ECH for DEMO

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Summary

Because ECH antennas have a minimal impact on a reactor wall, ECH is very attractive, possibly even essential, for heating the plasma in a fusion reactor such as DEMO. ECH can provide a reliable, maintainable source of plasma heating, current drive and instability control. The deposited power can be localized, the waves can be used to drive current as required and high power, long pulse operation has already been demonstrated. Recent advances also indicate that ECH systems show promise to operate at very high wall-plug efficiency, thus helping to achieve high Q. Although the required technological fundamentals have been demonstrated, ECH technology requires significant advances beyond the level of the ITER ECH system to fulfill its promise on machines such as DEMO. These advances include development of highly reliable, high frequency (>200 GHz), high power (>2 MW) gyrotrons and improvement of gyrotron efficiency to > 70%. Fast and slow frequency tunability should also be developed for enhanced plasma control. Transmission lines should be developed to transmit higher power levels with a range of frequencies. Launchers facing the plasma that can survive in the reactor environment should also be developed. In the near term, plasma experiments such as DIII-D could be employed to investigate the physics and engineering issues of fully ECH heated plasmas, which will lead to better definition of the requirements for next generation ECH Technology.

Issues, Gaps

The issues and "gaps" for ECH are clearly stated in the Report: Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy (Greenwald Panel Report, 2007). The report states [Greenwald Report, pages 167-168]:

"4.b.6. Plasma Modification By Auxiliary Systems

a. Gap: Plasma Heating: Even in a high gain plasma, some level of auxiliary plasma heating may be required for start-up, sustainment or instability control. This needs to be achieved precisely and efficiently. New systems/technologies have to be developed or expanded to meet the requirements of Demo.

b. Gap: Plasma Current Drive: For steady-state operation the plasma current will have to be produced in a non-pulsed (non-inductive) [manner], and owing to the low current drive efficiencies of most non-inductive means, a high fraction of internally generated current (bootstrap current) is desirable. However, high performance plasmas, with high bootstrap currents are very susceptible to instabilities, where tearing modes create zones of zero or low bootstrap current.

Mission Elements

• Higher frequency, high unit power, and higher efficiency microwave sources (gyrotrons) need to be developed for Electron Cyclotron Heating.

• EC Launching mirrors will have to be developed that minimize erosion and to handle the higher neutron and heat fluxes of Demo."

Development Opportunities and New Ideas

The development issues for DEMO were also summarized in the Greenwald Panel Report [page 49]: "The EC waves are produced in electron tubes called gyrotrons. The gyrotrons developed for ITER operate at 170 GHz, 1 – 2 MW, and cw operations. [Note: 2 MW may not be developed.] For several of the Demo concepts these gyrotrons will be sufficient. However, there are versions that operate at high magnetic fields or at high densities. For these applications higher frequency sources, 250 -300 GHz, will be required. Since the economics of EC Systems would improve with larger unit powers, development of higher power gyrotrons would reduce the capital cost of Demo."

The **ECH frequency requirements** were addressed in a White Paper for the Greenwald Panel written by P. T. Bonoli, A. E. Hubbard, R. R. Parker, and M. Porkolab. They said: "ECCD was not considered [for DEMO] since based on available technology a decade ago, RF sources would not have been available at the ultra-high frequencies that correspond to that required for Aries RS (= **220 GHz** or above for on axis absorption, O mode at the fundamental at 8.0 Tesla). In Aries AT, the magnetic field was lower but the dielectric constant approaches unity and therefore second harmonic may be necessary for accessibility, namely **324 GHz** at 5.8 Tesla field." We note that megawatt power level gyrotrons have been demonstrated at frequencies above 300 GHz in short pulse operation, but very significant development will be required to achieve cw operation at the required frequencies.

Gyrotrons with **frequency tunability** offer many advantages for plasma heating and current drive, but require major development. A multiple frequency gyrotron must overcome several obstacles: the internal mode converter of the gyrotron must operate at very high efficiency for several frequencies; the window at the gyrotron must pass several frequencies with very low loss; the external matching optics unit (MOU) must be able to match the output radiation onto the transmission line. **The remainder of the system, including the transmission line and launcher, must also work at several frequencies.** Although several research efforts are underway to demonstrate this frequency tunability, it is not required for ITER and will require a significant development effort.

To reduce system cost, it is necessary to develop **gyrotrons of higher average power**, up to at least 2 MW at frequencies up to 324 GHz. To fulfill the promise of ECH system performance, it would also be important to increase gyrotron efficiency. In theory, gyrotrons can operate at an efficiency of 40 to 50% without a depressed collector. With a multi-stage depressed collector, the **efficiency should rise to above 70%**. With efficient power supplies and transmission lines, the wall plug efficiency of an ECH system should exceed 55%. This is a major potential advantage of ECH / ECCD.

Transmission lines will also have to be developed to transmit higher power levels and operate at a range of frequencies. Launchers facing the plasma that can survive in the reactor environment should also be developed. Phase locking of high power gyrotron oscillators to each other in pairs or larger groups offers a way to increase power per launcher without degrading the gyrotron efficiency. Alternatively, if the power from several launchers is phase locked, the spot size at a focus can be substantially reduced compared to what is possible with a single launcher. Launcher concepts have been described in a separate White Paper submitted to Theme III: Taming the Plasma Material Interface.

Research Thrusts

Design

Theoretical research is needed to design higher power, higher frequency gyrotrons. Issues include mode competition in high order modes and techniques for achieving high efficiency at high power and high frequency. Modeling is also needed to design advanced components such as internal mode converters that operate at several frequencies, multi-stage depressed collectors, multi-frequency windows, etc. Theoretical research would include basic theory and code development.

Test Stand Demonstration

The proposed concepts should be tried on ECH test stand(s) prior to implementation on a major plasma heating experiment. Antenna and launcher designs can be tested at low power at available test stands at MIT and the Univ. of Wisconsin. Physics and microwave engineering issues of gyrotrons can be tested on the short pulse test stand at MIT. Long pulse testing, up to several seconds, can be conducted at General Atomics and cw testing at currents up to 25A can be conducted at CPI, Inc. An ECH test stand for ITER is under construction at Oak Ridge National Lab. That test stand will be capable of full CW testing of megawatt gyrotrons.

Confinement Experiment Demonstration

ECH technology should be tested on confinement experiments. The DIII-D experiment would be ideal for early testing of higher power gyrotrons for ECH, with greater than 1.5 MW power level per gyrotron considered desirable. This near term development would provide much needed additional ECH power for experimental research on DIII-D while answering questions related to gyrotron development. Frequency tuning would also be useful for ECH on DIII-D. Higher frequency gyrotrons would benefit the Alcator C-Mod research program. In the longer term ECH would be useful on future US fusion experiments, such as the proposed Fusion Development Facility and other, similar proposed plasma fusion demonstration devices.