Závěrečná zpráva

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

Řešitel: **Kulkov Sergei Ing.**

Informace o řešení projektu a dosažených výsledcích - rok 2023

Způsob a metody řešení, časový průběh řešení:

A novel method characterizes runaway electrons (RE) at COMPASS tokamak. The RE beam, generated during collisions with plasma-facing components, produces photoneutrons, which can be measured using 3He proportional chambers and the NuDET scintillation detector. A new technique successfully separates neutron and hard X-ray (HXR) peaks, utilizing Fourier spectral decomposition and a 100 kHz lowpass filter, and is more straightforward and accurate than conventional techniques. A comprehensive RE study requires information about key plasma characteristics, such as electron plasma density measured at GOLEM tokamak's interferometric diagnostics. Hardware upgrades and code enhancements now ensure reliable temporal evolution of electron plasma density.

The strip detector has undergone calibration and testing, integrating seamlessly into the RE diagnostic setup at the GOLEM tokamak. It now boasts fully automated data acquisition and analysis capabilities. Several methods aimed at enhancing the light yield of LYSO have been explored, encompassing tests on crystal wrapping materials and various optical coupling techniques. Additionally, three scintillating detectors with LYSO have been successfully produced. A GOLEM tokamak model, implemented in the Geant4 Monte Carlo toolkit, serves various purposes, including refining the analysis of strip detector results, providing detector response functions for HXR detectors, and aiding in the development of data processing methods for the Compton camera.

The energy deposition of REs on the calorimetry probe was modeled using the Monte-Carlo code FLUKA, simulating interactions of high-energy particles with solid matter. The energy distribution of REs in the GOLEM tokamak was estimated from HXR detectors. This information was then imported into the finite element analysis software ANSYS, where the temperature change was simulated. This workflow was also employed for predictive and interpretive simulations of RE impact on plasma-facing components in other tokamaks, including COMPASS, COMPASS-U, and JT-60SA.

The electron cyclotron emission (ECE) radiometer was relocated from IPP's COMPASS tokamak to FNSPE's GOLEM tokamak where it is currently installed. A noise generator with a coupler was incorporated, allowing calibration switching between the antenna and the noise source during a vacuum discharge. Due to low plasma density and temperature at GOLEM, the classical data processing approach was not applicable. Consequently, a model of thin plasma radiation was developed.

It was observed that the semiconductor pixel detectors with the Timepix3 chip heat up during measurements. Tests with the radiation standard 241Am at different temperatures (-20 °C to 45 °C) revealed the chip's temperature dramatic impact on energy spectra quality. Water cooling equipment CW-5200 was installed for detector cooling, with water hoses ensuring temperature stabilization throughout the Golem tokamak laboratory. Software for automated data acquisition for Timepix3-based detectors was enhanced, enabling measurements with multiple detectors controlled by a single computer via USB 3 optical cables. The raw data analysis approach was revised, allowing for obtaining energy spectra even in cases of high ionizing radiation flux, where the original method failed. This improvement is expected to enhance the Compton camera image quality, as demonstrated in measurements with 131I samples. The streamlined data analysis software now allows analyzing data from the Timepix3-based detector between Golem tokamak discharges without delaying other diagnostics.

Zhodnocení dosažených výsledků a jejich porovnání s cíli uvedenými v grantové přihlášce:

The main goal of the project was to investigate possible additions to the already existing spectrum of detection systems for both direct and indirect detection of runaway electrons in tokamaks. As the author of the project, I consider this goal achieved as numerous systems with different approaches were tested at the GOLEM tokamak (and some at the COMPASS tokamak, too), from scintillation and semiconductor detectors to radiation and direct RE impact measurements. Additionally, given that this project was conducted under SGS, the primary goal of the project - even if it wasn't mentioned in the goals during submission - was to provide a possibility for students to test their ideas and approaches on a real functional tokamak, even if it is a smaller and older generation machine. Finally, the project was a great introduction for the whole team to the world of grant projects, offering valuable learning experiences in both leadership and participation.

While L. Lobko's and V. Ivanov's ideas were not directly mentioned at the start of the project, their contributions were beneficial for the whole project and mainly for GOLEM's RE diagnostics. The addition of neutron diagnostics as well as a NuDET scintillation detector coupled with a bandpass filter for distinguishing between neutron and HXR peaks is also beneficial for other diagnostics that measure photoneutrons and HXR signals, namely the Timepix3-based detectors, for cross-comparison of the signals. The electron cyclotron emission (ECE) radiometer was successfully implemented at the GOLEM tokamak where it is now a part of the automatic data acquisition system. The mathematical model of thin plasma cyclotron radiation was developed, and it allowed making measurements of runaway energy distribution by ECE.

The strip and LYSO scintillation detectors mentioned in the grant application have been successfully integrated into the GOLEM RE diagnostics with fully automated data acquisition and analysis. Additionally, the tokamak Geant4 model could be beneficial for other GOLEM diagnostics.

As a part of the project, a prototype of a calorimetry probe for measuring heat loads by runaway electrons on plasma-facing components was developed and tested, however, no heat loads were measured due to the small total energy of the RE beams in the GOLEM tokamak. The interactions of RE with the probe head were modeled by FLUKA simulations, from these simulations, it was found that the energy is deposited in less than 0.5 mm depth of the graphite probe and that approximately 80 % of the electron energy is converted into heat (up to (253.7 +/- 0.1) keV from the maximum RE energy of 300 keV), while the rest is radiated in the form of X-ray radiation or scattered away. The probe head with sufficient sensitivity for measurable temperature change would need to have 80 - 90 % smaller volume. Additionally, the calorimetry probe measurements have been successful at the COMPASS tokamak, resulting in numerous publications.

Timepix3-based semiconductor pixel detectors appear to be a good tool for detecting HXR in the Golem tokamak environment. Results were also obtained from a Compton camera created from a Timepix3-based detector. A single-sensor Compton camera produced promising results, displaying regions of tokamak with the highest HXR production. The two-sensor camera didn't produce such good results. The problem is the mechanical construction of the camera itself, as it is difficult to place 2 sensors exactly above each other.

This is mainly due to the slightly different sizes of the sensors and the slight deviation in the attachment of the individual sensors on the modules. Despite these issues, the full potential of the two-sensor Compton camera has not yet been realized, with the primary focus currently on the single-sensor Compton camera.

Výstupy řešení pro prezentaci, k využití v praxi apod.:

Some of the results were published and presented at different conferences, mainly the European Physical Society (EPS) conference and the FuseNet Ph.D. event. Additionally, students' work was a part of their Master's or Doctoral theses, and all students who started as Master's students successfully defended their theses and then continued as Ph.D. students both at FNSPE and as a part of the project's team. Some of the codes used for data analysis are publicly available on the git repository services (GitHub).

A note on the list of publications for the final year of the project (2023): while publications are shown on the project's SGS website, the information is not complete as the conference proceedings have not been published, yet. Once they become publicly available, those publications will be updated in the V3S system.

Perspektiva a účelnost pokračování řešení problematiky projektu:

In general, the emergence of runaway electrons (RE) in tokamak plasma remains one of the biggest problems magnetic confinement fusion faces and it is considered one of the worst scenarios for large fusion devices (i.e. ITER) that can damage the vacuum vessel and sabotage the whole machine. On top of that, the physics of REs is far from being fully understood and the best way to change that is to use as many detection systems as possible.

Measurements and modeling of RE heat loads at present tokamaks can provide important insight into the termination of RE beams and their possible mitigation at future large tokamaks. Calorimetry probes are probably the best way to do that today, providing a relatively cheap and reliable way for direct measurements.

Measurements of the electron cyclotron emission yield RE energy distribution which is extremely useful for understanding of RE physics and their characterization.

Experience of working with Timepix3-based detector is especially beneficial today as Timepix4 chips that have 100 times better timing resolution become widely available today. Newer chips have similar architecture implying similar data acquisition. Therefore, data analysis methods that were developed for the Timepix3 detectors as part of this project potentially could be applied to newer generation chips as well.

Informace o problémech vzniklých v průběhu řešení a stručné shrnutí změn:

Two channels of the PH32 strip detector experienced malfunctions, likely attributed to the harsh environment within the tokamak vessel. Despite this issue not significantly impacting the detector's resolution, a decision was made to deactivate the affected channels rather than undergo the extensive process of replacing the entire setup. In certain tokamak discharges, the production of runaway electrons (RE) in substantial numbers led to the saturation of the built-in preamplifier in the SiPM modules of the LYSO scintillation detectors. While reducing the gain of the amplifier partially addressed this problem, it came at the cost of decreased sensitivity to lower energies at the start of the discharge. To address this trade-off, it was determined to measure with two detectors having different gains.

The sensitivity of the calorimetry probe prototype was deemed insufficient for measuring deposited RE energy, primarily due to the relatively small energy carried by runaway electrons in the GOLEM plasma. The fraction of energy deposited by runaway electrons into the probe, along with the limits for probe dimensions, were identified using numerical modeling.

To facilitate the comparison of Electron Cyclotron Emission (ECE) and Hard X-ray (HXR) measurements, the scintillation detectors were relocated 2 meters away from the tokamak to prevent scale distortion caused by high radiation intensity in the chosen plasma scenario.

The use of long USB 3 cables (5 meters or more) resulted in unreliable data transfer from Timepix3-based detectors to the measuring PC. This issue was resolved by replacing conventional USB 3 cables with optical USB 3 cables.

The Timepix3-based detector with SPIDR readout, provided by the Nikhef laboratory in Amsterdam, suffered damage during the first year of the project. The damaged detector was sent back to the laboratory for repairs. Unfortunately, after an extensive repair and testing process, the Nikhef team reported high dark current rates, indicating irreparable sensor-to-chip bonding issues. As a result, the detector has not returned to Prague.

Publikace a další výsledky navázané ve VVVS - rok 2023

[1] ČALOUD, J., et al. Monte-Carlo simulations of runaway electron impact on tokamak plasma-facing components. In: *49th EPS Conference on Plasma Physics, EPS 2023*. Mulhouse: European Physical Society, 2023.

[2] CHLUM, J., et al. Tokamak GOLEM for Fusion Education - Chapter 14. In: *49th EPS Conference on Plasma Physics, EPS 2023*. Mulhouse: European Physical Society, 2023.

[3] IVANOV, V., et al. Runaway electrons measurements by ECE on the GOLEM tokamak. In: *49th EPS Conference on Plasma Physics, EPS 2023*. Mulhouse: European Physical Society, 2023.

[4] LOBKO, L. and O. FICKER. Statistical Analysis of Measurements of Fusion Neutrons and Photoneutrons at the COMPASS tokamak. In: *FuseNet PhD Event 2023*. FuseNet, 2023.

Řešitelský tým v roce 2023

Jméno	Pracoviště	Zařazení v týmu	Do	Od
Kulkov Sergei Ing.	14102	Navrhovatel - dokt.		
Marčišovský Michal Ing. Ph.D.	14102	Školitel navrhovatele		
Linhart Vladimír Ing. Ph.D.	14116	Zaměstnanec - člen týmu		
Čaloud Jakub Mgr.	14102	Doktorand - člen týmu		
Malec Štěpán Ing.	FJFI	Student mag. programu - člen týmu	15.11.2023	
Svoboda Vojtěch Ing. CSc.	14102	Zaměstnanec - člen týmu		
Ivanov Vladislav MSc.	14102	Doktorand - člen týmu		
Tunkl Marek Ing.	14102	Doktorand - člen týmu		
Lobko Lukáš Ing.	14102	Doktorand - člen týmu		
Malec Štěpán Ing.	14102	Doktorand - člen týmu		20.06.2023

Hodnocení výkonu členů týmu

Jméno: **Kulkov Sergei Ing.**

Same as last year, I was mostly managing the administrative side of the project. As the Timepix3-based detector got damaged half-year into the project, I lost my main means of participating personally in the experiments at the GOLEM tokamak. Additionally, as the COMPASS tokamak was shut down for an upgrade, I've got my hands full with our projects where I was busy with experimental work. However, this project as a whole gave me a lot of experience in how to handle grant projects, and I hope this will be helpful to me in my future career. While I primarily oversaw the project's management, I find immense satisfaction in the fact that this project provided our students with opportunities and resources to conduct experiments and present their results to the broad scientific public at international conferences.

Jméno: **Marčišovský Michal Ing. Ph.D.**

My supervisor helped me with project management for the whole duration of the project with many valuable bits of advice.

Jméno: **Linhart Vladimír Ing. Ph.D.**

Doctor Linhart was mostly overseeing the Compton camera development done by his student, Ing. Š. Malec.

Jméno: **Čaloud Jakub Mgr.**

Mgr. Jakub Čaloud is working on a calorimetric probe for direct measurements of the runaway electrons' energy. After the primary tests of a calorimetry probe at the COMPASS tokamak, the student successfully developed and tested a similar prototype at the GOLEM tokamak. While the measurements were not entirely successful, mainly due to the larger size of the probe that was shown not suitable for the smaller GOLEM tokamak compared to COMPASS, the results were useful for RE energy measurements at other tokamaks, including the Japanese JT-60SA tokamak. Additionally, the student's results will be a part of his doctoral thesis. This year, Jakub presented his results from GOLEM and COMPASS tokamak at the 49th EPS conference.

Jméno: **Malec Štěpán Ing.**

Ing. Štěpán Malec works on a Compton camera based on Timepix3 sensors. The student successfully defended his Master's thesis last year where he presented the results achieved at the GOLEM tokamak. Additionally, the student has implemented a cooling system for the Timepix3 detectors that will help stabilize the sensor temperature and, therefore, provide more accurate results.

Jméno: **Svoboda Vojtěch Ing. CSc.**

Doctor Svoboda oversees everything at the GOLEM tokamak. Besides keeping the old tokamak operating, doctor Svoboda constantly works on improving the general performance of the machine and the diagnostic systems. Additionally, doctor Svoboda educates numerous generations of tokamak plasma students, not only from our faculty but from gymnasiums as well. Thanks to his work, GOLEM continues serving students as a machine for testing their ideas, getting more practice and experience in implementing and working with numerous plasma diagnostics.

Jméno: **Ivanov Vladislav MSc.**

Vladislav Ivanov works on the electron cyclotron emission (ECE) radiometer for the GOLEM tokamak. The student has successfully adapted the COMPASS ECE radiometer for the GOLEM tokamak. Combined with the simulations done by the student, the diagnostic is now a part of the GOLEM system for studying runaway electrons by providing information on their energy distribution. This year, Vladislav presented his results at the 49th EPS conference.

Jméno: **Tunkl Marek Ing.**

Ing. Marek Tunkl is working on a strip silicon detector and scintillation detectors based on a silicon photomultiplier (SiPM). Both diagnostics are now a part of the GOLEM diagnostic system with autonomous data acquisition and analysis systems. During the project, the student has covered probably every aspect of scientific work: from preparing and engineering different prototypes of the detectors himself to implementing them at the tokamak and programming simulations and a model of the whole tokamak that is beneficial for other diagnostics as well. This year, Marek's results together with other students' work were presented at the 49th EPS conference.

Jméno: **Lobko Lukáš Ing.**

Ing. L. Lobko has implemented two diagnostics for measuring photoneutrons that are produced during the contact of runaway electrons with the tokamak's plasma-facing material. Additionally, the student has participated in upgrading the tokamak's interferometry system and data analysis. This year, Lukáš presented his results at the FuseNet Ph.D. event. Additionally, based on the results covered in his Master's thesis, the student works on a paper. Finally, Lukáš decided to continue supporting students' research at the GOLEM tokamak by applying for an SGS grant.

Jméno: **Malec Štěpán Ing.**

Ing. Štěpán Malec works on a Compton camera based on Timepix3 sensors. The student successfully defended his Master's thesis last year where he presented the results achieved at the GOLEM tokamak. Additionally, the student has implemented a cooling system for the Timepix3 detectors that will help stabilize the sensor temperature and, therefore, provide more accurate results.

Využití přidělených finančních prostředků v roce 2023

Název položky	Částka [tis. Kč]			
	plánovaná	upravená	po změnách	čerpaná
1. věcné náklady	63	64	41	40
1.1. drobný hmotný a nehmotný majetek a materiál	20	20	2	2
1.2. práce, služby, poplatky	0	0	0	0
1.3. jízdní a pobytové výdaje	43	44	39	38
2. osobní náklady	190	190	213	212
2.1. stipendia studentů	177	177	200	200
2.2. mzdové prostředky zaměstnanců	9	9	9	9
2.3. dohody o pracovní činnosti (DPČ)	0	0	0	0
2.4. dohody o provedení práce (DPP)	0	0	0	0
2.5. odvody ze mzdových prostředků a DPČ	4	4	4	3
3. režijní náklady	51	51	51	51
4. investiční náklady	0	0	0	0
celkové náklady	304	305	305	303

Hlavní položky čerpání s konkrétním zdůvodněním

Položka: **1.1. drobný hmotný a nehmotný majetek a materiál**

Battery (accumulator) and a 2x relay shield for Raspberry Pi that were used to upgrade the strip detector setup.

Položka: **1.3. jízdní a pobytové výdaje**

Scholarship for V. Ivanov and J. Čaloud that partially covered their trip to the 49th EPS conference that was held in Bordeaux, France.

Položka: **2.1. stipendia studentů**

Students' scholarships.

Položka: **2.2. mzdové prostředky zaměstnanců**

Academic staff payment.

Položka: **3. režijní náklady**

20% of the total financing for the year 2023.

Stipendia studentů

Jméno	Částka [tis. Kč]			
	plánovaná	upravená	po změnách	vyplacená
Kulkov Sergei Ing.	32	32	35	35
Čaloud Jakub Mgr.	30	30	33	33
Celkem:	**177**	**177**	**200**	**200**

Jméno	Částka [tis. Kč]			
	plánovaná	upravená	po změnách	vyplacená
Malec Štěpán Ing.	25	25		0
Ivanov Vladislav MSc.	30	30	33	33
Tunkl Marek Ing.	30	30	33	33
Lobko Lukáš Ing.	30	30	33	33
Malec Štěpán Ing.	0		33	33
Celkem:	**177**	**177**	**200**	**200**

Osobní náklady akademických pracovníků

Jméno	Částka [tis. Kč]			
	plánovaná	upravená	po změnách	vyplacená
Marčišovský Michal Ing. Ph.D.	2	2	2	2
Linhart Vladimír Ing. Ph.D.	5	5	5	5
Svoboda Vojtěch Ing. CSc.	2	2	2	2
Celkem:	**9**	**9**	**9**	**9**

Příloha: náběhy na akci za rok 2023

Čerpáno	Zaúčtováno	Anal. účet	Text	Má dáti	Dal
31.03.2023	11.04.2023	6911500	161 - studentská grantová soutěž	0,00	305 000,00
30.05.2023	01.06.2023	5498210	režie	51 000,00	0,00
04.07.2023	13.07.2023	5211010	Odměny	9 000,00	0,00
04.07.2023	13.07.2023	5241000	ZP - organizace	810,00	0,00
04.07.2023	13.07.2023	5242000	SZ - Organizace	2 232,00	0,00
04.07.2023	13.07.2023	5277100	Tvorba sociálního fondu	90,00	0,00
11.07.2023	12.07.2023	5495123	PGS 6/23	89 000,00	0,00
07.08.2023	10.08.2023	5211020	Nákladové mzdy 2	229,00	0,00
07.08.2023	10.08.2023	5241000	ZP - organizace	21,00	0,00
07.08.2023	10.08.2023	5242000	SZ - Organizace	57,00	0,00
07.08.2023	10.08.2023	5277100	Tvorba sociálního fondu	2,00	0,00
07.09.2023	14.09.2023	5211020	Nákladové mzdy 2	1 048,00	0,00
07.09.2023	14.09.2023	5241000	ZP - organizace	94,00	0,00
07.09.2023	14.09.2023	5242000	SZ - Organizace	260,00	0,00
07.09.2023	14.09.2023	5277100	Tvorba sociálního fondu	11,00	0,00
08.09.2023	11.09.2023	5495124	PGS 8/23	38 491,00	0,00
06.10.2023	06.10.2023	5211020	Nákladové mzdy 2	285,00	0,00
06.10.2023	06.10.2023	5241000	ZP - organizace	26,00	0,00
06.10.2023	06.10.2023	5242000	SZ - Organizace	70,00	0,00
06.10.2023	06.10.2023	5277100	Tvorba sociálního fondu	3,00	0,00
13.10.2023	20.11.2023	5017162	Přídavné relé SB Components PiRelay	1 189,00	0,00
19.10.2023	31.10.2023	5017162	Akumulátor	468,00	0,00
06.12.2023	11.12.2023	5495123	PGS 11/23	111 000,00	0,00
08.01.2024	09.01.2024	5211020	Nákladové mzdy 2	-1 562,00	0,00
08.01.2024	09.01.2024	5241000	ZP - organizace	-141,00	0,00
08.01.2024	09.01.2024	5242000	SZ - Organizace	-388,00	0,00
08.01.2024	09.01.2024	5277100	Tvorba sociálního fondu	-15,00	0,00
			Celkem vč. záloh:	**303 280,00**	**305 000,00**
			Zálohy:	**0,00**	**0,00**
			Celkem bez záloh:	**303 280,00**	**305 000,00**