The use of High Power Microwaves in Fusion Research

A range of high power microwave systems is used in the Euratom/UKAEA (United Kingdom Atomic Energy Authority) fusion programme at Culham Science Centre, Oxfordshire, UK. Used primarily to heat and drive electrical current in tokamak plasmas, they are also important for inhibiting the growth of plasma instabilities and optimising plasma formation. One of the main systems uses superconducting magnets manufactured by Oxford Instruments.

A tokamak is a toroidal magnetic device, pioneered in the Soviet Union, for containing a fusion plasma. There are three currently in operation at the Culham Science Centre: JET (the world's leading tokamak), COMPASS-D and MAST.

Of these, JET and COMPASS-D are the more conventional ring-doughnut shape. MAST (the Mega-Amp Spherical Tokamak), is more nearly spherical - the plasma axis is much larger in comparison to the toroid axis. MAST started its physics programme in December 1999, and achieved a plasma current of over 1 MA in May 2000. It succeeds the pioneering Small Tight Aspect Ratio Tokamak, START, which was also built at Culham.

COMPASS-D uses two high power microwave systems. The first, a 1.3 GHz, 600 kW, 1.5 s system was built using components loaned by the Max Planck Institut für Plasmaphysik, Garching, Germany and by the CEA, Cadarache, France. This so-called 'lower hybrid current drive' (LHCD) system is particularly efficient for driving currents within the plasma.

The second, 2 MW, 5 s, electron cyclotron resonance heating (ECRH) facility operates at 60 GHz (5 mm wavelength). Completed in the early 1990's, it provides very effective plasma heating and can also be used to drive electrical currents within the plasma. A particular strength of the ECRH facility is its ability to provide very controllable and localised deposition of power within the plasma. The transfer of energy from the ECRH waves to the plasma electrons arises when the wave frequency ω (= $2\pi f$) is an integer multiple of the rotation frequency ω_{ce} (= eB/m) of the electrons around the magnetic field lines in the plasma.

The original ECRH system comprised ten 200 kW Varian gyrotron microwave sources. Power is transmitted to COMPASS-D via long (>50 m) circular cross section waveguides, designed to provide a transmission efficiency of ~ 90%. Using additional transmission lines, it has been possible to extend the operation of six of these gyrotrons into MAST, and the first plasma heating studies in MAST have been carried out. MAST is also equipped with a powerful neutral beam heating system, in which energetic particle beams, rather than microwaves, are used to heat the plasma.

Microwave generation within the gyrotrons relies upon the strong interaction of an energetic electron beam (80 kV, 8 A) and a powerful static magnetic field, which, in turn, depends on the cyclotron resonance condition which links the value of the static magnetic field to the microwave frequency. It is essentially the inverse of the process by which the microwaves eventually deposit their energy in the tokamak plasma. This type of coupling allows the gyrotron cavity dimensions to be large compared to the microwave wavelength (an 'over-moded' cavity) resulting in high microwave power per unit. The output microwave beam is circularly polarised.

Each gyrotron is equipped with an Oxford Instruments superconducting magnet (B_{max} ~ 3.5 T). To provide the required resonant magnetic field and the necessary control of the electron beam, each magnet actually has 3 coils, all of which sit in liquid helium at 4.2 K and are surrounded by a liquid nitrogen jacket. The coils are operated in persistent mode (coils shorted and excitation current off) to reduce liquid helium consumption.

COMPASS-D and MAST are used exclusively for the Euratom/UKAEA fusion research programme.
JET operates under the auspices of the European Fusion Development Agreement, EFDA.

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