**Topic: FT**

# Maturing ECRF Technology for Plasma Control*

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The availability of high power ≈1 MW, long pulse length, effectively cw, high frequency, >100 GHz, gyrotrons has opened the opportunity for enhanced scientific results on magnetic confinement devices for fusion research worldwide. This has led to successful experiments on electron cyclotron heating, electron cyclotron current drive, non-inductive tokamak operation, tokamak energy transport measurements, suppression of instabilities and advanced profile control leading to enhanced performance. The development in the gyrotron community that has lead to the realization of high power gyrotrons is the availability of edge cooled synthetic diamond gyrotron output windows, which have low loss and high thermal and mechanical properties. In addition to the emergence of reliable high power gyrotrons, ancillary equipment for efficient microwave transmission over distances of hundreds of meters, polarization control, diagnostics and flexible launch geometry have all been developed and proven in regular service.

The unique property of electron cyclotron heating to localize heating and current drive into the electron channel has been applied to drive current in the magnetic islands, thus replacing the missing bootstrap current, resulting in the suppression of neoclassical tearing modes (Fig. 1). The localized heating and current drive has also been used to establish and maintain an electron transport barrier near $\rho = 0.3$ (Fig. 2). Recent measurements of off-axis current drive have validated theoretical models including electron trapping effects and increasing current drive efficiency with increasing electron beta.

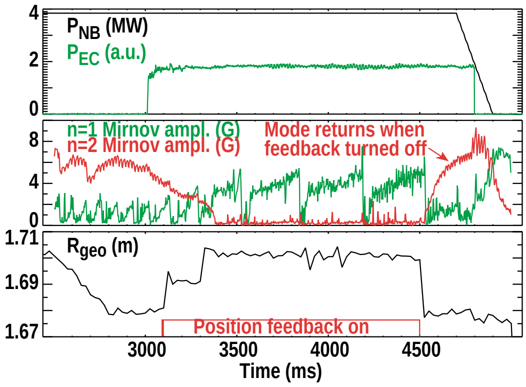

Fig. 1. Approximately 2.3 MW of ECCD is used to forms suppress an m/n=3/2 NTM in discharge #107396 after which neutral beam power is raised to increase beta. $\beta_N$ is increased by 55%.

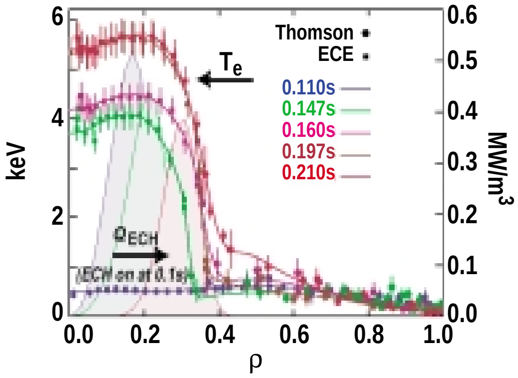

Fig. 2. Electron transport barrier immediately upon application of ECH power of 0.5 MW. Barrier lies just outside heating location.

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The 110 GHz Electron Cyclotron Heating (ECH) system installed on the DIII–D tokamak now comprises six gyrotrons injecting greater than 2.3 MW into the plasma. Three of the gyrotrons were made by Gycom (a Russian company), which nominally produces 750 kW for 2 s pulses (pulse length limited by the capabilities of the boron nitride, BN, ceramic output window). The other three 110 GHz gyrotrons were built by CPI (formally Varian), which have a nominal output power of 1 MW for 10 s pulses. The CPI gyrotrons utilize a single disc CVD (chemical-vapor-deposition) diamond window that employs water cooling around the edge of the disc. Calculation predict that the CVD diamond window should be capable of full 1 MW cw operation, which is supported by IR camera measurements, that show the window reaching equilibrium after 2 s. One of the CPI tubes has been tested at 1.0 MW, 5 s pulse length and all three have been tested at 650 kW for 10 s pulses.

All gyrotrons are connected to the tokamak by a low-loss-windowless evacuated transmission line using 31.75 mm diameter circular corrugated waveguide for propagation in the $HE_{11}$ mode (see Fig. 3). Transmission efficiencies of the waveguide lines have been measured directly, indicating 20% loss in about 100 m line length with eleven miter bends. Each waveguide system incorporates a two-mirror launcher, which can steer the rf beam poloidally from the center to the outer edge of the plasma. Initial tests of launcher assemblies capable of scanning the rf beams in two planes have demonstrated a poloidal scan across the tokamak upper half plane in about 2 s, a rate suitable for tracking target features in the plasma. Precise control of the location of the driven current in turn can lead to control of the current density profile.

Rapid calorimetric response has been achieved with mode conversion dummy loads. Loads have been fabricated in dispersion-strengthened copper with internal nickel plating to increase the absorption and external corrugations to improve the water cooling. When 1 MW was incident in several 5 s pulses, over 800 kW was absorbed at 110 GHz in a load 1.8 m long.

DIII–D has room for two more steerable launchers and gyrotron systems, bringing the total system capability to eight gyrotrons. With the development of 1.5 MW, 110 GHz gyrotrons by the U.S. Gyrotron Development Program, the DIII–D ECH system could have a source capability of 10 MW. With this system the DIII–D program could demonstrate current and pressure profile control under true non-inductive, stable, high performance conditions. This result will support and promote the value of tokamaks as the viable platform for future fusion energy production devices, (i.e. ITER, DEMO, etc.).

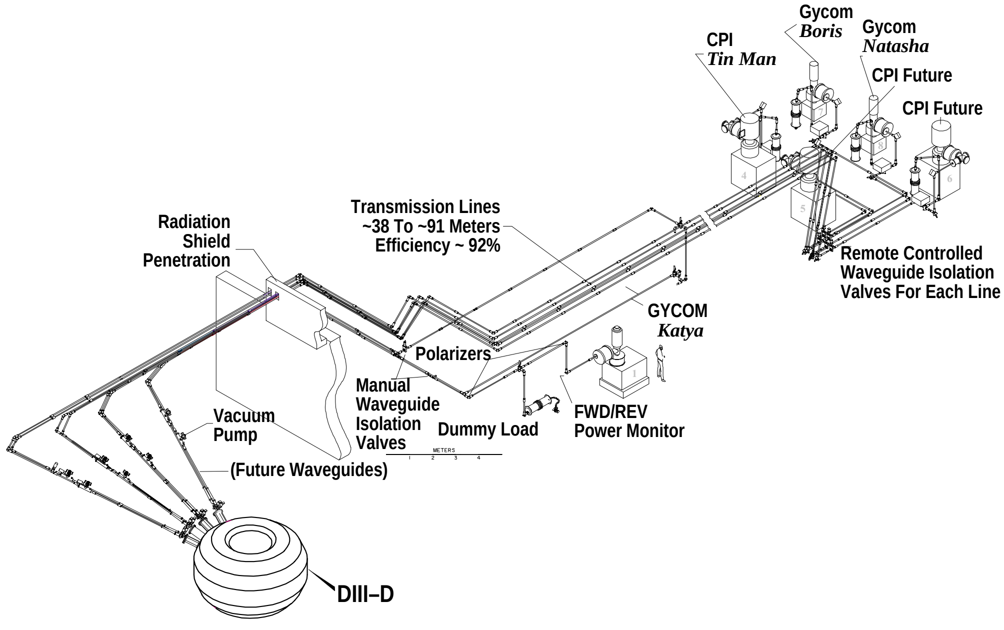

Fig. 3. Isometric view of the gyrotron installation on the DIII–D tokamak. The lineas are grouped in pairs at the tokamak. Each line includes dummy load, polarizer pair, power monitor, isolation valve, and pumping system.