example, [1] and references therein). As shown in Fig.1, the RFA consists of an input slit (Slit), two separately biased fine grids (G_1 and G_2) and a collector electrode (C). Grid G_1 selectively retards the plasma ions, while grid G_2 repells the plasma electrons and suppresses the secondary electrons from the collector C.

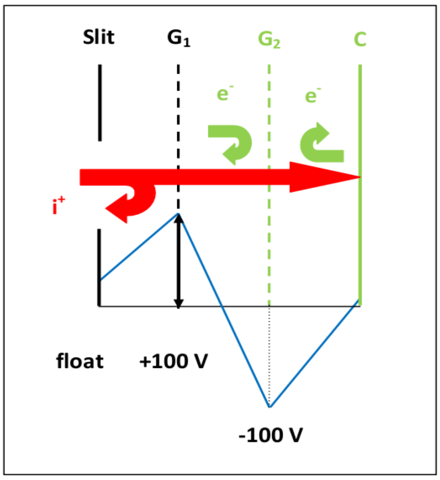

Fig.1. RFA schematic: G_1 is the ion retarding grid, G_2 is the plasma electron repeller and secondary electron suppression grid.

For an assumed shifted Maxwellian distribution the ion current, I_i, as a function of retarding potential, U, and ion temperature, T_i, is:

$$I_i(U) = I_{0i}, \qquad U < U_{shift},$$
$$I_i(V) = I_{0i}\exp[-q_i(U - U_{shift})/kT_i], \qquad U > U_{shift}, \qquad (1)$$

where I_{0i} is the ion current collected when none of the ions are repelled by the retarding potential, and U_{shift} is the potential equal to the difference between the plasma potential and the probe ground. According to Eq.1 the ion temperature is obtained by an exponential fit to the measured current-voltage (*I-V*) characteristic where only $U > U_{shift}$ is considered.

2 ISTTOK and TJ-II RFAs

2.1 RFAs description

Pictures of 1-and 3-channels RFAs developed for the tokamak ISTTOK and the TJ-II stellarator (Table 1) are shown in Fig.2.

Plasma device	R, m	a, m	B, T	I_p, kA	<ne>x10^{19} m^{-3}	$T_e(0)$, eV
ISTTOK	0.45	0.085	0.5	3-5	0.3-0.6	120
TJ-II	1.5	0.22-0.25	1		0.2-1	600

Table 1. Prameters of the tokamak ISTTOK and the TJ-II stellarator.

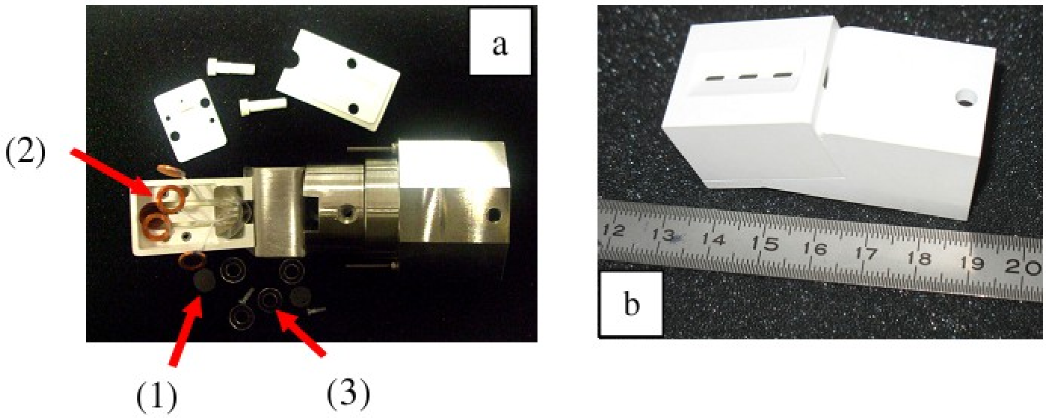

Fig.2. Pictures of 1- (a) and 3-channels (b) RFAs.

The small parts of the RFAs include [2]:
-- input tungsten slit: 100 μm of width (typical Debye length is 50-70 μm), 3 mm of length, 25 μm of thickness (Lenox Laser [3]);
-- 2 fine nickel grids (labelled (1) in Fig.2a): 18 μm of line width, 180 μm of spacing, 25 μm of thickness (80% of resulted optical transparency);
-- copper support washers (lebelled (2) in Fig.2a): 9.5 mm of external diameter, 6 mm of internal diameter, 0.8 mm of thickness;
-- MICA insulator washers (lebelled (3) in Fig.2a): 9.5 mm of external diameter, 5 mm of internal diameter, 0.1 mm of thickness;
-- boron nitride (BN) 20x20 mm^2 housing (Fig.2b) attached to the standard ISTTOK/TJ-II probe shaft allowing for the radial movement/reciprocation inside the vacuum vessel.

The RFAs are unidirectional (as the Mach number measured by a Gunderstrup probe in SOL of ISTTOK and TJ-II is about $M \sim 0.2$, the measured ion temperature will differ by only 20% from the unperturbed ion temperature value [4]). For the 3-channel RFA the separation between the collectors is 7 mm and the biased grids are common for all channels. The RFAs are installed at the horizontal and vertical diagnostic ports of the ISTTOK and the TJ-II respectively. On TJ-II the RFA is inclined at 30º to be aligned along the magnetic field direction using a special shaping of BN housing (Fig.2b). The current from the RFA collectors is measured across a resistors of 100 kOhm via an isolation amplifier and acquired by the ISTTOK and the TJ-II data acquisition systems with 2 MHz of sampling rate

2.2 Operation

Fig.3a presents an example of the signals from the RFA collector when a ramping voltage is applied to the retarding grid. Fig.3b shows the typical RFA *I-V* characteristics together with the rspective exponential fit.

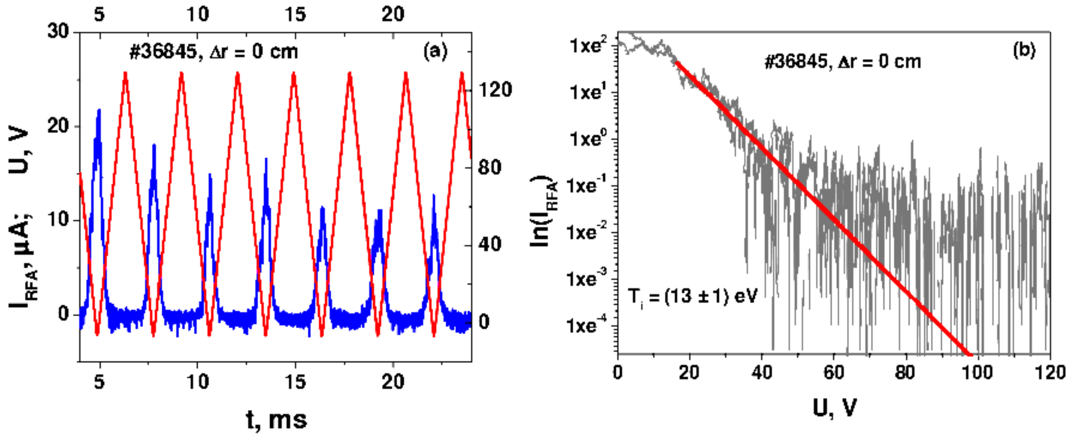

Fig.3. Typical signals observed from RFA collector with a ramping voltage (a). Exponential fit of RFA *I-V* characteristic during one ramping cycle (b).

It is important to note the absence of hysteresis on the *I-V* characteristic in Fig.3b indicating no influence of space-charge effects [5].

The temporal resolution of the measurements is 0.5 ms restricted by the stray capacitances of the RFA powering circuit. The spatial resolution is 5 mm radially and 2 mm poloidally determined by the sum of the slit dimentions with the ion Larmour radius. Uncertainties in the ion temperature measurements are typically within 10%-20% determined mainly by the signal noise.

3 Ion temperature profiles

The ion temperature profiles in the SOL of the ISTTOK (I_p = 3 -5 kA, $\langle n_e \rangle$=3-5×10^{18} m^{-3}, hydrogen plasma) and the TJ-II ($\langle n_e \rangle$ = 2.5×10^{18} m^{-3}, ECRH plasma) are presented respectively in Fig.4a and Fig.4b. As illustrated in Fig.4, flat ion temperature profiles are observed in both devices indicating strong transverse ion energy transport [6].

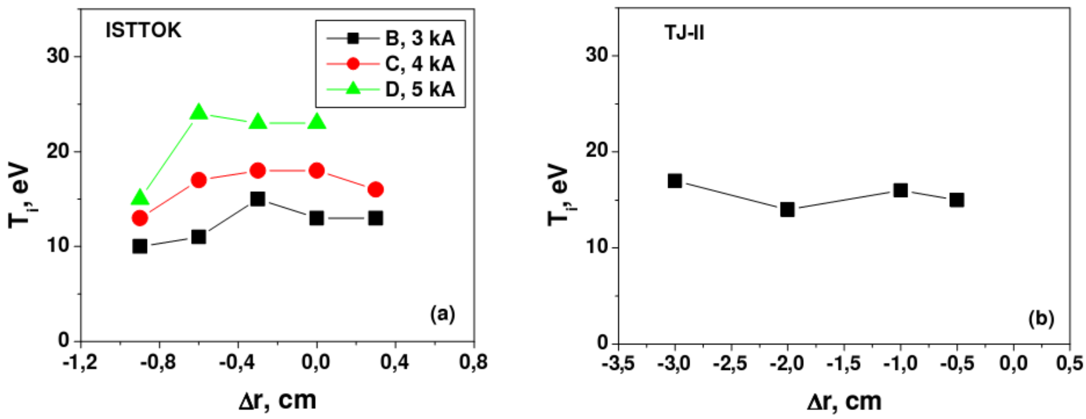

Fig.4. Ion temperature profiles in the SOL of the ISTTOK ($\Delta r = a_{lim} - r_{RFA}$) and the TJ-II ($\Delta r = a_{LCFS} - r_{RFA}$).

4 Operation limitations

4.1 RFA alignment

One requirement for the RFA operation is the alignment of the RFA axis parallel to the local magnetic field direction. In TJ-II experiments, the RFA reciprocates across magnetic field surfaces with different shapes, therefore operating at slightly different angles (up to 6° change) between the analyzer axis and the magnetic field lines. Poor alignment conditions have been investigated experimentally with the RFA inclined relatively to the magnetic field lines on the tokamak ISTTOK. As shown in Fig.5 modest variation in T_i is observed within the error bars, up to angles of 15°.

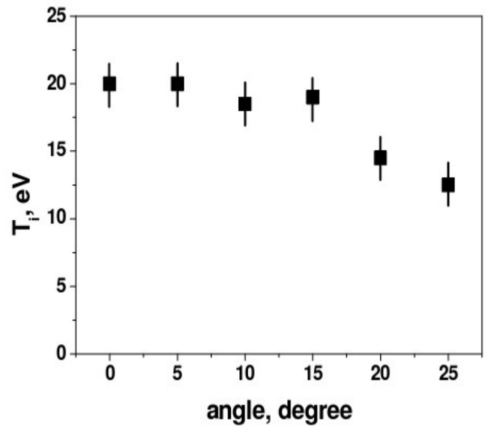

Fig.5. T_i, measured at different angles of RFA relative to magnetic field line of ISTTOK.

This result agrees with numerical simulations of poor RFA alignment (up to 10°) on the Tore Supra tokamak [7]. The proposed explanation is that since the parallel and perpendicular ion velocities are de-correlated, each value of perpendicular velocity contains the full set of parallel velocities. Therefore, the measured ion temperature depends weakly on the misalignment angle. However, the ion temperature starts to decrease at the angle when the ion beam transmission starts to decrease also, indicating the loss of mainly the high energy (higher Larmour radios) ions along the path from the slit to the collector inside the RFA.

4.2 Plasma loading

The deepest insertion of the RFA into the plasma is limited to $\Delta r = a_{lim} - r_{RFA}$ ~0.6 – 0.8 cm from the leading edge of the limiter in the ISTTOK and LCFS position in the TJ-II. The electron density and temperature measured by probes at that positions are $n_{eLCSF} \sim 10^{18}$ m^{-3} and T_{eLCFS} ~ 25 eV. Further radially inside the RFA signal degrades with the appearance of the negative offset and spikes. Example of such signal from RFA on ISTTOK is shown in Fig.6a.

The nature of phenomena is not definitely clear. As suggested in Ref [8] it could be due to space-charge effects when the ion current attains a value close to the space-charge limitation, $i_{RFAcrit}$, most likely occurring in the electron-free space between the electron repeller grid G_2 and the collector C (see Fig.1). For hydrogen plasmas estimations give $i_{RFAcrit}$ ~ 60 µA for the critical space-charge limited ion current for a slit with area of 0.1x3 mm^2 , Δl_{G2-C} =1 mm and ΔU_{G2-C} = 100 V (a higher $i_{RFAcrit}$ is obtained when the effective broadening of beam area by Larmour radius is taken into account). In addition, there is apparently no hysteresis on the disturbed *I-V* characteristics as one can conclude from Fig.6b. These observations indicate that space-charge effect may not be the only origin for the RFA signal degradation. Finally, it is important to note that normal operation is recovered when RFA is moved back into the SOL.

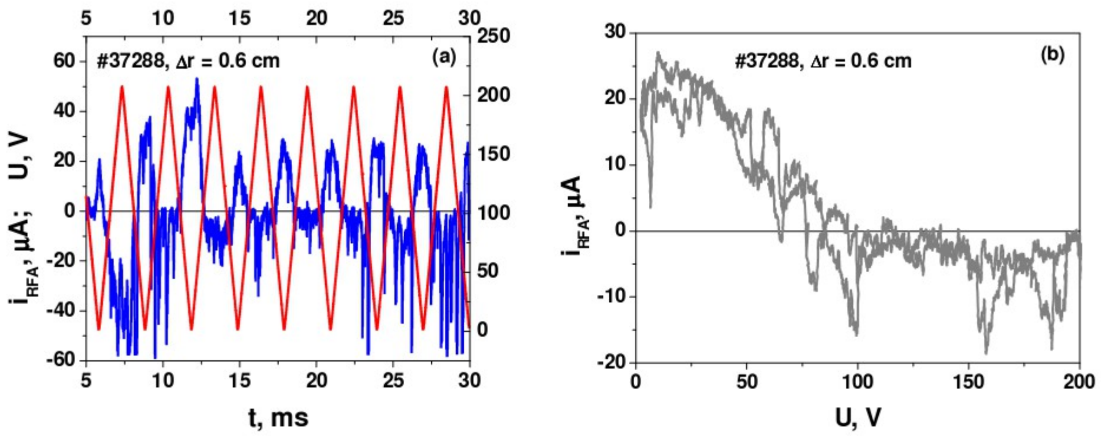

Fig.6. Example of RFA signal at Δr =0.6 cm on ISTTOK (a). One cycle of *I-V* characteristic (b) ($<n_e>$ = 7.5x10^{18} m^{-3}, I_{pl} = 5 kA).

5 Summary

The 1- and 3-channels RFAs have been developed for the ion temperature measurements in the SOL of the tokamak ISTTOK and the TJ-II stellarator. The temporal and spatial resolutions of the measurements are 0.5 ms and 5x2 mm^2, respectively. Errors in ion temperature measurements are between 10%-20%. Measurements in ISTTOK and TJ-II indicate flat ion temperature profiles in the SOL as expected for strong transverse ion energy transport. Finally, it is shown that measurements are limited by ~10^o of RFA misalignment along magnetic field direction, and by the limiter (ISTTOK) and LCFS (TJ-II) positions due to plasma loading effects.

Acknowledgements

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