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Pedagogical aspects of teaching nuclear fusion engineering basics

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Abstract

Over the last 5 years there has been a significant increase in the visibility of nuclear fusion as an important technology to aid in the transition to clean and sustainable energy production. Although the technology is not mature enough for commercial deployment yet, the field is rapidly moving from a basic science field to large projects that require engineering professionals from many disciplines. Aware of this trend, the department of Nuclear Engineering has included within its strategic plan the offering of a fusion engineering track.

One of the first steps towards achieving this is the curricular design of a course aimed as an overview of the many engineering aspects of magnetic nuclear fusion systems. Topics such as fusion power calculations, plant energy balance, magnetostatic calculations, microwave engineering, neutronics and plasma-material interactions are introduced to the students. To promote student engagement, the course was developed on a highly engaging online platform (TopHat), and the course included experiences aimed at connecting the knowledge gained in class with real systems. These experiences including coding using Python, immersive VR experiences on virtual models of existing machines, remote operation of a small experimental device and a field visit to a national laboratory where a medium-size magnetic fusion machine is located. Insights on the instructor and student experiences during this first time offer of the course will be shared as part of this paper. Contact with stakeholder (prospective students, prospective employers of students, prerequisite instructors, department leadership, courseware platform experts and experienced Python coders proved to be an extremely insightful exercise that helped in the construction of a very successful course.

Keywords

Faculty paper, nuclear engineering, nuclear fusion, Python, student engagement.

Introduction

Nuclear fusion is the process, unknown before 1920, by which stars in the universe, including our sun, generate their energy. The process involves getting two atomic nuclei very close to each other so their fusion into a single compound nucleus becomes favorable; such compound nucleus will tend to be unstable and short-lived, and will fall apart into two fragments, different from the original nuclei that formed it. The mass of the reactants is larger than the mass of the products, with the “missing” mass being converted into energy.

This process is difficult to accomplish because it requires two positive nuclei to approach each other close enough and overcome the electrostatic repulsion, since they are both positively charged. In order to achieve meaningful reaction rates, the reactants need to be heated to temperatures similar to those present in the core of the sun. Ever since the process was first observed in the laboratory in 1934, nuclear scientists realized the profound implications of taming the process on Earth to access a virtually limitless energy source [1]. And just like in the case of nuclear fission, the first practical demonstration of just how much power the fusion process releases would come in the form of a military device [2].

Over the past 70 years, great strides have been made towards making the dream of large-scale nuclear fusion reactors capable of supplying energy, and an important piece of evidence is the transition of the field from a purely physics focus to an engineering endeavor with multiple mega projects [3, 4]. Up to a few years ago, the field of nuclear fusion was heavily dominated by the plasma physics community, with the confined plasma as the main object of study. The stability of the confined system, the mass and heat transport phenomena within it, the plasma-material interface, development of plasma diagnostics and mechanisms of power absorption by the plasma were key knowledge required by the bulk of the workforce. As the field transitions from the physics domain to the engineering domain, professionals more aware of the technology behind plasma confinement will be required. This was confirmed by the author by interviewing HR managers from the ITER organization [5], the Science and Education Director of a US Department of Energy laboratory heavily focus on fusion research [6] and a senior management officers at one of the most successful nuclear fusion start-ups in the US [7]. The latest high visibility of fusion as more private capital starts getting involved has also produced a spike in the number of students entering undergraduate physics and engineering programs interested in pursuing a career focused on nuclear fusion [8].

Recognizing this shift, the Department of Nuclear Engineering at Penn State University has, as part of a strategy to broaden the scope of its research and academics, started to offer courses geared towards students interested in pursuing a career focused on fusion rather than fission. Two courses have been designed and already offered: one devoted to the physical principles of plasma physics, and one focused on the specifics of magnetic confinement fusion. This latter course is the focus of the present paper.

Content Development Strategy.

The overall goal of the introductory fusion engineering course is to give the student a global perspective on the technological requirements of a nuclear fusion device. In order to understand the material, some prerequisites need to be established. Given the nature of the content, the prerequisites established were:

- Fundamentals of modern physics
- Vector calculus
- Ordinary differential equations
- Fundamentals of electromagnetic theory

Being cognizant of the well-documented disconnect between math and physics courses with advanced courses in undergraduate engineering curricula [9] and talking with some of the instructors of courses that cover the prerequisite material, students were provided with a curated library of online videos to serve as refreshers for the students on some of those prerequisite topics.

The course content was designed around a generic fusion power plant shown in Figure 1, which illustrates all the different aspects of fusion technology. The course was divided into 6 units:

- Fundamental concepts: where fusion energy comes from, which atomic isotopes can fuse, what conditions are necessary, how much power is generated, how this power is shared among the resulting particles.

- Magnetic confinement: why gases at high temperature respond to magnetic fields, how is the equilibrium between kinetic pressure and magnetic pressure described mathematically, how do we find if such equilibrium is stable, how the study of magnetic open systems led the way to developing closed systems, how a closed system adds complexity to the confinement description, which magnetic field are required and how do we generate them.

- Material and energy transport: why the confinement is not perfect, how energy and particles leak from the plasma, how mass and energy confinement time are determined, how are mass and energy confinement times incorporated into the overall mass and energy balance of a fusion power plant.

- Power injection: why external power injection is needed, which mechanisms are available for injecting energy into the confined plasma, why Joule heating is insufficient, how a neutral beam injector works, how microwaves heat the plasma.

- Power exhaust: what kind of energy leaks the plasma, which reactor components are exposed to different kinds of leaked energy, what is the role of neutrons leaking from the plasma, how energy leakage presents a serious materials challenge, how energy from the plasma is recovered and incorporated into a regular thermal cycle.

- Diagnostics and control: why it is important to monitor the plasma state, which variables/parameters require close monitoring, which are some of the most common diagnostics to monitor these variables, which actuators are available to operators to achieve plasma control.

Each one of the topic mentioned above could lead to a full course on its own right, but the purpose of the course is to give an overview to the student with two main purposes in mind: facilitate communication with technical experts within the nuclear fusion field at the level of general understanding, and help the student decide which technical area they find more attractive if they decide to pursue an advanced career within the fusion field. Therefore, subjects as complicated as transport theory on magnetized plasmas or plasma/wave interactions are only covered at the level of generalities but highlighting their impact and importance within the global picture of a fusion power plant. Figure 2 presents the topics map of the course according to the 6 units mentioned.

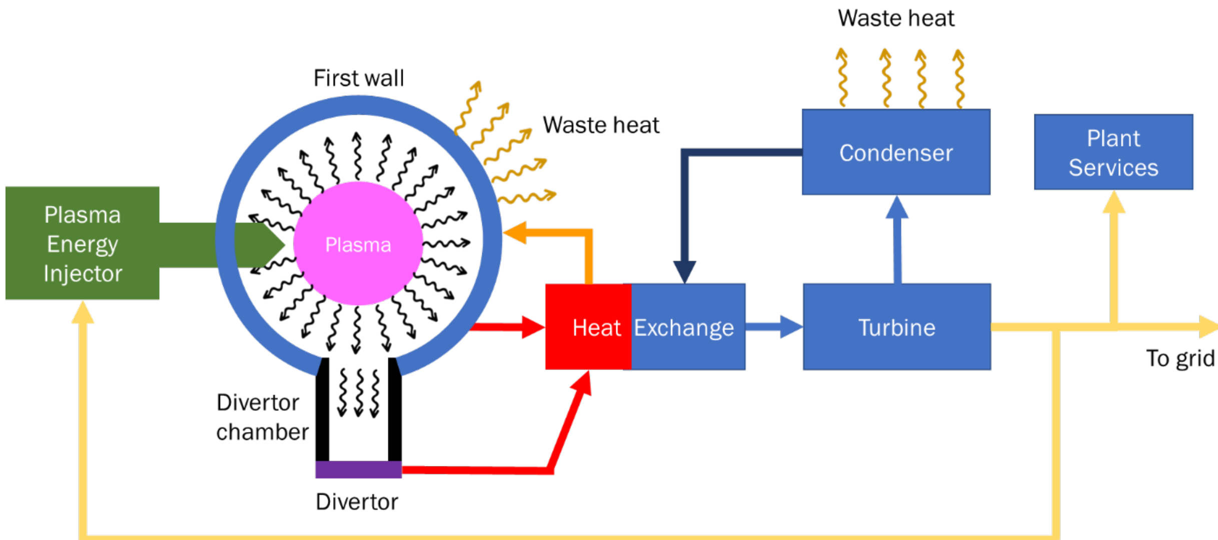

Figure 1. A generic fusion power plant used to introduce the student to the engineering aspects of fusion technology.

Figure 2. Topical map of the course on fundamentals of nuclear fusion engineering. The different shades of the blocks indicate the unit segmentation of the course. Arrows indicate the topic sequence.

Student engagement strategies.

Many previous works have highlighted the need to implement effective student engagement that will enhance the learning experience [10, 11]. This was considered especially critical for this course, so the following actions were taken to encourage student involvement in the course:

- The TopHat platform, which has been used with high success to promote student engagement owning to some of its features [12], was used to develop the content and present the course to the student. Some of the technical challenges reported on its use for engineering courses were also observed in this instance [13], primarily due to the hybrid nature of the course (50% of in-residence students, 50% remote students.

- Development of simple Python tools or use of already developed computational tools (such as the freegs Python module [14] and the ASTRA code) were initially visualized as strong engaging tools; however, the outcomes in this aspect were not the expected ones, as will be discussed in the next section.

- Contact was established with SciVista, a star-up company in Santa Fe, NM, which has developed VR environments that allow the visualization of data obtained from complex simulation codes relevant to fusion devices. The students had a VR session using those models.

- A visit to the National Spherical Torus Experiment (NSTX) [15] and the Magnetic Reconnection Experiment (MRX) [16] facilities at Princeton Plasma Physics Laboratory in Princeton, NJ, was arranged. The purpose was to give the students the opportunity to see the knowledge they acquired along the course applied to real life. Students not in residence were asked to perform a "virtual": visit to the ITER facility in lieu of the in-person visit to PPPL.

- Two experimental remote sessions were performed with the GOLEM tokamak [17], located at the Czech Technical University School of Physics, where the students had the opportunity to perform real experiments and present a report on them.

Figure 3 documents some of these activities of the students.

Course outcomes.

The course was taught as a pilot during the Fall 2022 semester at Penn State University. 25 students were enrolled: 15 in residence (4 undergraduate students, 9 graduate students) and 9 remote students (all graduate). The hybrid nature represented a significant barrier for engagement, especially for remote students that were not able to utilize the interactive features of TopHat during lectures. The fact that many of the remote students were taking the course asynchronously due to their work activities did not allow them to participate live in experiences such as the remote experiment with GOLEM, the visit to PPPL or the VR demonstration with SciVista, which were a hit with the in-residence students.

The mixed graduate/undergraduate student makeup presented another challenge, since the feedback from undergraduates was that, even though and effort was made to differentiate and make the difficulty lower for undergraduates, they still found it complex and difficult, as evidenced by the following comment left as part of the university's student instructor evaluation system, SRTE:

"More time to complete assignments would have been tremendously helpful for everyone, I feel. I also think that some of the projects and homework problems were quite demanding for the undergraduate section."

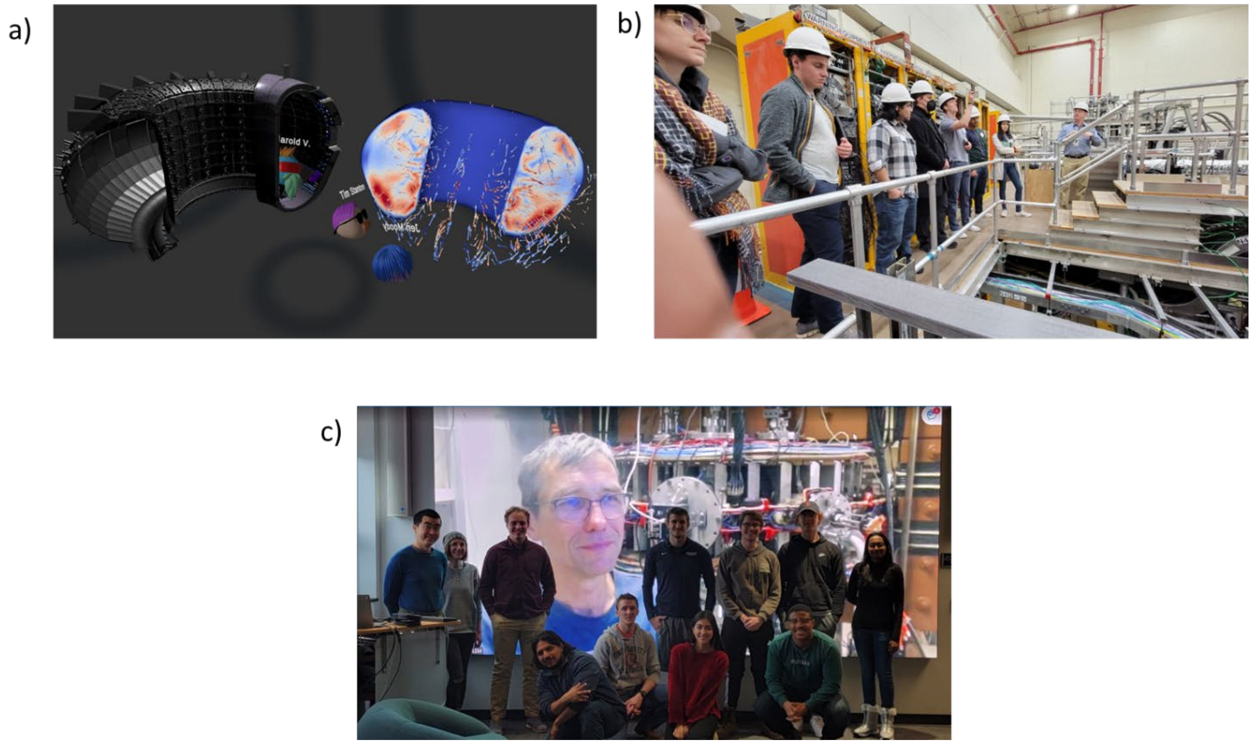

Figure 3. a) VR model of the ITER tokamak as seen using the SciVista platform. b) Dr. Eric Gilson (far right) explaining features of the NSTX tokamak to the students at the Princeton Plasma Physics Laboratory. c) Students pose after one of their remote sessions on the GOLEM tokamak.; professor Vojtěch Svoboda from the Czech Technical University is seen in the background screen.

Regarding the use of computational tools as an engagement tool revealed that its effectiveness is a very strong function of the prior experience of the student writing computer programs. While some were actually very accomplished and up to the challenge (see Figure 4 for an example of a plot generated by a student as part of a computer exercise), those with little or no experience regarded it more as a barrier, as expressed in the following comment left in the SRTE system:

"I wish I had been more knowledgeable of Python before taking this course. Videos suggested by the professor helped, but I was just simply not to the required level".

A strategy more oriented towards following properly annotated code and understanding it rather than generating code might be suitable for this case, which has been shown to be an effective way to build up computational skills on students [18].

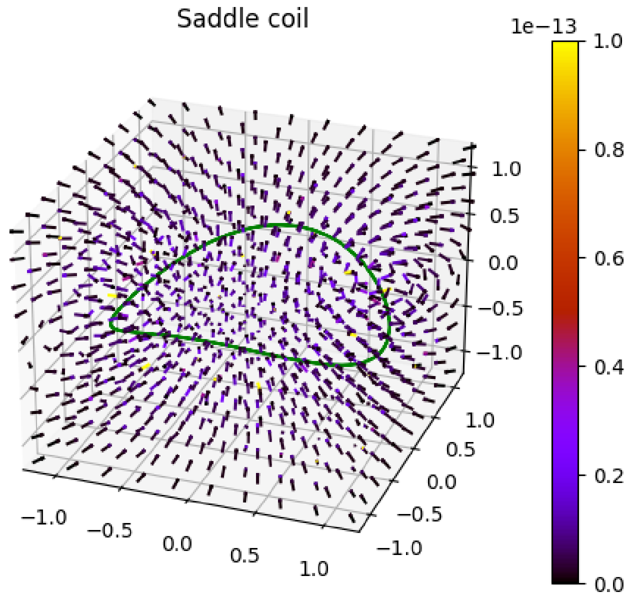

Figure 4. Visualization of the magnetic field due to a circular 2-period filamentary saddle coil generated by a Python script written by one of the course students.

A barrier that was completely overlooked during the planification of the course was the scheduling barrier. A specific time and place were assigned for the in-residence students to meet, and the duration of the session was fixed to 50 minutes. This did not present a challenge for the conventional lecture; however, the activities such as the remote experiment in GOLEM, the VR session and even the logistics of the PPPL visit (which took a whole day for the students) were hindered by the scheduling restrictions. The instructor had to negotiate for alternate spaces for expanding the lecture beyond the 50 minutes (this was required for both the VR session and the GOLEM experiments), and also for justifying absences of students with other instructors (for the case of the visit to PPPL). Future preparations should account for this scheduling conflicts and find strategies to introduce flexibility to the scheduling as well.

Conclusions.

A pilot teaching of an introductory course to nuclear fusion engineering was successfully done at Penn State University. The course surpassed the expected enrollment of 10 students by more than twice that number, showing that student interest on those topics is growing. A variety of student engagement strategies were implemented, with mixed results due mainly to the heterogeneous student background on programming and the hybrid nature of the student body. Both in-residence and remote students expressed satisfaction by being able to correlate the features of real systems with the concepts and topics discussed in class, and even more so at the opportunity to perform experiments in a real machine where they applied some of the concepts that were discussed in class. It was found that when planning for student engagement activities that require more time and/or a different location from the ones assigned to the course, measures need to be taken in advance to ensure those activities can take place and do not interfere with other student activities.

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