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2/14/89 JS ②

DR#0600-9

PPPL-2584 PPPL-2584

UC-420

THE COMPACT IGNITION TOKAMAK AND ELECTRON CYCLOTRON HEATING: DESCRIPTION OF NEED; ASSESSMENT OF PROSPECTS

By

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JANUARY 1989

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PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CHO-3073.

PPPL--2584

TI89 006876

The Compact Ignition Tokamak and Electron Cyclotron Heating: Description of Need; Assessment of Prospects

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Abstract

The CIT will benefit from auxiliary heating of 10 to 40 MW. The schedules of both the CIT construction project and the operating plan contain adequate time to develop and implement ECH systems based on the gyrotron and the induction free electron laser (IFEL). Each approach has advantages and is the object of R&D at the level of many millions of dollars per year. While the gyrotron is further advanced in terms of power and pulse length achieved, rapid progress is scheduled for the IFEL, including experiments on tokamaks. Plans of CIT, gyrotron, and IFEL make 1992 an appropriate time frame to commit to one or both systems.

1 Requirements

We divide requirements into physics and engineering. In general, physics is related to energy flows in the plasma, and engineering is related to flows outside the vacuum vessel, including the possible motion of tritium away from the vessel.

1.1 Physics

The basic CIT physics requirements for auxiliary heating can be specified by three parameters: power, frequency, and time. The nominal values for the full-performance device are 40 MW, 280 GHz, and 10 seconds. The following sections develop the motivation for these numbers. Section 1.1.1 discusses power based on the predictions of scaling laws for the size of the minimum auxiliary power required to reach ignition. Sections 1.1.2 and 1.1.3 discuss the frequency derived from the several levels of magnetic field needed for operation, and the requirement for modulation. Section 1.1.4 lists the pulse length. Finally, the second harmonic option is examined in 1.1.5.

The nature of the CIT design is summarized in Table 1, "Selected Parameters of the CIT Design."

1.1.1 Predictions of Scaling Laws

Figure 1 plots contours of required auxiliary power in temperature-density space, assuming Kaye-Goldston confinement.[1] The maximum required auxiliary power for maintaining an equilibrium is about 6 MW. A higher power is required to reach ignition in a sufficiently short time, owing to the effects of heat capacity.

There is uncertainty in plasma confinement. The Kaye-Goldston law of Fig. 1 is on the optimistic end of the range. A law of Goldston[2] from the Aachen meeting often is used in analyzing results. If an enhancement of a factor of 1.8 over the Goldston scaling is assumed, then CIT would not reach ignition, as shown in Fig. 2.

The confinement of Fig. 2 may not lead to ignition, but the fusion energy multiplication (Q) can be large, as shown in Fig. 3. These curves are contours of constant Q for the same parameters as Fig. 2, including 1.8 times Goldston confinement. Auxiliary heating power of 25 MW yields a Q of about 10. A steady-state power of 60 MW would be required to reach the estimated operational limits on beta and density.

If the enhancement over Goldston scaling is a factor of 2, then ignition becomes possible. Enhancements of this magnitude are consistent with some of the results found in large tokamaks. The Tokamak Fusion Test Reactor (TFTR) has been able to operate in a 'supershot' mode, in which an enhancement of confinement of approximately 3 is found in low-initial-density, neutral-beam-fueled discharges. While this low-initial-density mode, as it is known in TFTR, may not lead to ignition, it does offer hope of finding higher confinement than predicted by the Goldston scaling.

The impact of scaling laws is that auxiliary heating powers from 10 MW to 40 MW may be required to make high-Q or ignited plasma. The range quoted is broad in parallel with the range of uncertainty.

1.1.2 Operating Magnetic Fields

Operations at 7 through 11 Tesla Although the engineering design of CIT is aimed at 10 Tesla for a large number of pulses (3000), operation at 11 Tesla for fewer pulses (yet to be determined) is also an important design goal. The motivation is one final increase of the intrinsic performance if the goal of ignition is slightly beyond the reach of the 10-Tesla parameters.

Operation at 10 Tesla and 11 Tesla is the requirement for the tokamak systems (magnet coils, vessel, structure), but the initial construction project will deliver a power supply capable of 7 Tesla.

There are several avenues upgrading the power system, some of which are under discussion with the Soviet Union. For the moment, our planning should be based on the assumption that the 10 Tesla capability will follow the initial 7 Tesla installation by 3 years.

Another important feature of the 7/10 Tesla transition is that, according to the engineering philosophy, the number of pulses at 7 T is virtually unlimited by fatigue, whereas at 10 T the fatigue limit is in the range of 3000 pulses. Therefore, regardless of the eventual plan for upgrading power and energy, there will be extensive operation in the 7 T range to gain experience with CIT.

Heating During Ramp The pulse length of the machine is short to minimize the project cost. As a result, the flat top pulse length is 5 seconds. This time, while sufficient to reach and study ignition, does not contain a large margin for special formation techniques or shutting down the discharge smoothly. Therefore, we consider the possibility of heating during the ramp-up and ramp-down phase.

Figure 4 shows that an extra 3 seconds on the front side of the 10 Tesla flat top period can be obtained by operating when the field gets to 80% of the maximum and the current attains 1/2 of the nominal value. A similar possibility exists on the ramp-down side. Figure 5 gives a similar result for the 11 Tesla operation. although the flat top is shorter and the time from 80% to 100% of operating field is longer. Figure 6 shows the 7 Tesla case.

The frequency can be calculated approximately from the electron cyclotron resonance being proportional to magnetic field at 28 GHz per Tesla. Thermal and Doppler effects exist, but can be assumed small in the approach to heating being considered. Best results are expected with heating at the center, so there may be a benefit to sweeping the frequency of the microwave power with field. Thus, a nominal 10 Tesla case involves a ramp from 224 GHz to 280 GHz in 3 seconds, hold for 5 seconds, and ramp back to 224 GHz in 3 seconds. The few 11 Tesla experiments need 246 GHz ramped to 308 GHz and back. The majority of experiments, involving the 7 Tesla maximum field, needs 160 GHz ramped to 200 GHz and back.

Fixed Frequency, with Moving Resonance Ramping the frequency up and down requires a state of technology that is quite advanced considering the absence of any suitable source in this range at the moment. The problem with ramping is probably variations in microwave impedance with frequency, leading to resonant reflections and local power concentrations in the microwave generator and transmission system.

On the other hand, it is plausible that the plasma is not so demanding that the heat must be deposited exactly in the center. In fact, the elongated equilibria of CIT feature a large sawtooth mixing radius, equal to more than 60% of the minor radius. The effect of heating in the exact center can be obtained for heating within 60% of the minor radius of the center. Therefore, a choice of frequency that is the mean of the center frequencies of interest appears acceptable.

For 10 Tesla experiments the mean is 250 GHz; for 11 Tesla, the mean is 280 GHz; finally, at 7 Tesla, the mean is 180 GHz.

If a fixed frequency is used in a changing field, then the plasma must fill the region adequately. This point is addressed in Figs. 7 and 8. The Tokamak Simulation Code (TSC)[3] was used to make these calculations of the evolution of the equilibrium. Note that the final location of the plasma is reached 2 seconds from initiation, while the heating during the ramp in Fig. 4 needs to start 4 seconds after initiation.

Fixed Frequency, with Changing Launch Angle The Doppler shift can be used to adjust the location of heating. In some circumstances, which involve launch from the top of the tokamak, the adjustment can be extremely large: Mazzucato *et al.* find that a 10.5 Tesla compact ignition device can be heated successfully with only 190 GHz.[4]

A version of this technique can be used to keep central heating while the field is changing and the frequency is constant. A mechanism to steer the ECH launch angle relative to the magnetic field can be imagined inside a horizontal port. Estimates by M. Porkolab are that a 20 degree swing would be sufficient for following the last 20% ramp of the field.[5]

Summary on Operating Magnetic Fields In summary, the heating needs to be effective at nominal fields of 7, 10, and 11 Tesla. In addition, the heating should be effective as the magnetic field ramps through the last 20% of the nominal peak magnetic field. It appears that this could be handled by two separate frequencies, a nominal 180 GHz system for 7 Tesla and a nominal 280 GHz system for 10 and 11 Tesla. However, predicting the range of possible operating situations that will be desired is difficult, and tunability in small steps through this range would be an advantage, whether on the time scale of days or fractions of a second. Some effective tunability may be practical by changing the launch angle.

1.1.3 Rapid Modulation of Frequency and Power

The ability to place the resonance at the $q = 1$ surface, and the $q = 2$ surface could be important, allowing interaction with MHD activity in the plasma.

There is some experimental and theoretical evidence for improved plasma performance under such situations. It may also be desirable to heat at different locations at different times. However, this capability represents a new level of demand on the technologies that have not approached the basic requirements of high frequency and high power. Fine scale control of frequency and power is desirable once the basic requirements can be met.

Simple modulation of power should not be difficult, and it is expected to be one of the fundamental controls of plasma near ignition.

Variation on moderate time scales (0.5 sec) of the location of the power deposition may be possible with an aiming adjustment on the vertical location of the geometrical ray path.

1.1.4 Pulse Length

The discussion above on the waveform of field and current shows that the heating should be available for approximately 10 seconds. Of this time, 5 seconds represent flat-top time, and the other 5 seconds would be used during ramp-up and ramp-down.

This nominal 10 second pulse length applies to initial operations on CIT at 7 T, in which power and energy are limited. The 10 second pulse length also applies to the 10/11 Tesla operation with full power and energy installed. However, when full power and energy are installed, very long pulses are possible at the 7 Tesla magnetic field. For such pulses, it is possible that heating times on the scale of 20 seconds would be desirable.

1.1.5 Second Harmonic Heating

First harmonic heating (fundamental) has been discussed, rather than second harmonic. This is because significant power is now available at 140 GHz with gyrotrons, which is comparable to the 180 GHz required for 7 T. A second harmonic system is 360 to 560 GHz, representing an enormous advance in the state of the art.

However, the physics advantage to second harmonic heating is the increase in density that can be heated. Higher density is associated with better confinement, a rise in the product $n \cdot \tau \cdot T$ and an increased range of plasma parameters for ignition. Based on empirical evidence, CIT assumes that the density will be limited to

$$\bar{n}_e < 2.0B/(Rq_e) \quad ,$$

where n_e is in units of 10^{20} particles per m^3, B is in Tesla, R is in meters.[6] The engineering q, q_e, is defined as

$$q_e = 5a^2\kappa B/(RI) \quad ,$$

with I in MA and κ representing the elongation. The basis for this limit is not fully explained by theory, although it is generally believed that it is related to $B/(Rq)$ being proportional to current density, and therefore power input from the plasma current. If true, extra power input could presumably allow the density to rise. However, data proving this have not emerged.

At 10 T, the empirical density limit yields 5 × 10^{20} per cubic meter for the line-averaged density, while 280 GHz should propagate from launch on the outside midplane (ordinary mode) to 9.7 × 10^{20}. The two density limits are close enough that calculations of the refractive effects are necessary to examine the feasibility. The calculations show that acceptable trajectories of the ECH energy occur up to 0.8 of the cutoff density – or 8 × 10^{20}. Therefore, first harmonic looks satisfactory for useful heating at the nominal CIT density limit. However, advancing beyond this density would not be possible with 280 GHz.

At 7 T, the empirical limit on average density limit is 3.5 × 10^{20}, but the practical propagating limit for 180 GHz is about 3.2 × 10^{20} peak density. Therefore, a 180 GHz source for 7 Tesla actually limits the density to slightly less than the "2B/Rq" empirical formula.

1.2 Engineering

1.2.1 Space Requirements

The ECH power must be transmitted into a port with clear dimensions of approximately 35 by 100 cm. The total power should be up to 15 MW per port. This means an average transmitted power density of 10 kW/cm^2, assuming about half the port area is filled with ECH couplers.

The port size comes from the overall parameters of the design. The requirement on 15 MW per port comes from the apparent ability of ECH power to achieve this high power density, and the fact that ECH is to be a supplement to the original ion cyclotron heating (ICH) system, which requires three ports for 10 MW. If ECH has to use more ports than 1 per 10 MW, its use as a supplement will be difficult owing to limitations on the number of ports available for heating.

The equipment to generate and transmit the ECH power must fit into the site of CIT, which includes existing TFTR buildings. Surrounding land can be used, within limits imposed by the existing site.

1.2.2 Safety

Tritium streaming up the waveguides connecting the ECH power source(s) to the vacuum chamber is the major safety consideration. Numerical requirements need to be developed.

The design objective for CIT on radiation safety issues is a maximum site boundary dose of 10 millirem per year in normal operation, and a maximum site boundary dose of 5 rem in case of an extremely unlikely event, or 1 rem in the case of an unlikely event. An extremely unlikely event has a probability in the range of 10^{-6} to 10^{-4} per year. An unlikely event has a probability in the range of 10^{-4} to 10^{-2} per year.

There are two basic approaches to the waveguides: with windows and without windows. Gyrotron installations of the past have used windows, and engineers working on gyrotrons prefer windows for the future. However, R&D on windows at this high frequency will be required, and is not now funded. The IFEL installation at the Microwave Tokamak Experiment (MTX) at LLNL does not have windows, and the planning for an IFEL on CIT does not include windows.

If there are no windows, a differential pumping system with fast valves (or more accurately, fast conductance limiters) appears to be possible. There has been no design work on such systems for the CIT context.

In either case, waveguides may require a "jacket" as a tritium barrier. This will obviously make the design more cumbersome. Issues related to tritium will be explored in the near future.

1.2.3 Reliability

CIT has formal requirements on reliability for all systems, expressed in terms of a low probability for forced shutdown of operations from failures. The ECH system would have to match these requirements.

For example, the August 5, 1988 draft of the Systems Requirements Document states the following relative to ECH:

1. There shall be no credible failure modes ($P > 10^{-6}$) for the ECH system which, directly or indirectly, would compromise the CIT mission by precluding operation at 10 Tesla and 11 MA for a period in excess of 1 calendar year.
2. All credible failure modes shall be repairable with equipment funded in the construction project.
3. The downtime for unscheduled maintenance of the ECH system shall not exceed 2.7 hours per thousand hours of operation per 10 MW of installed power.
4. During full power operation (> 7 T) the probability of not successfully acquiring and archiving the necessary subset of data for achieving the goal of a given shot due to an anomaly related to the ECH system or of experiencing a failure in the ECH system which precludes the initiation of the next shot shall be less than 0.8 per thousand shots per 10 MW of installed power.

Other than reliability requirements as expressed above, there is no requirement related to reliability on the desired amount of power to come from one source. It is sometimes believed that a unit size smaller than 1 MW (or so) will lead to an unreliable system of 10 MW in size, and that the larger the power from a unit the better. This thought may turn out to be valid, but it remains to be demonstrated.

2 Schedule and Cost

2.1 CIT Schedule

2.1.1 Construction and Operating

The CIT Project Schedule, as of autumn 1988, is a reference for considerations pertaining to R&D on ECH sources. According to that schedule, operation with plasma starts at a 7 Tesla maximum field in July of 1996. The basic machine will be capable of 10 Tesla for a nominal 3000 pulses, and 11 Tesla for some limited number of discharges. The limitation to 7 Tesla operation comes from installed equipment for energy storage and conversion. The additional funding for operation at 10 and 11 Tesla is in the range of $70 M. Since the funds have not been identified, the time required to bring the CIT to 10 Tesla might be in the range of four years.

There are operating considerations as well. Since experience will be needed with the equipment and the plasma, and since the number of shots per day will be on the order of ten, four years of preparation for the highest field is reasonable.

Therefore, we estimate a requirement for an ECH system capable of heating a 7 Tesla plasma in 1996, and a 10/11 Tesla plasma after a time, depending on funding. Assuming four years to specify, construct, and install the ECH system, the R&D should be finished in 1992, with some continuing R&D on the higher frequency in progress until 1996.

2.1.2 Possible R&D Plans

R&D could be aimed strictly at the CIT schedule, meaning a source suitable for 7 T, ready for design and construction work in 1992, with continuing R&D for the higher field until 1996-8. Such a plan appears to be especially sound for the gyrotron approach, because the gyrotron is already achieving 800 kW for short pulses at 140 GHz, and is directed in the near term to 400 kW steady-state at 140 GHz.

Alternatively, R&D could aim at the 10 T condition, believing that, if such a goal is achieved, modifications for operation at 7 Tesla should be relatively simple. This plan would be consistent with the existing IFEL program, which is aimed at 250 GHz on a tokamak experiment.

Supporting either plan requires study of practical issues (cost and schedule) and relationships to other programs. The CIT design group favors a plan which focuses on the 10 Tesla implementation, since that is where the ultimate success of CIT is most likely to occur. A possible outcome of this strategy is that a 10 Tesla source is developed successfully, but that retreating to 7 Tesla resonance for the early implementation on CIT appears too expensive or too time-consuming. In that case, the 10 Tesla source could be used at 7 Tesla, through the technique of Doppler shifting the frequency with off-perpendicular launching. This does introduce complications with steering the beam, and the physics of heating fast electrons.

2.2 Gyrotron R&D and Fabrication Schedule and Cost

The CIT project has prepared cost estimates for a complete gyrotron program, including R&D and fabrication of a 10 MW installation.[7] The fabrication project takes advantage of existing TFTR neutral beam power supplies, which have an estimated value of $20 M, and finds that 10 MW would cost about $22 M.

This cost would have to be duplicated for each additional 10 MW system. Above 30 MW, TFTR power supplies would be fully used.

This cost estimate has a detailed logic behind it, including the following important milestones:

- 1 MW short pulse demonstration at the Massachusetts Institute of Technology (MIT) using an experimental 280 GHz tube;
  October 1989
- 1 MW short pulse demonstration at MIT using a cw-relevant 280 GHz tube;
  February 1992
- 1 MW long pulse demonstration at 140 GHz at Varian Associates, Inc.
  February 1991
- 1/2 MW long pulse demonstration at 280 GHz at Varian;
  October 1992

This schedule allows an informed decision in 1992 to proceed with the gyrotron approach.

2.3 IFEL R&D Schedule and Construction Cost

The R&D on the IFEL involves advances in IFEL capability and ECH experiments on the Microwave Tokamak Experiment (MTX) in three phases.

- Single pulse experiments in FY 89 (the US fiscal year starting October 1988, ending September 1989) with 140 GHz and 2.5 GW for 20 nanoseconds. This work will investigate issues related to plasma absorption as well as the functioning of the IFEL. Total energy is 50 J.
- Short burst experiments in FY 90 with 140 GHz and 3.8 GW at a pulse repetition frequency of 5 kHz. The burst time will be 10 milliseconds, for a total energy of 5 kJ. Each pulse is to be 35 ns long.
- High average power experiments in FY 91 with 250 GHz and 10 GW for 50 ns for a total average power of 2 MW over 0.5 seconds yielding 1 MJ. This will demonstrate the heating technology, and its effects on the plasma for heating and profile control. Current drive is a possible topic, also.
- Confinement and current drive experiments using high average power microwaves during FY 92.

After completion of these advances in the technology of the IFEL and demonstration of results on the MTX, a reliable estimate of cost and scientific performance can be made.

Preliminary estimates of the costs of a 10 MW, 280 GHz system for CIT show $41 M, assuming that a building and prime power are available. A 560 GHz system, which requires a 15 MeV accelerator, is estimated to be $43 M.[8]

3 Assessment of Sources for ECH

3.1 Summary of Technologies

The gyrotron, the Free Electron Laser (FEL), and the Cyclotron Autoresonance Maser (CARM) all require substantial additional development to meet the minimum CIT requirement of at least 10 MW average power at 280 GHz. Table 2 summarizes the present status of these possible sources for CIT ECH. Table 3 gives the major operating parameters such as electron beam voltage, magnetic field, and efficiency.

3.1.1 Gyrotron

The gyrotron is the best developed source technology at present. It appears very likely that 1 MW, continuous wave (cw) oscillators at 280 GHz can be developed. At 140 GHz 0.1 MW cw tubes are now available commercially with 0.4 MW projected to be available soon. At 240 GHz, 0.5 MW in 2 ms pulses in a cw relevant tube design has also been experimentally demonstrated. Relatively moderate frequency (< × 2) and power scaling (× 3) are needed to meet the minimum CIT requirement with 11 or 12 one megawatt gyrotron tubes.

In addition to the relative advanced state of development, another advantage of the gyrotron source technology is the relatively low electron beam voltage requirement. Existing neutral beam power supplies at the TFTR site can be readily adapted to provide the necessary voltage and power. This would represent a significant cost savings to CIT installation.

However, there are several key issues that need to be considered in the development of a gyrotron-based ECH system for CIT. These include: wall loading and higher order mode tube operation as the frequency is scaled to 280 GHz; the development of an efficient mode converter from the high order gyrotron oscillator mode to a low order mode useful for transmission and plasma heating; and the handling of many beams, up to 40, if a full 40 MW CIT requirement is to be met with 1 MW tubes.

A potential future difficulty with the gyrotron is extension to higher frequencies (>300 GHz), where difficulties increase significantly. However, some performance with degraded power would be perhaps possible if magnets are designed for operation at a field higher than the nominal operating field.

3.1.2 IFEL (Induction Free Electron Laser)

The induction linac driven FEL is the next best developed source technology. Its most likely form will be a rapidly pulsed amplifier, the oscillator driver at 280 GHz being a low power (1-10 kW) backward wave gyrotron. In short pulse operation, 20 ns, 1 GW at 35 GHz and 50-100 MW at 140 GHz have been demonstrated. However, the pulse repetition rate to date has been very slow, 0.5 Hz, and consequently the average power has been on the order of 10 and 1 W, respectively. To meet the minimum CIT requirement, the average power performance must be improved by a factor of about 10^6. This improvement is expected to be achieved in large part by an increase in the pulse repetition rate to the order of 10^4 Hz, using switching technology that has been demonstrated on injectors and accelerator sections in the laboratory. An integrated test of this IFEL technology will take place in the MTX program.

The main issue with the development of IFELs for CIT is the achievement of high average power. Pulse repetition rates on the order of 10^4 Hz or higher are needed to demonstrate feasibility and to resolve unknowns about possible nonlinear plasma effects using very high peak power pulses for ECH. Also, high cost and large size of 10 MeV electron beam accelerators makes the practicality of the IFEL very sensitive to the output power amount.

3.1.3 EFEL (Electrostatic Free Electron Laser)

The electrostatic accelerator driven FEL is in a similar state of development. In the concept of TRW, Inc., the EFEL is a continuous wave (cw) oscillator at unit power levels of 2-3 MW. Results to date in the 30-60 GHz range at TRW and at 400 GHz at the University of California at Santa Barbara have been much lower in peak and average power than those for the induction linac driven FEL.

The main advantages of FEL sources for CIT ECH are: readily scalable to high frequency operation; fundamental or low order mode output directly usable for transmission/heating, and larger power unit size reducing transmission line complexity. The FEL also has an advantage in frequency tunability discussed below.

3.1.4 CARM (Cyclotron Autoresonance Maser)

The CARM is the least developed source technology proposed for CIT. Because of its immature state of development, its configuration for CIT has not been determined. It could take the form of a rapidly pulsed amplifier or oscillator or as a cw oscillator in unit sizes of 2-3 MW or larger. There are no experimental results in the U. S. in this area at present though several groups (General Atomics Corporation, MIT, the Naval Research Laboratory, and the University of California at Los Angeles) are initiating or planning experimental work. In the Soviet Union there has been some experimental work at 125 GHz and lower frequencies. Velocity spread effects are a key issue to be investigated. The CARM can be viewed as providing the potential for an attractive compromise between the gyrotron and FEL technologies. The accelerator requirement of approximately 1 MeV is more than for a gyrotron (≈100 keV) but less than for an FEL (≈10 MeV). Hence, the CARM would operate in a low order mode like an FEL but with a much smaller and less expensive accelerator. The CARM has the capability to operate at much higher frequencies than the gyrotron, because its frequency depends on beam energy as well as magnetic field.

3.2 Frequency Tuning

There are several potential needs for a frequency tuning capability, depending on the time scale of the tuning. Table 4 summarizes the potential tuning capabilities of the possible CIT ECH sources.

On the shortest millisecond time scale, tuning can be used for profile control, sawtooth stabilization, or MHD instability feedback control. The gyrotron oscillator has the least tuning capability on this time scale due to the weak dependence of the resonance frequency on voltage pulling. The FELs operated as amplifiers can have 6-10% instantaneous bandwidth which would correspond to an equivalent millisecond tuning range given a rapidly tunable oscillator driver. The CARM potentially could have the largest millisecond tuning capability because, in addition to an instantaneous bandwidth comparable to an FEL, its $v_\perp/v_\parallel$ electron beam velocity ratio could be rapidly varied with a specialized electron gun. The Doppler shift term in the CARM frequency depends only on $v_\parallel$.

On the longer second time scale, a 30% tuning capability would be needed for heating during toroidal field ramp-up and ramp-down. All the sources have the potential to meet this requirement. The gyrotron could achieve this tuning capability by mode hopping due to a sweep of its magnetic field in synchronism with the toroidal field. A 60% tuning range centered at 185 GHz with 10 GHz steps already has been demonstrated for a gyrotron at MIT. However, a specialized hybrid superconducting magnet with a copper core and a wide bandwidth mode converter would need to be developed. The FEL could have a large second tuning capability by varying the wiggler magnetic field strength as recently demonstrated by the Electron Laser Facility (ELF) at Lawrence Livermore National Laboratory (LLNL). The CARM could also have up to a 30% second tuning capability by varying its magnetic field as well as the $v_\perp/v_\parallel$ electron beam velocity ratio.

A requirement for a frequency change on a much longer time scale - on the order of days or weeks - has also been stated. Slow frequency adjustments would be useful when CIT start-up operation at 7 T progresses to 10 T and possibly 11 T operation. If the second tuning capability as shown in Table 4 is built into the sources from the start, then the requirement would be satisfied. However, additional options exist for changing ECH source frequency on time scales of a week. In the case of gyrotrons, the gyrotron tube containing the electron gun, resonator, and mode converter could be replaced, keeping the magnet, power supplies, and transmission line the same. The gyrotron tube, once developed, represents a small fraction of the overall cost of a gyrotron-based ECH system. In the case of an FEL, the wiggler period or beam energy could be adjusted on day time scales to optimize performance at alternate frequencies.

3.3 Breakdown (Arcing in Transmission)

The power densities considered for CIT ECH are high enough that breakdown in the transmission line should be investigated. Above a threshold power density, breakdown occurs at millimeter wave frequencies when a few initial electrons are accelerated by inverse bremsstrahlung absorption to energies sufficient for ionizing gas molecules, producing additional electrons that continue the process until an electron density of greater than 10^{13} cm $^{-3}$ is produced. The resulting arc cuts off further millimeter wave transmission and can be damaging to the ECH system.

In a clean gas, the initial electrons needed to start a breakdown generally are not present. However, in the presence of contamination such as dust particles or at the surface of a mirror in the transmission line, the initial electrons can be readily produced by high peak fields.

For microwave electromagnetic beams with pulse lengths > 50 ns, it has been shown that the breakdown threshold in air is given approximately by

$$J \approx 2.6(p^2 + 2f^2) \quad ,$$

where J is the power density in W cm^{-2}, p is pressure in torr, and f is frequency in GHz. For 280 GHz at atmospheric pressure, this gives an approximate threshold of 2 MW cm^{-2}.[9]

For shorter pulses the breakdown threshold should scale inversely with the pulse length. However, data taken at 0.4 mm wavelength (second harmonic for CIT) with a pulsed D_2O laser has shown an air breakdown threshold as low as 0.5 MW cm^{-2} with 7 ns pulses.[10] The air in these measurements was pre-ionized by power densities as low as 1 MW cm^{-2} on a nearby surface.

Therefore, a conservative approach to avoiding breakdown in an air-filled transmission line for continuous power would be to design the ECH system so that power densities are less than 0.1 MW cm^{-2}. The peak power level of cw ECH sources for CIT such as the 1 MW gyrotron and the 2-3 MW TRW FEL is low enough that the beam power density can be kept under 0.1 MW cm^{-2} in waveguide diameters as small as 10 cm. Therefore, a conservative approach to the design of the transmission line with respect to breakdown is possible.

With high peak power pulsed ECH sources such as a pulsed IFEL or CARM, a different approach to the problem is necessary. The program or the IFEL at LLNL does consider that an evacuated waveguide is necessary. In fact, there will be no window between the ECH source and the plasma for the MTX experiment, and there is no window planned for CIT. An analysis by E. B. Hooper of LLNL (see the appendix) concludes that breakdown of the background gas in the quasi-optical transmission line will not be a problem. Moreover, the permitted gas pressures are much larger than required in the transmission line for cleanliness regarding the plasma and the IFEL source.

However, experiments will be needed to establish breakdown limits, which could be related to effects not yet identified, such as micro-particle contamination of the transmission line.

3.4 Decision Criteria

The decision on which source technologies are most appropriate for CIT will depend on a number of criteria. Possible criteria that could be used include:

1. Confidence level for meeting minimum objectives of performance and schedule;
2. Timetable to demonstrate important milestones;
3. Costs of both research and development and hardware;
4. Cost sensitivity to deviations from projected source performance;
5. Flexibility to accommodate evolution of the CIT design (field, density, tunability) and physics uncertainties.

The ranking of the various source technologies by these criteria could also change with time as these technologies mature. It would also be affected by the CIT timetable.

4 Discussion of Possible Strategies

4.1 Spanning Initial and Final Parameters

The ECH power system on CIT is to begin 7 Tesla operation in 1996. and continue for 1 - 4 years at this field. In the years 1997-9 the level should be raised to 10 and 11 Tesla.

There are three general approaches:

1. a tunable system which can span the range from 180 to 280 GHz (7 to 10 Tesla); this could be step-tunability, with steps on the scale of tens of GHz;
2. an upgrade to the initial 180 GHz system in which crucial frequency-sensitive components are changed;
3. installation of a 280 GHz system, which is operated on 7 Tesla discharges by launching with enough k. to resonate with electrons moving along the field.

Tunability is the best, if it can be obtained. However, the difficulties of reaching reliable high power at 180 GHz may be enough without the additional demands of optional operation at 280 GHz. Choice number three adds the demands of 280 GHz to the possible physics uncertainties associated with using the Doppler shift to resonate with lower fields, and the engineering of a practical, adjustable mirror.

The approach taken depends on progress in the coming years of the development program. At the present moment, a plan involving an upgrade looks favorable. Using the gyrotron approach as an example, a reasonable plan might be the following: develop and install a 180 GHz gyrotron system for 1996, but design the superconducting magnets and power supplies to be operable at 10 Tesla. When the toroidal magnetic field can be raised to 10 Tesla, upgrade or replace the gyrotron cavity, gun, drift tube, and collector as necessary.

Less favorable in appearance is a plan to install a full 280 GHz system at the beginning and operate it in a 7 Tesla environment for several years. Using the Doppler shift introduces new physics to the ECH interaction. In particular, the low field plasma has to be pre-heated to a significant degree to absorb power well. Also, it appears more probable that reliable high power will exist at 180 GHz than at 280 GHz during the early years of CIT.

4.2 Second Harmonic Heating

First harmonic heating (fundamental) has been discussed, rather than second harmonic. This is because significant power is now available at 140 GHz with gyrotrons, which is comparable to the 180 GHz required for 7 Tesla. A second harmonic system is 360 to 560 GHz, representing an enormous advance in the state of the art.

The second harmonic does have advantages in physics, particularly the ability to push the density much higher.

The strategy for CIT is to focus on an early implementation of high power first harmonic heating. Depending on progress of the CIT project itself and the R&D on ECH sources, a later decision to move the focus to second harmonic could appear advisable.

4.3 Rapid Frequency Control and Feedback

Fine tuning the frequency on short time scales to influence plasma stability and confinement could be advantageous. The technology to do this has not been developed and the benefits have not been demonstrated. This element should be considered for addition to the CIT program when technology and experiments are available.

As in section 4.2, the strategy for CIT is to focus on early implementation of high power heating. Depending on progress with sources and physics R&D, rapid fine tuning can be added, or some high power equipment can be converted to this purpose.

5 Conclusions

There are now two main approaches to the technology of ECH sources. The **gyrotron leads in terms of energy at high frequency now delivered** from a source, and an implementation of gyrotrons on CIT has the advantage of installed and paid-for DC power from the TFTR neutral beam system. **The IFEL holds the promise of tunability.** The tunability has the potential for being rapid enough to follow the ramp of the magnetic field, and to follow the location of certain magnetic surfaces in the plasma.

Important advances must occur with both the gyrotron and the IFEL to reach the performance desired for CIT. However, assuming adequate support is provided from now to the end of 1992, an informed evaluation of both technologies can be made in time to decide on the best path for CIT. Accordingly, the CIT schedule now shows a **decision point regarding a commitment to the gyrotron and/or the IFEL at the end of 1992.**

The best path may not involve a total system based entirely on one technology as opposed to the other. Assuming that both the gyrotron and the IFEL progress as hoped by 1992, a combination may be desired. For example, the gyrotron could provide the larger portion of the power while the IFEL provides rapid tunability for interacting with the plasma on a fine scale. Combinations within a technology may be interesting. Consider 10 gyrotrons with different frequencies, or IFELs with wigglers of different properties.

Funding is a concern, both for R&D and for a construction project. At present, the bulk of the required R&D is supported, but, the construction funds have not been identified.

This document has focused on the gyrotron and the IFEL because they occupy the largest fraction of the support for microwave sources in the Office of Fusion Energy of the US Department of Energy. **Other concepts deserve investigation,** including the quasi-optical gyrotron, the cyclotron autoresonance maser, and the electrostatic free electron laser with energy recovery.

Acknowledgments

This work was funded by the United States Department of Energy, Office of Fusion Energy. The activity at PPPL was performed under Contract DE-AC02-76-CHO-3073. The work at MIT was supported by Contract DE-AC02-78ET-51013.

Material on physics requirements is based on presentations by R. Parker and D. Ignat, who used material from M. Porkolab, S. Kaye, G. Bateman, W. Reiersen, S. Jardin, and N. Pomphrey. Comments received from T. R. James, K. Thomassen, E. B. Hooper, Jr., M. Porkolab, J. Casey, R. S. Post, and J. A. Schmidt have been incorporated. Advice from H. Jory and R. J. Temkin forms a background for the opinions expressed on the best aim for the development program on gyrotrons.

This report is adapted from CIT Document AA-881018-PPL-05, which was requested of the CIT Project Office by the Department of Energy, Office of Fusion Energy.

Appendix I

Explicit form of Scaling Laws

by

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Energy balance in CIT is modelled in zero dimensions by setting the total input power equal to the power flowing out of the plasma. If W is the total particle energy in the plasma, τ_E is the energy confinement time for conduction, P_{Rad} is power radiated in parallel with conduction, P_{OH} is the ohmic heating from the plasma current, P_α is the power from alpha heating, and P_{Aux} is the auxiliary heating power, then in steady state:

$$P_{OH} + P_\alpha + P_{Aux} = W/\tau_E + P_{Rad} \quad .$$

The scaling laws under discussion regard the parametric variation of τ_E and P_{Rad}.

We consider that discharges heated only by ohmic heating have one scaling law, and discharges with dominant auxiliary heating have another scaling law. For *ohmic heating*, the "Neo-Alcator" scaling[11] is used:

$$\tau_{N-A} = 0.07\bar{n}aR^2q_{cyl} \quad .$$

For discharges with strong auxiliary heating, one or the other of two scaling laws is discussed. The more favorable is "Kaye-Goldston" scaling[1]:

$$\tau_{K-G} = 0.055(M/2^{1/2})^{1/2}\kappa^{0.28}I^{1.24}P^{-0.58}a^{-0.49}R^{1.65}B^{-0.09}\bar{n}^{0.26}$$

and the less favorable is "Goldston-Aachen" scaling[2]:

$$\tau_{G-A} = 0.037(M/1.5)^{1/2}\kappa^{0.5}I^{1.0}P^{-0.5}a^{-0.37}R^{1.75} \quad .$$

The quantities and units are as follows:

τ	Confinement time, seconds
M	Average mass of hydrogenic species, amu
κ	Elongation ratio
B	Toroidal magnetic field, Tesla
I	Plasma current, Megamperes
n	Line-averaged electron density, $10^{20}/\mathrm{m}^3$
P	Auxiliary power (including alpha particle heating) in Megawatts
a	Minor radius (half-width at midplane), meters
R	Major radius, meters
q_{cyl}	cylindrical $q = 5a^2B(1 + \kappa^2)/2/(IR)$

To get one number for the confinement time, τ_E, the laws from ohmic heating and auxiliary heating are combined according to an inverse square law, which has as its foundation the rule of reasonability:

$$(1/\tau_E)^2 - (1/\tau_{N-A})^2 - (1/\tau_{Aux})^2 \quad ,$$

where τ_{Aux} is either of τ_{K-G} or τ_{G-A}, depending on which scaling law for auxiliary heating is being considered.

The radiation term, P_{Rad}, includes bremsstrahlung, but neither line radiation nor synchrotron radiation, which are neglected. The formula[12] adopted is:

$$P_{Rad} = 0.0168 Z_{eff} \int_{volume} n^2 T^{1/2} \quad ,$$

where Z_{eff} is the effective ion charge of the plasma, taken to be 1.5 in the examples in this document, and T is the electron temperature in units of 10 keV.

One should note that the scaling laws termed Neo-Alcator, Kaye-Goldston, and Goldston-Aachen, were derived ignoring radiation. This means that radiative losses were included in the scaling laws. In this analysis the radiative losses are added explicitly to a form of energy confinement which already included radiation in a sense. This is done to make sure that physically impossible results are not obtained at high densities and low temperatures where radiation is high.

The calculations of Figures 1 through 3 include profiles for density and temperature of the form

$$n(x) = n(0)(1 - x^2)^{\alpha_n}$$

and

$$T(x) = T(0)(1 - x^2)^{\alpha_T} \quad ,$$

where x is fractional distance from the center on the midplane. The powers $\alpha_{n,T}$ are noted on the Figures.

The enhancement over Goldston scaling of 1.8 in Figures 2 and 3 refer to an arbitrary multiplier on the formula above for τ_{G-A}.

Appendix 2

Breakdown in IFEL Quasi-Optical Transmission System

by

E. B. Hooper, Jr.
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Summary The issue of breakdown of background gas in the quasi-optical transmission system is examined for a range of parameters including MTX and CIT. The parameters are far enough from breakdown conditions that no problems are anticipated. Surface breakdown is not analyzed here, but fields are much less than in the waveguide where it has been argued not to be a problem.

Analysis During the IFEL pulse, heating of stray electrons will cause exponentiation of the electron density although, as will be seen, the pulse length is short enough that the density will not build up very far. Following the pulse, further ionization will occur as the electrons lose energy and the plasma recombines on the walls of the transmission line. At the low gas densities in the system, collisions are infrequent and the losses to the walls will be at the sound speed of the plasma.

The average electron density, n_e, in the transmission line will approximately vary as:

$$dn_e/dt = [n_o \langle \sigma v_e \rangle E \tau_p f - c_s/L] n_e \quad .$$

Here, $n_o = p \times 3.5 \cdot 10^{16}$ is the gas density in cm^{-3}, with p the pressure in torr; $\langle \sigma v_e \rangle$ is the ionization rate averaged over the electron distribution. E is the enhancement coefficient due to ionization following the IFEL pulse. τ_p is the pulse duration, f is the IFEL repetition rate, $c_s = 10^6 T_e^{1/2}/A$ is the speed of sound (with T_e the electron temperature in eV and A the atomic mass), and L is the effective distance to the walls.

We will get breakdown when the coefficient of n_e in the above formula is greater than 0, so that the electron density can exponentiate. Thus, for there to be no breakdown, we require:

$$p < 3 \cdot 10^{-11} T_e^{1/2} / [A\langle\sigma v_e\rangle E L \tau_p f] \quad .$$

We use the maximum value of the ionization rate for our estimates:

Gas	$A\langle\sigma v_e\rangle (cm^3/sec)$
hydrogen (gas or molecule)	$3.0 \cdot 10^{-8}$
oxygen (gas or molecule)	$1.5 \cdot 10^{-6}$
nitrogen (gas or molecule)	$1.3 \cdot 10^{-6}$
argon	$8.0 \cdot 10^{-6}$

The maxima all occur between 100 and 300 eV; for estimating purposes, take $T_e^{1/2} = 16$ and $E = 10$. We consider several applications:

MTX

Hydrogen in the transport system; $L = 30$ cm, $\tau_p = 50$ ns, $f = 5 \cdot 10^3$ Hz,

$$p < 0.2 torr.$$

In the port, L = 3 cm, and p is about 10 times that in the transport, both here and in the examples below.

Oxygen and nitrogen in the transport system;

$$p < 4 \cdot 10^{-3} torr.$$

Argon in the transport system;

$$p < 8 \cdot 10^{-4} torr.$$

These conditions are all easily met.

CIT

Dimensions and pulse lengths for CIT are similar, but f could be as large as $2 \cdot 10^4$ Hz. Thus, the limiting pressures are: hydrogen, $5 \cdot 10^{-2}$ torr; oxygen and nitrogen, 10^{-3}; and argon, $2 \cdot 10^{-4}$ torr.

Discussion The lack of ionization largely arises from the fact that the minimum ionization time, $(n_o \langle \sigma v_e \rangle_{max})^{-1}$, is long compared with the microwave pulse, 50 ns. For example, in hydrogen gas at 10^{-3} torr, the ionization time is 500 ns; and in argon at 10^{-6} torr, the ionization time is 4000 ns. Thus, there is very little buildup of electron density during a microwave pulse.

Finally, note that the permitted gas pressures are much larger than required in the transmission line for cleanliness and much larger than designed. Consequently, the crudeness of the model used in the analysis should not affect the conclusion that breakdown due to ionization of the background gas will not occur.

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Table 1: Selected Parameters of the CIT Design

Parameter	Value
Major Radius, R	2.1 m
Half-width, a	0.65 m
Half-height, b	1.3 m
Current, I	11 MA
Start-up value	7.7 MA
Toroidal Field, B	10 T
Start-up value	7 T
Fusion power at beta limit	800 MW
Flat top time	5 seconds
Number of pulses at full performance	3000
Fusion energy released during lifetime	6.5 Terajoule
Troyon parameter, β % /(I/aB)	3
Murakami parameter, n_{20} /(B/Rq_c)	2
Elongation, kappa	2
Safety factor, q at 95% flux	3.2, at least
Triangularity	0.25, at least
Enhancement over Goldston scaling in order to achieve ignition at 10 T	2
Enhancement over Kaye-Goldston scaling in order to achieve ignition at 7 T	2

Table 2: Comparison of status of possible sources for CIT ECH

	Gyrotron	IFEL Induction Free Electron Laser	EFEL Electrostatic Free Electron Laser	CARM Cyclotron Autoresonance Maser
CW or pulsed	CW	Pulsed >10GW	Either	Either
Probable unit size (av. power)	1 MW	10 MW	2-3 MW	2-3 MW
Current status (av. power)	$2 \cdot 10^5$ W @ 70GHz $1 \cdot 10^5$ W @140GHz as oscillator	10 W@ 35GHz 1 W@ 140GHz as amplifier	<1W@30 & 400GHz as oscillator and amplifier	Not demonstrated in U. S., some results at 125GHz in USSR as oscillator
(pk. power)	$9 \cdot 10^5$ W @140GHz	10^9 W @ 35GHz 10^8 W @ 140GHz	$4 \cdot 10^4$ W @ 400GHz	
Improvement needed				
av. power	$\times 10^1$	$\times 10^7$	$\times 10^7$	—
frequency	x2	x2	x1	—
Issues	High order mode competition, wall loading, output mode converters, windows, and scaling to high frequencies	Demonstration of high repetition rates 10^4 Hz, high peak power plasma nonlinearities, large physical size, and cost sensitivity to unit power size	Very low efficiencies, electron beam, energy recovery not demonstrated, costs	No U. S experimental experience, sensitive to electron beam quality

Table 3: Major Parameters of Possible CIT ECH Sources

	Gyrotron	IFEL	EFEL	CARM
Electron beam voltage	0.09 MV	5-10 MV	5-10 MV	≈1 MV
Magnetic field	11 tesla	≈1 tesla	≈1 tesla	≈5 tesla
Electro-magnetic mode	High order >50th	Fundamental	Fundamental or low order <5th	Fundamental or low order <5th
Achieved Wall-Plug Efficiency	30%	7%	1-5%	. . .
Theoretical Beam-Efficiency	50%	50%	5%	30%
RF output converters and transport	Difficult (many beams, very high order modes)	Easier (one fundamental mode beam)	Moderately easy	Moderately easy

Table 4: Frequency Tunability of Proposed Sources for CIT ECH

Tuning Time Scale	Gyrotron	IFEL	EFEL	CARM
Milliseconds	0.01%	6-10%	6-10%	10-20%
Seconds	≈50% (step tunability)	≈50%	≈50%	20-30%

Figures

FIG. 1. Plasma operation contours of constant auxiliary power (in MW) required to maintain a certain density (ordinate) and temperature (abscissa). The zero power contour at low temperature represents ohmic heating. Ignition is at threshold on the zero power contour covering 6 to 20 keV temperature. The scaling law assumed is that of Kaye-Goldston. Field and current are 10 Tesla and 11 MA. Soft operational limits on density and beta are shown by heavy solid lines. (G. Bateman)

FIG. 2. Plasma operation contours as in Fig. 1 according to the Goldston scaling law, enhanced by a factor of 1.8. This shows that 60 MW of auxiliary power does not lead to ignition in the steady state. (G. Bateman)

FIG. 3. Contours of constant energy multiplication (Q) for the case of Fig. 2. This shows, when examined in conjunction with Fig. 2, that an auxiliary power of 25 MW leads to a Q of 10. (G. Bateman)

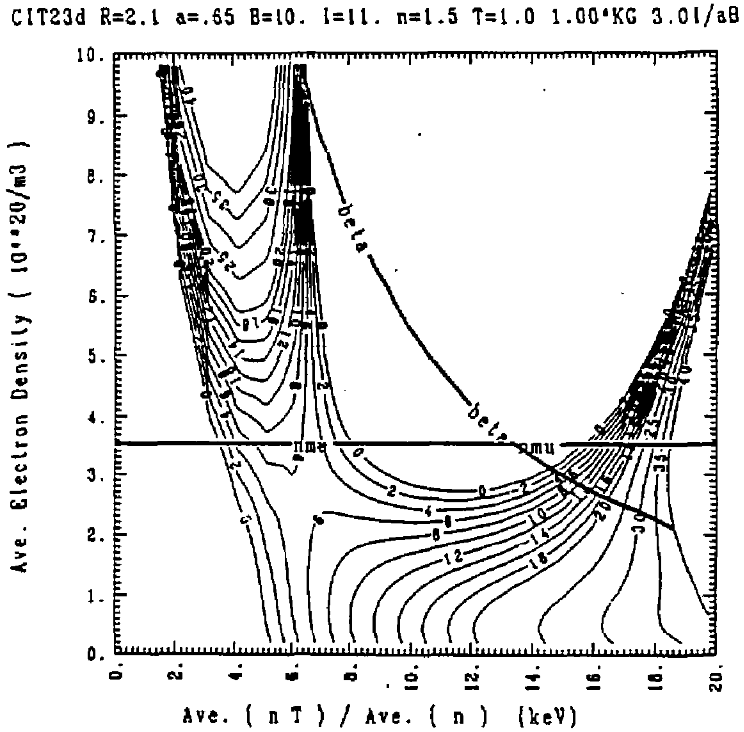
FIG. 4. Reference waveform for 10 Tesla and 11 MA operation. The flat portion of the toroidal field and plasma current is reached at 7.5 seconds from the initiation of the current. Half current and 80% of magnetic field is reached 3 seconds earlier. (W. Reiersen)

FIG. 5. Reference waveform for 11 Tesla and 11 MA operation. The flat portion of the toroidal field and plasma current is reached at 7.5 seconds from the initiation of the current. Half current and 80% of magnetic field is reached 4 seconds earlier. Flat-top time is limited to 3 seconds at 11 Tesla. (W. Reiersen)

FIG. 6. Reference waveform for 7 Tesla and 7.7 MA operation. The flat portion of the toroidal field and plasma current is reached at 7.5 seconds from the initiation of the current. Half current and 80% of magnetic field is reached 3 seconds earlier. This level of performance can be reached with fewer power supplies than in the case of Figs. 1-2. With the same power, the 7 Tesla current and field ramp could be faster. (W. Reiersen)

FIG. 7. Plasma position versus time during a ramp of the discharge current from zero to 11 MA, as shown by the major radius (top) and minor radius (bottom). (S. Jardin and N. Pomphrey)

FIG. 8. Equilibria during (a) ramp-up; (b) flat-top; (c) ramp-down. (S. Jardin and N. Pomphrey)



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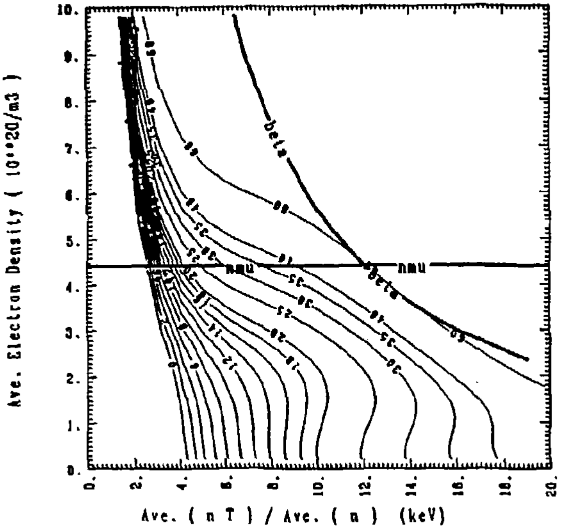

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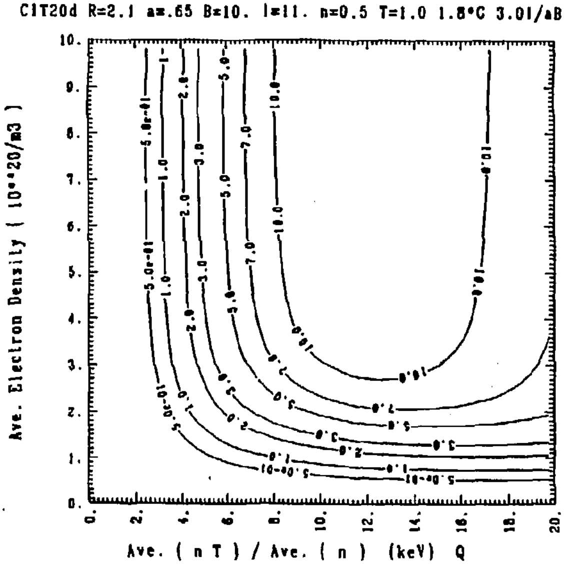

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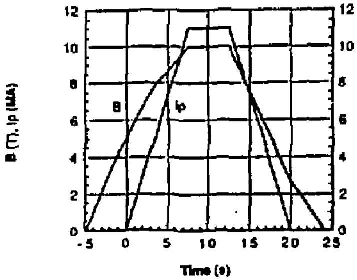


FIG. 4. *Reference waveform for* 10 Tesla and 11 MA operation. The flat portion of the toroidal field and plasma current is reached at 7.5 seconds from the initiation of the current. Half current and 80% of magnetic field is *reached 3 seconds earlier. (W. Reiersen)*

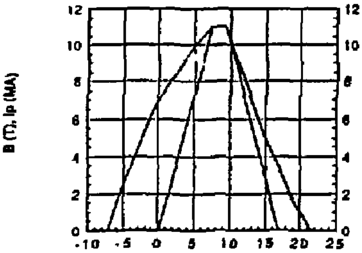


FIG. 5. Reference waveform for 11 Tesla and 11 MA operation. The flat portion of the toroidal field and plasma current is reached at 7.5 seconds from *the initiation of the current. Half current and 80% of magnetic field is* reached 4 seconds earlier. Flat-top time is limited to 3 seconds at 11 Tesla. (W. Reiersen)

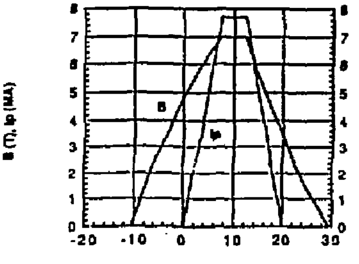


FIG. 6. Reference waveform for 7 Tesla and 7.7 MA operation. The flat portion of the toroidal field and plasma current is reached at 7.5 seconds from the initiation of the current. Half current and 80% of magnetic field is reached 3 seconds earlier. This level of performance can be reached with fewer power supplies than in the case of Figs. 1-2. With the same power, the 7 Tesla current and field ramp could be faster. (W. Reiersen)

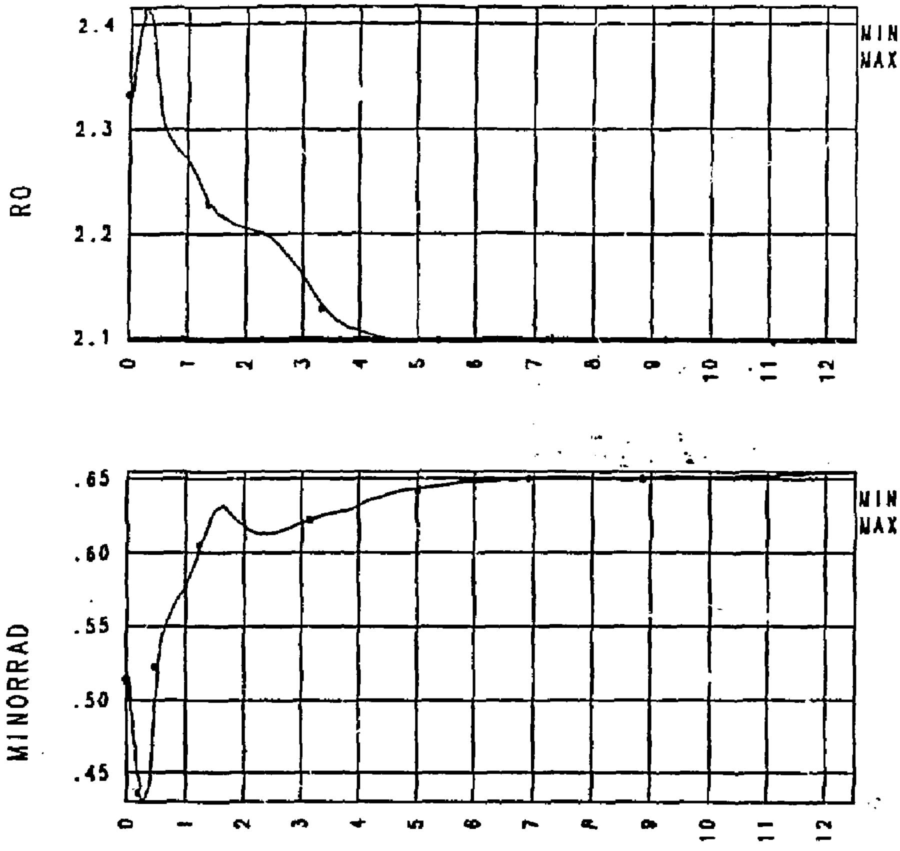
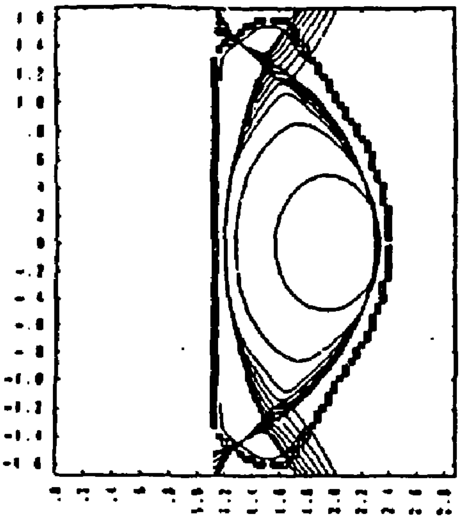


FIG. 7. Plasma position versus time during a ramp of the discharge current from zero to 11 MA, as shown by the major radius (top) and minor radius (bottom). (S. Jardin and N. Pomphrey)

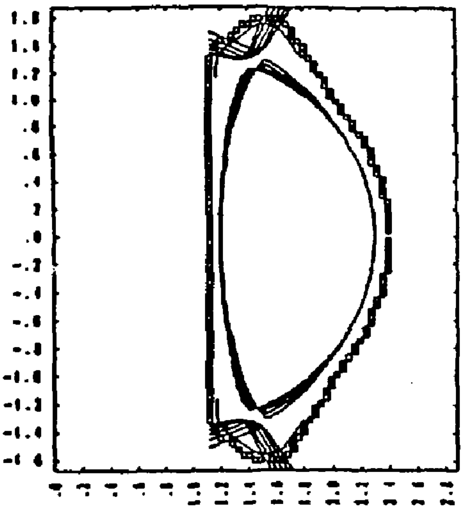


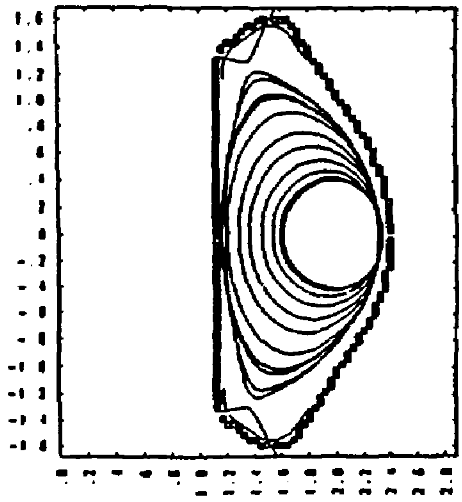
Current Ramp

t = 0 s - t = 5.8 s

Current Flattop

t = 5.8 s - t = 10.8 s





Current Rampdown

t = 10.8 s - t = 16.8 s

FIG. 8. Equilibria during (a) ramp-up; (b) flat-top; (c) ramp-down. (S. Jardin and N. Pomphrey)

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