FIRST MEASUREMENTS OF LINE ELECTRON DENSITY IN URAGAN-2M PLASMAS VIA 140 GHz HETERODYNE INTERFEROMETER

R.O. Pavlichenko, N.V. Zamanov and A.E. Kulaga

Institute of Plasma Physics of the NSC KIPT, Kharkov, Ukraine
E-mail: ssslavik@kipt.kharkov.ua

Commissioned a microwave 2 mm (140 GHz) superheterodyne interferometer, which allows to start the measurement of linear (average over the length of the chord passing through the plasma) of the electron density at the Uragan-2M torsatron. Compared with the previously used 8 mm interferometer, this diagnosis will significantly expand the limits of measurement. It is now possible to measure the plasma density up to the $2.43 \cdot 10^{20}$ m^{-3}. New receiving and transmitting waveguide line provided a significant reduction in attenuation of the microwave radiation introduced into the plasma. It ensures that the value of the minimum measured density does not exceed $1.5 \cdot 10^{16}$ m^{-3}. It is shown that a high signal-to-noise ratio and the temporal efficiency of the detection system allowed to measure the quasi-coherent plasma fluctuations in the range of 3…20 kHz.

PACS: 42.25Bs, 42.30Rx, 42.68Ay, 42.82Et, 55.25Os, 52.40Db, 52.55.Hc, 52.70 –m, 52.70.Gw, 92.60Ta

INTRODUCTION

Microwave interferometry is primarily a method for measuring the refractive properties of plasma [1-3], which in turn depends on the density and frequency of collisions. For small plasma collision frequencies compared to the plasma and operational frequencies ($\nu_{eff} << \omega_p << \omega$) the electromagnetic wave suffers almost no attenuation when passing through the plasma. Thus, only the knowledge of the phase evolution needed to measure the electron plasma density. In this case, there is a linear relationship between the average plasma density (n_e) and the magnitude of the phase shift (φ) as a result of the passage of electromagnetic wave through the plasma column in the radial or vertical direction.

Previously same system was operated at the older IPP stellarator device and it performance description could be found elsewhere [4, 5].

Key technical characteristics of the 140 GHz superheterodyne interferometer

operating frequency, GHz	140
output power of the radiation source, mW	40
receiver noise figure (less than), dB	<12.1
dynamic range of the receiver input signals with automatic gain control (AGC), dB	>40
amplitude of the I-Q channels signals proportional to sin (φ) and cos (φ), V	4±0.1
receiver bandwidth, MHz	1
operational phase drift (at most), ºC/ hour	± 2.5
phase measurement range, degree	0…360
phase angle between the I-Q channels at the quadrature mixer, degree	90±2

This phase relationship can be represented as $\varphi = \pi n_e l / (\lambda\, n_{cr})$, where l – width of the plasma column; λ – wavelength of operation (for corresponded probe frequency ω); n_{cr} – critical density for this wave. Taking into account that the Uragan-2M (U-2M) torsatron expected average electron plasma density is in the range of $10^{18} \le \langle n_e \rangle \le 2 \cdot 10^{19}$ m^{-3}, and the width of the plasma column is 0.2...0.45 m, thus, the operational frequency of interferometer equal to 140 GHz will be sufficient to operate. The corresponding frequency for this critical density is $2.43 \cdot 10^{20}$ m^{-3}. The main characteristics of microwave interferometer provided in the Table above.

General exterior view of the compact microwave interferometer and the power supply is shown in Fig. 1. The dimensions of the interferometer modules are: W410×H150×D460 mm (transmitter and receiver unit) and W210×H140×D230 mm (power supply unit).

Fig. 1. General exterior view of the interferometer and the power supply

1. INTERFEROMETER SYSTEM

The interferometer with high time resolution has been made as a circuit with a local oscillator based on 280 GHz prototype system [6]. It involves two components: a radiation source and a coherent receiver with a quadrature detector. A simplified block diagram of the interferometer is illustrated in Fig. 2. The circuitry operation could be described as follows.

To form the probe signal and local oscillator signal receiver uses a reference oscillator which is stabilized by dielectric resonator. Signal reference oscillator (Osc1 here and after see Fig. 2) frequency of 6.925 GHz frequency is fed to the multiplier (Mult1) with high multiplicity (x20). The output of the multiplier produces a signal with a frequency of 138.5 GHz and with a power of 15 mW (11.76 dBm) and is divided into two channels. One channel is used as a local signal of the heterodyne receiver (LO@Mix1) the other channel served as the input the upper converter (UpConv) and shifted by 1.5 to 140 GHz. Then, after the amplification to 16dBm level output signal is fed through a waveguide system into the plasma. Focused by the horn antenna probing signal, passed through the plasma, arrives at the receiving antenna and then putted to the RF mixer input (RF@Mix1), which performed the first frequency conversion (lowering it to IF level of 1.5 GHz). This signal is amplified by Amp3 and serve as RF input to the second stage mixer (RF@Mix2). The signal from the synthesizer (RFM) with frequency of 1.4 GHz is fed to the second stage mixer (LO@Mix2). This produce IF signal which is equal to frequency difference: 1.5 GHz - 1.4 GHz = 100 MHz (IF@Mix2). From the IF mixer output signal is amplified by automatic gain control (AGC) unit with the power of 2 dBm. Finally, it is fed to the RF input of the third stage mixer (RF@Mix3). From quartz oscillator 100 MHz signal at 3 dBm fed to the LO input (LO@Mix3) of the zero IF frequency mixer with two output channels which are operated in quadrature (one of the channels through a mixer stage obtains the phase shift by 90°).

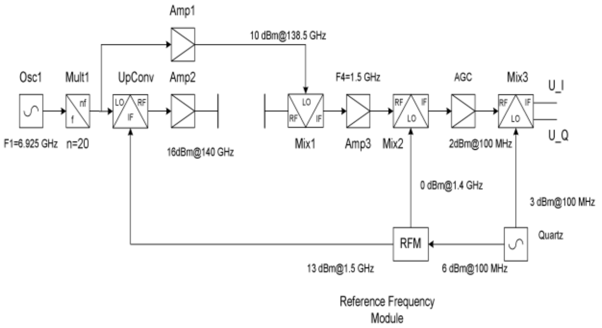

Fig. 2. Functional diagram of superheterodyne interferometer

To form the probe signal and local oscillator signal receiver uses a reference oscillator which is stabilized by dielectric resonator. Signal reference oscillator (Osc1 here and after see Fig. 2) frequency of 6.925 GHz frequency is fed to the multiplier (Mult1) with high multiplicity (x20). The output of the multiplier produces a signal with a frequency of 138.5 GHz and with a power of 15 mW (11.76 dBm) and is divided into two channels.

One channel is used as a local signal of the heterodyne receiver (LO@Mix1) the other channel served as the input the upper converter (UpConv) and shifted by 1.5 to 140 GHz. Then, after the amplification to 16 dBm level output signal is fed through a waveguide system into the plasma. Focused by the horn antenna probing signal, passed through the plasma, arrives at the receiving antenna and then putted to the mixer input (RF@Mix1), which performed the first frequency conversion (lowering it to IF 1.5 GHz). This signal is amplified by Amp3 and serve as RF input to the second stage mixer (RF@Mix2). The signal from the synthesizer (RFM) with frequency of 1.4 GHz is fed to the second stage mixer (LO@Mix2). This produce IF signal which is equal to frequency difference: 1.5 GHz - 1.4 GHz = 100 MHz (IF@Mix2). From the IF mixer output signal is amplified by automatic gain control (AGC) unit with the power of 2 dBm. Finally, it is fed to the RF input of the third stage mixer (RF@Mix3). From quartz oscillator 100 MHz signal at 3 dBm fed to the LO input (LO@Mix3) of the zero IF frequency mixer with two output channels which are operated in quadrature (one of the channels through a mixer stage obtains the phase shift by 90°).

Thus, at the output two types of signals are obtained A_Q=C·sin(φ); A_I=C·cos(φ). The main feature is that they have equal amplitude dependence. Getting phase is very quick procedure, through a combination of two simple algebraic functions ATAN (φ=atan(A_Q/A_I)) and WRAP (the function that monitors the crossing point phase value by 2π). Given that bandwidth video receiver is 1 MHz, it becomes possible to measure plasma density fluctuations with frequencies up to 500 kHz.

2. INTERFEROMETER OPERATION DURING RF PLASMA PRODUCTION AND WALL CONDITIONING

To reduce the attenuation in plasma of the microwave beam a new waveguide system was assembled. The number of the 90 degree turns became three time smaller. At the designated vacuum port, the input flange position has been optimized. The waveguide system has been rearranged to forms one straight line with the interferometer output. This waveguide optimization significantly improves (four times) the signal-to-noise level of the signal.

Probing a U-2M plasma provided by the ordinary polarized wave (**E_{wave}**||**B_0**, this is done by the launching/receiving horn antenna orientation with respect to the magnetic field) through horizontal equatorial port along the small axis of the elliptical shaped magnetic plasma surfaces. This imply, that the microwave beam is extending in the perpendicular direction only. The receiving antenna is located on the inner of the vacuum chamber edge plane (Fig. 3) at the low magnetic field side.

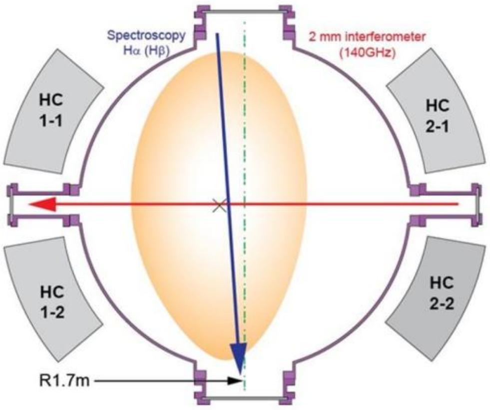

Fig. 3. The interferometer beam line arrangement crosses the vertically elongated plasma. Spectroscopy line of sight is shown for the reference only

The experiment aimed at interferometer response during different U-2M operational regimes, which are characterized by different temporal behaviors of line averaged plasma density and its fluctuations. In the case of RF wall conditioning discharge surfaces of the vacuum chamber, which is held at low magnetic field (0.01 T) and at low electron density $<n_e> \leq 4 \cdot 10^{17}$ m^{-3} were found very strong (amplitude modulation depth about 40 ... 80 %) 'sawtooth-like' coherent fluctuations (Fig. 4), having a distinct frequency of 10 kHz. During standard plasma discharges with higher magnetic field 0.35 T and with significantly higher (one order) electron density $<n_e> \approx 4.5 \cdot 10^{18}$ m^{-3} a clearly visible and quasi-coherent fluctuations are observed (Fig. 5). They have a wider frequency range (from 3 to 21 kHz) and a smaller amplitude modulation (10 ... 20 %).

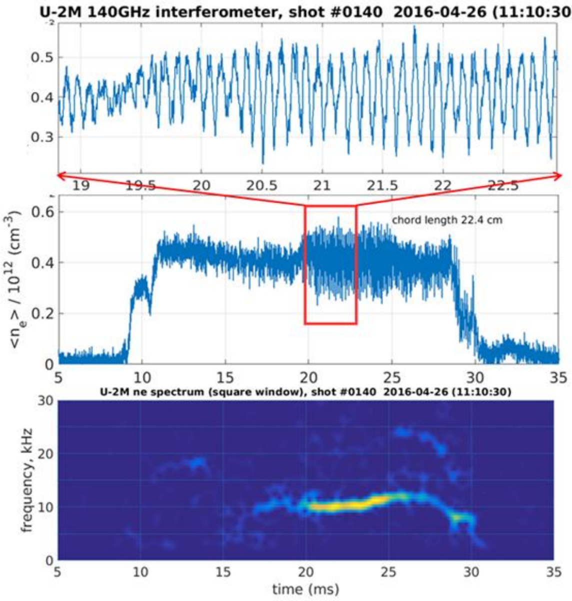

Fig. 4. The temporal behavior of line average density and corresponding density fluctuations during RF cleaning discharges

Fluctuations of electron plasma density, measured by microwave interferometer for some plasma conditions very well correlated with those measured by other sets of diagnostics, i.e. spectroscopic measurements in the optical and X-rays range [5].

3. RF PLASMA BREAKDOWN TIMING

Due to the geometric dimensions of U-2M plasma (l_{u2m} = 0.22 m) and critical density $n_{e,cr} = 2.4 \cdot 10^{20}$ m^{-3} of electrons to the which corresponds to the probing frequency of 140 GHz it is possible to estimate the value of minimal detectable density that may be measured. This estimation could be done using the following expression: $n_{e,min} = (\varphi_{min}\, \lambda\, n_{e,cr})/(\pi\, l_{u2m})$. If the accuracy of the phase of no more than one degree, then the smallest density: $n_{e,1^\circ} = 4.24 \cdot 10^{20}$ m^{-3}. Attenuation by the launching/receiving waveguide system increases this figure three times and gives a practical value of the minimal detectable density of electrons close to $n_{e,min} = 1.3 \cdot 10^{16}$ m^{-3}. The ability to measure such a low plasma density made it possible to determine the time of global breakdown of the plasma during RF production technique. The initial stage of the plasma production discharge (B_0=0.35 T, $p_{H2} = 1.4 \cdot 10^{-5}$ Torr) is presented in the Fig. 6, from which it is clearly seen (the plot is produced in semilogarithmic scale) the defined timing when the signal of the average density starts to exceed the noise fluctuations level.

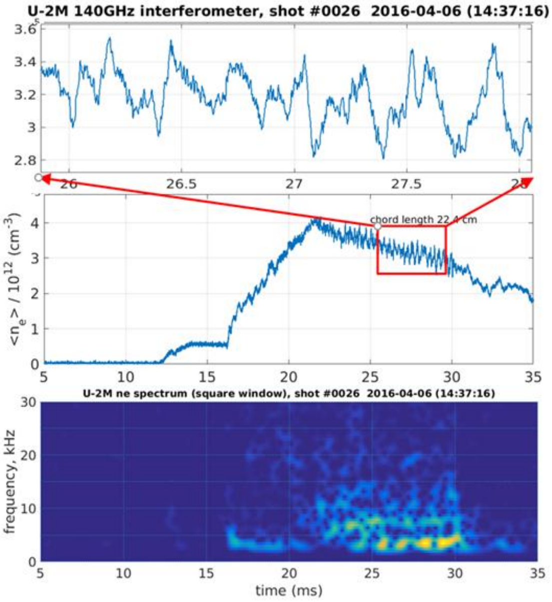

Fig. 5. The temporal behavior of line average density and corresponding density fluctuations during RF cleaning discharges

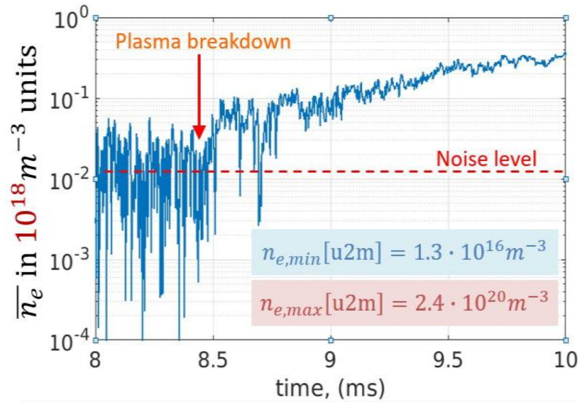

Fig. 6. The temporal behavior of line density and timing of the global plasma breakdown in U-2M

CONCLUSIONS

A 2 mm wave (140 GHz) superheterodyne interferometer greatly improves diagnostic capability on U-2M, enabling measurement of densities in excess of 10^{19} m^{-3}. Starting from the beginning of 2016 U-2M experimental campaign a single central chord system is in routine operation and its measurements provide reliable information on electron plasma densities and its fluctuations (up to 20 kHz) for the various operational regimes at low and intermediate plasma densities.

During described set of the hydrogen plasma experiments the interferometer operates up to a peak density of $8 \cdot 10^{19}$ m^{-3} with a temporal resolution of 5 μs. The designed maximum parameters are $2.4 \cdot 10^{20}$ m^{-3} and 1 μs.

High system versatility. This means that the system can be easily adapted to other devices than Uragan stellarators and that several possible configurations regarding wave guide system orientation, sampling and data transmission rates can be used at new locations.

ACKNOWLEDGEMENTS

The authors are grateful to the Uragan-2M device operation team and supporting group for the excellent arrangement of the experiments.

The authors are acknowledged the members of the engineering department: S.M. Maznichenko, V.I. Byrka, A.Yu. Krasyuk and A.V. Pogozhev for the construction of a new Ka band waveguide transmission line. Finally, we wish to thanks M.B. Dreval, D.L. Grekov, A.N. Shapoval and I.M. Pankratov for the constant and fruitful discussions.

REFERENCES

1. D. Veron. *Infrared and Millimeter Waves.* Vol. 2. NY:"Academic", 1979, p. 69-135.
2. I.H. Hutchinson. *Principles of Plasma Diagnostics.* NY: "Cambridge University Press", 1987, p. 87.
3. H.J. Hartfuss, T. Geist and M. Hirsch. Heterodyne methods in millimeter wave plasma diagnostics with applications to ECE, interferometry and reflectometry // *Plasma Phys. Control. Fusion*. 1997, v. 39, p. 1693-1769.
4. M.B. Dreval, Yu.V. Yakovenko, E.L. Sorokovoy, et al. Observation of 20…400 kHz fluctuations in the U-3M torsatron // *Physics of Plasmas*. 2016, v. 23, p. 022506.
5. V.S. Voitsenya, A.N. Shapoval, R.O. Pavlichenko, et al. Progress in stellarator research in Kharkov IPP // *Phys. Scr.* 2014, v. T161, p. 014009.
6. A.V. Zorenko, G.P. Ermak, M.O. Medved. Solid-state interferometer with the operating frequency 280 GHz signals // *Journal of Radiophysics and Electronics*. 2007, v. 12, № 1, p. 268-272.
7. V.V. Filippov, V.L. Berezhnyj, D.L. Grekov. Determination of plasma density by a new approach to measuring the phase shift of probing signals // *Journal of Radiophysics and Electronics*. 2012, v. 3(17), № 1, p. 71-75.

Article received 17.01.2017.

ПЕРВЫЕ ИЗМЕРЕНИЯ ЛИНЕЙНОЙ ПЛОТНОСТИ ЭЛЕКТРОНОВ В ПЛАЗМЕ УРАГАН-2М С ПОМОЩЬЮ 140 ГГц ГЕТЕРОДИННОГО ИНТЕРФЕРОМЕТРА

Р.О. Павличенко, Н.В. Заманов и А.Е. Кулага

На торсатроне Ураган-2М введён в эксплуатацию микроволновый 2 мм (140 ГГц) супергетеродинный интерферометр, позволяющий начать измерения линейной (средней по длине хорды, проходящей через плазму) плотности электронов. По сравнению с ранее применяемым 8 мм интерферометром данная диагностика позволила существенно расширить пределы измерений. В настоящее время стало возможным измерять плотность плазмы до величины $2{,}43\cdot10^{20}$ м$^{-3}$. Новая приемно-передающая волноводная линия обеспечила значительное уменьшение затухания микроволнового излучения, вводимого в плазму. Это дало возможность добиться того, что величина минимальной измеряемой плотности не превышает $1{,}5\cdot10^{16}$ м$^{-3}$. Показано, что высокое отношение сигнал-шум и временное быстродействие приёмной системы позволили измерить квазикогерентные флуктуации плазмы в диапазоне 3…20 кГц.

ПЕРШІ ВИМІРЮВАННЯ ЛІНІЙНОЇ ГУСТИНИ ЕЛЕКТРОНІВ У ПЛАЗМІ УРАГАН-2М ЗА ДОПОМОГОЮ 140 ГГц ГЕТЕРОДИННОГО ІНТЕРФЕРОМЕТРА

Р.О. Павліченко, М.В. Заманов та А.Є. Кулага

На торсатроні Ураган-2М введений в експлуатацію мікрохвильовий 2 мм (140 ГГц) супергетеродинний інтерферометр, що дозволяє почати вимірювання лінійної (середньої по довжині хорди, що проходить через плазму) густини електронів. У порівнянні з раніше застосовуваним 8 мм інтерферометром ця діагностика дозволила істотно розширити межі вимірювань. В даний час стало можливим вимірювати густину плазми до величини $2{,}43\cdot10^{20}$ м$^{-3}$. Нова приймально-передавальна хвильопровідна лінія забезпечила значне зменшення затухання мікрохвильового випромінювання, що вводиться в плазму. Це дало можливість домогтися того, що величина мінімальної вимірюваної густини не перевищує $1{,}5\cdot10^{16}$ м$^{-3}$. Показано, що високе відношення сигнал-шум і часова швидкодія приймальної системи дозволили вимірювати квазікогерентні флуктуації плазми в діапазоні 3…20 кГц.