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FUSION RESEARCH IN STELLARATOR DEPARTMENT OF IPP NSC KIPT

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This paper briefly describes intrinsic and collaborative scientific activities of the Stellarator Department (Institute of Plasma Physics of the National Science Center "Kharkiv Institute of Physics and Technology") within last two years. These activities include experiments and numerical modeling for JET, Asdex-U and TCV European tokamaks, stellarators Wendelstein 7-X, TJ-II, LHD, Heliotron-J and Uragan-2M, TOMAS toroidal device and theoretical studies related to conceptual development of the stellarator-mirror fission-fusion hybrid.

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INTRODUCTION

In these challenging years of war, the staff of the Department continue scientific activities. Many scientists and engineers leaved Kharkiv city for other locations more distant from the front line. In spite of this, due to usage of telecommunication tools, the Department went on with at least the same efficiency as before. The IPP-KIPT team participated in experiments under EUROfusion umbrella on JET, Asdex-U and TCV European tokamaks, stellarators Wendelstein 7-X, TJ-II, LHD and TOMAS toroidal device. Also, the work on processing the data of the past experiments on Uragan-2M continued. Below, the major scientific results of last two years are presented.

1. STABLE DEUTERIUM-TRITIUM JET PLASMAS WITH IMPROVED CONFINEMENT IN THE PRESENCE OF ENERGETIC-ION INSTABILITIES

Providing stable and clean energy sources is a necessity for the increasing demands of humanity. Energy produced by Deuterium (D) and Tritium (T) fusion reactions, in particular in tokamaks, is a promising path towards that goal. However, there is little experience with plasmas formed by D-T mixtures, since most of the experiments are currently performed in pure D. After more than 20 years, the Joint European Torus (JET) has carried out new D-T experiments with the aim of exploring some of the unique characteristics expected in future fusion reactors, such as the presence of highly energetic ions in low plasma rotation conditions. A new stable, high confinement and impurity-free D-T regime, with reduction of energy losses with respect to D, has been found. Multiscale physics mechanisms critically determine the thermal confinement. These crucial achievements importantly contribute to the establishment of fusion energy generation as an alternative to fossil fuels.

The good thermal confinement of discharge #99896 is obtained in the presence of generally-believed deleterious electromagnetic perturbations over a wide range of frequencies when ICRF heating is added, as shown in Fig. 1. We can identify perturbations generated by the interplay between energetic ions and Alfvén waves, such as toroidal Alfvén eigenmodes (TAE) and reversed-shear Alfvén eigenmodes (RSAE). Fishbone instabilities related to the interaction between energetic ions and MHD are also present. All of this activity corroborates the presence of highly energetic ions in the plasma.

The nonlinear interplay between fast ions and various modes has been analyzed with the global gyrofluid code FAR3D. It becomes clear that although magnetic perturbations do not prevent the reach of high confinement, they can lead to loss of fusion power. These results show the critical interaction between magnetic perturbations and alpha particles, and we conclude that it is essential to control such interactions to produce high fusion power in future tokamak reactors. Nevertheless, magnetic perturbations induced by energetic ions can also lead to beneficial effects that may have a positive impact on reducing energy losses by heat transport. This is the case of the interplay with the so-called zonal flows. The generation of zonal flows is studied by analyzing the energy transfer between fishbone and TAE perturbations. Two extra simulations with CGYRO were performed to reveal the physics mechanism by which turbulent transport is strongly reduced in the presence of energetic ions [1].

2. EXPERIMENTS ON EXCITATION OF ALFVÉN EIGENMODES BY ALPHA-PARTICLES IN JET DTE2 PLASMAS

2.1. BUMP-ON-TAIL DISTRIBUTION

Dedicated experiments were performed in JET DTE2 plasmas for obtaining an α-particle bump-on-tail (BOT) distribution aiming at exciting Alfvén eigenmodes (AEs) [2]. Neutral beam injection-only heating with modulated power was used so that fusion-born α-particles were the only ions present in the MeV energy range in these DT plasmas. The beam power modulation on a time scale shorter than the α-particle slowing down time was chosen for modulating the α-particle source and thus sustaining a BOT in the α-particle distribution. High-frequency modes in the toroidicity-induced Alfven eigenmode (TAE) frequency range and multiple short-lived modes in a wider frequency range have been detected in these DT discharges with interferometry, soft x-ray cameras, and reflectometry. The modes observed were localized close to the magnetic axis, and were not seen in the Mirnov coils. Analysis with the TRANSP and Fokker-Planck FIDIT codes confirms that α-particle distributions with BOT in energy were achieved during some time intervals in these discharges though no clear correlation was found between the times of the high-frequency mode excitation and the BOT time intervals. The combined magneto-hydrodynamic (MHD) and kinetic modelling studies show that the high-frequency mode in the TAE frequency range is best fitted with a TAE of toroidal mode number n = 9. This mode is driven mostly by the on-axis beam ions while the smaller drive due to the pressure gradient of α-particles allows overcoming the marginal stability and exciting the mode. The observed multiple short-lived modes in a wider frequency range are identified as the on-axis kinetic AEs (Fig. 2).

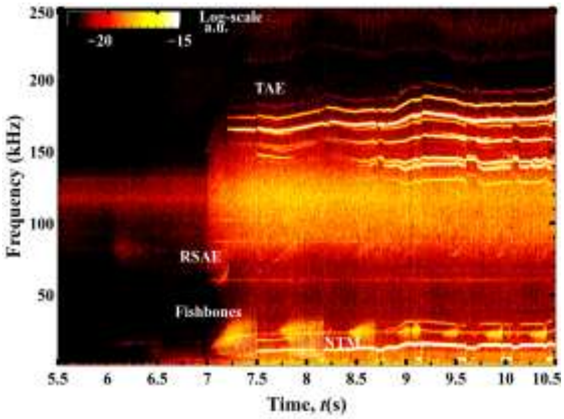

Fig. 1. Evolution of magnetic perturbations in #99627

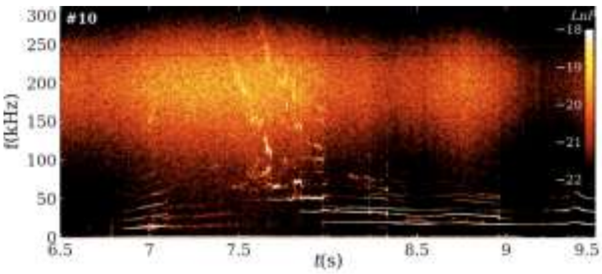

Fig. 2. MHD in frequency range 100…300 kHz seen with SXR camera Channel 10 in D-T pulse #99627

2.2. INTERNAL TRANSPORT BARRIER PLASMAS

A toroidal Alfvén eigenmode (TAE) has been observed to be driven by alpha particles in a JET deuterium-tritium internal transport barrier plasma [3]. The observation occurred 50 ms after the removal of neutral beam heating (NBI). The mode is observed on magnetics, soft-xray, interferometry and reflectometry measurements. We present detailed stability calculations using a similar tool set validated during deuterium only discharges. These calculations strongly support the conclusion that the observed mode is a TAE, and that this mode was destabilized by alpha particles. Non-ideal effects from the bulk plasma are interpreted as responsible for suppressing the majority of TAEs which were also driven by alpha particles, but the modes that match the observations are predicted to be particularly weak for these non-ideal effects. This mode located far from the core on the outboard midplane is found to be driven by both trapped and passing particles despite alpha particles originating in the core.

2.3. TAE OBSERVED IN LOW POWER DT PLASMAS

The Joint European Torus (JET) recently carried out an experimental campaign using a plasma consisting of both deuterium (D) and tritium (T) [4]. We observed a high-frequency mode using a reflectometer and an interferometer in a D-T plasma heated with low power neutral beam injection, P_{NBI} = 11.6 MW. This mode was observed at a frequency f = 156 kHz and was located at major radii 3.1 ≤ R (m) ≤ 3.3. The observed mode was identified as a toroidal Alfvén eigenmode (TAE) using the linear MHD code, MISHKA. Beam ions and fusion-born alpha particles were modelled using the full orbit particle tracking code LOCUST. We calculated the stability of the 21 candidate modes using the HALO code.

3. EXCITATION OF TOROIDAL ALFVÉN EIGENMODES WITH COUNTER-CURRENT NBI IN THE TCV TOKAMAK

In TCV unstable modes excited by resonant interaction between the shear Alfvèn waves in continuum gaps and energetic particles have been observed in scenarios with neutral beam injection (NBI) [5]. TCV is a middle-size device (R_0/a = 0.88/0.25) equipped with a 1 MW, 25 keV tangential neutral beam injector. The Alfvènic nature of the modes has been confirmed investigating their sensitivity against plasma parameters such as NBI energy, toroidal magnetic field, and cross-checking with the predictions from linear kinetic stability code. The mode radial profile is estimated using electron cyclotron emission measurement and agrees well with modelling results. In addition, the fast particle distribution function has been modelled using TRANSP/NUBEAM code. Even with counter-current NBI (leading to higher losses), the drive from the resonant particles is sufficient for the mode excitation. An additional diffusion model allows to estimate the fast particle transport, modifying the fast particle gradient at the mode location and matching the neutron rates [5].

4. DETERMINATION OF MHD MODE STRUCTURES USING SOFT X-RAY DIAGNOSTICS IN TCV

A forward modeling technique is developed for determining the characteristic features of observed MHD modes from the line-of-sight data of the soft x-ray (SXR) diagnostics with 64 vertical lines-of-sight in the Tokamak à Configuration Variable (TCV) tokamak [6]. A modeling technique of MHD mode structure analysis on the base of lines-integrated data of SXR diagnostics. The space structure of observed toroidal Alfvén eigenmode (TAE) are calculated using HELENA, CSCAS and MISHKA codes and used in further SXR modelling (Fig. 3).

A ballooning structure of the observed in TCV *n*=1 TAE mode [6] can be analyzed more easily due to the low poloidal mode number *m* in contrast to the high m modes analyzed by similar SXR technique in W7-X stellarator.

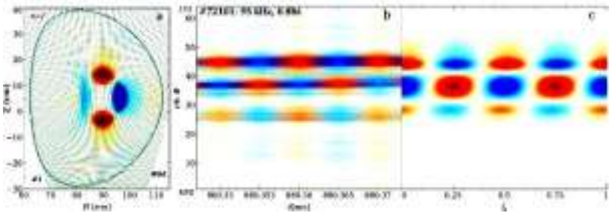

Fig. 3. SXR radiation distribution of MHD mode from the computed TAE eigenfunctions (a). Spatiotemporal evolution of (b) experimental emission data (#72101,0.88s); modeled data (c)

5. HIGH FREQUENCY ALFVÉN EIGENMODES IN ASDEX-U PLASMAS IN THE PRESENCE OF RF ACCELERATED NBI IONS

High frequency Alfvén eigenmodes in the ion cyclotron frequency range are actively researched on the ASDEX Upgrade tokamak (AUG) [7].

The general properties of this particular mode type are: (a) the mode is beam-and RF- driven; (b) the mode is sub-cyclotron with the frequency $\omega \sim 0.5\omega_{ci}$, where ω_{ci} corresponds to the on-axis cyclotron frequency of the beam ions; (c) the mode propagates in the counter-current/counter-injection direction; and (d) the field-aligned (~toroidal) mode number is large: $|n_{//}| \sim 50$. The radio frequency-(RF)-acceleration of beam-injected ions at the 3rd cyclotron harmonic significantly expands the number of excited modes. The RF-driven fast ion population is modeled using a combination of an orbit-following Monte Carlo code (ASCOT-RFOF) and an electro-magnetic wave code (TORIC). The application of this code combination is a first to model beam-ion RF-acceleration at the 3rd cyclotron harmonic. The RF-accelerated fast ion distributions are then used to analytically calculate anisotropy-driven mode growth rates (Fig. 4).

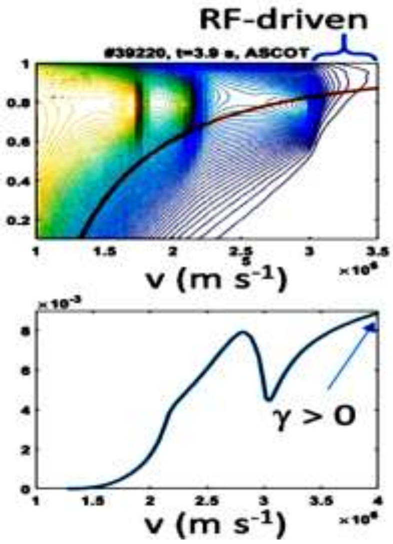

Fig. 4. The fast ion velocity distribution function and GAE growth rate

We see that the region of positive (unstable) growth rates is expanded by RF-accelerated fast ions in both the frequency and the mode number directions for the GAEs, consistent with the measurements.

6. ENERGETIC PARTICLE DRIVE AND DAMPING EFFECTS ON TAES IN AUG EXPERIMENT WITH ECCD

The impact of electron cyclotron current drive (ECCD)-driven current on TAEs in experiments on the AUG tokamak is investigated numerically [8]. The dynamical evolution of the plasma profiles and equilibria are modelled with European transport solver, while ion cyclotron resonance heating-accelerated H-minority ions exciting TAEs are assessed with the PION code. TAEs, their drive and damping are computed with the codes CASTOR and CASTOR-K. In the set of discharges analyzed, two groups of TAEs are observed, differing in frequency and radial location. Experimental observations show that when counter-ECCD is applied the higher frequency group of approximately 150 kHz is suppressed, while the lower frequency modes of 125 kHz are amplified. When co-ECCD is applied, depending on the location of the ECCD current deposition layer, both groups of TAE can be suppressed (Fig. 5).

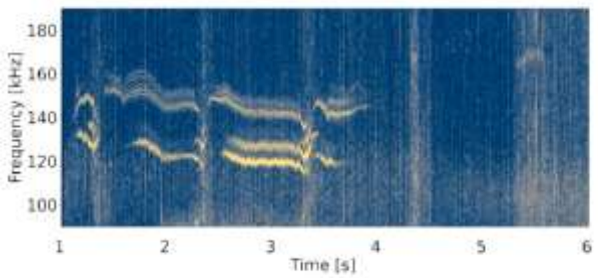

Fig. 5. Spectrogram of discharge # 38012

Numerical calculations of energetic particle drive and thermal plasma damping show that neither one effect could explain the variety of the experimental observations. The fine balance between the drive, sensitive to the TAE position, and the radiative and continuum damping effects could only explain the experiment if the effects are considered altogether.

7. ICRF PRODUCTION OF PLASMA WITH HYDROGEN MINORITY IN URAGAN-2M STELLARATOR BY TWO-STRAP ANTENNA

The experiments on medium-size stellarator Uragan-2M (U-2M) in Kharkiv, Ukraine, are carried on in support of the Wendelstein 7-X (W7-X) experimental program. The ICRF scenario of plasma production at the hydrogen minority regime had been experimentally tested on U-2M and was qualified at the Large Helical Device (LHD). The results of further research on the ICRF plasma production are presented in [9]. The ICRF discharge studies were carried out in a H_2 + He mixture with a controlled hydrogen concentration ranging from few percents to 75% (Fig. 6). The two-strap antenna mimicking the W7-X antenna operated in monopole phasing. The applied RF power was in the range of ~ 100 kW. Relatively dense plasma of up to $N_e \sim 10^{19}$ m^{-3} was produced near the first harmonic of the hydrogen cyclotron frequency. The maximum temperature of the electrons and ions was not more than a few tens of electron volt. The characteristic features of RF plasma production in connection with the propagation of electromagnetic waves and the experimental conditions are discussed.

The experiments on U-2M and LHD indicate that the minority scenario of ICRF plasma production appears to be scalable and could be used in large stellarator machines. This is, in particular, important for the future experiments ICRF production of target plasma in W-7X in conditions where electron cyclotron resonance heating start-up is not possible.

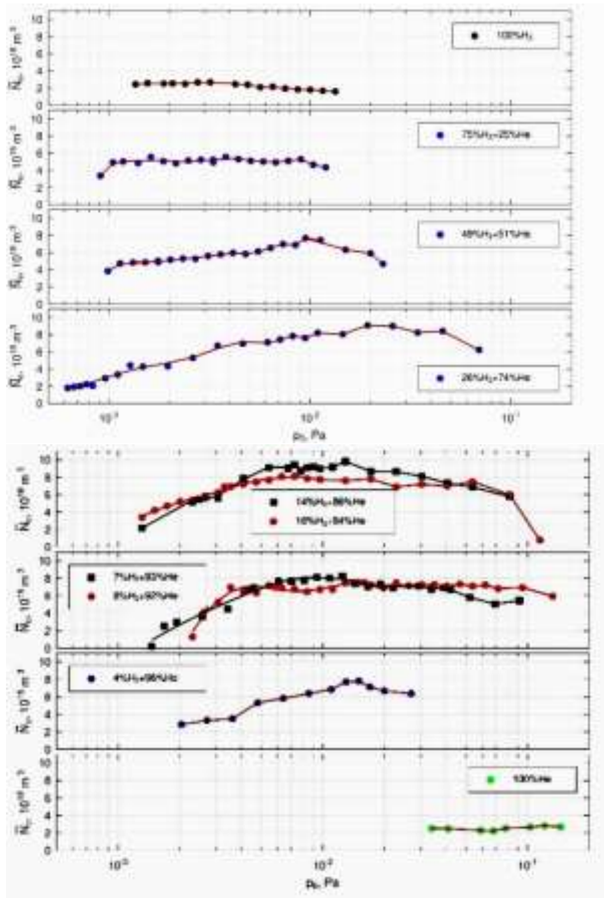

Fig. 6. Average plasma density as a function of the pressure. Data of experimental series [9–12] (f = 4.9 MHz and U_a = 7 kV)

The ICRF plasma production experiments with H_2+He mixture showed that the gas breakdown and plasma creation are achieved at lower pressure compared to operation with pure He and similar RF power [10,11]. Adding a hydrogen minority allowed one to triple the plasma density as compared with pure helium. The highest plasma density (10^{13} cm^{-3}) was obtained at a gas fueling mixture of 14% hydrogen in helium. While addition of deuterium minority to the H_2+He mixture leads to small changes in the parameters and characteristics of the plasma, in the D_2+H_2 mixture and a low hydrogen concentration (15…20%), only a low ~ density plasma of no more than 10^{11} cm^{-3} is produced.

At very low magnetic fields plasma is successfully produced in deuterium. This study compares results ICRF plasma production at hydrogen minority regime in

Uragan-2M (U-2M) and Large Helical Device (LHD) [12]. The comparison of plasma production in ICRF with hydrogen minority at U-2M and LHD indicate that this scenario can be scaled to larger stellarator devices.

8. PLASMA BEHAVIOR TO HYDROGEN SUPERSONIC MOLECULAR BEAM INJECTION IN THE URAGAN-2M STELLARATOR

The supersonic molecular beam injection SMBI system has been used in experiments on ICRF plasma production at the hydrogen minority regime [13]. Hydrogen was used for the additional pulse gas injection into the helium or hydrogen-helium plasmas. The maximum average plasma density was determined after pressure scanning and the steady-state gas injection. After the SMBI pulse the maximum average plasma density in helium had been increased two times up to $0.4 \cdot 10^{19}$ m^{-3}. The increase in density is likely due to the formation of hydrogen-helium plasma and a change in ICRF heating conditions. In hydrogen-helium plasma SMBI increased plasma density by 30% up to $1.3 \cdot 10^{19}$ m^{-3}.

9. RADIO FREQUENCY PLASMA PRODUCTION AT FREQUENCIES HIGHER THAN ION CYCLOTRON FREQUENCY AT URAGAN-2M STELLARATOR

This study is focused on RF plasma production at frequencies higher than IC frequency [14]. In the experiments on Uragan-2M, the frequency of the RF generator was range 4.9…5.1 MHz, magnetic field B_0 was range 0.01…0.21 T. The plasma was produced using a two-strap antenna. The experiments were carried out in the atmosphere of H_2 + He mixtures. The plasma parameters were measured for different values of neutral gas pressure and RF power. The plasma density obtained was below 10^{19} m^{-3}, the representative value for plasma production experiments in H_2 + He mixtures under the condition $\omega_{RF}=\omega_{ic}$ (H^+). The maximum density in current experiments was observed to be $3 \cdot 10^{18}$ m^{-3} under the condition $\omega_{RF}=2\omega_{ic}$ (H^+). The electron temperature was up to several tens of eV.

10. ICRF PLASMA PRODUCTION AT HYDROGEN MINORITY REGIME IN LHD

This study aim is to develop further an ion cyclotron range of frequencies (ICRF) method of plasma production in stellarators based on the minority heating [15]. The previous studies demonstrate production of low density plasma ($9.5 \cdot 10^{17}$ m^{-3}) at low power of up to 0.2 MW.

The higher ICRF heating power experiments become possible after introducing a programmable ICRF power ramp up at the front of the ICRF pulse. With this trick, all the shots went with the antenna voltage within the safe range. Increase of the ICRF power predictably results in increase of the density of produced plasma. Without pre-ionization the plasma density achieved was $6 \cdot 10^{18}$ m^{-3} which is 6 times higher than in previous experiments. However, the electron temperature was not high, the light impurities were hot fully stripped, and there were no recombination peaks after termination of the ICRF pulse. Plasma density is too low to provide good conditions for efficient plasma heating.

This study aims to improve further an ICRF method of plasma production in stellarators based on the light minority heating scenario. In previous studies on ICRF heated plasmas in LHD, without optimized pre-ionization scheme, the achieved plasma density was $6 \cdot 10^{18}$ cm^{-3}. However, the electron temperature was not high, the light impurities were not fully ionized, and there were no recombination peaks after termination of the RF pulse. In the case of ECRF pre-ionization, in the same experimental series, subsequent ICRF heating could sustain plasma at high-density and high temperatures for both electrons and ions. The antenna – plasma coupling was much better which result in a higher heating power and at the same time a lower antenna voltage. These preceding experiments indicate a clear possibility to arrange ICRF plasma production and heating in the same shot. By carefully tuning the gas puff and RF pulse, plasma production and heating with ICRF only had been demonstrated for the first time in a big stellarator machine, LHD. In a first optimized regime with continuous gas puff, the steady plasma density reaches about $1 \cdot 10^{19}$ cm^{-3} with an electron temperature over 1 keV. The coupled ICRF power of 0.7 MW substantially exceeds the radiation power, 0.2 MW. A second regime with pulsed gas fueling, the coupled ICRF power is higher, 1.2 MW. While the radiation power and plasma density remain the same, the electron temperature doubled to 2…2.5 keV [16].

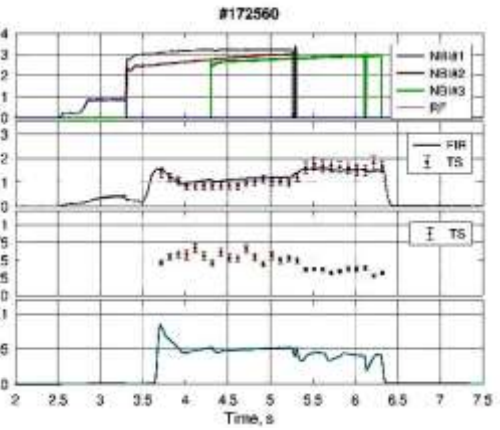

Fig. 7. Time evolutions of injection P_{NBI} (NBI#1, NBI#2, and NBI#3) and P_{RF} (total), average electron density N_e, electron temperature T_e, plasma energy content w_p, FIR is far-infrared laser interferometer (R = 3.669 m), TS is Thomson scattering (R = 3.602 m). B_0 = 0.5 T [17]

11. FIRST EXPERIMENTS ON RF PLASMA PRODUCTION AT RELATIVELY LOW MAGNETIC FIELDS IN THE LHD

Studies of plasma production by RF discharge (ω_{RF} >> ω_{ci}) in relatively small magnetic fields of 0.5…0.6 T at the LHD have shown the possibility of realizing such discharges in big helical devices [17,18]. A deuterium plasma with a density of up to ≈ $6 \cdot 10^{18}$ m^{-3} was obtained with an injected RF power of up to ≈1.43 MW. A linear dependence of the density on the

RF power was observed in the experiments. The electron temperature was low.

Plasma of RF discharge serves well as target plasma for NBI. Further NBI application allowed us to reach electron temperatures up to ≈0.9 keV and densities up to ≈ $2.4{\cdot}10^{19}$ m^{-3} (Fig. 7). The maximum value of $\langle\beta_{dia}\rangle$ was 2.6% in these experiments. These experiments open up the possibility of new regimes of operation at LHD and, in future, at world biggest stellarator W7-X. Besides, RF plasma with above mentioned parameters can be used for wall conditioning in helical devices.

12. WENDELSTEIN 7-X ULTRASHORT ELECTRON CYCLOTRON RESONANCE HEATING DISCHARGE FOR WALL CONDITIONING

The experiments have shown the realization of the series of consecutive ultrashort ECRH pulses at W7-X in a hydrogen atmosphere [19]. This scenario is aimed at providing atomic hydrogen generation for wall conditioning. A series of the 0.73 MW ECRH pulses of 7 ms duration creates the bursts of plasma with a maximum density of about $0.23{\cdot}10^{19}$ m^{-3}. Pulses are stable in series. The variation of times between ultrashort ECRH impulses does not significantly change the plasma parameters. The plasma decay time is shorter than the particle confinement time that indicates intense recombination which contributes to atomic hydrogen generation.

13. NON-RESONANT MICROWAVE DISCHARGE START-UP IN HELIOTRON J

The non-resonant microwave discharge in strong magnetic fields was investigated in Heliotron J under the condition, $\omega_{ce}/\omega_{RF}>1$. Following the production of a non-resonant microwave discharge plasma, it undergoes several phases in sequence: breakdown and formation of pre-ionized plasma, increase in linear and nonlinear phases of plasma density, and quasi-stationary stage. Several modes of non-resonant microwave discharge were investigated. In the power-scanning mode in non-resonant microwave discharge, a higher plasma density than that in the constant-power mode is achieved. The maximum average density achieved in the experiments is substantially greater than the critical density for O-wave (ordinary waves) $7.45{\cdot}10^{16}$ m^{-3} and can reach the value of $2.5{\cdot}10^{18}$ m^{-3} [20].

14. COMPARISON OF ION CYCLOTRON WALL CONDITIONING DISCHARGES IN HYDROGEN AND HELIUM IN JET

The explores the plasma parameters of helium and hydrogen Ion Cyclotron Wall Conditioning (ICWC) discharges performed in JET as part of a He/H fuelling changeover experiment. The conducted study shows that plasma with a higher density is formed in helium than in hydrogen. A distinct glow in the ion cyclotron resonance zone is observed throughout the discharge in He. In H-ICWC discharges, a lower radio-frequency coupling efficiency and coupled power was observed than in He-ICWC discharges. While the helium concentration decreased with the number of H-ICWC pulses and the same for hydrogen in He-ICWC, which is the intended changeover procedure, the main features of hydrogen as well as the helium IC discharge do not change dramatically [21]. Changeover between helium and hydrogen fueled plasmas in JET and WEST investigations described in [22].

15. MEASUREMENT OF HYDROGEN PLASMA PARAMETERS OF THE COMBINED ECR+RF DISCHARGE IN THE TOMAS FACILITY

The plasma electron density and temperature were measured in hydrogen electron-cyclotron resonance (ECR) plasma and combined ECR + radio-frequency (RF) discharges in the TOMAS facility. The results of ECR and combined ECR+RF discharges studies are compared. With an addition of RF, it is possible to vary the plasma parameters around the values provided by the ECR discharge. The propagation of slow (SW) and fast (FW) waves in hydrogen plasma is analyzed. Depending on the plasma density and the parallel component of the wave vector three cases are possible: SW propagation only, SW and FW simultaneous propagation, and FW propagation only [23]. For more information: overview of TOMAS plasma diagnostics present in [24]. ECRH and radio frequency discharges were also investigated at TOMAS in [25–32].

16. USING MICROWAVE REFRACTION TO DETERMINE LOCAL IN HOMOGENEITIES OF ROTATING PLASMA

To determine the local inhomogeneities of a rotating plasma, the method based on microwave refraction was used. The method is based on spectral and correlation analysis of the reflected signals from the rotating plasma layer at normal and inclined microwave incidence. This method allowed us to determine local inhomogeneities of plasma electron density, angles of azimuthal displacement of grooves, and their frequency of rotation. Using an additional horn antenna it was possible, in contrast to previous works, to find and analyze two regions with azimuthal inhomogeneities in the rotating plasma. Analysis of the reflected signals shows the presence of four grooves, and the angular frequency of rotation $\omega = 1.16{\cdot}10^4$ s^{-1} was also determined [33].

17. STELLARATOR-MIRROR FUSION-FISSION HYBRID – A FAST ROUTE TO CLEAN AND SAFE NUCLEAR ENERGY

The multiple recycle fuel cycle (MRFC) for uranium-238, if practically realized, can bring revolutionary changes in nuclear energy. Potentially full usage of uranium-238 makes its resources practically infinite. Besides the energy, the fuel cycle principal output is only fission products which are rather the co-products than the waste. For the same amount of energy produced, the amount of fission products is three orders of magnitude less than the amount of spent nuclear fuel produced within the currently exploited nuclear energy production scenario.

Using the simplest isotope balance model the key features of the multiple recycle fuel cycle for uranium-238 are investigated [34]. The repetition of this cycle results in smooth transformation of the initial fuel to the “stationary” fuel without strong variations.

The problem of the fuel cycle considered as well as other fuel cycles using plutonium is the deficit of delayed neutrons. A solution of this problem is a sub-critical nuclear reactor with an external neutron source, i.e. a fusion-fission hybrid system like stellarator-mirror (SM) fusion-fission hybrid.

The preliminary results for principal design of the SM hybrid nuclear reactor for multiple recycle fuel cycle for uranium-238 are presented [34]. The reactor has a design similar to the reactor for incineration of the spent nuclear fuel [35]. The difference is that instead of lead-bismuth eutectics gas cooling is used. Also, the reactor is bigger, 13 m in length and 2.86 m in outer radius, and more powerful, about 1.3 (2.6 for the DRACON case) GW_{th}. The SM hybrid fusion neutron flux should also be proportionally increased for this machine. This is not a problem since fusion neutron generation efficiency increases with the plasma part size. The proposal formulated needs experimental studies, but to build a big SM hybrid machine, big investments are necessary. A reasonable step is first to build a compact, less costly machine aimed for *demonstration* of MRFC f easibility which uses mainly plutonium fuel. This facilitates developments and improvements of SM hybrid related technologies, including the technologies for closed fuel cycles. A cost estimate for this machine is 0.5 billion EUR. With such a device, there is an important possibility to irradiate by neutrons the multiple recycle uranium-238 based fuel, which could be added to the reactor active zone in minority, and to study its recycling. The compact SM hybrid experiment will make a background for a big SM hybrid experimental machine.

As for spent nuclear fuel incineration, the straightforward approach to MRFC is to use transuranic mixture extracted from the spent nuclear fuel both as an initial fuel and the fuel addition during the cycling. This approach seems possible, but some unfavorable features like strong variation of the neutron multiplication factor k_{eff} and accumulation of americium isotopes would likely hamper its practicability. A solution proposed in [38] is addition of ^{238}U both to initial fuel and recycle fuel. In each sequence ^{238}U is added in different proportions. The variations of k_{eff} are reduced to minimum values. The americium content is decreased in 4.5 times in our calculations.

18. SUPPLEMENTARY STUDIES

Behavior of the ungrounded antenna electric potential in Uragan-2M torsatron had beern studied [36]. Time behavior of the Hα spectral line and the molecular hydrogen spectral line in hydrogen plasma in the Uragan-2M had been analyzed in [37]. In [38] the initial design corrugated horn antenna for microwave diagnostics in Uragan-2M is presented. The work [39] investigates sputtering yields of TiC and MAX phase Ti_2AlC using Ne, Ar, Xe ions. Optical emission spectroscopy of vanadium cathodic arc plasma at different nitrogen pressure is presented in [40].

The scientists of the department made contribution to the following overview papers [41–44].

SUMMARY

The analysis of experiments carried on at U-2M device continued in past two years, and the obtained important results are summarized above. Other significant works were carried on EUROfusion stellarators, Wendelstein 7-X and TJ-II. EUROfusion international collaboration programme allows the scientists of the Department to perform the experimental research at LHD and Heliotron-J (Japan). Plasma-wall interaction was studied at TOMAS. The participation in the EUROfusion tokamak exploitation work package stimulated the joint research on JET, Asdex-U and TCV European tokamaks. The notable study was done in development of the concept of the stellarator-mirror fusion-fission hybrid. Finally, the fruitful collaboration with Institute of Solid State Physics, Materials Science and Technologies of KIPT should be noticed.

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ТЕРМОЯДЕРНІ ДОСЛІДЖЕННЯ У ВІДДІЛІ СТЕЛАРАТОРІВ ІФП ННЦ ХФТІ

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Наведено короткий опис власної наукової діяльності та діяльності у колаборації відділу стелараторів Інституту фізики плазми ННЦ «Харківський фізико-технічний інститут» за останні два роки, включаючи експерименти та чисельне моделювання для європейських токамаків – JET, Asdex-U та TCV, стелараторів – Wendelstein 7-X, TJ-II, LHD, Heliotron-J та Uragan-2M, тороїдального пристрою TOMAS і теоретичні дослідження, пов'язані з концептуальною розробкою ядерно-термоядерного гібриду на основі комбінації стеларатор-пробкотрон.