ECR HEATING ON THE WEGA STELLARATOR

Y. Podoba[1]*, K. Horvath*[1]*, H.P. Laqua*[1]*, J. Lingertat*[1]*, M. Otte*[1]*, F. Wagner*[1]*, E. Holzhauer*[2]

[1] *Max-Planck-Institut fьr Plasmaphysik, EUROATOM Ass., D-17491 Greifswald, Germany;*
[2]*Institut fьr Plasma Forschung Universitдt Stuttgart, Germany*

The plasma in the WEGA stellarator is generated and heated by Electron Cyclotron Resonance Heating (ECRH). The microwave is emitted from the low field side mid-plane with power of up to 6+20 kW and with a frequency of 2.45GHz (λ=12.45 cm). The low cut-off density of $n_{cutoff}=7.5\times10^{16}m^{-3}$ makes ECRH on the WEGA stellarator inefficient in both O-mode and X-mode regime. This was confirmed in the first experimental campaign by perpendicular launch of the microwave with a TE_{11} antenna. In these experiments only edge heating was observed. Density and temperature profiles were hollow [1]. For the over dense plasma heating, mode conversion into the electrostatic electron Bernstein waves (EBW) is required. Two schemes have been tested: the direct X-B (X-mode to Bernstein mode) conversion, where an X-wave must be launched perpendicular to the magnetic field into an over dense plasma with a steep density gradient. In these experiments the strong reflection of the microwave power at the cut-off layer prohibited efficient plasma heating. Another possibility is the O-X-B conversion scheme [2]. The methods of its achievement with different antennas are the subject of this paper.

PACS: 52.50.Sw; 52.55.Hc

O-X-B CONVERSION

The O-X-B conversion process means in a first step conversion of an O-wave to an X-wave near the cut-off layer. Then the X-wave propagating to the upper-hybrid resonance layer is converted there to an EB wave (Fig.1). The EBW propagate freely in the over dense plasma and is absorbed near the plasma center.

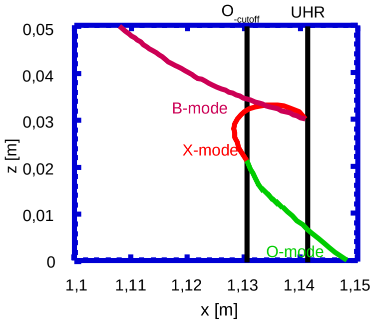

Fig.1. Ray tracing calculation for O-X-B conversion process

However, these arguments as well as Fig.1 are applicable only when the wave length is much smaller then the plasma dimensions. In case of WEGA (plasma diameter ~2×λ) it just gives us qualitative picture of the processes.

For maximum conversion efficiency of an O-wave to an X-wave, it must have the proper k vector direction. The angle between the magnetic field lines and k is 45^0 for first harmonic heating and 54^0 for the heating on the second harmonic. Due to limits of the space between the inner wall and the last closed flux surface the waveguide could not be titled towards the optimal launch angle and the oblique wave excitation had to be performed by antenna shaping.

ANTENNA PATTERN INVESTIGATION

Initially a cylindrical TE_{11} waveguide was used as an antenna for ECRH on WEGA. Than special "Two slot" antenna shape was chosen. The directivity pattern of this antenna one has two lobes near the optimum direction, and the efficiency of O-X conversion is higher than in the case of straight waveguide (Fig.2).

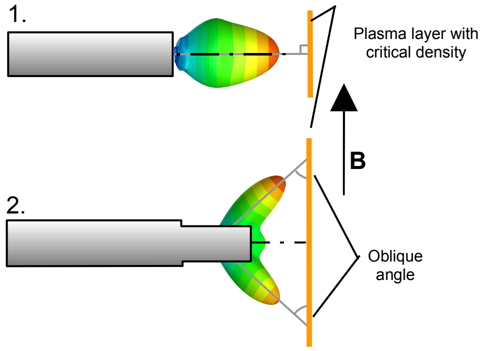

Fig.2. Antenna shape evolution

Antenna near and far field pattern calculated with the High Frequency Structure Simulator (HFSS) code [3]. It is based on the finite element method and solves Maxwell's equations with given boundary conditions. The measurement of the antenna pattern was made using a system with angular and radial probing positioning (Fig.3.).

A loop antenna with a diameter of 1 cm was used as a receiving antenna. In order to avoid reflections, the end of the antenna and the positioning system with the receiving antenna was mounted in a box covered with absorbing material. The data obtained are used for estimation of the microwave energy undergoing the O-X conversion process.

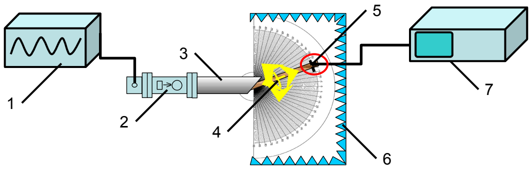

Fig.3. Scheme of antenna pattern measurement system 1- 2.45 GHz generator, 2 - rectangular to circular waveguide transition, 3 - emitting antenna, 4 - angular-radial positioning system, 5 - receiving antenna, 6 - box covered with absorbing material, 7 - receiver

RESULTS

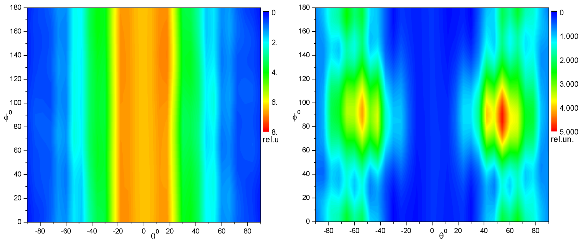

Fig.4.Far field patterns of antennas calculated via HFSS code in (θ,φ) coordinates

Various types of antennas have been investigated (Fig.4). For the cylindrical TE_{11} straight cut waveguide (Fig.4.left) estimations [4] show that for 1st harmonic heating only 6 % of the total power is converted into X-mode. The measured density and temperature profiles were hollow and the density of the electrons was 1.5 times larger than the cut-off density. Mainly, the edge plasma is heated because of multiple reflections between cut-off layer and wall. The "two slot" type antenna (Fig.4.right) with two slots in mid-plane is optimized to launch a big part of energy in lobes as shown in Fig.2. The estimated O-X conversion efficiency is ~22 %, The obtained density is more than 10 times higher than the cut-off density. The density profiles are flat or even pike.

PRESENT WORK

The preliminary calculation of full-wave equation system shows the possibility of resonant conversion of O-wave with proper $\vec{k}$ -spectrum to X-wave near O-cutoff layer (Fig.5).

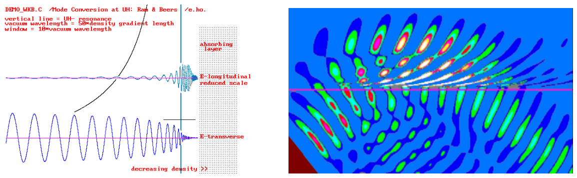

Fig.5 Calculations of full wave equations in the vicinity of O-cutoff and UHR layers (Dr. E. Holzhauer)

The resonant process means increasing of amplitude and decreasing of wave length in the region of resonance. To prove the existence of such a UH resonance region in WEGA stellarator plasma measurements of wave activity via HF probes in plasma could be used.

The probes must be:

- sensitive to short wave length, witch is in order of magnitude of the electron gyro rotation radius (0.01cm) in the case of Bernstein wave,
- not to be sensitive to a long wave length, which comes directly from heating antenna (12.24 cm),
- polarization sensitive for distinguishing of different modes,
- small enough to have a desirable spatial resolution,
- suitable for the Langmuir probe density measurements,
- to obtain information about the phase of waves probes must be moveable and interferometer scheme of measurements must be used.

In present time different types of probes are under discussion, some of them tested on the compact size linear plasma installation, for example the "2pin" and "3pin" probe. (Fig. 6)

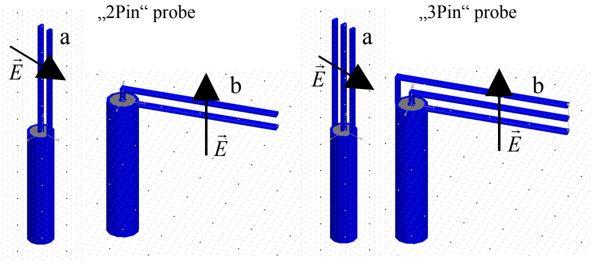

Fig.6 Two variants of each probe:
a) the prototype of the probe that could be used for the measurements in WEGA; b) bend probes used for testing in the small installation

The signal in the small plasma installation devise was exited using the same type probe as an emitting antenna. The signal was measured via the spectrum analyzer which is connected to receiving antenna on the opposite side of plasma column.

The dependence of signal amplitude from the magnetic field, plasma density and frequency was investigated with such system. Measurements show that "3pin"-probe type looks more promising for measurements.

Interferometer scheme of measurement means comparing of signal from plasma and reference signal from HF source. Down sampling mixers may be used for decreasing of frequency to the band which is suitable for oscilloscope measurements. The phase information is saved in this case if the base frequency for each channel have same source.

Probe optimization and down sampled interferometer building is the subject of our today work.

CONCLUSIONS & OUTLOOK

ECRH-Antenna optimization on the WEGA stellarator has been performed. Marked improvement of plasma parameters in the WEGA obtained

These results allow us to think that part of microwave energy is converted into Bernstein mode and absorbed in the plasma centre. To prove this assumption HF probing will be used for the wave activity investigation in plasma. Measurement system development and assembling in parallel with calculations of full wave equations are in process

In future plans we have the installation of measurement system on WEGA stellarator, further improvement of heating in WEGA by means of transition line improving, and heating antenna further optimization.

ACKNOWLEDGEMENTS

The technical support of D. AЯmus and N. Paschkowski is gratefully acknowledged.

REFERENCES

1. K. Horvath, J. Lingertat, M. Otte, F. Wagner. Investigation of properties of the WEGA plasmas // *31st EPS Conference on Plasma Phys. London, 28 June-2July 2004. ECA.* 2004, v.28G, P-1.212.
2. H.P. Laqua et al.// *PLR.* 1997, v.78, p.18.
3. www.ansoft.com .
4. E. Mjьlhus. // *J. Plasma Phys.* 1984, v.31, p.7.

ЭЦР- НАГРЕВ НА СТЕЛЛАРАТОРЕ WEGA

Ю. Подоба, К. Хорват, Х.П. Лакуа, И. Лингертат, М. Оттэ, Ф. Вагнер, Э. Хольцхауэр

Плазма в стеллараторе WEGA создается и нагревается при помощи СВЧ-нагрева на электронно-циклотронной частоте (ЭЦР). Ввод СВЧ-энергии производится с внешней стороны тора в его экваториальной плоскости на частоте 2.45 ГГц (λ=12.45 см) и с максимальной мощностью до 26 кВт. Низкая критическая плотность плазмы для данной частоты ($n_{cutoff}=7.5\times10^{16}$ м$^{-3}$) делает традиционный ЭЦР-нагрев неэффективным, как в режиме «обыкновенной» (О-волна), так и в режиме «необыкновенной» волны (Н-волна), что было подтверждено в ходе первой экспериментальной кампании, когда СВЧ-энергия вводилась перпендикулярно силовым линиям магнитного поля при помощи цилиндрического TE_{11} волновода. В этих экспериментах наблюдался нагрев периферийной плазмы, профили плотности и температуры имели полый характер [1]. Для нагрева плазмы с плотностью, выше плотности отсечки, необходима трансформация в электростатическую Бернштейн волну (ЭБВ). Два сценария нагрева были протестированы на установке: первый с непосредственной трансформацией Н-волны в ЭБВ, в этом случае Н-волна должна быть запущена перпендикулярно магнитному полю в плазму с плотностью, превышающей критическую. В этих экспериментах сильное отражение СВЧ-энергии в слое отсечки препятствовало эффективному нагреву плазмы. Во втором случае используется сценарий с двойной конверсией сначала О-волны в Н-волну с последующим превращением Н-волны в ЭБВ[2]. Методы реализации такого сценария и есть тема настоящей работы.

ЕЦР- НАГРІВ НА СТЕЛЛАРАТОРІ WEGA

Ю. Подоба, К. Хорват, Х.П. Лакуа, І. Лінгертат, М. Отте, Ф. Вагнер, Е. Хольцхауер

Плазма у стеллараторі WEGA утворюється та нагрівається за допомогою НВЧ-нагріву на електронно-циклотронній частоті (ЕЦР). Ввід НВЧ-енергії здійснюється із зовнішнього боку тору у його екваторіальній площині, на частоті 2.45 ГГц (λ=12.45 см) та з максимальною потужністю до 26 кВт. Низька критична щільність плазми для цієї частоти ($n_{cutoff}=7.5\times10^{16}$ м$^{-3}$) робить традиційний ЕЦР-нагрів неефективним, як у режимі «Звичайної» (З-хвиля), так і у режимі «Незвичайної» хвилі (Н-хвиля), що було підтверджено у ході першої експериментальної кампанії, коли НІЧ-енергія вводилась перпендикулярно силовим лініям магнітного поля за допомогою циліндричного TE_{11} хвилеводу. У цих експериментах спостерігався нагрів периферичної плазми, профілі щільності та температури мали порожній характер [1]. Для нагріву плазми з щільністю вище щільності відсічки необхідна трансформація в електростатичну Бернштейн хвилю (ЕБХ). Два сценарії нагріву було випробувано на установці: перший з трансформацією Н-хвилі у ЕБХ, в цьому випадку Н-хвиля повинна бути введена перпендикулярно магнітному полю в плазму з щільністю, яка перевищує критичну. У цих експериментах сильне відбиття НВЧ-енергії у шарі відсічки перешкоджало ефективному нагріву плазми. У другому випадку використовується сценарій з подвійною конверсією спочатку З-хвилі у Н-хвилю з наступною трансформацією Н-хвилі в ЕБХ [2]. Методи реалізації такого сценарію і є темою цієї роботи.