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Key diagnostic system for ITER reactor nears completion

In the Universe, thermonuclear fusion is a common reaction: it is the source of energy for stars. On Earth producing energy using this process is difficult due to problems with controlling the plasma emitting significant amounts of energy. Of critical importance here is the knowledge of the current state of the plasma and the power released in nuclear reactions. In the ITER reactor this knowledge will be gathered by a sophisticated neutron flux diagnostic system.

The ITER experimental reactor, which has been under construction for over a decade, is a milestone in the development of fusion energy: it is to be the first device using nuclear fusion, capable of generating several times more power than required for its operation. A critically important element of the plasma diagnostics system in this reactor – the High Resolution Neutron Spectrometer (HRNS) – has just been presented in the journal *Fusion Engineering and Design*. The spectrometer design is a joint effort by physicists and engineers from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Cracow, the University of Uppsala and the Istituto per la Scienza e Tecnologia dei Plasmi in Milan, developed in close cooperation with the ITER Organization.

"The spectrometer we have designed allows us to measure both the number and energies of neutrons emitted by plasma across the full range of fusion power expected for the ITER reactor. This provides us with information about the proportions of deuterium and tritium, hydrogen isotopes that combine with each other inside the reaction chamber," says Dr. Jan Dankowski (IFJ PAN), the first author of the article describing the spectrometer. He further clarifies: *"Measuring the fast neutron population from the two dominant reactions in the plasma is a direct indicator of fuel composition, ion temperature, and combustion quality. In ITER and future reactors, this will be a key tool for controlling and optimizing reactor operation. Lack of this information would effectively mean the loss of one of the most important plasma diagnostic tools, significantly hampering both scientific research at ITER and the safe operation of future power reactors".*

Thermonuclear energy can safely be described as 'green'. Energy is generated here similarly to the manner in which it is generated inside stars, i.e. through nuclear fusion reactions, the most promising of which appears to be the fusion of hydrogen isotopes (deuterium and tritium) into helium. Importantly, deuterium is found in vast quantities in the Earth's oceans, and tritium is not needed in large amounts and may in future be produced in the reactor itself (by bombarding more readily available lithium with neutrons). Furthermore, the fusion reaction is not chain-like, so it cannot lead to an explosion and the dispersion of large amounts of highly harmful radioactive materials. The risk of environmental contamination therefore remains minimal and is mainly limited to the reactor's structural elements themselves. Unfortunately, despite its enormous potential, fusion energy remains in the research and development phase. Practical implementation may take several years to complete – with the construction of the DEMO tokamak, a bridge between experimental reactors and a fusion power plant.

The nuclei of hydrogen isotopes form plasma, which, being electrically charged, can be held in isolation from the walls by a magnetic field inside the toroidal vacuum chamber of the reactor (these sorts of reactors are called tokamaks). Currently, this plasma must be additionally heated to reach a temperature of 150 million Kelvin, which guarantees the proper course of the reaction. The high-energy neutrons produced during fusion, being electrically neutral, escape towards the walls of the tokamak, allowing most of the energy produced to be recovered (and ultimately creating tritium in collisions with lithium).

The formation of helium nuclei would be of fundamental importance for the efficiency of future thermonuclear reactors. Endowed with high energy and electrically charged, they would remain inside the plasma in the tokamak's magnetic field and, in subsequent collisions with deuterium and tritium, would decrease own energy, ultimately increasing the energy of the thermonuclear fuel. This process would reduce the energy costs associated with external heating. The ITER reactor – under construction in Cadarache, France, since 2007, with a budget currently exceeding $20 billion and scheduled to start operating in the middle of the next decade – will not yet use helium nuclei to heat the plasma. Despite this limitation, it is expected to generate up to ten times more energy than it consumes, ultimately reaching a power output of 500 megawatts.

The HRNS spectrometer will be installed behind a thick concrete protective wall surrounding the fusion chamber, near an opening several centimetres in diameter, to be able to detect neutrons produced in the very center of the plasma. Depending on the power of the reactor, their flux will vary dramatically, reaching up to hundreds of millions of particles per square centimetre per second. During the measurement, HRNS will be able to analyze the neutron spectrum from the deuterium-deuterium reaction (neutrons with an energy of 2.5 megaelectronvolts) and from the deuterium-tritium reaction (neutrons with an energy of 14 megaelectronvolts).

In order to ensure the operation of the HRNS spectrometer under the full range of conditions anticipated in the ITER reactor, it had to be divided into four independent sub-assemblies. Each of these is essentially a separate spectrometer, operating on different principles and designed for a different range of neutron flux intensities. Physicists from the IFJ PAN are working on the development of the first subassembly, called TPR (Thin-foil Proton Recoil). Here, neutrons knock protons out of a thin polyethylene foil – and their scattering angles depend on the energies of the neutrons. Nearly 100 silicon detectors are responsible just for the detection of the protons. The second subassembly is the NDD (Neutron Diamond Detector) spectrometer, where neutrons are recorded by an array of over a dozen diamond detectors. The last two subassemblies, FTOF (Forward Time-of-Flight) and BTOF (Backscattering Time-of-Flight), measure the flight times of neutrons and estimate their kinetic energy based on the velocities determined in this way, with FTOF analysing neutrons that maintain a direction of motion similar to the original one, and BTOF analysing those scattered at large angles.

"The HRNS was designed to measure neutrons, but that doesn't mean it won't detect other types of radiation. In practice, many other particles, from gamma-ray photons to particles resulting from neutron interactions with reactor components and even with parts of our spectrometer, will produce a signal in the active part of the detector. All these factors results in the measured spectrum having an exceptionally complex structure. To properly interpret the data and extract reliable information about the amounts of deuterium and tritium, we must thoroughly understand the origin of this rich noise," emphasises Prof. Marek Scholz (IFJ PAN).

Due to limited access to the measuring system during tokamak operation, scientists need to know how to interpret the incoming data. This is especially important if, during the running phase, some of the detectors of one of the subassemblies or even the entire subassembly are damaged. It was also critically important to design shielding elements so that neither the neutron flux nor the parts of the equipment excited by it would interfere with the operation of electronic subsystems or other measuring devices operating in the vicinity of the entire spectrometer.

"The project required a huge amount of numerical calculations, not only those directly related to neutron measurements. For example, a group from our institute was responsible for, amongst others, Monte Carlo calculations that enabled the optimization of the HRNS spectrometer's radiation shielding by demonstrating the transport of neutrons and gamma radiation in the environment and within individual components of the entire system. Equally important was the calculation of the radioactive activity of individual components of the HRNS spectrometer. This knowledge guaran-

tees both the proper functioning of the device and the safety of the personnel operating it," notes Dr. Urszula Wiacek, head of the Department of Radiation Transport Physics at the IFJ PAN.

Scientists expect that a prototype of a high-resolution neutron spectrometer for the ITER fusion reactor will be developed within two years. Work on the device was financed by the Ministry of Science and Higher Education and the ITER Organization.

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SCIENTIFIC PUBLICATIONS:

"Development and performance of the thin-foil proton recoil spectrometer for ITER plasma diagnostics"
J. Dankowski, J. Bielecki, J. Błądek, S. Conroy, B. Coriton, G. Croci, D. Dworaka, G. Ericsson, J. Eriksson, A. Wójcik-Gargula, A. Hjalmarsson, A. Jardin, R. Kantor, A. Kovalev, K. Król, A. Kulińska, A. Kurowski, G. Mariano, R. Mehrara, D. Morawski, M. Rebai, M. Scholz, F. Scioscioli, M. Tardocchi, G. Tracz, M. Turzański, U. Wiącek
Fusion Engineering and Design, 2025, 219, 115263
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LINKS:

http://www.ifj.edu.pl/
The website of the Institute of Nuclear Physics, Polish Academy of Sciences.

http://press.ifj.edu.pl/
Press releases of the Institute of Nuclear Physics, Polish Academy of Sciences.

IMAGES:

IFJ250910b_fot01s.jpg **HR:** http://press.ifj.edu.pl/news/2025/09/10/IFJ250910b_fot01.jpg
Installation of a neutron diagnostics system in the laboratory of the Institute of Nuclear Physics of the Polish Academy of Sciences in Cracow. (Source: IFJ PAN)

IFJ250910b_fot02s.jpg **HR:** http://press.ifj.edu.pl/news/2025/09/10/IFJ250910b_fot02.jpg
The high-resolution neutron spectrometer HRNS. The yellow structural elements surround the TPR system designed at the Institute of Nuclear Physics of the Polish Academy of Sciences in Cracow. The lower part of the image shows the position of the HRNS spectrometer (green) relative to the tokamak's protective wall (red) and its fusion chamber (blue). (Source: IFJ PAN, ITER Organization)