Registrační číslo:

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Základní údaje

Soutěžní obor: **P3913 - Aplikace přírodních věd** Kategorie: **3T**

Navrhovatel: **Kulkov Sergei Ing.** Pracoviště: **FJFI - 14102**

Název česky: **New Diagnostic Methods for Study of Runaway Electrons in Tokamaks**

Název anglicky: **New Diagnostic Methods for Study of Runaway Electrons in Tokamaks**

Anotace česky:

This proposed project concerns study of generation and properties of Runaway Electrons (RE) on the GOLEM tokamak. REs emerge during discharge disruptions, where thermal electrons are accelerated by the induced toroidal electric field in the tokamak. When the intensity of the electric field overcomes the critical Dreicer field limit, electrons can experience acceleration up to nearly the speed of light . In addition, the population of accelerated REs can undergo an exponential growth in an avalanche fashion due to momentum transfer in collisions between relativistic electrons and thermal electrons. In severe cases, the relativistic REs can carry a large fraction of the original pre-disruption plasma electric current. When the RE beam is focused, it could severely damage plasma facing components of the vacuum vessel.

The current understanding of the RE phenomenology is limited, and research into REs is one of the key tasks for existing and future tokamak facilities in support of the operation of the future experiment ITER. Currently, the research of RE phenomenon is ongoing in the EUROfusion consortium of national fusion research laboratories.

In 2021, COMPASS, the largest tokamak in the Czech republic, which is located at IPP ASCR, will be decommissioned and upgraded into a new COMPASS-U machine. It is expected that the upgrade and commissioning process will take three years, and the GOLEM tokamak, located at FNSPE CTU, will be the only operating tokamak able to generate REs in the Czech republic. Therefore, this proposed project represents an opportunity to prepare and test RE detectors and instrumentation, perform measurements and data analyses and assure the continuity of the RE group.

The goal of the proposed project is to develop novel diagnostic techniques for direct and indirect detection of REs and study their emergence and evolution. There are several approaches to the RE measurements: detection of relativistic electrons, secondary X-ray and gamma ray radiation, and photoneutrons. For the direct detection, a silicon strip detector based on a PH32 readout chip developed at FNSPE CTU is envisaged. For the indirect detection system, a soft X-ray detection system based on a Timepix3 ASIC, which is provided by the NIKHEF laboratory in Amsterdam, will be used.

The foreseen hard X-ray diagnostic system will be used as a diagnostic system outside the vessel wall of the tokamak. It will be based on an advanced scintillating material coupled to a silicon photomultiplier (SiPM), which has the advantage of evaluation of local interactions between the REs and the vaccum vessel material. The scintillating detection system consists of CeBr3:Tl and LYSO (Lu1.8Y0.2SiO5:Ce) scintillating crystals covered by an aluminium shield.

Historically, the existing collaboration between the Institute of Plasma Physics of the CAS (IPP Prague) and the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University (FNSPE) has already shown promising results in implementation of the pixelated semiconductor detectors as well as scintillation detectors in the X-ray studies.

The generation of runaway electrons is a complex, nonetheless, an important phenomenon that impacts many areas of plasma physics. Therefore, it is crucial to continue the ongoing research in order to ensure success of the future tokamak facilities.

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Finance

Finanční prostředky v tis. Kč	**2021**	**2022**	**2023**	**celkem**
Neinvestiční náklady (NEI)	682	650	650	1982
Investiční náklady (INV)	0	0	0	0
Celkové náklady	682	650	650	1982

Zdůvodnění přihlášky

1 - Vědecká závažnost a aktuálnost:

Nowadays, nuclear fusion is thought to be a source of energy of tomorrow along with solar, hydro, wind, and fission energy. Although there are several ways to fuse atoms together, only one - thermonuclear fusion - have proven feasible as a viable source of energy. Historically, research in thermonuclear fusion was conducted via two approaches: Inertial Confinement Fusion (ICF) and Magnetic Confinement Fusion (MCF). The latter have shown more success with machines like tokamak and stellarator which led to the preparation of the largest fusion facility yet: the ITER project. While the main goal of ITER tokamak is to show the technical feasibility of MCF, there are still a lot of technical and physical barriers to overcome. In order to control the hot plasma, tokamaks have to work at limits of technology. Therefore, the contained plasma is a subject to a lot of instabilities of different nature. Nonetheless, they all result in worse confinement and therefore worse power outcome. Probably the worst among all instabilities are the ones that lead to a generation of highly energetic electrons called runaway electrons (RE).

Nowadays, it is widely acknowledged that in larger tokamaks, e.g., ITER, REs threaten integrity of the vacuum vessel and may compromise the success of the future machines. Therefore, it is important to study the mechanisms of the RE generation in tokamak plasma, their behavior and characteristics. Furthermore, it is crucial to find methods to suppress their appearance in tokamaks, e.g., massive gas or pellet injection and resonant magnetic perturbations. Currently, research into RE physics is conducted on many tokamaks worldwie with COMPASS, JET, FTU, DIII-D, and TEXTOR among them.

Application of semiconductor detectors is a novel approach in the detection of runaway electrons in tokamaks. Nonetheless, the technology proved itself as reliable and useful as they bring a possibility of both direct and indirect measurements of the particles. Additionally, such detectors have good energy, temporal and spatial resolution, as well as good radiation tolerance. However, their full potential is yet to be realized and a lack of experience with using semiconductor detectors in a tokamak environment still requires further investigation.

2 - Současný stav řešeného problému:

The physics and behaviour of REs in tokamaks is not yet fully understood. While it was found that the worst stage of tokamak operation in terms of RE generation is the so-called disruption - a series of events that eventually lead to a complete loss of plasma control - mitigation strategies are still not completely realized. The main mitigation strategy for ITER was chosen a massive gas or pellet injection which will suppress acceleration of electrons and therefore keep the vacuum vessel undamaged. However, still more time and work is required to study the details of the RE behavior in the tokamak plasma which on itself is a complicated task as the RE diagnostics are quite limited. As the events of RE generation and their interaction with both bulk plasma and tokamak components are rapid, a fast reliable diagnostic is neccessary. Furthermore, the most utilized way of the RE detection is measuring of the secondary X-rays generated by RE interaction mostly with the vacuum vessel. However, these X-rays cover a wide spectrum of energies and there is no such diagnostic that may detect them all. Therefore, detectors for measuring different energies are required. Another complication is high fluxes of both REs and X-rays which often lead to a saturation of the detection systems as the signals are generated more frequently than the system can handle.

Currently, there are a couple of different approaches in the detection of REs under development. Among them are semiconductor detectors for both soft X-ray and direct RE detection, probes for in-vessel RE detection, compact SiPM+scintillator systems for X-ray measurements.

The idea of using semiconductor pixel detectors came from particle physics. However, in fusion research, these detectors found themselves in a harsh environment of high radiation fluxes. Recently, a few experiments on the RE physics utilized semiconductor detectors, specifically ones based on the Timepix3 chip and the PH32 detector. While the results acquired were insightful, a couple of complications became clear that still require further investigation and testing, for instance, saturation of the readout system.

Calorimetry probe is a diagnostic capable of measuring the energy and power of the runaway electron beam striking the plasma facing components of the tokamak. Such probe have been already tested at the COMPASS tokamak which proved viability of the diagnostic for RE measurements. As the RE intensity at the GOLEM tokamak is much lower, the probe will be improved, providing better sensitivity to the temperature fluctuations. Measurements with the calorimetry probe will allow comparative studies of overall RE energy in different tokamaks.

3 - Původnost navrhovaného řešení:

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While SiPM-based detector have already found their use in the plasma diagnostics, such approach was not yet utilized at Czech tokamaks. However, some participants of the team have already tested basic setups of a SiPM+scintillator detectors at the GOLEM tokamak.

Considering the tokamak itself, the machine was recently upgraded with a sophisticated infrastructure. Even though the GOLEM tokamak is considered to be a smaller tokamak, its parameters - mainly high intensity of electric field - are opportune for RE dedicated experiments. While REs were studied at the GOLEM tokamak before, this project is aimed at development of new diagnostic methods for measuring REs in support of future experiments, specifically COMPASS-U.

4 - Koncepce, způsob a metodika řešení:

Experiments on the COMPASS tokamak have demonstrated that the segmented semiconductor detectors are sufficiently performant for RE studies and that the RE experimental programme can continue on the GOLEM tokamak while the COMPASS is undergoing upgrade. The measurements will be performed in dedicated RE campaigns on the GOLEM tokamak. 3 to 4 experimental campaigns are planned each year, each approximately one week long. The significant challenged in RE measurements, such as large required dynamic range of detectors and requirements of timing resolution in the order of nanoseconds, are adressed

by a combination of both direct and indirect measurements by using a combination of SiPM + LYSO/CeBr3 scintillating crystal, a Timepix3-based detector for external X-ray detection and spectral measurements through a beryllium window in the diagnostic port of the tokamak and finally silicon strip detectors for in-vacuo direct detection of RE electrons. The acquired data will be analysed after the campaing and instrumentation upgrades will be devised based on the results. In addition, we expect that other Bc. ans MSc. students will participate on the measurements and perform data analysis. The developed instrumentation will be integrated into the existing system for data acquisition of the GOLEM tokamak. During the campaign, the oscilloscopes and digitizers acquired by the CAAS infrastructure will be utilized.

Calorimetry probe consists of a graphite cylinder with temperature sensors inserted into the tokamak vessel. The impact of runaway electrons heat up the calorimeter and from this temperature increase it is possible to estimate the overall energy of the RE beam. A Langmuir electrostatic probe can also be included in the calorimetry head to obtain the temporal resolution of the RE impact on the surface of the cylinder. Additionally, experimentally acquired data will be supported with numerical simulations of the interactions of REs with the probe material in the Monte Carlo physics simulation code FLUKA.

5 - Cíle řešení projektu:

Understanding the physics of runaway electrons today is quite limited, partially due to the limited spectrum of instrumentation available. Furthermore, the renovated and upgraded COMPASS-U will require compact, reliable, and sophisticated detection systems in order to secure safe and successful operation of the tokamak. The main goal of this project is preparation of a series of detection systems based on semiconductor detectors for both direct and indirect measurements either of RE beams or X-rays generated by REs, on scintillating detectors with scintillators like NaI(Tl), LYSO, and CeBr3:Tl in particular. Additionally, a calorimetry probe, which has been already tested in a tokamak environment for in-vessel measurement of RE energy, still requires improvement for better energy resolution. The phenomenon of REs in tokamaks requires further detailed investigation in order to secure future machines from failure. Therefore, this project aims at providing the tokamak community with detection systems that will help to comprehend physics of REs.

6 - Předpokládané výstupy řešení:

As an outcome of this project, one can expect an X-ray detector based on the Timepix3 chip together with a calibration method for compensating temperature effects on the measured energy spectra and a sophisticated tool for an automated data analysis. Additionally, a series of scintillators coupled to silicon photomultipliers is planned to be prepared for future applications in X-ray imaging and especially as a RE diagnostic for the COMPASS-U tokamak. Also, a calorimetry probe for in-vessel measurements of the RE beam energy will be prepared and modified for better energy resolution. The results of the development, testing, and the analysis of the physics data are expected to be published in relevant journals and topical workshops. For the first year of the project, at least two publications are planned.

7 - Předpokládaná prezentace výsledků:

The team will present the results at the conferences, e.g., EPS (European Physical Society) 2021, which will take place in Sitges, Spain, and IEEE NSS and MIC (IEEE Nuclear Science Symposium and Medical Imaging Conference). Additionally, a series of publications in high-impact scientific journals is planned.

8 - Charakteristika týmu:

The team consists of two academic workers, two Ph.D. students and four Masters students.

The Ph.D. students continue their Diploma theses themes and their work conducted within the SGS project will serve as a part of their Doctoral theses.

The Masters students will continue with their theses.

All the participants have experience with measuring REs in tokamak environments, working with both semiconductor and scintillating detectors. Furthermore, some of the participants have background in particle physics and detector development. As enrollees of FTTF at FNSPE, all students have experience with operating the GOLEM tokamak, preparing the instrumentation setup and tokamak discharges. Furthermore, part of the students have performed similar RE experiments on the COMPASS tokamak at IPP CAS.

Vyjádření školitele

Školitel (je-li navrhovatel studentem): **prom. fyz. Václav Vrba, CSc.**

Slovní vyjádření:

Vyjádření vedoucího pracoviště

Vedoucí pracoviště:

- Soulad řešeného projektu s celkovou koncepcí a zaměřením pracoviště:
- Zajištění podmínek pro řešení projektu na pracovišti:
- Vyjádření k řešitelskému týmu:

Případné slovní vyjádření:

Vyjádření děkana (ředitele ústavu)

Děkan (ředitel ústavu):

- Soulad projektu se záměry fakulty - součásti:
- Finanční podpora projektu:

Případné slovní vyjádření: