OVERVIEW OF FIRST RESULTS FROM MAST UPGRADE

UK Atomic Energy Authority

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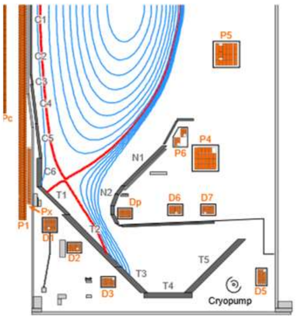
MAST Upgrade Characteristics



MAST Upgrade is a low aspect ratio spherical tokamak based on the MAST device with substantially improved capabilities, including:

- 19 new poloidal field coils for substantially improved shaping of the core plasma and divertor
- New solenoid with increased inductive flux
- Increased toroidal field
- On- and off-axis neutral beam heating and current drive
- Closed, tightly baffled divertor, up-down symmetric divertor chambers with Super-X capability
- Improved suite of diagnostics in the divertors

Machine Capabilities

Property	Design value	Value in 1st campaign	MAST value
Major radius (m)	0.7	0.7	0.85
Minor radius (m)	0.5	0.5	0.65
Aspect ratio	1.4	1.4	1.3
Inductive flux (Vs)	1.7	1.7	0.9
Maximum Ip (MA)	2.0	1.0	1.3
Maximum pulse length (s)	5.0	2.0	0.7
On-axis NBI heating (MW)	2.5	2.5	5.0
Off-axis NBI heating (MW)	2.5 (7.5 after 2023)	2.5	0.0
Divertor configurations	Conventional, Super-X, X-divertor, snowflake, X-point target	Conventional, Super-X	Conventional

Diagnostics Capabilities

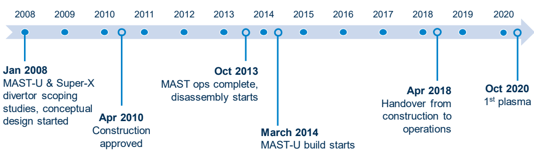
Core plasma diagnostics

- 130pt high resolution Thomson scattering (mid-plane n_e, T_e profiles)
- High resolution beam spectroscopy diagnostics, including:
  - Charge-Exchange Recombination Spectroscopy (Ti, rotation profiles)
  - Motional Stark Effect (pitch angle profiles)
  - Fast Ion D_α (fast ion density and distribution profiles)
  - Beam Emission Spectroscopy (electron density fluctuations)
- Magnetics sensors for equilibrium reconstruction and detecting instabilities
- 2 fast framing cameras (visible light emission in main chamber)
- Solid State Neutral Particle Analyser (fast ion energy spectra, UC Irvine)
- Synthetic Aperture Microwave Imaging (edge pitch angle, Univ. York)
- Doppler Backscattering & Cross-Polarization Scattering (density, rotation and magnetic field fluctuations, UCLA, SWIP)
- Fast Ion Loss Detector (distribution of lost fast ions, Univ. Seville)
- Neutron Camera (neutron density profiles, Univ. Uppsala)
- Reciprocating probe (edge n_e, $T_{e,i}$, V_{float}, rotation profiles)
- Edge Charge-Exchange Spectroscopy (edge T_i, rotation profiles)
- Soft x-ray emission
- 2 fission chambers (total neutron emission)
- 1D linear D_α camera (midplane D_α emission profiles)
- SPRED (VUV survey spectra)
- Penning Gauge (D, He pressure, Uni. Wisconsin)

Divertor diagnostics

- 850 Langmuir probes (divertor n_e, T_e, V_{float}, J_{SOL}, J^+_{SAT} profiles)
- 5 IR cameras (divertor heat flux profiles)
- 3 divertor spectrometers (ne, Te, emission profiles, with Uni. York and LLNL)
- Foil bolometry (divertor chamber radiation profiles)
- Imaging bolometry (x-point radiation profiles, with Uni. York and CFS)
- 10 channel multi-wavelength imaging (emission profiles across lower divertor, Uni. Durham and Uni. York)
- 4 channel multi-wavelength imaging (emission profiles across upper divertor, DIFFER)
- Penning Gauge (D, He pressure, Uni. Wisconsin)
- Divertor Thomson scattering (n_e, T_e profiles)
- Divertor SPRED (VUV survey spectra, LLNL)
- Divertor science facility (testing novel materials and diagnostics)

Design and Construction Timeline



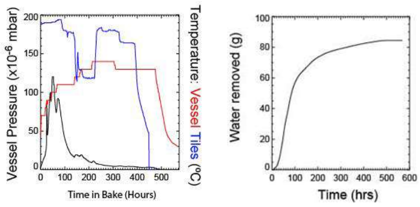
Plasma Commissioning Milestones Achieved

Following the first plasma on 27th October 2021, there was rapid progress to commission the vertical feedback control and the first diverted plasma within 3 months. In the following month, feedback control of the solenoid current ramp to maintain the plasma current was developed and both neutral beams were injected in the plasma.

Milestone	First plasma	Vertical position control	First diverted plasma	First beam into plasma	Plasma current feedback	First beam into plasma	Two beams into plasma
Date	27/10/20	22/1/21	29/1/21	10/2/21	12/2/21	19/2/21	24/2/21

Vessel Conditioning

Prior to plasma operations, MAST Upgrade was baked to 140 0C – 220 0C for 560 hours, resulting in a reduction in the gas pressure in the vacuum vessel from 2×10^{-6} mbar (mostly due to water and nitrogen) to 2×10^{-8} mbar. Approximately 85g of water was removed from the machine during the bake.



Coil Commissioning and Real-Time Control

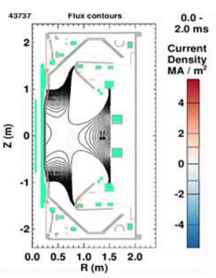
- The majority of the magnetic coils and power supplies are new and required commissioning prior to plasma operations
- Initially, power supplies were connected to a dummy load to check they produce the correct waveforms and operate safely in off-coil commissioning
- Then power supplies are connected to their associated coils and operated by the Plasma Control System (PCS) with DC and time-varying waveforms in on-coil commissioning
- The new sliding joints that connect the 12 toroidal field limbs to the central conductor were monitored closely to ensure good electrical contact throughout a pulse

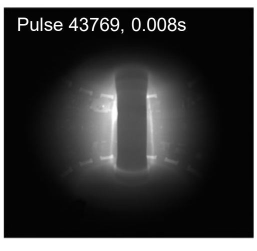
Main chamber coil(s)	TF	P1	P4	P5	P6			
Commissioned in 2020	18/11	24/8	5/8	25/8	15/12			
Divertor coil(s)	D1	D2	D3	D5	D6	D7	Dp	Px
Commissioned in 2020	22/11	22/10	23/10	3/11	23/10	23/10	30/9	16/12

- A low latency, high throughput (~400 MB/s) machine protection system was developed utilizing Field Programmable Gate arrays to prevent actions that could potentially damage the device, including:
  - Avoiding excessive currents flowing in the poloidal field coils
  - Enforcing I^2t limits to avoid excessive ohmic heating of the coils
  - Calculating forces on the poloidal field coils and enforcing that they remain within safe limits
  - Avoiding excessive impulse exerted on the solenoid
- 89 signals used, including analogue data from Rogowski coils (digitized at 500 kHz) and digital signals from Langmuir probes.
- All calculations are completed within 200 μs of signals being input to the analogue-to-digital converters, the majority of which is taken filtering the input data

Plasma breakdown and ramp-up

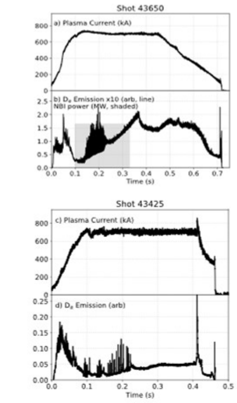
- Plasma breakdown is performed using the direct induction technique where the solenoid provides the toroidal electric field and the poloidal field coils generate a sufficiently large null to facilitate breakdown
- Two hot filaments mounted to the outer wall are used to provide an initial source of free electrons
- A semi-empirical model was used to develop the feed-forward currents required for reliable breakdown and initial ramp-up
- Timing of the breakdown in good agreement with modelling, suggesting the description of the passive elements is sufficiently accurate

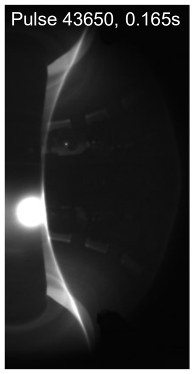




Plasma Operation

Ohmic and NBI heated 700 kA plasma scenarios have been developed with flat-top longer than 300ms with NBI heating (43650) and with ohmic H-mode phases (43425)

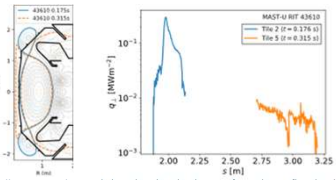




- Feedback control of the solenoid flux to maintain the plasma current has been commissioned
- Vertical position control has been developed to sustain divertor configurations
- Good plasma shaping has been achieved, with elongation κ ~ 1.8 and triangularity δ ~ 0.3

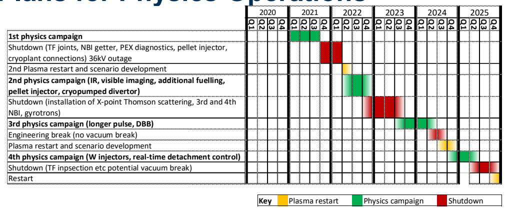
Divertor Operation

- The large number of poloidal field coils affords considerable flexibility to explore a wide range of divertor configurations, including conventional, Super-X, X-divertor and snowflake configurations
  - Able to vary outer strike point major radius and total flux expansion, poloidal flux expansion (and flaring) and the number of poloidal field nulls per divertor in single and double null
  - A wide array of diagnostics are available to characterize the plasma conditions in the divertor chamber (see "Diagnostics Capabilities" section)
- Initial studies have concentrated on producing initial conventional divertor configurations and sweeping the outer strike points to large major radius and reducing the poloidal field in the divertor chambers to produce Super-X configurations. Indicative equilibria are shown below.



- Initial findings indicate a substantial reduction in the surface heat flux in the Super-X configuration compared with a conventional divertor

Plans for Physics Operations



MAST-U Contributions to FEC 2021

- P4.771 "Modeling Snowflake Divertors in MAST-U Tokamak" by A. Khrabryi et al
- P5.746 "Modeling of deuterium radiation transport in Super-X and snowflake divertor plasmas in MAST-U tokamak" by V. Soukhanovskii et al
- P6.990 "ELM burn-through simulations for MAST-U Super-X plasmas" by S. F. Smith et al
- P6.1125 "Recent modelling of long-legged divertor configurations" by D. Moulton et al
- P7. 645 "Exploration of the Equilibrium and Stability Properties of Spherical Tokamaks and Projection for MAST-U" by J. Berkery et al

MAST contributions

- P4.801 "Overview of Merging Spherical Tokamak Experiments and Simulations for Burning, High-Beta and/or Absolute Minimum-B Plasma Formation" by Y. Ono et al
- P7.1212 "Study of fast ions redistribution and losses due to energetic particle modes in MAST" by M. Cecconello et al

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