ICRF Actuator for DEMO

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Summary

Ion cyclotron range of frequency (ICRF) systems have been used extensively in tokamak plasmas for heating, driving current, controlling plasma instabilities and more recently driving plasma flow. The ability to directly heat ions and drive plasma current and flow makes ICRF an attractive actuator for future devices and fusion reactors such as DEMO. The flexibility of the ICRF system is partly derived from the wide range of absorption scenarios available in this frequency regime including minority, mode conversion, and direct electron absorption. Validation of full wave simulations has been quite successful but the recent observation of flow drive highlights the continued need to develop and validate these simulations. Primary ICRF antenna challenges are: coupling at long distance and high pedestal density; compatibility with high performance discharges and metallic plasma facing components; reliably maintain coupled power despite load variations; and availability to deliver ICRF power on demand without burdensome antenna conditioning. The ICRF sources are already demonstrated at high power (~2 MW), high efficiency (~65-70%), and long pulse. The primary challenge is to improve tetrode lifetime and transmitter reliability. The transmission networks on ITER are designed to isolate the transmitter from the plasma load but these lower the system efficiency and require significant infrastructure to handle waste power. Future matching networks need to have loss low matching elements. A productive strategy to develop ICRF as an efficient actuator for DEMO would be to have a confinement device that represents a reactor environment well and address the ICRF utilization challenges on such a device in conjunction with focused test stand devices. This allows close interaction between the RF and other plasma physics groups, such as plasma surface interaction, to address key integration issues and focuses attention on the most pressing issues.

Issues, Gaps

Issues and “gaps” for ICRF are 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 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.

e. Gap: Rotation Control: To optimize plasma confinement in high beta plasmas, edge rotation improves performance by producing radial velocity shear, which acts to stabilize micro-turbulence and thereby improving plasma confinement.

Development Opportunities and New Ideas

Wave Propagation and Absorption:

The ICRF flexibility is partly derived from the wide range of absorption scenarios available in this frequency regime. The primary core physics opportunities are simulation validation of wave propagation and absorption, characterization of flow and current drive, and RF and plasma physics integration. Validation of full wave simulations has been quite successful but the recent observation of flow drive highlights the continued need to develop and validate these simulations. The previous tests have focused upon power deposition in cases where only one absorption mechanism is present or where large orbits effects are negligible. In future devices, wave propagation and absorption are likely to be complicated by multiple absorption mechanisms and particles with large orbits. The existing devices, C-Mod, DIII-D and NSTX, can provide an array of challenging absorption regimes and would provide critical platforms for validation of simulation package. This effort would require sufficient diagnostics to monitor the fast ion distribution and profiles, high spatial and temporal resolution of the electron and ion temperature profiles, means to measure the RF wave fields or associated density fluctuations like phase contrast imaging. In addition, the SOL and plasma density profiles need to be monitored to allow accurate power balance. For current drive, additional measurements of the current profile are required and could be accomplished with motional Stark effect or polarimetry. Recent observations of mode conversion flow drive were significantly advanced due to high spatial and temporal resolution toroidal and poloidal flow measurements. RF flow drive theory also needs support since the current theory is inconsistent with experimental observations. Finally, integration of RF physics with the overall plasma response is largely absent up to now. Flow drive could influence both global MHD stability and micro-turbulence that underlies transport. Theoretical and experimental research is required to develop and validate simulations that incorporate both the RF and plasma physics. The ICRF generated fast ions and driven current have an impact on MHD stability, and therefore require integrated physics modeling and validation. Significant simulation efforts are currently supported by RF SciDAC that need continued emphasis, and whose codes need to be experimentally validated.

Antennas:

ICRF utilization is often limited in present experiments as a result of the antenna performance. In future devices, several additional issues are likely: coupling at long distance; compatibility with high performance discharges and metallic plasma facing components; reliably maintain coupled power despite load variations; availability to deliver ICRF power on demand without burdensome antenna conditioning; and compatibility with the nuclear environment.

The development and validation of a simulation tool that can properly handle complicated antenna structure and the relevant plasma physics is critical. The challenge is to include the ability to have finite element, electromagnetic simulation of the antenna in the plasma edge with the core absorption modeled correctly. This situation is further complicated by nonlinear physics resulting from the strong RF fields in the SOL. The current devices can contribute to validation of such a code through comparison with experiment. This requires detailed knowledge of the scrape-off layer density at the antenna both with and without RF power. Detailed measurements of the plasma potential modification and localization of erosion/impurity sources will also be important.

The US historically has had a strategy where test stands play a central role but the test stands to date have not sufficiently replicated the plasma environment and the solutions developed have had limited success. Test stands can be useful for specific targeted investigations. For example relatively small devices can be utilized to investigate breakdown and the influence of magnetic fields, neutrals, and electrode materials on breakdown. The main emphasis is to validate antenna operation in plasma and vacuum testing has limited value since the RF fields and currents on the antenna are perturbed by the plasma.

Coupling at long distance is short hand for conditions that result in low antenna loading and longer propagation time in the scrape-off layer. Understanding of the impact on antenna operation can be addressed in the short term through measurements of the SOL density profile on D-IIID, C-Mod, and NSTX. Integrated efforts with plasma edge groups could lead to developing techniques to modify or control the SOL density profile. Prediction of the edge density profile should have high priority since projecting ICRF to future devices is critically dependent on the SOL density profile. Efforts to monitor and control the SOL density, via gas puffing for example, need to be done in expected reactor conditions and the experiments must be replicated by simulations to build confidence in the projection of these techniques to reactor environment. These techniques also need to be compatible with high performance discharges. In addition, antennas for DEMO should aim for significantly higher voltage capability than even ITER for increased reliability. One path forward is to utilize refractory metals as proposed for next step accelerators. Materials need to be identified and examined under condition where there is a strong external magnetic field, neutrals, and long pulse length. Understanding the underlying physics of breakdown in antennas is critical and likely to come from test stand experiments. From present devices, much can be learned for example the vacuum transmission line is most susceptible to arcing as evidenced by the arc damage in most devices.

For amelioration of impurity and density production with ICRF, ITER is proposing to utilize beryllium armor on the antenna limiter tiles and faraday screen. This is likely to require frequent replacement of this armor for ITER but for DEMO it is expected that the armor will erode too quickly for this to be a solution. Antenna designs that minimize the underlying cause, parallel RF electric fields, will be required. Due the dependency on the SOL density, this problem is best tackled on an integrated device and also requires strong simulation support to project amelioration techniques to reactor environment.

Antenna load tolerance will be necessary to provide efficient power coupling to the plasma. Large load fluctuations are observed routinely with edge density perturbations, for example ELMs. ITER plans to utilize the so-called conjugate T configuration to increase the load tolerance of its ICRF antenna. This technique requires the connected straps are independent, small mutual coupling, and also limits the flexibility of the antenna in frequency and phasing. As in the case of coupling at long distance, the primary issue is prediction and understanding of the SOL density profile. Development of alternative antenna designs that allow for greater flexibility would be highly desirable. Arc detection in the presence of load tolerance becomes more difficult and requires development of new techniques.

Antenna conditioning is more an art form than scientific method and ITER plans to apply the present recipes. Given the recent JET experience with the ITER like antenna, this may prove to be burdensome. A strong program will be required to place antenna conditioning on firm engineering/scientific principles and develop the proper diagnostic set to determine the state of an antenna. Focused test stand experiments could characterize the changes in the material surface as it is being conditioned.

The expected nuclear environment is likely to require use of different antenna materials at a minimum and perhaps geometries. As mentioned above, refractory metals could possibly allow higher voltage operation and are more compatible with the nuclear environment. One would need to demonstrate an ICRF antenna can be made from refractory metals and be operated on a confinement device for qualification.

Sources:

Since the development of the 2 MW tube in the early ‘90s, computational advances allow a more sophisticated examination of the tube and its lifetime issues, particularly those related to fatigue. The three current confinement devices, particularly C-Mod due to its routine use of ICRF, would allow some information regarding lifetime to be gathered and analyzed. This analysis would allow one to verify the simulation package and to determine the most important issues. To address long pulse and lifetime issues, a full test stand would require long pulse supplies and sufficient long pulse load capability. In combination with the long pulse testing, focused material studies could also be done to examine material properties and their impact on source lifetime. Operations, operational practices, and application of regulated power supplies could allow for increased lifetime. Full testing of these practices should be done both on a test stand and on confinement devices.

Matching Networks:

Plasma conditions significantly impact the design requirements of the matching network. The current research strategy is to isolate the transmitter from the plasma induced load variations. This has led to a number of different approaches to provide isolation: passive and active. The passive approaches have gained more acceptance than active load following. The passive approaches however tend to trade efficiency and/or flexibility in favor of load tolerance. Accurate predictions of antenna loads would allow development of network solutions that maximize system efficiency and flexibility. This requires development and validation of antenna-plasma models. Another is to develop active matching networks, such as ferrite based tuners, with minimal losses that will maximize the delivered power over a range of plasma conditions. In the case of ferrite material, the ultimate power limitation is often due to power losses and associated thermal issues. Obtaining near theoretical densities for ferrites would improve their overall losses and improve their thermal conductivity. Present ferrite tuners are constructed with the ferrite material glued to strip line and this attachment technique is similar to C-band circulators utilized in lower hybrid current drive systems. This glue has poor thermal properties and often leads to arcing when overheated. Research into improved ferrite attachment could lead to improved ferrite tuner performance. High voltage DC breaks are required to separate the machine ground from the RF plant ground. A poor DC break results in RF leakage that often leads to interference with critical diagnostics, including those for plasma control. New nano-particle based materials offer a path to higher dielectric constant, larger capacitance, and more compact devices. A combination of both test stand and experimental demonstration would be required for qualification.