The upgrade to the Mega Amp Spherical Tokamak

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Abstract. The Mega Amp Spherical Tokamak (MAST) [1] is one of the two largest tight aspect ratio, $R/a \approx 1.3$, tokamaks in the world. In the 10 years since construction, MAST has provided valuable contributions to the tokamak physics basis in support of ITER and DEMO as well as advancing the physics for next step Spherical Tokamak (ST) devices. A key issue for these future devices relates to the physics validation for a 'Component Test Facility' (ST-CTF) which offers a promising route to a cost efficient volume neutron source to perform nuclear testing of Fusion Reactor in-vessel components without the need to breed tritium in the device itself. A major upgrade of MAST is now underway which aims to address this issue and at the same time make a wide range of contributions to fusion science, for example testing novel divertor concepts such as the Super-X.

1. Introduction

The spherical tokamak (ST) concept is an extension of the conventional tokamak design (exemplified by JET and ITER) to low aspect ratio. The aspect ratio, A, the ratio of plasma major radius to minor radius, $A = R/a$, has a value of ~3.1 in ITER. In STs, A is typically ≤ 1.5. The distinctive physics and technological properties of the ST can be summarised as:

- low toroidal magnetic field;
- high normalised plasma pressure;
- compactness (low major radius for a given plasma cross section), leading to a high volumetric power density; and, due to the smaller magnetic energy,
- an option for normally conducting coils, even in a power-plant sized machine.

Exploitation of the ST concept began in the late 1980s with the emergence of designs for substantial ST devices in the US and EU. Since then, many devices have been built, with MAST and the US NSTX device the largest machines operating in the world at present.

A Component Test Facility (CTF, [2]) has been proposed to support the path to commercial fusion power and if possible help optimise the design of DEMO to reduce the technical risk of the DEMO programme. CTF would provide a complementary capability to ITER by focussing on a high neutron, high heat flux environment in a driven machine (i.e. substantially heated and controlled by external systems) to test and optimise power plant components such as breeding blankets in long pulse quasi-continuous operation.

Detailed studies have shown that the Spherical Tokamak is an excellent candidate for such a device [3]. An ST-CTF can access the conditions needed for high neutron fluence testing of components (~1-2MW/m^2, ~4MWyear/m^2), while making efficient use of tritium, in a

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compact machine. This reduces or obviates the need to make tritium breeding work at this first stage, allowing the CTF to meet its research goals based on existing tritium availability, and without relying on the development of breeding technology before other research can start.

An upgrade to MAST (MAST-U) has been designed and is being implemented; this should enable substantial progress on the most critical issues for the ST-CTF, and contribute strongly to aspects of ITER- and DEMO-relevant physics that can be studied best in a spherical tokamak. The first major stage of this programme is planned to deliver a machine that starts operation in 2015. This has two primary goals: first, the test of a novel "Super-X" divertor configuration (SXD) to reduce target heat loads, adapted from the super-X concept [4], and second, access to dominantly non-inductively driven pulses with constant plasma current $I_p >$ 1 MA for longer than two-three current diffusion times (for plasmas with $0.5s \le \tau_R \le 1s$).

2. Overview of the first stage of the MAST Upgrade

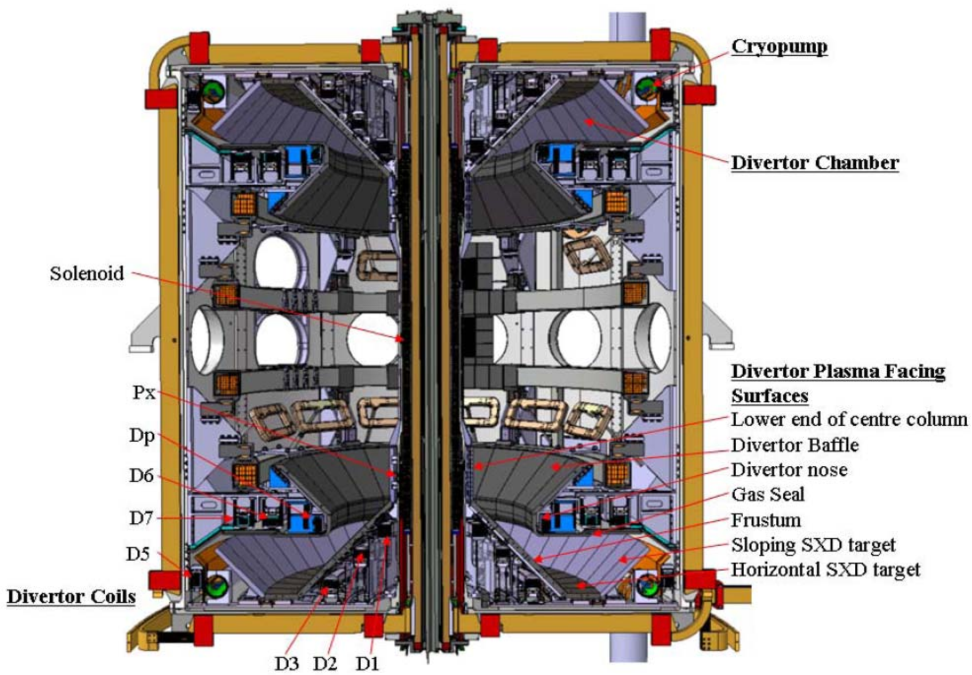

FIG 1. Cross Section of the MAST Upgrade Load Assembly

A cross-section of the MAST-U load assembly is shown in *FIG 1* [5]. Both MAST top and bottom divertors will be upgraded from the existing open configuration without density control to a closed, pumped divertor (cryogenic pumps based on supercritical helium). Using eight new coils, each divertor is designed to allow the outer divertor leg to be operated either in a conventional X-point configuration or the SXD configuration. In the SXD configuration, access to the detached regime on the outer leg is aided by a magnetic configuration that increases the connection length, in a part of the scrape-off-layer that is well separated from the confined plasma region. This is achieved by creating a region of very low poloidal field in the baffled region of the divertor, together with stretching the outer leg to a large radius ($R \approx 1.5$m cf. X-point major radius ~ 0.8m).

Gas puffing of both fuel and impurities can be used in this separated 'Super-X' region to further cool the divertor leg and aid detachment at given core parameters. Cryogenic pumps will be installed in both divertors to provide density control and access to low densities ($\bar{n}_e \approx 3 \cdot 10^{19}$ m^{-3} in the core plasma.).

The demonstration of dominantly non-inductively driven scenarios in MAST-U will be achieved using an upgraded neutral beam configuration. The first stage will have three neutral beam sources, each injecting up to 2.5 MW, with two of the sources installed in elevated positions (Z=0.65m) for off-axis current drive. Two of the beam sources will be installed in a new Double Beam Box [6].

Apart from the pumped divertor and the off-axis neutral beam injection, several other upgrades to MAST subsystems are planned to allow pulse length of several seconds at high I_p $\geq$ 1MA. These enhancements include a new centre column with three new shaping coils and 70% more flux capability, as well as a new long-pulse toroidal field power supply allowing 50% higher B_t for more than 2s ($I_{rod} \leq 3.2$ MA) compared to MAST.

TABLE 1 presents the main physics parameters already achieved on MAST, those projected for MAST-U following the first stage of the upgrade, and those for a conceptual design of an ST based CTF [2].

TABLE 1 MAIN PHYSICS PARAMETERS OF MAST, MAST-U AND A CONCEPTUAL ST-CTF.

		MAST	**MAST-U Stage 1**	**ST-CTF**
Major, minor radius	R, a (m)	0.85, 0.65	0.85, 0.65	0.84, 0.54
Elongation	κ	2.5	2.5	2.3
Plasma current, toroidal field current	I_p, I_{TF} (MA)	1.5, 2.0	2.0, 3.2	6.5, 10.5
Normalised pressures	β_N, β_T	4.5, 15%	5.5, 40%	3.5, 16%
Normalised confinement factor (ITER IPB98(y,2))	$H_{IPB98(y,2)}$	<1.3	<1.3	1.3
Auxiliary heating power	P_{aux} (MW)	3.8	7.5†	40
Normalised density	n/n_G‡	0.15 – 0.8	0.15 – 1	0.23
Non-inductive Current Drive, Bootstrap Current	f_{NI}, f_{BS} (%)	<30, <30	≤100, ≤40	≤100, ≤40
Neutron wall load	(MWm^{-2})	-	-	1.0
Pulse length	(s)	0.6	5	∞

†Of the 7.5 MW total injected power 5 MW are off-axis.
‡n_G is the Greenwald density defined as $n_G = 10^{14} I_p / \pi a^2$.

3. Physics scenarios for MAST-Upgrade

In order to develop a consistent design able to address the primary goals, a set of plasma scenarios have been developed, all at ~1MA except where stated:

Scenario A,B Stability and confinement of an ST-CTF like q-profile (q_{min}>2). A.1 and A.2 high and low density respectively.
Scenario C Off-axis NBI current drive efficiency (steady-state), q_{min}~1-1.5.
Scenario D Scaling of confinement with plasma current (up to 2MA) at high β_T.
Scenario E Close to present MAST plasmas.

Scenario F Effect of triangularity on MHD stability and confinement and performance.

Scenario G The effect of thermal β_N versus total β_N on MHD stability, up to 2MA, q_{min}>2.

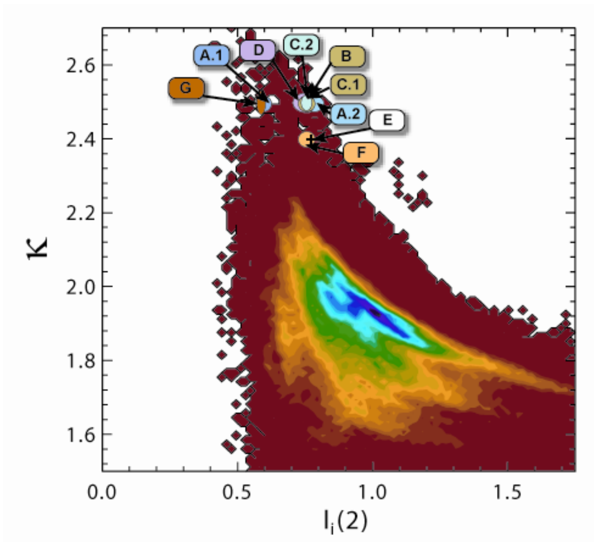

FIG 2: Operating space of MAST-U in κ and l_i with MAST-U scenarios overlaid. The colour coding represents the operational time in a given configuration.

Key to the physics studies on MAST-U is the optimisation of the current profile towards low l_i and elevated q > 1.3. This can be achieved via two alternative routes. On the one hand the bootstrap current can be maximised requiring high density operation. On the other hand, low density operation $\bar{n}_e \approx 0.24 \cdot n_G$ ($n_G = 10^{14} I_p / \pi a^2$) allows efficient active current drive methods (such as neutral beam current drive, NBCD) to shape the current profile independent of the underlying kinetic profiles.

Designing a device capable of low density is the most flexible approach. To maximise the bootstrap current for a given density, high elongation κ, and high normalised pressure β_N are needed. Both can be achieved at low l_i and high q.

The envisaged operational space[2] in κ and l_i is shown in *FIG 2* and clusters in the top left corner of the current operating space for MAST. The advanced (high q_{min}) q-profile is needed, because the combination of inherently low magnetic shear of the q-profile and high β is susceptible to global internal n=1 kink modes. Modelling has shown that at the expected β_N values for the MAST-U scenarios this mode is ideally unstable if q_{min} < 2, but the mode can be stabilised by toroidal flow shear at the q=2 surface as well as by fast particle pressure. Taking the estimated rotation profile, fast particle profile, and the effect of passive stabilisation plates into account, the envisaged MAST-U scenarios are expected to be MHD stable if q_{min} > 1.3. This is consistent with the stability analysis of existing discharges in MAST and NSTX.

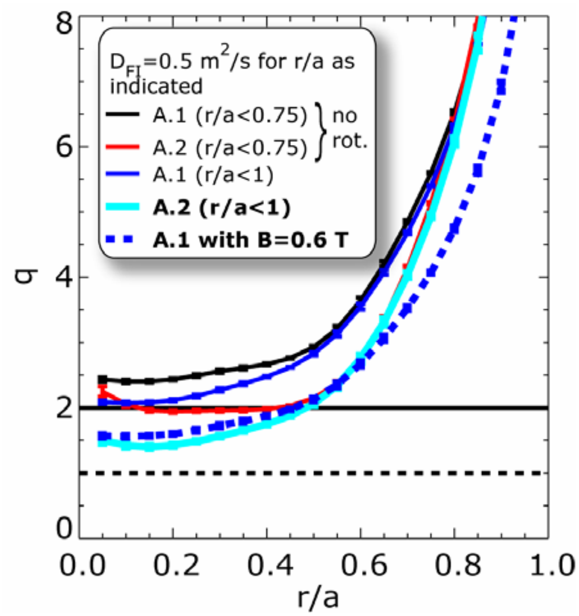

FIG 3: q-profiles for MAST-U scenario A.2 with (β_h/β~20%) and A.1 (β_h/β~60%) with different assumptions for the fast-ion redistribution.

A particularly important element of MAST-U core physics studies is the behaviour of fast particles: their effect on MHD stability and confinement, and their

[2] As modelled using equilibrium codes and TRANSP simulations .

behaviour determine the efficiency and localisation of NBCD. To help such studies stationary operation at similar q-profile but with different fast particle fraction β_h/β are a design goal. This is achieved in the simulated q-profiles shown in *FIG 3*. Here q-profiles with different assumptions for the unknown fast-ion redistribution for two variants of an I_p=1 MA, B_t=0.8 T plasma at different density $\overline{n}_e = 7\times10^{19}$ m^{-3} (A.1: n/n_G=0.6) and $\overline{n}_e = 3\times10^{19}$ m^{-3} (A.2: n/n_G=0.2) leading to β_h/β~20% and β_h/β~60% respectively. It should be noted that the scenario A.2 is fully non-inductive. Furthermore, the flexible heating system with on-axis and off-axis NBI allows variations of the fast-ion density from centrally peaked profiles, to hollow profiles via broad profiles. These studies will be aided by a suite of new diagnostics probing the confined and lost fast particles.

In the absence of a validated predictive model for an ST, the expected operating scenarios for MAST-U have been evaluated using the TRANSP code with prescribed profiles for T_e, T_i and n_e scaled to give $H_{HIPB98(y,2)}$ = 1. The simulations indicate that it should be possible to access scenarios with $I_p \geq$ 1 MA driven fully non-inductively, as well as scenarios with relaxed q-profiles, with q_{min} > 2.

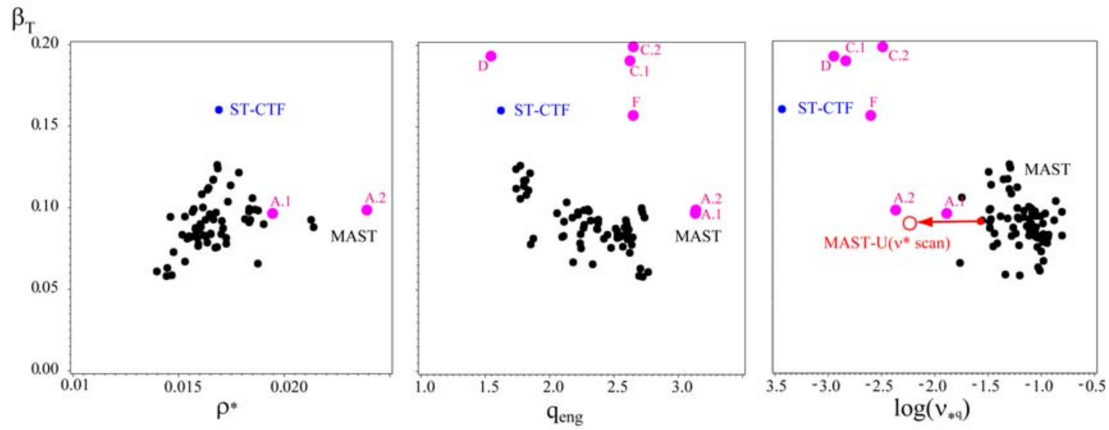

FIG 4: Expected operating space (magenta) in dimensionless parameters ρ_* (ion), q_{eng} and ν_* (electrons) in comparison with the current MAST (back) operating space. Also shown is the expected operating point for the ST-CTF(blue) and a dedicated dimensionless scan in ν_* (red), where the largest extrapolation is needed.

The new capabilities installed in the MAST-Upgrade will widen the operational space of MAST to lower collisionality, higher fast particle fraction β_h/β~60%, higher current $I_p \leq 2$ MA, higher toroidal field B_t(R=0.7m) ≤ 0.9 T, and stronger shaping (with elongation $\kappa \leq 2.5$ and triangularity $\delta \leq 0.6$). This is of particular interest for the energy confinement in the ST, which may be dominated by the electron transport due to ETG modes or Alfvénic instabilities. The ST shows a stronger scaling of confinement with B_t and slightly weaker scaling with I_p compared to the IPB98(y,2) scaling [7]. In MAST-U this can be tested at lower collisionality, ν_*. The accessible space in dimensionless parameters is shown in *FIG 4* in comparison with MAST and the expected ST-CTF. MAST-U will be able to bridge the gap between current STs and the ST-CTF. It should be noted that the operational points do not represent scans in the particular dimensionless parameter. A dedicated ν_* scan is also depicted.

4. Divertor studies – behaviour of a Super-X divertor

MAST-U is fundamentally a double-null divertor tokamak. The well-matched pair of divertors, one upper, one lower, are therefore an intrinsic part of the overall physics programme and are required to provide 'conventional' divertor power handling and particle control for experiments that focus on the behaviour of the core, confined plasma. In addition, the divertors must provide the operational flexibility and range of diagnostics that are necessary in order to carry out experiments that increase understanding and guide the design of divertors that are needed in future, higher power, fusion devices. In this latter respect, the "Super-X" divertor configuration is the main focus.

FIG 5 shows the predicted magnetic equilibrium for a conventional scenario with a plasma current of 1MA and the full toroidal field for MAST-U (0.8T at a major radius of 0.8m). The leftmost plot shows the trajectory of field lines from the mid-plane to the first material surface, at 1mm intervals from the separatrix. The connection length at the low field side and the local area expansion are calculated at the same millimetre intervals in radius at the mid-plane, starting at 1mm from the separatrix. The Super-X coils (D5, D6 and D7 - see *FIG 1*) are not energised in this scenario.

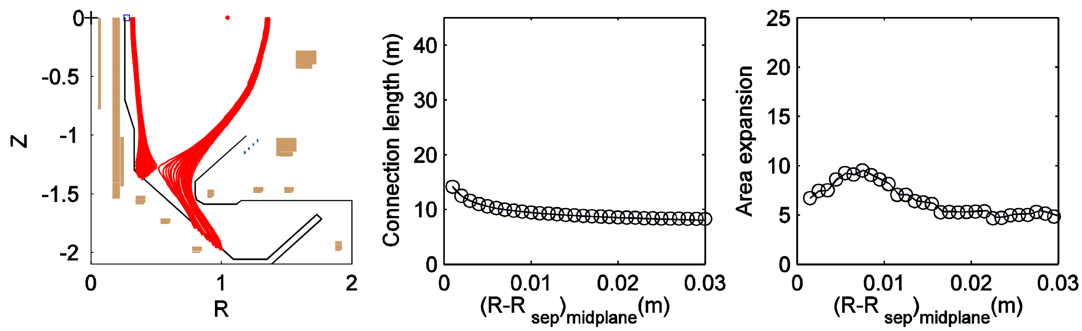

FIG 5. Predicted conventional equilibrium for MAST-U, together with the connection length and local area expansion at the target.

By using the Super-X coils D5, D6 and D7 equilibria comparable to the one presented in *FIG 6* can be achieved. The configuration is recognisable from earlier work on the Super-X divertor [4][8]. Note that in this case the Scrape Off Layer beyond 22mm is now striking on the surface adjacent to either the D7 or D6 coil – as seen both on the flux plot, and in the sudden drop in connection length. In addition, there is a trade off between the increase in connection length, and the decrease in expansion at the target, using this design of coils and targets. This highlights a specific and unavoidable underlying relationship between the connection length and the expansion of the poloidal flux that can be achieved within a fixed bounding geometry.

The equilibria shown demonstrate some of the flexibility in the magnetic configuration of the divertor that will be available in MAST-U, subject to the above-noted caveats regarding the trade off between the achievable connection length and the width of the SOL that can be fitted into a given divertor volume.

Early calculations using the coupled B2-EIRENE code suggest that the power density on the outer target plates can be reduced significantly e.g. by a factor of 3 or more when moving from the conventional divertor to the SXD configuration even in extreme power load cases with 10 MW flowing into a moderate density (10^{19} m^{-3} at the separatrix) narrow SOL. These calculations also show that the divertor is very closed with compression ratios in the range of $150 < n_D/n_V$ (n_D: neutral density in the divertor, n_V: neutral density in the main chamber) depending on the assumptions for the SOL width, $\lambda_{q,n,T}$ (q: heat flux, n: density, T: temperature). It should be noted that the closure is achieved at the divertor nose (see *FIG 1*), rather than the strike point, leaving flexibility in the strike-point position. This flexibility is needed for high current operation in the conventional configuration where target powers in excess of 10 MW/m^2 are expected as λ_q becomes thinner with increasing I_p. Here, strike point sweeping is required to achieve pulse length of the order of 1.5s – 2s.

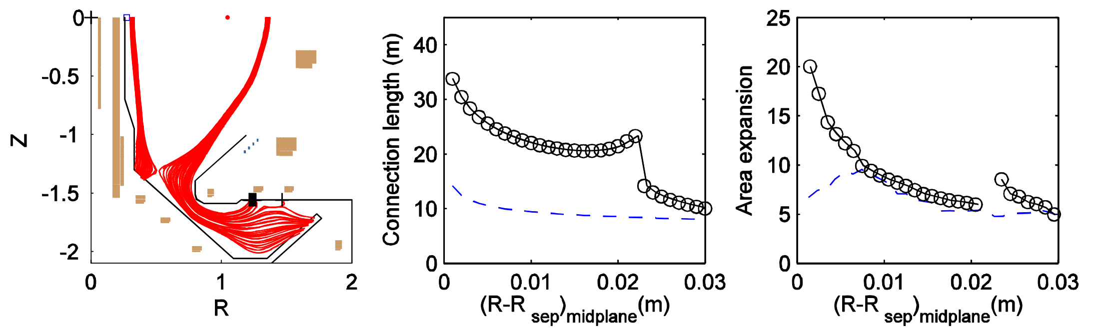

FIG 6. Predicted 'Super-X' divertor configuration for MAST-U, together with the connection length and local area expansion at the target (blue line corresponds to conventional case)

A comprehensive suite of new diagnostics will be installed to fully exploit the advanced MAST-U divertor (the lower divertor will include the most complete set of diagnostics, whilst the upper will include a more limited set, to diagnose the extent to which the two divertors are sharing the power acceptably). These diagnostics will include full accounting of the power balance (IR cameras, Langmuir probes, bolometer arrays) as well as basic plasma parameters such as n_e, T_e (Divertor Thomson Scattering, reciprocating probe) and impurity content (Spectrometer).

5. Engineering Issues in the upgrade design

To achieve the greatly enhanced performance, the centre column assembly, centre tube, divertors and poloidal coils of MAST require complete redesign. The increased toroidal field (from 0.52 to 0.78 Tesla at R = 0.85m), solenoid flux swing (0.9 to 1.7 volt-seconds) and pulse length mean that the existing MAST centre column sub-assembly would be subject to an increased twisting torque on the centre rod (138 kNm in MAST-U compared with 58 kNm on MAST) and has to be completely redesigned and replaced [9]. Overall, the torsional load on the joint between the centre rod and end crown is increased by a factor of around 2.5. Detailed stress analysis of the rod to crown joints, which are insulated and castellated, reveals the likelihood of de-bonding cracks initiating in the castellation corners. Further crack opening analysis indicates that these cracks will arrest before they reach damaging levels. The solenoid will no longer be wound directly onto the centre rod but rather as an independent coil. This brings numerous benefits but entails increased stress in the join between the two.

As in the current design of MAST, the TF current is carried to the centre rod by sliding joints to account for thermal expansion. The increased torsional loads create the challenge to design a sliding joint that will be capable of a 300 μm maximum deflection, while still operating at similar or better levels of contact pressure and current density throughout the pulse duration.

This is achieved by designing a deeper (150mm to 200mm), thicker (3mm to 4mm) double hinged tongue mechanism for the sliding joint.
In order to cope with the increased thermal and structural loads on the solenoid, the coil will be made with cyanate ester resin which greatly enhances it's strength at higher temperatures compared to standard epoxy resins. Manufacturing techniques for cyanate ester have been developed and tested on similar coil geometries [10] but this will be one of the first cyanate ester coils to be used in a Fusion device. To achieve longer pulse performance, the solenoid and centre rod will be cooled to -40ºC with a chiller system using Galden.

6. Concluding Remarks

The first stage of the MAST upgrade programme will greatly enhance the capabilities of the existing MAST, and addresses important issues for ST-CTF and DEMO physics. In particular the enhanced flexibility with respect to fast-particle studies and divertor configuration (SXD) should allow the exploration for exciting new physics studies. However, further steps in the programme, are needed to close critical gaps in the ST-CTF physics basis. These additional 'stage 2' enhancements envisage a 1-2 MW 19 GHz EBW heating and current drive system, up to two additional 2.5 MW beam sources including a counter current beam, a high frequency pellet injector, external ELM mitigation coils and diagnostic upgrades. We anticipate the involvement of collaborating organisations in their implementation.

Acknowledgements

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