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Planning for U.S. Ion Cyclotron Heating Research Relevant to the Compact Ignition Tokamak and Alcator C-Mod

D. W. Swain
J. J. Yugo

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EXECUTIVE SUMMARY

The Compact Ignition Tokamak (CIT) will need 10 to 20 MW of auxiliary heating power to achieve ignition, based on H-mode confinement scaling. Ion cyclotron heating (ICH) has been selected as the primary means of supplying the required power. Substantial research has already been done on ICH in tokamak plasmas, and heating results comparable to those observed for neutral beams have been observed in PLT, JET, ASDEX, JFT-2M, and other devices.

However, the use of ICH on CIT will require the extension of parameter space beyond the regimes used heretofore in ICH experiments, notably in radio frequency (rf) power flux through the antenna and in the heating of a diverted plasma operating in the H-mode. Significant development and technology (D&T) research and applications on large confinement experiments are necessary to ensure the reliable and successful operation of ICH on CIT.

Table E-1 lists issues for CIT that must be studied on large tokamaks and the machines that can address them (only existing or approved experiments are included). Of the machines listed, C-Mod is clearly the most relevant; its density and magnetic field are very close to those of CIT, it can operate with an H-mode diverted plasma, and it uses a high-power-density, compact launcher. Relative to CIT, the main drawbacks of C-Mod are its inability to operate in the He^3/D minority heating mode, unless radiation shielding is added, and the probable lack of definitive ICH results before late 1990. However, results from C-Mod will still be available in time to allow for any needed modifications of the ICH system on CIT.

To obtain information on ICH in H-mode diverted plasmas prior to C-Mod results, the U.S. program will have to rely on results from foreign experiments, notably JT-60, JFT-2M, JET, and ASDEX. The possible exception to this would be operation of the DIII-D machine with ICH, which could be done at the 2-MW level by about May 1988.

A unified research and development program combining D&T work with confinement experiments on C-Mod and CIT is proposed. The plan indicates that a logical path of testing CIT prototype components on C-Mod, with possible subsequent modification/improvement before installation on CIT, is possible. However, sufficient resources must be allocated to the activities required in FY 1988 if the program is to be accomplished on schedule.

Table E-1. Suitability of U.S. and foreign machines to address critical issues
(includes only existing or approved programs)

		Issue					
Machine	Estimated experiment date	Compact launcher	Effect of high rf power flux on impurities (MW/m^2)	High-density operation (fraction of CIT density)	H-mode, diverted	He^3/D-mode operation	Resistance to disruption forces
CIT	11/93	X	X(14)	X	X	X	X
C-MOD	7/89	X	X(17)	X	X		X
TFTR	8/87	X	X(10)			X	
TEXTOR	4/87					X	
JET	6/87				X	X	
ASDEX	1/87		X?(8)		X	X	
ASDEX-UP	1/89			X(0.48)	X	X	
TORE SUPRA	3/88	X	X(13)			X	
JIPPT-2U	86			X(0.34)			
JFT-2M	4/87	X	X(20)		X		
JT-60	12/87	X	X(25)		X		

1. INTRODUCTION AND BACKGROUND

Ion cyclotron heating (ICH) has been chosen as the primary method for providing auxiliary heating power to the plasma in the Compact Ignition Tokamak (CIT). Sustained progress in ion cyclotron range of frequencies (ICRF) heating experiments, together with supporting technology development, continues to justify selection of this technique as the preferred one for heating CIT to ignition. However, the CIT requirements are sufficiently different from existing achievements that continued experimentation and development are needed to meet the goals of the CIT experiment with a high degree of reliability.

1.1 PURPOSE AND ASSUMPTIONS

The purpose of this report is fourfold:

1. to review briefly the physics and technology research and development (R&D) needs for ICH on CIT,

2. to review the status of and planned programs for ICH on U.S. and international machines,

3. to propose a unified "mainline" R&D program specifically geared to testing components for CIT, and

4. to assess the needs for experiments including C-Mod, the Tokamak Fusion Test Reactor (TFTR), and DIII-D to provide earlier information and improved probability of success for CIT ICH.

This report is based on the following assumptions.

1. CIT will be built on a schedule that achieves first plasma operation in late 1993. Although some slippage in this schedule is likely, it will not cause a qualitative change in the program logic; rather, it will simply stretch out the time period involved.

2. C-Mod will achieve first plasma operation in mid-1989, with six months of ohmic heating (OH) checkout and startup. Definitive high-power ICH heating data in a diverted H-mode plasma is unlikely to be available before mid-1990.

3. The TFTR ICH program, with fast-wave heating power up to 10 MW, will be carried out. However, the goals of the program on TFTR are to enhance

> the possibility of attaining $Q = 1$ in the deuterium-tritium (DT) phase of operation. Although information of value to the CIT program will undoubtedly come out of the TFTR program, significant TFTR experimental time will not be dedicated to answering CIT-relevant questions.

This report specifically addresses the issues and plans for ICH on CIT. It does not discuss possible plans for electron cyclotron heating (ECH) and assumes that the near-term goals of the ICH program should be geared to providing information to ensure success of the CIT experiment.

1.2 NRFD PROGRAM PLAN

In 1982, the National RF Technology Research and Development Program Plan was compiled at the request of the U.S. Department of Energy, Office of Fusion Energy (DOE/OFE) Division of Development and Technology. This plan, developed by the Plasma Technology Section of the Fusion Energy Division (FED) at Oak Ridge National Laboratory (ORNL), contains detailed descriptions of technology requirements for systems for ICH, ECH, and lower hybrid heating (LHH). The technical issues identified at that time remain largely correct. However, that report was aimed primarily at the requirements for an engineering test reactor (ETR) and beyond. These long-range goals are still valid, but introduction of the CIT as a major element in the U.S. fusion plan forces a different emphasis to be placed on the near-term ICH program. The experimental program required for CIT is modified from that for ETR by changes in experimental parameters (e.g., density, frequency, magnetic field) and by recent experimental results (e.g., ICH coupling to H-mode, diverted plasmas).

1.3 DOE WORKSHOP, APRIL 1985

In April 1985, DOE/OFE sponsored a workshop to discuss ICRF development needs for CIT. A series of presentations dealt with the status of ICRF physics and technology, the requirements of an ICRF heating system for CIT, and proposed near-term programs to address the outstanding issues. A panel consisting of J. C. Hosea (PPPL), M. Porkolab (MIT), J. Rawls (GA), and D. W. Swain (ORNL) summarized the major physics R&D requirements for CIT:

> "The following physics R&D is needed to increase the confidence level in the success of the ICRF heating of a compact ignition device, and to support the design of such a heating system. In all cases, data gained at densities in excess of 10^{14} cm^{-3} at temperatures in excess of 7 keV, and for plasma dimensions and configurations comparable to those of the compact ignition device, is of greatest relevance.

- Accelerate experimental and theoretical research to optimize coupling at the plasma-antenna interface and to improve rf power deposition profiles and associated heating efficiencies, while maintaining or improving plasma stability. (The latter may be achieved by supplementary rf techniques such as ECH or LH.)

- Initiate studies on coupling in plasmas limited by divertors where the edge plasma conditions in the scrape-off layer may be significantly different from those in conventional limiter discharges.

- Intensify efforts to pinpoint what, if any, impurity generation effects are ICRH-specific. Focus on varying the edge boundary conditions, the discharge duration, and the wave power spectrum; determine the implications for launcher design and/or limiter/divertor design.

- Expand the data base on energy confinement with high power ICRF-heated discharges, with emphasis on scaling with density, current, field, and heating power."

The report emphasized the rf technology R&D that was needed, including a program to develop and test launchers at the requisite power levels and power fluxes in a suitable tokamak environment; an aggressive materials and testing program for Faraday shields to eliminate launcher-generated impurities; and long-pulse, high-frequency, high-field experiments (if possible) in the presence of high heat and neutron flux from the plasma.

The report also summarized the suitability of proposed ICH heating experiments for meeting critical physics and technology needs. As shown in Table 1 (adapted from the report), the DIII-D, TFTR, and C-Mod experiments (U.S. program) and the JET and JT-60 experiments (foreign programs) were assessed for their capability to address the issues shown. Section 3 of this document reviews the U.S. and international programs in more detail and presents more information on the ICH plans for a large number of tokamak experiments. However, the basic assessment indicated in Table 1 still appears valid.

1.4 DOE REVIEW, APRIL 1986

The physics basis for the CIT was reviewed again by the Ignition Physics Study Group and summarized at a meeting in Austin, Texas, in January 1986. Group members expressed concern about the resolution of key issues for ICH. In response to these concerns, DOE sponsored an ICH workshop in April 1986 to present project plans and proposals for experiments on TFTR, C-Mod, and DIII-D to a panel of

Table 1. Suitability of proposed ICRF programs to meet critical R&D needs of a CIT[a]

Issue	Suitability				
	DIII-D	TFTR	C-MOD	JET	JT-60
Ignition, compatible launcher	High	High	High	[b]	Medium
Confinement	Medium	Medium	High	Medium	Medium
Impurity generation and evolution	Medium	Medium	Medium	Medium	Medium
Compatibility with divertor	High	Low	High	Low	High
Optimization of coupling, propagation, and deposition	Medium	Medium	High	Medium	Medium

[a]Adapted from the report of a panel formed to discuss ICRF development needs for CIT at a DOE workshop in April 1985.

[b]Not in program plans; unlikely to be done.

senior fusion scientists and engineers. The panel, chaired by L. Berry (ORNL), was asked to answer the following questions.

1. Present plans call for ICRF to provide auxiliary heating for the CIT. Providing the knowledge and confidence that this can be done successfully should be the near-term focus of the U.S. ICRF program. Specific questions that must be answered are:

   a. Based on current experimental results, what heating method should be emphasized (fundamental, second harmonic, minority, ion Bernstein, etc.)? What backup methods, if any, should be explored? What are the best coupler design options to support this choice of auxiliary heating?

   b. What constitutes a sufficient test of the CIT ICRF concept/system?

2. In addition to specifically supporting CIT, the U.S. ICRF program should, to the extent allowed by limited resources, maintain a base from which it can support the future goals of the U.S. fusion program. These goals are currently focused on an ETR facility (e.g., INTOR, TIBER II). From the vantage point of the technical requirements of the U.S. ICRF program, what, if any, additional ICRF R&D beyond that needed for CIT is required to satisfy the needs of the U.S. fusion program to support these goals?

In response to the first question, the panel generally endorsed the baseline design of the ICH system. They agreed on the heating mode that should be used for CIT (He^3 minority with possible transition to second harmonic tritium heating using fast-wave ICH; see Appendix A). They also expressed general agreement with the coupler design presented as the baseline for CIT, with some concerns over specific design details (e.g., the use of graphite on the Faraday shield, the lack of movability of the antenna, and the cooling required on the Faraday shield during plasma burn).

The panel agreed that ion Bernstein wave (IBW) heating might be a possible backup heating method but that the existing data base was minimal. They recommended that, after the conclusion of IBW experiments on PLT and Alcator-C, the prospects for use of IBW in CIT should be examined. However, they stated that it would be necessary to carry out further IBW experiments, beyond the PLT and Alcator-C programs, to gain sufficient confidence that IBW could be relied on as a heating source.

Faced with choosing among the experiments proposed for DIII-D, TFTR, and C-Mod, the panel stated:

> ". . . no single experiment has all of the key CIT characteristics. While the D-shaped diverted plasma configuration can be studied in DIII-D or Alcator C-Mod, but not TFTR, the specific D-T-He^3 resonance layer geometry can only be studied on TFTR. Nonetheless, the time and effort to achieve a given level of rf system performance on the CIT can be significantly reduced by implementing and/or continuing the activities described below [C-Mod, DIII-D, TFTR]."

The key issues identified by the panel were very similar to those identified by the April 1985 panel, as shown in Table 1, and there was general agreement with the conclusions of the first panel as to the relative suitability of the different machines for studying various aspects of the critical issues. In particular, the panel concluded "that the C-Mod proposal is [the one] of most relevance to the CIT program," and the one most likely to simulate most closely the plasma and rf parameters desired for CIT. These included the CIT-like values of density and magnetic field, the capability for diverted operation and elongated plasma, and high-density operation. The main disadvantages of C-Mod were determined to be the inability to operate with deuterium (thus making accurate simulation of the He^3 minority with DT majority heating planned for CIT difficult) and the relative lateness in the program when definitive ICH data might be available from C-Mod. As will be seen in Sect. 4, C-Mod will probably produce data in time to allow for significant modifications to the CIT ICH system if necessary. The DIII-D experiment was also deemed worthwhile by the panel as the most relevant experiment for post-CIT tokamak facilities (e.g., ETR).

Section 2 is a brief review of CIT R&D needs. Section 3 covers the status of U.S. and foreign ICH research in tokamaks and evaluates the needs of the CIT program relative to available data. In Sect. 4, a coordinated plan for CIT/C-Mod ICH R&D is presented, and possibilities for earlier information of significant relevance for CIT are discussed.

2. REVIEW OF ICH NEEDS AND ISSUES FOR CIT

The CIT is a compact, high-magnetic-field, high-current device with a relatively low cost. As defined by the DOE/OFE,

> "The mission of the compact ignition tokamak will be to realize, study, and optimize fully ignited plasma discharges."

The CIT design used as a reference here is the one described in the conceptual design report.[1] Machine design parameters appear to be changing slightly from those given in the conceptual design report, with the general trend being to increase major radius for improved confinement properties, better access, and ease of machine fabrication. However, these changes will not alter the logic of the ICH R&D program. CIT can be operated either as a limiter-controlled discharge or with a divertor. The major machine parameters as described in the conceptual design report are:

Major radius	1.22 m
Minor plasma radius	0.45 m
Plasma elongation	1.8
Plasma current, limiter case	10 MA
Plasma current, divertor case	9 MA
Toroidal field	10.4 T
Toroidal field flat-top	3.7 s
Plasma burn time	3.1 s
Neutron wall loading at 300 MW fusion power	6.8 MW/m^2

A major assumption made in the confinement scaling of CIT is that it will be able to achieve H-mode operation with a diverted plasma. In this case, calculations using Kaye-Goldston H-mode scaling predict that auxiliary heating power $\geq$10 MW is required to achieve ignition. Figure 1, from a paper by Sheffield et al.,[2] indicates that, for optimum density and temperature, between 8 and 10 MW of auxiliary heating power is needed to pass from the ohmically heated plasma case (the curve labeled 0 at the left-hand side) to the ignition region on the right-hand side. The power curves are calculated for steady-state conditions. Higher heating power will be required if the time to increase the stored plasma energy is comparable to the energy confinement time.

Ion cyclotron heating has been chosen by the design team as the main heating system to supply the auxiliary heating power required for CIT. The ICH system is specified to deliver 10 MW of power to the plasma initially, with the capability for further upgrade to 20 MW. Electron cyclotron heating has been proposed and

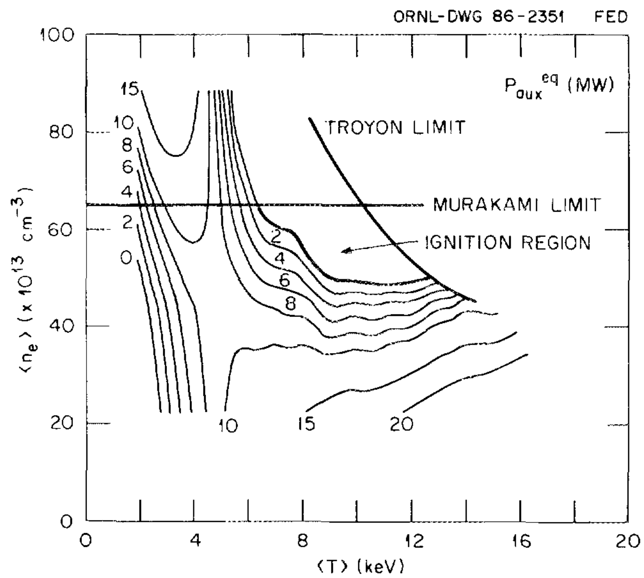

Fig. 1. Curves of constant auxiliary heating power in the CIT plasma operating space with Kaye-Goldston H-mode scaling. P_{AUX} = 0 corresponds to ignition. The operating space is constrained by the Murakami density limit and the Troyon beta limit (from Ref. 1).

accepted as a backup heating method for CIT. However, this report concentrates on the ICH system only and does not discuss the possibility of ECH. The baseline design for the ICH system is described in the conceptual design report,[1] and a description is also presented in Appendix A of this document. The present design uses three midplane ports to launch 10 MW of ICH power with approximately 3.3 MW per port. The launcher in each port contains two independently driven current loops of the resonant double loop design.[3] Each loop is powered by a 2-MW rf power unit. The plan for the rf power unit is to use modified FMIT power units that will operate in the 60- to 110-MHz frequency range.

The launchers are located on the outside (i.e., low-magnetic-field side) of the chamber and are oriented to launch the fast ion cyclotron wave into the plasma. The antennas will be designed to tune from approximately 65 to 110 MHz. Several heating modes can be used, depending on the machine magnetic field and the ion species mixture in the machine, as illustrated in Fig. 2.

- At low fields, during initial machine checkout with hydrogen operation, minority hydrogen heating will be possible for magnetic fields in the range of 4.2 to 7.2 T.

- He^3 minority heating or second harmonic tritium heating is accessible for fields in the range of 6.3 to 10.4 T.

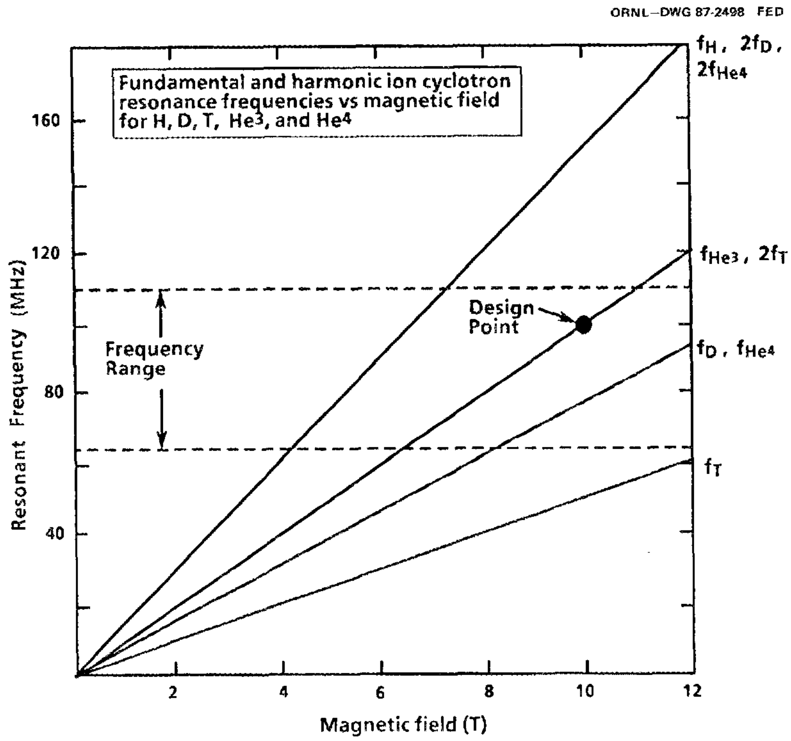

Fig. 2. Operational regime for the CIT ICH system for different heating modes and magnetic fields.

The nominal design point for the system is for full ICH power at a frequency of 95 MHz and at the maximum magnetic field of 10.4 T. This locates the ICH power deposition zone approximately one-third of the way out from the plasma center and should result in efficient heating. Calculations of ICH using these modes, carried out by Colestock et al.,[1,4] indicate good absorption and well-localized power deposition.

In April 1986, the DOE review committee approved the basic design concept and the selection of the heating modes. However, other modes, such as IBW, are possible as an ICH backup, and continued experimentation on IBW heating is highly desirable. This report will concentrate on implementation plans for the baseline fast-wave heating mode as described above.

CIT enters a new regime of operation for fast-wave ICH. The port size and the requirements for remote maintenance make the use of compact, removable ICH launchers a necessity. The remote maintenance requirement also mandates that the waves be launched from the low-field side. The limited amount of port space and the overall power requirements necessitate operation of these launchers at the highest possible amount of power per launcher and at the highest rf power flux (W/cm^2) through the launcher face. In addition, the system must operate at relatively high frequencies for multisecond pulse lengths in the presence of a high heat flux from the plasma and in the presence of neutron and gamma bombardment during the ignition phase. Finally, the antenna structure must provide good coupling to a diverted, H-mode plasma, while still being protected from the plasma. Preliminary results from the ASDEX and DIII-D experiments indicate that the load resistance seen by the antenna from the plasma decreases substantially in H-mode operation, and further experiments are required to better define the parametric dependencies of plasma load resistance on operation mode, plasma-antenna separation distance, density fall-off distance, etc.

Table 2 lists the major R&D needs and issues that should be addressed to provide a reliable ICH system for CIT. The tasks identified in the table are similar to the needs identified in earlier reports. Work is needed in theory, in development experiments, and in experiments on large confinement devices. A review of machines available for large confinement experiments will be presented in Sect. 3. Section 4 contains the specific plan proposed for R&D for CIT "mainline" work.

Table 2. CIT R&D needs and issues

	Theory	Development experiment	Confinement experiment
Study of compact launchers	X	X	X
Effect of high rf power flux on impurities		X(?)	X
Coupling to diverted, H-mode plasma			X
High-frequency, high-density operation			X
Launcher survivability with high plasma heat flux		X	X
Effect of single (toroidal) loop on heating efficiency	X		X
Resistance to radiation effects		X	
Voltage limits in plasma environment		X	X(?)
Faraday shield and feedthrough optimization	X	X	X(?)
Resistance to disruption forces		X	X

3. REVIEW OF U.S. AND INTERNATIONAL ICH PROGRAMS

The issues identified in Table 2 require three types of research: theory, development experiments, and confinement experiments. The necessary theoretical work requires relatively modest funding support, and considerable theoretical research is now going on in both U.S. and foreign laboratories and universities. Considerable work is still needed, but the resources exist to meet the needs, provided that funding support is adequate.

The development experiments needed for CIT are described in the plan in Sect. 4. They are not trivial and will require substantial funds if they are to be carried out successfully in time to ensure reliable CIT operation. Nevertheless, an adequate base of D&T expertise is available at ORNL and other U.S. laboratories and at several foreign laboratories (notably, the Max-Planck Institut für Plasmaphysik at Garching, Federal Republic of Germany, and JAERI in Japan) to carry out the needed research.

The "confinement experiments" identified in Table 2 will require the installation and operation of expensive hardware on large tokamaks and a substantial allocation of the experimental research time available on these machines to ICH research and testing. This section describes the ICH programs planned or proposed for large tokamak experiments worldwide and compares these programs with the confinement experiments needed for CIT from Table 2.

The CIT Ignition Physics Study Group sent a survey form to members of the tokamak ICH community requesting information about experimental plans over the next five years for ICH on machines with which they were associated. The results of the survey were intended to help CIT management and DOE/OFE to assess the ongoing and planned ICH programs in the international fusion community.

The goals of the study were

1. to document ICH experimental program plans worldwide for the next three to five years (in particular, to find out what significant questions relevant to ICH may be answered by each experiment);

2. to indicate the differences between the experiments currently planned and the research needed for future machines such as the CIT and ETR; and

3. to present this information in a form suitable for guiding the U.S. ICH technology development program in support of U.S. and international collaborative programs.

Figure 3 is a graphic indication of the major tokamak ICH experiments that exist or are planned from 1986 to 1994. The abbreviated name and major device parameters of each machine are listed to the left of the figure. Experimental ICH operations are indicated by solid or dashed lines. A solid line indicates an ICH experiment that is under way or has received definite approval; a dashed line indicates an ICH experiment that is planned but has not yet received approval from its funding organization. The numbers in parentheses on each line indicate the ICH power in megawatts and the frequency range over which the ICH system can be operated.

One obvious result of the survey is that ICH is being used or is planned for virtually all major tokamak facilities in the world. The diversity of heating modes and parameter ranges is substantial, and a substantial increase in knowledge of ICH physics and technology can be expected in the next five-year period, if the experiments that have been indicated by the survey results are all carried out.

Tables 3 and 4 summarize the survey results. Table 3 is a short listing of the results for all machines surveyed. In this table, one "typical" set of data is presented for each machine. The information presented consists of data collected directly from the survey forms (indicated with an asterisk by the information) and results calculated using the input information (e.g., confinement time and other plasma parameters). Details of the calculations are given in Appendix B. Table 4 is a subset of the information in Table 3, normalized to the parameter values expected for CIT machine operation. A more detailed listing of the survey response and calculated parameters is also given in Appendix B. The responses to the survey (retyped for uniformity and clarity) are reproduced in Appendix C.

Several comments should be made about the results presented in Tables 3 and 4.

1. With the exception of CIT data, all machine data were taken from the survey forms filled out by the institutions. CIT data are from the CIT conceptual design report. The November 1993 date is for first-phase ICH and no D-T; the November 1995 date is for D-T operation, with an assumed value of 25 MW of fusion power coupled to the plasma.

2. When a range of parameters and/or operating conditions was given for a specific machine at a given time of the survey form, those parameters corresponding <u>most closely</u> to CIT-like operation (e.g., maximum B_t and

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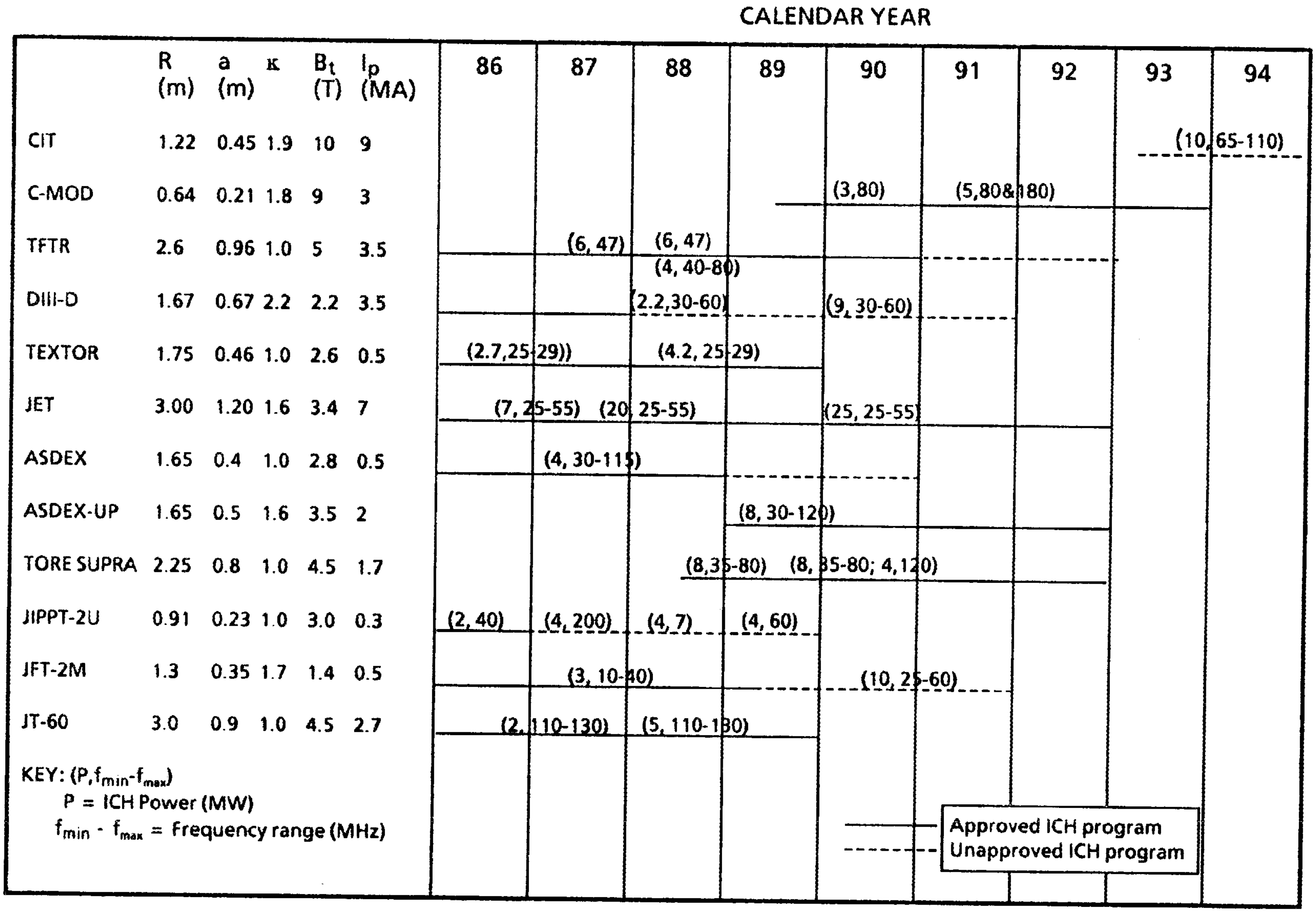

Fig. 3. Major tokamak ICH experiments.

Table 3. Summary of tokamak ICH experiments

TOKRF11	CIT 11/93	DIII-D 1/90	TFTR 4/88	ALC-C 9/86	C-MOD 1/90	TEXTOR 5/88	JET 6/87	ASDEX 1/87	ASDEX-U 1/89	T.SUP. 90	JIPPT-II 86	JFT-2M 4/88	JT-60 12/87
Geometry													
R^* (m)	1.22	1.67	2.60	0.64	0.64	1.75	3.00	1.65	1.65	2.25	0.91	1.30	3.00
a^* (m)	0.45	0.67	0.96	0.12	0.21	0.46	1.20	0.40	0.50	0.80	0.23	0.35	0.90
Elongation*	1.90	2.50	1.00	1.00	1.80	1.00	1.60	1.00	1.60	1.00	1.00	1.70	1.00
Volume (m^3)	9.27	37.00	47.30	0.18	1.00	7.31	136.44	5.21	13.03	28.43	0.95	5.34	47.97
B_{tor}^* (T)	10.40	2.20	5.00	12.00	9.00	2.60	3.40	2.80	3.50	4.50	3.00	1.40	4.50
I_p^* (MA)	9.00	3.50	3.50	0.30	3.00	0.50	4.00	0.50	2.00	1.70	0.30	0.50	2.10
$q(a)$	2.96	4.35	3.39	4.83	2.75	3.63	5.15	3.06	2.86	4.93	3.32	2.98	3.49
t_{pulse}^* (s)	3.70	1.50	3.00	0.10	1.00	3.00	15.00	10.00	5.00	30.00	0.10	1.00	10.00
Edge[b]	L,D	L,E	L,P	L	L,D	P	L,E	L,D	L,D	P	L	L,D,P	L,D
Power													
P_{oh} (MW)	4.5	1.8	1.8	0.2	1.5	0.3	2.0	0.3	1.0	0.9	0.1	0.3	1.1
P_{nbi}^* (MW)		14.0	27.0			3.0	18.0	3.3	6.0	7.0	1.0	1.6	20.0
P_{ich}^* (MW)	10.0	9.0	10.0	0.5	5.0	4.2	20.0	4.0	6.0	12.0	2.0	3.0	5.0
P_{lhh}^* (MW)		0.0						2.3		8.0	0.3	0.6	15.0
P_{ech}^* (MW)		2.0											
P_{other}^* (MW)												0.4	
P_{total} (MW)	14.5	26.8	38.8	0.7	6.5	7.5	40.0	9.8	13.0	27.9	3.5	5.9	41.1
ICH parameters													
f_{ich}^* (MHz)	95.0	60.0	47.0	210.0	80.0	29.0	55.0	115.0	120.0	80.0	40.0	40.0	130.0
f_{cH+} (MHz)	156.0	33.0	75.0	180.0	135.0	39.0	51.0	42.0	52.5	67.5	45.0	21.0	67.5
Mode*[a]	M2,2T	2H,2He,M	M2,2D	2H	M2	M1,M2,2D	M1,M2	M1,M2,2H	M1,M2,2H	M1,M2,2H	M1	M1,2H	2H
h_{port}^* (m)	0.80	0.50	0.85	0.30	0.60	0.73	1.60	0.80	1.00	0.60	0.50	0.70	0.52
w_{port}^* (m)	0.30	0.35	0.66	0.04	0.15	0.26	0.50	0.30	0.70	0.50	0.10	0.07	0.37
A_{port} (m^2)	0.24	0.18	0.56	0.01	0.09	0.19	0.80	0.24	0.70	0.30	0.05	0.05	0.19
N_{ports}^*	3.00	4.00	2.00	2.00	4.00	4.00	8.00	2.00	4.00	3.00	6.00	3.00	1.00
$P/A_{antenna}$ (MW/m^2)	13.89	12.86	8.91	20.83	13.89	5.53	3.13	8.33	2.14	13.33	6.67	20.41	25.99
P/V_{ich} (MW/m^3)	1.08	0.24	0.21	2.75	4.99	0.57	0.15	0.77	0.46	0.42	2.10	0.56	0.10
t_{ich}^* (s)	3.00	5.00	2.00	0.10	1.00	1.50	10.00	10.00	10.00	30.00	0.10	0.50	10.00
$Energy_{ich}$ (MJ)	30.00	45.00	20.00	0.05	5.00	6.30	200.00	40.00	60.00	360.00	0.20	1.50	50.00
Energy/A (MJ/m^2)	41.67	64.29	17.83	2.08	13.89	8.30	31.25	83.33	21.43	400.00	0.67	10.20	259.88
Plasma properties													
n_{max} (10^{20} m^{-3})	14.15	2.48	1.21	6.63	21.65	0.75	0.88	0.99	255	0.85	1.81	1.30	0.83
n_{oper} (10^{20} m^{-3})	4.00	1.86	0.91	4.00	4.00	0.56	0.66	0.75	1.91	0.63	1.35	0.97	0.62
H-mode multiplier*	2.00	2.00	1.00	1.00	2.00	1.00	2.00	2.00	2.00	1.00	1.00	2.00	2.00
τ_e (K-G) (s)	0.647	0.309	0.131	0.023	0.094	0.021	0.376	0.038	0.223	0.052	0.010	0.048	0.162
β (%)	2.34	11.54	1.07	0.14	1.89	0.81	2.39	2.27	4.55	0.62	1.05	6.67	1.71
$n(T_e+T_i)$ (10^{20} $m^{-3} \cdot keV$)	42.51	9.38	4.51	3.49	25.69	0.92	4.63	2.99	9.36	2.13	1.58	2.20	5.81
T_i (keV)	5.31	2.52	2.49	0.44	3.21	0.81	3.49	2.00	2.45	1.68	0.58	1.13	4.69
Dimensionless parameters													
f_{ci}/f_{pi}	0.27	0.08	0.27	0.31	0.23	0.18	0.22	0.17	0.13	0.29	0.13	0.07	0.30
λ/a	0.18	0.18	0.18	0.67	0.38	0.47	0.16	0.47	0.23	0.25	0.60	0.47	0.23
ρ_i/a ($\times 100$)	0.32	0.70	0.21	0.30	0.62	0.49	0.30	0.82	0.58	0.23	0.72	1.41	0.35
ν_i^*	0.019	0.070	0.048	6.683	0.030	0.336	0.028	0.066	0.075	0.098	0.786	0.178	0.015

[a] M1 = H minority in D; M2 = He^3 minority in D; M3 = H minority in He^3; M4 = H minority in He^4; 2H = second harmonic H; 2D = second harmonic D; 2T = second harmonic T; and 2He = second harmonic He^3.

[b] L = limiter; D = divertor; E = extended boundary; and P = pumped limiter.

Table 4. Summary of tokamak ICH experimental parameters normalised to parameter values for CIT

TOKRF11	CIT 1/93	DIII-D 1/90	TFTR 4/88	ALC-C 9/86	C-MOD 1/90	TEXTOR 5/88	JET 6/87	ASDEX 1/87	ASDEX-U 1/89	T.SUP. 1/90	JIPPT-II 86	JFT-2M 4/88	JT-60 12/87
Mode*[a]	M2,2T	2H,2He,M	M2	2H	M2	M1,M2,2D	M1,M2	M1,M2,2H	M1,M2,2H	M1,M2	M1	M1,2H	2H
Edge[b]	L,D	L,E	L	L	L,D	P	L,E	L,D	L,D	L	L	L,D,P	L,D
B_{tor}	1.00	0.21	0.48	1.15	0.87	0.25	0.33	0.27	0.344	0.43	0.29	0.13	0.43
κ	1.00	1.32	0.53	0.53	0.95	0.53	0.84	0.53	0.84	0.53	0.53	0.89	0.53
P_{ich}/A	1.00	0.93	0.64	1.50	1.00	0.40	0.23	0.60	0.15	0.96	0.48	1.47	1.87
P_{ich}/V	1.00	0.23	0.20	2.55	4.62	0.53	0.14	0.71	0.43	0.39	1.95	0.52	0.10
n_{oper}	1.00	0.47	0.23	1.00	1.00	0.14	0.17	0.19	0.48	0.16	0.34	0.24	0.15
β	1.00	4.93	0.46	0.06	0.81	0.34	1.02	0.97	1.94	0.27	0.45	2.85	0.73
f_{ci}/f_{pi}	1.00	0.31	1.01	1.15	0.87	0.67	0.80	0.62	0.49	1.09	0.50	0.27	1.10
λ/a	1.00	0.98	0.98	3.75	2.14	2.60	0.92	2.60	1.30	1.41	3.36	2.60	1.27
ρ_i/a	1.00	2.19	0.67	0.93	1.93	1.53	0.93	2.57	1.82	0.73	2.25	4.40	1.09

[a]M1 = H minority in D; M2 = He^3 minority in D; M3 = H minority in He^3; M4 = H minority in He^4; 2H = second harmonic H; 2D = second harmonic D; 2T = second harmonic T; and 2He = second harmonic He^3.

[b]L = limiter; D = divertor; E = extended boundary; and P = pumped limiter.

maximum I_p for a diverted plasma) were chosen to be listed in Tables 3 and 4. For example, JET can run at a plasma current of 7 MA with a limiter plasma boundary but at 4 MA maximum for an expanded boundary, so the 4-MA value was chosen for inclusion in Table 3.

3. To ensure uniform comparison among machines, all plasma parameters were calculated using Kaye-Goldston L-mode scaling for τ_E (see Appendix A). Machines with divertors or expanded boundaries were assumed to be able to achieve H-mode; this was accounted for by multiplying the L-mode τ_E value by 2.

Finally, the schedules and parameters for many of the machines listed are proposed but have not been necessarily approved by the appropriate funding agencies. The approval status is indicated to some extent on the completed survey forms (Appendix C) and is also indicated schematically by the dashed and solid lines in Fig. 3. It is unlikely that all of the experiments shown in the figure and tables will be performed.

3.1 DISCUSSION OF SURVEY RESULTS

The main questions to be answered are:

1. What machines will provide information on the critical R&D issues listed in Table 2?

2. When will this information become available? Of particular interest to the U.S. program is work occurring prior to C-Mod operation, in time to optimize the possible contributions of C-Mod to ICH research.

3. Are there major gaps in the planned experiments that should be addressed by new or modified experimental programs?

Table 5 indicates the suitability of U.S. and foreign machines to address the critical issues listed in Table 2. Only existing or approved programs are included in the table. More details on the numerical values of data for the different machines are given in Tables 3 and 4. The following paragraphs describe the "Issue" columns in Table 5.

Compact launcher – Results show that four machines are now planning to address the use of compact launchers in large devices prior to C-Mod: TFTR, Tore Supra, JFT-2M, and JT-60. In this context, a compact launcher is one that fits within a single port and operates at an rf power flux ≥ 10 MW/m^2. This is a necessary constraint on the design of launchers for future machines with high radiation levels.

RF power flux on impurities – Six or seven machines will be able to study the effect of high rf power flux on impurities. This capability is usually synonymous with the use of a compact launcher, because compact launchers generally have higher rf power fluxes than conventional antennas. Listed in parentheses in this column is the rf power flux through the antenna ports (in MW/m^2) for each machine. The only high-power flux experiment in the United States is TFTR. By running all of the available 6 MW power into one of the launchers proposed for TFTR (as is being planned), it will be possible to achieve flux levels on the order of 10 MW/m^2. Other information will come from foreign experiments, notably JFT-2M and JT-60. In the next year, these two machines will achieve rf power densities greater than or equal to those anticipated for CIT.

High density – No currently planned experiments will achieve high-density operation with ICH in the near term. The maximum density achievable in each machine was calculated using Greenwald scaling (see Appendix B; numerical values of the maximum calculated operating density are given in Table 3). According to this scaling, the ASDEX Upgrade experiment should achieve density values of approximately 0.48 that of CIT operation; however, ASDEX Upgrade operation will not occur until early 1989, only six months before C-Mod should begin operation. Although in principle JIPPT-2U can achieve better than 30% of the CIT value, this is a small machine whose experimental future is relatively

Table 5. Suitability of U.S. and foreign machines to address critical issues
(includes only existing or approved programs)

Machine	Estimated experiment date	Issue: Compact launcher	Effect of high rf power flux on impurities (MW/m^2)	High-density operation (fraction of CIT density)	H-mode, diverted	He^3/D-mode operation	Resistance to disruption forces
CIT	11/93	X	X(14)	X	X	X	X
C-MOD	7/89	X	X(17)	X	X		X
TFTR	8/87	X	X(10)			X	
TEXTOR	4/87					X	
JET	6/87				X	X	
ASDEX	1/87		X?(8)		X	X	
ASDEX-UP	1/89			X(0.48)	X	X	
TORE SUPRA	3/88	X	X(13)			X	
JIPPT-2U	86			X(0.34)			
JFT-2M	4/87	X	X(20)		X		
JT-60	12/87	X	X(25)		X		

uncertain. According to Greenwald scaling, TFTR should be able to achieve densities 20% to 25% of the expected CIT value.

Two possibilities exist for obtaining higher-density ICH information in the near term in the U.S. program. The first would be to extend the Alcator-C experiment, emphasizing ICH results at high density and possibly involving other laboratories in a collaborative effort with MIT. The second possibility is to perform ICH experiments in the DIII-D tokamak. This machine, according to Greenwald scaling, can achieve average density values almost 50% of the value expected for CIT, although at relatively low magnetic field strength.

H-mode, diverted – No experiment is planned in the U.S. program before C-Mod to study ICH heating of an H-mode diverted plasma, but low-power coupling experiments are being carried out on DIII-D. Four foreign machines (JET, ASDEX, JFT-2M, JT-60) will be carrying out experiments of this type in the next 12 months and should provide substantial information on this topic. ASDEX Upgrade will also have this capability but will not begin operation until January 1989.

He^3/D-mode – Several machines (notably, TFTR in the United States and JET and ASDEX in Europe) have the capability for doing fast-wave ICH using He^3 minority heating with a deuterium background. JFT-2M also appears to have the capability for He^3 minority heating in a deuterium background, but the high-field launch used on JFT-2M is different from C-Mod and CIT. Although it is not in the present JFT-2M experimental program, the transmitters there appear to cover the necessary frequency range. It is assumed that radiation levels from a JFT-2M-sized machine would not be a significant problem. C-Mod and JT-60 are apparently not planning to use this heating mode because of the radiation levels anticipated if deuterium were used as the majority species. Both could use He^3 minority in a He^4 background; however, the recycling characteristics of He^4 are so different from those of deuterium as to make validity of results obtained from this mode questionable.

Resistance to disruption forces – Disruption forces in launchers are caused primarily by the interaction of disruption-induced currents in the launcher structure with the toroidal magnetic field. For machines operating with similar q values and aspect ratios, the force per unit length scales approximately as B_t^2. The CIT and C-Mod experiments are about a factor of 4 over machines such as TFTR, Tore Supra, and JT-60 in this parameter, resulting in higher disruption forces on the launcher elements. Experiments on these machines will provide some information on this problem, but the C-Mod device will be the first tokamak experiment to approximate the forces expected on CIT.

Summary – In the U.S. program, the TFTR experiment is the only ICH now planned prior to C-Mod. It will provide information on the performance of a compact launcher at high power fluxes using the same mode of operation anticipated for CIT. However, the density will be substantially smaller than that expected in CIT, and the machine does not have the capability of operating with a diverted, H-mode plasma. The only possibility for doing experiments of this kind in the U.S. program before C-Mod would be to operate DIII-D with substantial amounts of ICH. However, this program is not currently funded. If this program were to be executed, studies of a compact launcher with high rf power flux at relatively high density in an H-mode diverted plasma could be carried out.

Overall, foreign experiments appear to offer the best likelihood of obtaining significant information relevant to CIT in the near term. The two Japanese experiments (JFT-2M and JT-60) will operate with compact launchers, with high rf power fluxes, and in H-mode diverted operation (JFT-2M has already achieved H-mode operation using ICH only; JT-60 has not as yet). In addition, JFT-2M appears to have the capability of running in the He^3/D-mode, although this operation is not planned. The JET and ASDEX ICH experiments will provide significant information on He^3/D heating in H-mode diverted plasma configurations well before the start of C-Mod operation.

4. CIT/C-MOD EXPERIMENTAL AND DEVELOPMENT PROGRAM

Sections 2 and 3 reviewed the needs and issues for CIT ICH and the experimental devices on which the confinement experiments could be carried out. Obtaining early information on H-mode coupling, high power flux operation, impurity generation, and transport in H-mode, diverted plasmas is highly desirable to achieve a more reliable and better-optimized ICH system. However, an ICH system design for CIT can be carried out now, prototype testing can be accomplished on C-Mod, and even significant changes to the basic launcher design based on C-Mod results can be accommodated in the existing CIT schedule. This section presents a coordinated development and experimental schedule, listing the necessary R&D elements as well as the design, fabrication, testing, and installation activities needed for C-Mod and CIT. This success-oriented program is based on the assumption that there are no fatal flaws in the basic premise of using fast-wave, He^3 minority heating as the primary auxiliary heating mechanism for CIT. Based on our present knowledge, it is likely that this assumption is valid and that the CIT requirements can be met using this heating technique.

Figure 4 is a logic diagram of the plan. The top part of the plan shows the C-Mod schedule and a summary schedule of the overall CIT design, fabrication, and operation. The third block indicates the CIT ICH system activities. The main goals of these activities are to provide conceptual, preliminary, and final designs of the CIT ICH system with specified interfacing to the other subsystems on CIT and to manage a portion of the tasks in the lower two sections (ICH launchers and power units). The bottom two sections indicate the development and test work, as well as the design, fabrication, assembly, installation and testing of launchers on both C-Mod and CIT. The goal of this logic diagram is to indicate in a comparatively simple way what should be done to meet the C-Mod and CIT schedules and how all these activities are linked together. Briefly, the plan is as follows.

Launchers

L1. Design a CIT-like launcher and test it in the ORNL Radio Frequency Test Facility (RFTF).

L2. Design and build a half-size CIT prototype launcher and test it in C-Mod, before fabrication for the CIT experiment begins, using rf power units available at C-Mod.

L3. Build CIT launchers and perform qualifying tests in the ORNL RFTF, before installation on CIT.

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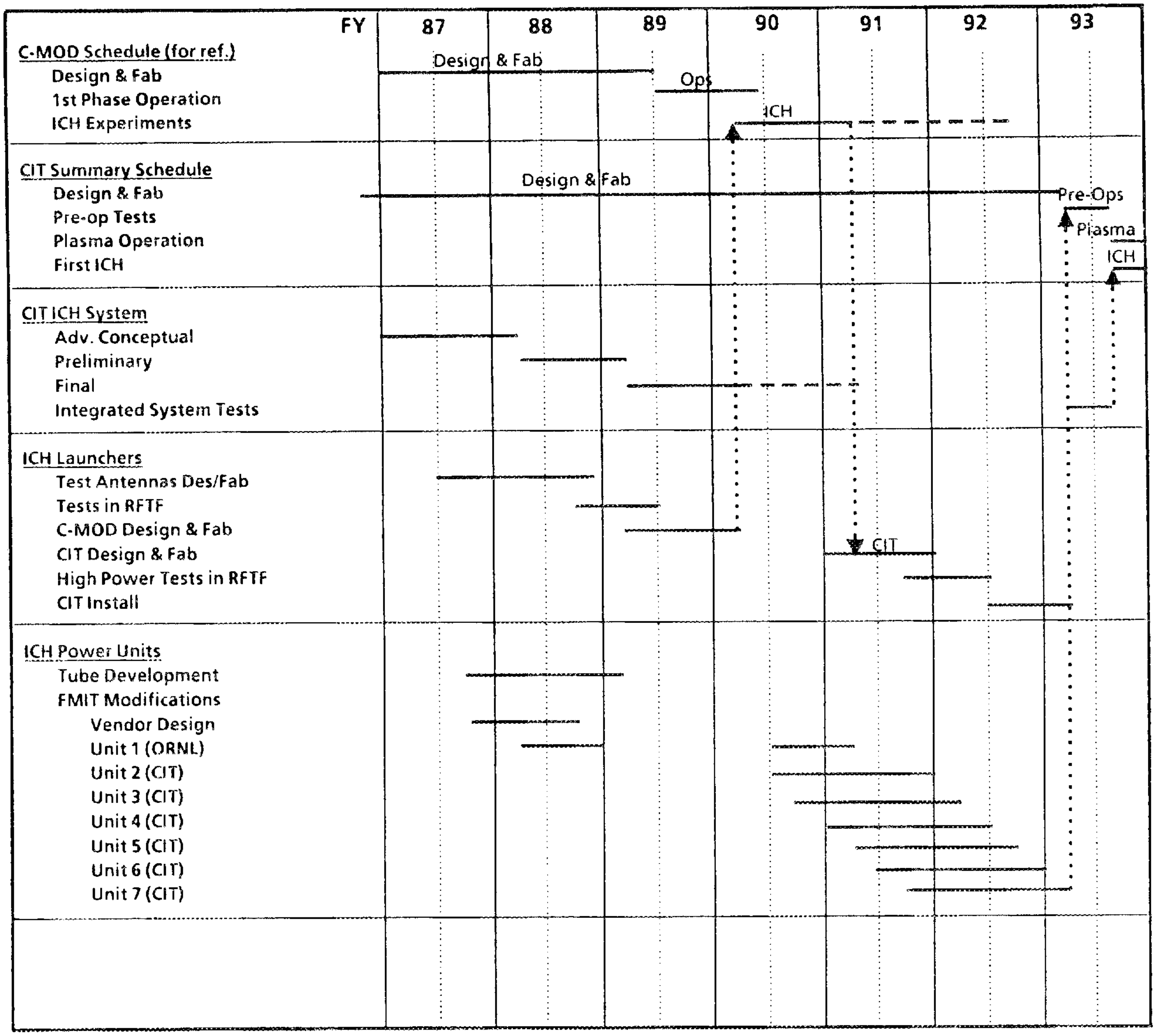

Fig. 4. CIT ICH schedule with C-Mod test of launcher and power unit.

L4. Install the launchers on CIT after the CIT preoperational tests but before first plasma.

Power Units

P1. Complete the engineering design for an FMIT 60- to 110-MHz, 2-MW modification and modify the low-power FMIT driver section at ORNL. Use this 100-kW source for the tests described in L1.

P2. Evaluate tubes available for use at 2 MW, 95 MHz; develop a high-power tube if needed.

P3. Modify the high-power section of the ORNL FMIT unit and test it at ORNL. Use this unit for qualification tests mentioned in L3.

P4. Modify FMIT units 2–7 at Continental and install them at CIT.

A detailed description of the elements in the plan is included as Appendix D, which contains a one-paragraph summary for each activity shown in Fig. 4.

It is hoped that, after suitable discussion and iteration of the plan among OFE, MIT, and the CIT project management, an agreed-upon plan can be implemented. It appears to be a logical method whereby the major R&D activities as well as preliminary testing of the prototype systems for CIT can be carried out on C-Mod in a timely manner.

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   For an overview, see C. A. Flanagan et al., "Overview of the Compact Ignition Tokamak," to be published in *Fusion Technol.* as part of the Proceedings of the 7th Topical Meeting on the Technology of Fusion Energy (Reno, June 15–19, 1986).

2. J. Sheffield et al., "Physics Guidelines for the Compact Ignition Tokamak," *Fusion Technol.* **10**, No. 3, Part 2A, 481-490 (November 1986).

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4. I. S. Lehrman and P. L. Colestock, "An Algorithm for the Analysis of Inductive Antennas of Arbitrary Cross-Section for Heating in the Ion Cyclotron Range of Frequencies," Princeton Plasma Physics Laboratory, PPPL-2383 (October 1986).

Appendix A

CIT ICH SYSTEM DESIGN DESCRIPTION

This appendix discusses the overall system requirements (Sect. A.1), the antenna design (A.2), the rf transmission system (A.3), and the rf power system and power supplies (A.4).

A.1 PERFORMANCE REQUIREMENTS AND SYSTEM OVERVIEW (FIG. A-1)

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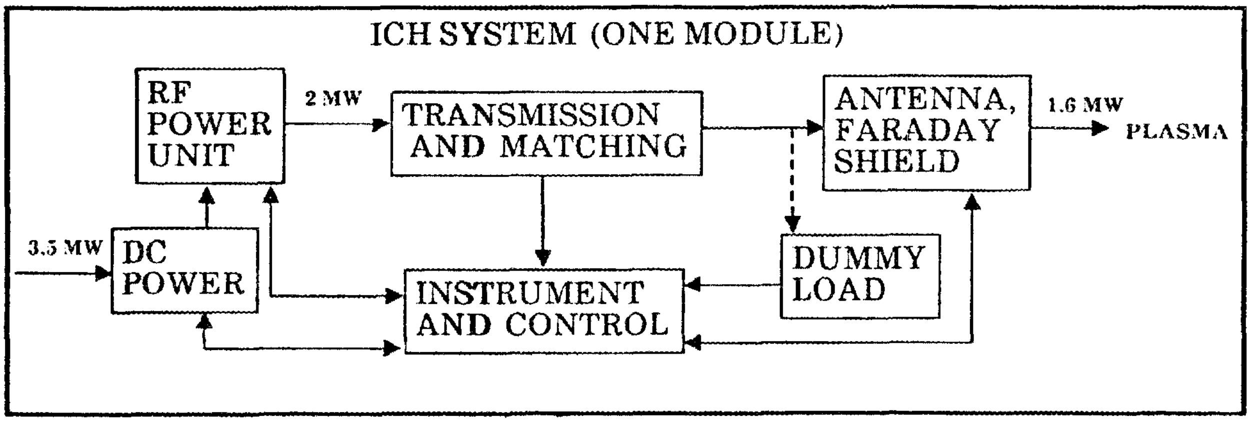

Fig. A-1. ICH system block diagram.

ICH SYSTEM SPECIFICATIONS

Frequency (maximum power)	95 MHz
Frequency range (reduced power)	80–110 MHz
Pulse length (flat-top time)	3.7 s
Modular system; power per antenna (to plasma)	1.6 MW
Antennas per port	2
Total power to plasma (initial operation)	10 MW
Number of ports for 10 MW to plasma	3
Time needed to change frequency	4–6 h

Antenna — A resonant double-loop structure with vacuum-variable capacitors at each end for tuning and matching and with a Cu current strap. Modular, compact construction for installation and removal through the midplane port; two antennas per port.

Transmission and matching — 50-Ω coaxial cable, 23 cm (9 in.) in diameter, pressurized to 1–2 atm with N_2, that matches directly to antenna input impedance.

Supply and power units — Six modified FMIT units, with X-2242 tetrodes or improved equivalent, for 2 MW rf power per transmitter at 95 MHz.

Faraday shield — Cu-coated Inconel tubing [1.3 cm (0.5 in.) OD] in a staggered double row. Graphite coating brazed to Inconel tubing on the plasma side. Gas-cooled for heat removal between shots, with ceramic insulators to prevent disruption current from flowing in Faraday shield elements.

Instrumentation & controls (I&C) — Monitoring and control of dc voltages and tuning elements (capacitors, tuning cavities in the transmitter, etc.), monitoring of forward and reflected power to/from antenna vs time. A dedicated minicomputer (e.g., MicroVAX II) with CAMAC control/data acquisition interfaces with main I&C for safety interlocks and data transmission and archiving; it can operate the rf unit in stand-alone mode into dummy load for system checkout.

A.2 ANTENNA

A.2.1 Description and Operating Characteristics

Reference 3 gives a general description of the resonant double loop (RDL) antenna, a conventional loop coupler that uses capacitive impedance matching elements at the antenna. A resonant circuit is formed by the combination of the antenna inductor and the two capacitors at the antenna ends. A real impedance at the input to the antenna results from tapping into the resonant circuit at some point along the antenna. The input impedance can be matched to the source impedance by adjusting the capacitors for a given tap arrangement as the load resistance is varied. For a given load resistance, an optimum tap point occurs when peak voltages at each end of the antenna are equal.

Advantages of the RDL over conventional loop coupler schemes are

1. no tuning stubs are required because the input is matched to the line impedance;
2. low voltage and current are maintained at the vacuum feedthrough; and
3. if ceramic supports are required, they occur in the feedline where voltages are low (<15 kV at 2 MW, 50 Ω input impedance).

The baseline design consists of a pair of RDLs in a CIT large port, with one antenna above and one below the equatorial plane. Power handling can be increased by up to a factor of 4 by breaking up a single long antenna into two short antennas. No more than two RDL modules are feasible in a single port because of practical limitations on the size of components.

For the two-module configuration, the maximum power handling capability of each module as a function of load resistance is plotted in Fig. A-2 for 80, 95, and 110 MHz.

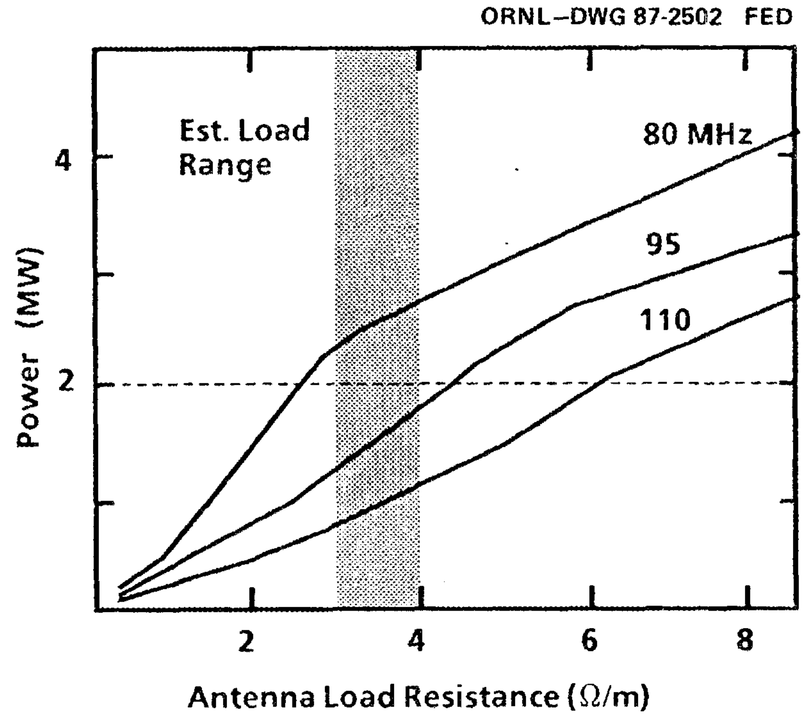

Fig. A-2. P_{max} vs R_{load} for 80, 95, and 110 MHz.

A maximum voltage on either capacitor of 50 kV has been assumed. Antenna inductance has been estimated from $L \approx Z_0/\omega \tan(\beta\ell)$ with $Z_0 = 50\ \Omega$ and $\ell = 35$ cm, where ℓ is the antenna length. A constant lead inductance of 0.03 μH has been added to account for radial currents at the antenna ends. A tap point has been selected that gives optimum power handling for 95 MHz at a plasma load resistance of 4 Ω/m. At this voltage level and resistance, each RDL module can handle up to ~2 MW at a frequency of 95 MHz, for a total of 4 MW per port. Power handling increases at lower frequencies and decreases at high frequencies, as seen in Fig. A-2.

The antenna load resistance depends on the plasma density profile (and to a lesser extent, the temperature profile) and is particularly sensitive to the density profile in the plasma scrape-off region between the plasma edge and the antenna. Theoretical calculations give values from 1 Ω/m of antenna length to >10 Ω/m, depending on the assumptions made about the plasma profiles. Based on ICH coupling calculations and also on experimental measurements of antenna loading in other tokamaks, a load resistance of 2–6 Ω/m is estimated, with a "best guess" of 3–4 Ω/m.

Figure A-3 shows tuning capacitor values at 95 MHz. Capacitors in the range of 45–70 pF are required to match loads of 0.3–9 Ω/m to the 50-Ω line impedance at 95 MHz. Simple structures with very high voltage capability can be used to achieve these capacitance values. Capacitor resonances can be made to occur at frequencies well above 95 MHz. To match the line to the antenna for a load resistance in the 0.3–9 Ω/m range over a frequency range of 80–110 MHz, the required capacitor range increases to 30–100 pF. Tuning over a range of ~65–110 MHz should be possible.

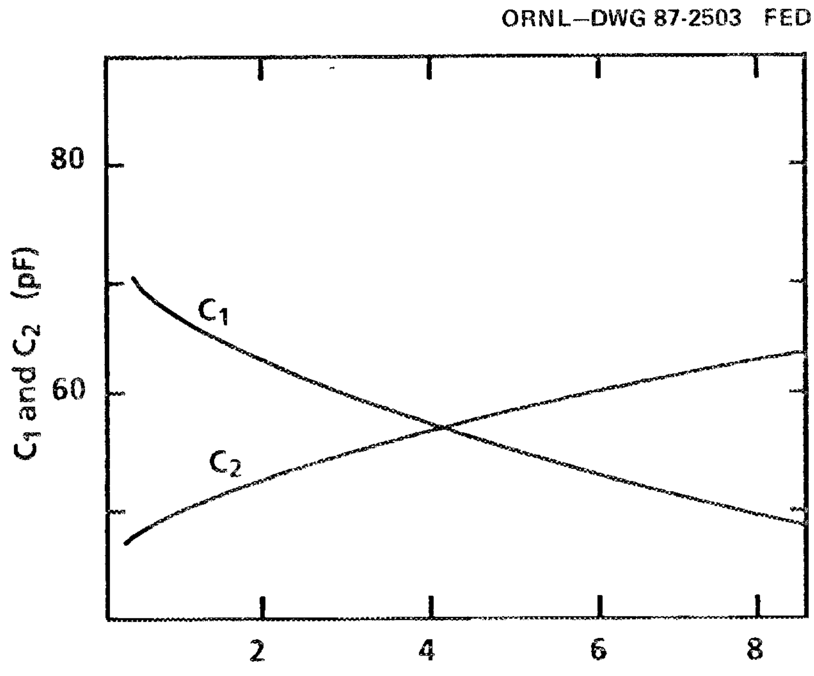

Fig. A-3. C_1 and C_2 vs R_{load} at 95 MHz.

A.2.2 Antenna Mechanical Design

The antenna system interfaces with the transmission system at an ORNL-designed constant impedance vacuum feedthrough. The feedthrough uses a brazed alumina dielectric to separate the pressurized input 23-cm (9-in.) transmission line from the evacuated 15-cm (6-in.) antenna feed. Figure A-4 shows details of the baseline antenna configuration. The center conductor is supported by the vacuum feedthrough and a λ/4 shorted stub so that no dielectrics are used in the antenna system except at the feedthrough, which can be shielded. The antenna transmission line is 50 Ω impedance. The conductor feeds the 35-cm-long antenna off center at $\ell_{tap}/\ell_{total} = 0.64$.

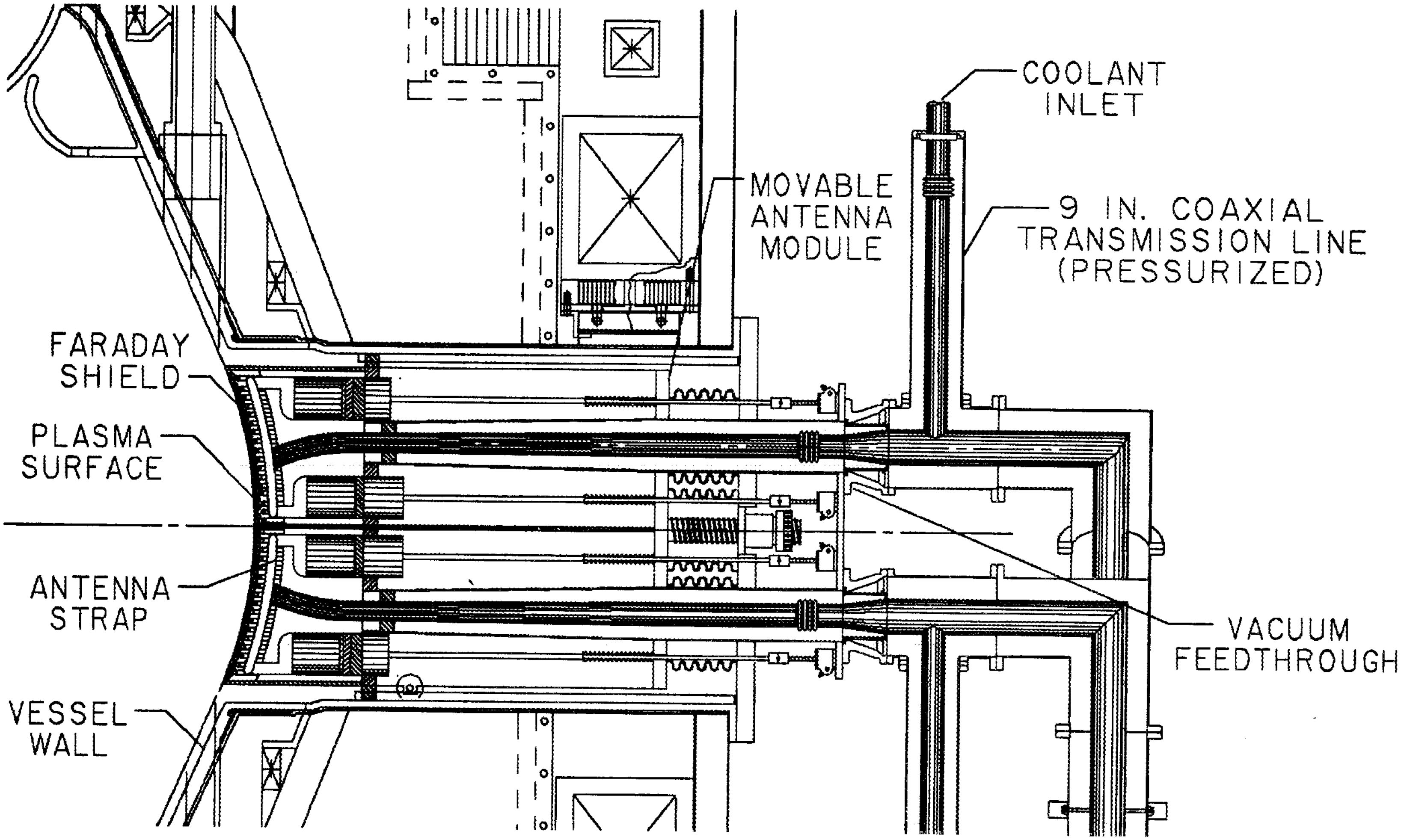

Fig. A-4. CIT antenna design.

Each end of the antenna is connected to ground through a compact variable capacitor that allows tuning of the antenna to match a range of frequencies and loading impedances. The variable capacitors are made of concentric cylinders. The position of the grounded side of the capacitor can be adjusted by moving it axially, using a bellows arrangement for vacuum integrity. The current strap and the high-voltage ends of the capacitors are held in place by the rigid center conductor of the vacuum transmission line, which is connected to the tap point near the center of the current strap. The gas pressure between the capacitor plates is that of the tokamak; however, the capacitor plates are shielded from direct exposure to the plasma environment by the Faraday shield. Each capacitor is tunable from about 20 to 150 pF; this can be accomplished remotely by computer control between tokamak shots to optimize the matching to the plasma load.

An alternate matching network design replaces the variable capacitors with variable shorted stubs. This design has the advantage of giving solid support to the antenna ends without dielectrics and removing the small gaps in the capacitors, which would be potential breakdown problems. However, this approach may narrow the usable antenna bandwidth.

The entire antenna system is designed to hold off a peak voltage of 50 kV. Minimum gaps in the design are 1 cm (for a peak electric field of 50 kV/cm); these gaps occur in the capacitor, between the antenna and Faraday shield, and between the end of the antenna and the port walls. The antenna elements are designed for inertial cooling during each pulse and cold gaseous nitrogen cooling between pulses ($\sim$1 hr).

A.3 TRANSMISSION SYSTEM AND DUMMY LOAD

The transmission system is based on a nominal 23-cm (9-in.) diameter rigid coaxial transmission line pressurized to 1–2 atm with dry nitrogen. The transmission distance from the rf sources to the vacuum feedthroughs is approximately 100 m and introduces a total power loss of 2–4% of the transmitted power, depending on the number of bends and joints actually required. Dielectric spacers in the transmission line are alumina, and joint seals are metallic to be compatible with high neutron flux environments. Power dissipation is low enough that the transmission system requires no cooling other than radiation and convection to the ambient environment.

Each transmission line will require a dc break near the vacuum vessel to isolate the transmitters from high voltages caused by tokamak disruptions. The dc break will be required to withstand up to 20 kV of pulsed dc.

Two 2.5-MW rf dummy loads with a 50-Ω impedance will be required for testing and tuning the rf supplies. Two-position coaxial switches will switch each rf power unit between the antenna and a dummy load. The load will be a commercial water-cooled unit capable of handling the full rf output power steady-state.

A.4 RADIO FREQUENCY SUPPLIES

The ICH rf supplies are modified FMIT transmitters originally manufactured by Continental Electronics. The baseline design is for sources that are manually tunable over a frequency range of 60–110 MHz. At 95 MHz, approximately 2 MW of rf power will be generated by each transmitter. To guarantee delivery of 10 MW to the plasma, up to 6 transmitters may be needed to feed 6 antennas in 3 ports. Each transmitter is configured as shown in Fig. A-5. Each class C final power amplifier (FPA) using an EIMAC X-2242 tetrode (with modifications) is fed by an intermediate power amplifier (IPA) and a phase- and level-controlled frequency source. Each antenna's phase and power level are then controlled by the ICH control I&C unit. Each transmitter unit contains high-voltage crowbars for the FPA and IPA and is fed from a dedicated 13.8-kV/25-kV transformer/rectifier set.

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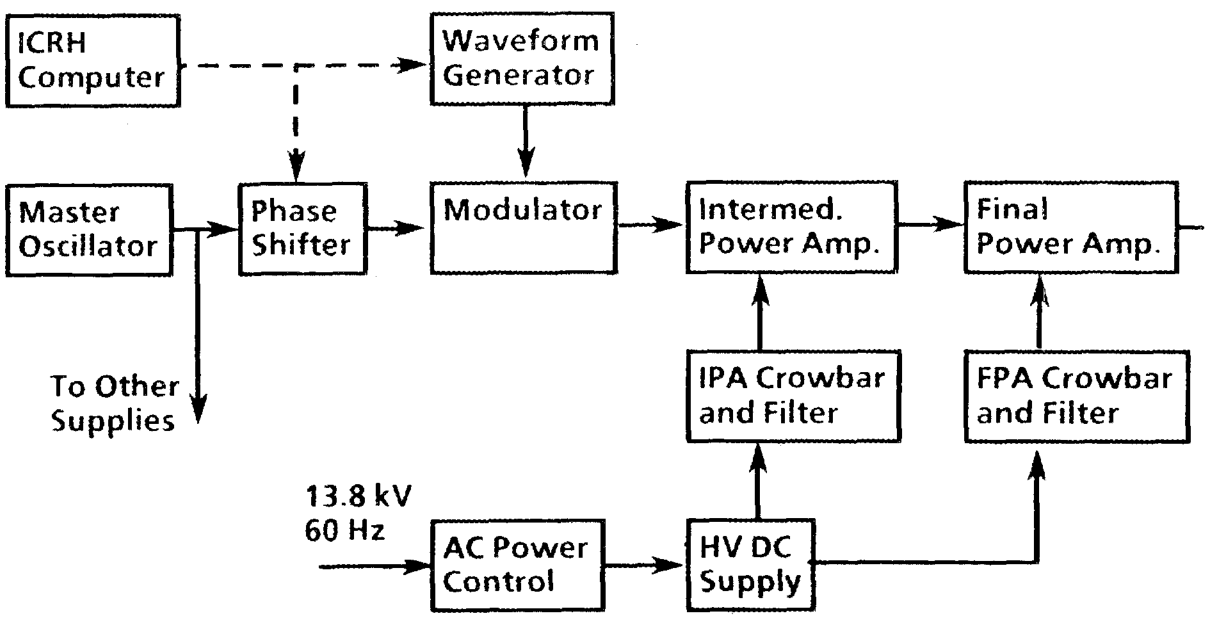

Fig. A-5. RF power system diagram.

The transmitter will be designed to be tuned over a range of 60–110 MHz, which is greater than the nominal design range of 80–110 MHz for the entire system. However, it should be reasonably easy to design the transmitter to cover this frequency range. The power deliverable by the transmitter should be greater than 2 MW at frequencies below 95 MHz but will probably fall off rapidly at higher frequencies.

The requirements of 2 MW per power unit are beyond the capabilities of currently available rf tubes at 95 MHz. Development effort will be required to improve the X-2242 tetrode from EIMAC to operate at this power level and frequency. In addition, modifications to the FMIT transmitters will be required and testing of the modified units with the improved tetrodes will be needed early in the program.

Appendix B
CALCULATIONS OF PLASMA PARAMETERS

B.1 UNITS

All quantities in the tables and formulas are given in the following units:

Length—meters
Magnetic field—tesla
Plasma current—MA
Power—MW
Energy—MJ
τ_E—seconds
η—10^{20}m^{-3}
T—keV

B.2 FORMULAS

Plasma volume

$$V = 2\pi^2 R\kappa a^2 = 19.74\ R\kappa a^2$$

Plasma q at edge (approximate, with correction for finite aspect ratio)

$$q = 2.5\frac{B_t a^2}{I_p R}\frac{(1+\kappa)^2}{[1-(a/R)^2]^2}$$

Ohmic heating power

$$P_{oh} = 0.5 I_p$$

(assumes 0.5 V loop voltage during auxiliary heating)

ICH power density at the antenna(s)

$$P_{\text{ICH}}/A = P_{\text{ICH}}/(h_{\text{port}} w_{\text{port}} N_{\text{ports}})$$

Plasma confinement time (Kaye-Goldston scaling)[2]

$$\tau_E = [(1/\tau_{\text{ohmic}})^2 + (1/\tau_{\text{aux}})^2]^{-1/2}\ ,$$

where

$$\tau_{\text{ohmic}} = 0.07\ nR^2 aq^*$$
$$\tau_{\text{aux}} = 0.056\ I_p^{1.24} R^{1.65} \kappa^{0.28} n_{\text{oper}}^{0.26}/(P_{\text{total}}^{0.58} a^{0.49} B_t^{0.09})$$
$$q^* = 2.5\ a^2 B_t(1+\kappa^2)/(I_p R)$$

are the equations for neo-Alcator ohmic scaling, L-mode auxiliary heating scaling, and "circular" q equivalent, respectively.

Plasma pressure

Using $P\tau_e/V = 3/2\ n(T_e + T_i)$ and converting to the units given earier (n in 10^{20} m^{-3}, T in keV gives $n(T_e + T_i) = 41.7\ P_{\text{total}}\tau_e/V$.

Plasma beta (%)

$$\beta = \frac{P_{\text{total}}\tau_E}{VB_t^2/2\mu_0} = 2.5\frac{P_{\text{total}}\tau_E}{VB_t^2} \times 100$$

Maximum density attainable (Greenwald scaling, for auxiliary heated plasma)

$$n_{\max} = I_p/\pi a^2$$

Maximum normal operating density

$n_{\text{oper}} = 0.75\ n_{\max}$ or 4.0, whichever is smaller. The value of 4.0 is the density at which CIT will operate to achieve ignition (see Fig. 1).

Dimensionless ICRF parameters

$$f_{ci}/f_{pi} = \frac{eB_t}{M(ne^2/\epsilon_0 M)^{1/2}} = 7.23 \times 10^{-3} B_t/(nA_i)^{1/2}$$

$$\lambda_{rf}/a = \frac{V_{\text{Alfvén}}}{f_{ci}a} = 0.143\ A_i^{1/2}/an^{1/2}$$

$$\rho_i/a = (2kT_i/M_i)^{1/2}/\omega_{ci}a = 4.6 \times 10^{-3}(T_i A_i)^{1/2}/B_t a$$

$$\nu_i^* = \nu_i/\omega_{\text{bounce}} = 8.33 \times 10^{-3}\ n\ q\ R_0(R_0/a)^{3/2}/T_i^2$$

where

$$\nu_i = \frac{ne^4 \ln \Lambda}{12\pi(\pi M_i)^{1/2}\epsilon_0^2(kT_i)^{3/2}}$$

is the ion collison frequency and

$$\omega_{\text{bounce}} = \frac{(kT_i/M_i)^{1/2}(a/R_0)^{1/2}}{qR_0}$$

is the trapped ion bounce frequency.

All numbers were calculated for $A_i = 1$.

B.3 TABLES

Tables B-1 and B-2 list tokamak ICH experiments and parameters.

Table B-1. Complete list of tokamak ICH experiments

TOKRF11	CIT 11/93	CIT 11/95	DIII-D 1/87	DIII-D 1/88	DIII-D 1/90	TFTR 6/87	TFTR 4/88	TFTR 1/90	ALC-C 9/86	C-MOD 1/89	C-MOD 1/90	C-MOD 1/91	C-MOD 1/92
Geometry													
R^* (m)	1.22	1.22	1.67	1.67	1.67	2.60	2.60	2.60	0.64	0.64	0.64	0.64	0.64
a^* (m)	0.45	0.45	0.67	0.67	0.67	0.96	0.96	0.96	0.12	0.21	0.21	0.21	0.21
Elongation*	1.90	1.90	2.20	2.50	2.50	1.00	1.00	1.00	1.00	1.80	1.80	1.80	1.80
Volume (m^3)	9.27	9.27	32.56	37.00	37.00	47.30	47.30	47.30	0.18	1.00	1.00	1.00	1.00
B_{tor}^* (T)	10.40	10.40	2.20	2.20	2.20	5.00	5.00	5.00	12.00	9.00	9.00	9.00	9.00
I_p^* (MA)	9.00	9.00	2.50	2.50	3.50	3.50	3.50	3.50	0.30	3.00	3.00	3.00	3.00
$q(a)$	2.96	2.96	4.91	6.09	4.35	3.39	3.39	3.39	4.83	2.75	2.75	2.75	2.75
t_{pulse}^* (s)	3.70	3.70	1.50	1.50	1.50	3.00	3.00	3.00	0.10	1.00	1.00	1.00	1.00
Edge[b]	L,D	L,D	L,E	L,E	L,E	L,P	L,P	L,P	L	L,D	L,D	L,D	L,D
Power													
P_{oh} (MW)	4.5	4.5	1.3	1.3	1.8	1.8	1.8	1.8	0.2	1.5	1.5	1.5	1.5
P_{nbi}^* (MW)			10.0	14.0	14.0	12.0	27.0	27.0					
P_{ich}^* (MW)	10.0	20.0	0.0	2.2	9.0	6.0	10.0	10.0	0.5	3.0	5.0	5.0	5.0
P_{lhh}^* (MW)			0.0	0.0	0.0								3.0
P_{ech}^* (MW)			1.4	2.0	2.0								
P_{other}^* (MW)		25.0											
P_{total} (MW)	14.5	49.5	12.7	19.5	26.8	19.8	38.8	38.8	0.7	4.5	6.5	6.5	9.5
ICH parameters													
f_{ich}^* (MHz)	95.0	95.0	74.0	60.0	60.0	47.0	47.0	47.0	210.0	80.0	80.0	80.0	80.0
f_{cH+} (MHz)	156.0	156.0	33.0	33.0	33.0	75.0	75.0	75.0	180.0	135.0	135.0	135.0	135.0
Mode*[a]	M2,2T	M2,2T	2H	2H	2H,2He,M	M2,2D	M2,2D	M2,2T	2H	M2	M2	M2	M2
h_{port}^* (m)	0.80	0.80	0.50	0.50	0.50	0.85	0.85	0.85	0.30	0.60	0.60	0.60	0.60
w_{port}^* (m)	0.30	0.30	0.35	0.35	0.35	0.60	0.66	0.66	0.04	0.15	0.15	0.15	0.15
A_{port} (m^2)	0.24	0.24	0.18	0.18	0.18	0.60	0.56	0.56	0.01	0.09	0.09	0.09	0.09
N_{ports}^*	3.00	5.00	1.00	2.00	4.00	2.00	2.00	2.00	2.00	2.00	4.00	4.00	3.00
$P/A_{antenna}$ (MW/m^2)	13.89	16.67	0.00	6.29	12.86	5.00	8.91	8.91	20.83	16.67	13.89	13.89	18.52
P/V_{ich} (MW/m^3)	1.08	2.16	0.00	0.06	0.24	0.13	0.21	0.21	2.75	2.99	4.99	4.99	4.99
t_{ich}^* (s)	3.00	3.00		5.00	5.00	2.00	2.00	2.00	0.10	1.00	1.00	1.00	1.00
$Energy_{ich}$ (MJ)	30.00	60.00	0.00	11.00	45.00	12.00	20.00	20.00	0.05	3.00	5.00	5.00	5.00
Energy/A (MJ/m^2)	41.67	50.00	0.00	31.43	64.29	10.00	17.83	17.83	2.08	16.67	13.89	13.89	18.52
Plasma properties													
n_{max} (10^{20} m^{-3})	14.15	14.15	1.77	1.77	2.48	1.21	1.21	1.21	6.63	21.65	21.65	21.65	21.65
n_{oper} (10^{20} m^{-3})	4.00	4.00	1.33	1.33	1.86	0.91	0.91	0.91	4.00	4.00	4.00	4.00	4.00
H-mode multiplier*	2.00	2.00	2.00	2.00	2.00	1.00	1.00	1.00	1.00	2.00	2.00	2.00	2.00
τ_e (K-G) (s)	0.647	0.433	0.276	0.227	0.309	0.192	0.131	0.131	0.023	0.098	0.094	0.094	0.090
β (%)	2.34	5.34	5.55	6.16	11.54	0.80	1.07	1.07	0.14	1.36	1.89	1.89	2.62
$n(T_e+T_i)$ (10^{20} $m^{-3}\cdot keV$)	42.51	97.06	4.51	5.01	9.38	3.37	4.51	4.51	3.49	18.44	25.69	25.69	35.63
T_i (keV)	5.31	12.13	1.70	1.88	2.52	1.86	2.49	2.49	0.44	2.30	3.21	3.21	4.45
Dimensionless parameters													
f_{ci}/f_{pi}	0.27	0.27	0.10	0.10	0.08	0.27	0.27	0.27	0.31	0.23	0.23	0.23	0.23
λ/a	0.18	0.18	0.21	0.21	0.18	0.18	0.18	0.18	0.67	0.38	0.38	0.38	0.38
ρ_i/a (×100)	0.32	0.48	0.57	0.61	0.70	0.18	0.21	0.21	0.30	0.52	0.62	0.62	0.73
ν_i^*	0.019	0.004	0.124	0.125	0.070	0.086	0.048	0.048	6.683	0.059	0.030	0.030	0.016

Table B-1. (cont.)

TOKRF11	C-MOD 1/93	TEXTOR 1/86	TEXTOR 4/87	TEXTOR 5/88	JET 6/86	JET 6/87	JET 6/87	JET 1/90	JET 12/92	ASDEX 1/87	ASDEX-U 1/89
Geometry											
R^* (m)	0.64	1.75	1.75	1.75	3.00	3.00	3.00	3.00	3.00	1.65	1.65
a^* (m)	0.21	0.46	0.46	0.46	1.20	1.20	1.20	1.20	1.20	0.40	0.50
Elongation*	1.80	1.00	1.00	1.00	1.40	1.60	1.60	1.60	1.60	1.00	1.60
Volume (m^3)	1.00	7.31	7.31	7.31	119.39	136.44	136.44	136.44	136.44	5.21	13.03
B_{tor}^* (T)	9.00	2.60	2.60	2.60	3.40	3.40	3.40	3.40	3.40	2.80	3.50
I_p^* (MA)	3.00	0.50	0.50	0.50	5.00	7.00	4.00	4.00	4.00	0.50	2.00
$q(a)$	2.75	3.63	3.63	3.63	3.42	2.94	5.15	5.15	5.15	3.06	2.86
t_{pulse}^* (s)	1.00	3.00	3.00	3.00	15.00	15.00	15.00	15.00	15.00	10.00	5.00
Edge[b]	L,D	L,P	P	P	L,E	L	L,E	L,E,P	L,E,P	L,D	L,D
Power											
P_{oh} (MW)	1.5	0.3	0.3	0.3	2.5	3.5	2.0	2.0	2.0	0.3	1.0
P_{nbi}^* (MW)				3.0	9.0	18.0	18.0	18.0	18.0	3.3	6.0
P_{ich}^* (MW)	5.0	2.7	2.7	4.2	7.0	20.0	20.0	25.0	25.0	4.0	6.0
P_{lhh}^* (MW)	3.0							10.0	10.0	2.3	
P_{ech}^* (MW)	2.0										
P_{other}^* (MW)											
P_{total} (MW)	11.5	3.0	3.0	7.5	18.5	41.5	40.0	55.0	55.0	9.8	13.0
ICH parameters											
f_{ich}^* (MHz)	80.0	29.0	29.0	29.0	55.0	55.0	55.0	55.0	51.0	115.0	120.0
f_{cH+} (MHz)	135.0	39.0	39.0	39.0	51.0	51.0	51.0	51.0	51.0	42.0	52.5
Mode*[a]	M2	M1,M2,2D	M1,M2,2D	M1,M2,2D	M1,M2	M1,M2	M1,M2	M1,M2	M1,M2,2T	M1,M2,2H	M1,M2,2H
h_{port}^* (m)	0.60	1.38	0.73	0.73	1.60	1.60	1.60	1.60	1.60	0.80	1.00
w_{port}^* (m)	0.15	0.25	0.26	0.26	0.50	0.50	0.50	0.50	0.50	0.30	0.70
A_{port} (m^2)	0.09	0.35	0.19	0.19	0.80	0.80	0.80	0.80	0.80	0.24	0.70
N_{ports}^*	3.00	2.00	4.00	4.00	3.00	8.00	8.00	8.00	8.00	2.00	4.00
$P/A_{antenna}$ (MW/m^2)	18.52	3.91	3.56	5.53	2.92	3.13	3.13	3.91	3.91	8.33	2.14
P/V_{ich} (MW/m^3)	4.99	0.37	0.37	0.57	0.06	0.15	0.15	0.18	0.18	0.77	0.46
t_{ich}^* (s)	1.00	1.50	1.50	1.50	10.00	10.00	10.00	10.00	5.00	10.00	10.00
$Energy_{ich}$ (MJ)	5.00	4.05	4.05	6.30	70.00	200.00	200.00	250.00	125.00	40.00	60.00
Energy/A (MJ/m^2)	18.52	5.87	5.33	8.30	29.17	31.25	31.25	39.06	19.53	83.33	21.43
Plasma properties											
n_{max} (10^{20} m^{-3})	21.65	0.75	0.75	0.75	1.11	1.55	0.88	0.88	0.88	0.99	2.55
n_{oper} (10^{20} m^{-3})	4.00	0.56	0.56	0.56	0.83	1.16	0.66	0.66	0.66	0.75	1.91
H-mode multiplier*	2.00	1.00	1.00	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00
τ_e (K-G) (s)	0.087	0.036	0.036	0.021	0.385	0.417	0.376	0.313	0.313	0.038	0.223
β (%)	3.06	0.54	0.54	0.81	1.29	2.75	2.39	2.73	2.73	2.27	4.55
$n(T_e+T_i)$ (10^{20} $m^{-3}\cdot keV$)	41.70	0.61	0.61	0.92	2.51	5.33	4.63	5.31	5.31	2.99	9.36
T_i (keV)	5.21	0.54	0.54	0.81	1.51	2.30	3.49	4.00	4.00	2.00	2.45
Dimensionless parameters											
f_{ci}/f_{pi}	0.23	0.18	0.18	0.18	0.19	0.16	0.22	0.22	0.22	0.17	0.13
λ/a	0.38	0.47	0.47	0.47	0.15	0.12	0.16	0.16	0.16	0.47	0.23
ρ_i/a ($\times 100$)	0.79	0.40	0.40	0.49	0.20	0.24	0.30	0.32	0.32	0.82	0.58
ν_i^*	0.011	0.754	0.754	0.336	0.123	0.064	0.028	0.021	0.021	0.066	0.075

Table B-1. (cont.)

TOKRF11	T.SUP. 88	T.SUP. 89	T.SUP. 90	JIPPT-II 86	JIPPT-II 87	JIPPT-II 88	JIPPT-II 89	JFT-2M 4/87	JFT-2M 4/88	JFT-2M 4/90	JT-60 10/86	JT-60 12/87
Geometry												
R^* (m)	2.25	2.25	2.25	0.91	0.91	0.91	0.91	1.30	1.30	1.30	3.00	3.00
a^* (m)	0.80	0.80	0.80	0.23	0.23	0.23	0.23	0.35	0.35	0.35	0.90	0.90
Elongation*	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.70	1.70	1.70	1.00	1.00
Volume (m^3)	28.43	28.43	28.43	0.95	0.95	0.95	0.95	5.34	5.34	5.34	47.97	47.97
B_{tor}^* (T)	4.50	4.50	4.50	3.00	3.00	3.00	3.00	1.40	1.40	4.00	4.50	4.50
I_p^* (MA)	1.70	1.70	1.70	0.30	0.30	0.30	0.30	0.50	0.50	1.50	2.10	2.10
$q(a)$	4.93	4.93	4.93	3.32	3.32	3.32	3.32	2.98	2.98	2.84	3.49	3.49
t_{pulse}^* (s)	30.00	30.00	30.00	0.10	0.10	0.10	0.10	1.00	1.00	2.00	10.00	10.00
Edge[b]	L,P	P	P	L	L	L	L	L,D	L,D,P	L,D,P	L,D	L,D
Power												
P_{oh} (MW)	0.9	0.9	0.9	0.1	0.1	0.1	0.1	0.3	0.3	0.8	1.1	1.1
P_{nbi}^* (MW)		3.5	7.0	1.0	2.0	2.0	2.0	1.6	1.6	2.5	20.0	20.0
P_{ich}^* (MW)	8.0	12.0	12.0	2.0	4.0	4.0	4.0	3.0	3.0	10.0	2.0	5.0
P_{lhh}^* (MW)	4.0	8.0	8.0	0.3	1.0	1.0	1.0	0.6	0.6		7.0	15.0
P_{ech}^* (MW)		0.2				0.5	0.5	0.3				
P_{other}^* (MW)								0.1	0.4	2.0		
P_{total} (MW)	12.9	24.6	27.9	3.5	7.2	7.7	7.7	5.9	5.9	15.3	30.1	41.1
ICH parameters												
f_{ich}^* (MHz)	80.0	80.0	80.0	40.0	200.0	7.0	60.0	40.0	40.0	60.0	130.0	130.0
f_{cH+} (MHz)	67.5	67.5	67.5	45.0	45.0	45.0	45.0	21.0	21.0	60.0	67.5	67.5
Mode*[a]	M1,M2	M1,M2,2H	M1,M2,2H	M1	?	Alfvén	IBW	M1,2H	M1,2H	M1,2H	2H	2H
h_{port}^* (m)	0.60	0.60	0.60	0.50	0.50	0.50	0.30	0.70	0.70	0.70	0.52	0.52
w_{port}^* (m)	0.50	0.50	0.50	0.10	0.10	0.10	0.30	0.07	0.07	0.07	0.37	0.37
A_{port} (m^2)	0.30	0.30	0.30	0.05	0.05	0.05	0.09	0.05	0.05	0.05	0.19	0.19
N_{ports}^*	2.00	3.00	3.00	6.00	4.00	8.00	2.00	3.00	3.00	10.00	1.00	1.00
$P/A_{antenna}$ (MW/m^2)	13.33	13.33	13.33	6.67	20.00	10.00	22.22	20.41	20.41	20.41	10.40	25.99
P/V_{ich} (MW/m^3)	0.28	0.42	0.42	2.10	4.21	4.21	4.21	0.56	0.56	1.87	0.04	0.10
t_{ich}^* (s)	30.00	30.00	30.00	0.10	0.10	0.10	0.10	0.50	0.50	1.00	10.00	10.00
$Energy_{ich}$ (MJ)	240.00	360.00	360.00	0.20	0.40	0.40	0.40	1.50	1.50	10.00	20.00	50.00
Energy/A (MJ/m^2)	400.00	400.00	400.00	0.67	2.00	1.00	2.22	10.20	10.20	20.41	103.95	259.88
Plasma properties												
n_{max} (10^{20} m^{-3})	0.85	0.85	0.85	1.81	1.81	1.81	1.81	1.30	1.30	3.90	0.83	0.83
n_{oper} (10^{20} m^{-3})	0.63	0.63	0.63	1.35	1.35	1.35	1.35	0.97	0.97	2.92	0.62	0.62
H-mode multiplier*	1.00	1.00	1.00	1.00	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00
τ_e (K-G) (s)	0.081	0.056	0.052	0.010	0.007	0.007	0.007	0.048	0.048	0.130	0.193	0.162
β (%)	0.45	0.59	0.62	1.05	1.44	1.48	1.48	6.67	6.67	5.79	1.50	1.71
$n(T_e+T_i)$ (10^{20} $m^{-3}\cdot keV$)	1.53	2.01	2.13	1.58	2.17	2.24	2.24	2.20	2.20	15.56	5.09	5.81
T_i (keV)	1.21	1.59	1.68	0.58	0.80	0.83	0.83	1.13	1.13	2.66	4.11	4.69
Dimensionless parameters												
f_{ci}/f_{pi}	0.29	0.29	0.29	0.13	0.13	0.13	0.13	0.07	0.07	0.12	0.30	0.30
λ/a	0.25	0.25	0.25	0.60	0.60	0.60	0.60	0.47	0.47	0.27	0.23	0.23
ρ_i/a ($\times 100$)	0.20	0.23	0.23	0.72	0.84	0.86	0.86	1.41	1.41	0.76	0.33	0.35
ν_i^*	0.190	0.110	0.098	0.786	0.417	0.393	0.393	0.178	0.178	0.091	0.019	0.015

[a] M1 = H minority in D; M2 = He^3 minority in D; M3 = H minority in He^3; M4 = H minority in He^4; 2H = second harmonic H; 2D = second harmonic D; 2T = second harmonic T; and 2He = second harmonic He^3.

[b] L = limiter; D = divertor; E = extended boundary; and P = pumped limiter.

Table B-2. Complete list of tokamak ICH experimental parameters normalized to parameter values for CIT

TOKRF11	CIT 1/93	CIT 1/95	DIII-D 1/87	DIII-D 1/88	DIII-D 1/90	TFTR 6/87	TFTR 4/88	TFTR 1/90	ALC-C 9/86	C-MOD 1/89	C-MOD 1/90	C-MOD 1/91	C-MOD 1/92	C-MOD 1/93
Mode*[a]	M2,2T	M2,2T	2H	2H	2H,2He,M	M2	M2	M2	2H	M2	M2	M2	M2	M2
Edge[b]	L,D	L,D	L,E	L,E	L,E	L	L	L	L	L,D	L,D	L,D	L,D	L,D
B_{tor}	1.00	1.00	0.21	0.21	0.21	0.48	0.48	0.48	1.15	0.87	0.87	0.87	0.87	0.87
κ	1.00	1.00	1.16	1.32	1.32	0.53	0.53	0.53	0.53	0.95	0.95	0.95	0.95	0.95
P_{ich}/A	1.00	1.20	0.00	0.45	0.93	0.36	0.64	0.64	1.50	1.20	1.00	1.00	1.33	1.33
P_{ich}/V	1.00	2.00	0.00	0.06	0.23	0.12	0.20	0.20	2.55	2.77	4.62	4.62	4.62	4.62
n_{oper}	1.00	1.00	0.33	0.33	0.47	0.23	0.23	0.23	1.00	1.00	1.00	1.00	1.00	1.00
β	1.00	2.28	2.37	2.63	4.93	0.34	0.46	0.46	0.06	0.58	0.81	0.81	1.12	1.31
f_{ci}/f_{pi}	1.00	1.00	0.37	0.37	0.31	1.01	1.01	1.01	1.15	0.87	0.87	0.87	0.87	0.87
λ/a	1.00	1.00	1.16	1.16	0.98	0.98	0.98	0.98	3.75	2.14	2.14	2.14	2.14	2.14
ρ_i/a	1.00	1.51	1.79	1.89	2.19	0.58	0.67	0.67	0.93	1.63	1.93	1.93	2.27	2.45

TOKRF11	TEXTOR 1/86	TEXTOR 4/87	TEXTOR 5/88	JET 6/86	JET 6/87	JET 6/87	JET 1/90	JET 12/92	ASDEX 1/87	ASDEX-U 1/89	T.SUP. 1/89	T.SUP. 1/89
Mode*[a]	M1,M2,2D	M1,M2,2D	M1,M2,2D	M1,M2	M1,M2	M1,M2	M1,M2	M1,M2,2T	M1,M2,2H	M1,M2,2H	M1,M2	M1,M2
Edge[b]	L,P	P	P	L,E	L,E	L,E	L,E,P	L,E,P	L,D	L,D	L	L
B_{tor}	0.25	0.25	0.25	0.33	0.33	0.33	0.33	0.33	0.27	0.34	0.43	0.43
κ	0.53	0.53	0.53	0.74	0.84	0.84	0.84	0.84	0.53	0.84	0.53	0.53
P_{ich}/A	0.28	0.26	0.40	0.21	0.23	0.23	0.28	0.28	0.60	0.15	0.96	0.96
P_{ich}/V	0.34	0.34	0.53	0.05	0.14	0.14	0.17	0.17	0.71	0.43	0.26	0.39
n_{oper}	0.14	0.14	0.14	0.21	0.29	0.17	0.17	0.17	0.19	0.48	0.16	0.16
β (%)	0.23	0.23	0.34	0.55	1.17	1.02	1.17	1.17	0.97	1.94	0.19	0.25
f_{ci}/f_{pi}	0.67	0.67	0.67	0.72	0.61	0.80	0.80	0.80	0.62	0.49	1.09	1.09
λ/a	2.60	2.60	2.60	0.82	0.70	0.92	0.92	0.92	2.60	1.30	1.41	1.41
ρ_i/a	1.25	1.25	1.53	0.61	0.75	0.93	1.00	1.00	2.57	1.82	0.62	0.71

TOKRF11	T.SUP. 1/90	JIPPT-II 86	JIPPT-II 87	JIPPT-II 88	JIPPT-II 89	JFT-2M 4/87	JFT-2M 4/88	JFT-2M 4/90	JT-60 10/86	JT-60 12/87
Mode*[a]	M1,M2	M1	?	Alfvén	IBW	M1,2H	M1,2H	M1,2H	2H	2H
Edge[b]	L	L	L	L	L	L,D	L,D,P	L,D,P	L,D	L,D
B_{tor}	0.43	0.29	0.29	0.29	0.29	0.13	0.13	0.38	0.43	0.43
κ	0.53	0.53	0.53	0.53	0.53	0.89	0.89	0.89	0.53	0.53
P_{ich}/A	0.96	0.48	1.44	0.72	1.60	1.47	1.47	1.47	0.75	1.87
P_{ich}/V	0.39	1.95	3.90	3.90	3.90	0.52	0.52	1.73	0.04	0.10
n_{oper}	0.16	0.34	0.34	0.34	0.34	0.24	0.24	0.73	0.15	0.15
β	0.27	0.45	0.61	0.63	0.63	2.85	2.85	2.47	0.64	0.73
f_{ci}/f_{pi}	1.09	0.50	0.50	0.50	0.50	0.27	0.27	0.45	1.10	1.10
λ/a	1.41	3.36	3.36	3.36	3.36	2.60	2.60	1.50	1.27	1.27
ρ_i/a	0.73	2.25	2.63	2.67	2.67	4.40	4.40	2.37	1.02	1.09

[a]M1 = H minority in D; M2 = He^3 minority in D; M3 = H minority in He^3; M4 = H minority in He^4; 2H = second harmonic H; 2D = second harmonic D; 2T = second harmonic T; and 2He = second harmonic He^3.

[b]L = limiter; D = divertor; E = extended boundary; and P = pumped limiter.

Appendix C

SURVEY RESPONSES

IPSG ICRH SURVEY (Part 2)

Machine: Alcator-C

This survey is intended to provide a data base for ICH heating, physics, and technology from 1986 through 1990. Please indicate in the spaces below what the main objectives of the ICH experimental program will be for different time periods of machine operation. The intent of this part of the survey is to obtain a qualitative indication of the main questions that the research you will do will answer.

Time period: 8/18 - 9/18/86

Major goals/questions: Test $2\omega_{ch}$ fast wave heating at B = 6T at high densities and high fields; test antenna spectrum; may also test minority (H+) heating in D+ at B = 12T.

Time period: 7/18 - 8/18/86

Major goals/questions: Test ion Bernstein wave hookup at $\omega = 3/2\ \omega_{ch} = 3\ \omega_{cd}$ at B = 7.6T at high densities (linear and nonlinear absorption).

Time period: ____________

Major goals/questions: ____________

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Time period: ____________

Major goals/questions: ____________

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Time period: ____________

Major goals/questions: ____________

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IPSG ICRH SURVEY (Part 1)

Machine: ALCATOR-C/MOD Filled out by: M. Porkolab Date: 6/28/86

DATE	1/89	1/90	1/91	1/92	1/93
MACHINE & GEOMETRY					
1. R (m)	0.64	0.64	0.64	0.64	0.64
2. a (m)	0.21	0.21	0.21	0.21	0.21
3. Elongation (b/a)	1.8	1.8	1.8	1.8	1.8
4. B_{tor} (T)	7-9	7-9	7-9	7-9	7-9
5. I_p (MA)	3	3	3	3	3
6. t_{pulse} (s)	1	1	1	1	1
7. Edge (L, D, E, P)	L,D	L,D	L,D	L,D	L,D
POWER					
8. P_{NBI} (MW)					
9. P_{ICH} (MW)	3	5	5	5	5
10. P_{LHH} (MW)				3	3
11. P_{ECH} (MW)					2
12. P_{OTHER} (MW)					
ICH PARAMETERS					
13. f_{ICH} (MHz)	80	80 & 180	80 & 180	80 & 180	80 & 180
14. h_{ant} (m)	60	60, 60	60, 60	60, 60	60, 60
15. w_{ant} (m)	15	15, 15	15, 15	15, 15	15, 15
16. N_{ant}	2	4	4	3	3
17. t_{ICH}(s)	1	1	1	1	1
18. Mode	FW	FW + IBW	FW + IBW	FW + IBW	FW + IBW
19. Frac. oper. time	0.5	0.8	0.6	0.6	0.4
PLASMA PROPERTIES					
20. n_e ($10^{20}m^{-3}$)	1-4	1-5	1-5	1-5	1-5
21. T_e (keV)	2	3	4	4	5
22. T_i (keV)	3	5	5	5	5

Notes: 1/89 - Fast wave, minority ^{3}He in D (loop antenna)
1/90 - Fast wave (loop) + IBW (dielectric loaded waveguide, loop)
1/91-92 - Add LHSW and LHFW current drive.
1/93 - Add 250 GHz ECH, 2 MW.

IPSG ICRH SURVEY (Part 2)

Machine: ALCATOR C-MOD

This survey is intended to provide a data base for ICH heating, physics, and technology from 1986 through 1990. Please indicate in the spaces below what the main objectives of the ICH experimental program will be for different time periods of machine operation. The intent of this part of the survey is to obtain a qualitative indication of the main questions that the research you will do will answer.

Time period: 1/89 - 1/90

Major goals/questions: FW minority heating (^{3}He-minority in D majority), scaling of confinement with ICRH in diverted plasmas (3 MW)

Time period: 1/90 - 10/90

Major goals/questions: Above, but raise power to 5 MW. Also, test IBW heating at 80/180 MHz with loop and dielectric loaded waveguide. $\omega = 1.5\ \omega_{cd}$ and $\omega = 2.5\ \omega_{cd}$ (180 MHz).

Time period: ________________

Major goals/questions: ____

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Time period: ________________

Major goals/questions: ____

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Time period: ________________

Major goals/questions: ____

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IPSG ICRH SURVEY (Part 1)

Machine: ASDEX   Filled out by: F. Wesner   Date: 3/7/86

DATE	1/87				
MACHINE & GEOMETRY					
1. R (m)	1.65				
2. a (m)	0.4				
3. Elongation (b/a)	1				
4. B_{tor} (T)	1.5 - 2.8				
5. I_p (MA)	0.2 - 0.5				
6. t_{pulse} (s)	3 - 10				
7. Edge (L, D, E, P)	D (L)				
POWER					
8. P_{NBI} (MW)	3.25				
9. P_{ICH} (MW)	4				
10. P_{LHH} (MW)	2.3				
11. P_{ECH} (MW)	—				
12. P_{OTHER} (MW)	—				
ICH PARAMETERS					
13. f_{ICH} (MHz)	30 - 115				
14. h_{ant} (m)	0.8				
15. w_{ant} (m)	0.3				
16. N_{ant}	2				
17. t_{ICH}(s)	10				
18. Mode	Min./2Ω_c				
19. Frac. oper. time	~0.3				
PLASMA PROPERTIES					
20. n_e ($10^{20}m^{-3}$)	<5.0				
21. T_e (keV)	<1.5				
22. T_i (keV)	<2				

Notes Heating modes: H^- minority in D; He^3 minority for comparison (only off-axis deposition possible); $2\Omega_{CH}$ in H^- plasmas and H/D mixtures.

IPSG ICRH SURVEY (Part 2)

Machine: ASDEX

This survey is intended to provide a data base for ICH heating, physics, and technology from 1986 through 1990. Please indicate in the spaces below what the main objectives of the ICH experimental program will be for different time periods of machine operation. The intent of this part of the survey is to obtain a qualitative indication of the main questions that the research you will do will answer.

Time period: May 1984 - 1988

Major goals/questions: ICRH in a divertor tokamak; combination with NI, LH, pellets; coupling and confinement (H mode), impurity question at minority and second harmonic heating for long pulses (several seconds).

Time period: 1989 - ______

Major goals/questions: ICRH - physics

Optimization of loop antennas

ICRH with waveguide antennas

Time period: ______

Major goals/questions: ______

Time period: ______

Major goals/questions: ______

Time period: ______

Major goals/questions: ______

IPSG ICRH SURVEY (Part 1)

Machine: ASDEX - Upgrade Filled out by: F. Wesner Date: 3/7/86

DATE	1/1989				
MACHINE & GEOMETRY					
1. R (m)	1.65				
2. a (m)	0.5				
3. Elongation (b/a)	1.6				
4. B_{tor} (T)	2 - 3.5				
5. I_p (MA)	1 - 2				
6. t_{pulse} (s)	2 - 5				
7. Edge (L, D, E, P)	D (L)				
POWER					
8. P_{NBI} (MW)	6				
9. P_{ICH} (MW)	6				
10. P_{LHH} (MW)	----				
11. P_{ECH} (MW)	---				
12. P_{OTHER} (MW)	---				
ICH PARAMETERS					
13. f_{ICH} (MHz)	30 - 120				
14. h_{ant} (m)	1.0				
15. w_{ant} (m)	0.7				
16. N_{ant}	4				
17. t_{ICH}(s)	10				
18. Mode	Min.; $2\Omega_{CH}$				
19. Frac. oper. time					
PLASMA PROPERTIES					
20. n_e ($10^{20}m^{-3}$)	<1.5				
21. T_e (keV)	<3				
22. T_i (keV)	<3				

Notes Power: 8 MW RF at 80 MHz for 6 MW in plasma. The frequency range allows operation of He^3 and H minority as well as second harmonic heating.

IPSG ICRH SURVEY (Part 2)

Machine: ASDEX - Upgrade

This survey is intended to provide a data base for ICH heating, physics, and technology from 1986 through 1990. Please indicate in the spaces below what the main objectives of the ICH experimental program will be for different time periods of machine operation. The intent of this part of the survey is to obtain a qualitative indication of the main questions that the research you will do will answer.

Time period: 1989 - ____

Major goals/questions: Effective heating to reach the physical goals of ASDEX-Upgrade. ICRH in an open divertor geometry; effectiveness of minority and $2\Omega_C$ heating in a high density, high temperature plasma; influence of different k-spectrum.

Time period: ________________

Major goals/questions: ________________

Time period: ________________

Major goals/questions: ________________

Time period: ________________

Major goals/questions: ________________

Time period: ________________

Major goals/questions: ________________

IPSG ICRH SURVEY (Part 1)

Machine: DIII-D   Filled out by: R. Prater/M. Mayberry   Date: July 22, 1986

DATE	1/87	1/88	1/90		
MACHINE & GEOMETRY					
1. R (m)	1.67	1.67	1.67		
2. a (m)	0.67	0.67	0.67		
3. Elongation (b/a)	2.2	2.5	2.5		
4. B_{tor} (T)	2.2	2.2	2.2		
5. I_p (MA)	3.5L, 2.5E	3.5-2.5	5L, 3.5E		
6. t_{pulse} (s)	1.5 s Full I_p 10s 50% I_p	1.5-10	6S full I_p w/ P/S upgrade		
7. Edge (L, D, E, P)	LE	LEP	LEP		
POWER					
8. P_{NBI} (MW)	10	12-14	14		
9. P_{ICH} (MW)	0.0001	2.2	9.0		
10. P_{LHH} (MW)	0	0	0		
11. P_{ECH} (MW)	1.4	2.0	2.0		
12. P_{OTHER} (MW)	0	0	0		
ICH PARAMETERS					
13. f_{ICH} (MHz)	20-74	30-60	30-60		
14. h_{ant} (m)	.50	.50	.50		
15. w_{ant} (m)	.35	.35	.35		
16. N_{ant}	1	2	4		
17. t_{ICH}(s)	CW	5	5		
18. Mode	2H	2H	2H, 2He^3, (H)/He^3He^4		
19. Frac. oper. time	.05	.2	.4		
PLASMA PROPERTIES					
20. n_e ($10^{20} m^{-3}$)	0.5	0.6	1.0		
21. T_e (keV)	4.0	4.6	7		
22. T_i (keV)	4.0	4.6	7		

Notes

IPSG ICRH SURVEY (Part 2)

Machine: DIII-D

This survey is intended to provide a data base for ICH heating, physics, and technology from 1986 through 1990. Please indicate in the spaces below what the main objectives of the ICH experimental program will be for different time periods of machine operation. The intent of this part of the survey is to obtain a qualitative indication of the main questions that the research you will do will answer.

Time period: 6/86 - 3/87

Major goals/questions: Coupling tests for resonant cavity antenna, using very low power. Absorption measurements for 2nd harmonic hydrogen heating with $\beta < 5\%$ and for He^3 minority heating.

Time period: 9/87 - 6/88

Major goals/questions: High power coupling tests for resonant cavity antenna using 2.2 MW of heating at 2nd harmonic of hydrogen. Confinement with ICH at $\beta \gtrsim 5\%$ (generated with NBI) is main issue.

Time period: 1/89 - 1/90

Major goals/questions: 9 MW heating using 4 antennas in phased array. Goal is simulation of CIT heating. $2\Omega_H$ or $2\Omega_{He}3$ in $H-_{He}3$ plasma to simulate $2\Omega_D$ or $2\Omega_T$ in CIT; or $\Omega H \rightarrow 2\Omega He^4$ in $(H)-He^3-He^4$ in DIII-D to simulate the $\Omega_{He}3 \rightarrow 2\Omega_T$ or $\Omega_H \rightarrow 2\Omega_D$ transitions from minority to second harmonic heating of CIT.

IPSG ICRH SURVEY (Part 1)

Machine: JET **Filled out by:** P.P. Lallia/JET **Date:** 1 July 1986

DATE	6/86	6/87	1/90	12/92	
MACHINE & GEOMETRY					
1. R (m)	3.00	3.00	3.00	3.00	
2. a (m)	1.20	1.20	1.20	1.20	
3. Elongation (b/a)	1.4	1.60	1.60	1.60	
4. B_{tor} (T)	2 - 3.4	2 - 3.4	2 - 3.4	3.4	
5. I_p (MA)	1 - 5	1 - 7	1 - 7	7	
6. t_{pulse} (s)	15	15	15	15	
7. Edge (L, D, E, P)	L,E	L,E	L,E,P	L,E,P	
POWER					
8. P_{NBI} (MW)	9	18	18	18	
9. P_{ICH} (MW)	7	20	25	25	
10. P_{LHH} (MW)			10 (E)	10 (E)	
11. P_{ECH} (MW)					
12. P_{OTHER} (MW)					
ICH PARAMETERS					
13. f_{ICH} (MHz)	25 - 55	25 - 55	25 - 55	32 or 51	
14. h_{ant} (m)	1.6	1.6	1.6	1.6	
15. w_{ant} (m)	0.5	0.5	0.5	0.5	
16. N_{ant}	3	8	8	8	
17. t_{ICH}(s)	1 - 10	1 - 10	1 - 10	5	
18. Mode	see A,B	see A,B	see A,B,C	D	
19. Frac. oper. time	1/3	1/3	1/4		
PLASMA PROPERTIES					
20. n_e ($10^{20}m^{-3}$)	0.2 - 0.6				
21. T_e (keV)	2.5				
22. T_i (keV)	2				

Notes

A. ^{3}He or H minority in deuterium plasma

B. Combined ICRF + D beam injection + Pellet

C. Combined ICRF + D beam + LH Current Drive + Pellet

D. ^{3}He & second harmonic of T or H & second harmonic of D.

E. Proposed

IPSG ICRH SURVEY (Part 2)

Machine: JET

This survey is intended to provide a data base for ICH heating, physics, and technology from 1986 through 1990. Please indicate in the spaces below what the main objectives of the ICH experimental program will be for different time periods of machine operation. The intent of this part of the survey is to obtain a qualitative indication of the main questions that the research you will do will answer.

Time period: 6/86 - 6/87

Major goals/questions: Heating of pellet fueled plasma

Synergetic effects ICRF - NBI

Low q operations

Time period: 6/87 - 6/90

Major goals/questions: As above + sawteeth control by LHCD - Maximum ion pressure on axis

Time period: 1/90 - 12/92

Major goals/questions: Qualify and perform D-T operations

α particle heating

Time period: __________

Major goals/questions: __________

Time period: __________

Major goals/questions: __________

IPSG ICRH SURVEY (Part 1)

Machine: JFT-2M **Filled out by:** K.Odajima **Date:** July, 1986

DATE	4/'87	4/'87-4/'89		4/'90 (not authrized)	4/'91
MACHINE & GEOMETRY					
1. R (m)	1.3	→		1.3	→
2. a (m)	0.35	→		0.35	→
3. Elongation (b/a)	1.5-1.7	→		1.5	→
4. B_{tor} (T)	1.4	→		4.0	→
5. I_p (MA)	0.5	→		1.5	→
6. t_{pulse} (s)	1.0	→		2.0	→
7. Edge (L, D, E, P)	L,D	L,D,P		L,D,P	→
POWER					
8. P_{NBI} (MW)	1.6	→		2.5	→
9. P_{ICH} (MW)	3.0	→		10	→
10. P_{LHH} (MW)	0.6	→		see A	→
11. P_{ECH} (MW)	0.3	→		1.0	→
12. P_{OTHER} (MW)	0.1(200MHz)	0.4		see A	→
ICH PARAMETERS					
13. f_{ICH} (MHz)	10 - 40	→		25- 60	→
14. h_{ant} (m)	0.7	→		0.7	→
15. w_{ant} (m)	0.07	→		0.07	→
16. N_{ant}	3	→		10	→
17. t_{ICH}(s)	0.5	→		1	→
18. Mode	(H)/D, 2H			(H)/D, 2H	
19. Frac. oper. time	0.6	0.4		0.2	→ 0.6
PLASMA PROPERTIES					
20. n_e ($10^{20} m^{-3}$)	1	1		3	
21. T_e (keV)	2	2.0		5	
22. T_i (keV)	1.5	2.0		5	

Notes A --- Fast wave Current Drive(0.6MHz) 2MW,

IPSG ICRH SURVEY (Part 2)

Machine: JFT-2M

This survey is intended to provide a data base for ICH heating, physics, and technology from 1986 through 1990. Please indicate in the spaces below what the main objectives of the ICH experimental program will be for different time periods of machine operation. The intent of this part of the survey is to obtain a qualitative indication of the main questions that the research you will do will answer.

Time period: 4/'86 - 4/'87

Major goals/questions: 3MW net input Power, (H)/D mode Conv. Regime,
Confinement Scaling, H mode like plasma.

Time period: 4/'87 - 4/'88

Major goals/questions: Current Profile Control via ICRF current drive,
improvement of confinement by active current profile control.

Time period: 4/'88 - 4/89

Major goals/questions: High β_T plasma,
improvement of β_T limit by active current profile contorl.

Time period: 4/'89 - 4/'90

Major goals/questions: Power up and reconstruction of JFT-2M, and move
to Naka Research Establishment.
(4T, 1.5MA, ICRF Power 10MW)

Time period: 4/'90 - 4/'91

Major goals/questions: Machine start up, Ohmic Heating , Confinement Scaling,
low power (3MW) ICRF heating.

IPSG ICRH SURVEY (Part 1)

Machine: JIPP T-IIU **Filled out by:** T. Watari **Date:** July 15th

DATE	1986	1987	1988	1989	
MACHINE & GEOMETRY					
1. R (m)	0.91	0.91	0.91	0.91	
2. a (m)	0.23	0.23	0.23	0.23	
3. Elongation (b/a)	1	1	1	1	
4. B_{tor} (T)	3.0	3.0	3.0	3.0	
5. I_p (MA)	0.3	0.3	0.3	0.3	
6. t_{pulse} (s)	0.1	0.1	0.1	0.1	
7. Edge (L, D, E, P)	L	L	L	L	
POWER					
8. P_{NBI} (MW)	2	2	2	2	
9. P_{ICH} (MW)	4	4	4	4	
10. P_{LHH} (MW)	0.3	1 MW	1	1	
11. P_{ECH} (MW)			0.5	0.5	
12. P_{OTHER} (MW)					
ICH PARAMETERS					
13: f_{ICH} (MHz)	40	200	7	60	
14. h_{ant} (m)	0.5	0.5	0.5	0.3	
15. w_{ant} (m)	0.1	0.1	0.1	0.3	
16. N_{ant}	6	4	8	2	
17. t_{ICH}(s)	0.1	0.1	0.1	0.1	
18. Mode	H-minority	tast wave	A. W.	I. B. W.	
19. Frac. oper. time	1/2	1/2	1/2	1/2	
PLASMA PROPERTIES					
20. n_e ($10^{20}m^{-3}$)	1	0.5	0.5	0.5	
21. T_e (keV)	2	1	1	1	
22. T_i (keV)	1.5	0.5	0.5	0.5	

Notes We are discussing now about future plans.
So, this is a very tentative one.

IPSG ICRH SURVEY (Part 2)

Machine: JIPP T-IIU

This survey is intended to provide a data base for ICH heating, physics, and technology from 1986 through 1990. Please indicate in the spaces below what the main objectives of the ICH experimental program will be for different time periods of machine operation. The intent of this part of the survey is to obtain a qualitative indication of the main questions that the research you will do will answer.

Time period: 1986 - 1987

Major goals/questions: establishment of confinement scaling on High power ICRF Heating.

Time period: 1987 - 1988

Major goals/questions: proof of ICRF current drive at 200 MHz (40 MHz already done)

Time period: 1988 - 1989

Major goals/questions: proof of current drive at very low frequency.

Time period: 1989 - 1990

Major goals/questions: proof of I.B.W. current drive

Time period: ______

Major goals/questions: ______

IPSG ICRH SURVEY (Part 1)

Machine: JT-60 Filled out by: M. Yoshikawa Date: July, 1986

DATE	10/86	12/87			
MACHINE & GEOMETRY					
1. R (m)	3.0				
2. a (m)	0.9				
3. Elongation (b/a)	1.0				
4. B_{tor} (T)	4.5				
5. I_p (MA)	2.1 DIVERTOR 2.7 LIMITER				
6. t_{pulse} (s)	10				
7. Edge (L, D, E, P)	D & L				
POWER					
8. P_{NBI} (MW)	20	20			
9. P_{ICH} (MW)	1-2	5			
10. P_{LHH} (MW)	7	15			
11. P_{ECH} (MW)					
12. P_{OTHER} (MW)					
ICH PARAMETERS					
13. f_{ICH} (MHz)	110-130				
14. h_{ant} (m)	0.52				
15. w_{ant} (m)	0.37				
16. N_{ant}	1(2×2 Loop Array)				
17. t_{ICH}(s)	10	10			
18. Mode	$2\omega_{CH}$				
19. Frac. oper. time	1/3-1/6	1/2-1/3			
PLASMA PROPERTIES					
20. n_e ($10^{20}m^{-3}$)	0.5	0.8			
21. T_e (keV)	10	17			
22. T_i (keV)	10	17			

Notes

IPSG ICRH SURVEY (Part 2)

Machine: JT-60

This survey is intended to provide a data base for ICH heating, physics, and technology from 1986 through 1990. Please indicate in the spaces below what the main objectives of the ICH experimental program will be for different time periods of machine operation. The intent of this part of the survey is to obtain a qualitative indication of the main questions that the research you will do will answer.

Time period: 4/85 – 7/86

Major goals/questions: Ohmic heating. No aux. heating $I_p = 2.1$ MA Divertor

Time period: 8/86 – 11/86

Major goals/questions: Coupling experiment and Heating experiment with phase control at $2\omega_{CH}$, 120 MHz, 1–2 MW, 2 sec.

Time period: 1/87 – 3/87

Major goals/questions: Fast wave current drive and combined heating ($2\omega_{CH}$, 2.5 MW, 5 sec) with NBI

Time period: 4/87 – 12/87

Major goals/questions: Combined heating ($2\omega_{CH}$, 5MW, 5 sec) with NBI. Break-even experiment.

Time period:

Major goals/questions:

TEXTOR

DATE	1/86	4/87	5/88		
MACHINE & GEOMETRY					
1. R (m)	1.75	1.75	1.75		
2. a (m)	0.46	0.46	0.46		
3. Elongation (b/a)	1	1	1		
4. B_{tor} (T)	2-2.6	2-2.6	2-2.6		
5. I_p (MA)	0.2-0.5	0.2-0.5	0.2-0.5		
6. t_{pulse} (s)	3	3	3		
7. Edge (L, D, E, P)	L,P*	P**	P**		
POWER					
8. P_{NBI} (MW)	–		3		
9. P_{ICH} (MW)	2.7	2.7	4.2		
10. P_{LHH} (MW)	–	–	–		
11. P_{ECH} (MW)	–	–	–		
12. P_{OTHER} (MW)	–	–	–		
ICH PARAMETERS					
13. f_{ICH} (MHz)	25-29	25-29	25-29		
14. h_{ant} (m)	1.38	0.73			
15. w_{ant} (m) +	0.25	0.26			
16. N_{ant}	2	4			
17. t_{ICH}(s)	1.5	1.5			
18. Mode	see A,B,C	A,C	A,C		
19. Frac. oper. time	0.3				
PLASMA PROPERTIES					
20. n_e ($10^{20}m^{-3}$)	2-6				
21. T_e (keV)	0.7-1.3				
22. T_i (keV)	0.5-1.2				

Notes
A H minority or $2\omega_{eD}$ in D(H) plasma
B H_3 mode conversion in D(H) plasma
C H_e^3 minority in D(H_e^3) plasma
* ALT-1 (localized pump limiter module)
** ALT-2 (toroidal pump limiter : segmented belt)
+ width central conductor + aperture gaps

IPSG ICRH SURVEY (Part 2)

Machine: TEXTOR

This survey is intended to provide a data base for ICH heating, physics, and technology from 1986 through 1990. Please indicate in the spaces below what the main objectives of the ICH experimental program will be for different time periods of machine operation. The intent of this part of the survey is to obtain a qualitative indication of the main questions that the research you will do will answer.

Time period: 1986

Major goals/questions: Confinement time studies with ICRH with different heating scenarii

Time period: 1987

Major goals/questions: ICRH in presence of toroidal pump limiter and pellet injection. Heating mode : minority H or H_e^3 in D plasma

Time period: 1988

Major goals/questions: Combined ICRH and NBI heating

Time period:

Major goals/questions:

Time period:

Major goals/questions:

IPSG ICRH SURVEY (Part 1)

Machine: TFTR **Filled out by:** J. Hosea **Date:** 9/11/86

DATE	6/87	4/88	1/90		
MACHINE & GEOMETRY					
1. R (m)	2.6	-	-		
2. a (m)	.96	-	-		
3. Elongation (b/a)	1	-	-		
4. B_{tor} (T)	5	-	-		
5. I_p (MA)	3.5	-	-		
6. t_{pulse} (s)	3	-	-		
7. Edge (L, D, E, P)	L, P_{ort}	-	-		
POWER					
8. P_{NBI} (MW)	12	27	-		
9. P_{ICH} (MW)	6	10	-		
10. P_{LHH} (MW)					
11. P_{ECH} (MW)					
12. P_{OTHER} (MW)					
ICH PARAMETERS					
13. f_{ICH} (MHz)	47, 40-80	-	-		
14. h_{ant} (m)	.85	-	-		
15. w_{ant} (m)	.7, .5	-	-		
16. N_{ant}	2	-	-		
17. t_{ICH}(s)	2	-	-		
18. Mode	Minority H^3e/H, $2\omega_{CD}$	-	Minority ^3He, $2\omega_{CT}$		
19. Frac. oper. time	0.3	0.5 (with beams)	0.8 (with beams)		
PLASMA PROPERTIES					
20. n_e ($10^{20}m^{-3}$)	.5-2	-	-		
21. T_e (keV)	2-10	5-15	-		
22. T_i (keV)	5-20	10-30	-		

Notes A final modification of antenna elements may be required prior to tritium operation (- signifies continues at same value as for previous period)

IPSG ICRH SURVEY (Part 2)

Machine: TFTR

This survey is intended to provide a data base for ICH heating, physics, and technology from 1986 through 1990. Please indicate in the spaces below what the main objectives of the ICH experimental program will be for different time periods of machine operation. The intent of this part of the survey is to obtain a qualitative indication of the main questions that the research you will do will answer.

Time period: 4/86 - 5/87

Major goals/questions: Design, fabrication, and test of high power antennas. Design for $\sim$1.5 kW/cm^2 power density at antenna Faraday shield. Incorporate D&T features relevant to CIT where practical.

Time period: 6/87 - 4/88

Major goals/questions: Operate at 6 MW on TFTR. Test central heating scenarios at high density ($\gtrsim 10^{14}$ cm^{-3}) and in hot ion mode. Evaluate power handling capability of antennas to support modifications as may be required for full 10 MW operation. Fabricate and install modifications as needed.

Time period: 5/88 - 12/89

Major goals/questions: Operate at 10 MW on TFTR. Optimize Q=1 scenarios in conjunction with beam heating. Push power density tests on antenna to $\sim$2 kW/cm^2 in support of CIT design.

Time period: 1/90 - 9/90

Major goals/questions: Operate at 10 MW on TFTR for D-T plasmas. Evaluate physics performance for tritium case at highest possible temperatures and densities ($T_i \sim$ 20-30 keV, $T_e \gtrsim$ 10 keV, $n_e(o) \gtrsim 3 \times 10^{14}$ cm^{-3}). Support physics and antenna extrapolations to CIT.

Time period: ______

Major goals/questions: ______

IPSG ICRH SURVEY (Part 1)

Machine: TORE SUPRA **Filled out by:** J. ADAM **Date:** Sept 3,86

DATE	88	89	90		
MACHINE & GEOMETRY					
1. R (m)	2.25	2.25	2.25		
2. a (m)	0.7-08	0.7-0.8	0.7-0.8		
3. Elongation (b/a)	1	1	1		
4. B_{tor} (T)	≤ 4.5	≤ 4.5	≤ 4.5		
5. I_p (MA)	≤ 1.7	≤ 1.7	≤ 1.7		
6. t_{pulse} (s)	30	30	30		
7. Edge (L, D, E, P)	L.P	P	P		
POWER					
8. P_{NBI} (MW)	0	3.5	?		
9. P_{ICH} (MW)	<8	<12	< 12		
10. P_{LHH} (MW)	4	8	8		
11. P_{ECH} (MW)	0	0.2	?		
12. P_{OTHER} (MW)					
ICH PARAMETERS					
13. f_{ICH} (MHz)	35-80	35-80+120	35-80 + 120		
14. h_{ant} (m)	0.6	0.6	0.6		
15. w_{ant} (m)	0.5	0.5	0.5		
16. N_{ant}	2	3	3		
17. t_{ICH} (s)	30	30	30		
18. Mode	See A	See B	See C		
19. Frac. oper. time	0.2	0.3	0.2		
PLASMA PROPERTIES					
20. n_e ($10^{20} m^{-3}$)	0.5-1				
21. T_e (keV)					
22. T_i (keV)					

Notes
A. First tests : H or He^3 minority with D
B. H or He^3 minority with D; $2\omega CH$ or $2\omega c$ He^3
C. Most efficient mode - Test of $2\omega CH$ using guides

IPSG ICRH SURVEY (Part 2)

Machine: TORE SUPRA

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Time period: 1988

Major goals/questions: Ohmic heating / Startup phase

2 resonant double loop antennas supplied by 4 2 MW power amplifiers.

Experiments expected to start in middle /88 -H or 3 He minority in D.

Time period: 1989

Major goals/questions: Heating using 3 RDL antennas. Comparison between minority (He^3 or H/D) and $2\omega ci$ (H or $'He^3$) - ICH heating with LH current drive

Time period: 1990

Major goals/questions: ICH with NBI and LH at full power.

Test of 2ωCH heating using ridged or folded wave guide (120 MHZ)

Time period: ________

Major goals/questions: ________

Time period: ________

Major goals/questions: ________

Appendix D

CIT ICH SYSTEM TASK NAMES AND DESCRIPTIONS

D.1 CIT SUMMARY SCHEDULE

Design and Fabrication

Advanced conceptual design, preliminary and final designs, fabrication, modification, delivery, and installation of all CIT subsystems at the CIT site.

Pre-Operational Tests

Pre-operational, integrated testing of all CIT systems and controls prior to generation of the first plasma. ICH launchers are installed in the vacuum vessel before first plasma but are not tested in CIT until after the first plasma is generated. Pre-operational testing of the ICH system is limited to testing of the dc power supplies, rf transmitters, I&C, and part of the transmission line system to the rf dummy loads. Testing of the launchers will occur after plasma can be generated in the vacuum vessel and will be essentially an extension of pre-operational testing into the plasma operation phase. Launchers will have been tested and conditioned at full power in the RFTF at ORNL as part of the launcher production program. This will minimize the additional testing and conditioning required once the launchers are installed on CIT and should allow correction of design and fabrication errors before installation on CIT.

Plasma Operation

Initial plasma operation will begin at reduced magnetic field with an ohmically heated plasma. Integrated system testing of the ICH system also occurs during the first 6 months of plasma operation because of the need for a plasma load for launcher testing.

First ICH

ICH experiments on CIT begin about 6 months after the beginning of plasma operation on CIT. This gives time to run ohmic heating experiments prior to adding the ICH. The initial plasma operation will be at reduced magnetic field (8 T) such that He^3 minority heating can be accomplished at 80 MHz. Second harmonic deuterium (or fundamental hydrogen) heating could be done at a further reduced magnetic field of about 7 T. At full magnetic field, the heating mode options are limited to fundamental deuterium, second harmonic tritium, minority He^3, and minority He^4.

D.2 CIT ICH SYSTEM

Advanced Conceptual Design

Completion of the conceptual design and advanced conceptual design report. Completion of this task occurs when PACE funding begins. At the end of conceptual design, an overall system configuration will have been generated with a proposed launcher concept. The launcher concept is assumed to change throughout the launcher R&D program but is retained in the PACE design to help identify potential interferences with other CIT systems, to give a basis for the cost estimate, and to help direct the R&D program to the greatest benefit of the CIT experiment.

Preliminary Design

Preliminary detailed design of ICH subsystems ends with the formal Preliminary Design Review of the system. Each ICH subsystem is designed in enough detail to determine that the design is feasible and to identify all subsystem interfaces and potential design, fabrication, assembly, installation, or operational problems. Each subsystem of the ICH system will have a conceptual design and some design details at the end of this period.

Final Design

Final design of the ICH system generates fabrication and installation drawings of all ICH subsystems, including launchers. Final design changes after the preliminary design phase are incorporated into the design in preparation for fabrication. Purchase, fabrication, and modifications begin immediately after the final design phase.

Integrated System Test

Testing of the entire ICH system, as installed into the launchers on CIT. This requires a plasma to be present and therefore follows the CIT integrated system tests. As much of the ICH system as possible is tested before this test so that only part of the transmission line and the antennas must be tested at this point. Prior to this test, each launcher will have been conditioned and tested to full current and voltage into a plasma load in the ORNL RFTF.

D.3 ICH LAUNCHERS

The overall goal of the CIT antenna development program is to develop a launcher operable at high frequency (>100 MHz), long pulse (5 s), and high power density (2–2.5 kW/cm^2) in a high magnetic field and high neutron fluence environment with high disruption loads. Eliminating dielectrics, increasing power density capability, and increasing frequency of operation are design goals. Generating a mechanical design that is able to withstand large disruption forces and is remotely maintainable are goals in the mechanical design of the launcher. The antenna R&D program is designed to address these specific needs.

Test Antennas Design/Fabrication

Design and construct low-power models of the CIT prototype launchers ($P < 1$ W). Test designs and variations to determine the electrical parameters of the launchers and aid in the development of the mechanical design, assembly and maintenance procedures. Explore potential mechanical and electrical designs of the Faraday shield. Generate fabrication and assembly techniques suitable for the CIT environment (high disruption loads, high neutron fluence, high magnetic fields, remote maintenance). Investigate effects of changes in launcher and port dimensions and parameterize the launcher before higher-power tests in RFTF.

Tests in RFTF

Design and fabricate a moderate-power (100-kW) developmental antenna based on low-power antenna tests. Attempt to incorporate as many rf and mechanical design features of the final design as possible in the RFTF test antenna. Test electrical and mechanical operation in RFTF at high voltage and high current. Iterate the design as necessary to develop a design usable at high power density (2–2.5 kW/cm^2) in the CIT environment. Later tests in RFTF will be at full power and will use a modified FMIT transmitter.

C-Mod Design and Fabrication

Design and fabricate a CIT-like ICH launcher for testing in Alcator C-Mod. This should be a scaled version of the CIT launcher and should incorporate as many of the design features of the CIT launcher as possible. This task must occur early enough that design improvements in CIT are still possible. The launcher will then be operated in C-Mod with the C-Mod power units, transmission line, and I&C system.

CIT Design and Fabrication

Based on results of low-power, RFTF, and C-Mod tests and the CIT R&D program, modify the design as necessary and fabricate CIT launchers that meet the system requirements.

High-Power Tests in RFTF

Production test and condition each launcher in RFTF at high rf voltage and current to verify its integrity and to condition the launcher before installation on CIT. This is necessary to minimize the amount of experimental time needed to bring a new launcher up to full operational capability. This will be essential later in the CIT program because the activated CIT machine will preclude any hands-on maintenance of the launchers once they have been installed on the machine.

CIT Installation

Install the tested and conditioned launchers on CIT. The launchers are modular and are designed for remote maintenance, so this task will be mainly a "plug-in" operation with a minimum number of cooling, instrumentation and rf power connections necessary. Leak-check and test the installed launcher module mechanically and electrically in preparation for high rf power testing.

D.4 ICH POWER UNITS

Tube Development

Test the EIMAC X-2242 tube to determine its power handling capability versus frequency. If the X-2242 will not meet the requirements for CIT, award a subcontract to a tube manufacturer to develop or modify a tube to meet the CIT requirements.

FMIT Modifications, Vendor Design

Issue a subcontract to industry to design the upgrades to an FMIT power unit to meet the CIT rf power requirements. CIT requires a tunable frequency range of 60–110 MHz, with an output power of 2 MW per transmitter at 95 MHZ. Modifications will require using a new final power amplifier tube, upgrading the dc power supplies, and installing a new cavity to meet frequency and power requirements. In addition, I&C modifications will be required to allow remote control and monitoring of the transmitter.

FMIT Modifications–Unit 1 (ORNL)

The first modified FMIT unit will be installed at ORNL. The modification will be done in two phases. The first phase in FY 1988 will upgrade the low and intermediate power stages of the unit to the 60–110 MHz range, and will provide an output power of ~100 kW that can be used in antenna tests in RFTF. The second phase, in FY 1990, will be the modification of the final power amplifier stage and testing to full rated output power.

FMIT Modifications–Units 2–7

An industrial subcontractor will modify Units 2–7 based on the design and testing of Unit 1. The subcontractor will perform factory tests up to but not including the final acceptance tests, which will be performed at the CIT site after installation. The units will be shipped to the CIT site, where they will then be installed and tested. This will be done in a sequential manner, with approximately three months between the completion of installation of each FMIT unit.

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