Numerical investigation on the validity of ion temperature measurements by a retarding field analyzer in turbulent plasma

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1. Introduction. The ion temperature, T_i, in the scrape-off layer (SOL) has an important role in the plasma-wall interactions in tokamaks. Sophisticated electric probes such as a retarding field analyzer (RFA) are used to measure T_i. In practice, T_i is obtained from the exponential fit to an RFA current-voltage (*I-V*) characteristic, assuming Maxwellian ions. As observed in simulations [1] and recent experiments [2] in ASDEX Upgrade (AUG), SOL turbulence is associated with strong fluctuations of T_i. Since the plasma fluctuates faster than the RFA voltage is typically swept, it is legitimate to ask if the RFA provides correct T_i measurements in a way it is used. A closer look at this problem is important especially now, when RFAs are used in a number of tokamaks such as AUG, C-Mod, ISTTOK, MAST and Tore Supra. In the present study, we build on our recent publication [2], and use the gyrofluid code GEMR [3-5] to investigate various techniques for measuring T_i by an RFA in a turbulent SOL.

2. RFA technique. Fig. 1 shows a type of an RFA that is typically used in the tokamak SOL. A negatively-biased slit plate repels electrons back into the plasma and admits a fraction of the incident ion flux inside an RFA through a narrow aperture. The slit plate measures the ion saturation current density, j_{sat}. Ions transmitted through the aperture proceed to grid 1, biased to $V_{g1} > 0$. Ions with the energy $E_i > Z_i e V_{g1}$ proceed to a collector, which measures the ion current I_c. An additional grid, grid 2, biased to a high negative voltage, is placed between grid 1 and the collector. Grid 2 repels the electrons that are energetic enough to overcome the slit plate voltage and suppresses secondary electrons emitted inside an RFA. Electrodes are perpendicular to the total magnetic field vector, ***B***, making an RFA sensitive to ion velocities parallel to ***B***. It is a standard practice to sweep V_{g1} at a few kHz and obtain T_i from the exponential fit to the decaying part of an *I-V* characteristic, $I_c \propto \exp(-V_{g1}/T_i)$. The difficulty of using such a simple and convenient model arises due to plasma fluctuations. This problem is illustrated in Fig. 1, which shows a typical *I-V* characteristic (and the corresponding j_{sat}) measured by an RFA in the AUG SOL. The *I-V* characteristic features a number of intermittent bursts due to fluctuations of the plasma density and temperatures. In such transient conditions it is clearly unjustified to adopt the standard RFA model, which assumes that ions in the *I-V* characteristic have the same temperature. Plasma fluctuations are ubiquitous in the tokamak SOL [6], so, undoubtedly, the problem is not restricted to the AUG RFA. In earlier RFA experiments, insufficient sampling frequencies smeared out the filamentary structure of I_c and did not allow the experimentalists to see the problem.

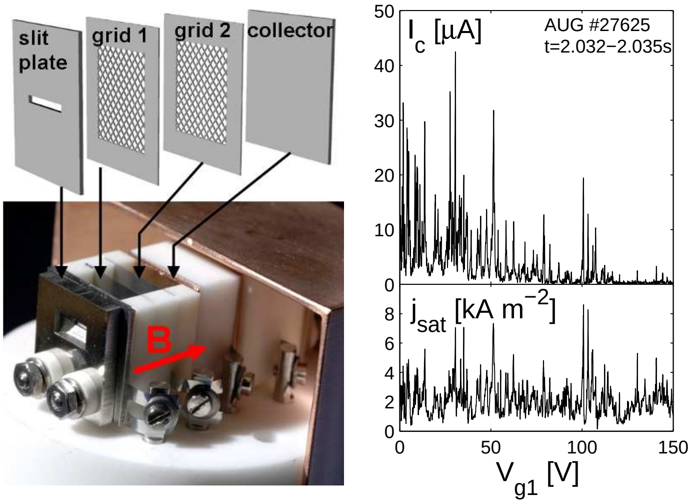

Fig. 1. *Left: AUG RFA (more details can be found in [2]). Right: Collector current and ion saturation current density plotted against the grid 1 voltage. Signals were acquired 2.5 cm outside the separatrix in AUG ohmic discharge by an RFA facing the outer divertor along **B**. Signals were measured over 3 ms at the sampling rate of 2 MHz.*

3. Simulations of RFA measurements in a turbulent SOL. GEMR is a global non-linear three-dimensional gyrofluid turbulence code, which calculates (among other parameters) time traces of fluctuating SOL ion and electron temperatures, $T_{i,e}$, and plasma density, n, in a circular flux surface geometry. The simulation domain comprises $r/a = 1 \pm 0.06$. Code input parameters used in the present study conform with a typical AUG L-mode discharge and are similar to those used in [2]. The time traces of $T_{i,e}$ and n are acquired over 9 ms at 4 MHz sampling frequency. An RFA sensor is located in the SOL near the outboard midplane separatrix. The ion saturation current density $j_{sat} = enc_s$, with c_s the ion sound speed, is rescaled arbitrarily in order to match the typical experimental values. A sawtooth waveform 0→270 V with the frequency f_{g1} is imposed to $V_{g1.}$ The collector current is evaluated as follows: $I_c = j_{sat} \exp[-(V_{g1}-V_{sheath})/T_i]$ for $V_{g1} > V_{sheath}$ and $I_c = j_{sat}$ for $V_{g1} < V_{sheath}$ [2]. The sheath potential, V_{sheath}, accounts for the ion acceleration in the Debye sheath in front of a slit plate. The classical sheath theory predicts $V_{sheath} = -0.5T_e \ln[2\pi(m_e/m_i)(1+(T_i/T_e))(1-\delta_{see})^{-2}]$. We assumed $\delta_{see} = 0.8$ [7] for the secondary electron emission coefficient. A 2 ms portion of the time traces is illustrated in Fig. 2. Also shown for comparison is I_c evaluated for $V_{sheath} = 0$ (this time trace is not considered in what follows). Time traces of j_{sat} and I_c feature intermittent bursts due to turbulent filaments, similar to those observed in Fig. 1. Note that in GEMR the fluctuations of $T_{i,e}$ and n are correlated due to the $\boldsymbol{E}\times\boldsymbol{B}$ advection. Statistical properties of the simulated j_{sat} (relative fluctuation level: 1.12, skewness: 1.79, excess kurtosis: 3.92, steep front and trailing wake of the conditionally sampled bursts) conform with experimental observations in AUG [2] and elsewhere. This provides some confidence that salient features of the SOL turbulence are realistically simulated.

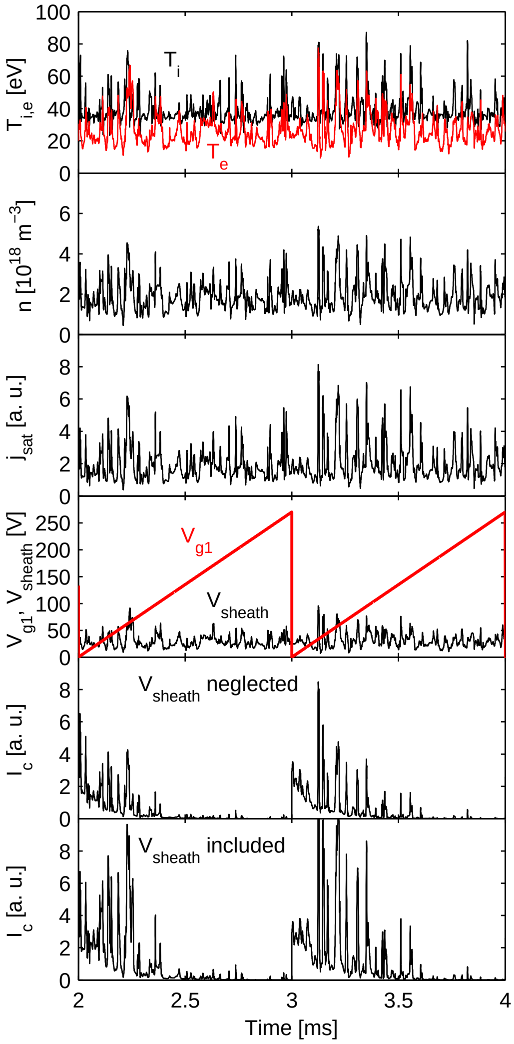

Fig. 2. *Time traces of ion and electron temperatures and plasma density from GEMR. Also shown is the voltage imposed to grid 1 (f_{g1} = 1 kHz), ion saturation current density, sheath potential and collector currents. Signals are acquired at 4 MHz sampling frequency.*

4. T_i measured by a standard RFA technique. First, we operate a synthetic RFA in a way it is used in most tokamak experiments. Grid 1 swept at $f_{g1} = 1$ kHz and T_i is inferred from both, a linear fit to $\log(I_c)$ plotted against V_{g1} and from an exponential fit to I_c plotted against V_{g1}. Collector currents measured for $V_{g1} < \langle V_{sheath} \rangle$, with $\langle V_{sheath} \rangle$ the mean sheath potential of the simulated time trace, are excluded from the fit. The results are compiled in Fig. 3. The linear fit yields $\langle T_i^{RFA} \rangle = 39$ eV on average, which is close to the time-averaged T_i. The exponential fit yields somewhat higher $\langle T_i^{RFA} \rangle = 49$ eV on average. As observed from Fig. 3, the scatter of $\langle T_i^{RFA} \rangle$ obtained from the exponential fit is considerably larger compared with the linear fit. This is due to the fact that the exponential fit is sensitive to large current bursts, emerging randomly over the voltage sweep. By decreasing f_{g1}, and thus involving more filaments in each I-V characteristic, the exponential fit becomes less sensitive to individual current bursts, the scatter of $\langle T_i^{RFA} \rangle$ reduces, and $\langle T_i^{RFA} \rangle$ gets closer to the time-averaged T_i.

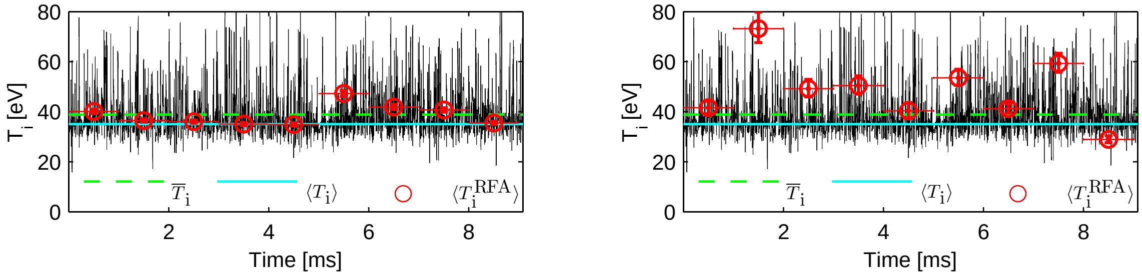

Fig. 3. Temporal evolution of T_i from GEMR simulations (black curve). Dashed line: mean value. Full line: most frequent value corresponding to maximum of the probability distribution function of T_i. Symbols correspond to $\langle T_i^{RFA} \rangle$ deduced from the synthetic RFA I-V characteristics. Horizontal bars correspond to the sweep period of V_{g1}. Left: Linear fit to $\log(I_c)$-V_{g1}. Right: Exponential fit to I_c-V_{g1}.

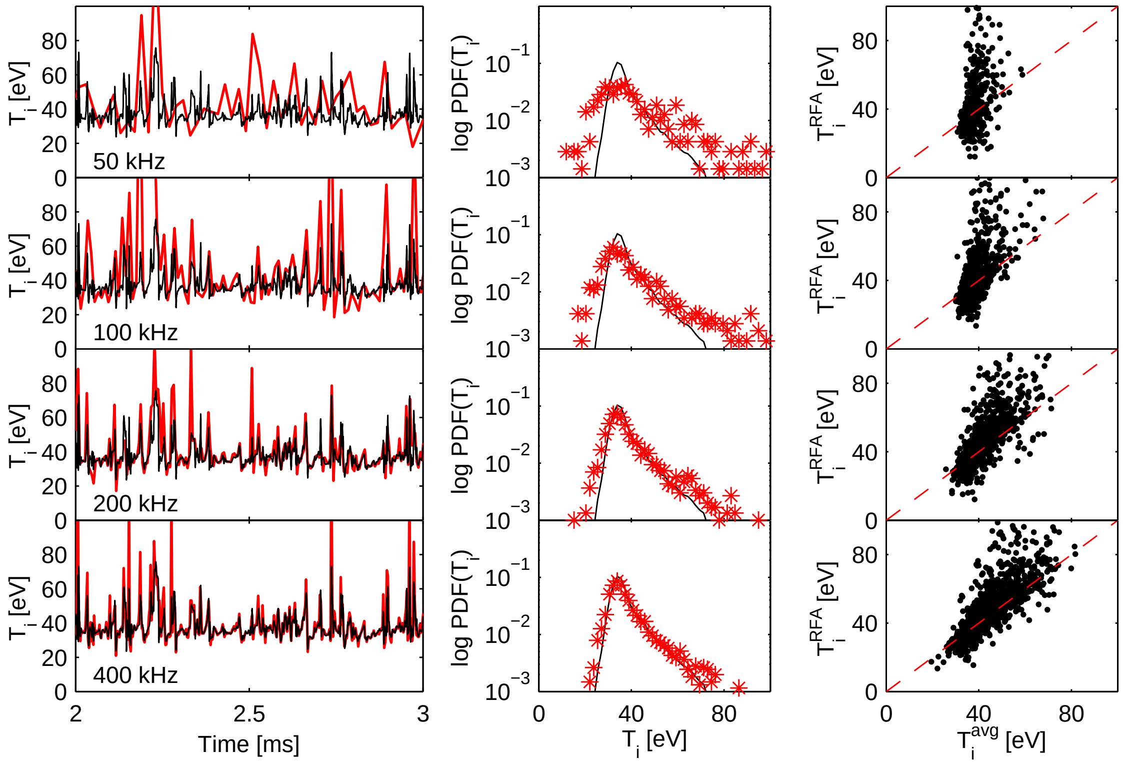

Fig. 4. Left: Temporal evolution of the simulated ion temperature (black) and T_i^{RFA} estimated from fast-sweeping RFA (red) for grid 1 sweeping frequencies f_{g1} = 50, 100, 200, 400 kHz. Middle: probability distribution functions of simulated T_i (full curve) and measured T_i^{RFA} (symbols). Right: Scatter plot of T_i^{RFA} against T_i from GEMR, averaged over the sweep period of grid 1.

5. T_i measured by a fast-sweeping RFA. The measurements of T_e fluctuations by virtue of a fast-sweeping (i.e sweep frequency above the typical fluctuation frequency) Langmuir probe is known to be a formidable problem, mainly because of the effect of the fast sweep on the very parameter one tries to measure [8]. In an RFA, however, grid 1 is separated from the plasma by a slit plate, meaning that at least in theory, V_{g1} could be swept at any frequency without affecting the plasma. In practice, the problems of high f_{g1} (capacitive currents, slew rates) could be overcome by virtue of on-board amplifiers. One can approximate the characteristic fluctuation frequency e.g. as $f_{fluc}=\langle|(1/j_{sat})(dj_{sat}/dt)|\rangle$, which is easily accessible in experiment. The present simulation is characterized by $f_{fluc} \approx 100$ kHz (T_i fluctuates with a similar frequency). The RFA measurements were simulated by sweeping grid 1 at f_{g1} = 50, 100, 200 and 400 kHz. The results are compiled in Fig. 4. The dynamics of T_i fluctuations is reasonably well reproduced only at highest f_{g1}, corresponding to $4f_{fluc}$. At $f_{g1} \approx f_{fluc}$ or lower, an RFA does not reproduce the dynamics of T_i fluctuations with any accuracy and cannot be expected to measure T_i fluctuations in the correct range other than by coincidence.

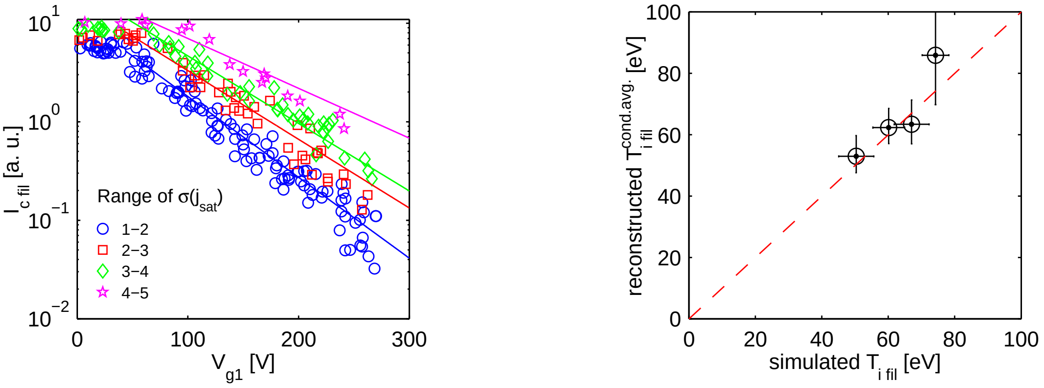

Fig. 5. *Left: Semi-logarithmic plot of the filament ion I-V characteristics. Data characterized by similar* $j_{\mathrm{sat\ fil}}$ *are color coded. Exponential fit (full) is used to deduce* $T_{\mathrm{i\ fil}}$. *Right: Filament ion temperature* $T_{\mathrm{i\ fil}}$ *from conditionally sampled characteristics, plotted against the mean* T_{i} *of all data points included in the characteristic. Vertical error bars: confidence interval of the exponential fit, Horizontal error bars: standard deviation of the simulated* T_{i}.

6. T_{i} measured from conditionally-averaged *I-V* characteristics. As was shown in [2,9,10], a conditional sampling of the *I-V* characteristics is a practical approach for estimating T_{i} and T_{e} in turbulent filaments from electric probes when the bias voltage cannot be swept fast enough to measure the temperature fluctuations directly. In this section we use the conditional sampling method from [2]. Grid 1 voltage is swept at 1 kHz. The peaks larger than $\sigma(j_{\mathrm{sat}})$ (the standard deviation) above the time-averaged mean, $j_{\mathrm{sat\ fil}}$, and the corresponding collector current, $I_{\mathrm{c\ fil}}$, are selected from the time trace of j_{sat}. The values of $j_{\mathrm{sat\ fil}}$ are sorted into groups characterized by the same $j_{\mathrm{sat\ fil}}$ within $\pm 0.5\sigma(j_{\mathrm{sat}})$. As shown in Fig. 5, for each group, the filament ion temperature, $T_{\mathrm{i\ fil}}$ is deduced from the exponential fit to $I_{\mathrm{c\ fil}}$, plotted against the corresponding V_{g1}. The conditionally-sampled $T_{\mathrm{i\ fil}}$ agrees reasonably well with the simulated $T_{\mathrm{i\ fil}}$. The reason is mainly a strong correlation between the plasma density and temperature fluctuations in GEMR. The same correlation was measured in [10] and elsewhere.

7. Summary. This paper addressed various aspects of T_{i} measurements in turbulent SOL plasma by an RFA (though the results apply to other ion sensitive probes as well). The RFA measurements were simulated by the gyrofluid turbulence code GEMR. In a way it is typically used (i.e. V_{g1} sweeping frequency f_{g1} of the order of 1 kHz), an RFA measures T_{i} which, on average, is close to the time-averaged fluctuating ion temperature. Direct measurements of T_{i} fluctuations would require f_{g1} a few times higher than the characteristic fluctuation frequency, i.e. a few 100 kHz. Alternatively, T_{i} in turbulent filaments can be measured from the conditionally-sampled filament *I-V* characteristics acquired at a low f_{g1}. Obviously, this technique does not provide complete information about the dynamics of T_{i}. It would be also worthwhile to refine a model of ion transmission through an RFA slit plate aperture and measure T_{i} fluctuations from the comparison of j_{sat} and I_{c}, sampled at constant V_{g1}. These techniques could provide valuable information about T_{i} fluctuations for modelers and the data for comparison with other experiments dedicated to fast SOL T_{i} measurements.

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