MW Gyrotron Development for Fusion Plasma Applications

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Gyrotrons are microwave oscillators based on the Electron Cyclotron Maser (ECM) instability. The free energy is the rotational energy of weakly relativistic electrons ($1 < \gamma \leq 1.2$) in a longitudinal magnetic cavity field. In contrast to klystrons the interaction circuit is a high-order-mode cavity allowing higher power at higher frequencies.

At present, gyrotrons are mainly used as high power microwave sources for various applications in tokamak and stellarator plasmas for controlled thermonuclear fusion research. Long-pulse (a few sec) gyrotrons utilizing open-ended cylindrical resonators which generate output powers of 100-960 kW per unit, at frequencies between 8 and 140 GHz, have been used very successfully for plasma formation, electron cyclotron resonance heating (ECRH), noninductive electron cyclotron (ECCD) and lower hybrid current drive (LHCD), plasma stability control and active plasma diagnostics at system power levels up to 4.5 MW.

As fusion machines become larger and operate at higher magnetic fields ($B \cong 6T$) and higher plasma densities in steady state, it is necessary to develop CW gyrotrons that operate at both higher frequencies and higher mm-wave output powers. The requirements of the stellarator W7-X and the tokamak ITER are between 10 and 40 MW at the frequencies 140 GHz and 170 GHz, respectively. This suggests that mm-wave gyrotrons that generate output power of at least 1 MW, CW, per unit are required. Since efficient plasma applications need axisymmetric, narrow, pencil-like mm-wave beams with well defined polarization (linear or elliptical), pure-mode gyrotron emission is necessary in order to generate a TEM_{00} Gaussian beam mode. Single-mode 110-170 GHz gyrotrons with conventional cylindrical cavity, capable of 1 MW per tube, CW are currently under development in several scientific and industrial laboratories. The maximum pulse length of 1 MW gyrotrons (110 GHz, 140 GHz, 170 GHz) with synthetic diamond window is 5-12 s, with efficiencies slightly above 30%. The energy world record of 160 MJ (0.89 MW at 180 s pulse length and 140 GHz) has been achieved by the European FZK-CRPP-CEA-TED collaboration. Total efficiencies around 50% have been obtained using a single-stage depressed collector (SDC). The present state-of-the-art will be discussed in this invited paper.

To reduce the costs of the ECRH system on ITER and to make its poloidal launcher for neoclassical-tearing-mode stabilization more compact, a further increase of the output power per gyrotron is desirable. To achieve output powers in excess of around 2 MW, CW at the ITER reference frequency 170 GHz it is necessary to switch to coaxial cavity geometry. A maximum output power of 2.2 MW at 165 GHz (1 ms pulse length) was obtained at FZK with an efficiency of 28%. At the nominal output power of 1.5 MW the efficiency increases from 30% to 48% in operation with a SDC. The availability of sources with fast frequency tunability would permit the use of a simple non-steerable mirror antenna at the plasma torus for local current drive experiments. This paper also reports on the status of the development of advanced coaxial cavity gyrotrons and step-wise frequency tunable gyrotrons.