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FUSION RESEARCH IN STELLARATOR DEPARTMENT OF IPP NSC KIPT

V.E. Moiseenko[1,2,3], M.B. Dreval[1,3], Yu.V. Kovtun[1], Yu.S. Kulyk[1], G.P. Glazunov[1], Ye.O. Kazakov[4], J. Ongena[4], S.E. Sharapov[5], H. Thomsen[6], I.E. Garkusha[1,3]

[1]Institute of Plasma Physics, National Science Center “Kharkov Institute of Physics and Technology”, Kharkiv, Ukraine;
[2]Uppsala University, Uppsala, Sweden;
[3]V.N. Karazin Kharkiv National University, Kharkiv, Ukraine;
[4]Laboratory for Plasma Physics - ERM/KMS, Association EURATOM - Belgian State, Brussels, Belgium;
[5]Culham Centre for Fusion Energy (CCFE), Culham Science Centre, Abingdon, United Kingdom;
[6]Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

E-mail: moiseenko@ipp.kipt.kharkov.ua

This paper briefly describes intrinsic and collaborative scientific activities in the Stellarator Department of the Institute of Plasma Physics of the National Science Center “Kharkov Institute of Physics and Technology” in last two years. These activities include experiments on JET tokamak, stellarators Wendelstein 7-X and Uragan-2M, TOMAS toroidal device and theoretical studies related to modeling of radio-frequency fields in plasma and conceptual development of the stellarator-mirror fission-fusion hybrid.

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DETERMINATION OF SPACE MHD MODE STRUCTURE USING A SOFT X-RAY CAMERA ARRAY IN W7-X

A modeling technique of MHD mode structure analysis on the base of lines-integrated data of SXR diagnostics are used in W7-X [1]. The poloidal mode structures are modeled by the Gaussian-shaped emission regions rotating along the magnetic surfaces (Fig. 1,a). A set of models of the mode structure and phase velocity are considered. Two techniques based on the comparison of calculated and measured data are used. The calculated spatiotemporal phase evolution of line-integrated modeled data is compared with the experimental data in the first technique (see Fig. 1,c). The mode time-averaged amplitudes dependence on the SXR channel number is compared in the second technique. It allows us to determine reliably the radial location ρ, poloidal mode number *m* and mode rotation direction of high-*m* modes with a single *m* and to discriminate single *m* modes from other modes. The 20...40 kHz modes are identified as three single *m* mode branches with poloidal mode numbers $m = 8$, $m = 10$, $m = 11$ localized at $\rho \approx 0.3$ and rotating in the clockwise direction (see Fig. 1,b) [1]. This SXR modeling technique is currently used for the MHD modes analysts in TCV.

D-^{3}He ICRF HEATING ON JET

3-ion scheme is used for fast ions generation in JET. The electric field of excited ion cyclotron range of frequencies (ICRF) waves can be decomposed as a sum of two components, E^+ (left-hand polarized, rotating in the direction of the ions) and E^- (right-hand polarized, rotating in the opposite direction). The plasma ions interact mainly with the left-hand polarized RF component E^+.

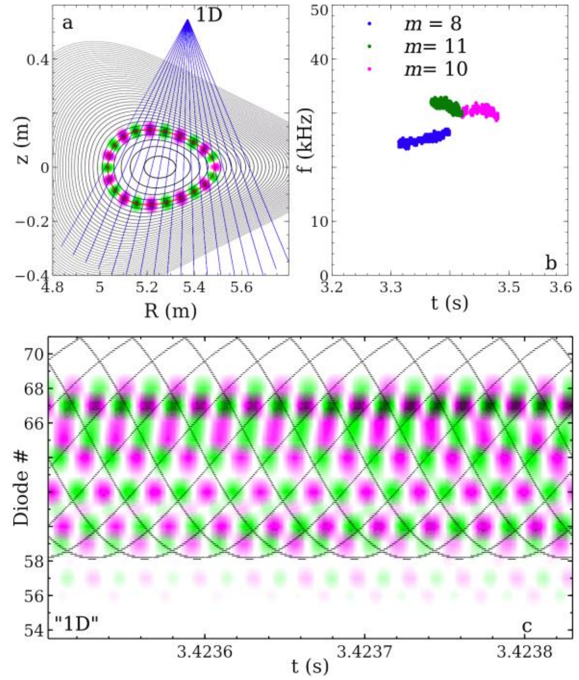

Fig. 1. a – Lines-of-sight of the SXR camera and model distribution of 20 Gaussian perturbations, (m = 10 at ρ ≈ 0.3); b – calculated poloidal mode numbers; c – spatiotemporal evolution of experimental data and m = 10 mode path calculated for a thin mode indicated by the black lines

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The E^+ component is strongly increased in vicinity of the ion-ion hybrid layer in a multi-spices plasma. The ion cyclotron zone of the third ion spice is located in this ion-ion hybrid layer formed by first and second ion spices in the 3-ion ICRF heating scenario [2]. Thus, strong wave energy absorption by the third ion spice is formed and very efficient ion heating is obtained in this 3-ion ICRF heating scenario. The 3-ion ICRF heating scenario application in the JET tokamak cause strong fusion neutrons generation, as it is shown in Fig. 2 [2-4].

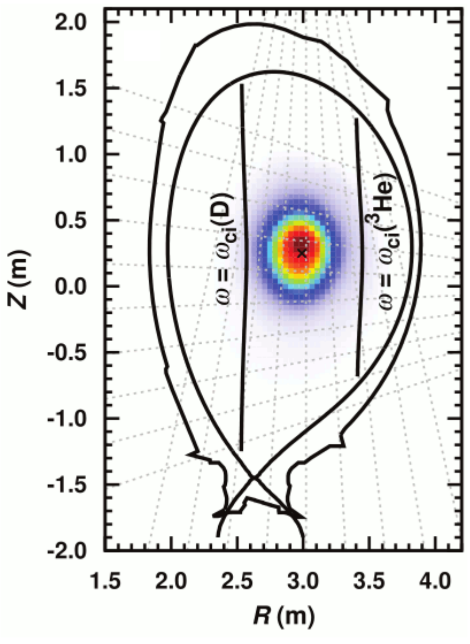

Fig. 2. Fusion nuetrons emission in 3-ion ICRF heating in JET tokamak

The NBI deuterons accelerated to higher energies with 3-ions ICRF, which leads to the generation of neutrons and alpha particles from fusion reactions [2-5].

ALFVÉN CASCADE ABOVE TAE AND LOCALIZATION OF ALFVÉN MODES IN D-^{3}He PLASMAS ON JET

In JET NBI energy is low enough for Alfvén eigenmodes (AEs) excitation and ICRF is used for the AE studies [6]. A large variety of 80...700 kHz AEs are destabilized by fast ions in 3-ion ICRF D-^{3}He JET experiments by fast D ions [7]. Radial localization of these AEs was identified with a range of internal diagnostics such as the X-mode reflectometer, multiline interferometer and SXR. According to these experimental measurements ACs at frequency 80...180 kHz and high frequency ACs (HFAC) at 330...450 kHz were localized in the plasma core at $s \approx 0.2\ldots0.4$ (Fig. 3).

The AE mode structures calculated with the MHD codes are found to be consistent with the measurements [7]. The high frequency ACs exists due to the extremum in Alfvén continuum structure caused by the minimum of the safety factor $q_{\min}$, similarly to the low frequency ACs. Our analysis shows that the HFAC resonant interaction is mostly caused by passing ions at energy of several hundred keV, which are uniquely generated at JET using the three-ion ICRF scheme (Fig. 4).

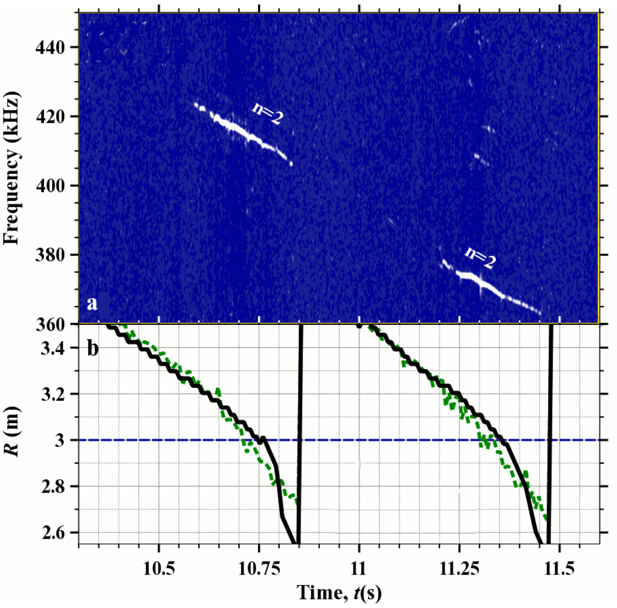

Fig. 3. Localization of HFAC modes by reflectometer: a – spectrogram; b – location of microwave cut-off

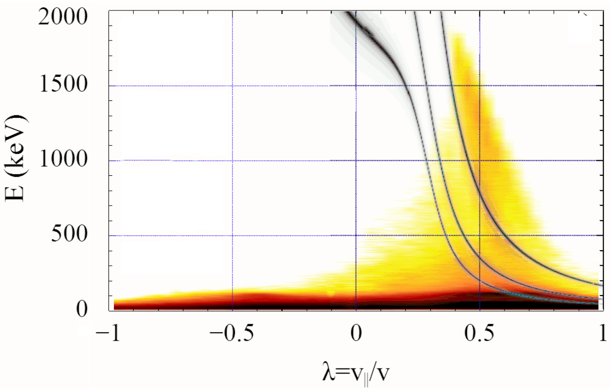

Fig. 4. The distribution function of ICRF-accelerated deuterons at the HFAC location (in yellow-brown) and the regions where energetic ion resonate with 410 kHz n = 2 HFAC (in gray)

Although HFACs are not often seen on JET, these modes could be highly relevant for future ITER and fusion reactor plasmas dominated by ~ MeV energetic ions.

ALPHA PARTICLES DRIVEN EAE IN D-^{3}He PLASMAS ON JET

The D NBI ions accelerated to MeV range by 3-ion ICRF produce fusion-born alpha-particles from the D-^{3}He reaction. This alpha-particles are able to excite elliptical Alfvén eigenmodes (EAEs) with toroidal mode numbers $n = -1$ and $n = 0$ [3, 4], as it is shown in Fig. 5.

According to the calculated resonance maps (see similar to Fig. 4) accelerated D-ions cannot interact with negative toroidal EAE [3] in contrast to the fusion-born alpha-particles. The $n = 0$ EAE can only be excited if a fast-ion population energy distribution have so-called 'bump-on-tail distribution (where $\partial f/\partial E > 0$). This distribution is formed by a periodic modulation of the fusion source due to sawtooth crashes [3, 4].

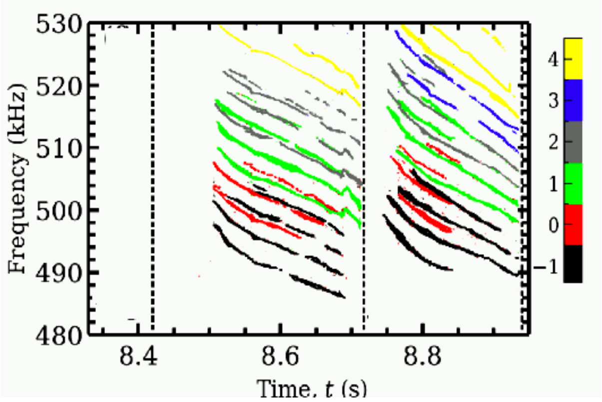

Fig. 5. Dynamics of EAE activities in D-^{3}He 3-ion ICRF

ENHANCED PERFORMANCE IN FUSION PLASMAS THROUGH TURBULENCE SUPPRESSION BY MEV IONS

The impact of fast ions on plasma dynamics was studied in JET D-^{3}He plasmas. While the presence of TAEs is usually accompanied by energy loss and particle confinement degradation, it was shown [8, 9] that reduced ion heat losses and high ion temperatures can be reached in plasmas with MeV-range fast ions and TAEs driven by fast ions (Fig. 6).

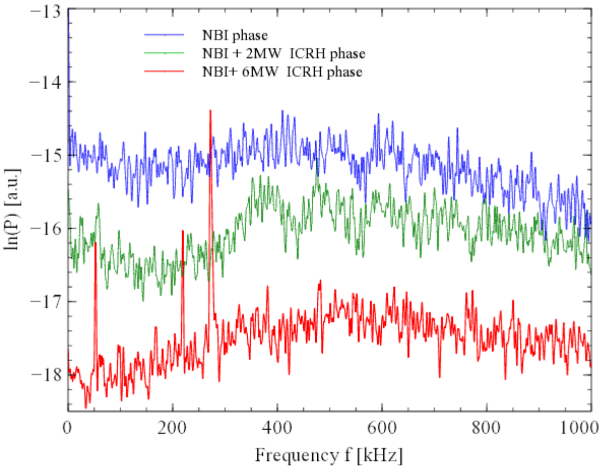

Fig. 6. Amplitudes of density fluctuations in NBI-only discharge and discharge with TAE and MeV ions

HIGH FREQUENCY MHD AND FAST PARTICLES EXPERIMENTS

The identification of TAEs at different radial locations in counter-current NBI scenarios has been presented in TCV [10]. These modes are significantly different from the ones observed in previous work, which were observed in scenarios with co-current off-axis NBI and ECRH. Fourier analyses of the Fast-Ion Loss Detector (FILD) revealed coherent fast-ion losses in the range of the 1...2 MHz in MAST-U [11]. The losses are correlated with modes identified as Compressional and Global Alfvén Eigenmodes (CAEs and GAEs) by the Mirnov coils as their frequency is 0...0.45 times the cyclotron frequency of deuterium at the magnetic axis. The toroidal phase measurements show a nearly perpendicularly (to the background magnetic field) propagating wave, for the core ion cyclotron emission (ICE) oscillations in ASDEX Upgrade [12]. The mode characteristics of the shear-polarized (or global) Alfvénic eigenmode are: the mode propagates toroidally in the counter-current, counter-injection direction with a high (> 20) mode number [12].

THE UPGRADED TOMAS DEVICE: A TOROIDAL PLASMA FACILITY FOR WALL CONDITIONING, PLASMA PRODUCTION, AND PLASMA-SURFACE INTERACTION STUDIES

The Toroidal Magnetized System device has been significantly upgraded to enable development of various wall conditioning techniques, including methods based on ion and electron cyclotron (IC/EC) range of frequency plasmas, and to complement plasma-wall interaction research in tokamaks and stellarators [13]. The toroidal magnetic field generated by 16 coils can reach its maximum of 125 mT on the toroidal axis. The EC system is operated at 2.45 GHz with up to 6 kW forward power. The IC system can couple up to 6 kW in the frequency range of 10...50 MHz. The direct current glow discharge system is based on a graphite anode with a maximum voltage of 1.5 kV and a current of 6 A. A load-lock system with a vertical manipulator allows exposure of material samples. A number of diagnostics have been installed: single- and triple-pin Langmuir probes for radial plasma profiles, a time-of-flight neutral particle analyzer capable of detecting neutrals in the energy range of 10...1000 eV, and a quadrupole mass spectrometer and video systems for plasma imaging. The majority of systems and diagnostics are controlled by the Siemens SIMATIC S7 system, which also provides safety interlocks.

COMPARATIVE ANALYSIS OF THE PLASMA PARAMETERS OF ECR AND COMBINED ECR + RF DISCHARGES IN THE TOMAS PLASMA FACILITY

This paper [14] explores for the first time the parameters in helium electron-cyclotron resonance (ECR) plasma and combined ECR + radio-frequency (RF) discharges in TOMAS. The ECR discharge in this work, at 2.45 GHz and 87.6 mT, is the main one for creating and maintaining the plasma, while the addition of RF power at 25 MHz allows to broaden the achievable electron temperature and density at a given gas flow, as evidenced by triple Langmuir probe measurements. This effect of the combined ECR + RF discharge provides flexibility to study particular aspects of wall conditioning techniques relevant to larger devices, or to approach plasma conditions relevant to fusion edge plasmas for particular surface interaction studies.

CURL-FREE POSITIVE DEFINITE FORM OF TIME-HARMONIC MAXWELL'S EQUATIONS WELL-SUITABLE FOR ITERATIVE NUMERICAL SOLVING

A new form of time-harmonic Maxwell's equations is developed on the base of the standard ones and proposed for numerical modeling [15]. It is written for the magnetic field strength H, electric displacement D, vector potential A and the scalar potential Φ. There are several attractive features of this form. The first one is that the differential operator acting on these quantities is positive. The second is absence of curl operators among the leading order differential operators. The Laplacian stands for leading order operator in the equations for H, A and Φ, while the gradient of divergence stands for D. The third feature is absence of space varied coefficients in the leading order differential operators that provides diagonal domination of the resulting matrix of the discretized equations. A simple example is given to demonstrate the applicability of this new form of time-harmonic Maxwell's equations.

RADIO FREQUENCY WALL CONDITIONING DISCHARGES AT LOW MAGNETIC FIELDS IN URAGAN-2M STELLARATOR

For removing impurities accumulated at the inner surfaces of fusion devices, the ion cyclotron wall conditioning is used. It is also possible to use radio-frequency (RF) discharges with frequencies above the ion cyclotron frequency $\omega \gg \omega ci$ to sustain the wall conditioning discharges. This method is routinely used at the Uragan-3M and 2M stellarators. The main advantages of this method of wall conditioning are: the reliable start-up, the intense particle recycling, good antenna-plasma coupling and a possibility to create low-temperature weakly ionized plasma. In the present work [16], an RF wall conditioning scenario with the usage of the two-strap antenna which mimics the W7-X stellarator antenna is studied at a low magnetic field $B_0 \approx 0.01$ T. In the experiments, the frequency of the RF generator was 5 MHz, the input RF power was up to ≈ 70 kW. The experiments were carried out in a hydrogen atmosphere. The plasma parameters were measured for different values of pressure and RF power. Plasma production with an average plasma density up to $\sim 7\times10^{11}$ cm^{-3} was observed. The ions charge state and plasma elemental composition were determined through the optical emission spectroscopy. The partial pressure of residual gases was measured with a mass-spectrometer during the series of the wall conditioning discharges. The results of the measurements indicate a good wall conditioning effect.

FIRST EXPERIMENTS ON PLASMA PRODUCTION USING FIELD-ALIGNED ICRF FAST WAVE ANTENNAS IN THE LARGE HELICAL DEVICE

The results of the first experimental series to produce a plasma using the ion cyclotron range of frequency (ICRF) in the large helical device (LHD) within the minority scenario developed at Uragan-2M (U-2M) are presented [17]. The motivation of this study is to provide plasma creation in conditions when an electron cyclotron resonance heating start-up is not possible, and in this way widen the operational frame of helical machines. The major constraint of the experiments is the low RF power to reduce the possibility of arcing. No dangerous voltage increase at the radio-frequency (RF) system elements and no arcing has been detected. As a result, a low plasma density is obtained and the antenna-plasma coupling is not optimal. However, such plasmas are sufficient to be used as targets for further neutral beam injection (NBI) heating. This will open possibilities to explore new regimes of operation at LHD and Wendelstein 7-X (W7-X) stellarator. The successful RF plasma production in LHD in this experimental series stimulates the planning of further studies of ICRF plasma production aimed at increasing plasma density and temperature within the ICRF minority scenario as well as investigating the plasma prolongation by NBI heating.

THERMAL DESORPTION DIAGNOSTICS IN THE URAGAN-2M STELLARATOR

The improved thermal desorption diagnostics has been manufactured, installed and tested in the Uragan-2M (U-2M) stellarator for in-situ characterization a stainless steel (SS) wall outgassing rate and a number of molecular layers of residual gases on its surface in four different positions. The detailed description of this diagnostics, the location of thermal desorption stainless steel probes, the methodology of determining the outgassing rates and the number of molecular layers of residual gases on the probe surfaces are presented [18]. It has been found that the difference between of the data taken from the probes being at different position in the U-2M vacuum chamber lies within the measurement accuracy. Using the present diagnostics together with the mass-spectrometer measurements, some studies were made to investigate the release of gases from the thermal desorption probes before and after radio frequency (RF) or glow discharge (GD) cleaning with hydrogen, helium and argon plasmas. It has been observed that hydrogen sorption by the SS probes surface during the discharge cleaning leads to significant hydrogen desorption even at the temperature of 250...300°C. In this case, hydrogen can be the one of the main gases which desorbs. After U-2M glow discharge cleaning with Ar plasma, the thermal desorption experiment has shown Ar as a significant component which is desorbed from the SS probe surface. Two kinds of desorbed Ar were registered with two different activation energies. The characteristics of the U-2M vacuum system are presented, too, including the block scheme, the list of pumps used to attain the ultimate vacuum, the equipment for measuring the total and partial pressures of residual gases.

DEVELOPMENT OF TECHNOLOGY FOR VACUUM SURFACE CONDITIONING BY RF PLASMA DISCHARGE COMBINED WITH DC DISCHARGE

From the research on the combined RF and DC discharge [19] the following may be concluded:

– the anode voltage of combined discharge is lower than in the case of glow one;

– the stainless steel 12Kh18N10T erosion coefficient is about 1.5 times less in the case of combined discharge than in the case of glow one;

– the thermal desorption diagnostic of wall conditions in the DSM-1 has shown better efficiency with the combined discharge: the glow discharge conditioning during 5 hours causes 5 times decrease in stainless steel 12Kh18N10T outgassing rate, while the combined discharge conditioning under the same initial conditions causes 15 times decrease in the outgassing rate;

– the combined discharge may be realized in both small and big vacuum chambers.

Further improvements in the combined discharge efficiency in wall conditioning are associated with increasing microwave power that is quite small in our experiments, especially, in the case of U-2M.

As a result, the research has shown good prospects for using the combined discharge for plasma devices walls conditioning. The research results have been implemented at Uragan-2M and will be proposed for EURO fusion devices.

CONTRIBUTION TO THE 3RD INTERNATIONAL WORKSHOP ON GAS-DYNAMIC TRAP BASED FUSION NEUTRON SOURCE (GDT-FNS)

The 3rd International Workshop on Gas-Dynamic Trap-based Fusion Neutron Source (GDT-FNS) was held through the hybrid mode on 13-14 September 2021 in Hefei, China. Vladimir Moiseenko (KIPT) made a presentation about status of stellarator-mirror fusion-fission hybrid concept [20]. KIPT is developing a stellarator-mirror neutron source and associated fusion-fission reactor concept [21, 22]. Fusion neutrons are generated in a stellarator-type system with an embedded magnetic mirror. Fusion reactions occur in the magnetic mirror, where a hot component of sloshing tritium ions is trapped. The magnetic mirror is surrounded by a fission reactor mantle where the transmutation and the energy production take place. The stellarator-mirror system is a modified DRACON magnetic trap. A modification from the classical DRACON is the use of a single (instead of double) magnetic mirror with a relatively short size [23]. The Uragan-2M stellarator device is used to experimentally check key points of the concept. An embedded magnetic mirror in Uragan-2M is arranged by switching off one toroidal coil [23]. In the U-2M experimental studies, key properties have already been demonstrated for the stellarator-mirror hybrid. Estimates for a proof-of-principle hybrid machine give a cost within 0.5 billion EUR [24].

ICRF PLASMA PRODUCTION WITH THE W7-X LIKE ANTENNA IN THE URAGAN-2 M STELLARATOR

The results of the plasma start-up with ICRH of U-2M RF discharges in H_2 + He mixture with newly implemented controlled gas H_2 concentration are presented [25]. The W7-X like ICRH antenna operated in monopole phasing with applied RF power of ~ 100 kW. We investigated plasma start-up in the pressure range $p = (6\times10^{-4})...(9\times10^{-2})$ Pa. Plasma production with an average density of up to $N_e \sim 10^{13}\ \text{cm}^{-3}$ was observed at frequencies the fundamental harmonic of the hydrogen cyclotron frequency.

PLASMA PRODUCTION IN ICRF IN THE URAGAN-2M STELLARATOR IN HYDROGEN-HELIUM GAS MIXTURE

Plasma production experiments in helium at Uragan-2M have been performed to investigate the role of the hydrogen minority in helium [26]. The experiments presented here were carried on with a controlled minority hydrogen concentration. The hydrogen minority allowed one to increase plasma density more than three times as compared with pure helium. The obtained plasma density is highest for whole time of Uragan-2M operation. The developed scenario allowed to decrease the neutral gas pressure at which the plasma production is possible. This is a requirement for achieving regimes of plasma production with full ionization. Although the initial gas mixture 14 %H_2 + 86 %He can be treated as optimum, there is no sensitive dependence on hydrogen minority concentration, which makes the scenario robust. This study, together with initial LHD experiments, confirm the prospects of target plasma production by ICRF waves for stellarator type machines.

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ТЕРМОЯДЕРНІ ДОСЛІДЖЕННЯ У ВІДДІЛІ СТЕЛАРАТОРІВ ІФП ННЦ ХФТІ

В.Є. Моісеєнко, М.Б. Древаль, Ю.В. Ковтун, Ю.С. Кулик, Г.П. Глазунов, Є.О. Казаков, J. Ongena, С.Є. Шарапов, Г. Томсен, І.Є. Гаркуша

Наведено короткий опис власної наукової діяльності та діяльності у колаборації відділу стелараторів Інституту фізики плазми ННЦ «Харківський фізико-технічний інститут» за останні два роки. Уся діяльність включає експерименти на токамаку JET, стелараторах Wendelstein 7-X та Ураган-2М, тороїдальному пристрої TOMAS і теоретичні дослідження, пов’язані з моделюванням високочастотних полів у плазмі та концептуальною розробкою ядерно-термоядерного гібриду на базі стеларатора з вбудованою відкритою пасткою.