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Topical Review

A review of collaborative studies between the NSTX/-U and MAST/-U spherical tokamaks

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Abstract
The National Spherical Torus Experiment (NSTX) at the Princeton Plasma Physics Laboratory in the United States, and the mega ampere spherical tokamak (MAST) at the United Kingdom Atomic Energy Authority in the United Kingdom, and their respective upgrades (NSTX-U and MAST-U) are two MAST fusion devices that have operated roughly over the past two decades. Both devices have made significant contributions to understanding spherical tokamak (ST) plasma physics, and fusion plasmas in general, and both have contributed data to multi-machine database studies. Several diagnostics have been physically moved from one machine to the other by diagnostic teams working on both devices. Collaboration has benefited both research teams in the areas of operational expertise, scenario development, and equilibrium reconstruction techniques. More focused comparative studies between the two devices have been pursued over the years in many areas as well, including stability calculations, disruption characterization, pedestal and edge localized mode stability, confinement and transport, energetic particles, and heating and current drive modelling. Together NSTX/-U and MAST/-U set the stage for the future of STs, which is entering the phase of design of demonstration power plant devices.

Keywords: spherical tokamak, NSTX-U, MAST-U

1. Introduction

A spherical tokamak (ST) is a device which produces energy from fusing hydrogen isotope ions in plasmas that are heated to millions of degrees, and held away from material walls with magnetic fields which are created by a combination of external magnets and a current in the plasma itself. Tokamaks have a toroidal shape, and STs have a smaller aspect ratio (the ratio of the major to minor radius) that is often compared to a cored apple, rather than a doughnut shape of conventional aspect ratio tokamaks. There are multiple advantages to lower aspect ratio tokamaks: because they have a physically smaller engineering structure per plasma volume, they can be lower cost to build, and because of the way the magnetic field lines spiral around the device, particles spend more time near the inner surface with more stable curvature and less time near the outer surface with less stable curvature, meaning that

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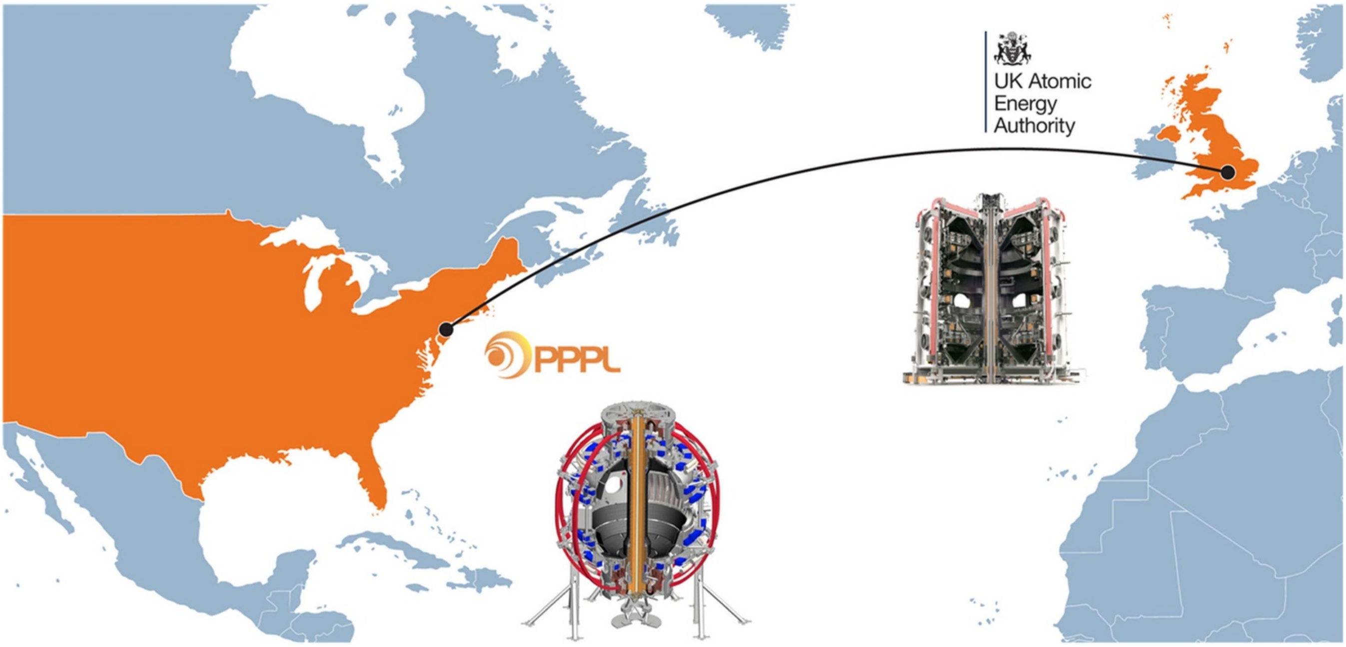

Figure 1. Schematic of NSTX-U, at the Princeton Plasma Physics Laboratory in Princeton, NJ, USA and MAST-U at the United Kingdom Atomic Energy Authority in Culham, UK.

higher pressures can be obtained more stably in STs. There are also certain challenges to STs: smaller surface area leads to a challenge with handling the heat flux emanating from the plasma, and lack of space in the core for a transformer coil leads to challenges starting up and maintaining the plasma current for a long pulse.

STs began to be designed and explored experimentally after these theoretical advantages were realized, to test the theory. The first larger scale ST to be built, in the early 1990s, was the Small Tight Aspect Ratio Tokamak, or START, in the UK. START achieved record levels of beta [1], the ratio of plasma pressure to magnetic pressure, and launched the era of mega-ampere plasma current class STs, from 1999 to the present day. Numerous smaller, or university-scale ST devices have been built over the years in various countries (US, Japan, Russia, Korea, Spain, and more), working on important aspects of ST physics and engineering challenges, but these will not be discussed in the present paper.

The two mega-amp class devices that operated during that time were: the National Spherical Torus Experiment (NSTX) [2] at the Princeton Plasma Physics Laboratory in the United States, and the mega amp ST (MAST) [3] at the United Kingdom Atomic Energy Authority in the United Kingdom (see figure 1). These two devices (and their upgrades NSTX-U [4] and MAST-U [5], see table 1) are the focus of the present review, and they will each be described in detail next, but in particular this paper reviews all the collaborations and comparisons between the two devices over the years and the benefits obtained from the comparative studies. Since 2007 these collaborations (including other STs as well) have been formalized through the International Energy Agency's Implementing Agreement for Co-operation on Spherical Tori.

Even as the two major STs are in their upgrade years, the future era of ST design and research is beginning. In China, the company ENN has developed an ST device called EXL-50 [6]. In the United Kingdom a private company, Tokamak Energy, has built and operated a research device ST40 [7], which has recently achieved a milestone of 100 million degrees plasma temperature [8], and has plans for an ST with superconducting magnets to increase the magnetic field. The UK government has committed to a ST for Energy Production (STEP), the design of which is underway [9, 10]. In the US, design studies are also progressing with the goal towards a demonstration power producing device as well [11, 12].

The United States and United Kingdom have recently formalized a collaboration agreement on fusion energy, but the research highlighted here demonstrates that, as far as their flagship STs are concerned, productive and continuous collaboration has already been proceeding for many years.

This review is presented as follows. First, the two devices and their upgrades are briefly summarized. Then the comparative studies between the two are outlined, starting with overviews and topical reviews of ST physics and inclusion in multi-machine databases. After those sections, the focus of the rest of the present paper is different, concentrating specifically on collaborative work between the two devices, but encompassing many topics of study. These include diagnostics, scenarios, control, equilibrium reconstruction, stability, disruptions, H-mode, pedestal, edge-localized modes, scrape-off layer (SOL), divertor, transport, confinement, fusion performance, heating and current drive, and energetic particles.

Table 1. Comparison of parameters between NSTX, NSTX-U, MAST, and MAST-U.

	NSTX	NSTX-U[a]	MAST	MAST-U[a]
Major radius (m)	0.85	0.94	0.85	0.82
Aspect ratio	1.3	1.7	1.3	1.56
Toroidal field (T)	0.5	1	0.5	0.8
Plasma current (MA)	1	2	1	2
Heating (MW)	6 (NBI) 4 (HHFW)	12 (NBI) 6 (HHFW)	5 (NBI) 0.1 (EBW)	10 (NBI) 1.6 (EBW)
Wall/divertor	Carbon, Lithium coatings	Carbon, Lithium coatings (+liquid)	Carbon	Carbon, Super-X geometry

[a] Planned full capability.

2. NSTX/-U and MAST/-U

2.1. NSTX/-U

The NSTX operated at the Princeton Plasma Physics Laboratory from 1999 until 2010. Nominally, the major radius of plasmas in NSTX was 0.85 m, the aspect ratio >1.3, the toroidal field 0.5 T, and the plasma current 1 MA. The device was upgraded with the intention of doubling the toroidal field, plasma current, and beam heating, and increasing the pulse duration, with only a slight increase in major radius and aspect ratio. The upgraded machine, NSTX-U, operated from 2015–2016 before a short in a coil necessitated a shutdown.

Though NSTX/-U and MAST/-U are in many ways similar devices, they also have unique capabilities. Some examples for NSTX are as follows. Because of its high heating power, NSTX achieved high normalized beta (peak $\beta_N > 7$ and flat-top average $\beta_N > 5.5$), and therefore made great advances in the study of high beta instabilities, like the resistive wall mode (RWM) [13–16]. NSTX also had unique capabilities like the ability to study lithium as a surface coating and its effect on plasma performance [17–19], a gas puff imaging (GPI) diagnostic to study edge plasma turbulence [20, 21], and a unique high-harmonic fast wave (HHFW) antenna for heating [22, 23]. NSTX was the largest experiment to explore coaxial helicity injection (CHI) for plasma start-up [24]. Recent overviews of NSTX-U research can be found in [25–27].

2.2. MAST/-U

The MAST operated at the Culham Centre for Fusion Energy from 1999 to 2013. Nominally, the specifications of MAST were similar to NSTX, with a major radius of about 0.85 m, aspect ratio of >1.3, toroidal field around 0.5 T, and plasma current on the order of 1 MA as well. MAST was also upgraded to MAST-U with the intention of larger toroidal field, plasma current, and pulse length. MAST-U began operation in 2020.

Crucially the addition of many more poloidal field coils and expanded divertor chambers allowed for flexible divertor configurations including the Super-X divertor [28]. The Super-X divertor is a unique capability of MAST-U and great progress has been made in utilizing and understanding it [29, 30]. MAST had other unique capabilities, including an extensive array of internal coils to apply resonant magnetic perturbations (RMPs) to control edge localised modes (ELMs) [31, 32], and a design that enabled wide-angle imaging of turbulence in the plasma boundary and ELMs [33, 34]. MAST was also the largest experiment with merging-compression plasma start-up [35]. A recent overview of MAST-U research can be found in [36].

3. Comparative studies

3.1. Overview and topical reviews of ST physics

Various ST overviews over the years have heavily featured results from NSTX/-U and MAST/-U. Some examples include the following.

- In 2001, the still fairly new idea of STs was reviewed by Gusev [37].
- In 2003 the advances in ST research from the new NSTX and MAST devices were explained for a Japanese audience by Takase [38]. Japan would go on to be the site of multiple university-scale ST research programs.
- Similarly, in 2009 Lloyd [39] laid out the advances in ST research, focusing on MAST and NSTX, for a engineering oriented audience at the Symposium on Fusion Engineering.
- A review article on worldwide ST research was published by Ono and Kaita in 2015 [40].
- A joint presentation between the two machines was made most recently at the 2018 IAEA Fusion Energy Conference [41].

Some topical reviews also already exist for different aspects of ST physics, and generally these also include more STs than just NSTX/-U and MAST/-U. Some examples include the following.

Raman and Shevchenko [42] reviewed solenoid-free plasma start up in STs, with emphasis on CHI on NSTX, and the merging-compression and electron Bernstein wave (EBW) methods on MAST. In the transient CHI method currents are driven along magnetic field lines that connect the inner and outer divertor plates on one end of the machine. About 200 kA of closed flux current was generated using the transient CHI method on NSTX, but due to changes in the machine this research will not be carried forward in NSTX-U, rather other STs such as QUEST and Pegasus-III will continue to investigate helicity injection. About 400 kA of closed flux currents were generated on MAST with merging compression, but it uses poloidal field coils inside the vacuum vessel

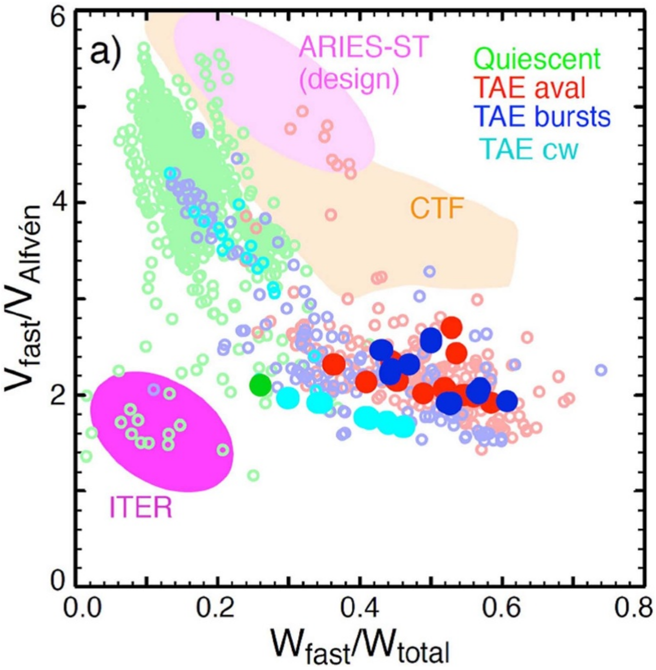

Figure 2. Parameter space of toroidal Alfvén eigenmodes detected in NSTX (open circles) and MAST (filled circles). Reproduced from [43]. © IOP Publishing Ltd. All rights reserved.

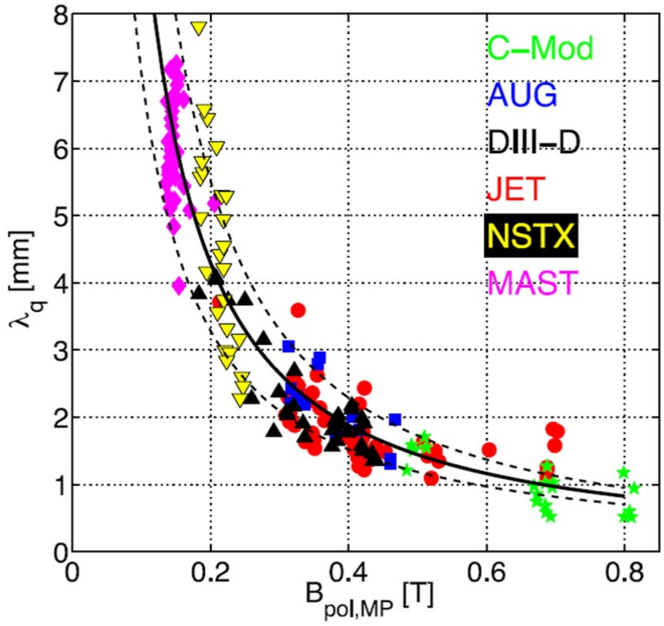

Figure 3. Poloidal magnetic field at the outer midplane versus power fall-off length (λ_q) from [50]. NSTX and MAST provided data at lower B_{pol} and higher λ_q, contributing importantly to the regression. Reproduced courtesy of IAEA. Figure from [50]. Copyright (2013) IAEA.

to generate two rings of plasma that then reconnect and merge to form a tokamak-like plasma. This method does not seem practical in an FPP, so EBW start-up studies will continue on MAST-U instead.

Energetic particle (EP) physics in STs was reviewed by McClements and Fredrickson [43] more specifically than an earlier, more general overview of EP physics from Gorelenkov *et al* [44], which also included NSTX and MAST data. Due to their low magnetic fields, STs with neutral beam injection, such as NSTX and MAST, have EPs with speeds exceeding the Alfvén velocity (see figure 2), thus providing strong drive for Alfvénic instabilities. These, together with bulk plasma-driven instabilities, can cause EP redistribution and loss. Experimental results were used for validation and verification efforts for several computational tools such as NOVA, HINST, MISHKA, M3D-C1, NUBEAM and others. The observations also deepen understanding of EP confinement in regimes close to burning plasmas in tokamaks where fast ions are expected to be super-Alfvénic.

Kaye *et al* [45] reviewed thermal confinement and transport in STs, finding that energy confinement time for both NSTX and MAST showed a stronger scaling on toroidal magnetic field than on plasma current. This built upon previous work [46] in which the addition of the low aspect ratio STs to confinement datasets opened a new scaling dimension with aspect ratio, but it was found to be highly correlated with β. ST confinement will be discussed in more detail in section 3.10.

3.2. Multi-machine tokamak database studies

Naturally, NSTX/-U and MAST/-U data have been included in larger multi-machine tokamak database studies over the years. Generally these studies also include higher aspect ratio devices, and often the inclusion of STs provides the ability to consider aspect ratio as a parameter in various analyses. From the beginning it was recognized that STs have unique physics [47], and that they provided an opportunity to remove degeneracies or provide further physics understanding in multi-machine studies [48].

Some examples of multi-machine studies which included both NSTX/-U and MAST/-U are the following. Though it would be difficult to include all such studies, some are included here, where we have made an effort to include recent references so that the interested reader can follow the development of the work from the references therein.

Chapman *et al* [49] included MAST and NSTX data in a multi-machine database that was aimed at determining an acceptable sawtooth period to avoid triggering neoclassical tearing modes (NTM). A critical β_N at which a sawtooth crash will trigger an NTM was derived.

NSTX and MAST data were similarly included in a multi-machine database (see figure 3) by Eich *et al* [50] for the H-mode SOL power fall-off length, λ_q, an important parameter to know for understanding how ITER and other future devices will manage their heat loads. The STs provided data at the larger end of λ_q, and it was found that the same inverse proportionality on poloidal magnetic field at the outer mid-plane held, and an aspect ratio dependence was uncovered [50].

Chapman *et al* compiled databases of three dimensional plasma boundary displacements induced by applied non-axisymmetric RMPs [51] and saturated MHD instabilities [52]. In NSTX the RMP induced displacements were relatively small and consistent with three dimensional equilibrium

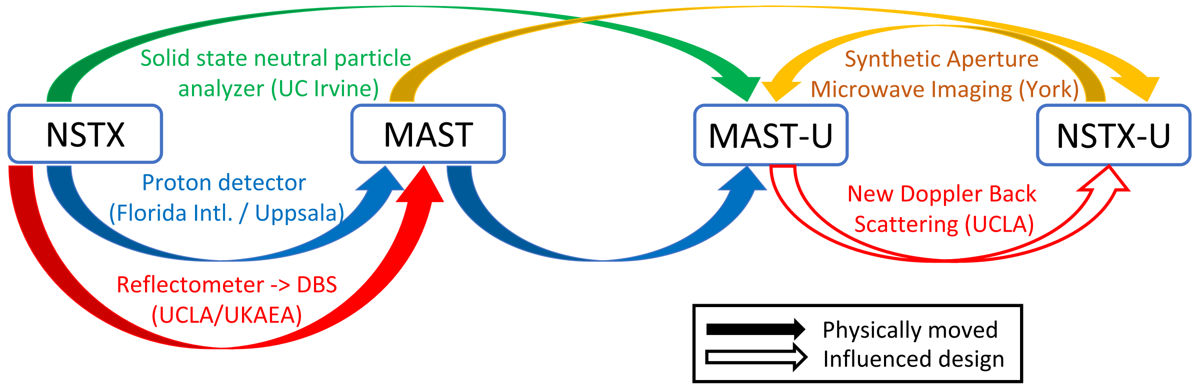

Figure 4. Schematic of some of the physical movement of diagnostics between the different devices and also the design work by the same teams on both.

modelling, while in MAST with larger resonant applied field they were significant, but were also still underpredicted by modelling. Displacements induced by internal and external kink modes in NSTX were again relatively modest, while in MAST they could be significant, which was attributed to cases with low rotation.

The disruption characteristics of multiple tokamaks were studied by Eidietis *et al* [53]. NSTX and MAST were generally found to have lower area-normalized current quench duration times, below the lower ITER design limit, than the conventional tokamaks, but they also generally exhibited lower toroidal peaking factors of halo currents and lower halo current fractions as well [53].

Liu *et al* [54] included both NSTX and MAST data in a compilation of high frequency sensor signal noise for the purpose of design of the feedback control system for RWMs in ITER. In this case aspect ratio did not factor into the collected data, the STs simply contributed valuable data points to the scoping study.

In 2021, Verdoolaege *et al* [55] contributed the latest in a long series of studies on H-mode confinement in tokamaks. Though much of the focus of multi-machine database inclusion of STs is on increasing the range of aspect ratios in the database (as it also is here), in this case the authors also point out the utility of the NSTX and MAST data for increasing the range of toroidal beta, β_t, and cylindrical safety factor, q_{cyl}.

Finally, Wurzel and Hsu [56] presented a review of the Lawson criterion of fusion ignition in which many fusion devices were represented, including NSTX and MAST for STs.

As mentioned, ST confinement and also fusion triple product density time temperature time energy confinement time, $nT\tau_E$, will be discussed further in section 3.10.

3.3. Diagnostic development and sharing

Different periods of operation/outages between the two devices over the years allowed for the opportunity for diagnostics developed and tested on one device to be moved to the other. An overview is shown in figure 4.

A proton detector originally developed for NSTX [57] was installed in MAST [58], where it was used to investigate the redistribution and loss of fast ions [59] and a discrepancy between predicted and measured D-D fusion product rates, which identified possible overestimates of the neutron emissivity in the NUBEAM model in TRANSP [60]. The diagnostic was later upgraded and used on MAST-U as well [61].

Similarly, an array of reflectometers was developed and deployed on NSTX [62], where it was used to measure the structure of Alfvén eigenmodes (AEs) and coupled kink and tearing modes. Later this diagnostic was moved to MAST and the same AE structures were measured there (see figure 5) [63]. The diagnostic was then expanded in capability as a Doppler back scattering (DBS) diagnostic [64], with the ability to also operate as a cross-polarization scattering (CPS) diagnostic to measure turbulent magnetic fluctuations that scatter the incident beam into the orthogonal polarization. This diagnostic was used to measure large poloidal flows in internal transport barriers and the wavenumber spectrum of density fluctuations at scales below the ion gyroradius [65]. Additionally, measurements of density fluctuations (via DBS) and magnetic fluctuations (via CPS) were compared to theory for microtearing modes [66], and DBS measurements of flows which were compared to a model of the collisionality dependence of the radial transport of toroidal angular momentum [67].

Subsequently, because of the timing of the upgrades, the experience of developing new reflectometer [68] and DBS systems for MAST-U [69, 70] was able to turn back around and influence the design of the new diagnostic for NSTX-U [71]. Theory predicted, and the MAST-U DBS data confirmed, that as the DBS poloidal angle (and hence the measured $\tilde{n}$ wavenumber) increased a larger toroidal angle DBS launch was required (otherwise the signal can decrease into the noise level). This informed the design of the DBS system for NSTX-U with an adjustable toroidal launching angle.

A synthetic aperture microwave imaging diagnostic was originally deployed on MAST [72], where it observed bursts of microwaves during edge localized modes (ELMs) [73]. The diagnostic was later moved to NSTX-U where the feasibility of measuring the edge pitch angle with 2D DBS

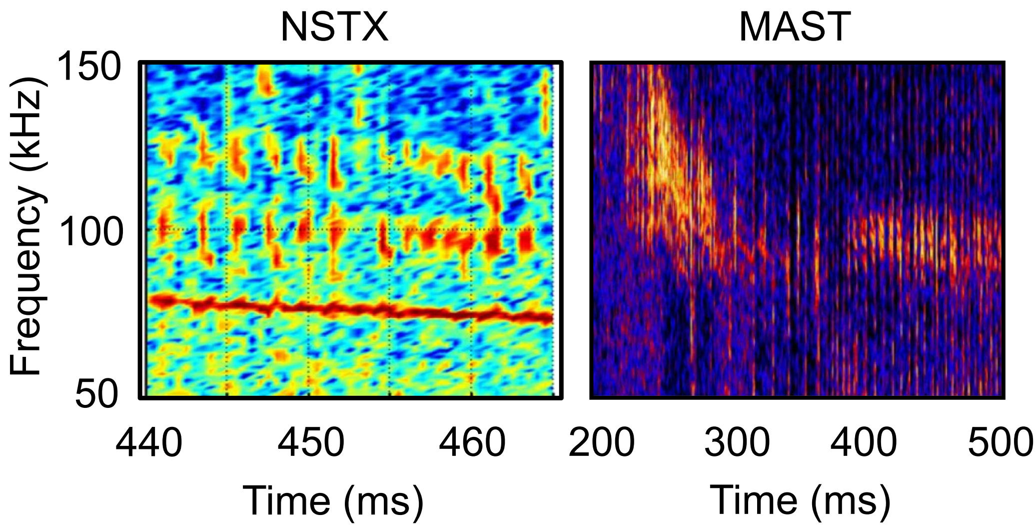

Figure 5. Density fluctuation spectrograms showing toroidal Alfvén eigenmodes for (left) NSTX and (right) MAST, measured with the same millimeter wave diagnostic, which was configured as a reflectometer on NSTX and a Doppler backscattering system on MAST. Note that while the frequency axis is the same, the time axis is quite different between the two spectrograms. The NSTX case is a reflectometry $\tilde{n}$ spectrum, while the MAST case is a Doppler back scattering $d\tilde{\varphi}/dt$ spectrum (of which $\tilde{n}$ is the dominant component). Reproduced from [62]. © IOP Publishing Ltd. All rights reserved. Reproduced with permission from [63].

was demonstrated [74]. The system was then upgraded and deployed on MAST-U [75].

Finally, a solid state neutral particle analyser from NSTX [76] was moved to MAST-U [77], where it was subsequently used to diagnose fast particle losses [78], with a new method of separating the active and passive parts of the signal [79].

3.4. Operational scenarios, control, and equilibrium reconstruction

Each device had an upgrade outage, and when MAST-U returned to operation while NSTX-U was still not operating, collaboration with the operational and equilibrium reconstruction teams from NSTX, and a control team which is engaged with both machines helped accelerate the development of plasma scenarios in MAST-U to accelerate physics studies.

Battaglia *et al* [80] created a reduced model for plasma breakdown which considered prefill gas and time-dependent vacuum field calculations, which helped MAST-U in initial first-plasma attainment. Induced currents and flux surfaces from this model for NSTX/-U and MAST/-U are shown in figure 6. Plasma initiation was later revisited for MAST-U with the DYON code [81].

Berkery *et al* [82] applied equilibrium reconstruction techniques developed on the experience of NSTX/-U to MAST/-U. Additionally, the induced current model used for MAST-U equilibrium reconstructions was benchmarked by Kogan *et al* against the VALEN code techniques used for NSTX/-U [83]. This work helped inform the interpretation of MAST-U magnetic signals as well [84].

In 2023 then used the MAST-U equilibria were subsequently used by Berkery *et al* [85] to create operational space diagrams of the first physics campaign of MAST-U, in some cases comparing to limits derived from NSTX experience.

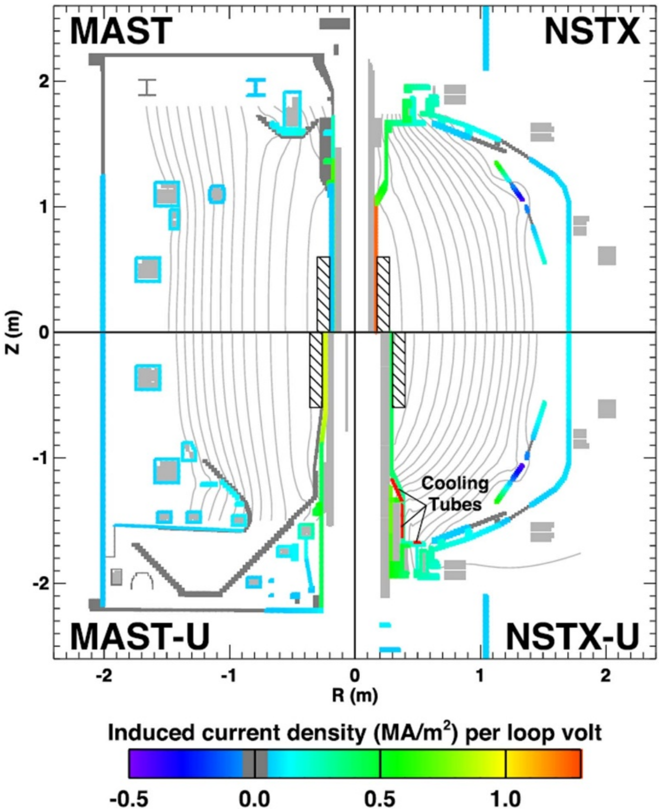

Figure 6. Current density induced in the toroidal structures, and flux surfaces due to the induced current for each device, as modelled from Reproduced courtesy of IAEA. Figure from [80]. Copyright (2019) IAEA.

Control of the plasma shape in the challenging environment of MAST-U advanced divertor configurations was achieved with the help of a team from the United States

[86]. Members of this same team are already engaging with NSTX-U to prepare for control of scenarios when it resumes operating [87, 88].

Finally, achieved plasma scenarios in NSTX/-U and MAST/-U have been used to inform and inspire other current machines, such as GLOBUS-M2 [89], or future STs, such as STEP [90].

3.5. Global stability limits and disruptions

In recent years, the pause in operations of NSTX-U allowed a team of researchers from the United States to fill a need in the MAST-U team for expertise in stability and disruptions.

First, the kinetic RWM stability codes MISK and MARS-K were benchmarked by the code authors Berkery and Liu, *et al* [91]. Though that particular reference did not explicitly analyse both NSTX and MAST data, it is mentioned here because it solidified the foundation of kinetic RWM stability calculations and was instrumental in the main authors being awarded the Landau-Spitzer award for collaboration between Europe and the United States of America. MISK was used extensively to analyse NSTX stability [92] while MARS-K was primarily used for MAST/-U [93], but also in one case for NSTX [94].

In a related extension, Piccione *et al* [95] developed a neural network that trained on a database of stability calculations from NSTX and emulated a previous derived [96] reduced model for ideal magnetohydrodynamic stability. When the NSTX-trained algorithm was applied to MAST data it performed well for a small amount of test cases [93].

The newly developed disruption event characterization and forecasting (DECAF) code [97] was used by Sabbagh *et al* [98] to compare the disruptivity of NSTX and MAST plasma databases, finding that in both cases by the time of the disruption the β_N is generally already reduced by preceding events, so it is best to examine the chain of events leading to disruption.

Later, some of the specific events were examined in more detail. First, Berkery *et al* [99] considered the Greenwald density limit for databases of NSTX and MAST discharges, as well as a local island power balance criteria for NSTX, which was found not to be an improved criteria yet, and both an empirical critical edge line density and a boundary turbulent transport limit for MAST-U, which were found to be potentially useful for a real-time disruption forecasting system.

Zamkovska *et al* [100] used large databases of discharges from both NSTX-U and MAST-U to characterize abnormalities in plasma vertical position and current leading to disruptions, with the DECAF code. Disruption causes and rates were found to be particular to the both the plasma state and operational differences between devices and campaign years; see for example figure 7.

Similarly, Tobin *et al* [101] used databases from both MAST-U and NSTX to create a data-driven approach to identify vertical displacement events with a high degree of accuracy.

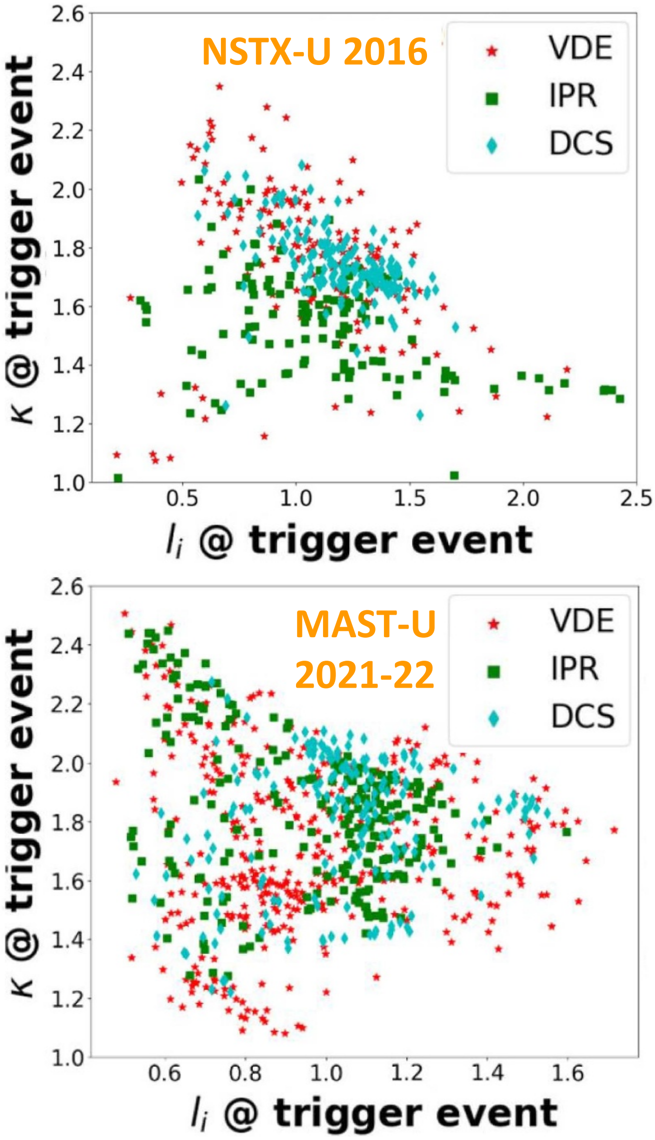

Figure 7. Disruption trigger event occurrence (VDE: vertical displacement event, IPR: plasma current not meeting request, and DCS: disruptive current spike) for (top) NSTX-U 2016 database, and (bottom) 2021–22 MAST-U database. Reproduced from [100].

3.6. H-mode, pedestal stability, and ELMs

The high confinement H-mode can be beneficial to plasma performance by creating a pedestal which elevates the plasma pressure inside the confinement region, but can also lead to detrimental ELMs. Each of these aspects has been studied in NSTX/-U and MAST/-U over the years, and physical understanding has benefited from collaborative efforts.

Initially, Meyer *et al* [102] used similarity experiments in NSTX to confirm the finding in MAST that the power threshold for H-mode access was reduced in a double null configuration compared to single null, and that the reduction was larger than in a conventional aspect ratio device.

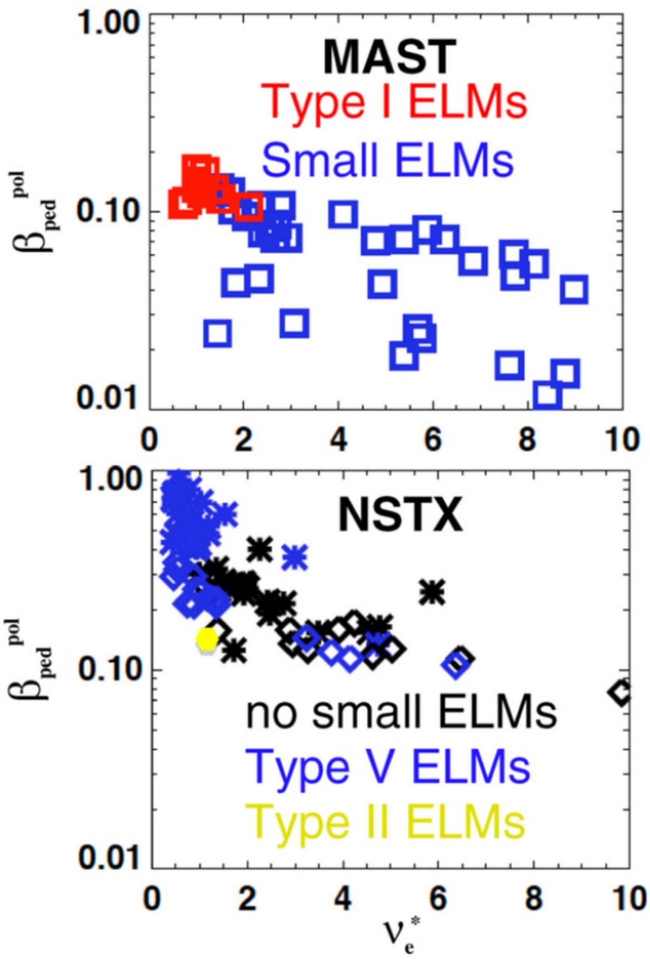

Figure 8. Small ELM operational space for (top) MAST and (bottom) NSTX, from Reproduced courtesy of IAEA. Figure from [103]. Copyright (2011) IAEA.

The characteristics of ELMs was compared between NSTX and MAST by Maingi *et al* [103] (Alcator C-Mod was also included in this study). They found that small type II ELMs appeared in both devices in double null configurations, and both had multiple filaments with propagation in the co-I_p direction, while type V ELMs in NSTX were distinct. The operational spaces can be found in figure 8.

Later Kleiner *et al* [104, 105] developed an extended MHD model for calculating the stability of peeling-ballooning modes. This is expected to be important in STs since resistive kink-peeling modes were found to drastically lower the edge stability threshold in NSTX. Studies on resistive edge modes in MAST/-U are currently ongoing [106] and there are indications that MAST is limited by ideal modes, whereas MAST-U appears to be limited by resistive ballooning modes, which extend the unstable domain similar to the resistive peeling modes in NSTX [107].

It has long been recognized that the height and width of the so-called pedestal at the edge of NSTX plasmas did not follow the same scalings as for higher aspect ratio devices. ST pedestal scalings have also been recently revisited for MAST [108] and MAST-U [109] as well. Recently a series of papers by Parisi *et al* [110, 111] explained the deviation at NSTX by proposing a new gyrokinetic critical boundary condition. Though mostly using NSTX examples, a MAST case was also included in [112]. Subsequently, an effort was made to illustrate a mechanism by which turbulent transport (in particular, starting with electron temperature gradient modes [113, 114]) could potentially saturate pedestal growth before ELMs occurred [115], and both NSTX and MAST-U cases were utilized. Cases from both machines were again used to determine the effect of geometric inputs (in particular squareness) to the gyrokinetic pedestal prediction [116].

Finally, an automatic profile fitting algorithm has been employed at MAST-U which was used to look at pedestal characteristics in a large dataset [117], and this algorithm is currently being ported to NSTX-U as well.

3.7. SOL and divertor

An important part of the scientific program of an ST is its technical divertor solution and the physics of the SOL of plasma outside closed flux surfaces that ultimately interacts with the divertor. In fact, a primary motivation for the MAST-U project is to investigate particle and heat flux handling using the Super-X divertor, as well as other alternative divertor configurations.

One such divertor configuration, the ‘snowflake’ divertor, was developed for STs on NSTX by Soukhanovskii *et al* [118], and later brought to MAST-U by the same team (Soukhanovskii, Khrabry *et al* [119–121]). In NSTX, effective heat flux dissipation was achieved with a radiative snowflake divertor, maintaining good core confinement and pedestal performance in H-mode discharges with up to 6 MW of NBI heating. In MAST-U, the divertor coil set, consisting of sixteen coils, along with advanced control system and diagnostic capabilities, enables focused studies of MHD and transport mechanisms responsible for heat and particle exhaust across eight strike points.

Super-X divertor studies in MAST-U highlighted the role of neutral atoms and molecular processes in divertor heat and particle dissipation [29, 30]. At higher divertor neutral densities, deuterium radiation opacity may affect divertor ionization and radiation distributions, as demonstrated by a recent modelling study [122]. Similar processes are expected to play a role in NSTX-U high-density lithium vapour box divertors, and the same radiation transport modelling approach can be applied to future lithium experiments in NSTX-U [123]

SOL width studies have been mentioned already in section 3.2 and figure 3, studies of plasma ‘blobs’ in the SOL of the two machines tended to be more complementary rather than collaborative, with MAST focusing on the use of a wide-angle view camera and reciprocating probe measurements [124, 125], while NSTX pioneered the use of GPI [126, 127].

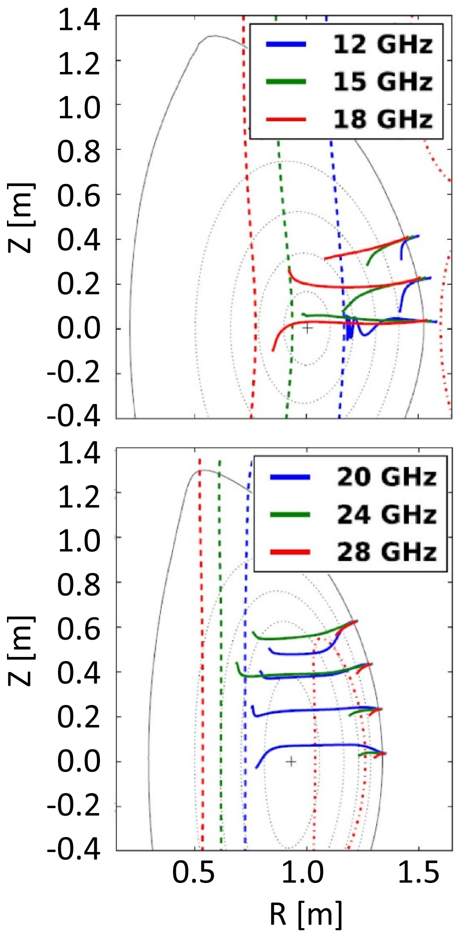

Figure 9. Ray trajectories for various frequencies and launch positions for an EBW assessment of (top) NSTX and (bottom) MAST-U. Reproduced courtesy of IAEA. Figure from [130]. Copyright (2011) IAEA.

3.8. Heating and current drive

Though both machines have dominantly been heated by neutral beams, and NSTX was equipped with a HHFW antenna, there has been constant interest in EBW heating and current drive, motivated by the tendency of STs to be overdense for conventional electron cyclotron wave heating.

First, on a related topic, Preinhaelter *et al* [128] simulated EBW emission (not heating) from both NSTX and MAST, finding that it could be helpful for refining the reconstruction of the magnetic field as well as measuring the plasma temperature.

As early as 2001, though, EBW heating and current drive was considered by Ram *et al* [129] for both NSTX and MAST. Later Urban *et al* [130] carried out another numerical study surveying the potential for EBW heating and current drive for NSTX and MAST-U, see figure 9. They found that EBW should be a viable method for depositing power and efficiently driving current across the plasma radius of those and potential future STs.

Though it took many years, MAST-U will finally implement a 1.6 MW EBW heating and current drive system in 2027

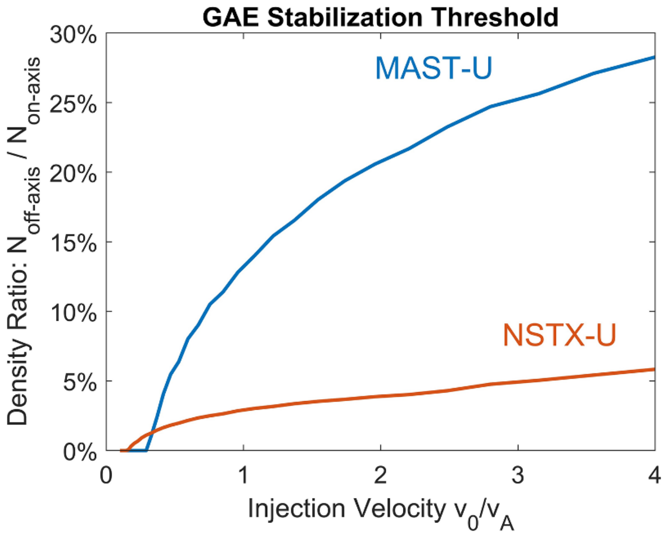

Figure 10. The threshold of number of fast ions from the off-axis beam relative to the fast ions in the on-axis beam (proxy for beam power) that is needed to stabilize GAEs that are excited by the on-axis beam for NSTX-U and MAST-U. The linear analysis only calculates the fast ion drive, so an estimate of the electron damping rate of $10^{-3}\omega_{\rm ci}$ was used. Reproduced with permission from [136].

[131], motivated at least in part by the desire to validate the technique for the STEP programme [132, 133].

3.9. Energetic particles

STs are important test facilities for energetic particle studies because they have beam-injected ions that can exceed the Alfvén speed and therefore excite Aflvenic instabilities that are relevant to alpha particles in burning plasmas. The study of energetic particles and their associated modes has already been mentioned through the review paper, [43], as well as some of the shared diagnostics, but several other areas have been jointly investigated as well.

Wang *et al* [134] investigated energetic particle driven fishbone instabilities that appeared at $q_{\rm min}$ values above one in both MAST and NSTX. They found that fishbones are excited by trapped beam ions and can induce (2, 1) magnetic islands, while non-resonant internal kink modes can lead to significant energetic particle redistribution.

EP-driven compressional Alfvén waves and the ion cyclotron emission that they produce, were found to be measurable in both NSTX and MAST by Gorelenkov [135].

Linear stability analysis of high frequency AEs in MAST was carried out by Lestz *et al* [136, 137]. They also made predictions for MAST-U, in particular that MAST-U's new off-axis beam could excite co-propagating modes and stabilize counter-propagating ones. This result built upon experience and analysis tools previously applied to interpret the excitation of these instabilities in NSTX [138], their observed suppression via off-axis NBI on NSTX-U [139], and successful simulation of the observations [140]. As shown in figure 10, because of differences in their beam velocity space distributions, MAST-U is predicted to require a larger ratio of off-axis to on-axis beam particles to stabilize counter-propagating global AEs than NSTX-U, but the effect should still be observable [141].

Finally, Marchenko *et al* [141] theorized that Alfvén avalanches in NSTX and bursting modes in MAST, which both result in a loss of EPs, could be explained by bifurcations of limit cycles of infernal AEs.

3.10. Transport, confinement, and fusion performance

Transport and confinement are fundamental to fusion plasma physics, and in addition to the multi-machine databases and reviews previously mentioned, several other efforts have utilized both NSTX and MAST results, which are especially beneficial to projecting for future ST fusion performance.

Impurity transport was studied by Henderson [142], primarily for MAST [143, 144], but comparisons were also made to measurements from NSTX [145–147]. In both machines a region of low transport in the plasma core was observed (see figure 11). Transport on the level of neoclassical is consistent with turbulent ion transport being suppressed in the core of *ST*s.

The momentum pinch was studied in both NSTX and MAST Guttenfelder *et al* [148], finding that quasilinear gyrokinetic predictions were unable to reproduce the experimental values in NSTX [149], and uncertainties were too large to quantitatively validate the predictions also in a follow-up experiment in MAST [150].

With an eye towards ST fusion pilot plants, Buxton *et al* [151] reviewed and compared the thermal energy confinement time between NSTX and MAST. A plot of the experimental confinement times compared to an NSTX gyro-Bohm scaling is shown in figure 12. Finding the limitation that both devices were of approximately equal size, they then developed an extension of size scaling using physics-based dimensional arguments, which is useful for projection to ST reactors of different sizes.

Similarly, Costley and McNamara [152] expanded upon the energy confinement time projection and made projections, based largely on NSTX and MAST data, for fusion performance of a future ST reactor. They found that STs might have three times higher fusion triple product, $nT\tau_E$, and an order of magnitude higher fusion power gain, than a similar field larger conventional tokamak.

STs, in particular NSTX and MAST/-U, have shown great promise for future fusion devices in terms of normalized confinement dependence on collisionality, $B\tau_E \sim \nu^{*-0.8}$. This dependence means energy confinement improves much more strongly in future devices with lower collisionality than for larger aspect ratio tokamaks, and is due to suppression of turbulence in STs. Still, a large projection remains between present devices and FPPs, which motivates the crucial future programs with higher power in MAST-U and the resumption of operation of NSTX-U with a doubling of NBI power, plasma current, and magnetic field. These experiments, and comparison through collaboration between the two devices, will provide a proof of the promise of the ST as a fusion power concept.

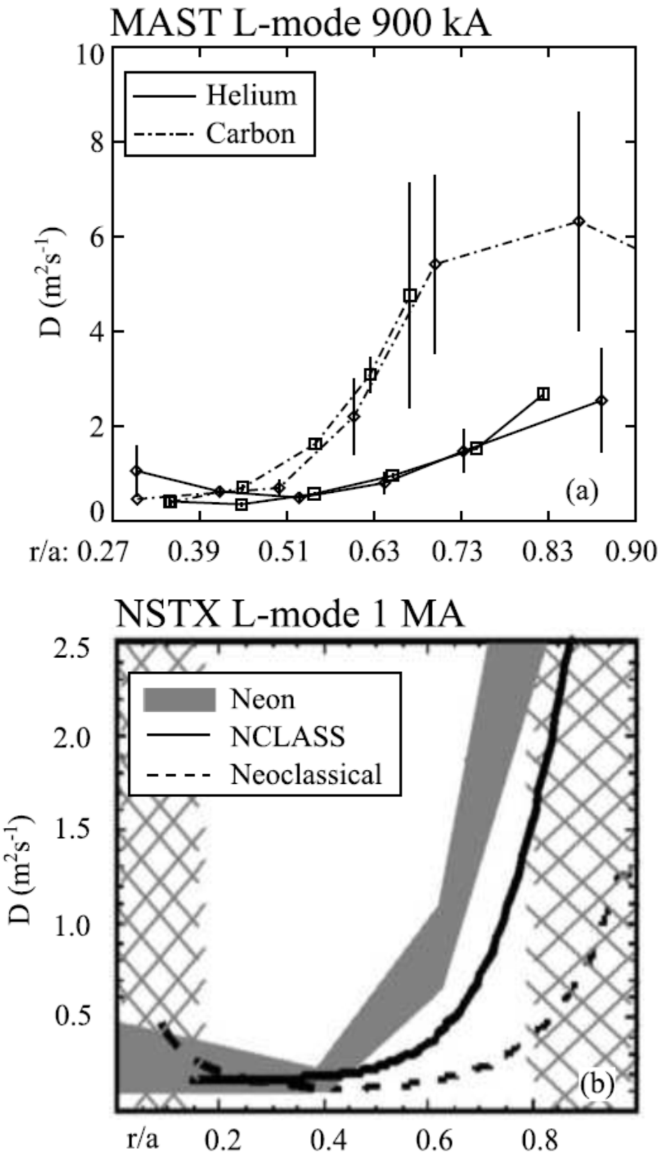

Figure 11. Impurity transport coefficients for (top) helium and carbon in MAST and (bottom) neon in NSTX. Reproduced with permission from [142].

4. Conclusion

NSTX and MAST were both constructed and operated around the same time with the goal of following on the promising results from START and exploring the physics of STs. After many important discoveries and advances, both programs proposed upgrades which would enable further exploration of important questions remaining to make projections for the design of ST pilot plants. MAST-U has already begun important explorations of Super-X divertors, and will soon test EBW heating and current drive, while NSTX-U, when it starts operating, will explore the trend of confinement at lower collisionality, and will further explore lithium as a plasma facing component.

However, in addition to those unique and complementary contributions, NSTX/-U and MAST/-U have historically also

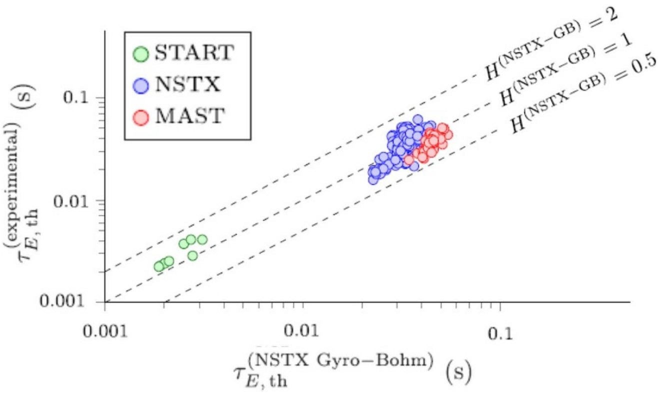

Figure 12. Experimental vs. NSTX gyro-Bohm scaling energy confinement times for a database of START, NSTX, and MAST plasmas. Reproduced from [151].

benefitted from extensive collaboration, and each has greatly benefited from the existence of the other. Both have contributed to topical reviews of ST physics as well as multi-machine database studies, where often they have provided an essential aspect ratio component to parameterizations. Many diagnostics have been shared quite literally between the two devices. The programs have benefited greatly from operational expertise that has been shared between the research teams, as well as equilibrium reconstruction knowledge. Finally, numerous physics topics have used data, analysis, or modelling of both devices, including stability and disruptions, H-mode, pedestals, ELMs, SOL, divertor, transport, confinement, fusion performance, heating and current drive, and energetic particles. As MAST-U continues and NSTX-U begins operation, collaborative studies on many of these topics are expected to continue.

As fusion energy research enters a new stage of private company investment and substantial interest in the ST concept as a power plant, the publicly-funded NSTX/-U and MAST/-U have provided much of the knowledge that supports that choice. Collaboration between the United States and United Kingdom in fusion energy has recently been formalized, but this example shows that it has always been strong, and mutually beneficial.

Data availability statement

No new data were created or analysed in this study.

Acknowledgment

The NSTX/-U and MAST/-U teams have included hundreds of individuals over the years and can not be fully captured by the author lists of any individual papers. A recent representative list for NSTX/-U is in [25], though, and for MAST/-U in [36]. We have usually acknowledged the lead author of each collaborative reference throughout this paper when their work was introduced. There are, however, >825 individuals from >120 institutions in >25 countries explicitly listed in our best attempt to categorize the author lists of all the references in this paper, to give an idea (though, admittedly, not all the references herein are NSTX/-U/MAST/-U collaborative papers). In this work we have attempted to comprehensively include all collaborations between the two devices, but of course we may have missed some. In particular, conference proceedings were more difficult to search than published papers. We apologize for any oversight.

There were, of course, many other studies that exist in which a reference from one device is cited in a separate publication from the other device. Some of these cases must have been the result of collaboration and discussion between individuals at each institution. These were often not included here however; rather, the focus here was mostly on published works which contain data or analysis from both machines.

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