CONFERENCE PRE-PRINT

THE CONSTRUCTION AND COMMISSIONING OF THE ELECTRON BERNSTEIN WAVE HEATING AND CURRENT-DRIVE SYSTEM FOR MAST-U

P. JACQUET
UKAEA (United Kingdom Atomic Authority),
Culham Campus, Abingdon, Oxfordshire, OX14 3DB, United Kingdom.
Email: philippe.jacquet@ukaea.uk

H. WEBSTER, S. COX, A. WEST, P. STEVENSON, S. FREETHY, A. HATTON, G. BRETT-DRINKWATER, A. MUNASINGHE, R. SEALEY, C. McKNIGHT, J. CROCKETT, S. SURENDRAN, H. SHEIKH, S. DESAI, J. LOVELL, J. PEARL, J. ALLEN, J. ROBERTS, J. HAWES, M. HILL
UKAEA (United Kingdom Atomic Authority),
Culham Campus, Abingdon, Oxfordshire, OX14 3DB, United Kingdom.

M. HENDERSON
UK Industrial Fusion Solutions Ltd, Culham Campus, Abingdon, OX14 3DB, United Kingdom.

Abstract

The MAST-U Electron Bernstein Wave (EBW) system consists of the high-power microwave sources (two 0.9 MW gyrotrons) and their ancillaries, the attached High Voltage power supplies, the transmission lines to a microwave dummy load and to the MAST-U vessel, the MAST-U microwave launcher, the Control and Instrumentation, machine protection systems and personal protection systems. The aim of the project is to test the coupling of the microwave power launched into MAST-U plasmas to EBW and verify Current Drive at high power in a spherical tokamak. The project is in the installation and commissioning phase. The gyrotrons will be commissioned on dummy load in late 2025 and beginning of 2026, and the system will be connected to the MAST-U tokamak in 2026/27. MAST-U experiments to assess EBW-Heating and Current Drive capabilities on spherical tokamaks could then be performed in 2027 and provide important information to steer the STEP heating and current drive system design.

1. INTRODUCTION

The UK's Spherical Tokamak for Energy Production (STEP) programme was established to design and build a prototype powerplant with the aim of achieving net energy production [1]. Heating and Current drive (HCD) is a key driver for a fusion power plant design and it has been concluded that the optimum HCD system for STEP is microwave-based, using a combination of the Electron Cyclotron and Electron Bernstein Wave (EBW) approaches [2]. HCD studies for STEP indicate that EBWCD could enhance current drive efficiency [3][4], when compared to Electron Cyclotron Resonance Heating Current Drive (ECCD) at $\rho>0.4$ (ρ: normalised minor radius). Combining EBWCD (driving current in the outer part of the plasma) with ECCD (driving current in the plasma centre) could result in a significant reduction of the required power for the installed microwave sources as compared to a ECCD system only. The EBWCD solution hence offers potentially a reduction of the recycling power for HCD (an increase of the net generated electrical power) and important economic benefits for a STEP reactor [2].
However, EBW Current-Drive (EBCD) has a lower readiness level, having not been demonstrated at high power (MW scale or above) in spherical tokamaks. Therefore, to progress the readiness level, an ambitious development programme has been initiated to integrate a 1.8MW EBW system on the MAST-U tokamak [5]. In addition to enhancing the experimental capabilities of the MAST-U device, the EBW system aims at validating theoretical predictions of enhanced current drive capabilities (relative to conventional electron cyclotron current drive) [4] [6]. Microwave coupling to the EBW mode has been demonstrated on other devices [7][8]; the MAST-U EBW experiments aim to provide an experimental test of the EBCD technique in a Spherical Tokamak [4]: EBW studies predict that coupling to EBW will be accessible on MAST-U (see Fig. 1 and Fig. 2); the MAST-U EBW experiments will examine open issues regarding the Low Field Side coupling scheme (O-X-B mode conversion) such as the effects of density fluctuations (driven by MHD, ELMs, etc), collisional damping and non-linear effects. Current drive capabilities will be verified (compare experimental versus modelled Current-Drive efficiencies ~ 0.1-0.14 A/W). Schemes for real-time optimisation of the O-X-B coupling will be developed. Additionally, the original MAST experiments on EBW-based solenoid free start-up [9] will be extended.

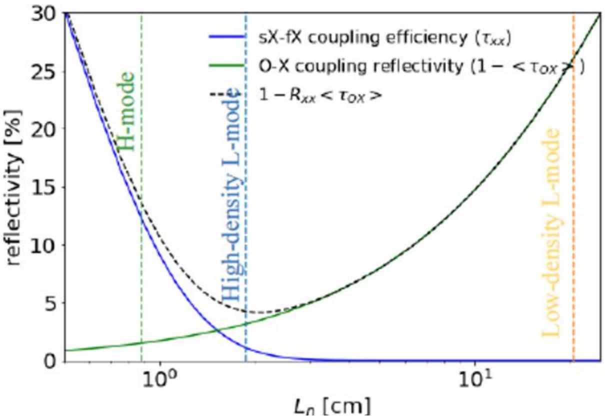

Fig. 1. O-X-B reflectivity vs L_n (electron density scale length) for MAST Upgrade parameters. From reference [4].

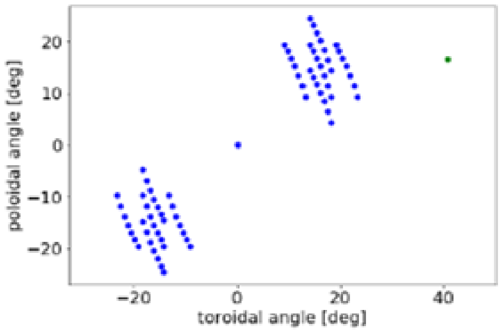

Fig. 2. Anticipated steering range for the mid-plane launcher. The two groups of points represent the co- and counter- directions. From reference [4].

The EBW system will also serve as a test bed for high power microwave technology which is a key element of the STEP program and is a vehicle to grow knowledge and expertise in this field.

2. SYSTEM OVERVIEW

2.1. The gyrotrons

The MAST-U EBW system is equipped with 2 dual frequency gyrotrons [11][12]. Fig. 3 is a block diagram of the gyrotrons. They are triode type, the High Voltage (HV) feeding scheme for the gyrotrons is shown on Fig. 4. The tubes are manufactured by Canon Electron Tube Division; the gyrotron systems are supplied by Kyoto Fusioneering (KF); KF is also assisting in the gyrotron commissioning activities at the UKAEA site. The gyrotron specifications are listed in table 1:

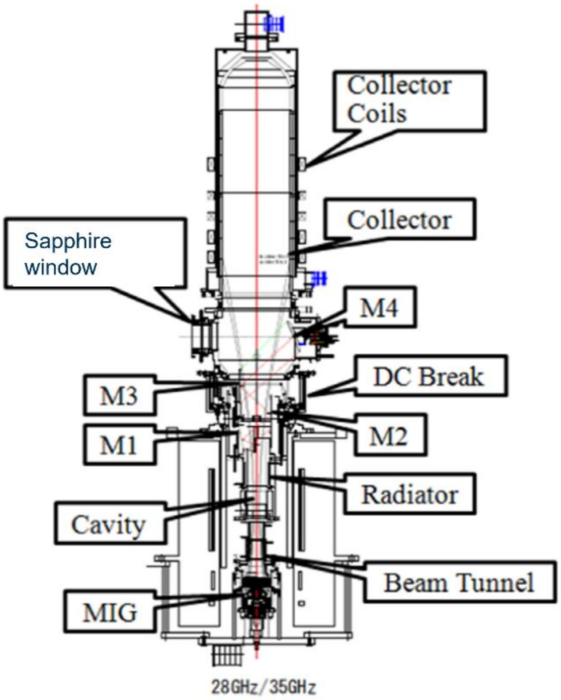

Fig. 3. Gyrotron block diagram.

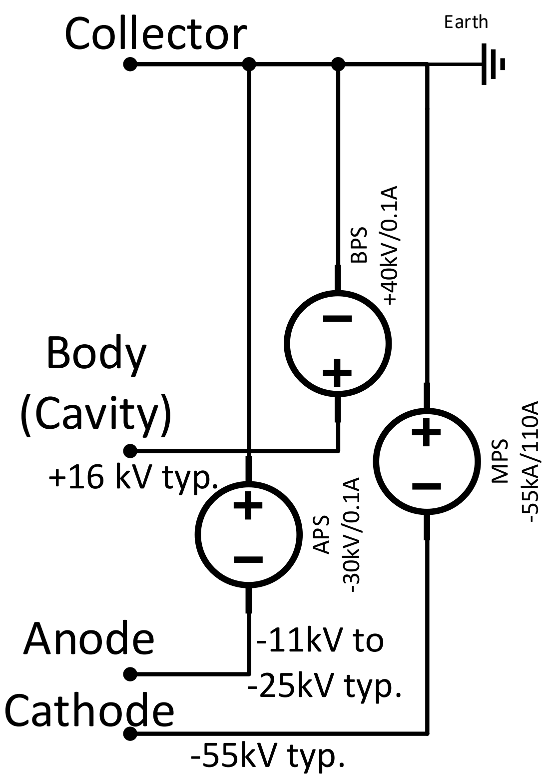

Fig. 4. Gyrotrons High Voltage Power Supplies configuration.

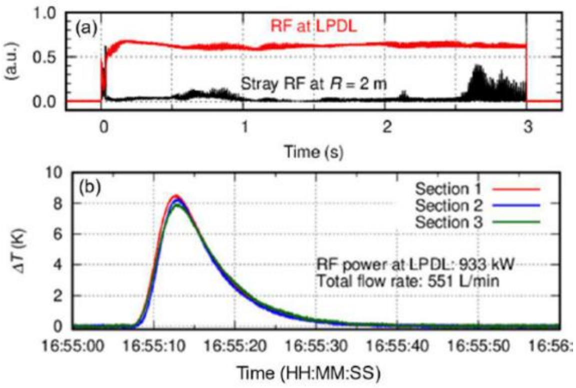

Fig. 5. 3 sec. pulse at 34.8 GHz. (a) microwave measurements; (b) calorimetry in Long Pulse Dummy Load (LPDL) electron beam acceleration voltage is ~ 72 kV. From [12].

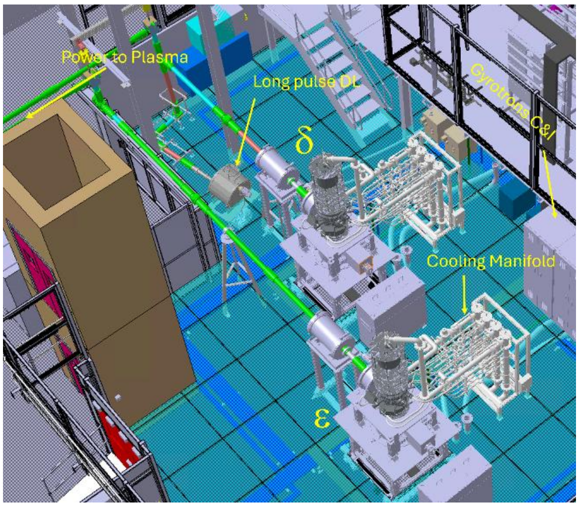

Fig. 6. View of the MAST-U gyrotron area.

TABLE 1

Dual frequency gyrotron parameters		
Frequency	28 GHz	34.8 GHz
Output Power	900 kW (3 sec); 800 kW (4.5 sec)	
Efficiency	50 %	
Beam Voltage	80 kV	
Beam Current	55 A	
MIG	Triode	
Cavity mode	$TE_{8,5}$ (28GHZ)	$TE_{10.6}$ (34.8GHz)
Output Mode	Gaussian-Like	
Collector	Depressed Collector, Sweeping coils	
Window	Sapphire, single disk	

The tubes operate in conjunction with Superconducting Magnets (SCMs) cooled to 4 K by a cold head with helium gas as refrigerant. The magnets can operate at 1.6 T (55 A). The microwave power from the gyrotrons is coupled into the HE11 mode in the transmission lines through the Matching Optical Units (MOU).

As part of the Factory Acceptance tests the Gyrotrons were tested at the National Institute for Fusion Science, Japan. At 34.8 GHz, 930 kW 3-sec was achieved (see Fig. 5). At 28 GHz, 750 kW-0.6 sec was achieved; 28GHz performance will be further improved with more conditioning during the Site Acceptance Tests.

Fig. 6 is a view of the MAST-U gyrotron systems. The two Gyrotrons are designated as delta (δ) and epsilon (ε).

2.2. The High voltage Power supplies

The High Voltage Power Supplies (see also Fig. 4) consists of cathode (Main Power Supply-MPS), body (BPS) and anode (APS) power supplies. For cost and space optimisation the cathode supply (MPS) is shared between the two gyrotrons, rated for 110A, -55kV. Each gyrotron has a dedicated APS (rated -30kV, 0.1A) and BPS (rated 40 kV, 0.1 A).

The MPS is fed from the UKAEA 35kVAC network. It includes a 35kVAC/1kVAC matching transformer, a 1kVAC multi-winding transformer, an AC/DC rectifier and a DC-DC converter. Key requirements are:

- Low voltage ripple (<0.5%).
- High accuracy (Better than 0.5%).
- Ability for fast transients during modulation. Including requirements for very low overshoot (<1%) and short settling times (<50 μs).
- Fast shutdown (<6 μs) and arc protection (dissipated energy <10J).

The BPSs are fed from a 415VAC LV distribution circuit; they integrate 415VAC multi-winding transformers, AC/DC rectifiers and DC/DC converters.
APSs integrates 'off-the-shelve' HV power supplies fed from a 415VAC LV distribution circuit, supplied by Technix (France), with output switches and protection systems.

2.3. The gyrotron and Dummy load cooling system

The water-cooling system exhausts the energy dissipated in the gyrotrons and the long pulse dummy load. (~1 MW-5 sec. energy dissipated in each device). The system branches off the MAST-U cooling system. A 2000 litre buffer tank is used because the circulation capacity from the MAST-U water system is small compared with the flow requirement for the EBW equipment. Each gyrotron and the dummy load are fed by individual pumps (total of 3 pumps). The gyrotrons pumps capacity is 1300L/min@7bar and the dummy load pump capacity is 240L/min@8bar. Most of the cooling system (buffer tank, pumps, water filtering and de-oxygenation, cooling system C&I, etc) is mounted on a skid in a room adjacent (~25 metre away) to the gyrotron system.

2.4. The transmission line system

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 lines are made of HE11 corrugated waveguide with an internal diameter of 88.9mm, and associated mitre bends. The diameter was 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 lines are 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 (also referred as long pulse dummy load).
- Provide polarisation control of the output beam. Polarisation angles can be adjusted during a pulse so real time optimisation to react to changing plasma conditions can be implemented.
- 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 the tokamak).
- Provide pumping access for maintaining vacuum in the lines.
- Provide electrical isolation between the gyrotron system and the MAST-U vessel.

2.5. The launcher

The launcher system directs the microwave beams towards the plasma aiming at the optimum launch angle required for EBW coupling; the direction of the beam launched into the plasma is adjustable in both the toroidal and poloidal directions. Steering mirrors angle is adjustable during a pulse so real time optimisation to react to changing plasma conditions can be implemented. The MAST-U EBW system will have two launchers, the on-axis / mid-plane launcher and the off-axis / upper launcher. A picture of the MAST-U EBW launchers is shown

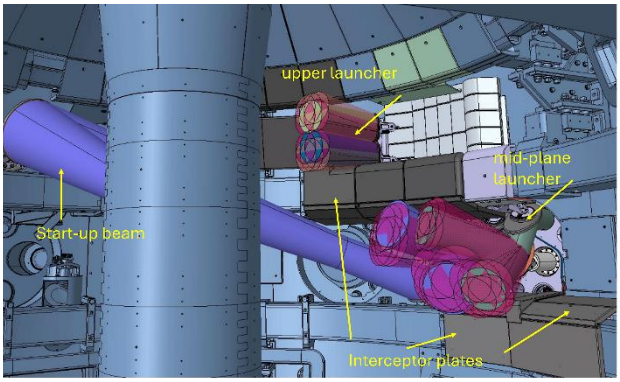

Fig. 7. CAD view of the MAST-U EBW In-Vessel Components

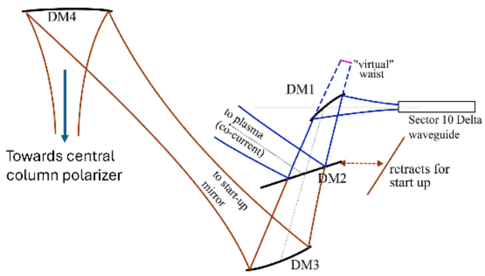

Fig. 8. Sketch of the start-up launcher. From [10]

in Fig. 7. Four vacuum gate valves (not shown on the figure) are located at the interfaces between the waveguides and the launchers (delta-midplane, epsilon-midplane, delta-upper, epsilon-upper). The EBW system integrates interceptor plates (also shown in Fig. 7) which spread the microwave power reflected from the plasma; this is to avoid damages to MAST-U components in case of plasma conditions that lead to inefficient O-X-B coupling. These will be monitored by infra-red cameras and fitted with thermocouples; these measurements will be used to optimise the microwave beams launched angles and for machine protection. Microwave sniffer probes will also be fitted around the launchers; their purpose is mostly machine protection. Gyrotrons will be tripped if sniffer probes signals or interceptor plates temperature are too high).

2.5.1. On-axis / Mid-plane Launcher

The on-axis launcher is designed so the launched beams couple to EBW resulting in co-current drive, counter-current drive of balance current drive (plasma heating regime). To achieve this symmetry, the steering mirrors are located at the midplane. The two midplane mirrors will each have the capability to be steered so co or counter EBCD is generated. The launcher uses one fixed mirror and one steering mirror per beam (see Fig. 8). The steering is flexible to cover a range of plasma parameters around the optimum coupling locations. This gives a steering range as shown in Fig. 2. This launcher could operate at 28Ghz or 34.8GHz.

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. The launching mirrors are designed to be large enough to maximize transmission efficiency (>99%) and minimise stray radiation inside the vessel, whilst not restricting diagnostic lines of sight. The mirror size is dictated by the 28GHz beam, which has the larger beam width.

2.5.2. Off-axis / Upper Launcher

The upper launcher will couple the microwave beams to EBW driving current in the co-current direction exclusively. It is located ~600mm above midplane to favour current drive at $\rho>0.7$. It will exclusively operate at 34.8GHz (due to space constraints). The main design constraint is the small upper-port dimensions. The off-axis design uses a four-mirror system for each of the delta and epsilon beams; three fixed mirrors and one steering mirror per beam. The two first mirrors for each line (4 in total for delta and epsilon) are located in a “ex-vessel vacuum chamber” added to the port flange. This provides a larger surface area for the waveguide interface, allowing for the gate valves to be positioned and appropriately spaced.

2.5.3. The start-up launcher.

A view of the delta beam when directed to the start-up launcher is shown on Fig. 7. MAST-U EBW start-up experiments will extend the initial MAST experiments [9]. In the start-up mode, at 28 GHz, the delta microwave beam from the mid-plane launcher is directed towards the central column where a polarizer was installed when MAST-U was built (see Fig. 8). The polarizer converts the incoming O-mode polarisation from the beam crossing the plasma to X-mode; the X-mode microwaves propagating from the high field side can convert to EBW, efficiently driving start-up current.

2.6. Control and Instrumentation (C&I) and Personal Access Safety System (PASS)

A simplified block diagram of the C&I and PASS system is shown on Fig. 9. The system is modular, to allow step by step addition and commissioning of subsystems. Asynchronous pulses (gyrotrons pulses into dummy loads) or synchronous pulses (microwave power into MAST-U) modes are supported. The C&I system controls and monitors the local subsystems via ‘local’ controllers (controllers use National-Instruments cRIO modules or Siemens PLCs). All the controllers are orchestrated by the EBW central server, which also provides an interface to the MAST-U server. All the local servers are connected via the private ‘EBW-Ops’ network. Whilst certain field devices are directly interfaced with the process control servers over the network, they are also connected over a dedicated “Field Network”. The EBW Engineering PC is also connected to that private network to allow debugging and remote configuring. The aggregated fault signal produced by each controller is hardwired to the Fault Processors: the FTO (Fast Turn Off) processor handles fast trip events, while the STO (Sequential Turn Off) processor handles all the other fault events.

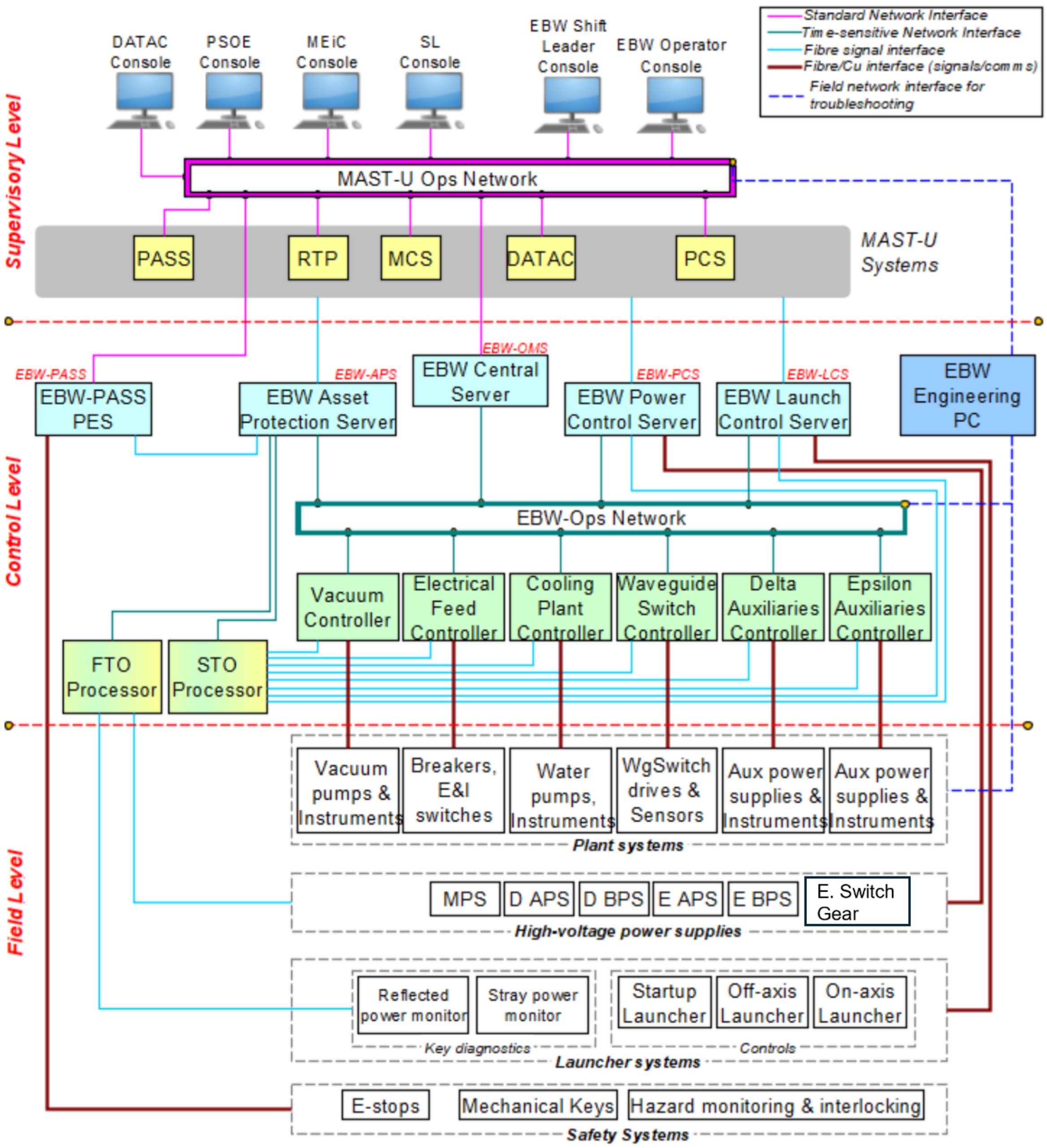

Fig. 9. Simplified block diagram of the MAST-U EBW C&I and PASS system.

The PASS system includes three subsystems. The Master (Mechanical) Key Interlock System (MKIS) is a key interlock system that manages personal access to the HV and gyrotron areas ensuring safe access (HV supplies isolated). The Emergency (E-Stops) system is an independent hardwired system that can isolate the HV and LV power in case of an emergency, using daisy-chained push buttons. A PES (Programmable Electronic Subsystem) hazards monitoring and interlocking systems based on safety PLCs will be installed when the EBW system will be integrated into the MAST-U system.

3. INSTALLATION AND COMMISSIONING STATUS

Fig. 10 is an extract of the gyrotron system installation and commissioning plan from the end of September 2025. The HV power supplies are installed, APSs and BPSs have been commissioned. The MPS will be commissioned mid-November 2025. The water-cooling system is in the final installation stage and will be commissioned in October 2025. The ancillaries for the SCMs have been installed and commissioned, and magnet alignment is complete. The gyrotrons were installed within the magnet at the end of September 2025. Connection of the gyrotrons to the water system, connection to the HVPS and connection to the C&I will take place in the autumn

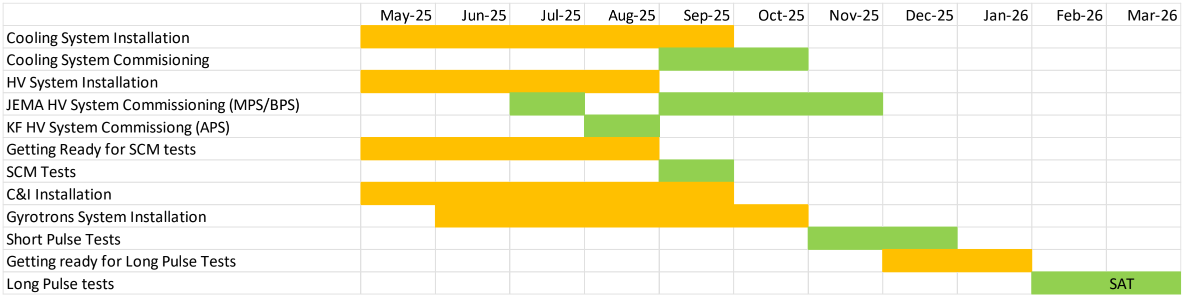

Fig. 10. Extract of the gyrotron system installation and commissioning plan.

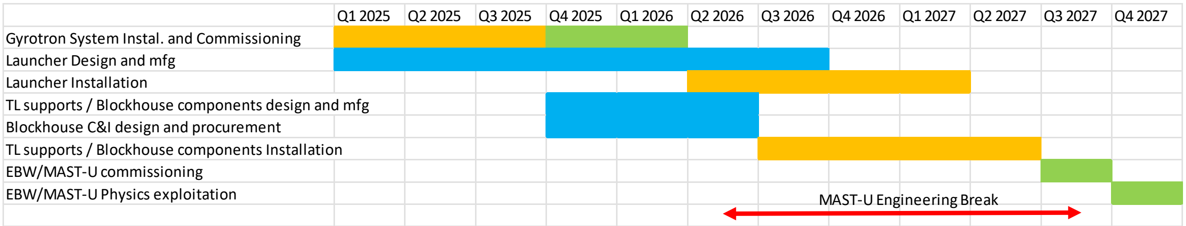

Fig. 11. Extract on the MAST-U EBW installation and commissioning plan.

2025, the goal is to operate the gyrotrons in short pulse dummy loads in December 2025. Connection to the long pulse dummy load and testing of the gyrotrons to the maximum power and pulse length is planned for the first semester of 2026. All transmission line elements and the parts for the evacuation systems are on site.

Fig. 11 is the high-level plan for the integration of the EBW system in MAST-U. A long MAST-U engineering break (so called MUB-04), devoted to the installation of the EBW system and additional neutral beam heating capabilities will start in May 2026. The EBW project activities are planned so all in-vessel components and subsystems in the MAST-U blockhouse are installed during MUB-04. Some of these subsystems are still in the design phase.

The launcher system design is complete, prototypes for critical components were produced, and 70% of the launcher parts have been manufactured. The design of the in-vessel interceptor plates and sniffer probes will be finalised before the end of March 2026. The Supports for the Transmission line elements between the gyrotron area and the MAST-U vessel are also in the design phase. In parallel, the C&I design for launch control (steering mechanism, polarisers), and for machine protection based on sniffer probes and interceptor plates temperature (IR cameras and thermocouples) will be finalised in the first part of 2026. The integration of the EBW system in the MAST-U machine control environment will also be finalised. For safe (machine safety) application of EBW into MAST-U plasmas, Real-Time control and protection based on plasma parameters will be implemented; this system is being designed and will be distributed between the MAST-U plasma control system and the EBW Asset protection System.

4. PROSPECTS AND LESSONS LEARNED

The MAST-U EBW system project is in the installation and commissioning phase. The gyrotrons will be commissioned on dummy load in late 2025 and in the beginning of 2026. The system will be connected to the MAST-U tokamak in 2026/27. The system will be available for MAST-U experiments in 2027 to assess EBW-Heating and Current Drive capabilities on spherical tokamaks. Some discussions are ongoing with a view to adding two extra gyrotrons by 2029.

As many large-scale engineering projects for fusion research the project has experienced delays. At this point the following ‘project-management’ points should be considered.

- A project team with members dedicated 100% to the project is much more efficient than ‘salami-sliced’ allocation.
- Staff turn-over and the overhead associated with catch-up and re-training also has a negative impact on projects.
- Contracting design tasks externally is only beneficial if these tasks are self-contained (and of course well defined). When the systems are highly integrated with other sub-systems or require multiple or complex interfaces which evolve during the project (complex projects have large level of uncertainties

throughout) design by the local team is more efficient, as there is no need to re-negotiate a contract each time design constraints change.

- Having contractor adhering to / meeting the quality assurance requirements and applicable standards (especially if these standards are not internationally uniform) is a challenge. The projects must have enough contingency to absorb delays and the necessary rework when end-products fail to meet these standards.
- Projects plans are not always useful to the team. The plan must be developed by those experienced with similar projects or (in case the technology is new to the organisation) after consulting with some people/organisation who have run a similar project, and taking into account the specific local constraints (review and approval of documentation, compliance to Quality Assurance policies, internal reviews of documentation for contract etc is often missed from initial planning). The plan must be owned and policed by someone in authority and with the technical knowledge, ideally the project leader.

ACKNOWLEDGEMENTS

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