US ITER Electron Cyclotron System White Paper

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General Atomics, Calabazas Creek Research, Communications and Power Industries, Massachusetts Institute of Technology, Princeton Plasma Physics Laboratory, University of Maryland, University of Wisconsin

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1.0 Executive Summary

The purpose of this White Paper is to review the very strong and unique capability of the United States (US) to provide all components of the Electron Cyclotron Heating (ECH) system for ITER and to urge that the US supply the ECH system as a high priority for US participation in the ITER project.

The US presently has a leading role worldwide in the development of the technology and the physics for ECH and Current Drive (ECCD) in fusion plasmas. A two decade effort has developed the technology of sources of power in the 100 GHz range and the necessary transmission and launching systems to enable physics research on ECH and ECCD. Significant results have been obtained on electron cyclotron heating, electron cyclotron current drive, non-inductive tokamak operation, tokamak energy transport, suppression of instabilities, and advanced profile control techniques leading to enhanced plasma performance. The European Union, Japan, and Russia have recently demonstrated equally exciting technical advances. Perhaps the most compelling evidence for the maturation of this field of research is that ITER plans to rely heavily on electron cyclotron (EC) power, as will future advanced tokamaks, for it is the most flexible and precise plasma control technique to achieve the required plasma performance and operating regimes. The US should follow up on its pioneering history in developing EC technology and physics by supplying the EC system for ITER, particularly since the EC system will be a key tool in achieving and exploring Advanced Tokamak regimes in ITER.

The US is also in the unique position that, with the coordinated efforts of the National Labs, Universities, and Industry, a complete turnkey EC system can be supplied to ITER that encompasses the wall plug to the launching of the RF beam into the plasma. A synergism between the US RF physics research scientists, with their codes and experience, and the hardware expertise of the labs, universities, and industry, would make a fully competent team that can produce the system that is needed to support the experimental program of ITER. The US has expertise to define the EC physics requirements and address the EC technical issues. In addition during the design, development, and construction of the ITER EC system, valuable knowledge in the areas of gyrotron development and issues of compatibility with a nuclear environment will be learned. These technologies and experiences will be directly applicable to the fusion program as it proceeds to DEMO.

To support the US EC ITER program, a strong EC R&D program is needed to provide the tools and develop workable solutions for the technical challenges that are being presented by ITER and other advanced tokamaks. The physics of the advanced tokamak is pushing the EC systems to provide higher power levels at higher frequencies and pulse lengths, to deliver that power into the tokamak in a nuclear environment, and to operate with a high level of reliability. The R&D program needs to develop the gyrotrons, upgraded RF transmission line components, and the launchers to meet these more demanding performance levels.

As part of the US ITER EC program, a National EC System Test Facility should be established and built to demonstrate the performance and reliability of complete ITER EC systems under long-term operation, to test developmental components and diagnostics, and to condition the production devices for ITER.

The United States has sufficient technical capabilities to provide the entire ITER EC system. General Atomics (GA) is qualified to be the system integrator for the ITER EC system based on GA's two decades of experience in fielding complete EC systems on the Doublet III and DIII-D

tokamaks. Gyrotron development in the United States has been done by the team of Massachusetts Institute of Technology (MIT), Communications and Power Industries (CPI), Calabazas Creek Research, GA, and the Universities of Wisconsin and Maryland, and that team can develop the ITER gyrotrons. CPI can fabricate the US gyrotrons for ITER. To reduce the risk associated with the development and manufacturing of this critical EC component, multiple gyrotron vendors and institutions will participate in the development and fabrication of gyrotrons that satisfy the ITER requirements. GA has developed low loss, high power density transmission lines and other components and is the principal industrial supplier worldwide of them. Calabazas Creek Research also has expertise in EC components. GA and Princeton Plasma Physics Laboratory (PPPL) have developed state-of-the-art EC launchers. GA has a long history of designing for nuclear environments. Sandia National Laboratory has supported these developments with materials and heat transfer expertise. Additional industrial participants will be sought for the gyrotron high voltage power supplies. Details of the program and the roles of the participating institutions contributing to the US ITER EC program are provided in the following sections.

The US should supply the EC system to ITER.

2.0 Electron Cyclotron Advances

As a precision tool for experiments, electron cyclotron waves stand alone. The power absorption and driven current are localized to a volume with a diameter less than ten per cent of the plasma minor diameter. Flexible antennas can place the location of power absorption virtually anywhere it is required. Modulation of the RF power, under the command of the plasma control system in response to values of measured parameters, provides the ability to tailor target plasmas for experimental requirements. Modulation also enables time dependent energy deposition at specific plasma locations for direct measurements of transport. Although usually considered a method for control of the temperature of the plasma electrons, the well known density pumpout effect can be used to provide limited density control using electron cyclotron heating.

Recent experiments made possible by advances in the production of high power millimeter waves have shown that electron cyclotron heating and current drive (ECH and ECCD) will be critical elements in the next generation of magnetic fusion devices leading to power producing reactors. One of the earliest successes of electron cyclotron current drive was the mitigation of the sawtooth instability. ECCD has recently been used to suppress both the m/n=3/2 and 2/1 neoclassical tearing modes. The H-mode regime has been accessed using electron cyclotron heating only. ECH has produced internal and extremely steep pressure gradients with substantial bootstrap currents. Current profile control enabling high performance tokamak operation has been demonstrated. The high power sources for these millimeter waves, gyrotron oscillators, are capable of continuous operation, which becomes a significant factor for reactor-relevant fusion plasmas with long current penetration times and quasi-continuous operational scenarios.

Major electron cyclotron heating and current drive installations are in place at seventeen fusion laboratories worldwide, with several more being planned, testifying to the importance of these systems in international magnetic fusion programs. The physics of electron cyclotron heating and current drive are well understood and have been verified experimentally. Ray tracing and Fokker-Planck codes provide well benchmarked predictive capability for experiments. Coupling from the propagating electron cyclotron waves to the plasma imposes no special requirements on the edge plasma and can be done continuously. The density cutoff at 170 GHz in ITER will be about $3.5 \times 10^{20}/m^3$, which is well above the planned operational densities for the device.

The US gyrotron development program began in 1975 and proceeded approximately in parallel with similar work in Russia. By 1980 a 28 GHz gyrotron had been produced by Varian (now CPI) which operated continuously at 212 kW of generated RF power. A ten gyrotron 60 GHz complex consisting of 190 kW, 0.5-1.0 sec Varian units was installed on the DIII-D tokamak in 1986. The present CPI 110 GHz production tubes are rated at 1.0 MW for 10 sec pulse length and have been tested to full power for 5 sec pulses at 32% RF generation efficiency. The US program, funded by the DOE, is now developing a 1.5 MW, 110 GHz depressed collector gyrotron having 50% efficiency for eventual application on DIII-D. That tube would be the forerunner of the ITER gyrotrons. The European program has recently operated a 140 GHz gyrotron for 3 minutes at 892 kW generated RF power and more than 15 minutes at 540 kW. Gycom in Russia and JAERI/Toshiba in Japan are also producing 1 MW gyrotrons in the 100 GHz range with several second output pulses.

Fusion will require extremely reliable heating and current drive systems. Overall reliability of gyrotron systems now is approaching that of the more mature neutral beam systems. New development work is increasing the unit power for gyrotron oscillators above the 1 MW level. Simultaneously, the RF generation efficiency is being increased from >30% to >50% through the use of electron beam energy recovery in depressed collectors. Extremely efficient transmission lines with the necessary ancillary components are available, which permit the gyrotrons to be located some distance from the fusion device without appreciable compromise in overall system performance and with very small tritium contaminated volumes. Intensive international development efforts and the experiments to exploit these tools have pointed to ECH and ECCD as major program elements in magnetic fusion research.

3.0 ITER EC System Overview

3.1 ITER EC System Design Description

As described in the ITER Plant Description Document, 20 MW at 170 GHz is to be available for injection into ITER at the start of operations. The configuration of the ITER EC System is shown in Fig. 1.

This power can be connected to two types of launchers. The equatorial launcher, which is mainly used for heating and current drive, has 24 input waveguides. Using three mirrors, it has the capability to toroidally steer the RF beams in groups of eight. Three upper launchers are primarily used for stabilization of neo-classical tearing modes by ECCD. Each uses four mirrors to steer eight RF beams poloidally, focusing the beams at resonant flux surfaces vertically offset from the magnetic axis. The 20 MW of EC power is switched between the equatorial launcher and the upper launchers by changing waveguide connections. In addition, 2 MW at 120 GHz is needed for plasma start up. This power is transmitted by three waveguides to the equatorial launcher and the switching between 120 GHz and 170 GHz can occur during the plasma discharge.

Each gyrotron is to be capable of 1 MW steady-state with an RF generation efficiency of ~50% using depressed collector geometry. The RF transmission system uses water-cooled corrugated circular waveguide and other components. The total line lengths will vary between 70 meters and 100 meters. With an expected RF transmission loss of 20%, twenty four 170 GHz gyrotrons and three 120 GHz gyrotrons are required to deliver 20 MW and 2.4 MW of injected power at 170 GHz and 120 GHz, respectively. Regulated and adjustable high voltage DC power supplies provide the electric power to the gyrotrons. Each gyrotron unit has normal and superconducting magnets with their respective power supplies, support systems, water cooling, and instrumentation and control systems.

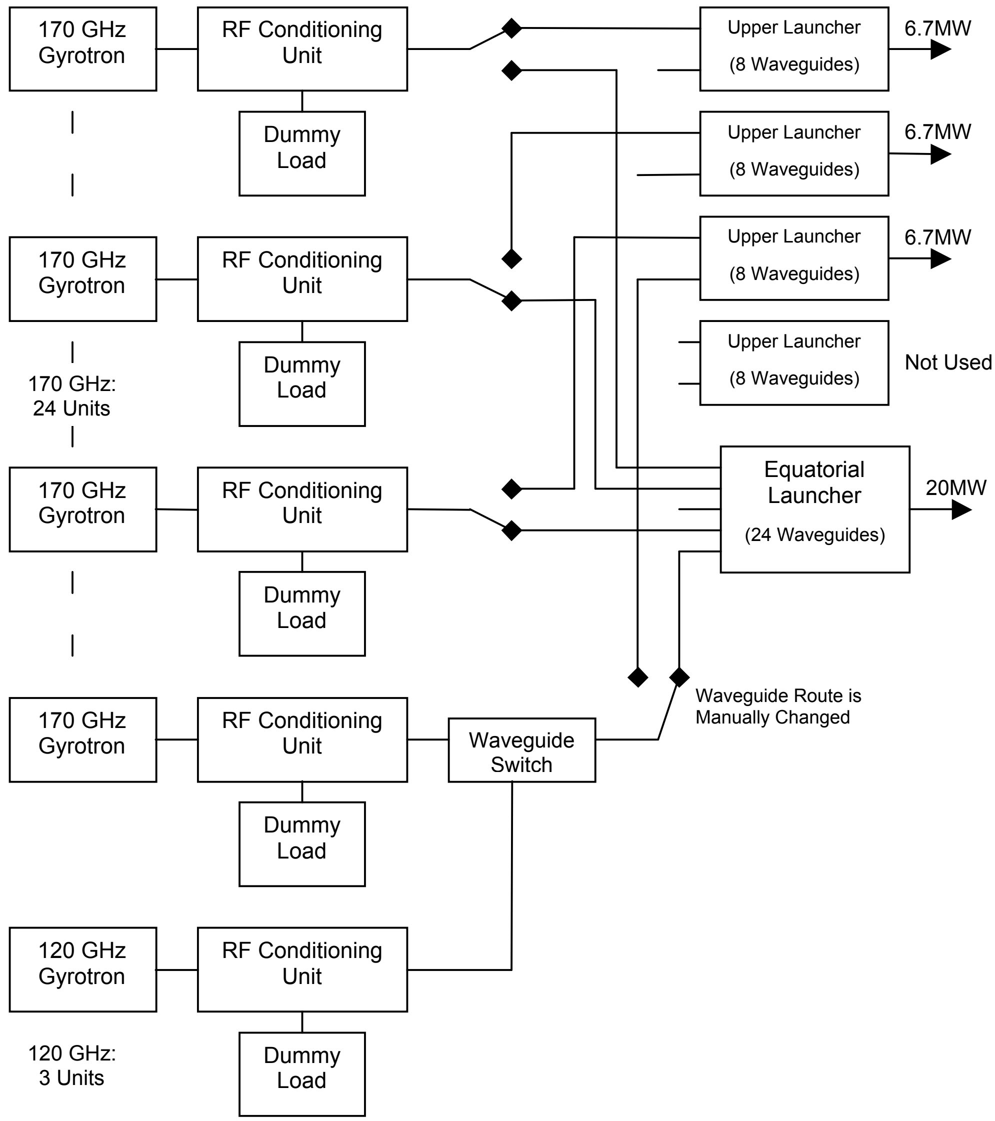

Figure 1: ITER EC System configuration

3.2 ITER Plan

Figure 2 shows several ITER milestones leading to the start of ITER plasma operations. ITER is currently in the site-selection process, with the site expected to be chosen by July 2003. The start of construction at the selected site will depend on when the license to construct is issued by the regulatory authority, which may take up to two years. From this point, the ITER plan allots eight years for construction, assembly, and commissioning of ITER and to achieve the first H-plasma milestone. This would occur by the end of 2013. According to the ITER plan, the design and tooling for a prototype 170 GHz gyrotron would begin early in 2008, with fabrication of the 24 production 170 GHz gyrotrons to begin in 2010. This requires the development of a gyrotron that meets the ITER requirements be completed prior to the prototype. Because of the long-term testing needed to demonstrate the reliable performance of these gyrotrons, the development needs to begin as soon as possible, as shown on the schedule in Figure 2.

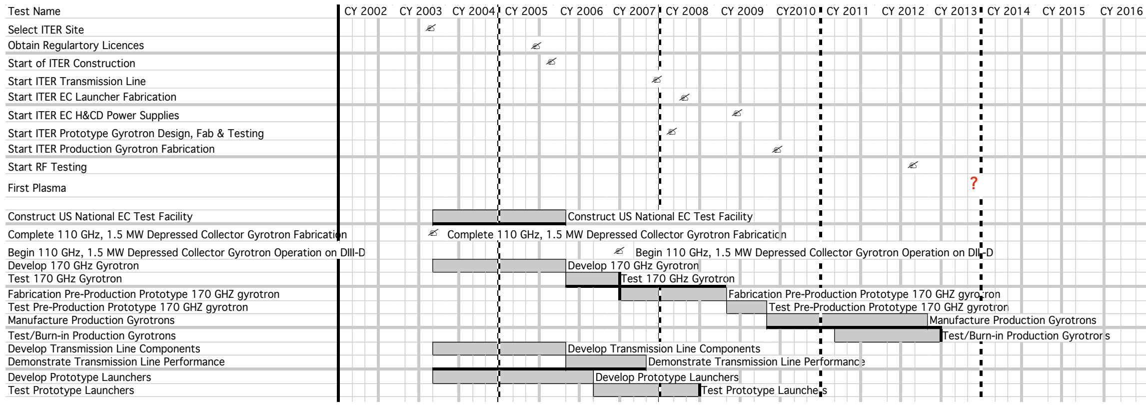

Figure 2: ITER Plan and US ITER EC Schedule

The US is currently developing a 110 GHz, 1.5 MW gyrotron with a depressed collector. The first article is scheduled to be completed by the end of calendar 2003. The US would then be in a position to immediately start the development of the ITER 170 GHz gyrotron. At the same time, the US should begin to construct a dedicated facility to perform long-term testing of these developmental gyrotrons, as well as other ITER EC developmental components. Following the schedule shown in Figure 2, the US would be able to develop the gyrotron, prototype launchers, and other EC components and subsystems to meet the ITER construction schedule.

Therefore, in order for the US to maintain its leading role in EC system physics and technology, the US needs to expand its R&D program and to construct a dedicated facility to perform long-term testing of EC gyrotrons, components, and subsystems. Using these tools and refining the physics requirements for the ITER EC system as the results come from existing experiments, the US can design, fabricate, test, and deliver a turnkey EC system to ITER that will best meet the requirements of ITER and advance the EC system performance for future advanced tokamaks.

4.0 ITER EC R&D

The US R&D program has been making steady but slow progress in gyrotron development that was needed for the near term experimental programs. A US ITER R&D program needs to quickly develop the solutions for the technical challenges that are being presented by ITER and other advanced tokamaks.

4.1 Gyrotron R&D

The physics requirements for the advanced tokamaks are pushing the gyrotrons to operate at higher power and higher frequencies. These gyrotrons need to generate the RF power more efficiently to reduce system cost (from reduced power supply and cooling requirements) and to alleviate thermal-mechanical design issues for the collectors of these tubes. Also, if the same power can be delivered to the tokamak with fewer gyrotrons, generating 1.5 MW or 2 MW, instead of 1 MW per tube, significant cost savings can be achieved.

Within the Virtual Laboratory for Technology, the US has a consortium of universities and industries for gyrotron development, including CPI, MIT, GA, the University of Wisconsin, the University of Maryland, and Calabazas Creek Research (CCR), with MIT serving as ECH Technology program leader. This consortium is currently developing a 1.5MW, 110 GHz gyrotron with a depressed collector. As part of the gyrotron development effort, this consortium has been working to improve the ability to design gyrotrons. For example, very promising computer codes have been developed and are being refined to design the RF cavity, launcher, mode converters, and mirrors of the 110 GHz and 140 GHz gyrotrons at power levels up to 1.5 MW. A test stand at MIT can test these geometries at short pulse lengths to verify proper modes of oscillation, power level, frequency, RF output beam quality, and efficiency. The synergism between these codes and the test stand affords the opportunity to more efficiently define the RF design of a gyrotron and test it, thereby validating the RF design of the gyrotron prior to fabrication of a complete cw gyrotron. The development of these tools needs to continue so that the predicted performance is consistent with the test stand performance and to better understand the variations in performance resulting from variations in geometries.

As the gyrotrons are pushed to higher power levels and to cw operation, cathodes with higher current capability and with improved uniformity need to be developed. Improved thermal-mechanical designs are needed to handle the higher power dissipation in the collector and other internal components of the gyrotron. Once the RF energy has been extracted from the electron beam, the design codes that are being developed to model the spent electron beam and production of secondary electrons need to more accurately track the power deposition in the collector. The depressed collector technology being developed in the R&D program needs to be expanded. Both single stage and two-stage depressed collector designs need to be developed and tested to further improve the efficiency of the gyrotron and reduce the thermal loads on the collector.

4.2 Transmission Line Component R&D

The components of the RF transmission lines need to be able to transport the power from the gyrotron to the launcher reliably at higher power levels, and essentially continuously. Since the operation is approaching cw for these EC systems, instead of pulse lengths of a few seconds, all components will need to be water-cooled and these designs and techniques need to be developed and demonstrated. Very low loss components such as waveguides can be cooled either by natural convection or possibly with forced air. Other components such as miter bends and waveguide switches already incorporate water cooling. DC breaks, pump-out tees, and CVD diamond transmission line windows will need to have design modifications to incorporate water-cooling to assure reliable cw operation. An entire prototypical ITER transmission line should be built and operated to demonstrate that all components function as expected in the ITER environment. GA pioneered the use of corrugated waveguide transmission lines for EC systems. Evacuated corrugated waveguides and other waveguide components were first designed and fabricated by GA for use on DIII-D. The international fusion community quickly recognized the advantages of this approach for high-power low-loss transmission of microwaves over long distances. GA has fabricated and delivered corrugated waveguide transmission lines, not only for DIII-D, but also for fusion devices in Japan (JT-60U at Naka, LHD at Toki, TRIAM-1M at Fukuoka), Europe (TCV at Lausanne, Tore Supra at Cadarache, FTU at Frascati) and Australia (H-1NF). Building on this extensive experience, GA can perform the remaining development work needed for ITER transmission lines.

4.3 Launcher R&D

Both GA and PPPL have designed launchers for the DIII-D EC system that provide steering for pulse lengths up to ten seconds. However, the launchers of ITER and future machines present additional technical challenges that must be overcome. Existing launchers have inertial cooling, but future launchers must be designed to provide the proper cooling for cw operation. Due to the neutron fluxes, the designs must include neutron shielding and the need for remote handling of the launchers for maintenance and repair, as well as address the degradation of material properties under intense neutron exposure. The moving parts for steering the RF beams must be designed to withstand the hostile environment, or alternatively, removed from the hostile environment. This latter approach, called remote steering, was conceived by General Atomics and has been under development by GA in collaboration with JAERI over the last five years. This design is considered in the ITER-FEAT final design document as one of the design options for the ITER upper launchers, and it is also being considered by JAERI as the design for equatorial launchers. GA has built one low power and two high power launcher apparatuses to demonstrate the physics, fabrication, and performance issues of the concept, and as a result is the leading organization in developing the concept. Because of the clear advantages of this remote launcher concept for ITER, the University of Stuttgart in Germany has also built prototype low power remote steering launchers to demonstrate the physics principles.

PPPL has successfully designed and built EC launchers in use on DIII-D that steer two 800 kW RF beams over a range of ±20° poloidally and ±20° toroidally (well within the ITER requirements), but limited to pulse lengths of ten seconds every ten minutes, owing to inertial cooling limits. PPPL, through applied R&D efforts, can take this concept and apply it to the ITER requirements, including the effort to make it compatible with the neutron and plasma environment. GA can complete the development of the remote steering launcher for ITER, including the design changes to make it compatible with the ITER neutron, thermal and stress environment. In addition, a methodology for testing the RF performance of either of the launchers needs to be developed.

4.4 Diagnostics R&D

Improved diagnostic capability and techniques need to be developed for calorimetry and for RF power measurements. This is especially important for the determination of the RF power delivered to the tokamak, where this measurement needs to be very reliable, stable, and accurate for long periods of time.

New and improved diagnostics need to be developed to determine the RF and thermal performance of the gyrotron windows under even higher RF power levels, to measure the RF profile and mode purity of the RF beam exiting the gyrotron, and to measure the RF profiles of the multiple beams from the launchers.

Highly reliable arc detectors need to be developed to rapidly turn off the RF power should arcs occur anywhere along the RF transmission system, especially near the diamond windows of the gyrotron and at the ITER vacuum vessel, and in the launchers.

5.0 National EC System Test Facility

The National EC System Test Facility would perform fully integrated testing of complete EC systems, as well as test developmental components. This facility would have the capability to operate multiple gyrotrons simultaneously. The facility would be designed with and test ITER, or ITER-like, components and subsystems, such as the power supply and control system architectures simultaneously operating multiple gyrotrons. It would test developmental and prototype gyrotrons, RF transmission line components, prototype launchers, and diagnostics and new measurement techniques. It would perform long-term testing of these components to demonstrate cw power handling and reliability. The facility would validate the performance of a fully integrated ITER EC system prior to ITER commissioning and operation, and can burn in the production gyrotrons before being put on line at ITER. This facility can also train EC system personnel for ITER and other facilities. Besides directly supporting the US ITER program, the facility would support future advanced tokamaks and the EC community by continuing the development and performance enhancement of EC components.

This facility can be colocated at the DIII-D National Fusion Facility. The synergism between these two facilities would more rapidly advance the EC technology for the fusion community. The National EC System Test Facility can profit from the experience of more than 15 years of EC system operations at DIII-D. Some of the infrastructure already at DIII-D can be shared with the EC Test Facility, such as AC power and water cooling systems. In addition, a 170 GHz EC system can heat the high performance plasmas in DIII-D at the third harmonic. This would afford the opportunity to have a demonstration of full operation and control of a prototype ITER EC system into a plasma prior to operation of the EC systems at ITER.

6.0 US ITER EC Program

The following sections describe a US ITER EC program and its organization.

6.1 US ITER EC Organization

Figure 3 presents a diagram of the organization for the US ITER EC H&CD program. GA, using its extensive management experience on a wide range of high technology programs, can direct the integration of the EC system, drawing from its leadership role in EC physics and its experience in EC system operation. GA can lead the development of the physics requirements for the EC system with the support of the EC community. In addition, GA can coordinate the ITER R&D, integrate the hardware designs, and oversee the fabrication of the various components and subsystems for the ITER EC system.

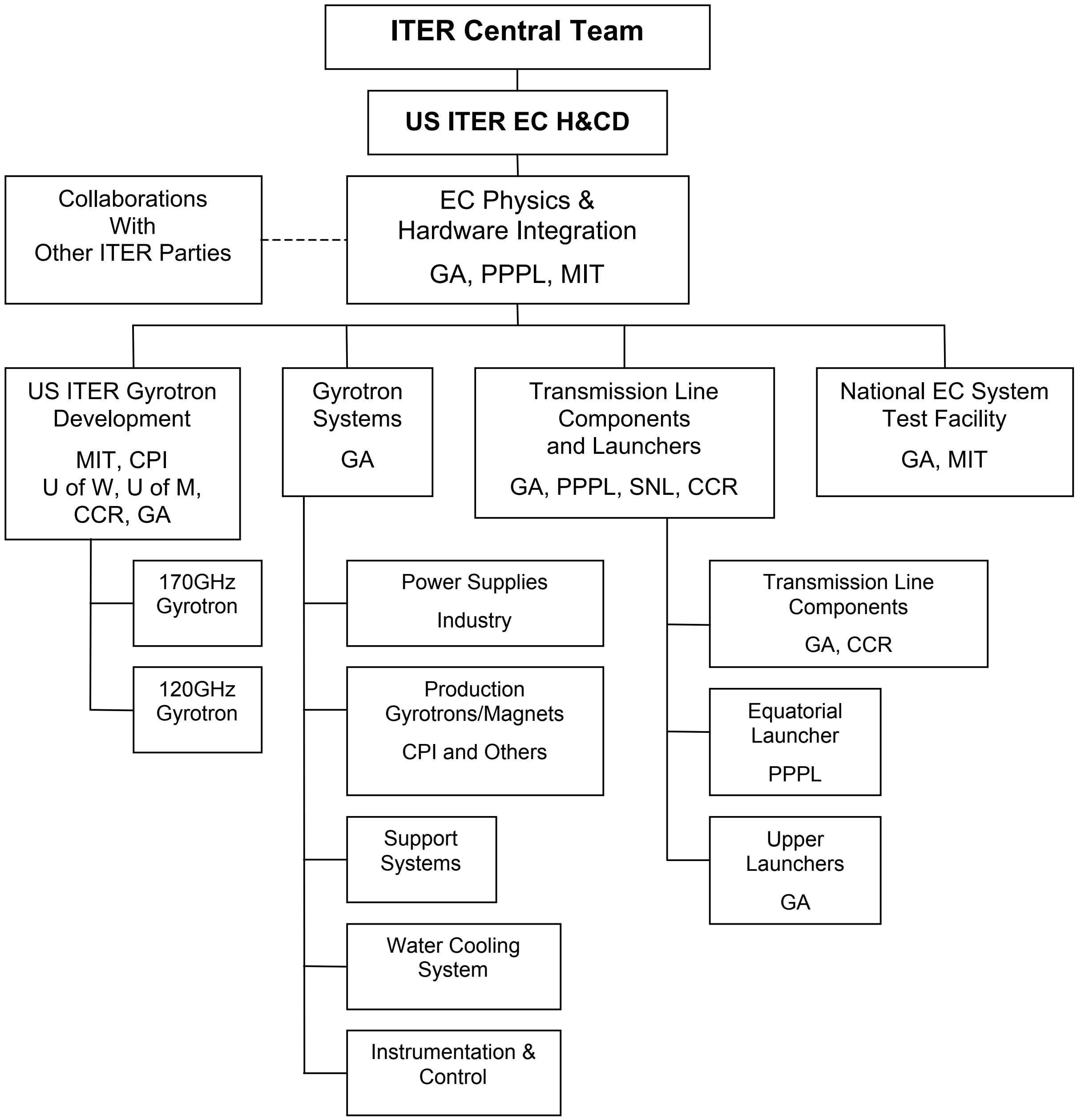

Figure 3: US ITER Program Organization

As a world recognized expert in the design and manufacturing of EC RF transmission line components, GA can develop and fabricate the components for the ITER RF transmission lines.

Some specialized components can be supplied by other institutions, such as dummy loads from Calabazas Creek Research. In addition, GA may perform the development of the upper ITER launchers.

The talents and expertise of several national labs, universities, and industries are to be brought together to carry out the US ITER program.

The present US Gyrotron Development Program, a university-industrial team, can develop the ITER gyrotrons under the US ITER EC Program. This team includes MIT, the University of Maryland, the University of Wisconsin, Calabazas Creek Research, GA, and CPI, the manufacturer of the gyrotrons. This team has been developing the gyrotrons for the fusion program for the past twenty years.

PPPL can perform the development of the equatorial launcher for ITER. PPPL has been an important contributor in this effort, having designed and fabricated the steerable launchers now in use on DIII-D.

Sandia National Laboratory (SNL) can provide support in the areas of materials and high heat flux.

The following subsections describe the breakdown of the program in more detail.

6.2 Physics and Hardware Integration

A critical function is the integration of the EC physics functional requirements with the performance requirements of the EC hardware. GA, PPPL, and MIT can provide this leadership role in EC physics. This group will define the physics requirements and review the hardware designs to ensure that they meet the physics requirements. Many issues need to be properly addressed while defining these requirements, such as the power levels and steering capability required for heating, for plasma control, and for transport diagnosis so that the correct set of EC tools are available for the physics team.

6.3 ITER Gyrotron Development

Under the leadership of MIT, the university-industrial consortium, consisting of MIT, CPI, University of Maryland, University of Wisconsin, Calabazas Creek Research, and GA, has been developing gyrotrons and can develop the US 170 GHz gyrotron and the 120 GHz gyrotron for ITER. Initial testing of the gyrotrons to full power will occur at CPI. The long-term testing and performance evaluation will occur at the National EC System Test Facility.

6.4 Gyrotron Systems

6.4.1 Gyrotron Power Supplies

Test Facility power supplies will be developed and built with an architecture equivalent to that of ITER and suitable for the operation of multiple gyrotrons. They will use advanced solid-state high voltage designs. GA can take responsibility for the overall power system architecture integration and specification, drawing upon its diverse power system experience, especially its experience with similar power supplies for the Accelerator Production of Tritium Project. The various power supply subsystems will be competitively procured from industry to performance specifications. The designs and their performance will be proven in the National EC System Test Facility. These designs will be scaled up for the production power supplies of ITER and procured from industry for installation at the ITER site, incorporating appropriate design changes based on the operational experience at the Test Facility.

6.4.2 Production Gyrotrons

To reduce the technical and schedule risks, it is very likely that there will be multiple vendors for the production 170 GHz gyrotrons. Since only three 120 GHz gyrotrons are needed, these will likely come from a single vendor. It is envisioned that the US gyrotron vendor will produce a portion of the production gyrotrons, but not all of them. Pre-production prototype gyrotrons from the various ITER gyrotron vendors will be tested at the EC System National Test Facility prior to the fabrication of the production units. The production gyrotrons will be conditioned at the Test Facility and delivered to ITER.

6.4.3 Support Systems

The support systems mechanically support the gyrotron and magnet and provide the oil insulation for the cathode of the gyrotron, if required. The procurements will be a build-to-print.

6.4.4 Water Cooling Systems

The water cooling system consists of the manifold that distributes low conductivity water to the various water cooling circuits of the gyrotron, RF transmission line and dummy loads. It contains the necessary water cooling sensors and interlocks. These will be procured as a build-to-print.

6.4.5 Instrumentation & Control

The instrumentation and controls will provide the control and monitoring circuitry for the various gyrotron systems, such as the gyrotron and the magnet power supplies, RF transmission lines, water cooling system, and operation control of the gyrotron power supply. The control system will be developed to comply with ITER standards and architecture.

6.5 Transmission Line Components

Because of the unique and in-depth design and fabrication experience GA has in supplying corrugated transmission line components to facilities all over the world, GA can perform the development of the RF transmission line design for ITER. ITER prototype lines and components will be tested at the Test Facility to demonstrate long-term power handling capability and reliability, validate RF losses, and confirm cooling under cw power transmission. The performance of the specialized RF diagnostics and measurement techniques will be demonstrated. GA can subsequently fabricate and deliver the production components of the RF transmission lines to ITER. Expertise at other institutions can be drawn upon for the development of specialized components, such as 1 MW cw loads by Calabazas Creek Research.

6.6 Launchers

The US ITER EC program will develop, build and test a prototype section of the equatorial launcher and a prototype for the remotely steerable upper launchers compatible with the nuclear environment to which the launchers will be subjected on ITER. The testing will demonstrate the required remote maintenance and handling features of both designs. RF power testing will be performed to demonstrate cw power handling, cooling, and directional control of RF beams, and to measure RF profiles. The launchers for ITER will be scaled up from the prototypes and fabricated as a build-to-print. Their performance will be demonstrated prior to delivery to ITER.

In PPPL, GA, and Sandia, the US has the capability to develop and deliver the launchers to ITER. PPPL has the experience developing and fabricating the dual EC launchers for the DIII-D tokamak that can independently steer two RF beams both poloidally and toroidally. GA has been and continues to develop the remote steering concept for the EC launchers in collaboration with JAERI for application to ITER. The ITER design report has identified this concept as being attractive for the upper launchers on ITER. GA brings the needed expertise for the development of designs compatible with the neutron environment on ITER, and to address the remote handling issues. Sandia has extensive expertise on material properties in neutron environments which will be critical for the long-term performance of the designs.

7.0 Expertise

The US has the expertise to define the physics requirements and to solve the technical issues.

General Atomics	EC physics EC system design and operation Project management and integration RF transmission line component fabrication High voltage power systems Nuclear designs Remote handling designs
Calabazas Creek Research	Depressed collector Dummy loads Improved cathode performance Gyrotron RF design RF mirror design and optics
Communications and Power Industries	Gyrotron design, fabrication, and testing
Massachusetts Institute of Technology	Gyrotron design Gyrotron RF design testing and validation Gyrotron prototype testing RF mirror design and optics Transmission line design Oversight of Industrial Gyrotron Development
Princeton Plasma Physics Laboratory	RF launcher design and fabrication
Sandia National Lab	Materials High heat flux expertise
University of Maryland	Gyrotron cavity and operational theory Depressed collector theory and design
University of Wisconsin	RF mirror design and corrective optics Transmission line design

8.0 Benefits to US Fusion Program

The US can deliver a turnkey system to ITER. By capitalizing on decades of US investment, the US can continue to advance the application and the understanding of electron cyclotron power to fusion plasmas. The US is ready and able to develop the EC systems and hardware components that are responsive to the physics requirements of ITER and in doing so be prepared to address those of the future advanced tokamaks. This will be critical to the performance of future tokamaks, which will rely more heavily on EC power for plasma heating and control.

Because of the development of the designs and testing of the ITER EC components, computer codes will continue to be improved and developed to aid in the designs, as well as building up the capability to validate the designs early in the design and development process. For example, an improved capability for the design and validation of the RF performance of a gyrotron will yield functional gyrotron designs more efficiently, in less time and at lower costs, and with reduced technical risk. The construction of a National EC System Test Facility will give the US a dedicated test facility that can support existing and future experiments. Such a facility can test EC systems and components thereby ensuring their proper performance. The expertise will be developed to use these tools and to be able to address the future demands that will be placed on the EC systems.

Improved EC system capability and performance will result from the proper integration of the gyrotron, power systems, RF transmission lines, launchers, and controls. Advanced, more efficient power supplies will be developed, exploiting the advances in high power, high voltage solid-state devices. Proper coupling of the higher power gyrotrons to the RF transmission system will be demonstrated, as well as reliable, lower loss transport to the tokamak using improved EC RF transmission line components. Improved launchers will be available to handle high power continuously, as well as be compatible with fusion reactor environments, such as in DEMO. These launchers will be remotely handled and maintained, and their development will expand the knowledge base and expertise necessary to develop future designs.

As a result of the US rejoining ITER, there will be an increase in the technology base that will not only benefit the EC program, but also have applications elsewhere. For example, the development of advanced solid-state high voltage power supplies will have many applications. The advancement of the technology for high power collectors, and in particular for depressed collectors, will benefit many high power tubes in the future.

9.0 Summary

With the coordinated efforts of the National Labs, Universities, and Industry, the US has the unique capability to design, fabricate and deliver a turnkey EC system to ITER. If the US chooses to rejoin ITER and negotiate to perform this task, valuable knowledge in the areas of EC system performance, gyrotron and EC component development, and on the issues of compatibility with a nuclear environment will be learned. This capability and expertise will be directly applicable to the fusion program as it proceeds to DEMO.

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