MAST Upgrade microwave heating and current drive system – engineering design overview

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Abstract. MAST-Upgrade (MAST-U) is undergoing several enhancements to deliver increased performance and functionality. One such enhancement is the design, development, and implementation of an Electron Bernstein Wave (EBW) Heating and Current Drive (HCD) System. The MAST-U EBW System aims to provide experimental data for model validation, and to provide a greater understanding of EBW physics and its capabilities. The MAST-U EBW System provides up to 1.8 MW of microwave power into the plasma, through a system comprising: high voltage power supplies; two gyrotrons; evacuated transmission lines; a steerable in-vessel launching system; and associated control and ancillary systems. The gyrotrons from Kyoto Fusioneering have a 0.9 MW output power capability at the dual frequencies of 28GHz and 34.8GHz, allowing start-up and current drive studies to be carried out at their respective optimum frequencies. Additional diagnostics, termed interceptor plates, are proposed to sit in the path of the first reflection. These will measure the reflected power from the plasma, to both act as an interlock if the reflected power is too high, and provide key information on the coupling efficiency.

1 Introduction

MAST-Upgrade (MAST-U) is undergoing several enhancements to deliver increased performance and functionality. One such enhancement is the addition of a 1.8MW, 4.5s Electron Bernstein Wave Heating and Current Drive System (EBW H&CD), operating at 28GHz / 34.8GHz.

The primary aim of the system is to provide an experimental basis for the use of EBW Current Drive on a spherical tokamak, in support of the STEP (Spherical Tokamak for Energy Production) programme, examining open issues, and providing data on experimentally achieved coupling efficiencies to assist with model validation. The system is designed to provide a high degree of flexibility, particularly in the launching system, to provide a broad experimental data set. Additionally, the system provides the capability to extend earlier MAST experiments into EBW based solenoid free start-up. More details of the motivation for this system can be found in these conference proceedings [1].

The two roles of the system (solenoid free plasma start-up and high-density current drive) have differing requirements. The first of these requires excitation of Electron Bernstein Waves at the fundamental electron cyclotron frequency, and the latter at the second harmonic.

The power requirements of the system are defined by the need to drive a clearly measurable current. The high-level requirements are shown in Table 1, along with the design parameter values chosen to meet these requirements. This paper provides an overview of the engineering design at the current preliminary design phase.

2 System Overview

The system designed to meet these requirements is termed the MAST-U EBW System. The system external to the MAST-U vessel comprises: high voltage power supplies; two dual frequency gyrotrons; evacuated transmission lines; a long pulse dummy load; and associated services such as water cooling and vacuum pumping. Inside the MAST-U vacuum vessel, a steerable in-vessel launching system provides flexible options via two separate launchers – off-axis and on-axis. Finally, additional diagnostics termed “interceptor plates” sit in the path of the first reflection.

The off-axis launcher has a small steering range, and can operate in co current drive only, whereas the on-axis launcher can operate in the co and counter plasma current directions (independently for each beam).

In the present system design, with the gyrotron output power offset by the transmission and launcher losses, a power to the plasma of up to 1.6MW is predicted. A summary of the design values against the requirements is shown in Table 1.

The system is located primarily within the existing MAST-U building. Co-location of the high voltage power supplies and gyrotrons in the same area minimises the cable length between them, reducing cable stored energy and minimising risks of gyrotron damage, in case of a

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gyrotron arc event. The location of the gyrotrons within the building allows for a minimal length and number of bends in the transmission line route to minimise power losses.

Table 1. System requirements and design values

	Parameter	Requirement	Design Value
Heating and Current Drive	Frequency	Second harmonic, 35-37GHz	34.8GHz
	Power (to the plasma)	>1200kW	1500-1600kW
	Launch	Launch to achieve on and off axis current drive	Two on-axis beam paths, Two off-axis beam paths
Solenoid Free Start-Up	Frequency	Fundamental, 28GHz	28GHz
	Power (to the plasma)	>200kW	650-750kW
	Launch	X mode, to provide co-current drive	Quasi-high field side launch from centre column polarising tile (see Section 6.4)

3 Power Supplies

The High Voltage Power Supplies are designed to meet the gyrotron requirements; for a triode type gyrotron this consists of cathode, body and anode power supplies. For cost and space optimisation the cathode supply is shared between the two gyrotrons, rated for 110A, -55kV.

Initially, modulation can be carried out using the cathode supply at 1kHz. Future modifications are proposed to use a switching system on the anode power supplies to enable independent modulation. Examples of the desirable power modulation are shown in Figure 1. Shown here are examples of maintaining a constant average power whilst changing the maximum instantaneous power, allowing non-linear effects in the EBW coupling scheme to be investigated.

The power supplies are designed to keep the arc energy low (<10J), and output over/under shoot, ripple and stability to acceptable levels. The power supplies have an overall duty cycle of 1/60, equating to a 5 second pulse every 5 minutes (with a higher intra-pulse duty cycle).

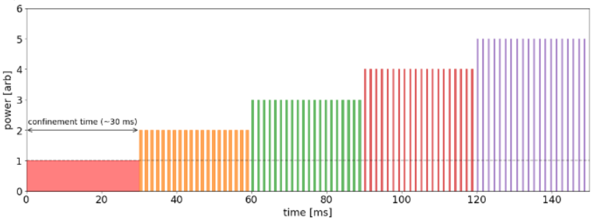

Fig. 1. Example of desirable modulation capability

4 Gyrotrons

The gyrotrons are supplied by Kyoto Fusioneering, and include the gyrotron tubes, cryogen-free Superconducting Magnets (SCMs), Matching Optics Unit (MOU), and low voltage power supplies.

The gyrotrons have two ratings, 800kW for 4.5 seconds, and 900kW for 3 seconds (see Table 2). These power values are coupled into the transmission line after the MOU in the HE_{11} mode. The power output can be varied from <100kW to the values specified above.

The gyrotrons are dual frequency, at 28GHz and 34.8GHz, allowing start-up and current drive studies to be carried out close to their respective optimum frequencies (more detail of frequency selection can be found in these conference proceedings [1]). The MOU is designed to couple into an HE_{11} waveguide at both frequencies without modifying the MOU optics; the mirrors are optimised for an average of the two frequencies.

One full power and pulse length dummy load is provisioned, shared between the two gyrotrons. The function of this is to absorb the power from the gyrotrons for testing and commissioning. It contains appropriate instrumentation on the cooling circuit to obtain calorimetric measurements.

Table 2. Operating parameter combinations for the gyrotrons

Frequency (GHz)	Power (kW)	Pulse Length (s)
28.0 / 34.8	800	4.5
	900	3

5 Transmission Line Design

The transmission line connects the MOU output to the interface with the ports on the MAST-U vessel. There is one transmission line per gyrotron.

Transmission of power from the gyrotron to the MAST-U vessel is achieved through the use of cylindrical corrugated waveguide with an internal diameter of 88.9mm, and associated mitre bends. 88.9mm is chosen to provide a balance between losses at the chosen frequency, and the size of the line to integrate into an existing building (whilst maintaining typical or standard diameters). The line is evacuated to high vacuum due to the need to avoid breakdown arising from the high power of the beam, and also the need to share a vacuum with MAST-U.

The transmission lines perform additional functions as follows:

- Deviate power to a calorimetric load.
- Provide polarisation control of the output beam.
- Monitor the forward power to detect potential mode jumps in the gyrotron and ensure microwaves are being transmitted as expected.
- Deviate power to either upper or mid-plane launcher.
- Provide isolation from the tokamak vacuum (when not operating into tokamak).
- Provide pumping access for maintaining vacuum in the line.
- Provide electrical isolation of the transmission line where required.

These functions are met by the design shown in Figure 2. Each line contains an elliptical and a plane polariser to give full polarisation control of the output beam, and several switches to provide the deviation to the load, or to the two launch options. There is no window at the interface to the MAST-U vessel, instead, gate valves provide the vacuum isolation when required. Vacuum pumping is carried out on the MOU, dummy load, and on or near the isolating gate valves on the interface with the MAST-U vacuum vessel. Electrically insulating breaks are located at the MOU interface and MAST-U vessel interface.

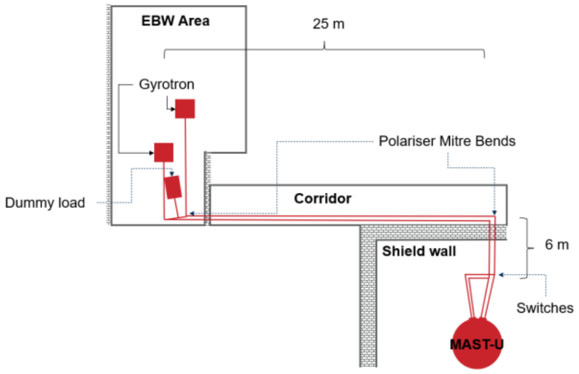

Fig. 2. Illustrative layout of the transmission line showing key components (top view)

The transmission lines achieve a calculated 85-90% transmission efficiency. The route is optimised to reduce the number of mitre bends, since at the given frequencies, each bend contributes a 2-2.5% loss [2].

6 Launcher Design

The primary function of the launcher system is to direct the microwave energy towards the plasma as required for EBW coupling. To meet the system requirements, the direction of the beam needs to be adjustable in both the toroidal and poloidal directions. The launcher system needs to be able to launch the beams on and off axis. To achieve this, the system has two launchers, termed the off-axis / upper launcher, and the on-axis / mid-plane launcher.

6.1 On-axis / Mid-plane Launcher

The requirement that the on-axis mirrors can be used to send beams in the co- and counter-plasma current direction requires placement of the final mirror at the midplane (later referred to as M2 mirrors). The symmetry of this location gives equal magnitude current in both directions, allowing a balanced, zero current configuration (one co- and one counter-).

The two midplane mirrors each have to provide a capability to steer the beam in one of two principal directions, corresponding to two plasma locations where the best coupling of the microwaves is expected for each of co- and counter-current drive. The steering is also required to be flexible for a range of plasma parameters, and to cover a range around the optimum coupling locations. This gives a steering range as shown later in Figure 6.

The mirrors are designed to achieve a large beam waist (>50mm) after the final steering mirror, which minimises the beam divergence (<4°) for optimum EBW coupling, and also to achieve the start-up beam requirements (see Section 6.4).

The launching mirrors are designed to be large enough to transmit >99% of the power which lands on them to maximise the transmission efficiency to the plasma edge and to minimise stray radiation inside the vessel, whilst not restricting diagnostic lines of sight. The mirror size is dictated by the 28GHz beam, which has a larger beam width.

The mid-plane launcher consists of two fixed mirrors delta-M1 and epsilon-M1, and two steering mirrors, delta-M2 and epsilon-M2; these are shown in Figure 3, with delta beams on the left as shown in the image. The image shows the expected range of output beams.

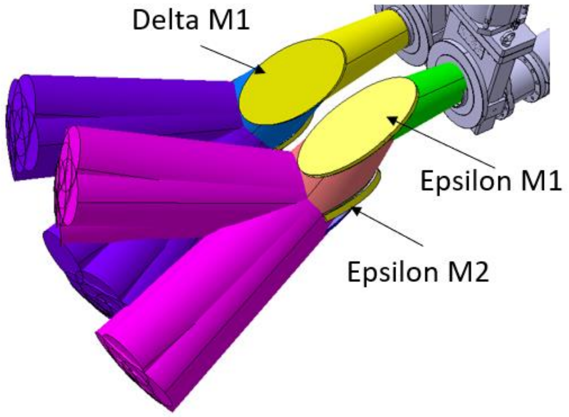

Fig. 3. CAD model of on-axis launcher showing the two beams, and a range of output beams in the co and counter plasma current directions, and for a range of plasma parameters.

6.2 Off-axis / Upper Launcher

The requirement for the off-axis mirrors is to send beams in the co-current configuration only. Achieving counter-current would have required a separate set of mirrors, which was discounted for the scope of the initial system due to the cost, complexity, and port availability. The beams need to be launched with a given beam diameter, and at a given toroidal angle, whilst avoiding clashes with other in-vessel equipment.

The off-axis design uses a four-mirror system. The design uses three fixed mirrors per beam, and one steering mirror for each beam (four mirrors for each of the delta and epsilon beams).

Figure 4 shows the design of the beam path. The mirrors are numbered in sequence from the gate valve. M1, M2 and M3 are fixed mirrors, and M4 is a steering mirror. The primary function of the M1 and M2 mirrors, which are ex-vessel, is to focus and cross the beams so that they pass through the port cleanly. The M3 mirror provides the final focussing, and the M4 mirror is flat, and provides the final positional adjustability and launch, with the M4 mirrors positioned to ensure the beams enter the plasma with equivalent poloidal launch geometry.

The M4 steering mirror only requires a small steering range, since it is only required to achieve co-injection (the small steering range is then to accommodate different plasma configurations).

This design also requires an additional "vacuum chamber" added to the port flange. This accommodates the M1 and M2 mirrors, and provides a larger surface area for the waveguide interface, allowing for the gate valves to be positioned and appropriately spaced.

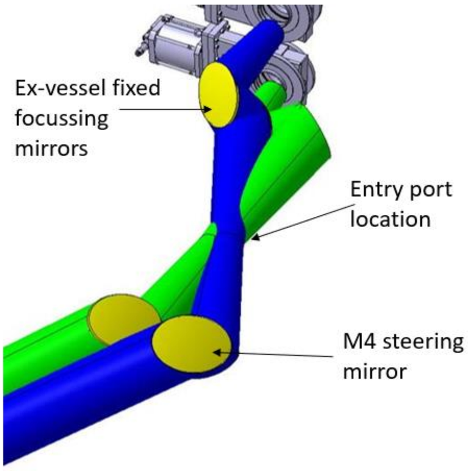

Fig. 4. Off-axis launcher geometry showing four mirror system with beams crossing through the entry port into the vessel

6.3 Launcher Engineering Design

The on-axis and off-axis launchers described in the previous sections need to be realised into an engineering design. Key considerations at this design stage are the choice of mirror material and beam steering mechanism, hence these aspects are considered in the following sections.

The mirror material chosen is copper coated graphite. This combination provides maximum reflection via the high electrical conductivity of the copper, whilst minimising electromagnetic forces (see Section 6.3.1).

6.3.1 EM Force Calculations

Analysis was undertaken to determine the likely electromagnetic forces acting on the mirrors, as this also impacts the mechanical design. The analysis uses a main formula for forces experienced by a conducting, rectangular plate in a changing magnetic field, with vector manipulation used to align the magnetic field data with the orientation of the EBW System mirrors. The methodology considers three origins of forces, from the changing magnetic field due to:

- Standard fluctuations in the MAST-U field
- The intra-pulse steering of the mirrors (for the steering mirrors only)
- Disruptions

It is concluded from the preliminary analysis results that the mirror needs to be made primarily of a material such as graphite with a lower electrical conductivity, to ensure that the forces remain low. This is particularly significant for the steering mirrors, where a motor will be required to hold the mirror in position. This eliminated the use of pure copper, or copper alloy, as a mirror material, and also gave a maximum acceptable copper coating thickness.

6.3.2 Thermal Analysis

Preliminary thermal analysis was undertaken to determine an appropriate material choice. This is based around the use of copper as the main reflective surface due to the high electrical conductivity leading to higher microwave reflection. The incident beam, modelled as a Gaussian, was simulated as an incident heat flux with appropriate absorption parameters. Multiple pulses were simulated in accordance with the expected duty cycle to investigate the ratchetting effect. A structural assessment was subsequently performed to determine the stresses induced by the thermal expansion.

Using the data obtained from the simulations, and evidence of prior experience from ASDEX [3], it was found that using a graphite body mirror with a thin (<100μm) copper coating on the mirror face would be suitable. The simulations found that when using conservative values, including accounting for additional factors such as plasma radiation, the temperatures and stresses reached were acceptable. Figure 5 shows the maximum temperature reached after several pulses when the ratchetting effect has stabilised for a copper coated (front face only) graphite mirror.

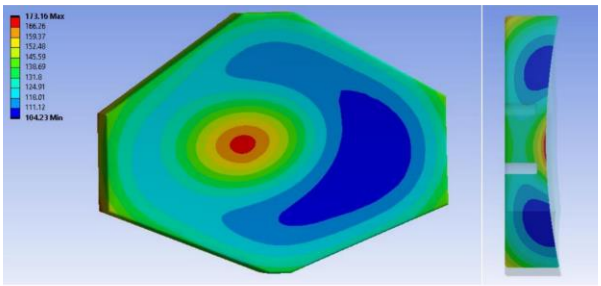

Fig. 5. ANSYS model of a simplified mirror geometry, showing the maximum temperature (~170°C) reached after ratcheting with a graphite mirror with a copper coated front face. Left – front view, right - cross section view.

6.3.3 Mechanical Design

Mirrors M4 (off-axis) and M2 (on-axis) are steerable mirrors. The steering mechanism design is for an externally actuated pushrod-based system for both launchers. The system consists of:

- External motors
- Linear actuators with vacuum feedthrough through ConFlat flange
- Stainless steel pushrods
- Stainless steel mounting brackets
- Vacuum compatible bearings and joints

The mid-plane launcher requires a large steering capability, with the anticipated range shown in Figure 6. Ideally, the rotation point is also about the front face.

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Therefore, a tip-tilt style system is proposed which provides an effective rotation point around the front face as required. This consists of 3 pushrods each with a ball joint and sliding joint at the mounting plate. The mirror attaches to the mounting plate.

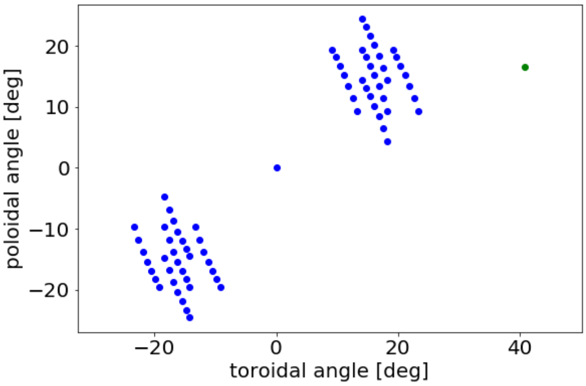

Fig. 6. Anticipated steering range for mid-plane launcher. Two groups of points represent co- and counter- directions; points cover range of plasma parameters.

6.4 Start-up

The start-up design aims to achieve a quasi-high field side launch (high field side launch is not achievable with MAST-U geometry). This approach involves launching a beam in O-mode through the plasma towards a polarising tile on the centre column, which changes the polarisation from O-mode to X-mode, and the wave is then absorbed by the plasma.

The design for the system makes use of an existing polarising tile already installed on the MAST-U centre column, shown in Figure 7. The tile was designed for 28GHz, so the use of the dual frequency gyrotron enables the tile to be used without modification.

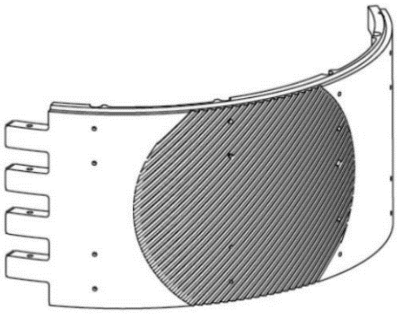

Fig. 7. Centre column polarising tile

In order for the start-up beam to reach the polarising tile, the design uses the on-axis launcher, and the delta beam. The steering mirror delta-M2 can achieve an additional position, using the steering mechanism, which directs the beam towards a final fixed mirror (mirror "H") opposite the polarising tile. That mirror focusses the beam onto the polarising tile. In the initial system, only one beam is used for start-up.

The final mirror is designed to achieve a given spot size on the centre column polariser tile. The tile has a fixed radius of polarising pattern, and hence the fixed mirror size and focussing is optimised to give a beam less than or equal to the given pattern size. This is illustrated in Figure 8, which shows the beam propagation through the in-vessel system. The beam path chosen, min w_CC, minimises the spot size on the centre column tile.

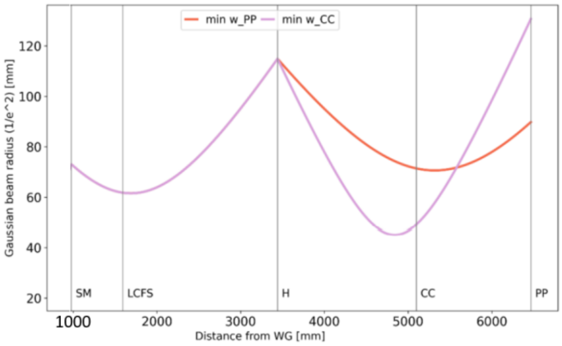

Fig. 8. Approximate beam envelope (1/e^2 power radius) for start-up. SM – steering mirror; mirror H, final fixed mirror; CC – centre column tile; PP - low field side Protection Plate.

7 Interceptor Plates

The microwave beams have a maximum theoretical coupling efficiency of 96% [1]. The coupling is sensitive to the incident angle of the microwaves with respect to the magnetic field and the plasma surface, and the polarisation of the microwave beam; if any of these parameters is not optimal, the coupling efficiency falls, with an extreme of 100% reflection in the worst case. Additionally, the spatial distribution of the reflected power is of scientific interest, since this can be used to support model validation.

To provide this required information on the coupling efficiency, a component which intercepts the microwave beam as it reflects from the plasma is proposed. These are termed "interceptor plates" and sit in the path of the predicted first reflection of the microwave beam over a range of parameters.

The functions of the interceptor plates as described above can be summarised as follows:

- Provide diagnostics on the amount of energy escaping the plasma, with sufficient information on the reflected beam.
- Provide diagnostics for a fast response interlock to protect the machine in case the power fails to couple with the plasma.
- Protect the poloidal magnets and other in vessel components from being damaged by the reflected microwave beams.
- Diffuse the remaining beams so that any further in vessel interactions with the scattered microwaves are reduced to a relatively benign energy density.

Figure 9 shows the approximate location of the interceptor plates around the MAST-U P5 coils. These capture the reflected beams for a range of plasma currents and plasma radii. The plates are designed to "wrap" around the coils to ensure they have minimal impact on diagnostic lines of sight, and to provide good protection for the coils themselves. Interceptor plates are provisioned for each of the beam launch options – off-axis, on-axis co, on-axis counter.

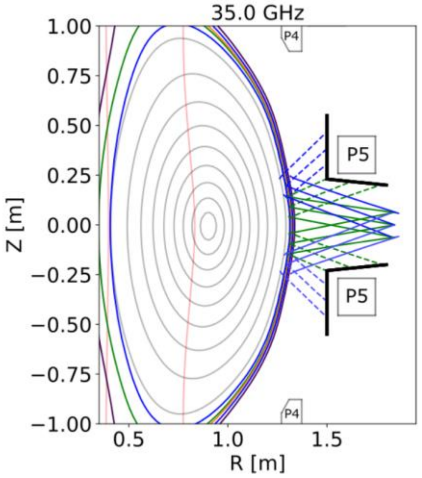

Fig. 9. A schematic plot of the poloidal cross-section of the beams from the midplane launcher for Ip = 800kA (green) and Ip = 2000 kA (blue). The dashed lines represent the beam reflected from the plasma after coupling. Thick black lines represent "interceptor plates" [1].

The concept design for any given interceptor plate is shown in Figure 10 and consists of two graphite plates, >10mm thick. These plates have a scattering / diffusive machined surface to achieve the function of reducing the overall stray power density within MAST-U. One of the graphite plates is inclined at ~5° to the horizontal. The graphite plates are attached to a strap which fits around the MAST-U in-vessel coil, with feet to provide adjustment. The graphite is chosen for its thermal and moderately low microwave absorption properties.

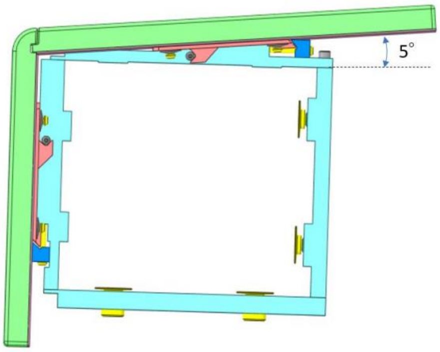

Fig. 10. Concept of an interceptor plate

The plates achieve their diagnostic capabilities via two methods. Firstly, Infra-Red camera(s) are positioned to view the surface of the plates (this drives the need for the nearly-horizontal graphite plate to be angled). By directly viewing the front surface, a fast response is achieved, and hence this can be used as both an interlock (high rate of change of temperature viewed with camera means that coupling is too low and the system shuts down) and a diagnostic.

A second measurement method, embedded thermocouples, is used for redundancy. The thermocouples are embedded to a depth of ~3mm from the front surface of the plates, which gives a fast enough response for both an interlock, and some limited diagnostics.

8 Control and Ancillaries

The EBW System as described is augmented by a supporting infrastructure. The most significant elements are the control system, and the cooling system.

The philosophy for the control system is for a distributed system, to support staged testing and commissioning, including separation of initial testing into a dummy load from integrated testing into the MAST-U tokamak. The control system is divided into five main sub-systems:

- Personnel Access Safety System, providing personnel protection.
- Launch Control Sub-System, controlling set up of transmission line and launch parameters.
- Power Control Sub-System, controlling power supplies and gyrotron to achieve desired power output.
- Operation Management Sub-System, providing slower timescale plant control and monitoring.
- Asset Protection Sub-System, providing primarily fast protection for the gyrotrons.

The control system is designed to be remotely operable and combines primarily commercially available solutions into a robust and coherent design.

The primary function of the cooling system is to cool the gyrotron and dummy load during and after pulses, and provide sufficient heat rejection capability to maintain the gyrotron inlet water temperature below 35°C.

The EBW cooling sub-system comprises multiple circuits with separate pumping all fed from a buffer vessel. The buffer vessel is connected to a wider MAST-U plant cooling system, and stores the heat during a pulse, before slowly exchanging the water with the MAST-U cooling system between pulses. The MAST-U cooling system is then responsible for the overall heat rejection through an existing cooling tower system.

9 Conclusion

This paper has reported the key design specifications, principal components, key challenges and innovative features of the MAST-U EBW System at the preliminary design phase. The System achieves a high degree of experimental flexibility through the modulation capability and range of power inputs, and the variety of in-vessel launch options, hence providing significant support to model validation, and information on EBW physics and its capabilities in spherical tokamaks. The MAST-U EBW System is now entering the detailed design phase.

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