Résumé of the Fusion Theory Division of the Kyiv Institute for Nuclear Research

Research topics and international collaboration

Fusion Theory Division (FTD) is headed by Prof. Ya. I. Kolesnichenko. It deals with theoretical research of physical processes in plasmas of advanced systems of nuclear fusion: tokamaks, optimized stellarators, and spherical tori (spherical tokamaks), see http://www.kinr.kiev.ua. The emphasis is done on the study of processes associated with energetic (superthermal) ions, which are produced by fusion reactions, neutral beam injection, and high-frequency heating of the plasma. In particular, kinetic and magnetohydrodynamic plasma instabilities are being investigated, as well as the classical and anomalous transport of energetic ions. Both fundamental theory and theory aimed at explaining particular experimental data and predicting new effects are being developed.

At the earlier stage of research (before 1980), the foundations of physics of fusion-produced alpha particles and thermonuclear burn in plasmas were laid [1]. In particular, in 1967 a new class of instabilities of reactor plasmas – instabilities driven by energetic ions – was discovered (Ya. Kolesnichenko, V. Oraevskij). Now instabilities of this class are studied in many laboratories throughout the world both theoretically and experimentally. New methods of current drive in tokamaks were proposed [2, 3]. An idea of a qualitatively new magnetohydrodynamic (MHD) process with reconnection of magnetic field lines was advanced, which is of importance for understanding of physical phenomena in laboratory and space plasmas [4].

After Ukraine became independent in 1991, extensive international collaboration became possible and played an important role.

In particular, due to the Contract Dnr 96/152 of STINT (Swedish Foundation for International Cooperation in Research and Higher Education) the nature of superthermal ion cyclotron emission (ICE) from tokamak plasmas was clarified (Ya. Kolesnichenko was a winner of the STINT competition) [5]. It was shown that the ICE arises because of a magnetoacoustic instability enhanced by the toroidal drift of energetic ions. This explained a number of ICE frequency spectrum peculiarities in experiments on the European tokamak JET.

Since the end of 90s, fruitful collaboration of FTD with the Princeton Plasma Physics Laboratory (PPPL), USA, and Max-Planck-Institut für Plasmaphysik (IPP), Germany, takes place.

Collaboration with PPPL took place within four CRDF Projects: #UP2-290 (1997 – 1999), #UP2-2114 (2000 – 2001), #UP2-2419-KV-02 (2002 – 2004), and #UKP2-2463-KV-05 (2005 – 2007). (Note that the probability to be awarded in each CRDF competition was about $10^{-1}$, so the probability to get four CRDF grants was $10^{-4}$!) The leader of all these projects from the US side was R. White, from Ukrainian side – Ya. Kolesnichenko. Due to the projects, a new theory of fast ion transport in the presence of sawtooth oscillations (a typical form of MHD activity) was developed [6, 7]. The existence of the critical energy of the ions was predicted: The ions with the energies above the critical energy are insensitive to the MHD-activity, whereas the ions with lower energies are expelled by the MHD-perturbations from the plasma core to the periphery. This prediction was confirmed experimentally on TFTR – the largest American tokamak [S. S. Medley et al., Nuclear Fusion 38 (1998) 1283]. It was shown for the first time that high $\beta$ ($\beta$ is the ratio of the plasma pressure to the magnetic field pressure) tends to stabilize the low-frequency fishbone branch induced by energetic circulating particles [8]. It was shown, also for the first time, that high $\beta$ may deteriorate the confinement of trapped energetic ions in spherical tori during reconnection events [9]. It was predicted that the energetic ions lose their
ability to stabilize MHD activity at high $\beta$ \cite{10}; this prediction agrees with the fact that the large fast ion population in the spherical torus NSTX (PPPL) plasmas does not stabilize the sawtooth instability \cite{E.D. Fredrickson et al., 29th EPS Conf. on Plasma Physics and Controlled Fusion, Montreux, 2002, Rep. P1.104}. An important role of stochasticity of the beam ion motion during sawtooth crashes in NSTX was revealed \cite{11}. A theory of the destabilization of fast magnetoacoustic waves was developed, and important features of the fast magnetoacoustic instability observed in NSTX were explained \cite{12}. The code OFSEF for calculation of the particle transport during sawtooth oscillations was developed \cite{7}.

Collaboration with IPP was started in the framework of the STCU Partner Project No. P-034 (1999 – 2008). Originally, the major objective of this project was to investigate the physics of energetic ions in the IPP basic fusion facilities – Wendelstein-line stellarators and the tokamak ASDEX Upgrade. After the stellarator research moved from Garching bei München to Greifswald, the joint research effort concentrated on stellarators. Depending on time, the project leaders from German side were S. Günter, H. Wobig, A. Weller; from Ukrainian side – Ya. Kolesnichenko. Due to the IPP–KINR collaboration, a theory of the non-ideal fishbone instability was developed, which explained thermal crashes observed during fishbone activity in ASDEX Upgrade \cite{13}. New types of Alfvén modes and wave–particle resonances resulting from the lack of the axial symmetry in stellarators were predicted \cite{14, 15}. It was found that successive changes of the frequencies of destabilized modes observed in the stellarator Wendelstein 7-AS (W7-AS) correlate with an “estafette” of wave–particle resonances during temporal evolution of the plasma density \cite{16}. Various Alfvén instabilities in W7-AS were identified \cite{17}. A new mechanism of anomalous heat conductivity in plasmas was found, which explained experiments on W7-AS, where strong drops of the plasma energy content during instability bursts were observed \cite{18}. The existence of Non-conventional Global Alfvén Eigenmodes was predicted \cite{18, 19}. A new mechanism of the stochastic diffusion in stellarators, which plays the dominant role in optimized stellarators, was revealed \cite{20}. Several codes were developed: the code COBRAS calculating the Alfvén continuum, the code BOA calculating Alfvén eigenmodes, the code GAMMA calculating the growth rate of instabilities in stellarators. Theoretical results obtained in the framework of the project were confirmed on the LHD stellarator, Japan \cite{S. Yamamoto et al., Phys. Rev. Lett. 91 (2003) 245001}. They were also used in the development of a concept project of a Helias reactor \cite{21}.

Since 2008, the FTD team collaborates with Max-Planck-Institut für Plasmaphysik (the leader A. Weller, and now P. Helander), the Princeton Plasma Physics Laboratory (R. White) and the University of California – Irvine, USA (W. Heidbrink) within the STCU Regular Project No. 4588, which expires on September 30, 2011. Interesting and practically important results were obtained. Here we mention only that a new phenomenon – spatial channelling of energy and momentum of energetic ions by instabilities driven by these ions – is discovered \cite{22, 23}. Because of this phenomenon, the radial profile of the plasma heating can drastically change and the frequency chirping during instabilities can take place. Therefore, the role of energetic-ion-driven instabilities in ITER and future reactors can be more significant than one thinks at present. The project resulted in publications in peer-reviewed journals, such as Physical Review Letters, Europhysics Letters, Nuclear Fusion Letters, Physics of Plasmas, Plasma Physics and Controlled Fusion, and others, see Refs. \cite{24–34} (several other publications are expected before the end of the project). The project results were presented at many international and national conferences.
A small FTD group takes part in research on the European tokamak JET (UK). In the past, there was also collaboration with the National Institute for Fusion Science (Japan), where Ya. Kolesnichenko was a guest professor in 2003. In addition, FTD had several IAEA projects and International Science Foundation grants.

**Future plans**

The energetic ions are present in all types of fusion systems. They affect the plasma performance and the first wall of the device. Therefore, the study of physics of energetic ions in plasmas belongs to key directions of fusion research and will be continued in FTD. The influence of energetic-ion-driven instabilities on transport processes and plasma heating will be investigated. In particular, the following experimentally observed in NSTX phenomena, which seem mysterious, will be studied: first, “avalanches” of instabilities, second, predominant heating of ions (rather than electrons) by beam ions, third, formation of a strongly non-monotonic energy distribution of injected ions. The study of the spatial channeling energy and momentum of the energetic ions, which was predicted in Refs. [22, 23], will be continued. Numerical modeling of experimental observations and predictive calculations will be carried out. This includes modeling of sawtooth-induced transport of energetic ions in the DIII-D tokamak (USA), investigation of effects of energetic ions in the Wendelstein 7-X stellarator (which is under construction in Germany), a study of thermonuclear burn in the presence of sawtooth oscillations in the international reactor-tokamak ITER (which is under construction in France). New types of plasma instabilities will be considered.

The planned research will be carried out in collaboration with both American and European institutions. Detailed plans depend on format of collaboration, which is not clear yet.

**Conference series started**

- IAEA Technical Meetings on “Energetic Particles in Magnetic Confinement Systems” (Kyiv, Aspenäs, Trieste, Princeton, Abingdon, Naka, Göteborg, San Siego, Takayama, Kloster Seeon, Kyiv)
- International conferences “Innovative Concepts and Theory of Stellarators” (Kyiv, Greifswald, Madrid)
- Ukrainian Conferences on Plasma Physics and Controlled Fusion

**References**