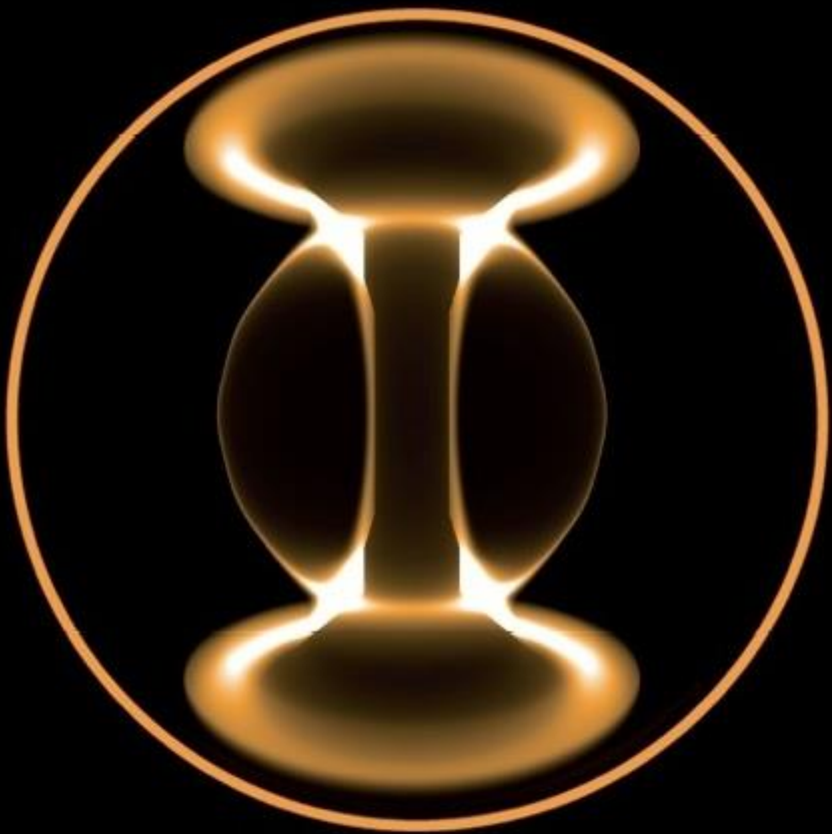

MAST Upgrade Research Plan

November 2019

CCFE
CULHAM CENTRE FOR FUSION ENERGY

1 INTRODUCTION AND BASIC INFORMATION ABOUT MAST UPGRADE

The MAST Upgrade programme has three main objectives that are central to the drive towards commercial fusion power:

1. **Adding to the knowledge base for ITER:** The international experiment that will be the precursor to a demonstration fusion power plant (DEMO). MAST Upgrade will help to resolve important plasma physics questions and develop predictive models to help enhance ITER's performance and ensure its success.

2. **Testing alternative divertor concepts:** MAST Upgrade will be the first machine to include the capability to develop Super-X and related divertor designs, i.e. innovative plasma exhaust systems, aspects of which if successful, could be adopted by future fusion devices, including DEMO. MAST Upgrade will also test steady state operation with current driven by neutral beams.

3. **Exploring the case for a future fusion device based on a Spherical Tokamak:** MAST Upgrade will explore the suitability of the spherical tokamak as a candidate for a future fusion device– looking at current drive, steady state behaviour, handling of high heat flux, plasma confinement, high beta operation, and performance reliability.

The main elements of the project are to upgrade the existing MAST machine and associated facilities to:

- Increase the plasma pulse length and maximum current by increasing the solenoid flux available;
- Introduce a closed pumped divertor allowing a wide range of divertor configurations, including the 'Super-X' divertor, to be produced and diagnosed;
- Increase the maximum toroidal magnetic field and the maximum I^2t that the toroidal field system can sustain;
- Increase the heating power and pulse length. The neutral beam heating is planned to be increased eventually to 10MW for 5 seconds. An ECRH system is also planned;
- Facilitate q-profile control using enhanced shaping capability (elongation and triangularity) and off-axis neutral beams;
- Modify the vertical stabilisation system to meet the requirements of the new configurations;
- Develop advanced shape and divertor configuration control using the 21 poloidal field coils and the solenoid, 7 coils in each divertor

MAST has been upgraded to what is known as Core Scope, with further enhancements ongoing.

Core Scope: This refers to all activities completed within the first MAST Upgrade project, which was completed in 2018. Commissioning started in 2019 with first plasma due in 2020. The list of system upgrades in Core Scope are discussed in section 4.

Enhancements: This refers to the addition of a third and fourth beam system to MAST Upgrade (taking the total power to 10MW), a cryoplant to service the divertor cryopumps, advanced cooling of the centre column, a pellet injector and some additional diagnostics. These systems are currently in the final design stage and should be delivered by 2022. An RF heating/current drive system based on Electron Bernstein Waves is also being investigated.

The key plasma parameters for MAST and MAST Upgrade are given in Table 1.

Table 1 Key plasma parameters for MAST and MAST Upgrade (core scope)

Parameter	MAST	MAST Upgrade	2020
Major radius (m)	0.85	0.85	0.85
Minor radius (m)	0.65	0.65	0.65
Plasma current (MA)	1.3	2.0	1.0
Magnetic field at R=0.85m (T)	0.52	0.75	0.6
Total NBI power (MW)	3.8	5.0	3.5
On-axis NBI power (MW)	3.8	2.5	2.0
Off-axis NBI power (MW)	0.0	2.5	1.75
Pulse length (s)	0.6	5	2

MAST Upgrade will operate as a EUROfusion supported device within the Medium Sized Tokamak (MST) programme, complementing two other tokamaks, namely ASDEX Upgrade (Germany) and TCV (Switzerland). EUROfusion formulate an annual work plan for exploitation of these devices in concerted collaboration; this period of operation will be supplemented by UK-funded operation.

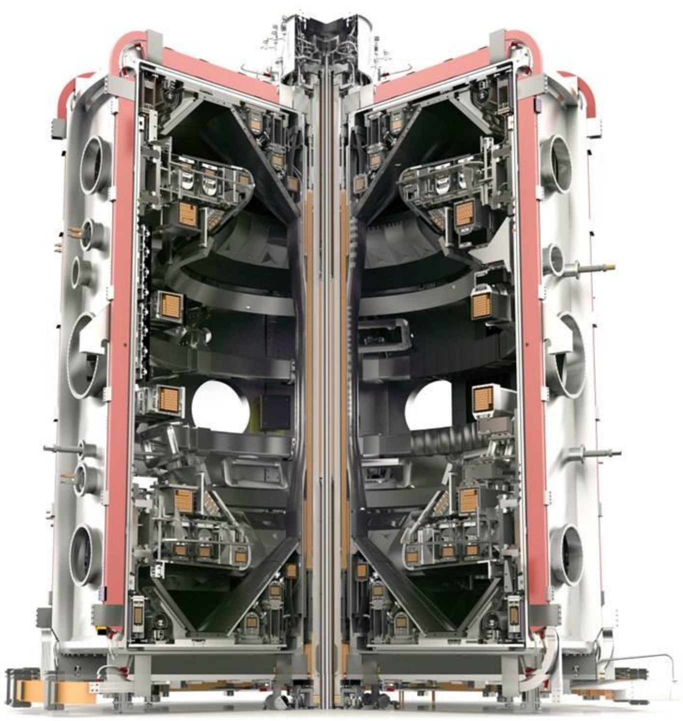

Figure 1: Cross-section of the MAST Upgrade showing the 17 new shaping and divertor coils and the new closed divertors.

2 RESEARCH STRATEGY

The development of a fusion power plant requires substantial advances in plasma science and technology. MAST Upgrade has been identified as one of Medium Sized Tokamaks supported by EUROfusion funding because there are many aspects which require research and development that are either complementary to ITER or go beyond ITER parameters and the spherical tokamak (ST) line may help with this research.

For example, the prototype fusion power plant, known as DEMO, will go beyond ITER divertor heat loads with up to five times higher heating power normalised to plasma radius. It will also require the development of technology for a much more aggressive neutron environment, for which new components need to be tested (particularly in relation to how their power handling and/or high temperature properties can be maintained in a high neutron environment). It will further require the development of techniques for quasi-continuous operation (on the scale of weeks or more, rather than hours), with fully self-sustaining plasmas (still largely relevant even if a long pulse, e.g. ~1 day, DEMO is adopted, as there are clear attractions of a continuous fusion core for a power plant), strong current drive, tritium breeding, and self-reconditioning, at performance levels where new instabilities may need to be controlled from the energetic fusion products. This is highlighted by a consideration of key parameters as set out in table 1.

The importance of the MAST Upgrade programme with respect to DEMO research is most evident in the inclusion of a novel divertor concept. The unique open design of the MAST Upgrade vessel is instrumental in this novel concept, which may provide a path towards a solution to the divertor power challenge in a future ST and DEMO should the conventional approach not be acceptable. There is a strong overlap between the R&D needs for DEMO (ITER) and a future ST, many of which are more pronounced in the latter, and MAST Upgrade research aims to address both.

Table 2 *Key performance parameters /metrics for a tokamak fusion plasma: maximum parameters achieved to date (not simultaneous), ITER goal with extended burn (and steady-state in parentheses), DEMO based on EU Model C from D Maisonnier et al, Nucl Fusion, 47, 1524 (2007) and ST-CTF according to G Voss et al, Fus Eng Des, 83, 1684 (2008). These CTF parameters are indicative and are likely to evolve in future design studies, and other ST CTF/FNSF designs exist*

Property	**Unit**	**Metric**			
		To Date	**ITER Goal**	**DEMO**	**ST-CTF**
Major Radius	R (m)	3	6.2	7.5	0.84
Plasma Volume	V_p (m^3)	100	840	~1650	~10
Magnetic Field (toroidal)	B_t (T)	11	5.3 (5.2)	6.0	2.5
Plasma Current	I_p (MA)	7	15 (9)	20	6.5
Fusion Power	P_f (MW)	16	500 (356)	3410	35
Fusion Power Gain	Q	0.6	10 (6)	30	0.9
Average Plasma Pressure	$\langle p \rangle$ (MPa)	0.2	0.3 (0.24)	3	0.9
Fusion Power Density	(MWm^{-3})	0.16	0.6 (0.4)	~2.0	3.5
Plasma Duration (P_{heat}> 1MW)	(s)	180	400 (3000)	∞	∞
Self Driven Current Fraction	f_{BS} (%)	80	25 (50)	63	40

Plasma Exhaust/Pulse	W (GJ)	1	60 (420)	∞	∞
Divertor Power Challenge	P_{heat}/R (MW/m)	~10	~20	~80	~90
Neutron Wall Loading	Γ_n (MWm^{-2})	0.1	0.5 (0.4)	2.2	1

A Component Test Facility (CTF) has been proposed to help speed the path towards DEMO and power plants and improve their designs. The principle here is to have a facility that allows testing, development, and validation of ideas particularly aspects of nuclear technology (especially breeding blankets) at meaningful dimensions, so that one can make advances and developments to complement the integrated approach of ITER and DEMO. In particular the emphasis with a CTF is on a high neutron, high heat flux, environment in a driven machine (ie substantially heated and controlled by external systems) in order to understand the optimisation of device components for a power plant and the ramifications of high heat flux and long pulse quasi-continuous operation. A major potential advantage of an ST-based CTF is that in some designs the tritium consumption could be low enough to avoid the necessity for self-sufficient tritium breeding, hence avoiding the reliance for continued operation on the main components being tested, and removing the constraint that every blanket development component needs have all the overhead and hardware for inclusion in the tritium cycle. It is in this context that MAST Upgrade has a strong role, alongside NSTX-U especially (the other major ST).

Research on MAST Upgrade as a EUROfusion-funded medium-sized tokamak will be conducted using the headlines of the 2013 EUROfusion roadmap (see Appendix F). The headlines in which MAST Upgrade will make the most significant contributions are expected to be:

- Headline 1.1: Increase the margin to achieve high fusion gain on ITER
- Headline 1.2: Operation with reduced or suppressed ELMs
- Headline 1.7: Optimise fast ion confinement and current drive
- Headline 1.9: Qualification of Advanced Tokamak scenarios
- Headline 2.1: Detachment control for the ITER and DEMO baseline strategy
- Headline 2.3: Optimise predictive models for ITER and DEMO divertor/SOL
- Headline 2.4: Investigate alternative power exhaust solutions for DEMO

With respect to burning plasma physics (headline 1.7), the addition of off-axis NBI will allow a much larger variation of the fast particle distribution than previously possible and the better density control with possible access to lower densities will allow access to plasmas where the fast particle pressure dominates. The injected fast particles in MAST Upgrade are born with velocities well above the resonant Alfvén velocity, such that the resonance resides in the near thermalised region of the distribution and is approached from higher energies, as would be the case in a burning plasma.

The projected performance of MAST Upgrade indicates that access to plasmas with fully non-inductive current drive of I_p>1MA for flat top times exceeding several current redistribution times should be possible (helping to address headlines 1.7 and 1.9). High current fully non-inductive plasmas will only be possible using neutral beam current drive

(NBCD), most efficient in low density plasmas. However, operation at high κ, high β_N and higher density will also allow access to plasmas with a high bootstrap fraction (advanced scenarios). Therefore, plasma control without a solenoid as well as transport and current drive can be studied in detail. Furthermore, this can be done in an environment with high super Alfvénic fast particle fraction, which mimics important aspects of burning plasmas.

The addition of the flexible divertor in a closed pumped volume provides a unique capability for MAST Upgrade and will provide an integral contribution to headlines 2.1, 2.3 and notably 2.4. This key capability to explore new configurations potentially provides a route towards a solution to the plasma exhaust problem of next generation fusion devices. Exploring the controllability, stability and performance of the divertor as one moves from a classic or conventional configuration to the configuration with an extended outer leg will be pivotal for developing alternative exhaust options for DEMO/CTF. The overall flexibility of this design will also allow studies of the general aspects of divertor physics such as SOL cross-field transport and radiative detachment, which are crucial issues for the ST-CTF and conventional aspect ratio power plant paths alike, whatever divertor configuration is adopted. The long leg and closed divertor may allow greater decoupling of the divertor and core plasma, as well as providing a flexible platform for divertor physics studies.

3 RESEARCH THEMES AND OPPORTUNITIES 2017-18

3.1 In this section, the main research themes in the present CCFE programme for the initial operating period of MAST Upgrade are outlined (with the Core Scope hardware available, see section 4). The programme as a whole will be developed with collaborators (who are assumed to take leading roles), and some examples are given of areas where CCFE has fewer staff, implying even stronger opportunities for collaborators. The part of the programme funded by the EUROfusion MST1 work package will be organized by the MST1 Task force leaders, and it is expected that the remaining part will be designed to complement. Furthermore the choices for hardware enhancements will be discussed jointly with the MST1 leadership so that the MAST-U programme complements the wider EU programme. See Appendix E for more information. Exhaust

The closure of the divertor in MAST Upgrade is a major change from MAST and allows closure concepts like that of the original ASDEX machine, complementing that of JET for example. The aim is both on improving impurity and density control over MAST, and on decoupling the effect of changes in the physical processes of the divertor from those of the core plasma. The early experiments on MAST Upgrade will explore this fundamental precept of the MAST Upgrade design. They will explore and quantify the effectiveness of the gas sealing within the divertor assembly, and the extent to which the closure is limited by the interaction of the far scrape-off layer (SOL) with the surfaces outside the divertor chambers.

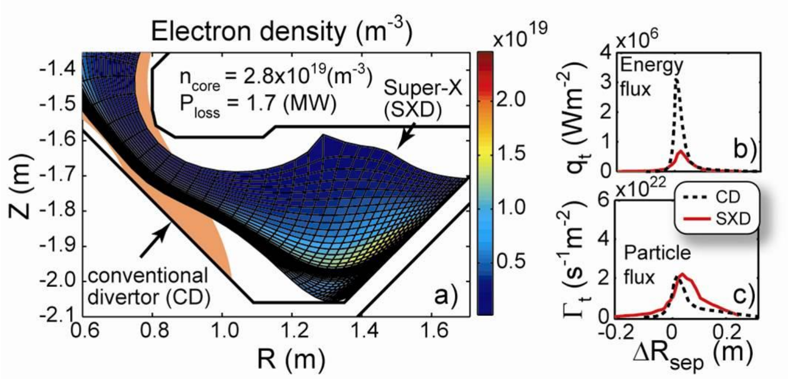

Figure 2 Modelling of Super-X divertor (SXD) compared to conventional divertor (CD).

The effective pumping of the divertor chambers and their surfaces will be a key aspect of MAST Upgrade experiments in general. Therefore in addition to divertor physics studies, early exhaust experiments and supporting modelling work will need to quantify and explain this in sufficient detail to allow for effective design of experiments on core plasma phenomena.

In the wider exhaust area, the Super-X divertor (SXD) and other long leg configurations have clearly the highest impact. MAST Upgrade is the only device that will be able to operate a closed pumped divertor in these configurations. We will aim to realise the first Super-X divertor configuration in a closed divertor early in the 1st year of MAST-U operation, with feed-forward control to demonstrate the potential of MAST-U as a flexible exhaust physics research facility. IR cameras and Langmuir probes will be available to assess the power load in comparison with the conventional divertor operation. Having established operation with a long-leg divertor, also aspects of the core confinement and the effect of SOL connection length on H-mode will be studied. In particular the effect of fuelling, recycling and SOL flows on the L-H transition will be studied. The ability of changing the divertor characteristics independently from the up-stream conditions will make this research unique.

However, the flexible divertor allows access not just to the Super-X configuration, but to a range of advanced divertor configurations. Indeed, the flexibility is such that MAST Upgrade will be able to transition smoothly from a conventional divertor configuration to a Super-X configuration with the strike point located at any point in between. It will also be possible to study the so-called snowflake configuration with multiple divertor legs, as shown in Figure 3. Furthermore, it is also possible to generate a long-legged inner divertor utilising the closed divertor chamber with the outer strike point on the divertor nose – starting to address options for advanced inner legs.

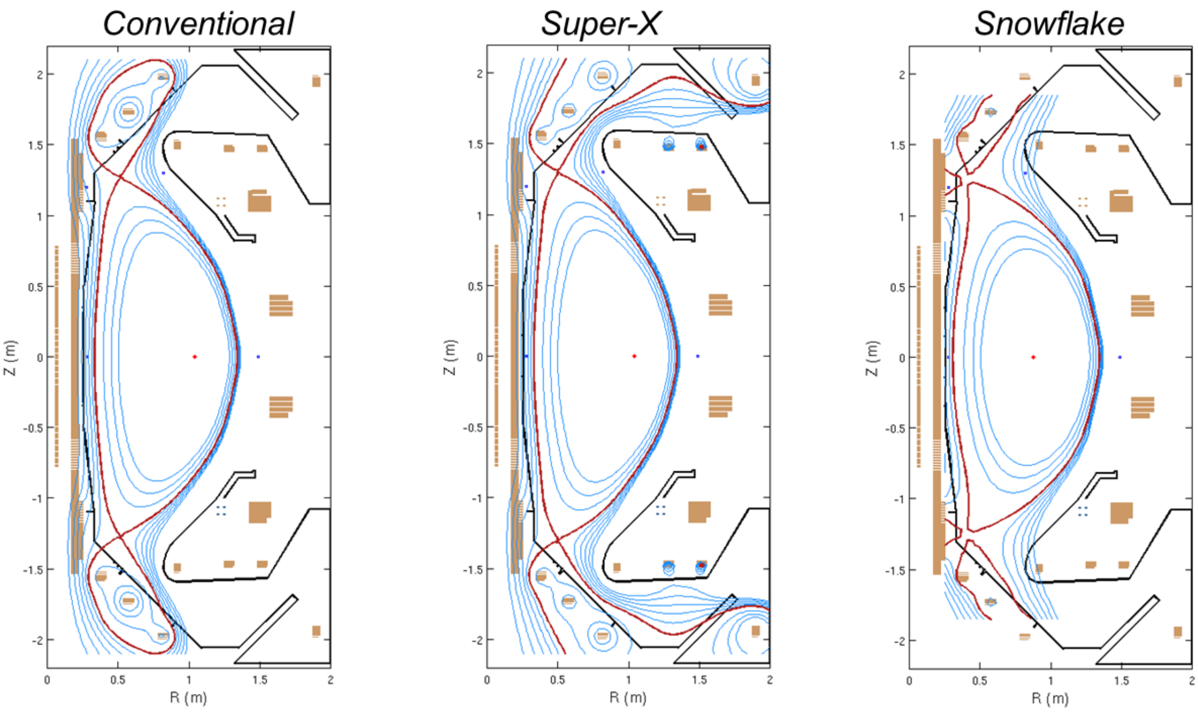

Figure 3: Plasma shapes achievable in MAST Upgrade, showing the core plasma is approximately the same with either a conventional divertor configuration, a snowflake or a Super-X configuration.

The exhaust programme will also focus on volumetric loss mechanisms and parallel and cross-field transport processes (turbulence and filaments). The first area will be aided by divertor bolometry as well as spectroscopic measurements (e.g. 2D narrow band imaging). This research can be done early as soon as sufficient control capability of the SXD and similar configurations is established. Cross-field transport studies can include detailed investigations of the changes in cross field transport with varying connection length, and their origin. This will require higher accuracy control as well as turbulence measurements such as fast visible imaging and reciprocating probe measurements.

Early experiments should probably focus on the underlying physics while waiting for the additional power and pulse length capability from the later upgrades. The configurations will be established for a few particle confinement times to achieve stationary conditions with the core plasma.

Finally, the scaling of SXD performance to next step fusion devices requires a wide operating space coupled with detailed divertor modelling as well as a comprehensive diagnostic set. High current capability is needed to access low collisionality regimes. High power is needed to access a hot sheath limited SOL at various densities. Access to other divertor configurations such as a snowflake divertor are also possible. A detailed comparison of open and closed divertors, as well as pumping effects can also be studied (for the first time in a spherical tokamak).

Installed diagnostics: Divertor Langmuir probes (approx. 850 probes), midplane reciprocating probe, divertor science facility, 4 IR cameras, 3 high-speed visible cameras, 6 filtered imaging cameras, 1 coherence imaging system to measure impurity flows, 32 channel gold foil divertor bolometer, 1 multi-channel grating spectrometer, 5 survey

spectrometers, divertor Thomson scattering, mid-plane and divertor, X-point imaging bolometer, divertor AXUV diodes, divertor SPRED and fast ionization gauges.

Desirable new hardware: Divertor reciprocating probe.

3.2 Pedestal and ELMs

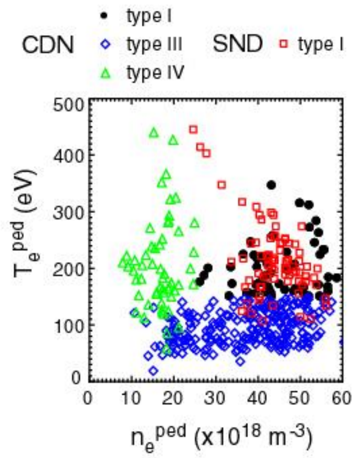

Figure 4 Pedestal operating space achieved on MAST as a function of ELM type.

MAST Upgrade will be equipped, like MAST, with excellent diagnostics for exploring the pedestal structure and ELM dynamics, including when resonant magnetic perturbations (RMPs) are applied to control the ELMs. The new closed divertor means that much lower pedestal collisionality, relevant to ITER and DEMO regimes, will be accessible, allowing investigations of the pedestal structure at low collisionality and at higher plasma current and field. Furthermore, the new poloidal field coils will allow the pedestal structure to be investigated for a much wider variation in elongation and triangularity, as well as for variation in the divertor configuration and thus the upstream SOL and pedestal foot conditions. The effect of impurity species on the pedestal is a key issue for operation of ITER, and the increased flexibility in gas fuelling in MAST Upgrade will permit studies of the effects of a variety of impurity species on the pedestal and ELM behaviour.

MAST Upgrade will have 12 in-vessel coils (reduced from 18 in MAST), with four in the upper row and eight in the lower row. This will allow RMPs with configurations n=1, n=2 and n=4 to be applied. There will be excellent diagnostics to assess the effect of the RMPs on the plasma edge and ELM behaviour. Consequently, MAST Upgrade will allow an exploration of RMP ELM control at lower collisionality with the closed divertor as well as testing the compatibility of ELM control by RMPs (and the resultant lobe structures) with the Super-X configuration.

Key hardware: High resolution 130-channel Thomson scattering system with sub-cm resolution; charge exchange systems, fast imaging cameras with 120kHz frequency and ~6mm spatial resolution, BES for instabilities, 2 Doppler Back Scattering (DBS) systems, long-wavelength IR thermography, in-vessel coils for applying RMPs, synthetic aperture microwave imaging for measuring changes in pitch angle to infer edge current profiles.

Desirable new hardware: Pedestal turbulence diagnostics

3.3 Current drive and fast particle physics

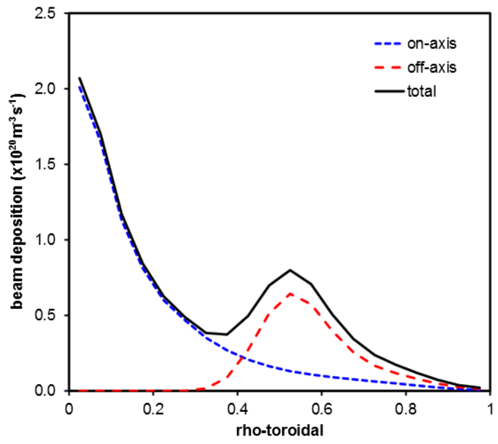

Figure 5 *Typical MAST Upgrade beam deposition profiles.*

MAST Upgrade is equipped with two neutral beams that have different injection geometries. One beam is injected in the equatorial plane of the tokamak, which provides strong on-axis deposition, while the other beam is displaced vertically upwards to provide off-axis deposition. Typical deposition profiles for the two beams are illustrated using a TRANSP simulation in Figure 5. The central deposition of the mid-plane beam is predicted to generate non-inductive current drive that is peaked at the plasma magnetic axis, whereas the vertically displaced beam is expected to produce off-axis current drive. This provides an opportunity to investigate both current drive physics and the effect of on- and off-axis non-inductive current on plasma behaviour.

The deposition profile for the on-axis beam is quite resilient to variations in plasma parameters provided that the magnetic axis is close to the equatorial plane of the tokamak. The deposition of the vertically displaced beam, on the other hand, depends on plasma geometry and provides great flexibility. Reducing the height of the plasma or displacing it downwards acts to move the off-axis deposition peak to larger normalised minor radius.

Neutral beam current drive is strongly sensitive to plasma density and electron temperature. This is illustrated in the simulations by varying the plasma density while maintaining H_{98} =1 (where $H_{98}=\tau_E/\tau_{IPB98(y,2)}$). It is assumed that the neutral beam injected fast ions behave ‘classically’ with no redistribution by MHD instabilities. Previous experiments on several tokamaks, including MAST, have shown that neutral beam fast ions can be redistributed from their ‘classical’ orbits by MHD instabilities and that the measured effect of neutral beam current drive can depart from that predicted by ‘classical’ simulations. It has been found that fast ion redistribution due to fishbone instabilities can be mitigated by displacing the plasma vertically or by increasing the plasma density, both of which act to decrease the fast ion pressure gradient that is believed to provide the drive for these instabilities. This is illustrated in Figure 6 where the predicted fast ion pressure gradient is plotted against plasma density, showing that as the density is increased there is a rapid reduction to the ‘critical’ level where the fast ion behaviour becomes ‘classical’.

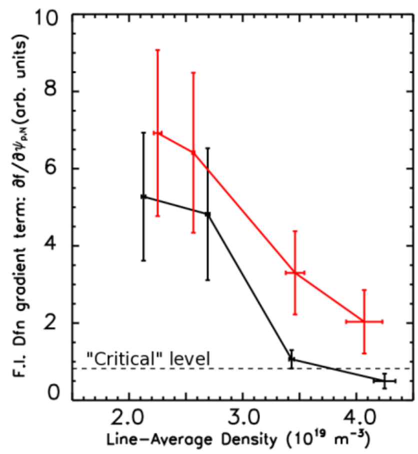

Figure 6 *Peak fast ion pressure gradient as a function of plasma density for MAST on-axis beams (black=1 beam, red=2 beams)*

The vertical displacement of one of the beams to an off-axis location in MAST Upgrade provides an opportunity to extend the investigation of MHD instabilities driven by fast ion pressure and to study the effect of a wide range of instabilities on fast ions at different radial locations. Studies of the effect of non-axisymmetric field perturbations on central and off-axis fast ions will also be possible to investigate the impact of techniques to mitigate ELMs on fast ions in the plasma.

Key hardware: motional Stark effect diagnostic, total neutron rate and steerable collimated neutron camera, fast ion D_α, fast ion loss detector, MHz fast magnetic probes, fusion proton detector.

Desirable new hardware: Additional fast ion loss detectors or Faraday cups.

3.4 Other physics studies

In addition to the main topics described above, MAST Upgrade provides the opportunity for investigations in a variety of other areas. Two such examples are given below, though ideas to study any area of plasma physics will be considered through the elaboration of the MAST Upgrade research programme (see appendix E).

3.4.1 Core transport and turbulence

MAST allows studies of core transport and turbulence in extreme conditions where beta, fast ion pressure and plasma rotation are large. Such studies have shown that ion heat transport can be close to neoclassical in contrast to conventional tokamaks where it is commonly dominated by ITG or TEM modes. The displacement of one of the heating beams to an off-axis location in MAST Upgrade will allow the profiles of q, fast ion pressure and applied torque to be varied while the increase in plasma current, magnetic field and pulse duration will expand the parameter-space of transport investigations. Having a similar plasma cross-section to ASDEX Upgrade and DIII-D allows multi-machine studies of the effect of varying the plasma aspect ratio. The closure of the MAST Upgrade divertor together with a range of fuelling techniques (NBI, pellet and gas injection) also provides the potential for particle transport investigations. Studies of the effects of fast ions on turbulence will benefit from the fast ion fraction, super-Alfvênic particles and wide Larmor radius achievable in MAST.

STs offer a potentially attractive route to compact burning plasma devices, such as a component test facility. However, further investigations are required to establish a robust basis for extrapolation from present devices to the conditions required for significant fusion gain. For example, previous studies have suggested that confinement may scale differently with respect to plasma current and magnetic field compared with conventional tokamaks. Indeed, the closed divertor and higher current and field will allow access to much lower collisionality than in MAST, and the step in collisionality to an ST-based CTF is the largest in dimensionless parameters, emphasising the need to understand this confinement scaling. MAST Upgrade will allow such investigations to be extended as well as the study of the influence of different divertor configurations on core plasma performance (e.g. access to H-mode), which is at the heart of the requirement to integrate high fusion output with realistic exhaust strategies.

Key hardware: Beam Emission Spectroscopy, FIDA, high resolution Thomson scattering, charge exchange recombination spectroscopy, neutron camera, neutral particle analyser,

fast particle loss detector, flexible system of divertor and shaping coils, high frequency pellet injector.

Desirable new hardware: Upgrades to the BES, high-k scattering diagnostics.

3.4.2 Performance limiting MHD instabilities

A key research point in MAST-U will be to avoid performance-limiting MHD instabilities, that reduce the achievable pulse length. The high values of beta accessible on MAST and the similarity between the typical MAST q-profile and that used in advanced scenarios (e.g. 'hybrid') on conventional tokamaks allows studies of various performance limiting MHD instabilities in the domain of interest for future devices. The expansion of the plasma operating space on MAST Upgrade in terms of q-profile, pressure profile and plasma shape will provide the opportunity to extend these physics studies. The application of results will be required to develop techniques for the control and avoidance of performance limiting MHD instabilities (e.g. by q-profile tailoring) to access stationary plasma conditions. Such work will include the study of plasma disruptions and their mitigation.

Key hardware: MSE, HRTS, Mirnov coils, SXR arrays, disruption mitigation valve, error field correction coils.

Desirable new hardware: further diagnostics of internal structure of instabilities, shattered pellet injection, additional disruption mitigation valves.

4 CAPABILITIES IN CORE SCOPE (2020 ONWARDS)

4.1 Core scope constituents

Core scope will include 17 new shaping and divertor poloidal field coils (14 inside the vessel), see Figure 1, and a new closed pump-able divertor structure to make a highly flexible exhaust physics platform. This stage of the upgrade will also provide a 50% increase in the toroidal field (from 0.585 (85kA) to 0.92 (133 kA) Tesla at R = 0.7m) and a near doubling of the inductive flux from the central solenoid (0.9 to 1.7Vs (1.6 Wb)), which should allow access to plasma current of 2MA and an off-axis neutral beam injector. One of the present neutral beams will be moved off-axis for improved current profile control and fast ion physics studies. The neutral beam power will be up to 2.5 MW from each of the two NBI systems with a pulse length of up to 5 second duration. Plasma can be run in hydrogen, deuterium or helium (with hydrogen or deuterium beams).

MAST-U will be equipped with an extensive gas fuelling system comprising 76 gas outlets allowing a good toroidal uniformity in the gas fuelling. The gas fuelling system will comprise 8 outlets at the HFS midplane and 4 outlets on the LFS midplane. In addition there are 4 outlets on the HFS at the top and bottom of the centre column. There are 12 outlets for fuelling through the X-point region and an additional 24 outlets that allow gas injection in the location of a conventional strike point. Finally, there are a further 24 outlets in the super-X divertor chamber.

While the cryopump is incorporated in Core Scope, including a variable shuttering system to allow control of the pumping speed, there is no cryoplant and hence there will only be limited gas pumping during plasma operation provided by the turbo pumps, co-deposition and volume filling. However, the super-X divertor chamber does allow for a significant closure due to a well-designed divertor gas baffle. The closure is designed to allow two orders of magnitude between the neutral pressure in the divertor chamber and the neutral pressure in the main chamber. The pumping in the divertor chamber will depend on the wall conditions. It is planned that Glow Discharge Cleaning will occur between shots, which will deplete the wall inventory and allow the walls to pump. While a pellet injector is not in core scope provision has been made for both HFS and LFS pellet flight lines.

4.2 Diagnostics

The diagnostics that will be available during the 1st physics campaign are listed in table 2. More details can be found on internal webpages for MAST Upgrade users.

Table 3 *: MAST-U diagnostics for 1st physics campaign*

Diagnostic	Physics parameters
Magnetic Diagnostics	Coil currents, real-time plasma current, halo currents, diamagnetic flux, magnetic fluctuations, locked mode analysis, high frequency fluctuations, plasma position, signals for equilibrium reconstruction and control
CO_2 Interferometer	Line integral electron density
Thomson Scattering (mid-plane)	130 channel Multi-time, multi-point $T_e(r)$, $n_e(r)$
Thomson Scattering (divertor)	8 channel Multi-time, multi-point $T_e(r)$, $n_e(r)$
Charge exchange recombination spectroscopy (CXRS)	Ion temperature and velocity profiles
Beam emission spectroscopy (BES)	2D density fluctuations (32 ch., 2 MHz)
Doppler Back Scattering	Radial electric field and fluctuation measurements
Motional Stark effect (MSE)	Magnetic pitch-angle profile
Doppler backscattering (DBS) system	Measurement of density fluctuations and perpendicualr rotation profiles
Target Langmuir Probes	Plasma potential, T_e, J_{sat}
IR Cameras	Medium and long wavelength IR thermography
High speed video	High speed colour and black and white imaging
Mid-plane reciprocating Probe Systems –with heads	Retarding Field Energy Analyser - T_i, T_e, J_{sat} Mach probe - Flow velocity, T_e, J_{sat} Gundestrupp probe - Plasma potential, T_e, J_{sat}
Fission Chamber	Total neutron flux
Neutron Camera	Radial distribution of the neutron flux
Divertor Camera (DIVCAM)	2D spectral line imaging
Fast ion D_α (FIDA)	Confined fast ion profiles (toroidal view only)
Compact Neutral Particle Analyser (CNPA)	Fast particle distributions
Synthetic aperture microwave imaging (SAMI)	2D doppler scattering allowing magnetic pitch angle measurements in the pedestal region
Fast ion loss detector	Energy and pitch angle of fast ion losses
Soft X-ray Cameras	Soft X-ray emission (poloidal and toroidal arrays)

D_α fibrescope	D_α intensities
Fast Ion Gauge	Main chamber and divertor neutral gas pressure
Hard X-ray monitors	Hard X-ray emission
VUV spectroscopy (SPRED)	VUV emission spectrum
Activation Samples	Total neutron fluence
D_α Linear Camera	D_α intensities
Divertor Science Facility	Allows introduction of different test probe heads, dust samples etc.
Main chamber and divertor Bolometer systems	Measurements of P_{rad}
Survey Spectrometer	Routine survey spectra in the divertors (340-730 nm) and at the midplane (400-750 nm)
Colour imaging spectroscopy (RGB)	2D D_α, CVI, HeI , SW BE/green/blue bremsstrahlung
Only available in 1st campaign if additional resources are available	
Divertor reciprocating Probe Systems	Retarding Field Energy Analyser - T_i, T_e, J_{sat} Mach probe - Flow velocity, T_e, J_{sat} Gundestrupp probe - Plasma potential, T_e, J_{sat}
Edge Doppler spectroscopy (E-Celeste)	Edge velocity and Er profiles from passive HeII, Edge ion temperature from CVI (CX)
Reflectometer	Density profile and fluctuations

4.3 Achievable Pulse length with water-cooled centre column and 2 beams

In the first physics campaign the centre column will be cooled using water, rather than Galden. This means that the allowable I^2t in the solenoid is effectively halved from its maximum value to 1500 kA^2s, which will have implications on the maximum achievable pulse length. While we plan to develop scenarios with low internal inductance (l_i) and high non-inductive current fraction this may take some time. For the first physics campaign a good starting point in order to calculate an expected shot duration is to use the longest shots achieved in the final campaign on MAST (M9). Assuming these shots are run with a TF current of 100 kA, with a ramp up/ramp down time of 500 ms, then a 1.5 s flat top has an I^2t of 18 000 kA^2s well within the limit set by the sliding joints of 40 000 kA^2s (with water otherwise 50 000 kA^2s with Galden). Based on the available flux it would be possible to obtain a 1 MA plasma shot heated with 3MW of NBI with a flat top of 0.9 s.

5 OPPORTUNITIES AND ENHANCEMENTS

5.1 MAST-U Enhancements project

The components presently planned for the Enhancements project are listed in table 3. The timescales for implementation are shown in Figure 7.

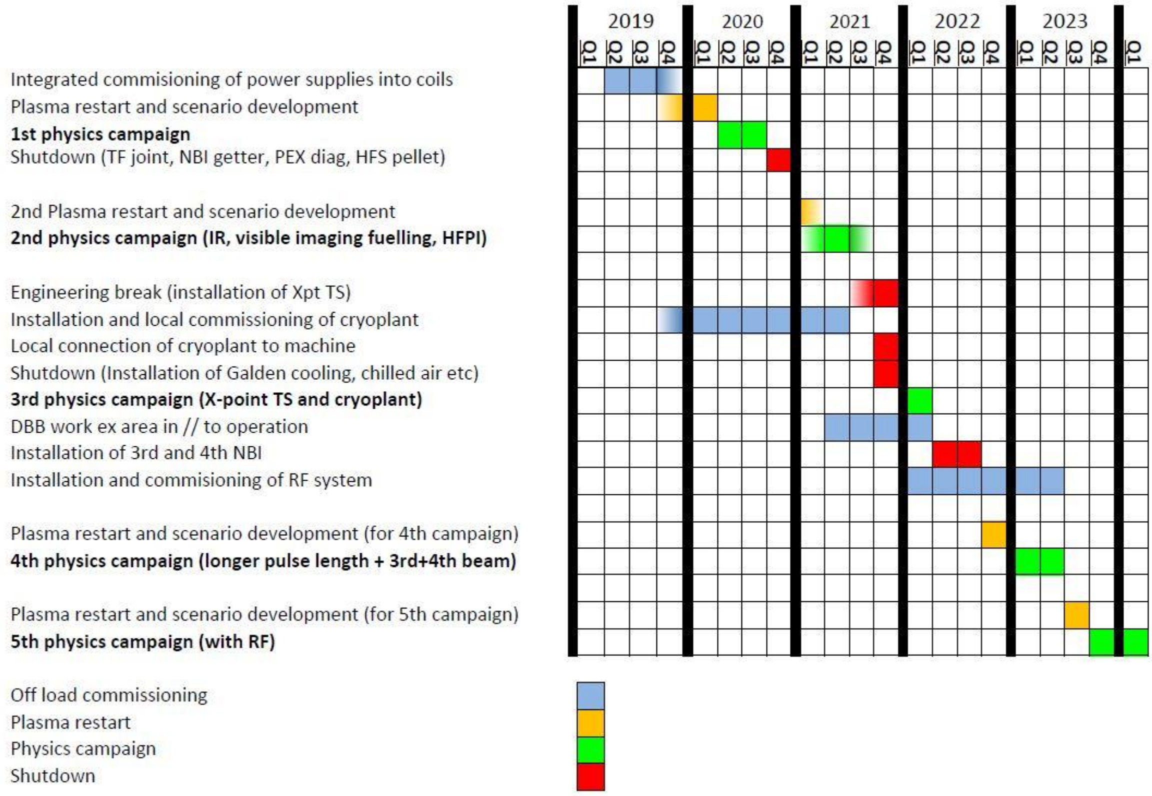

Figure 7 Campaign and Enhancements timeline (Nov 2019)

The additional heating power will facilitate a wider H-mode operating space in toroidal field, plasma current and plasma density, and more robust access to H-mode over a broad range of plasma conditions. It will also notably increase the heat flux to the divertor extending the operating space for SOL transport, heat flux and divertor detachment experiments. The increased power also enables access to high β physics together with an increased probability of operation at $q_{min} > 1.3$ enabling longer pulses by broadening the temperature profile, driving ancillary off-axis current which together enable access to higher β_N and higher elongation giving rise to higher bootstrap fraction.

The installation of the cryoplant will provide access to stationary divertor conditions enabling a lower divertor density facilitating improved control of detachment. The improved particle control will access lower density and lower collisionality which in turn will increase the fast particle fraction, result in more efficient current drive and a hotter pedestal which may increase the pulse length. The divertor pumping may also enable better access to type-I ELMy H-mode and cleaner plasma conditions due to impurity gas pumping.

Core Scope (From 2020)	Enhancements
• New solenoid • New centre rod • New TF Sliding Joints • New Divertor assembly (supporting standard and super X configurations)	Core scope + • 3rd beam (off-axis), 2.5MW • 4th on-axis beam, 2.5MW • Cryoplant (LN2 and LHe subsystems)

• New in-vessel coils (D1, D2, D3, Dp, D5, D6, D7, P6) • Relocation of the P5 coils • New Airside coils (P1, Px, Pc) • New CFC beam dumps • New Divertor Cryopump (with variable pumping speed) • New TF Power Supply • New Divertor Field Power conversion System • New Radial Field Power Supply • Upgraded Power Supplies infrastructure • Error field correction system. • In-vessel ELM coils (8 lower, 4 upper) • 2 beamlines, 2.5MW, >2.5s, one on-axis, one off-axis • Upgraded vertical stabilisation system (passive and active) • Upgraded machine control and protection system. • Upgraded plasma control and data acquisition systems. • New diagnostics in Super X divertor region. • Maintenance of pellet capability (in-vessel work only) • Modification to allow addition of future RF systems, including 28GHz Heating and Start Up System and 19GHz Heating and Current Drive System	• Additional diagnostics • High frequency pellet injector • Advanced centrepost cooling (Galden) • EBW system for heating and current drive

Table 4 *MAST Upgrade Programme Stage Definition*

5.2 Desirable New Diagnostics and plant

A large range of diagnostics is already foreseen on MAST Upgrade. As well as implementing new diagnostics there are clear opportunities for collaborators to run already existing diagnostics ensuring that high quality analysed data is routinely available (and allowing deeper involvement in the programme).

Key diagnostics that would be welcome include divertor diagnostics (improved thermography, reciprocating probe heads, and bolometry), turbulence diagnostics (for example a high-k scattering diagnostic) and fast ion diagnostics. A provisional list of desirable diagnostics is provided in table 4 (their relation to programme lines was described above). This will be adapted after further input from collaborators and the MST leadership

Table 5 List of desirable hardware extensions

Divertor gas puff imaging	Lithium beam diagnostic
Divertor reciprocating probe head to detect charge-exchange neutrals	Additional fast ion loss detectors or Faraday cups
Shattered pellet injection	Upgrades to the BES
High-k scattering diagnostics	

6 FUTURE FRAMEWORK OF OPERATION CAMPAIGNS

In terms of operational schedule the following assumptions have been made about the first physics campaign:

- It will have a duration of 6 months (25 weeks – 75 days of operation). It is planned that at least 25 days will be made available for MST1 experiments.
- The machine will operate 3 days per week (Tuesday-Thursday) from 08:30 until 18:00 to allow for maintenance/fault finding/diagnostics maintenance on the Monday with Friday being a contingency day.
- The shot repetition rate will be 2 shots per hour so 16 shots per day. Hence the first physics campaign will consist of approximately 1200 plasma discharges.

The duration of the first physics campaign is only indicative. This initial guess is based on the need for the inspection of the TF sliding joints after ~ 2500 pulses (restart + 1st physics). In addition, by this stage the machine will have been operated continuously for 9 months through commissioning/restart and 1st Physics and the detailed planning and milestones will need to adapt to the manpower available (not presently known exactly). The aim would be to have a 2 month maintenance break, without a vacuum break unless absolutely essential, in order to allow the 2nd physics campaign to begin relatively soon after the completion of the first campaign.

APPENDICES

A. RESTART SCOPE AFTER VESSEL PUMPDOWN

The planning has been performed assuming there are 3 periods of approximately 3 months duration each:

- Integrated commissioning
- Restart
- First physics campaign

Each period in the operations plan consists of several phases. MAST-U integrated commissioning is up to the end of phase 3, the restart period is phases 4 to 8 and the first physics campaign starts at phase 9. The detailed scope and planning of each phase will be elaborated by the restart team and MPEC. Phase 10 represents the full capability of MAST-U core scope, which will be achieved as soon as possible during subsequent campaigns, following the installation of the Galden chilled centre column and engineering assessment of the various systems (TF, solenoid, NBI).

These phases define the key milestones or events that will form the basis of an "Integrated Master Plan" currently being developed. Each key event will be supported by specific accomplishments with specific criteria to be satisfied for its completion. As such these milestones are key to defining the plan. The descriptions given below give a generic view of what must be accomplished at each stage, the detailed breakdown will be given at a later date.

Phase 1 – Pump Down

This stage starts the integrated commissioning and will involve intensive leak testing.

Phase 1.1 – Gas calibration (1 week)

The aim of this activity is to measure and calibrate the rates and response times of each of the gas injection positions under the control of the Machine Control System.

Phase 1.2 – Glow discharge cleaning and bake preparation (4 weeks)

Ensure that the GDC system is working correctly and that the vessel is prepared ready for baking. During this period there will be tests of the divertor heater modules.

Phase 2. – Vessel bake and bake recovery (4 weeks)

From the state of a successfully leak tested vacuum vessel, the vessel will be baked for 3 weeks and have a GDC to improve the achieved vacuum. This is the first major integrated test of the machine and requires a large number of the control systems to be working.

Phase 3. – Integrated power supply commissioning, coil Test Shots and Calibrate Magnetics (12 weeks)

This stage commissions the integrated coil controls between the Pulsed Power Supplies, Machine Control System, Plasma Control System and the Machine Protection System.
This stage is used to confirm that the MAST-U systems are controlling each individual coil and any set of coils (current or voltage control, not yet flux control). Calibration of magnetic sensors will be performed in parallel.

Phase 4 – Plasma startup (4 weeks)
This is the first part of the plasma restart and commissions the systems needed to achieve a consistent breakdown of the plasma. There will be a period when the predicted and measured time-dependent fields and fluxes are compared. This phase requires a commissioned Plasma Control System to create a sustained breakdown of the plasma. This will require learning a new method of how to initiate the MAST-U plasma in a structured and repeatable manner, given that the original MAST P3 coils and supporting capacitor banks have been removed. The target is a ~100kA limited plasma with credible equilibrium reconstruction.

Phase 5 – Limiter Plasma – Develop Control (2 weeks)
This phase commissions and establishes the processes and systems needed to establish and control a sustained limiter plasma. The aim of this activity is to ensure that the Plasma Control System and MAST-U equipment can sustain a Limiter Plasma, achieving a flat-top (>200ms) plasma with current of 500kA and a plasma density of $3*10^{19}$ m^{-3}. The radial position will be controlled (target to be constant to ~+/- 2cm). The shape control using at least P4 and P5 will be started. It will also set up and develop the control systems for vertical control for slightly unstable plasmas, and error field correction. These shots will provide additional conditioning of the vessel. NBI into plasma would be demonstrated at a basic level.

Phase 6 – Conventional Divertor (2 weeks)
This phase takes the limiter plasma and elongates it and produces X-points such that the inboard and outboard legs are striking the T1-3 target tiles, double null. This will also give the opportunity to measure the effectiveness of the nose region and gas baffle in giving a differential pressure between the main chamber and the divertor chambers. This is likely to require good fuelling control. It will depend on achieving robust vertical position control. Fast current ramps could replace off-axis NBI if l_i needs to be reduced. NBI: demonstrate simultaneous injection of two beams

Phase 7 – Demonstrate Extended Leg (2 weeks)
This stage extends the outboard leg so that it is striking the T4 or T5 tile, probably using feed forward algorithms. The aim of this activity is to control the outboard leg to strike the T4/T5 tiles of the divertor. Double null.

Phase 8 –Extended Leg control (2 weeks)
The aim and scope of this stage is to ensure that the extended leg can be maintained during the solenoid swing – full control by PCS, including using real time EFIT will be commissioned during the first and subsequent physics campaigns. Plasma current at least 400kA. Continued development of NBI

Phase 9 – First physics campaign (25 weeks)
At this phase, the machine is ready to start the first physics campaign; however, a period of scenario development and additional NBI commissioning will be required, which will form part of the campaign.

Phase 10 – Full Capability (Core)
Following the initial physics campaigns, the Galden cooling system will be is installed and all the systems are commissioned individually and together (where needed) to their full capability.

NBI commissioning
The neutral beam systems will be commissioned in parallel with the restart activities. The phases include NBI commissioning, which will be performed during phases 1-3. NBI Conditioning during phase 4, which will allow the injection of one beam into plasma with 1.5 MW for 1 second duration by the end of phase 5. Conditioning of this first beam up to 2 second duration combined with conditioning of the second beam up to 1.5 MW 2 second pulses will be complete by phase 7 allowing synchronous operations at 3 MW, each beam operating for 2s by phase 8. As each level of capability is reached the NBI will be integrated into the rest of the MAST system. Indicative intermediate NBI targets are included above in the later phases. By the start of the 1st physics campaign the on-axis beam should be commissioned to 2 MW and the off-axis to 1.5MW.

Diagnostic commissioning
The diagnostics will be commissioned in parallel with the restart phase with the scheduling arranged to ensure that each diagnostic is available as required by the programme. Priority will be given to the divertor diagnostics.

B. OPERATING SPACE AND SCENARIOS

The key plasma parameters for MAST and MAST Upgrade are given in Table 1, although it should be noticed that a cautious approach will be adopted for the expansion of the operating space in terms of plasma current, magnetic field, heating power and pulse duration. For example, shots at full TF are represent lifetime limiting events and hence will be restricted especially in the early campaigns.

In addition to a wide range of divertor geometries discussed in section 3, MAST Upgrade provides the opportunity to vary the shape of the last closed flux surface, allowing investigations of the effect of the plasma shape on core and edge phenomena. Figure 8 illustrates the potential for plasma triangularity changes due to the variation of the current in the 'PX' coil and MAST Upgrade will be capable of operation with single- or double-null X-point geometries.

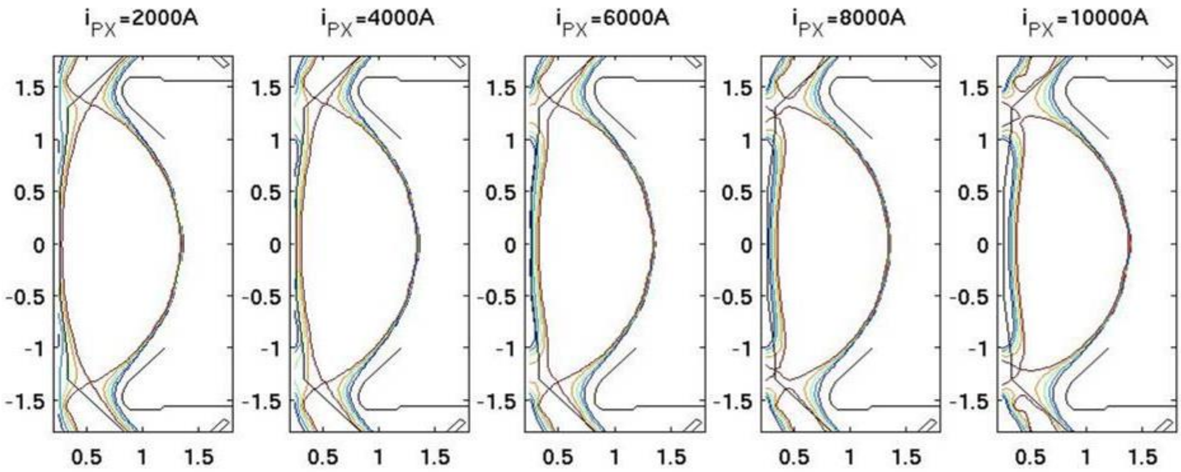

Figure 8 *Main plasma shape variation as current in 'PX' coil is varied*

A range of plasma scenarios is envisaged for MAST Upgrade from low density plasmas, where neutral beam current drive is significant and plasma rotation and fast ion pressure is large, to high density plasmas where the neoclassical bootstrap effect dominates the non-inductive current drive and fast ion physics becomes more classical due to the reduced drive for energetic particle modes. In practice, the achievable range of plasma density will depend on many factors including: the balance of plasma fuelling, recycling and pumping; the accessibility of H-mode the associated ELM behaviour, and the particle transport behaviour in the core plasma and scrape-off layer. Nevertheless, projections have been made for the operating parameters of MAST Upgrade to provide notional plasma profiles that can serve as guidelines for the development of experimental proposals for the first campaigns.

Plasma profiles for notional low and high density MAST Upgrade plasma scenarios are shown in Figure 8. These are simply projected using typical temperature and density profile shapes obtained in H-mode in experiments on existing ST devices. The plasma pressure has been normalised to provide H_{98}=1 with a MAST Upgrade plasma shape. The plasma current and magnetic field were set to be 1MA and 0.75T (at R=0.85m), respectively, and the NBI heating power was 5MW. The current drive has been calculated self-consistently with the kinetic profiles to provide a likely q-profile shape.

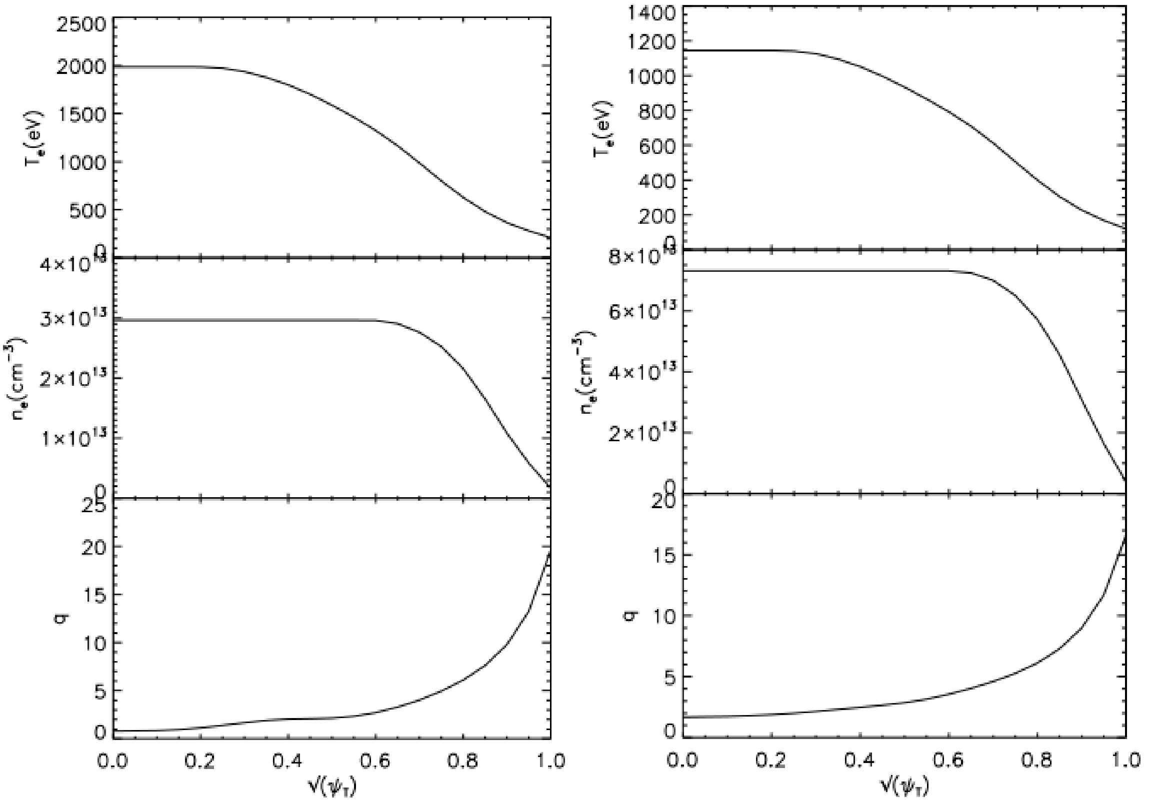

Figure 9 *Notional plasma profiles for low and high density MAST Upgrade plasmas*

C. DATA ACCESS

The granting of access to unpublished MAST Upgrade data by collaborators is at the discretion of the chair of the MAST Upgrade Programme Execution Committee (MPEC). Access will usually be granted only to those involved in a formal collaboration with UKAEA, and whose organisation has signed a Memorandum of Understanding. Only collaborators who have signed this agreement may be given direct access to unpublished MAST Upgrade data.

Those granted access should not transmit unpublished MAST Upgrade data to a third party without the prior agreement of the chair of MPEC. Users of MAST Upgrade data shall ensure that it is properly validated by the relevant diagnostic responsible officers before it is included directly or indirectly in any publication or presentation. The results of analysis of MAST Upgrade data shall be made fully available to the MAST Upgrade Team.

D. PUBLICATION POLICY

All publications concerning MAST Upgrade work should use only the official names: MAST Upgrade or MAST-U.

CCFE clearance is required for all publications and presentations reporting on MAST Upgrade data, including material uploaded to externally accessible web sites. CCFE contact persons can advise on the clearance procedure which involves provision for adequate Peer Review prior to formal approval. Ad-hoc presentations in "working meetings" involving staff from the collaborating institution and/or CCFE (i.e. not formal workshops or conferences) are allowed as long as the preliminary or unvalidated status of the data is clearly stated.

The author list of any publication or presentation should normally include the collaborating CCFE staff and/or "The MAST Upgrade Team" with the affiliation address:

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Oxon, OX14 3DB, UK.

even if the primary author is not an employee of Authority.
An acknowledgement of the funding organisation, and any agreement under which the work is carried out, as well as a statement on how requests for the underlying data should be made (for refereed journal papers only).

EPSRC require all bodies they fund, which includes CCFE, have an "open access" policy on all published scientific paper. The EU funding, through the Horizon 2020 programme has similar requirements, which apply to CCFE's EuroFusion funding.
The EPSRC implementation of this policy can be found at
http://www.epsrc.ac.uk/about/standards/researchdata/Pages/policyframework.aspx.

For publications the lead author has overall responsibility for ensuring that agreed Research Data management requirements are observed. Publications can be regarded as composed of a set of elements (e.g. figures) for which the Research Data management requirements are to be applied by the person producing that data. The required metadata relating to journal publications should be made available immediately after the paper is published. For conference papers the metadata should be made publicly available within 1 year of the conference.

For MAST Upgrade data the MAST Data Management Committee has responsibility for ensuring that research data management requirements are observed, whilst the Publication Board will ensure that the data provenance has been maintained. To allow MAST Upgrade researchers adequate time to analyse their data an embargo period of 3 years will be adopted before public release.

E. EXPERIMENT PLANNING AND APPROVAL PROCESS

The experimental campaign on MAST-U will have two elements: the internal campaign and the MST1 campaign. The experimental planning for the internal campaign with commence with the definition of the main goals or thrusts for the campaign. These will initially be defined by the Tokamak Science Forum (TSF) before being agreed by the Tokamak Science council. These goals/thrusts will be presented to the MAST Upgrade research forum for discussion.

Following the approval of the goals/thrust for the internal campaign a call for proposals will be issued. The proposals will be collated by the appropriate Topical Leader who will develop an experimental programme to meet the goals. This experimental programme will be presented to the TSF for approval and the individual shot plans will then be developed, in collaboration with the MAST-U campaign co-ordinator who will allocate a lead session leader. The shot plans will be presented to the MAST-U Programme Execution Committee (MPEC) two weeks prior to the experiment for approval.

The MST1 campaign will be co-ordinated by the MST1 task force leaders in the way that happens now for other MST1 devices. Details can be found here:
http://users.euro-fusion.org/iterphysicswiki/index.php/Work_Package_MST1
MST1 experiments will still require MPEC approval two weeks before execution.

F. EUROFUSION ROADMAP (2013) HEADLINES

- Headline 1.1: Increase the margin to achieve high fusion gain on ITER
- Headline 1.2: Operation with reduced or suppressed ELMs
- Headline 1.3: Avoidance and mitigation of disruption and runaways electrons
- Headline 1.4: Integration of MHD control into plasma scenarios
- Headline 1.5: Control of core contamination and dilution from W PFCs
- Headline 1.6: Determine optimum particle throughput for rector scenarios
- Headline 1.7: Optimise fast ion confinement and current drive
- Headline 1.8: Develop integrated scenarios with controllers

- Headline 2.1: Detachment control for the ITER and DEMO baseline strategy
- Headline 2.2: Prepare efficient PFC operation for ITER and DEMO
- Headline 2.3: Optimise predictive models for ITER and DEMO divertor/SOL
- Headline 2.4: Investigate alternative power exhaust solutions for DEMO