Research Thrust for Reliable Plasma Heating and Current Drive using ICRF

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Research Thrust Summary

We propose a Research Thrust dedicated to addressing the issues needed to ensure reliable ICRF heating and current drive. Such a thrust will include an integrated modeling effort to understand the science of RF interactions from the antenna to the core plasma. Validation of the models will be achieved using both dedicated test stands, including one focused on near-field RF plasma interactions and another one focused on PMI issues, and also existing/upgraded confinement devices.

Issues and Gaps with ICRF Antennas

Plasma heating and current drive using the Ion Cyclotron Range of Frequencies (ICRF) are important elements for the success of fusion. Most DEMO concepts identify ICRF as the main heating system. While there has been significant success in using ICRF systems on current experiments, there are numerous issues and gaps that must be addressed before they can be used reliably in making fusion energy a reality. The need to predictably and dependably couple ICRF power to produce the required heating profile, plasma current, and transport/stability control impacts most of the issues and gaps identified in the Greenwald Report [1]. Gap 7, "Development of Reactor-Capable RF Launch Structures," is perhaps the most explicit, which states that stresses on launching structures for ICRH or LHCD in a high radiation, high heat-flux environment will require designs that are less than optimal from the point of view of wave physics and that may require development of new RF techniques, new materials, and new cooling strategies. The issues and gaps cut across the disciplines of plasma theory and simulation, RF technology, materials, diagnostics, and reactor engineering (reliability and maintenance).

Many of the issues concerning the interaction of the near field of the antenna with the plasma in the scrape of layer (SOL) are not well understood. There is a need to predict, measure, adjust for, and modify this edge environment since it is the region through which the power is coupled. The issues include:

1. The formation of the RF plasma sheath, which can lead to focused particle and energy fluxes on the antenna and on surfaces intersected by the magnetic field lines connected to the antenna, depends on the antenna structure and phasing.
2. The resulting hot spot formation and enhanced local erosion serves as a local impurity source and can degrade core confinement.
3. The parasitic RF losses in this region include edge modes (shear Alfven and cavity modes), parametric instabilities, and non-linear wave-particle interactions.

Other issues concern the antenna structure and surfaces.

1. RF breakdown/arcing is one of the main power limiting issues with operating the antenna in the plasma environment and is poorly understood. The anticipated large outer gap on DEMO (and ITER) and the resulting impact on loading will likely push operating voltages to at least as high as the ITER design limit of 45 kV.
2. The interaction of the plasma with the antenna surfaces (including ELMs) and the role of the resulting particles and local gas load on breakdown and loading are issues

3. The antenna structure and Faraday shield will likely be constructed from layered or coated materials. The behavior of these structures in a nuclear environment and the survivability in long-term operations is a concern.
4. The exposed antenna surfaces must be resistive to high heat (1-10 MW/m^2) and neutron fluxes with acceptable levels of impurity production.
5. Issues that result from operating at ~600 °C, as required by DEMO, need to be addressed.

Scientific and Technical Requirements to Address the Issues

There are fundamental gaps in our understanding of the RF/plasma interface. Reliable and predictable antenna operation will not be possible unless these gaps are closed. Integration of fully 3-D heating codes with realistic antenna and confinement device geometry is needed to understand the coupling of RF power from the antenna to the core, as well as fundamental understanding of factors that will limit antenna operation, such as ELMs, parasitic losses, breakdown, and nuclear materials issues. To address these gaps, we propose an integrated effort that includes fundamental improvements in modeling coupled with experimental validation of the models on both dedicated test stands and on confinement devices.

Modeling Effort:

The modeling effort requires integration of many existing codes as well as improvement in or construction of new codes. Sheath and near field modeling need 3D antenna structures with self-consistent current distribution in the presence of anisotropic magnetized plasma in the scrape off region. TOPICA [3] can handle the antenna geometry (antenna box and Faraday shield) but not the SOL plasma (at present). VORPAL [3] or PIC codes may contribute to sheath computations. The relevant processes include the near-field region defined by equilibrium field lines that connect to the wall or divertor plates, wave propagation (arguably slow waves with a cold plasma conductivity), parallel and perpendicular transport, recycling, erosion, sheath dynamics, non linear wave particle interactions, transition to the closed-field line regions from the separatrix to the start of fast wave propagation, and absorption (linear and likely non linear). A substantial level of integration between both the physical regions and between the various physics and engineering elements will be required. The models must also be able to explain why the presence of the plasma degrades vacuum voltage standoff, including ELMs, and why this observed degradation scales with power instead of with voltage or electric field limit. Modeling will also be required to determine the effects of high neutron fluxes and tritium retention on antenna materials. Such models must include not only erosion expectations, but also structural effects including joining/bonding of materials and heat transfer at elevated temperatures.

Validation on dedicated Test Stands:

Modeling results need to be validated. Some modeling components can be validated on Test Stands, while others need to be validated on Confinement Experiments. The Test Stands required for model validation include an RF Test Stand and a plasma material interaction (PMI) test stand.

An RF Test Stand can be used to develop and validate many elements that will be part of the modeling program. Such a test stand will allow for the detailed study and understanding of antenna/plasma interactions without impacting valuable confinement machine time until the majority of the model inputs are verified. Issues that can be addressed include:

1. The interaction of the antenna with the SOL can be simulated, including RF sheath dynamics, antenna phasing effects, hot spot formation, localized erosion, transport along and across magnetic field lines, and wave-particle interactions.

2. Detailed and accurate measurements of plasma density, electron temperature, and potentials can be made in the vicinity of the antenna, together with IR measurements to determine power fluxes.
3. Arcing/breakdown issues can also be addressed where multiple parameters can be controlled and tested.
4. New diagnostics, control models, and antenna concepts can be developed and operationally verified before implementation on a confinement experiment.
5. In addition, a dedicated RF test stand will allow for easy access and rapid changes in antenna geometry or test conditions.

The requirements of an RF Test Stand would include a plasma volume on the order of a cubic meter at a density of $\sim 10^{18}/\mathrm{m}^3$, a magnetic field strength of ~1 Tesla, a test region large enough to insert a moderate size two-strap variable phase antenna (30 cm wide, 60 cm high), magnetic connection lengths of ~1 meter, and numerous plasma diagnostics. The plasma can be created by a variety of methods, including high-field launched microwaves (whistler mode with no density cutoff) at 28 GHz (or 53.2 GHz) or by using a helicon-based plasma source. Long pulse operation (several minutes) is desirable for testing realistic antenna conditions. A secondary plasma source, such as a plasma washer gun, could be located on a flux tube attached to the test antenna and pulsed to simulate ELMs. Diagnostics for the test stand would include numerous antenna probes (voltage/current), Langmuir probes, capacitive probes, visible/IR cameras, spectrometers, energy analyzers, deposition/erosion probes, a reflectometer, and an interferometer.

A PMI test stand will be required to validate models related to materials to ensure qualified solutions. Some of the main issues include thermal stresses at the joints subjected to high heat and neutron fluxes, cracking due to voids in brazes, erosion of coatings, and similar issues. The requirements of such a facility [e.g. as in ref 2] would include high incident heat fluxes (1-10 $\mathrm{MW/m}^2$) and the ability for handling neutron irradiated materials at elevated temperatures.

Validation on Confinement Experiments:

Final testing and validation of the modeling efforts will require significant operational time on a confinement experiment. While dedicated test stands can better address validation of certain elements of the modeling effort and antenna/plasma interactions, they cannot adequately address fast wave propagation, power absorption, and wave interactions with closed flux surfaces. More dedicated run time will be needed on existing machines, such as Alcator C-Mod, NSTX, and DIII-D to properly test integrated performance in a realistic environment. Some progress can be made using existing antennas in these machines, but new or modified antenna structures will also be needed to test and validate predictions of plasma-wave interactions, plasma heating/current drive, parasitic losses, large-gap coupling issues, impurity generation, elevated temperature operations, and diagnostic/control strategies. Many of the plasma physics and material science issues can be adequately addressed in these machines, but operations and validation of all aspects in a fully nuclear environment at elevated temperatures and long pulse lengths will eventually be needed. The neutron damage and tritium retention in layered/coated materials in the antenna structure may cause blistering, swelling, and potential delamination of these materials. The potential for RF breakdown and coolant contamination would be greatly increased and needs to be addressed.

References:

[1] Greenwald Panel FESAC Report, Gaps 1, 2,4 ,5 ,7, 9, 10, 12, 13, and 15
[2] White paper “Research Thrust to Address PMI Knowledge Gaps for DEMO and ITER”
[3] TOPICA is a 3D EM code, VORPAL is a 3D supercomputing computational framework.