US ITER Forum
Activity Proposal Form

Your name: David W. Swain
Your institution: Oak Ridge National Laboratory
Your E-mail address: swaindw@ornl.gov
Your phone number: 865-574-1163

What is the scope of your proposed activity?

Design, build and test all (or part) of the ITER ion cyclotron system, and carry out needed R&D; prepare for and participate in the ITER experimental program.

In which phase(s) would the activity be conducted?
✔ Pre-construction (2003-5) ✔ Construction (2006-13) ✔Research (2014-34)

In which phase(s) would the US benefit be realized?
✔ Pre-construction (2003-5) ✔Construction (2006-13) ✔Research (2014-34)

What do you see as the US interest in the programmatic area of your proposed activity?

High. The three major present US experiments as well as planned ones all utilize ion cyclotron heating/current drive systems. Expertise gained working on the ITER system will provide results that should directly benefit present-day US machines, enabling better operation of their rf systems. International collaboration opportunities will be enhanced in the near-term. Based on past experience, greater influence and participation in the ITER experimental program should result when ITER begins operation.

For design and fabrication activities, what do you see as the US interest in performing the design and fabrication scope in your proposed activity?

High, particularly for the antenna. Interest in the rf sources is medium.

Indicate the nature(s) of the proposed activity:
✔ US preparations for Negotiations
✔ US preparations for the Construction Phase
✔ US preparations for the Research Phase

✔ R&D and design work
✔ Fabrication of US components/systems
✔ Preparation of tools for the Research Operations Phase
❑ Other: ____

US ITER Ion Cyclotron System White Paper

D. W. Swain[1], J. Hosea[2], D. A. Rasmussen[1], J. R. Wilson[2]

[1] *Oak Ridge National Laboratory*

[2] *Princeton Plasma Physics Laboratory*

April 29, 2003

Table of Contents

1 Executive Summary

We propose that US research institutions take a major role in the design, construction, testing, and operation of the ITER ion cyclotron system. Ion cyclotron (IC) heating and current drive systems are ubiquitous in fusion energy research. They are installed on the three major US tokamaks as well as a number of university-level experimental facilities, and are planned for proposed near-term US experiments (NCSX, QPS,…). IC systems are in use on most present international fusion experiments (e.g., JET, Tore Supra, JT-60U, W7-AS, W7-X, ASDEX-U). Ion cyclotron systems are a major component of the heating and current drive system designs for *all* the burning-plasma experiments (ITER, FIRE, and IGNITOR) studied at the Snowmass meeting in July 2002.

The US Office of Fusion Energy Science has sponsored an IC Research and Development Program (with participation by GA, MIT, ORNL, PPPL and others) for many years. It carries out R&D in direct support of present US experiments (NSTX, C-Mod, DIII-D, ET, MST) as well as doing research on advanced concepts for future experiments both nationally and internationally; for example, the US program is building and testing a high-power prototype of an advanced, "ITER-like" antenna in collaboration with the JET program. During the ITER CDA and EDA (1989 – 1998) the US was a major contributor to the design and R&D for the ITER IC system.

The ITER ion cyclotron system offers new challenges. The antenna must operate in a nuclear environment and withstand heat loads and disruption forces beyond present-day designs. It must operate for long pulse lengths and be highly reliable, delivering power to a plasma with properties that will change during a pulse. A development and testing program will be required to validate the proposed ITER antenna design, and to modify it if needed.

The US should take the lead in the design, R&D, and construction of the ITER ion cyclotron system, particularly the antenna. The US lead in this program will maintain the present capability of cutting-edge research, and will further the goal of understanding the power limits in antennas and in developing improved IC systems. It is likely to lead to increased international collaboration opportunities (e.g., on JET and Tore Supra) for testing of advanced or prototypical antennas. The results will be available for implementation on present and planned US experiments, thereby providing direct benefits to the US program.

Finally, major US participation in IC physics experiments on ITER will be much more likely if the US is responsible for the IC system. We have seen in the past that hardware delivered to international machines (e.g., IC antenna to Tore Supra, pellet injector to JET) has led to substantial US participation in experimental programs using the equipment. In addition, US rf theory support will be needed during the design, construction, and operation of the IC system as the design and operating scenarios are refined.

For these reasons, it would be to the distinct advantage of the US fusion program to be responsible for the design, R&D, modeling, and construction of the ITER ion cyclotron system, and the eventual experimental program using the system on ITER.

2 Overview of the ITER IC System

The ITER ion cyclotron (see **Fig. 1**) consists of one eight-strap antenna mounted in a horizontal midplane port; eight rf sources covering the 35-55 MHz frequency range that can deliver a total of 20 MW of IC power to the plasma, and associated high-voltage DC power supplies; and a set of transmission lines connecting the antenna to the sources, with matching and decoupling components[1]. An upgrade to a 40-MW system using antennas in two ports is possible.

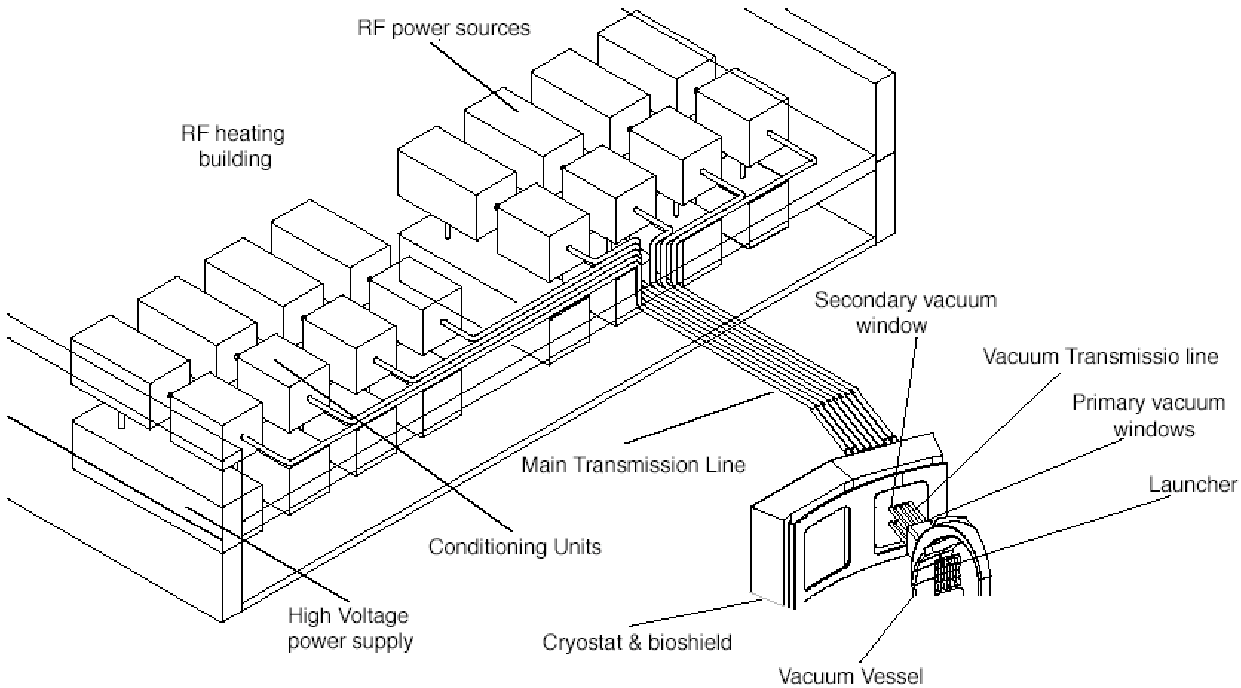

Fig. 1. General layout of ITER IC System

2.1 Physics Requirements

The IC H&CD system is designed to:

- access H mode and heat plasma at Q>10. (with preference to bulk ion heating),
- provide steady state current drive capability for DT, D, H and He plasmas, in particular to provide central current drive in high bootstrap fraction scenarios,
- accomplish several functions of plasma control, including burn and plasma transport, control by sawtooth frequency control, and current profile control,
- achieve plasma break-down, burn-through and assisted current rise at low start-up electric fields.
- conduct IC resonance discharge cleaning (ICR-DC) at full BT[2]

From the ITER Plant Description Document: [3]

> "The main heating scheme of the IC system (Table 2.5.4-1) is at the tritium second harmonic, in a 50-50% DT mixture at f = 53 MHz and B_T = 5.3 T with typical 50-50% power partition among the bulk ions and electrons. Addition of ^{3}He (< 3%) minority [DT-(^{3}He)] results in a significant increase of the fraction (up to 70%) deposited on bulk

ions. The alternative deuterium minority heating scheme is less efficient because it is in strong competition with absorption by Be and a-particles.

The frequency window for on-axis current drive is at the peak of the electron absorption (f□□6 MHz, with a central current drive efficiency of ~ 20 kA/MW). Ion minority current can be driven at the outboard q = 1 surface for the control of the sawtooth period, by setting the IC frequency to 45 MHz.

Thus the operating range □f = 40 – 55 MHz encompasses all the IC physics scenarios and allows operation at a toroidal field that is 70% of the nominal value. An extension of the range (35 to 60 MHz), could be desirable for improved flexibility, and would be possible at somewhat reduced performance.

Table 2.5.4-1 Ion Cyclotron Resonances

Resonance	f (MHz)	Comments
2□$_T$=□$_{3He}$	53	Second harmonic + minority heating
□$_D$	40	Minority heating. Strong competition of Be and □-particles
FWCD	56	On axis current drive
□$_{3He}$	45	Minority ion current drive at sawtooth inversion radius (outboard)"

2.2 Present System Design – Antenna

Antenna modules are mounted in mid-plane ports and can be remotely installed. A resonant-double-loop (RDL)[4] load-tolerant antenna with internally-adjustable (i.e., in vacuum) matching components is the present design; the concept will be tested on Tore Supra and JET.

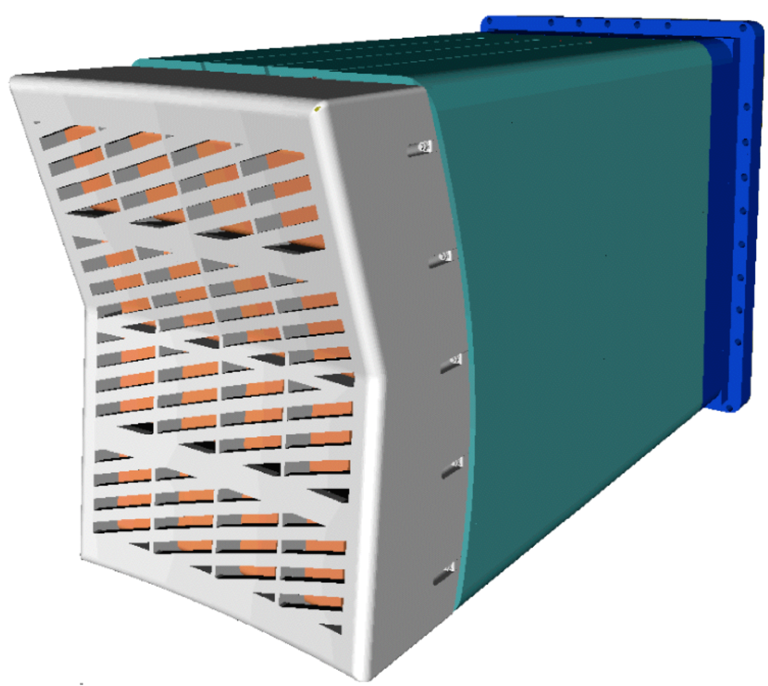

Fig. 2 Front view of antenna

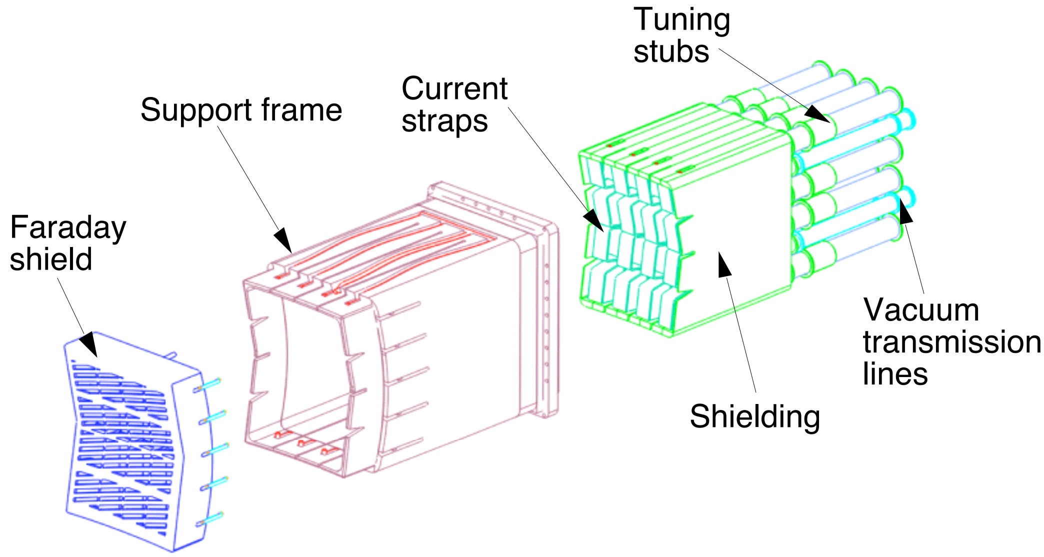

Fig. 3. Exploded view of antenna

2.3 Present System Design – Transmission Lines, Matching, and Decoupling System

The coaxial transmission lines used by the IC system are commercial items. The main transmission line is rigid coax of 280 mm OD, having a characteristic impedance of 30 Ω. The inner conductor is radiation-cooled and operates at $T_{in} < 110°C$. The outer conductor is water-cooled and operates at $T_{out} \sim 45°C$. The two conductors are coated with high emissivity material to enhance radiative thermal exchanges.

The voltage stand-off of the main transmission line is 80 kV, well in excess of the expected maximum RF voltage (< 15 kV). This large margin should provide low maintenance and a high reliability to this component.[5]

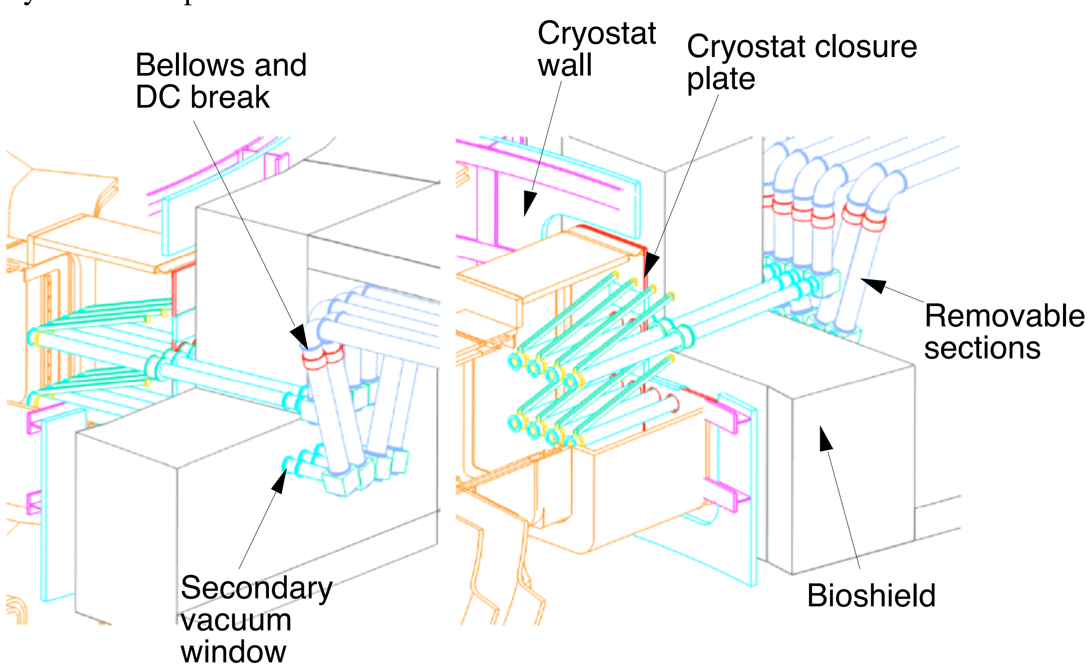

Fig. 4. Transmission line system

2.4 RF Sources and DC Power Supplies

The IC power sources are commercial multi-stage amplifiers equipped with tetrode tubes. The power source delivers at least 2.5 MW CW into a mismatched load with VSWR < 1.5. A detailed study has shown that this source can be constructed either using two existing commercial tetrodes combined in the end stages, or by a single-tube end-stage, with an upgraded anode power dissipation.[6]

3 Proposed US Program

We propose that US research institutions take a major role in the design, construction, testing, and operation of the ITER ion cyclotron system. The US could take responsibility for the entire IC system, or some subset of the components. The EU is the only other ITER participant that has expressed interest in this system, and an arrangement where responsibility would be shared between the US and EU is possible.

Based on past experience, the US has a particularly strong interest in supplying the antenna. US industry also has the capability to deliver the transmission line and matching components, and likewise the transmitters. In particular, EIMAC (a US vendor) manufactures the most powerful output tetrode in the world, one that has had good success in IC heating and current drive systems on present-day fusion experiments.

3.1 Hardware and associated R&D

The ITER ion cyclotron system offers new challenges. The antenna must operate in a nuclear environment and withstand heat loads and disruption forces beyond present-day designs. It must operate for long pulse lengths and be highly reliable, delivering nearly full power to a plasma with properties that will change during a pulse. A development and testing program will be required to validate the proposed ITER antenna design, and to modify it if needed.

Figure 5 shows an approximate schedule for the ITER IC antenna. It consists of three parts: design, R&D directly associated with the antenna, and fabrication and testing of the antenna. A substantial design effort will be required, since the designs for all the heating and current drive systems are, at best, at a conceptual level. The ITER JCT made the decision to defer detailed design until the construction stage of the project, since these could be done in that time frame without impacting the overall machine construction schedule. The schedule shown is approximate, and is based on the assumption of a 10-year delay between start of work and delivery for installation in ITER, and that work will start in 2004.

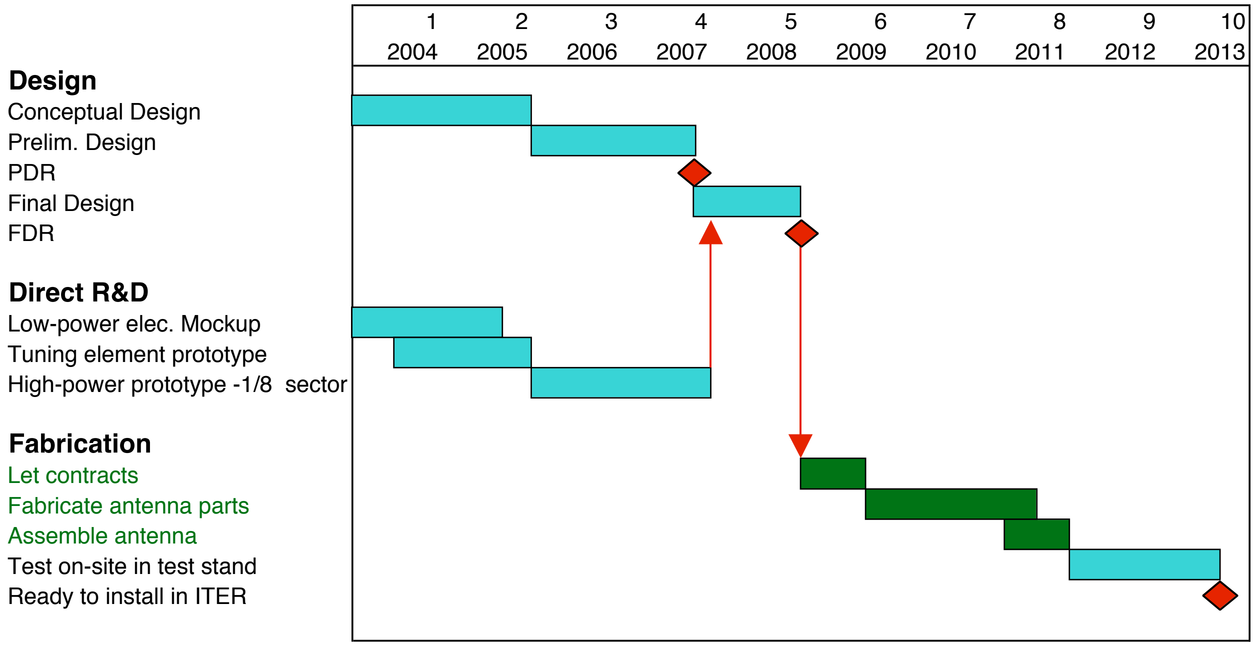

Fig. 5. Overall schedule for ITER antenna design, R&D, and construction

There are three R&D tasks that must be completed successfully before the final design of the antenna. First, a low-power electrical mockup of the antenna must be made to validate the functioning of the antenna and to optimize the design. Second, the antenna uses internal tuning mechanisms that consist of a triax cable with two independent sliding shorts. A prototype of the tuning mechanism must be designed and tested to assure that it will work. Finally, a high-power prototype antenna must be built. This will be one current strap (i.e., 1/8 of the full antenna) with the tuning mechanisms, vacuum coax and feedthrough, which will be tested under vacuum at voltages similar to those expected for ITER operation. The R&D will be carried out at US labs.

The fabrication of the antenna will be done by US industry. Once the antenna is assembled, it will need to be tested under vacuum in a test stand to assure that it can operate at specified voltage and current levels before it is delivered to ITER; this will most likely be done at a US lab.

3.2 Physics

The U.S has participated strongly in developing the ITER physics scenarios utilizing ICRF. This contribution has come both from the theory/modeling community and the experimental community. The planned ITER ICRF scenarios were arrived at with strong input from U.S. calculations and experiments. The U.S suite of codes can be applied to all aspects of the ICRF performance. Codes exist to calculate antenna performance, wave coupling and propagation, wave absorption and plasma response- driven current or flow. In many cases several parallel codes exist that best describe certain aspects of each problem. The U.S. ICRF modeling community has a demonstrated ability to work as a group to benchmark and recently through the SCIDAC initiative develop codes jointly. The U.S. experimental program has developed several of the physics scenarios proposed for ITER, particularly the second harmonic heating.

On-going experiments on the utilization of ICRF in AT regimes and for current and flow shear drive will contribute strongly to the ITER planning. Responsibility for the ITER IC system will help focus the long-term efforts of the US ion cyclotron experimental and theoretical community to:

- Demonstrate on present-day machines the main heating and current drive scenarios planned for ITER.

- Measure heating and current drive characteristics on present experiments, and explain the results using present or improved rf codes.
- Based on experimental and theoretical results, propose modifications or optimizations of the heating and current drive scenarios proposed for ITER.

4 US Expertise

The US has significant expertise in both ion cyclotron physics and technology. IC systems have been a major part of most US experiments during the last 20 years (e.g., PLT, DIII-D, TFTR, ATF, C-Mod, NSTX),. Constructing and operating these IC systems has provided an abundance of "real-world" experience. In addition, DOE has funded an IC Technology R&D program, in which issues for the long-term improvement of IC system operation are addressed. A partial list of potential participants and their areas of expertise are:

Experimental physics: Many US institutions have participated in the operation of ion cyclotron systems, including (but not limited to) GA, MIT, ORNL, PPPL, UCLA, U. Wisc.

Modeling: Many laboratories and universities have significant capability for modeling the interaction of rf waves with ITER-like plasmas. Contributions in this field have been made by researchers from Auburn, GA, MIT, ORNL, UCSD, PPPL, U. Wisc., and many others.

Technology: ORNL has carried out a technology program for DOE for years and has wide expertise. PPPL and GA have designed and built rf systems and components and likewise have valuable experience in this field.

The US has a large number of experienced rf physicists and engineers who could contribute to this work.

5 Benefits to the US Program

During the ITER conceptual and engineering design phases, the US physics and technology program priorities became significantly driven by the needs of the ITER program. Assuming that the present negotiations result in US participation in ITER again, the same outcome is likely.

It is important that the US role in ITER have a large component of high-tech activities that will position the US for significant physics responsibilities during ITER operation, as well as providing near-term benefits to the US program. Responsibility for the ion cyclotron system fills that role.

ITER-relevant R&D on both the physics and technology of ion cyclotron heating and current drive fits very well into the present US program. IC systems are in use on the three large operating US tokamaks (DIII-D, C-Mod, NSTX) as well as on several university-scale experiments (e.g., ET, CDX-U, MST), and are major components of the heating systems for the proposed US stellarators (NCSX, QPS).

In the technology area, leadership of the ITER IC effort will maintain the present cutting-edge research capability, and will further the causes of understanding the power limits in antennas and in developing improved IC systems. It is likely to lead to increased international collaboration opportunities (e.g., on JET and Tore Supra) for testing of advanced or prototypical antennas. The results will be available for implementation on present and planned US experiments.

In the physics area, carrying out the ITER-relevant research described in **Sec. 3.2** will provide the nearer-term benefit of improving the knowledge of IC operation on present-day machines, which should lead to improved operation and better experimental results on these machines.

Responsibility for the ITER IC system will encourage support of improved modeling capabilities and better codes. US rf theory support will be needed during the design, construction, and operation of the IC system as the design and operating scenarios are refined.

Finally, major US participation in IC physics experiments on ITER will be much more likely if the US is responsible for the IC system. We have seen in the past that hardware delivered to international machines (e.g., IC antenna to Tore Supra, pellet injector to JET) has led to substantial US participation in experimental programs using the equipment.; we expect the same to be true of ITER. Based on past experience, it is reasonable to expect that the US would have major responsibility for the operation of the IC system and resulting physics experiments if the US delivers the system to ITER. This will give the US physics community access to many aspects of the experimental physics program on ITER.

References

1 D. Campbell, Snowmass Viewgraphs

2 ITER Design Requirements Document, ITER doc. no. G A0 GDRD 2 01-07-13 R 1.0

3 ITER Plant Description Document, Chap. 2.5, ITER doc. no. G A0 FDR 1 01-07-13 R1.0

4 T. Owens et al., in *Proc. Sixth Topical Conf. on Radiofrequency Plasma Heating*, p. 95 (AIP Conf. Proc. No 129, 1985).

5 Ref. 3, Sec. 2.5.4.3

6 Ref. 3, Sec. 2.5.4.4