Introduction

This article tries to summarize our effort and experience with education and training of a new generation of fusion scientists in the tokamak department of the Institute of Plasma Physics, Academy of Sciences of the Czech Republic.
Structure of the paper is as follows: At first, we describe briefly history of fusion research in the Czech Republic and two operational tokamaks, COMPASS and GOLEM. We also mention necessity of education of young fusion physicist for these facilities as well as for next facilities such as ITER. Section 2 demonstrates how we deal with education of students in the tokamak department. We mention in detail education of undergraduate as well as PhD students and collaboration with the several Prague Universities in this effort. Section 3 is devoted to description of training courses we organize annually in the tokamak department since 2003. These courses, called SUMTRAIC and EMTRAIC are mostly attended by students from abroad, but some domestic students have been trained as well.

Section 1.

Brief history of fusion research in the Czech Republic.

The plasma/fusion physics is investigated in IPP since 1959. At the beginning, several experiments on interaction of magnetized plasmas with electron beams and RF waves were accompanied with relevant theories and modelling. An important breakthrough happened in 1977, when a small soviet tokamak TM-1-MH was successfully put in operation. Experiments on this facility (later re-named to CASTOR) have continued until 2007. However, there was lack of experienced plasma physicists, in particular until 1989, namely because of limited number of available positions mostly due to financial reasons. At this time, the CASTOR tokamak was operated by 9 experimentalists (7 PhDs) accompanied by 4 theoreticians (all PhDs) and their average age was well above 40. Financial as well as political situation in 90^{th} has broadened possibilities to enlarge involvement in fusion research in the Czech Republic.

An important breakthrough happened in 1999, when the Czech Republic has associated to EURATOM. After that, the research on CASTOR became more visible in European fusion laboratories, and started to be attractive for international collaboration. Since that time, we started seriously to think on systematic education and training of new generation of fusion physicists. Possibilities of practical training in experimental fusion research have increased again in 2009, when the COMPASS tokamak became operational at IPP. Since that time, two tokamaks are available in the Czech Republic, because the CASTOR tokamak was moved to the Faculty of Nuclear Science and Physical Engineering of the Czech Technical University in Prague, and renamed (again) as GOLEM. It has to be emphasized that both these facilities, besides of their scientific capabilities, have great educational and training potential.
In summary, our educational and training effort, started after 1989, continues mainly in two directions:

- Strengthening the link between the tokamak department of IPP and two Prague Universities.
- Practical training of domestic and foreign students in tokamak operation in the experimentally oriented schools, which started at CASTOR in 2003, and continue till now.

Let us introduce at first the main experimental facilities.

The COMPASS tokamak

The Institute of Plasma Physics, Academy of Sciences of the Czech Republic (IPP) operates the tokamak COMPASS since 2009. Its mission is to contribute to world wide effort to design future fusion reactor. COMPASS is small/middle size tokamak with the major/minor radius 0.56/0.2 m, the toroidal magnetic field up to 1.8 T, the plasma current < 400 kA, and the pulse length < 0.5 s. COMPASS is equipped with

an additional plasma heating system by means of the neutral beam injection. Tokamak operation in advanced discharge regimes such as the ELMy H mode, plasma detachment, e.t.c, are routinely achieved [1]. A sophisticated set of plasma diagnostics allows detail study, focused in particular to physics at the plasma edge [2].

The picture of COMPASS in the torus hall and its comparison with fusion facilities is shown in Fig. 1.

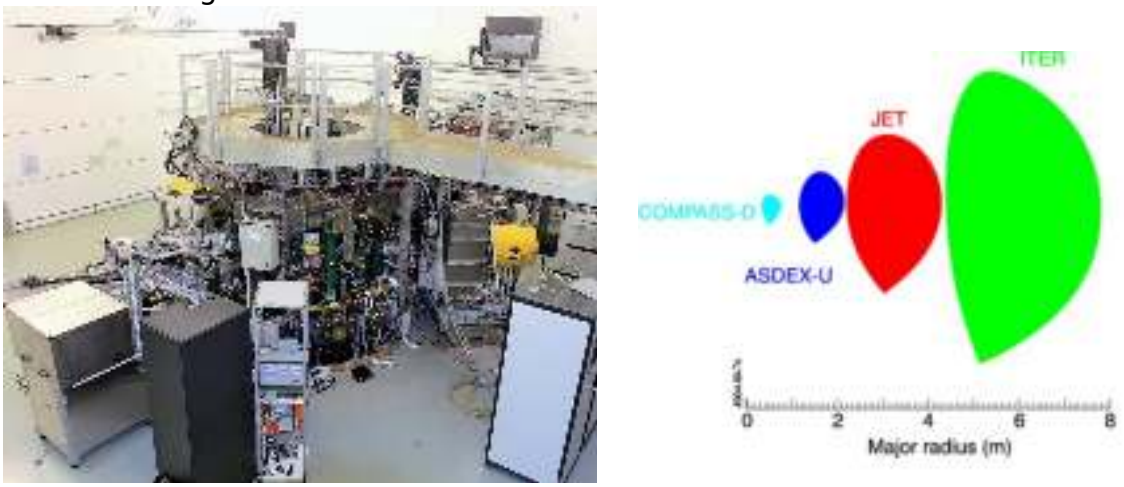

Fig. 1. *Left – picture of COMPASS in the torus hall. Right – plasma cross section of COMPASS compared to large European tokamaks and future tokamak ITER.*

The magnetic configuration of COMPASS is similar to existing European facilities and the future ITER tokamak. This similarity contributes to scaling studies of plasma performance. Research on COMPASS is fully integrated in joint European effort on nuclear fusion under the umbrella of EURATOM, which leads to a strong international collaboration.

After more than 10 year operation of COMPASS, the tokamak will be upgraded to be even more relevant to ITER. It was decided recently to upgrade COMPASS for operation at toroidal magnetic field up to 5 T. this will allow us to operate in more relevant discharge regimes to ITER (and possibly to DEMO) with longer discharge duration (2 s), higher plasma current (up to 1 MA), more flexible magnetic configuration with close divertor, etc. [3]. The COMPASS-U is planned to operate in 2022. It is clear that COMPASS and its upgraded version strongly require an experienced team of plasma physicist and engineers.
Current personal situation in the COMPASS tokamak [11] is given in the next table:

Senior physicists		45
PhD students	18	
Technicians+ Engineers		35
Undergraduate students		16
Total staff		**114**

The GOLEM tokamak

GOLEM is a small tokamak with the circular plasma cross section. The major/minor radii are 0.4/0.085 m, the toroidal magnetic field is less than 0.5 T, plasma current is below 8 kA, and the discharge duration is up to 25 ms. Experiment is equipped by set of basic diagnostics and advanced data acquisition system. GOLEM belongs to first generation of tokamaks, being the oldest tokamak in the world which is still fully operational. It is necessary to note that tokamak staff is extremely limited and consists of one senior scientist and a technician with part time employment (0.5 ppy).

Fig. 2. Picture of the GOLEM tokamak in a small torus hall.

A unique feature of GOLEM is possibility to operate it remotely via Internet described in [4,5]. This capability is frequently exploited by universities from abroad (mainly in the frame of FUSENET [17] consorcium) for practical training of students in tokamak operation and physics . More then 60 remote educational sessions have been organized for ~ 15 universities performing remotely more then 3 thousands discharges over the Czech Republic borders.
The main mission of GOLEM is practical training of domestic bachelor and master students in fusion research, which will be describe later. However, some basic experiments exploiting flexibility of GOLEM are also performed, such as testing of high temperature superconductors in tokamak environment [6], comparison of hydrogen and helium plasma performance [7], edge plasma research with various electrostatic probes and run-away studies [16].

Section 2. Education

Bachelor and master students
According our long term experience, students interested in fusion physics have to be attracted already during their bachelor and master studies at a university. Majority of the undergraduate students are usually recruited from Prague universities where the plasma physics is taught.
Last 15 years, the Faculty of Nuclear Science and Physical Engineering (FNSPE), Czech Technical University in Prague is our dominant partner in student's education and practical training, which is mainly active in two directions.

- Establishment the curriculum "*Physics and technology of thermonuclear fusion*"
- Operation of the GOLEM tokamak

Let us describe these issues in more detail.

The curriculum "*Physics and technology of thermonuclear fusion*"
This curriculum was established at the Department of Physics of FNSPE in 2007. Physics subjects cover mechanics, electricity and magnetism, waves and optics, thermodynamics, theoretical physics and experimental physics, and applied physics. Mathematical subjects include parts of mathematical analysis, algebra, numerical methods, mathematical physics equations, and mathematical statistics. IT subjects develop basic computer skills, a basic knowledge of programming and use of the Internet.
The course is focused on research and development of nuclear fusion with a view to its future use in power engineering. Students gain a detailed knowledge in plasma physics, principles of thermonuclear installations and the technology of their components. An integral part includes methods of measurement, numerical modelling, fun-

damentals in material physics, physics of ionizing radiation, and fundamentals in power engineering. For more detail see [8].

It has to be mention that not only the physics of magnetized plasma is studied, but also laser physics and technology. Here, we focus to the tokamak plasmas, which represents a majority.

Senior IPP scientists are teaching in the frame of this curriculum.

Most recently, the faculty member of the Erasmus Mundus EP fusion master program.

GOLEM
The first touch of FNSPE students with experimental tokamak physics is the "*Hands-on experiment at GOLEM*", which is the part of the experimental practicum for the 1st year students. Students are at first acquainted with basics of tokamak physics, technology, diagnostics and operation. They personally install on GOLEM a set of basic diagnostics to measure the loop voltage, plasma current, toroidal magnetic field and the visible emission by means of a photodiode. Signals of individual diagnostics are recorded by a 4 channel digital oscilloscope.

Fig.3 Students performing the hands-on experiment on GOLEM

Students operate the tokamak themselves according to their experimental program, and process data by using an available software (mostly Python,...) and they are encouraged to make the basic estimation of the electron energy confinement time in the GOLEM tokamak. Finally write a report , which is credited.

The most motivated students then select the topic of their bachelor thesis, which is mostly related to plasma physics on GOLEM or to COMPASS, as seen from a few examples of topics of bachelor thesis:
GOLEM: *Feedback control of plasma position on GOLEM, Magnetic field configurations and their measurement on tokamak GOLEM, Measurement of plasma parameters by means of the combined Ball Pen and Langmuir probe on GOLEM, etc.*
COMPASS: *Plasma tomography on the COMPASS tokamak, Study of visible plasma radiation by high resolution spectroscopy at additional plasma heating by neutral beams injection on the COMPASS tokamak, Characterization of edge plasma fluctuations at COMPASS, etc.*

Until now (2020), 34 students defended their bachelor and master thesis in frame of this curriculum. The list of absolvents accompanied with topics of their thesis is available at [9]. 22 bachelor and master thesis were COMPASS oriented. Currently, 18 students are in the magister program of the curriculum [10], and 11 of them are focused to magnetized plasmas in tokamaks. Furthermore, 8 new bachelor students participate in the program. 10 of master students continue as PhDs.
It is also interesting to note involvement of high school students at GOLEM. They can contribute to GOLEM performance and diagnostics development, which motivate them to start studies at the faculty (O Grover,..).

IPP has also links to other Universities teaching plasma physics, such as the Masaryk University in Brno, and Comenius University in Bratislava (Slovakia). However, only a few students were captured from there. However, the dominant source of undergraduate students is FNSPE as seen from the current situation of involvement of undergraduate students in the tokamak department as shown in the next table.

Undergraduate students	
FNSPE CTU	12
Other universities	4
Total	**16**

Other activities

Recently, the Czech Technical University was founded by an ERDF grant (to be specified) to create a student laboratory with several plasma lab apparatus (Langmuir probe measurements, Paschen law, linear magnetic trap...). Majority of these experiments could be performed remotely. Therefore, students and young researchers from abroad can take part. (more details are required – Jana Brotankova). This activity is related to membership of the faculty to FuseNet. An example of the FuseNet report-can be find at [14].

Furthermore:

- Annual meetings on plasma physics of FNSP students are organized at Marianska.
- Extra grants are given to master students to found their participation at international conferences. Since 2010, already 20 such grants were given to master students to participate at EPS conferences on Plasma physics and Symposium on fusion technologies (SOFT) [13].
- A practical training course GOMTRAIC is organized on the GOLEM tokamak mainly for students from abroad. The third edition of this activity is planned in 2020.
- The research on GOLEM is also part of the project of the International Atomic Energy Agency "*Research on Using Small Fusion Devices*". Participation in this collaborative project enlarges possibilities of collaboration of GOLEM with other small tokamaks around the world, and brings some extra money (12 kE/year).

Besides of our close link to FNSPE, several additional ways to find and attract bachelor and master students are:

- Personal links of the tokamak staff to university teachers (mostly in past)
- The tokamak staff also give lectures at the Charles University in Prague, in particular in plasma physics theory
- Organizing excursions for university and high school students at COMPASS and GOLEM

PhD education

According Czech law, the Institutes belonging to the Academy of Sciences have not license for education of students on the PhD level. So, PhD studies are organized under the umbrella of a University. Currently, we do have two official partner universities:

- Faculty of Mathematics and Physics (FMP), Charles University in Prague. In particular, the Department of Surface and Plasma Science organizes the doctoral program "*Physics of Plasma and Ionized Media*" since 90th.

- Faculty of Nuclear Science and Physical Engineering (FNSPE) of the Czech Technical University in Prague since 2015. New accreditation is approved for next ten years,

2020-2030. Recently, new agreement for joint PhD program between CTU and Ghent University in Belgium have been signed.

The system of PhD study is similar at both universities. At first, candidate students have to pass an entrance exam. If successful, the students select the topic of their thesis proposed by a supervisor. Then the faculty organizes teaching of them in different topics (mathematics, plasma physics, ….[ref]), obligatory exams, and the defense of doctoral thesis, and finally delivers the title PhD. What is important that the faculty provides to students a stipendium for the first four years of their study. Faculties can also arrange reasonably cheap accommodation of students in a dormitory, if requested. Faculties are also organizing some additional activities for PhD students. For example, FMP organizes annually the Week of Doctoral Students, where the students present their recent results either in an oral presentation or in the form of posters. Results are also published in Proceedings of WDS, available on request at [15]. Furthermore, faculty organizes annually a winter seminar/workshop outside Prague every year. It helps in exchanging information between faculties and students, and also provides team building. Also founds to support participation of PhD students at conferences, and workshops is available.

Once IPP is interested to have a new PhD student in fusion physics, it has to formulate a topic of thesis and to propose a supervisor from the senior COMPASS staff. The faculty nominates a consultant of its own staff to assure a closer link between faculty and IPP. The first duty of supervisors is to formulate topics of the thesis, which have to be relevant to current research performed on COMPASS. The current topics can be split into several groups.

- Design, commissioning and operation of individual diagnostics and performing relevant plasma physics research on COMPASS, such as measurements of ion temperature (2 students), microwave diagnostics – reflectometry (2 students), tomography of plasma radiation (2 students), and Thomson scattering (1 student).
- Edge plasma physics and turbulence (5 students)
- Physics of runaway electrons and disruptions (3 students)
- Advance data processing (2 students)
- Technology of fusion reactors (1 student)

The topics have to be also selected with vision to defend thesis in a due time.

As it was mentioned above, PhD students receive a stipendium from the faculty for the first four years, which is usually not sufficient to survive in Prague. To improve their financial situation, the Institute of Plasma Physics offers them a part time job, starting from 0.2 ppy for first year of their study. Their involvement increases gradually during PhD study, depending on their research activity. This has sometime drawback for students, because being financially secured, they prolong their study until the limit, which is max 9 years according university rules (which is unfortunately almost always the case).

In summary, 18 PhD students is currently educated at the tokamak department of IPP. As evident from the following table, majority of them is recruited from FNSPE, mainly

because of their previous experience on GOLEM and finishing the master curriculum at the faculty.

Source of current PhD students

FMP, Charles University in Prague	5
FNSPE, Czech Technical University	9
FS Czech Technical University	1
Comenius University, Bratislava	1
Masaryk University, Brno	1
Foreign PhD student	1
Total	**18**

What we are doing for PhD students at COMPASS?

Main duty of PhD students is, of course, to take care on particular diagnostics, i.e. in commissioning of hardware, assure its routine operation, and developing reliable software for data processing. Like on the tokamak facilities, the research is performed in experimental campaigns, in which students actively take part. Achieved results are presented at regular seminars of the department, and students receive useful feedback from the senior staff. Later on, students also contribute to planning of the experimental program to adjust it to the topics of their PhD thesis.

On top of that, selected PhDs are trained as operators of the COMPASS tokamak. In this way, students become quite soon fully integrated into the research team.

The COMPASS tokamak is a part of the European effort in fusion research in the frame of EURATOM. IPP collaborates with fusion facilities, in particular such as JET, ASDEX-U, TCV, and MAST. The joint research is governed by the EuroFusion program. This program offers a unique possibility for our PhDs to be regularly seconded to other European tokamaks.

PhDs become frequently supervisors of bachelor and master thesis of university students.

Currently, almost all PhDs are now partially involved in design of COMPASS-U.

The institute organizes several additional activities for students:

- Internal workshops outside the institute.
- PhD students can apply for individual grants funded by the institute to purchase hardware/software required for executing their PhD program, and secure their almost regular participation at international conferences and workshops.

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