European Journal of Physics

PAPER

From theory to hands-on: teaching experimental plasma physics using small plasma devices at DTU

To cite this article: Jesper Rasmussen *et al* 2022 *Eur. J. Phys.* **43** 065803

IOP Publishing

European Journal of Physics

Eur. J. Phys. **43** (2022) 065803 (14pp)

https://doi.org/10.1088/1361-6404/ac93c4

From theory to hands-on: teaching experimental plasma physics using small plasma devices at DTU

Jesper Rasmussen[1,*], **Olaf Grulke**[1,2] **and Stefan Kragh Nielsen**[1]

[1] Technical University of Denmark, Dept. of Physics, Fysikvej 309, DK-2800 Kgs. Lyngby, Denmark

[2] Max Planck Institute for Plasma Physics, Greifswald, Germany

E-mail: jeras@fysik.dtu.dk

Received 1 July 2022, revised 22 August 2022

Accepted for publication 21 September 2022

Published 11 October 2022

Abstract

At the Technical University of Denmark (DTU), we have in recent years acquired or developed three small plasma devices. These consist of a small tokamak (NORTH), an inertial electrostatic confinement device, and a linear plasma device. This has enabled a restructuring of our teaching in plasma physics and nuclear fusion, allowing courses with a dedicated experimental focus. Here we describe the use of these devices in our teaching of fusion plasma physics, with particular emphasis on their integration in a new experimental Master's level course. We also present examples of BSc and MSc projects completed at these experiments and offer some didactic reflections on student learning during our courses and projects. Our experience so far has validated the potential for student-driven activities at all levels to make useful scientific contributions to the experimental study of laboratory plasmas.

Keywords: plasma physics education, fusion technology, experimental plasma physics, magnetically confined plasmas, electrostatically confined plasmas, fusion engineering physics

(Some figures may appear in colour only in the online journal)

1. Introduction

Practical training with the operation of fusion plasmas is becoming increasingly relevant, as the demonstration of the scientific and technical viability of net energy production from nuclear

[*] Author to whom any correspondence should be addressed.

fusion is drawing closer. To this end, small to medium-sized plasma devices are commonly used in university education within plasma physics and nuclear fusion, both at undergraduate and graduate/masters level. Examples range from the use of small tokamaks such as GOLEM [1–3] and ISTTOK [4, 5], through glow discharge experiments [6], to experiments focussing on inertial electrostatic confinement [7], dusty plasmas [8], and laser–plasma interactions [9]. Some of these experiments can even be operated remotely, also allowing students outside the relevant host facility to gain familiary with the operation and interpretation of plasma experiments.

At the Technical University of Denmark (DTU), we have recently acquired and developed two experimental plasma devices for research and education in fusion-relevant laboratory plasmas: a small tokamak, NORTH [10], for magnetic confinement of plasmas, and an inertial electrostatic confinement device, the DTU Fusor [11], for studies of fusion plasmas. A third experiment, a linear plasma device, is currently being commissioned. These facilities have been incorporated in our teaching of experimental plasma physics, partly as an integral element of a new MSc-level experimental course, and partly as the focus of student-driven research or development projects leading to BSc and MSc Theses.

This article describes the educational use of these devices at DTU, with an emphasis on their application within a newly restructured MSc course on experimental plasma physics [12]. In its present incarnation, this course has so far been taught in the spring of 2021 and 2022, with a total of 24 students having followed the course. The focus is on the physics and characterization of laboratory plasmas, primarily as used in fusion research. The course is intended to complement, but be independent of, an existing more theory-focussed MSc-level course offered within our department [13]. A specific feature is the combined use of our very different devices, enabling us to elucidate a wider range of topics within fusion plasma physics than would be possible on a single, small experiment.

This paper is organized as follows. In section 2 we briefly describe our experimental plasma devices. Section 3 details the course structure and the pre-defined experimental activities included in the course curriculum, along with some of the project-based studies conducted by students in the course. Section 4 discusses examples of the use of our experimental devices in a number of recently completed BSc/MSc projects, while section 5 concludes with some didactic reflections on these activities and the associated student learning.

2. Experimental plasma devices

The facilities involved in our teaching comprise NORTH and the DTU Fusor, discussed in detail elsewhere [10, 11], along with a linear plasma device, described here for the first time. Figure 1 shows photos of all three experiments.

NORTH is a small tokamak with major radius $R_0 = 0.25$ m, minor radius $a_0 = R_0/2 = 0.125$ m, and a maximum on-axis toroidal magnetic field of 0.4 T. The current in the eight toroidal field coils (each 12 turns) is supplied by discharging four super-capacitor banks with a stored energy of 0.5 MJ each. At present, the maximum pulse duration is of order 20 s, limited mainly by the capacitor discharging, but typical pulses discussed here are designed to run for a few s. Plasma breakdown and heating is achieved using electron cyclotron resonance (ECR) heating based on 2.45 GHz microwaves, with up to 3 kW injected from the outboard (low-field side (LFS)) in ordinary (O-mode) polarization and up to 3 kW from the inboard (upper high-field side (HFS)) injected as extraordinary (X-mode) waves. In our teaching so far, the tokamak has been operated primarily as a simple magnetized torus, i.e. without a toroidal plasma current driven by the central solenoid. Users can control the background pressure, magnetic field, discharge length, and auxiliary heating scheme. Diagnostics incorporate Langmuir

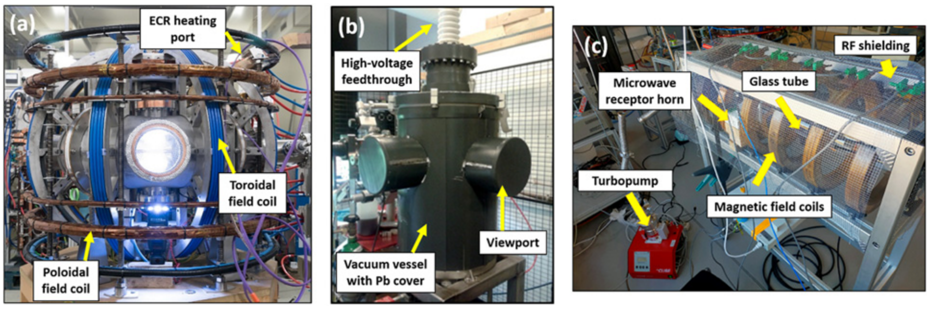

Figure 1. Photos of (a) the NORTH tokamak, (b) the DTU Fusor, and (c) the linear plasma device used in our teaching, with key components labelled.

probes, a Rogowski coil, optical cameras and diodes, optical and microwave spectrometers, and a residual gas analyzer.

In the DTU Fusor, a transparent cathode grid is suspended in a grounded cylindrical vacuum chamber of height 56 cm and diameter 36 cm. By applying a large negative voltage to the grid, plasma breakdown can occur, with the resulting ions performing an oscillatory motion through the grid until colliding with other particles or with the grid itself. Electrons remain confined by their Coulomb attraction to the ions. When the Fusor is operated with D gas at cathode voltages $V \geqslant 10$ keV, ions can undergo nuclear fusion in the device, with 50% of the reactions proceeding as $\mathrm{D} + \mathrm{D} \rightarrow {}^{3}\mathrm{He} + n$. The device is operated continuously in constant-current mode, with the maximum discharge voltage being limited by the input current. For a given gas species and cathode grid, students can control the background pressure and voltage/current. Standard diagnostics include optical cameras, a neutron detector, and an optical spectrometer, while an x-ray spectrometer has been used for a few selected discharges.

While both NORTH and the Fusor have formed the basis for a number of experimentally focussed BSc and MSc projects at our department—occasionally including publishable results—their use in the present course is more restricted; their involvement is mainly aimed at highlighting specific physics topics relevant for the study of laboratory plasmas and only secondarily as research devices for addressing open questions or for developing diagnostic techniques.

In the 2022 edition of our course, we have also incorporated a newly constructed linear plasma device. This consists of a cylindrical glass tube (length 1.0 m, diameter 10 cm), evacuated using a Pfeiffer vacuum HiCube integrated turbopump. Six coils of radius and separation 15 cm are supplied with a current up to 50 A to produce an axial magnetic field of $B \leqslant 0.1$ T for radial plasma confinement. Since the setup is otherwise unshielded, a wire mesh surrounds the glass tube to prevent unwanted transmission of radio-frequency (RF) waves into and out of the plasma. An azimuthal RF antenna operating at 13.56 MHz with a maximum input power of 1 kW is currently being commissioned for plasma breakdown and heating. Alternatively, the device can potentially be operated as a DC glow discharge using electrodes at the ends.

3. Educational activities

Student experiments with our three devices have been made an integral part of a redesigned course on plasma physics, now running as an elective full-semester (13 weeks) course at the M.Sc. education at DTU Physics. The course targets 4th- and 5th-year students, not necessarily with any prior knowledge of plasma physics, and provides a credit of five ECTS corresponding to one-sixth of the study activity of a semester.

3.1. Course content and structure

Our new course on experimental plasma physics [12] progresses through a series of lectures and written exercises covering basic plasma theory and plasma breakdown, sources and sinks of particles and energy in fusion plasmas, plasma heating, wave propagation, magnetic equilibrium in toroidal plasma devices, and plasma diagnostic methods. The associated exercises are custom-designed to support both the lecture material and the interpretation of experimental measurements to be taken during the course. These measurements are divided into four experimental sessions, in which small groups of 2–3 students conduct pre-defined experiments with clear learning objectives on the different plasma devices. Finally, students spend three weeks completing a more open-ended group-based experimental case/design study, in which they have some freedom to pursue specific open questions and design the experimental procedure—and if relevant, the necessary equipment—themselves.

3.2. Pre-defined experiments

This course element consists of four experimental activities, equally divided between NORTH and the Fusor, in order for students to become familiar with the operation and experimental analysis of both magnetically and electrostatically confined laboratory plasmas. For each experiment, students spend about 1 h in the lab per group under supervision, in addition to an estimated 7–8 h for preparation, data analysis, and report writing (see also section 5).

In the first experiment encountered by students in the course, students establish the conditions for plasma breakdown in the Fusor at a given background pressure p and electrode potential difference V. Among the relevant course learning objectives [12], this aims at promoting the ability to identify breakdown methods and passive diagnostics for lab plasmas. Modifying p, V, and the limiting electrode/plasma current I, the resulting breakdown voltage V_b is identified primarily by the onset of a finite plasma current and secondarily by visible means using an optical camera viewing the plasma. The measurements are compared to expectations for a Townsend discharge between plane-parallel electrodes, in the form of Paschen's law,

$$V_b = \frac{Bpd}{\ln(Apd) - \ln[\ln(1 + 1/\gamma)]}, \tag{1}$$

where d is the electrode separation, γ is the secondary electron emission coefficient for the relevant electrode material and gas species, and A and B are gas-specific parameters. Figure 2 shows example measurements taken by students in the course. The measurements indicate a power-law dependence of V_b on p at low pressure (associated with the lower frequency of ionizing collisions at lower p), as well as a flattening or slight rise at higher p (due to the average particle energy gained between collisions slowly decreasing with increasing p). However, the results are only qualitatively similar to the expectation of equation (1), encouraging students to reflect on possible causes such as the non-planar electrode geometry and non-uniform electric field in the Fusor, the dependence of γ on ion energy, and the possible presence of impurities in the plasma.

Plasma breakdown is also studied on NORTH, here driven by ECR heating. The capacitor banks that provide current I in the toroidal field coils are slowly discharged, allowing several plasma discharges in rapid succession at progressively lower on-axis magnetic field B.

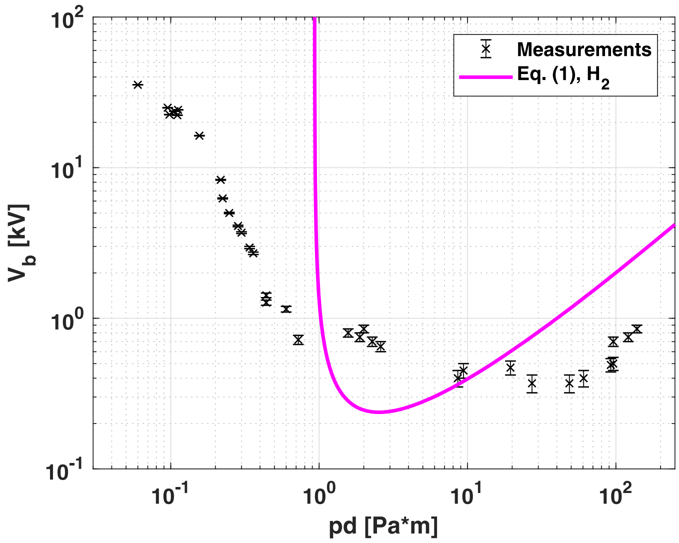

Figure 2. Student measurements of breakdown voltage in the DTU Fusor as a function of the product pd, for a spherical Ti cathode grid in H_2 gas. The results assume $d = 0.2$ m. Solid curve shows the corresponding expectation from equation (1), assuming $A = 3.83$ m^{-1} Pa^{-1}, $B = 93.8$ V m^{-1} Pa^{-1}, and $\gamma = 0.03$ [14].

From Ampere's law in the relevant toroidal geometry, and ignoring Doppler effects (currently negligible in NORTH), the n'th harmonic of the ECR frequency is

$$\omega_{\rm ce}(r,t) = n\frac{q_{\rm e}\mu_0 N I(t)}{2\pi r m_{\rm e}}, \tag{2}$$

where μ_0 is the magnetic permeability, $N = 96$ is the total number of windings in the field coils, r is the radial distance from the centre of the torus, and $q_{\rm e}$ and $m_{\rm e}$ is the elementary charge and electron mass, respectively. Decreasing $I(t)$ between discharges thus moves the ECR location (and harmonics thereof) radially inwards at fixed injected microwave heating frequency $\omega_0 = \omega_{\rm ce}(r,t)$. Students identify breakdown for a range of pressures and resonance locations by means of a photo diode voltage, aided by measurements of the floating potential from a Langmuir probe and of current in a Rogowski coil. As shown in figure 3, this establishes that breakdown occurs only when the $n = 1$ resonance location lies inside the vacuum vessel, thus motivating the realization that externally applied power is required to achieve breakdown in NORTH in the absence of a solenoid-driven toroidal emf. Students also identify the greatly reduced breakdown efficiency for $n = 2$ O-mode heating, promoting considerations on the lower optical thickness of this resonance. The associated learning objectives, in addition to those listed above, comprise the ability to explain heating methods and wave propagation in magnetically confined lab plasmas, and more broadly to analyse experiments on NORTH.

A further experiment on NORTH involves Langmuir probe measurements of electron temperature $T_{\rm e}$ and density $n_{\rm e}$, along with plasma floating potential. In large tokamaks, Langmuir probes can normally only be used for measurements at the plasma edge, but the low temperature in NORTH renders such probe measurements possible across the plasma volume. The

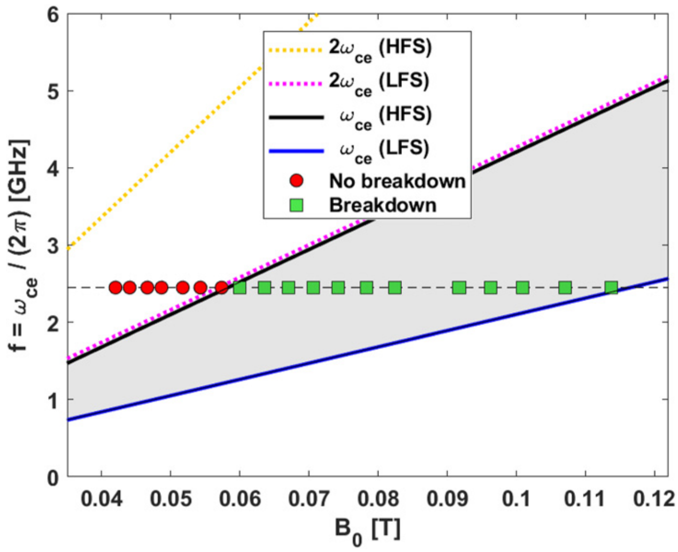

Figure 3. Identification of plasma breakdown in NORTH as a function of on-axis magnetic field for He discharges #4073–#4075 at neutral pressures 0.2–1.0 μbar. Shaded region marks the parameter space in which the $n = 1$ ECR is located between the LFS and HFS walls of the tokamak. Data points are (arbitrarily) shown at frequencies corresponding to the ECR heating frequency of $f = \omega_0/(2\pi) = 2.45$ GHz.

current I flowing through the biased probe head with area A is obtained by measuring the voltage drop V across a serially connected resistor. By sweeping the bias voltage and hence I within a discharge, students obtain I–V curves from which the ion saturation current I_{sat} and n_{e} and T_{e} at location x can be obtained from

$$I_{\mathrm{e}} = I - I_{\mathrm{sat}} = n_0 q_{\mathrm{e}} A \sqrt{\frac{kT_{\mathrm{e}}}{2\pi m_{\mathrm{e}}}} \exp\left(\frac{-q_{\mathrm{e}}|\bar{\phi}(x)|}{kT_{\mathrm{e}}}\right) \tag{3}$$

for a thermalized plasma with total particle density n_0, a probe potential $\bar{\phi}(x)$ relative to the local plasma floating potential, and where k is Boltzmann's constant. Figure 4 shows examples of results based on automated fitting of the I–V curves obtained from several He discharges. Furthermore, NORTH is operated without a toroidal plasma current or vertical magnetic field in this experiment, so a significant outwards radial plasma transport results from the uncompensated $\vec{E} \times \vec{B}$ drift in the device. Students can verify this using probe measurements taken on either side of the ECR position and noting the higher density on the outboards side, as seen in figure 4. Hence, this experiment connects with learning objectives involving measurements of basic laboratory plasma properties using active and passive diagnostics, in addition to reinforcing the students' ability to describe plasma confinement and magnetic equilibria in toroidal devices.

The typical electron temperatures in NORTH of ≈10–20 eV, as seen in figure 4, are too low to allow nuclear fusion. To incorporate an experimental fusion element, students conduct a second experiment on the Fusor, where ion energies up to 60 keV are possible. Here, nuclear fusion involving D ions with density n_{D} can take place in the form of ion–ion fusion (fusion power $P_{\mathrm{fus}} \propto n_{\mathrm{D}}^2 \propto I^2$) or between ions and quasi-stationary neutral D atoms with density n_{n} ($P_{\mathrm{fus}} \propto n_{\mathrm{D}} n_{\mathrm{n}} \propto I$). Here I is the current of the recirculating ions in the device. Measurements

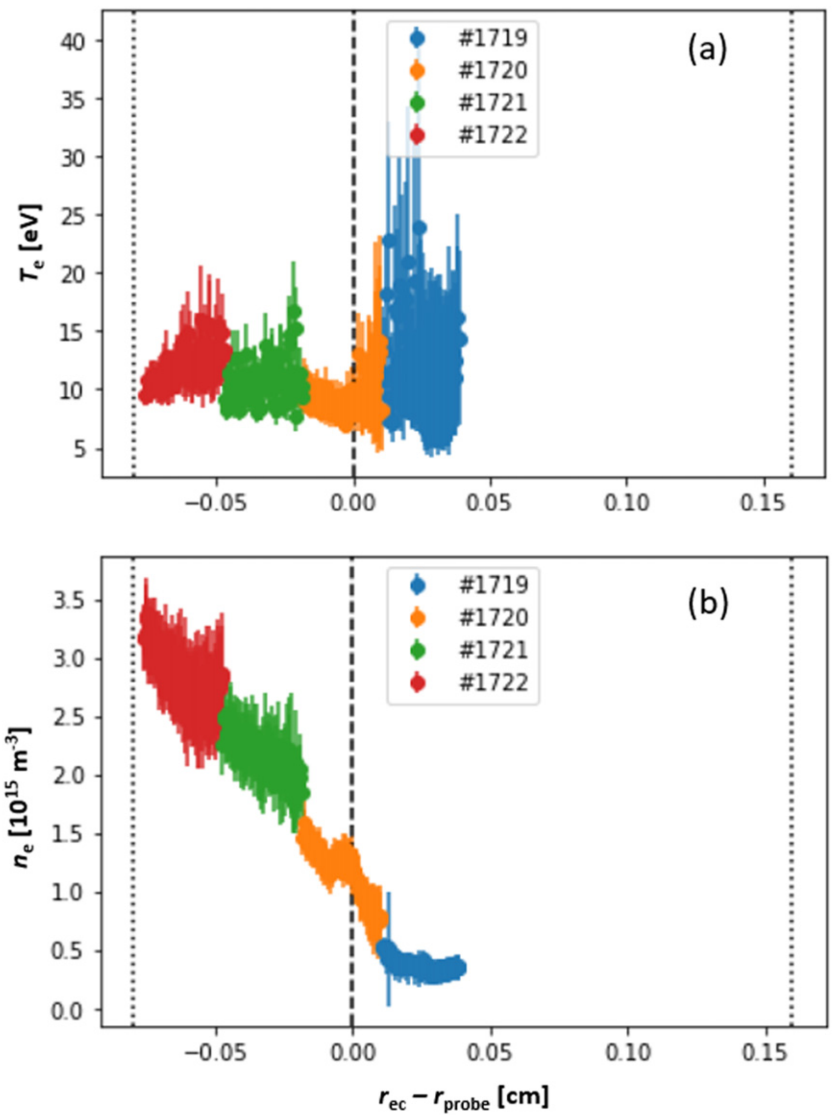

Figure 4. (a) Electron temperature and (b) density based on Langmuir probe measurements in NORTH discharges #1719–#1722. Results are shown as a function of the distance between the ECR location r_{ec} and the probe location r_{probe}, where negative values imply an ECR location further inboard than the probe. Since the NORTH field-coil current decays slightly within discharges, even a fixed probe position allows measurements at many values of $r_{ec} - r_{probe}$. Dotted lines mark the locations of the (left) HFS and (right) LFS walls.

of neutron rates are made using a neutron detector at varying current and approximately fixed voltage and neutral pressure. From the observed linear behavior of P_{fus} with I, students are then able to identify ion–neutral fusion—involving a mixture of D^+, D_2^+ and D_3^+ for the ions and D and D_2 for the neutrals [15]—as the dominant fusion process in the Fusor, see figure 5(a) for an example.

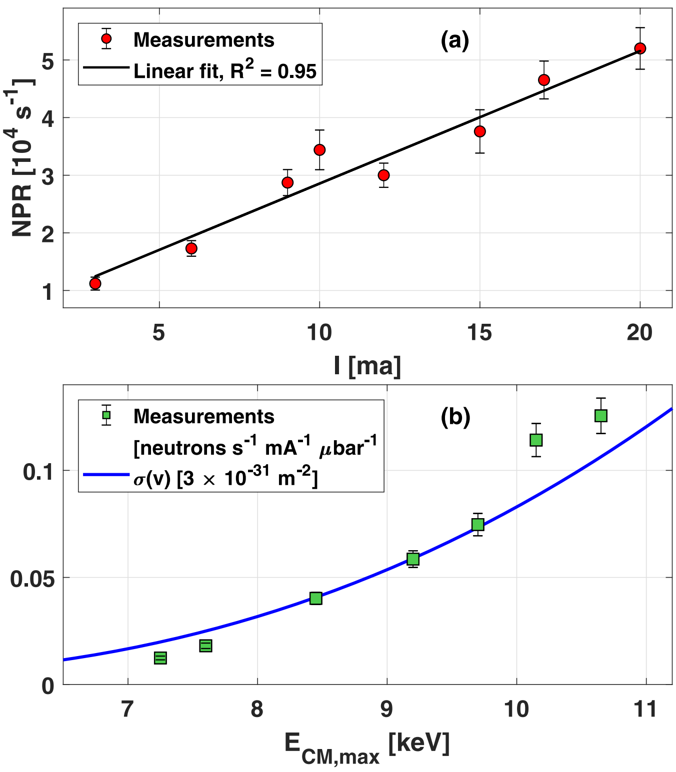

Figure 5. (a) Example measurements of neutron production rates *NPR* in the Fusor at fixed $V \approx 17$ kV as a function of plasma current. Observed rates are approximately linear with *I*. (b) Measured neutron rates normalized by current and neutral pressure as a function of the maximum center-of-mass energy $E_{\mathrm{CM,max}} = q_e V/2$ of the D reactants. Solid line shows a scaled parametrization of the D–D fusion cross section from [16].

With this result established, the fusion power density in the fusor, $S_{\mathrm{fus}} = E_f n_D n_n \langle \sigma v \rangle$, implies that the measurable quantity $P_{\mathrm{fus}}/(pI)$ scales linearly with the D–D fusion reactivity $\langle \sigma v \rangle$ at a given fusion product energy E_f. By conducting measurements at varying voltage (and hence maximum ion velocity v_{max}) at any I and p, students can verify the strong monotonic behaviour of $\langle \sigma v \rangle$ expected theoretically. If assuming mono-energetic ions at $v = v_{\mathrm{max}}$, a comparison to parametrizations of $\sigma(v)$ as taken from e.g. [16] can further be made as in figure 5(b). The activity also invites student reflections on how the measured fusion gain in the Fusor, $Q = P_{\mathrm{fus}}/P_{\mathrm{aux}} \approx P_{\mathrm{fus}}/(IV) \sim 10^{-9}$, compares to requirements for a future fusion power plant, thus linking to the learning objective that students can describe the main sources and sinks of power in fusion plasmas.

3.3. Larger experimental projects

The experimental activities in the course conclude with a more open-ended three weeks project with frequent supervisor interaction. In these, students have some freedom to design and evaluate different experimental options and steer the project in their direction of interest. These projects typically require at least two lab sessions each lasting 2–3 h (but significantly more for projects with a hardware development focus), with a typical total commitment per student

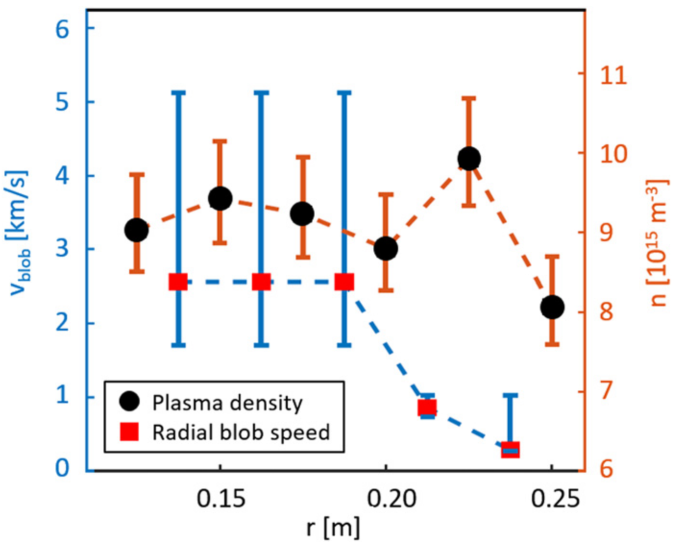

Figure 6. Profiles of plasma density and radial blob speed in NORTH discharge #4360 at $t = 0.511–0.512$ s. Uncertainties on blob speeds are obtained assuming half a point of uncertainty in the temporal index of the peak of the cross correlation.

estimated at ∼25–30 h including report writing. As described below, several of these projects have involved the design of basic plasma diagnostics for current, density, or temperature measurements, which represents the highest-level learning objective associated with the course [12]. Here we provide a brief description of example projects completed at each of our devices so far.

In an extension of the T_e and n_e measurements performed on NORTH (section 3.2), a Langmuir multi-probe array was designed and installed for measuring radial profiles of plasma density and temperature. Six probes fixed on a rod were inserted into NORTH along a horizontal line at one toroidal position, allowing simultaneous measurements at six locations equidistantly spaced across the outboard minor radius of the tokamak. The aim was to quantify the strong radial transport of plasma blobs expected in the device, based on the inferred propagation of density fluctuations between neighbouring probe locations. Students obtained *I–V* curves from each probe to obtain local density estimates, and computed pairwise cross correlations between the density evolution as measured by the individual probes at a sampling rate of 100 kHz. For each probe, the nearest neighbouring probe for which a temporal displacement could be discerned was then identified, enabling estimates of the radial blob speed in the tokamak at different times during a discharge. Example results are shown in figure 6. The inferred blob speeds represent a significant fraction of the ion sound speed $c_s = \sqrt{k(T_e + T_i)/m_i} \approx 10^4$ m s^{-1} for the relevant ion mass m_i and temperature $T_i \approx T_e$. This illustrates the substantial radial plasma transport caused by the $\vec{E} \times \vec{B}$ drift when operating NORTH without a toroidal plasma current.

On the Fusor, students have quantified the ion core convergence for different gases and cathode grids. This is evaluated based on measurements of the spatial distribution of visible light from excited neutrals [17]. This distribution, assumed intrinsically spherical, can be deprojected using Abel inversion in order to derive experimental estimates of the characteristic core radius r_c in the ion density distribution [11]. This allows identification of systematic

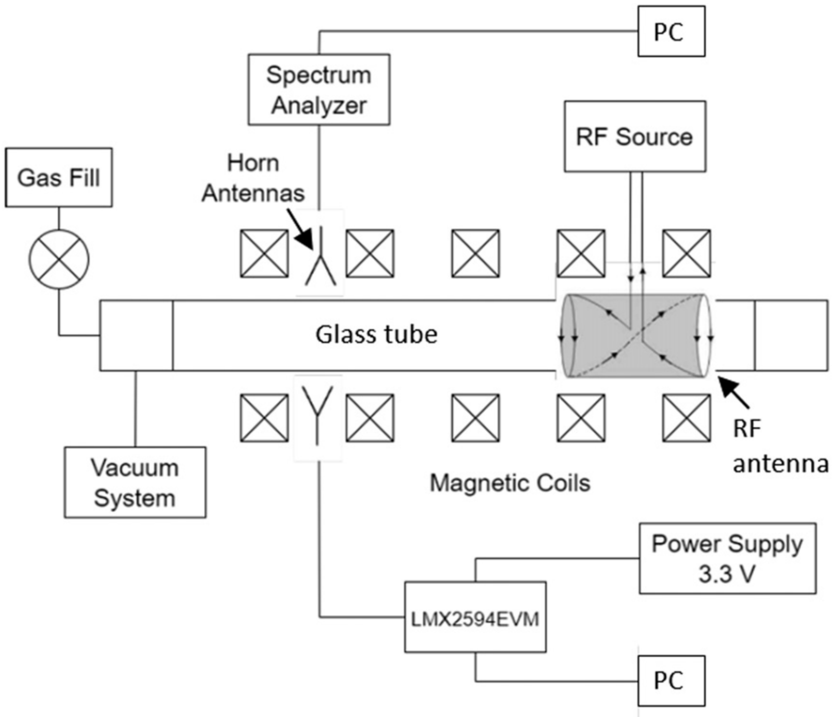

Figure 7. Setup of the linear plasma device, including components relevant for assessing microwave transmission through the plasma.

trends in the inferred r_c with operational parameters and cathode grid sizes/geometries. Given r_c, the measured grid current further allows a rough estimate of the core ion density n_i, and hence—for a quasi-neutral, isothermic H plasma ($n_e \approx n_i$, $T_e \approx T_i$)—the approximate electron Debye length

$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e q_e^2}} \tag{4}$$

at the cathode. Here ϵ_0 is the vacuum permittivity. Students can then compare λ_D to the scale of the grid openings, and the inferred r_c to predictions for a collisionless, spherically convergent ion flow in which ion angular momentum is the only source of defocussing of radial orbits [17]. This promotes reflections on the impact of particle collisions and asymmetries in the cathode electric field in establishing the observed ion trajectories in the Fusor. Findings include that more symmetric electric fields at the cathode (smaller grid openings) lead to improved core convergence, and that gas species with higher m_i are subject to a systematically larger defocussing at fixed operating parameters. The latter may be a consequence of the lower ion velocities for higher m_i at fixed rate and level of ionization (results have so far been recorded for H, N, and Ar, with comparable ionization energies in the range 13.6–15.8 eV), which would imply higher n_i in the core of the device and an increased efficiency of Coulomb scattering at higher m_i.

Practical training with RF and microwave systems is an integral part of several fusion education programmes [18]. As an example of incorporating this in our course, students have helped to devise a setup for assessing microwave transmission through our newly constructed linear plasma device, see figure 7. Injecting microwaves into the plasma using an LMX2594 wideband synthesizer and a horn antenna, and intercepting any transmitted radiation via a similar antenna on the opposite side, allows identification of the plasma cutoff frequencies at which the refractive index $N^2 \to 0$. By generating and detecting broadband spectra in both O- and X-mode polarization (or rapidly sweeping the emitted frequency), one can thus determine n_e and B in the plasma as a function of, e.g., input heating power and coil current. For this experiment, students also designed and manufactured single-loop and helical RF antennas, to be used for subsequent experiments with plasma breakdown and heating. Actual plasma measurements with the linear device will be integrated into future editions of the course.

4. Use in general BSc/Msc education

Besides their use in a new experimental course, our plasma devices offer opportunities for a wide range of student-driven research or development projects in plasma physics and fusion engineering. With proper preparation, we have been able to offer projects ranging from high-school and first-year university level to BSc/MSc Thesis studies on both NORTH and the Fusor. Examples of the former projects include experimental characterization of the turbopumps and mass flow controllers used to maintain the desired pressure in both devices; measurements of intensity ratios and of Doppler broadening of optical emission lines; and blackbody modelling of measured spectra of cathode grid glow in the Fusor to determine the grid temperature. These projects have allowed students hands-on experience with our devices at an early stage in their education, and have been important for attracting and maintaining students at later stages.

Regarding larger projects, an extensive research and development programme with substantial student involvement is being carried out on NORTH. The focus of such larger projects is typically on diagnostic development in support of the research strategy of NORTH which includes the study of microwave transport and plasma turbulence. However, also the understanding of basic electrodynamics in relation to tokamak operation can be trained during student projects on NORTH. Figure 8 shows an example from a student project characterizing and operating the central solenoid for inducing plasma current. Here the students developed their own model describing fast discharging of the capacitor banks through the solenoid. The model was first benchmarked by calculating and measuring the induced loop voltage above the plasma chamber (figure 8), and Rogowski coil measurements in He plasmas were subsequently used to demonstrate that a $\sim$300 A current was indeed induced in the plasma.

On the Fusor, which has been constructed from the ground up at DTU, students have also been involved in both commissioning of the device and larger experimental projects. Some of these studies have had a clear engineering focus, such as construction and characterization of the experiment and development of feedback-based pressure control. More theoretical studies include measurements and electrostatic (COMSOL [19]) modelling of ion orbits for different cathode grids, of plasma breakdown for comparison to measurements, and of optimizing the voltage-stalk design before subsequent manufacturing and implementation. This has been complemented by projects aimed at improving the physics understanding of the experiment, such as detailed characterization of fusion rates using different cathode grids and of Doppler broadening of spectral lines as a function of plasma conditions. Several of these projects have contributed to publishable research results [11], thus validating the potential for

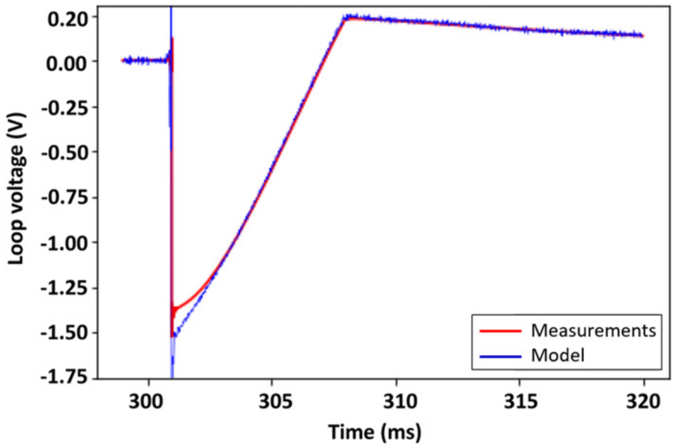

Figure 8. Timetraces of measured and simulated loop voltages in NORTH discharge #3450, where the solenoid was operated to induce plasma current from $t = 301–307$ ms during a 1.0 s discharge.

student-based activities—also at the undergraduate level—to make useful contributions to the study of laboratory plasmas.

5. Didactic reflections on course structure and student learning

When organizing the experimental course described in section 3, we placed heavy emphasis on clearly connecting lectures, exercises, and experiments with each other and with the learning objectives [12] and the final assessment form. The latter takes place as an individual oral exam, based on a randomly drawn experimental group report and including questioning in the full curriculum. The intention with this exam form is to enforce constructive alignment between the course assessment on the one hand and the learning objectives and course activities on the other. Furthermore, it promotes individual accountability for the group work and eliminates 'backwash', i.e. the concern that students prepare only for what they expect to be tested in.

A key element in the course is the extensive use of feedback to both students and teachers. This includes quizzes, polls, and small exercises during the lectures to enable students to test their understanding of the presented material and lecturers to adapt their teaching accordingly. In their groups, students also produce short reports on each conducted experiment, to which formative feedback is provided in time for students to reflect on this and apply it for the subsequent experiments. As such, the report writing serves not only to reinforce learning of the course material, but also promotes reflections on how to improve the interpretation and presentation of experimental results.

Based on metrics such as the correct answering rate in anonymous quizzes during lectures, the quality of the experimental group reports, and student performance at the final exam, students have generally met the learning objectives of the course to a highly satisfactory degree in both its iterations. Student satisfaction surveys also showed that the experimental activities were perceived to be very well aligned with the learning objectives and lecture material. The extensive use of feedback to students has also been well received, and adjustments to the teaching activities and styles based on continual *student-driven* feedback likely played a role in this.

However, some aspects of the course can still be improved. Due to extenuating circumstances (the COVID-19 pandemic), both iterations of the course had to be structured with all experimental activities following the initial six lectures. From a didactic perspective, this might be justified by a wish to gradually progress through Bloom's taxonomy levels [20], from levels 1–3 (knowledge → application) using lectures and exercises, through 2–4 (comprehension → analysis) during the subsequent pre-defined experiments, and to 4–6 (analysis, synthesis, evaluation) in the final project-based study. Nevertheless, feedback from students strongly indicated a desire to have lectures and experiments interspersed, allowing time for them to absorb and apply the lecture material in practical sessions before proceeding to the next topic. This structure was indeed our initial intention, and it would furthermore allow the accompanying exercise problems to become more firmly anchored in the experimental activities. We will pursue this in future course iterations.

A final consideration concerns the larger experimental project. The intention with this is to promote higher-level thinking skills [20], by requiring the students to design and subsequently evaluate different experimental options. Partly building on the previous experiment sessions, this activity also serves as didactical *institutionalization* [21] of these and of the course material at large. Whereas the initial pre-defined experiments are aimed both at developing students' lab skills and reinforcing relevant physics concepts—which is relevant since the experiments generally require high-level knowledge in order to conduct and interpret the measurements—the larger project is more specifically focussed on improving experimental skills and enhancing student agency during lab activities. Comprehensive statistical studies suggest that physics lab courses that emphasize this element rather than reinforcing already presented concepts tend to be more successful in improving student learning [22], at least at the undergraduate level. For these reasons, the project study will remain as an important concluding activity in the course. It is also clear that students enjoy the scientific freedom inherent in this, which enables them to take responsibility for more research-oriented activities at our experimental devices. Ultimately, this also serves to prepare them for more advanced studies at these and other plasma devices, including MSc projects such as those described in section 4.

Acknowledgments

We are grateful to Thomas Jensen and Riccardo Ragona for practical assistance with the student experiments described here.

ORCID iDs

Jesper Rasmussen https://orcid.org/0000-0002-3947-1518
Stefan Kragh Nielsen https://orcid.org/0000-0003-4175-3829

References

[1] Svoboda V, Huang B, Mlynář J, Pokol G I, Stöckel J and Vondrášek G 2011 Multi-mode remote participation on the GOLEM tokamak *Fusion Eng. Des.* **86** 1310–4

[2] Grover O, Kocman J, Odstrcil M, Odstrcil T, Matusu M, Stöckel J, Svoboda V, Vondrasek G and Zara J 2016 Remote operation of the GOLEM tokamak for fusion education *Fusion Eng. Des.* **112** 1038–44

[3] Stockel J, Cavalier J, Mlynar J, Hron M and Panek R 2021 More than 30 years of experience in fusion education at the institute of plasma physics of the Czech academy of sciences *Eur. J. Phys.* **42** 045703
[4] Varandas C A F *et al* 1996 Engineering aspects of the tokamak ISTTOK *Fusion Technol.* **29** 105–15
[5] Instituto Superior Técnico Lisbon 2021 ISTTOK tokamak training https://isttok.tecnico.ulisboa.pt/~isttok.daemon/index.php?title=Training (accessed September 2022)
[6] Princeton University 2014 Princeton plasma physics laboratory remote glow discharge experiment (RGDX) https://www.pppl.gov/remote-glow-discharge-experiment-rgdx (accessed September 2022)
[7] Oosterbeek J W 2011 Technical University of Eindhoven (TU/e) PlasmaLab https://plasmalab.eu/ (accessed September 2022)
[8] Choudhary M 2021 Perspective: dusty plasma experiments—a learning tool for physics graduate students *Eur. J. Phys.* **42** 053001
[9] Pasley J R *et al* 2020 Innovative education and training in high power laser plasmas (PowerLaPs) for plasma physics, high power laser matter interactions and high energy density physics: experimental diagnostics and simulations *High Power Laser Sci. Eng.* **8** E5
[10] Nielsen S K *et al* 2021 First results from the NORTH tokamak *Fusion Eng. Des.* **166** 112288
[11] Rasmussen J, Jensen T, Korsholm S B, Kihm N E, Ohms F K, Gockenbach M, Schmidt B S and Goss E 2020 Characterization of fusion plasmas in the cylindrical DTU inertial electrostatic confinement device *Phys. Plasmas* **27** 083515
[12] Nielsen S K and Rasmussen J 2022 Course webpage for the DTU course 'experimental plasma physics' https://kurser.dtu.dk/course/10401
[13] Salewski M and Nielsen A H 2022 Course webpage for the DTU course 'plasma physics' https://kurser.dtu.dk/course/10400
[14] Liberman M A and Lichtenberg A J 2005 *Principles of Plasma Discharges and Materials Processing* (New York: Wiley)
[15] Emmert G A and Santarius J F 2010 Atomic and molecular effects on spherically convergent ion flow: II. Multiple molecular species *Phys. Plasmas* **17** 013503
[16] Bosch H-S and Hale G M 1992 Improved formulas for fusion cross-sections and thermal reactivities *Nucl. Fusion* **32** 611–31
[17] Thorson T A, Durst R D, Fonck R J and Wainwright L P 1997 Convergence, electrostatic potential, and density measurements in a spherically convergent ion focus *Phys. Plasmas* **4** 4–15
[18] Hillairet J, Achard J and Ragona R 2020 Radio-frequency hands-on for nuclear fusion Master's students *Eur. J. Phys.* **41** 024001
[19] Comsol, Inc. 2017 *COMSOL Multiphysics® software v5.3* https://comsol.com/ (accessed September 2022)
[20] Bloom B S 1984 *Taxonomy of Educational Objectives: I. Cognitive Domain* (New York: Longman)
[21] Brousseau G 1997 *Theory of Didactical Situations in Mathematics* (Dordrecht: Kluwer)
[22] Wilcox B R and Lewandowski H J 2017 Developing skills versus reinforcing concepts in physics labs: insight from a survey of students' beliefs about experimental physics *Phys. Rev. Phys. Educ. Res.* **13** 010108