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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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.

Řešitelský tým v roce 2023

Jméno	**Zařazení**	**Studijní obor**	**Pracoviště**	**Stipendium - odměna**
Kulkov Sergei Ing.	doktorand	3901V016	14102	32
Marčišovský Michal Ing. Ph.D.	vědecký či odborný pracovník		14102	2
Linhart Vladimír Ing. Ph.D.	výzkumný a vývojový pracovník		14116	5
Čaloud Jakub Mgr.	doktorand	3901V016	14102	30
Malec Štěpán Ing.	student mag. programu	3901T062	FJFI	25
Svoboda Vojtěch Ing. CSc.	odborný asistent		14102	2
Ivanov Vladislav MSc.	doktorand		14102	30
Tunkl Marek Ing.	doktorand		14102	30
Lobko Lukáš Ing.	doktorand		14102	30
Malec Štěpán Ing.	doktorand	3901V016	14102	0
Celkem stipendia:				225
Celkem mzdové náklady:				9

Charakteristiky členů týmu

Jméno: Kulkov Sergei Ing.

Bachelor's thesis: Relativistic transparency of solid targets for contrast enhancement of ultra-intense laser pulses. Defended: 07.2018
Research project: Runaway electrons and their detection using segmented silicon detectors
Master's thesis: Runaway electrons in tokamaks and their detection using segmented silicon detectors. Defended: 09.2020

As a fresh doctoral student (first year of PhD), Ing. Sergei Kulkov has started experimental work on novel diagnostic techniques which will be a part of his doctoral thesis. While the main goal of the Master's thesis was testing of a detector based on the Timepix3 chip, outcome of which was successful, the Doctoral thesis will continue the preparation of a semiconductor-based detectors for RE studies. Furthermore, testing of novel scintillating materials is also planned as a part of the doctoral thesis. Both approaches are planned to be applied at the GOLEM tokamak. In the next two years starting from the 2020 academic year, exams in the following subjects are planned (the codes are used for brevity):
D02FRT, D02FVT, D02VKFP, D02FFR
The defence of the doctoral thesis is planned in the summer/autumn of 2024.

During his Master's degree studies, Ing. Sergei Kulkov have participated in the EPS 2019 conference where the student represented the results of students research at the GOLEM tokamak which was conducted for the whole academic year. Additionally, the student have led a group that realized measurements with semiconductor detectors, which were conducted in a collaboration with Nikhef and CERN, during a RE-dedicated experimental campaign at the COMPASS tokamak in February 2020 and November 2020.

The proposed scholarship is based on the complete dedication to the project, as it is planned as the main source of data for the planned doctoral thesis, along with participation in all of the project branches, mainly testing the X-ray detector based on the Timepix3 chip together with data analysis from the detection systems.

Publications:

[1] S. Kulkov, P. Macha, V. Istokskaia, D. Kropackova, F. Papousek, J. Adamek,J. Cerovsky, O. Ficker, O. Grover, K. Jirakova, J. Stockel, V. Svoboda "Tokamak GOLEM for fusion education - chapter 10", http://ocs.ciemat.es/EPS2019PAP/pdf/P1.1068.pdf

[2] L. Novotny, J. Cerovsky, P. Dhyani, O. Ficker, M. Havranek, M. Hejtmanek, Z. Janoska, V. Kafka, S. Kulkov, M. Marcisovska, M. Marcisovsky, G. Neue, P. Svihra, V. Svoboda, L. Tomasek, M. Tunkl and V. Vrba, "Runaway electron diagnostics using silicon strip detector", https://doi.org/10.1088/1748-0221/15/07/C07015

[3] M. Tunkl, D. Bren, J. Cerovsky, P. Dhyani, M. Farnik, O. Ficker, M. Havranek, M. Hejtmanek, Z. Janoska, V. Kafka, S. Kulkov, M. Marcisovska, M. Marcisovsky, J. Mlynar, G. Neue, L. Novotny, P. Svihra, V. Svoboda, L. Tomasek, V. Vrba, "The direct detection of runaway electrons using the semiconductor stripdetector", http://ocs.ciemat.es/EPS2019PAP/pdf/P4.1010.pdf

Jméno: Marčišovský Michal Ing. Ph.D.

H index 98 (WoS)

Co-investigator of GACR 18-02482S

Scientific director of the centre of advanced detection systems at FNSPE CTU

Member of a research team: LM2015058 - Research Infrastructure for Experiments at CERN (2016-2017, MSM/LM).

TE01020069 - "Advanced Detection Systems of ionizing radiation" (2012-2019, TA0/TE) - head of a research team, leader of a group for research and development of communication SW interface, design of system architecture for control and data collection, design, simulation and testing of detectors, study of radiation hardness of sensors and readout electronics.

Lead physicist in the project TH04010294 "Radiation orbital monitor based on the Spacepix sensor" (2019-2022) - preparation of the detection system concept.

Head of a research team in the project FV30073 "Monolithic pixel detector for the detection of ionizing radiation" (2018-2020) - verification of system parameters, analysis and interpretation of experimental data.

Lead physicist in the project FV30018 "Lightweight Orbital Radiation Detection System" (2018-2020) - global strategy of detection system design, evaluation of detection parameters.

Diploma thesis: Monte Carlo simulation of Calorimeters for Future Particle Physics Experiments

Dissertation: A study of the bb production mechanisms with the ATLAS experiment.

According to the Web of Science, Dr. Marcisovsky has more than 870 publications with total number of citations over 38000.

In November 2020, Ing. Michal Marcisovsky, Ph.D. was approved as a supervisor for Ph.D. students at FNSPE, CVUT. Therefore, Dr. Marcisovsky will act as a supervisor of the student-proposer Ing. Sergei Kulkov.

Jméno: Linhart Vladimír Ing. Ph.D.

2014 -: Researcher at KDAIZ, FNSPE

Main research topic: development and applications of ionizing radiation detectors. At FNSPE, Dr. Linhart designs and constructs detection systems and develops software for the instrumentation. Got a Ph.D. at FNSPE, then worked as a researcher at Laboratoire de l'Accélérateur Linéaire CNRS, France, and Instituto de Fisica Corpuscular, Spain. According to the Web of Science, Dr. Linhart is a co-author of 58 publications with more than 4000 citations (excluding self-citations) and H-index of 16.

Jméno: Čaloud Jakub Mgr.

Master's thesis: Study of energy of runaway electrons in tokamaks
Doctoral thesis: Study of runaway electrons

As a fresh doctoral student of FTTF at FNSPE, Ing. Jakub Caloud have chosen exams in following subjects (the codes are used for brevity):
D02FRT, D02FVT, D02VKFP, D02FFR
The defence of the doctoral thesis is planned in the summer/autumn of 2024.

The main Jakub's goal in the project is preparation of a calorimetry probe for in-vessel direct measurements of RE energy. The probe has been already tested at the COMPASS tokamak with a successful outcome. However, at the GOLEM tokamak, intensity of the REs is much lower. Therefore, the probe will be modified in order to enhance sensitivity to temperature fluctuations.

The proposed scholarship is based on the ambitious goal of preparing a calorimetry probe which has been already tested in a tokamak environment and will be modified for future experiments. As there are not many ways to directly measure the REs characteristics, especially energy, and the unprecedented utility of such instrumentation makes it highly beneficial for the study of REs.

Jméno: Malec Štěpán Ing.

Bachelor's thesis: Characterization of X-rays produced by runaway electrons on GOLEM tokamak
Masters thesis: Pixel detectors for detection of hard X rays produced on tokamak GOLEM by run-away electrons

Stepan Malec will prepair a readout system for the detector based on the Timepix3 chip which will utilize Raspberry Pi and will be operated via software written in Python. It was shown, that the energetic spectra measured with the detector are dependent on temperature, it is required to compensate this effect via some sort of a stabilization. Furthermore, a calibration method will be prepared for the Timepix3-based and similar semiconductor detectors. If the proposed system will prove functional, a Compton camera based on a series of Timepix3-based detectors will be constructed and tested at the GOLEM tokamak. The complete system will be further used as a routine diagnostic at the tokamak and may be applied in other machines. Additionally, the student will participate in the experiments and analyse data from the detectors.

The proposed scholarship is based on the dedication of the student to the project along with ambitious goals to prepare a calibration technique for Timepix3-based and similar semiconductor detectors and preparation of a sophisticated system capable of carring a series of semiconductor detectors.

Jméno: Svoboda Vojtěch Ing. CSc.

1991 -: Teaching in the basic course of physics: Physics practice at KF FNSPE CTU.
1998 -: Physics seminar (http://fyzsem.fjfi.cvut.cz).
2005 -: Guarantor of a new specialization Physics and Technology of Thermonuclear Fusion at FNSPE CTU (http://fttf.fjfi.cvut.cz).
2006 -: Reinstallation of the GOLEM tokamak as a European educational center for experimental teaching in the field of thermonuclear fusion at the FNSPE CTU.
1993 -: Research activity in cooperation with the Institute of Plasma Physics of the ASCR (recent projects):
1999-2009: Numerical modeling of anomalous diffusion of plasma particles in time-varying electromagnetic fields.
2007-2009: Processing of neutron data from the JET tokamak by the method of inverse analysis (deconvolution of spectra and tomography of the spatial distribution of sources).

Grant activity of recent years:
2005-2007: GAAV, co-investigator: IAA100430502 Influence of turbulence in tokamak edge plasma on particle transport.
2004 -: Development project of the Ministry of Education, Youth and Sports: University of the Third Age at the FNSPE CTU (course Physics friendly http://fyzu3v.fjfi.cvut.cz and Computers for the elderly and advanced http://pcu3v.fjfi.cvut.cz).
2007 -: Member of VZ MŠMT MSM6840770039: Mathematical, computer and experimental methods in physics.
2004 - 2009: Development project of the Ministry of Education, Youth and Sports: Modern information technologies in teaching.
2006 -: Development project of the Ministry of Education, Youth and Sports to support the development and innovation of study programs: Preparation of a new study focus at the FNSPE Physics and Technology of Thermonuclear Fusion ".
2008 -: FUSENET - (European Fusion Education Network), within the EURATOM Coordination and Support Activity (CSA) for fusion education in Europe.
2009: FRVŠ - Methodological Center for Thermonuclear Fusion.
2010 - 2012: The GOLEM tokamak (additional grant under FUSENET).

Publications:
[1] Markovič, T.; Gryaznevich, M.; Ďuran, I.; Svoboda, V.; Vondrášek, G. Evaluation of applicability of 2D iron core model for two-limb configuration of GOLEM tokamak; Fusion Engineering and Design. 2013, 88 835-838. ISSN 0920-3796. Available from: http://www.sciencedirect.com/science/article/pii/S0920379613002573
[2] Svoboda, V.; Kocman, J.; Grover, O.; Krbec, J.; Stöckel, J. Remote operation of the vertical plasma stabilization @ the GOLEM tokamak for the plasma physics education; Fusion Engineering and Design. 2015, 96-97 974-979. ISSN 0920-3796. Available from: http://www.sciencedirect.com/science/article/pii/S0920379615300740
[3] Svoboda, V.; Gryaznevich, M.; Oost, G.; Stöckel, J.; Kamendje, R.; Kuteev, BN; Melnikov, A.; Popov, T. Contribution to fusion research from IAEA coordinated research projects and joint experiments; Nuclear Fusion. 2015, 55(10), ISSN 0029-5515. Available from: http://iopscience.iop.org/article/10.1088/0029-5515/55/10/104019
[4] Svoboda, V.; Markovič, T.; Gryaznevich, M.; Duran, I.; Panek, R. Development of 3D ferromagnetic model of tokamak core with strong toroidal asymmetry; Fusion Engineering and Design. 2015, 96-97 302-305. ISSN 0920-3796. Available from: http://www.sciencedirect.com/science/article/pii/S0920379615002100

[5] Svoboda, V.; Gryaznevich, M.; Oost, G.; Stöckel, J.; Kamendje, R.; Kuteev, BN; Melnikov, A.; Popov, T.
Contribution to fusion research from IAEA coordinated research projects and joint experiments
Nuclear Fusion. 2015, 55(10), ISSN 0029-5515.
[6] Svoboda, V.; Markovič, T.; Gryaznevich, M.; Duran, I.; Panek, R.
Development of 3D ferromagnetic model of tokamak core with strong toroidal asymmetry
Fusion Engineering and Design. 2015, 96-97 302-305. ISSN 0920-3796.
[7] Svoboda, V.; Dvornova, A.; Dejarnac, R.; Prochazka, M. et al.
Remote operation of the GOLEM tokamak with hydrogen and helium plasmas
In: Journal of Physics: Conference Series. Bristol: IOP Publishing Ltd, 2016. Journal of Physics: Conference Series. vol. 768. ISSN 1742-6588.

Jméno: Ivanov Vladislav MSc.

Vladislav Ivanov, MSc., has joined FNSPE CTU in 2021 via a joint Ph.D. program in fusion physics proposed by FNSPE CTU and Universitait Gent in Belgium. At FNSPE, Vladislav has chosen the following courses: D02FFR Physics of Fusion Reactors, D02FRT Fusion Reactor Technology, D02FVT Research on TOKAMAKS, D02PPFT Advanced Laboratory Courses in TOKAMAK Physics and Technology, and D04AJM
English Language (Intermediate) -- the final exams are planned from the first three courses. His chosen topic for the doctoral thesis is: "The study of diagnostics and physics of runaway electrons in GOLEM tokamak". During his Master's study at Ioffe Institute, Russia, he participated in the IPP Summer University for Plasma Physics 2019 in Munich, Germany, and SUMTRAIC 2017 in Prague, Czech Republic winter/summer schools. Vladislav also has experience with grant projects, namely RSF 17-12-01110 "Self-organisation of the multi-scale turbulence and mechanisms of the isotope effect in a tokamak plasma confinement", RFBR 16-02-00580 "The diagnostic of the radial plasma velocity fluctuations and investigation of the turbulent particle flux in a tokamak".
As a part of our team, Vladislav will be developing a mathematical model of an ECE (electron cyclotron emission) diagnostic for the GOLEM tokamak, recovering and repairing the broken channels of the ECE radiometer from the COMPASS tokamak for a further installation of the diagnostic at GOLEM. Additionally, the development of a calibration procedure for the ECE radiometer is planned.
Vladislav Ivanov, MSc., is a co-author of the following publications:
"Comparative lower hybrid ion heating experiments in hydrogen and deuterium high-density plasma at FT-2 tokamak" // 46th EPS Conference on Plasma Physics P4.1080,
EPS 2019; Milan, Italy; 8-12 July 2019
"Local measurements of the radial plasma velocity fluctuations in the FT-2 tokamak core plasmas by equatorial enhanced scattering" // 46th EPS Conference on Plasma Physics P1.1006, EPS 2019; Milan, Italy; 8-12 July 2019
"Particle confinement isotope effect in FT-2 tokamak" // 44th EPS Conference on Plasma Physics P1.159, EPS 2017; Belfast, UK; 26-30 June 2017

Jméno: Tunkl Marek Ing.

Bachelor's thesis: Application of segmented semiconductor detectors for runaway electron diagnostics. Defended July 2020.
Master's thesis: Application of segmented semiconductor detectors for runaway electron diagnostics. Defended May 2022.

Marek Tunkl will primarily work on the scintillator-based and semiconductor detectors. His work on the

project will be above else described in his Master's thesis. Additionally, the student will participate in preparation of the
experiments, diagnostics setup, and data analysis.

The proposed scholarship is based on the number of activities the student will participate in, specifically the preparation of new detection systems based on a scintillator coupled to a silicon photomultiplier. Additionally, Marek will conduct data analysis which will serve as material for the Master's thesis.

Publications:
[1] M. Tunkl, D. Bren, J. Cerovsky, P. Dhyani, M. Farnik, O. Ficker, M. Havranek, M. Hejtmanek, Z. Janoska, V. Kafka, S. Kulkov, M. Marcisovska, M. Marcisovsky, J. Mlynar, G. Neue, L. Novotny, P. Svihra, V. Svoboda, L. Tomasek, V. Vrba, "The direct detection of runaway electrons using the semiconductor stripdetector", http://ocs.ciemat.es/EPS2019PAP/pdf/P4.1010.pdf
[2] L. Novotny, J. Cerovsky, P. Dhyani, O. Ficker, M. Havranek, M. Hejtmanek, Z. Janoska, V. Kafka, S. Kulkov, M. Marcisovska, M. Marcisovsky, G. Neue, P. Svihra, V. Svoboda, L. Tomasek, M. Tunkl and V. Vrba, "Runaway electron diagnostics using silicon strip detector", https://doi.org/10.1088/1748-0221/15/07/C07015

Jméno: Lobko Lukáš Ing.

Bachelor's thesis: Measurement of neutrons on the COMPASS tokamak
Research project: Influence of energy of neutrons, source geometry and background hard-X-rays on the neutron flux measurements at tokamaks
Master's thesis: Statistical analysis of measurements of fusion neutrons and photo-neutrons at the COMPASS tokamak

Lukas Lobko primarily works on measurements of neutrons at the COMPASS tokamak. Nonetheless, in his measurements he utilizes detectors based on NaI(Tl) scintillators which besides neutrons also detect HXR incoming from the tokamak. Therefore, Lukas will work mainly with and analyze data from scintillator-based detectors.

The proposed scholarship is based on although a well-tested approach to the measurements of the RE-generated X-rays, nonetheless, arguably the most utilized technique.

Jméno: Malec Štěpán Ing.

Bachelor's thesis: Characterization of X-rays produced by runaway electrons on GOLEM tokamak
Masters thesis: Pixel detectors for detection of hard X rays produced on tokamak GOLEM by run-away electrons

Stepan Malec will prepair a readout system for the detector based on the Timepix3 chip which will utilize Raspberry Pi and will be operated via software written in Python. It was shown, that the energetic spectra measured with the detector are dependent on temperature, it is required to compensate this effect via some sort of a stabilization. Furthermore, a calibration method will be prepared for the Timepix3-based and similar semiconductor detectors. If the proposed system will prove functional, a Compton camera based on a series of Timepix3-based detectors will be constructed and tested at the GOLEM tokamak. The complete system will be further used as a routine diagnostic at the tokamak and may be applied in other machines. Additionally, the student will participate in the experiments and analyse data from the detectors.

In his PhD studies, Stepan continues on implementing the Compton camera based on the Timepix3 semiconductor detectors on the GOLEM tokamak for runaway electron measurements.

The proposed scholarship is based on the dedication of the student to the project along with ambitious goals to prepare a calibration technique for Timepix3-based and similar semiconductor detectors and preparation of a sophisticated system capable of carring a series of semiconductor detectors.

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

Finanční položky pro rok 2023 podrobně

Položka: **1. věcné náklady**
Částka: **63 tisíc Kč**

Položka: **1.1. drobný hmotný a nehmotný majetek a materiál**
Částka: **20 tisíc Kč**

Specialized literature, material for 3D printing, e.g., plastic holders for the detectors and scintillators, electrical components for interfacing of instrumentation, development of a custom printed circuit boards. Components for upgrade of the calorimetric probe, PH32 strip detector and the Compton camera.

Položka: **1.2. práce, služby, poplatky**
Částka: **0 tisíc Kč**

Položka: **1.3. jízdní a pobytové výdaje**
Částka: **43 tisíc Kč**

Students will present their results at the upcoming EPS 2023 conference. The requested financing will cover the registration fee and travel costs.

Položka: **2. osobní náklady**
Částka: **190 tisíc Kč**

Položka: **2.1. stipendia studentů**
Částka: **177 tisíc Kč**

Položka: **2.2. mzdové prostředky zaměstnanců**
Částka: **9 tisíc Kč**

Položka: **2.3. dohody o pracovní činnosti (DPČ)**
Částka: **0 tisíc Kč**

Položka: **2.4. dohody o provedení práce (DPP)**
Částka: **0 tisíc Kč**

Položka: **2.5. odvody ze mzdových prostředků a DPČ**
Částka: **4 tisíc Kč**

Položka: **3. režijní náklady**
Částka: **51 tisíc Kč**

20% of the final financing requested.

Položka: **4. investiční náklady**
Částka: **0 tisíc Kč**

Položka: **celkové náklady**
Částka: **304 tisíc Kč**

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:

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. Through the course of the last two years, detector based on the Timepix3 chip was used in a series of RE dedicated experimental campaigns at the COMPASS and GOLEM tokamaks.

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.

9 - Upřesnění cílů pro druhý rok řešení:

During the first year of this project, CeBr3:Tl and LYSO scintillation detectors were successfully integrated into the tokamak system, which allows them to run automatically. All of the necessary components for the calorimetric probe were acquired. However, it is still necessary to implement them and test the probe at the tokamak. The strip detector PH32 underwent some adaptations for the GOLEM tokamak and also requires more experiments to test the detector. For one of the Timepix3-based detectors, software for automated data acquisition and analysis was prepared and successfully tested at the tokamak. However, the detector was damaged and has been sent to Nikhef, Amsterdam for repair. While Timepix3 was successfully tested at the COMPASS tokamak, it is still necessary to test the detector at GOLEM. Our new teammate Vladislav Ivanov plans to adapt the ECE (electron cyclotron emission) radiometer from the COMPASS tokamak for GOLEM, which will require repairing the broken channels of the diagnostic, as well as geometric adaptations for the smaller tokamak. The GOLEM tokamak also underwent major improvements in its infrastructure. Additionally, vacuum components and adapters for tomography measurements using fast cameras were acquired. To summarize, most of the necessary preparations of the diagnostics are done and the team plans to continue testing their technology during the second year of the project.

10 - Upřesnění cílů pro třetí rok řešení:

During the second year of the project, a couple of milestones were achieved. The Compton camera with a single Timepix3 sensor showed promising results. The two-sensor camera, however, still requires attention as the calibration of the camera has shown some issues. Bc. Štěpán Malec plans to defend his Master's thesis in January-February 2023 and after that, he will continue working and improving the Compton camera. The silicon strip detector PH32 was recalibrated and refurbished with a new data acquisition system for faster and more reliable operation. The recalibrated detector is yet to be tested in the tokamak plasma. The calorimetric probe was unsuccessful in measuring the energy of runaway electrons at the tokamak due to the insufficient sensitivity of the sensors. In support of a new design, Mgr. Jakub Čaloud prepared COMSOL simulations to adapt the probe for the GOLEM tokamak. The new version of the probe will be prepared and tested in the following year. The electron cyclotron emission (ECE) radiometer, that Vladislav Ivanov, MSc, works on was successfully tested at the tokamak. The student also did a set of simulations to describe the ECE at the GOLEM tokamak. However, the results do not agree with the experiments due to the abundance of non-thermal electrons in the tokamak plasma. In the following year, the model will be improved. Additionally, the radiometer data acquisition and analysis will be automated. One of the students, Ing. Lukáš Lobko, returns to the project after defending his Master's thesis. He will rejoin the team where he will work mainly with the scintillating detectors.

Vyjádření školitele

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

Slovní vyjádření:

Téma projektu je vysoce aktuální, nové detekční metody mohou poskytnout experimentální data ke studiu vzniku, evoluce svazku ubíhajících elektronů (RE) a případně k jeho potlačení. Použitá kombinace rychlých scintilátorů s křemíkovými fotonásobiči a křemíkový pixelový detektor s vyčítacím čipem Timepix3 disponují řadou výhod, oproti existujícím detekčním a diagnostickým metodám.

Výhody zvoleného pixelového detektoru spočívají primárně ve vysoké účinnosti detekce měkkých rentgenových fotonů v křemíku, vysokém prostorovém rozlišení daném jemnou granularitou pixelového senzoru, schopnosti měřit energie jednotlivých detekovaných fotonů a zejména možnosti měřit dobu příletu jednotlivých částic s rozlišením lepším než 5 ns. Na druhou stranu vyvíjené scintilační detektory na bázi krystalů LYSO a CeBr3 s vysokou účinností konverze signálu na světlo a krátkou dobou dosvitu předčí svými schopnostmi používané detektory na bázi NaI:Tl, což umožní studovat strukturu a časový vývoj populace RE. Pro realizaci měření byla zahájena spolupráce s laboratoří NIKHEF, kde byl zapůjčen vlastní detektor na bázi Timepix3 s 200 mikronovým Si senzorem a vyčítacím systémem SPIDR, který umožňuje zpracovat až 80 Mhits/s, což v současnosti není možné dosáhnout žádným jiným dostupným vyčítacím systémem. Tyto parametry jsou nutné z důvodu saturace vyčítacího systému při intenzivní produkci RE ve výbojích, jak bylo zjištěno při předchozích měřeních. Mimo nepřímou detekci projekt předpokládá využití radiačně odolných křemíkových stripových detektorů pro in-vacuo přímou detekci RE.

Celkově má, dle mého názoru, řešitelský tým rozsáhlé zkušenosti z provozu detekční instrumentace a analýzy experimentálních dat na tokamacích COMPASS (ÚFP AVČR) a GOLEM a je plně kompetentní řešit předložený projekt. Navrhovatel projektu se aktivně zapojil do vývoje detekčních systémů v detektorovém centru na FJFI, pracoval samostatně a efektivně řešil problémy fyzikálního, technického a softwarového rázu. Věřím, že Sergei má před sebou slibnou kariéru v oboru termojaderné fúze a že

tento projekt mu umožní start.

Vyjádření vedoucího pracoviště

Vedoucí pracoviště: **doc. Ing. Martin Štefaňák, Ph.D.**

- Soulad řešeného projektu s celkovou koncepcí a zaměřením pracoviště: **ano**
- Zajištění podmínek pro řešení projektu na pracovišti: **v plném rozsahu**
- Vyjádření k řešitelskému týmu: **schopen projekt úspěšně řešit**

Případné slovní vyjádření:

Projekt cílí na diagnostiku ubíhajících elektronů v tokamacích. Jedná se o důležité a aktuální téma v oblasti fyziky plazmatu, na kterém se podílí i výzkum na tokamaku Golem na KF FJFI ČVUT v Praze. Navrhovaný projekt je tedy v plném souladu s dlouhodobou koncepcí katedry. Projekt využije existující infrastrukturu tokamaku Golem a detektorového centra na KF. Řešitelský tým má dostatek zkušeností s výzkumem toho typu, jak na tokamaku Golem tak i na tokamaku Compass z ÚFP AVČR. Lze tedy očekávat, že cíle projektu budou splněny. Projekt má moji plnou podporu.

Vyjádření děkana (ředitele ústavu)

Děkan (ředitel ústavu): **prof. Ing. Igor Jex, DrSc.**

- Soulad projektu se záměry fakulty - součásti: **ano**
- Finanční podpora projektu: **ano (v plném rozsahu, projekt podpořit)**

Případné slovní vyjádření:

Doporučuji