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Applications of high power millimeter waves in the DIII–D fusion program

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ABSTRACT

First operation of a new generation of MW level, 110 GHz generator (gyrotron) on the DIII–D fusion experimental device has been achieved. The desire for high power, cw millimeter (mm) wave sources to support fusion research and development is just now beginning to be realized. Plasma heating and current drive with directed mm waves rely on the strong absorption achieved when the wave frequency matches the natural "cyclotron" frequency of electrons in a magnetic field, or its harmonics. Recent progress in fusion experiments highlights the need for control of the interior details of the hot plasma, and mm wave systems are ideally suited for this role. A brief status of fusion research is given, and the importance of mm waves in the future directions for fusion research is described.

The vacuum transmission components necessary for transmitting, monitoring, and launching high power 110 GHz waves into a plasma have been developed at General Atomics (GA) and will be described. High power mm waves have a number of attractive technological features for fusion applications compared with other candidate plasma heating and current drive technologies. Millimeter waves can be transmitted with high power density over large distances with low losses by utilizing corrugated waveguides, so the generators can be sited remotely, facilitating maintenance and saving valuable space near the fusion device.

Keywords: fusion, gyrotrons, millimeter waves, DIII–D.

1. FUSION PRIMER

Fusion is the energy source of the sun and other stars, and results from the "fusing" of light elements to form a heavier element with a net gain of energy. Figure 1(a) shows that light elements have an energy excess, as do the very heavy elements which can be split in the fission process to produce net energy. The most energetically favorable fusion reaction is the fusion of deuterium and tritium, heavy isotopes of hydrogen, to form helium with a net release of energy. This process is illustrated in Fig. 1(b). Other potential fusion reactions are shown in Fig. 1(c), but note that the ignition temperature required is much larger than for the D+T reaction. Hence, most fusion power plant designs rely on deuterium and tritium as the fuel.

A key advantage of this fusion process is that the waste product, helium gas, is environmentally benign. In fact, helium is a useful byproduct since it is used, for example, as an essential coolant in superconducting technology. Fusion is the source of heat and replaces the coal or oil burning portion of a power plant. The energy from DT fusion reactions is released in the form of neutrons, a chargeless constituent of most nuclei. In order to recover the energy, the reaction chamber must be surrounded with enough mass to stop the neutrons and hence recover their kinetic energy. The use of lithium-based compounds in the energy-absorbing blanket has the advantage of producing the required tritium fuel from the collision of neutrons with lithium. Hence, the tritium fuel, which is a slightly radioactive alpha emitter, is produced at the site and does not have to be transported. The containment vessel itself can become radioactive by collisions of the neutrons with the elemental constituents of the vacuum vessel, so access to the reactor chamber will be controlled and remote handling will be required for some maintenance and repair operations. By optimum selection of materials and materials recycling, the activation products and waste can be minimized. However, there is no danger of a "meltdown" in the fusion process and there is no long-lived radioactive fuel waste that needs to be reprocessed or buried. There is also no release of carbon dioxide or nitrogen oxide noxious emissions which can exacerbate the greenhouse effects. Fusion looks like the most viable long term energy source for the world, although it has had a long, but difficult, development process. The worldwide technical progress over the past few years has been phenomenal, and the continued progress in the future may well rely on the application of high power mm waves to control the interior details of the burning plasmas.

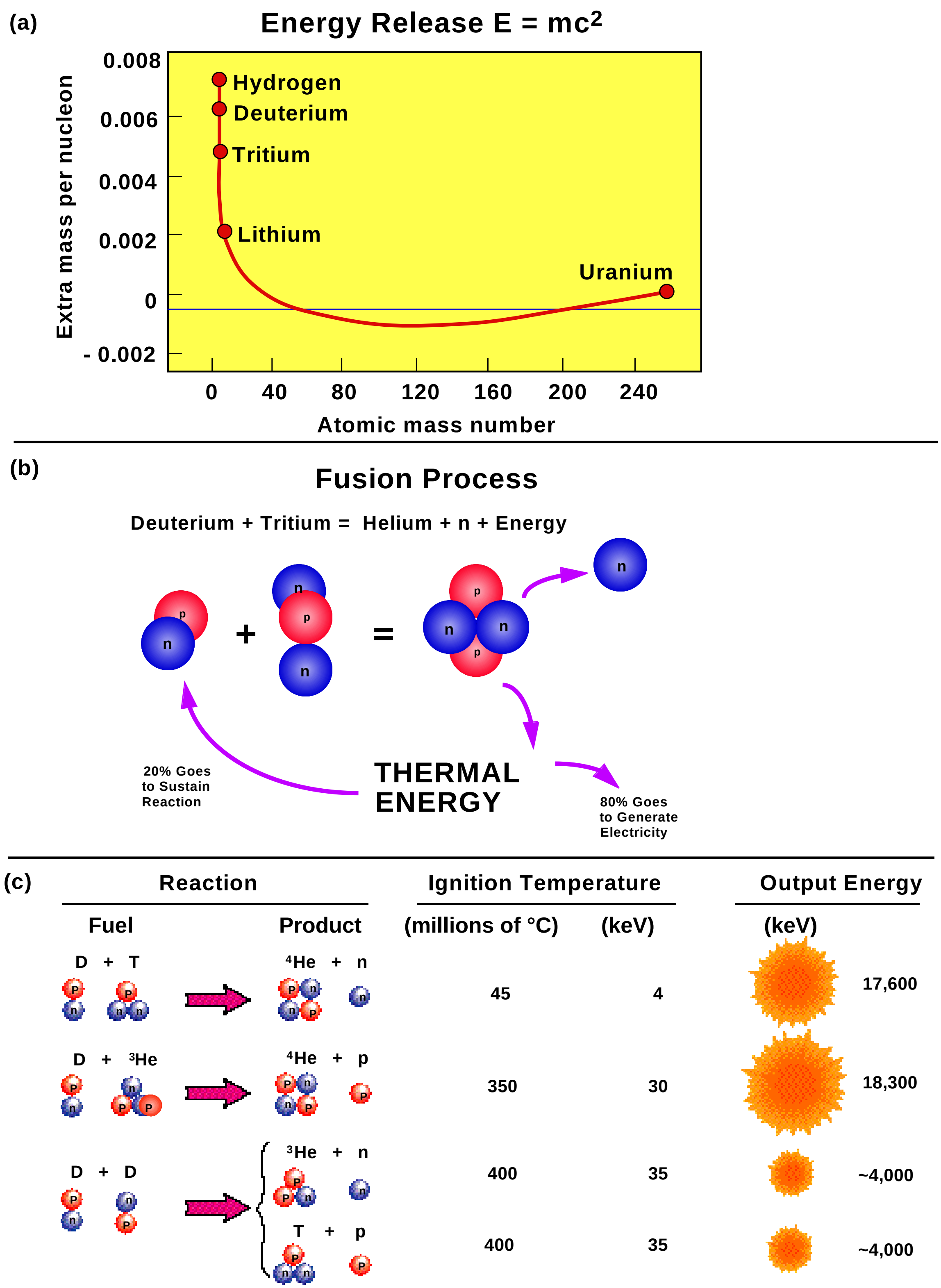

Fig. 1. (a) Excess energy per nucleon shows ‘‘fusion’’ of low mass nuclei liberates energy as does ‘‘fission’’ of high mass nuclei; (b) most energetically favorable fusion reaction is deuterium with tritium, which releases helium and an energetic neutron; and (c) other fusion reactions.

2. MAGNETIC FUSION STATUS

The goal of producing clean, inexhaustible energy by the fusion of light elements is becoming a reality. Significant fusion power output (up to 10 MW) was demonstrated in two experiments over the past few years, one in the U.S. (TFTR) and one in Europe (JET).[1,2] Figure 2 dramatically illustrates the worldwide progress in magnetic fusion by plotting the steady increase in the fusion power output as a function of time for the major fusion devices. Most of the experiments operate with deuterium, but the results from JET and the recent record results from Princeton (TFTR) used a mixture of deuterium and tritium (DT), as required for optimum power production. The DT results give over two orders of magnitude more fusion power for the same operating conditions. Both experiments relied on a magnetic confinement geometry based on the tokamak concept which was originally developed by the Russians, but is now pursued by all of the major fusion research participants.

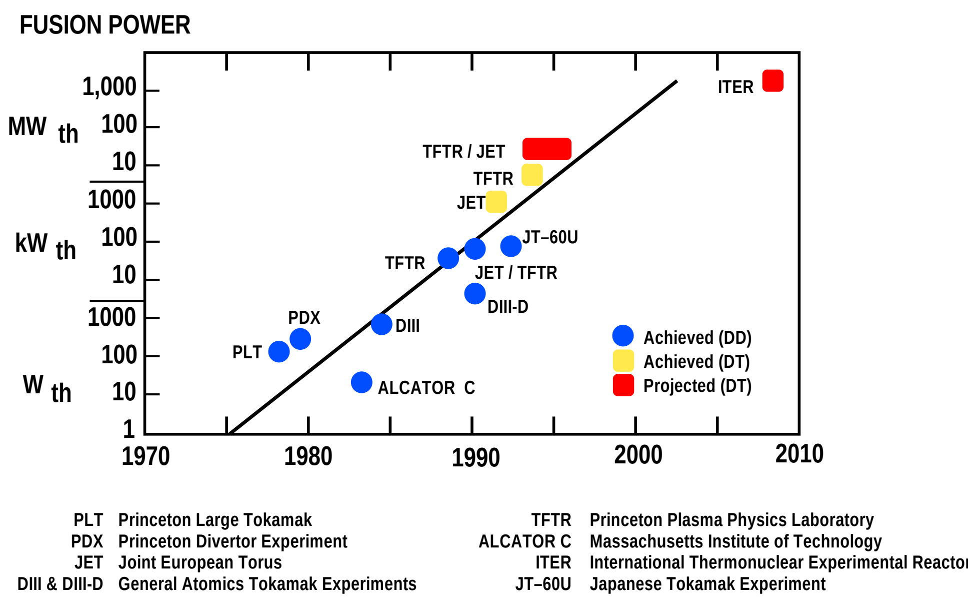

Fig. 2. Fusion power produced in worldwide experimental devices as function of time showing six orders of magnitude increase over the past twenty years.

The tokamak confinement geometry is illustrated in Fig. 3 by the cross-sectional view of the DIII-D device. The DIII–D tokamak[3] at GA in San Diego is a DOE-funded national research facility and its design is prototypical of future tokamak reactors. The nuclei of deuterium and tritium each have a single unit of positive electrical charge, so they must be given enough energy to overcome the potential barrier in order to fuse. Isolation of the hot plasma from the doughnut-shaped containment vessel walls in a tokamak is achieved by a combination of magnetic fields produced by an externally-applied toroidal magnetic field plus a poloidal magnetic field generated by a current flowing in the plasma. Single particles should be perfectly confined by toroidally-closed magnetic surfaces generated by these magnetic fields, but collisions between particles produce some loss of particles across the magnetic “surfaces” to the wall. Decades of research have shown that the losses typically are much larger than expected due to collective instabilities, but recent experimental successes demonstrated regimes in which the transport loss is closer to the theoretical minimum level.

Physics understanding of toroidal plasmas has improved substantially, and the limits to performance in most tokamak experimental devices are caused by the development of internal instabilities which can lead to rapid cooling of the plasma and consequent reduction in the power output. Theoretical understanding of these instabilities indicates stability can be improved

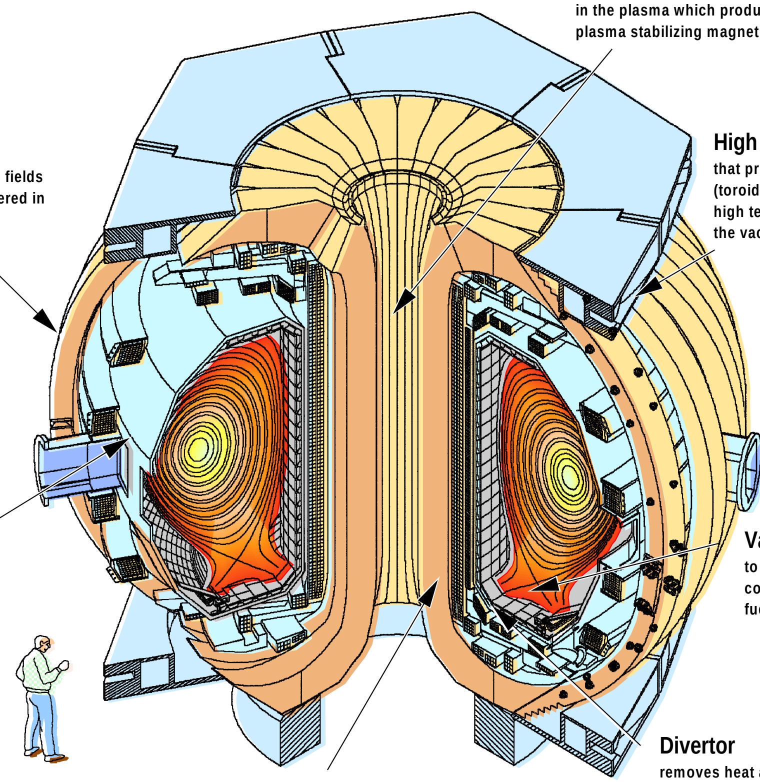

Fig. 3. A cross-sectional view of DIII–D showing the major features of a tokamak device, including the various coils for producing the confining magnetic fields and shaping the plasma.

by elongating and shaping the plasma cross section and controlling the internal pressure and current profiles; creating and maintaining the desired internal plasma profiles can be done with millimeter waves. Operation with transiently-improved performance has recently been demonstrated in all of the major shaped tokamaks around the world (DIII–D, JET, JT–60U).[4–6] Even in the circular TFTR and Tore Supra devices, improved performance has been demonstrated by shaping the internal pressure and current density profiles.[7] An international effort is underway to design and build a large elongated tokamak device called the International Thermonuclear Experimental Reactor (ITER) which will demonstrate all of the essential elements of a fusion power plant.

3. APPLICATIONS OF HIGH POWER MM WAVES

As indicated, most of the tokamak experiments demonstrating improved confinement regimes have relied on transient methods to modify the internal current density and pressure profiles of the plasma, but sustaining these improved performance regimes requires the ability to deposit energy and momentum at spatially-controlled locations for a wide range of plasma conditions. By launching millimeter waves directed along the torus, current can be driven inside the plasma and the detailed distribution of the current and pressure within the plasma cross section can be controlled. The use of millimeter waves for heating electrons (ECH) and driving current in a plasma (ECCD) is well established.[8] The initial operation of a new generation of 110 GHz internal converter gyrotrons with MW-level output has been completed, and Fig. 4 shows a profile of the electron temperature before and after the application of about 0.5 MW of 110 GHz power for 200 msec from a Russian (Gycom) built gyrotron. As indicated, the center of the "doughnut-shaped" toroidal plasma has the highest temperature and it falls towards the containing walls. The application of the millimeter waves has more than doubled the central electron temperature and hence the central electron pressure.

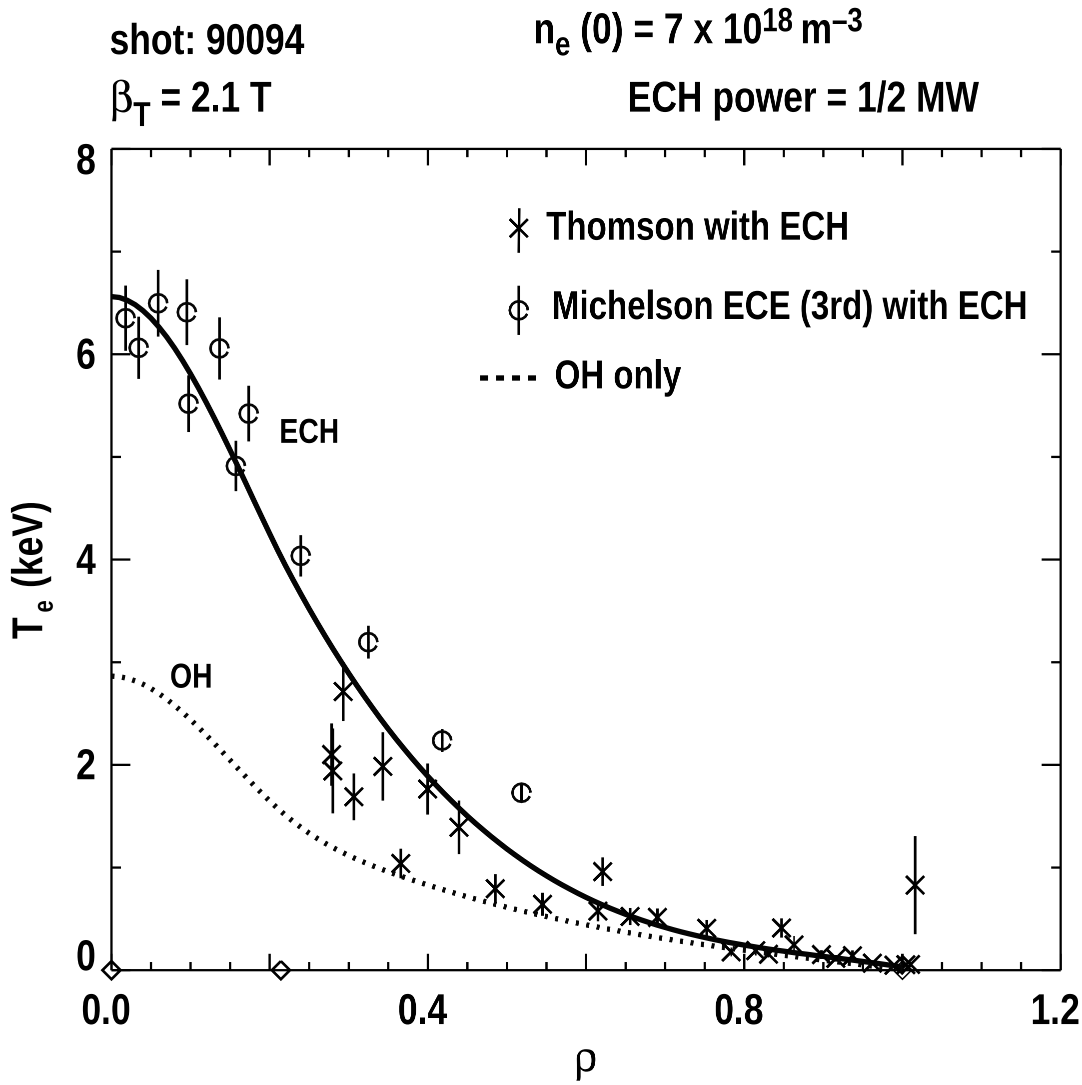

Fig. 4. Electron temperature as a function of normalized minor radius with ohmic heating alone (OH) and with 0.5 MW of millimeter wave power added.

The use of the millimeter waves to heat the electrons and drive plasma current in a spatially-controlled manner will be further explored using the DIII–D tokamak. The DIII–D tokamak has an elongated poloidal cross section, a poloidal divertor, and flexible heating and current drive systems, so it contains the main features envisioned for ITER and future tokamak reactors. It is an ideal facility to investigate the detailed control of the pressure and current profiles in advanced tokamaks using mm waves, and an ambitious mm wave program is planned with 10 MW of 110 GHz power achieved in several steps, beginning with 3 MW experiments next summer.

Gyrotrons in the desired 110 GHz frequency range with MW-level capabilities are now available from several vendors [CPI (formerly Varian), Gycom, Toshiba, and Thomson]. The DIII–D three gyrotron system will consist of two CPI MW gyrotrons and one Gycom MW, 2 sec gyrotron. The pulse length of the Gycom gyrotron is limited to 2 sec by the heating of the boron nitride output window. The pulse length of the CPI gyrotrons will depend upon the success of on-going window development activities. The gyrotron itself is designed to be cw, but the present double disk sapphire window limits operation to 0.8 sec for MW power output. Figure 5 shows a photograph of both gyrotrons.

The MW gyrotron source is the basic building block for the DIII–D system and Fig. 6 shows a block diagram.[9] The DIII–D transmission line utilizes the $HE_{1,1}$ mode in an oversized evacuated transmission line. Corrugated waveguides,

GYCOM **(a)** **CPI** **(b)**

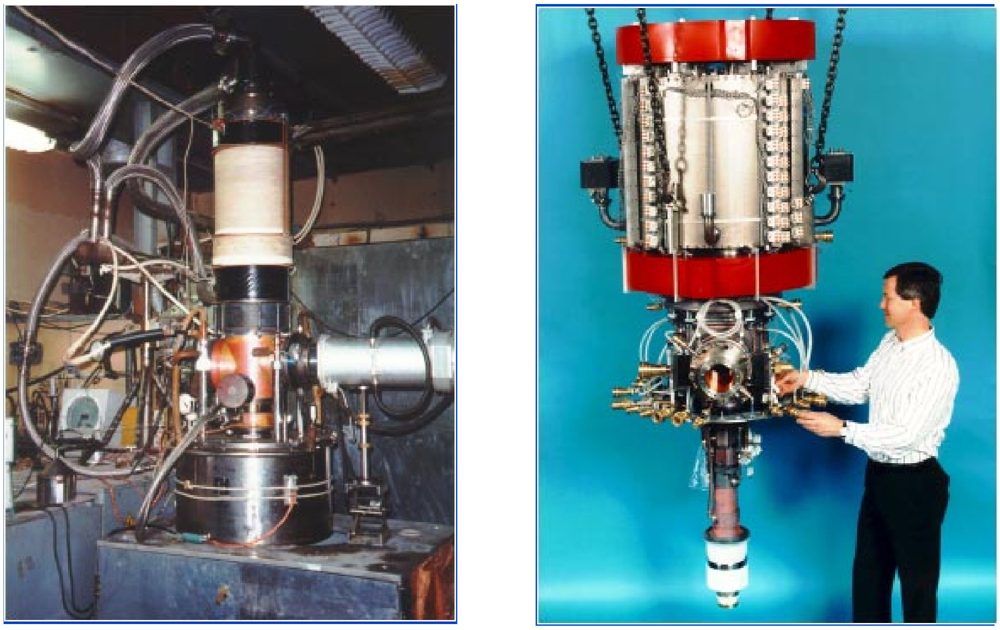

Fig. 5. MW-level, 110 GHz gyrotrons with internal mode converters: (a) Gycom; (b) CPI. The microwave outputs are from windows on the side and the unspent beam is collected at the top.

miter bends, pump-outs, directional couplers, waveguide switches and dummy loads have been developed at GA for MW power levels at 110 GHz. Figure 7 shows some of the microwave components developed by GA for transmitting high power mm waves, including a photograph of a prototype "distributed" window. A distributed window capable of MW, cw operation at 110 GHz is under construction at GA for installation on the CPI gyrotron. The distributed window consists of strips of sapphire separated by water-cooled metal slats which form a polarization sensitive antenna; the unit is about 10×10 cm and has 42 sapphire strips.[10]

Corrugated waveguide can propagate the $HE_{1,1}$ mode with very low loss, even in moderately small diameters. For example, 31.8 mm diameter was chosen for the DIII–D 110 GHz system due to its predicted loss in aluminum being only 2% in 40 m. Small angle bends can be achieved in reasonable lengths and it is insensitive to misalignments from thermal effects or mechanical impact.

Phase-correcting mirrors have been designed to allow the use of 90˚ miter bends with low loss in the 31.8 mm size. The small size also provides large losses for the high order modes that typically are generated and reflected from miter bends. Low power transmission tests of a 10 m assembly of straight sections show a loss consistent with the predicted value (< 0.5%), and, as expected, the transmission line was shown to be insensitive to gentle deflections. The miter bends were also tested at low power, with six bends connected as a group of two separated from a group of four by 2 m of straight waveguide. The measured transmission loss was < 6%, consistent with the expected loss of 1% per bend. Furthermore, over a 500 MHz sweep, there was no evidence of any trapped modes between the two groups of bends, showing that the higher order modes generated at the bends are effectively damped in the 31.8 mm corrugated waveguide.

A fast-closing shutter is located near the tokamak, and is instrumented to close when a pressure threshold is exceeded at the gyrotron side of the transmission line. A vacuum valve is used to isolate the transmission line from the tokamak.

Radiation from the end of the $HE_{1,1}$ corrugated waveguide is focused and rotated by two mirrors. The fixed mirror at the end of the waveguide slightly focuses the free space Gaussian beam generated by the radiating $HE_{1,1}$ mode. The focusing produces a beam spot approximately 13 cm in diameter 1 m from the radiating waveguide. This beam spot contains 98% of

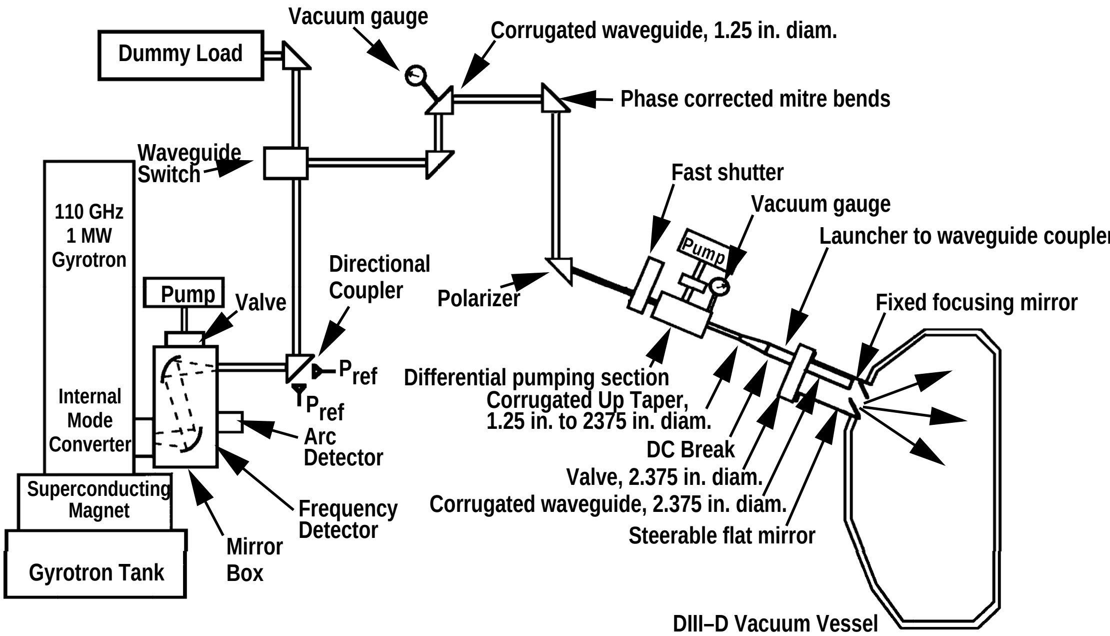

Fig. 6. DIII–D 1 MW, 110 GHz gyrotron sytem (not to scale).

the power. Rotation of the flat mirror provides broad poloidal coverage of the DIII–D plasma. Initially this mirror is only rotatable poloidally and requires a machine opening to change its toroidal angle. Both mirrors are fabricated from copper-coated graphite.

Since previous physics experiments have demonstrated the efficacy of electron cyclotron heating in a plasma, the future work will focus on the profile control applications. As an example of the application of millimeter waves, Fig. 8(a) shows the profile of plasma current needed to duplicate an enhanced confinement regime in DIII–D as compared with a normal centrally peaked current profile. The desired current profile can be produced by combining several different current sources including a self-generated bootstrap current. The key component is the “off-axis” current driven with the millimeter wave system. Figure 8(b) shows the launcher system in DIII–D which allows the millimeter wave power to be steered towards the central region or off-axis as required for the scenario in Fig. 8(a).

4. SUMMARY AND FUTURE PROSPECTS

The recent availability of high power sources in frequencies above 100 GHz coupled with the discovery of the enhanced confinement regimes in tokamaks provides new impetus to utilize this technology in fusion experiments. A demonstration of the ability to maintain these enhanced confinement regimes in tokamaks for long times with millimeter waves can lead to smaller, more compact fusion reactors.

Initial experiments on DIII–D with three MW-level 110 GHz gyrotrons are scheduled to begin next spring, and success in these experiments can greatly impact the progress in the development of magnetic fusion as an energy source for the future.

5. ACKNOWLEDGMENT

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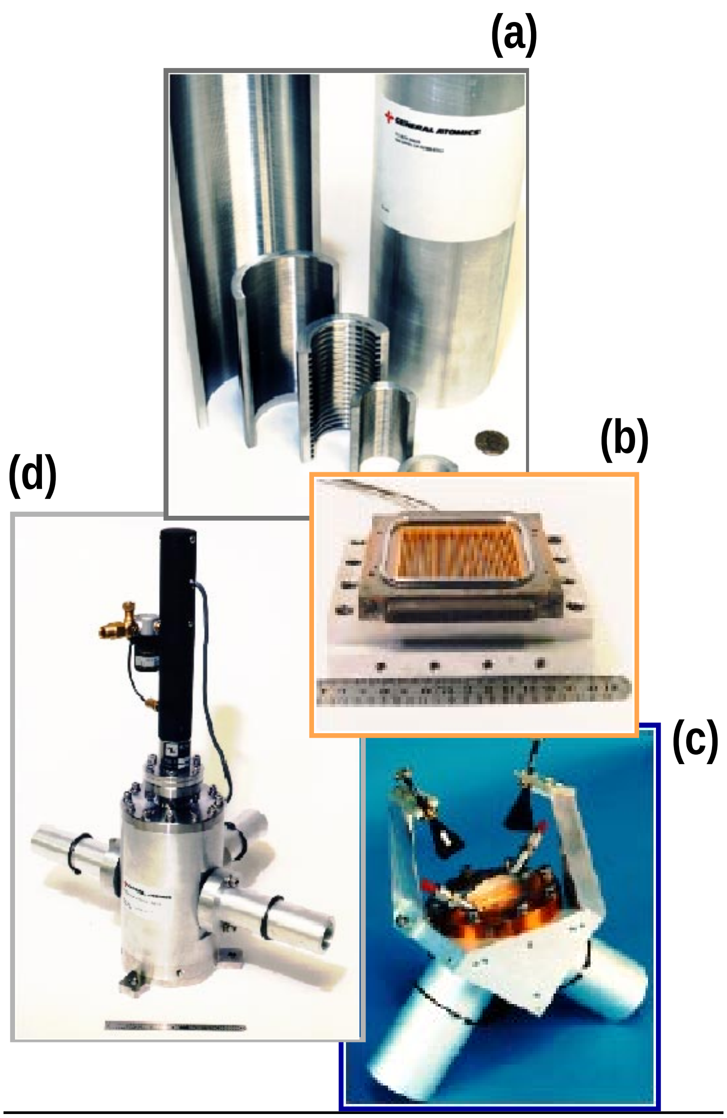

Fig. 7. General Atomics high power millimeter wave transmission line components. Clockwise from top: (a) corrugated waveguides; (b) distributed window; (c) directional coupler; and (d) waveguide switch.

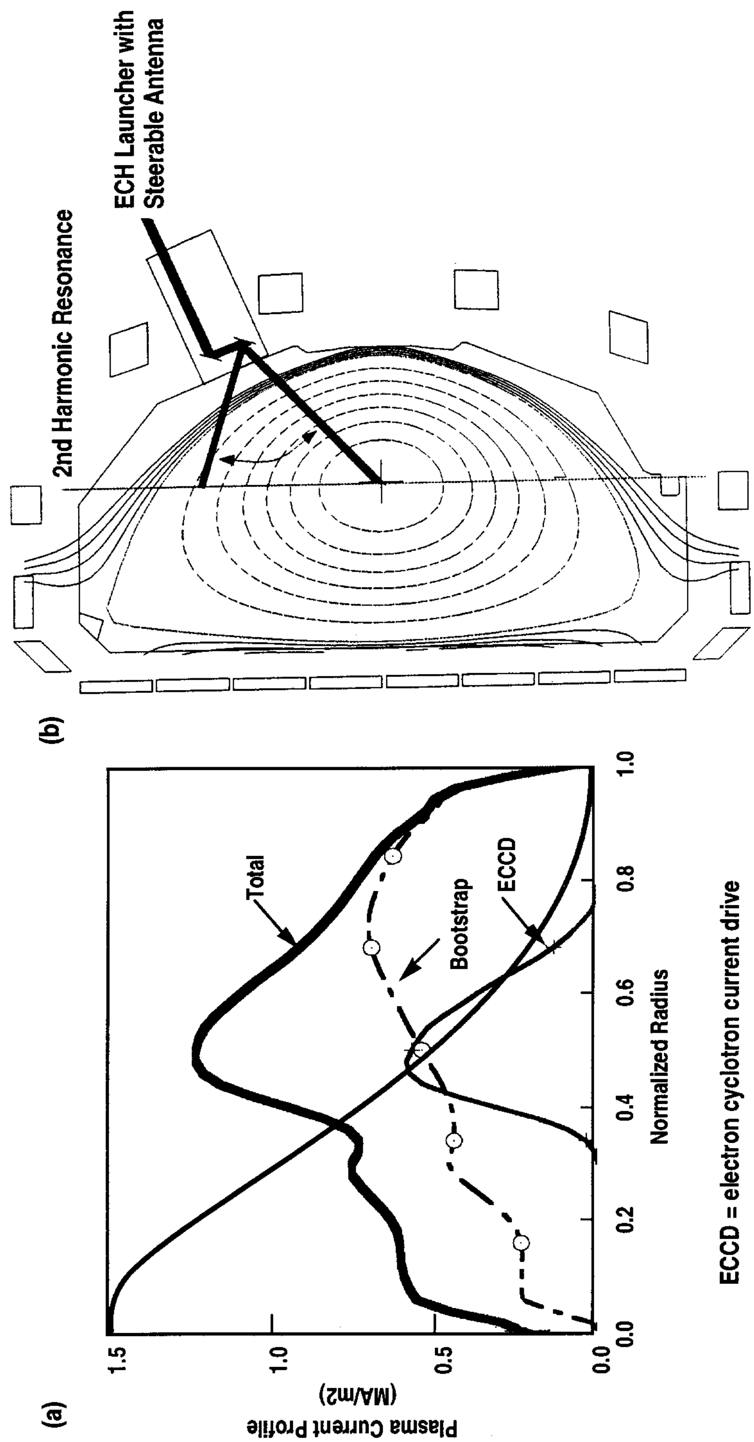

Fig. 8. (a) Current profile needed for enhanced performance in DIII–D compared with the normal peaked profile. The component of the current from bootstrap and from millimeter waves (ECCD) is shown; (b) the DIII–D millimeter wave power can be steered to the desired location with a movable mirror launcher.

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