CONF-830406--34

DE83 012067

RADIO-FREQUENCY ENERGY IN FUSION POWER GENERATION

CONF-830406--34

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ABSTRACT

The history of radio-frequency (rf) energy in fusion experiments is reviewed, and the status of current efforts is described. Potential applications to tasks other than plasma heating are described, as are the research and development needs of rf energy technology.

INTRODUCTION

Early studies of controlled thermonuclear fusion, around 1953, proposed methods of heating that generally included radio-frequency (rf) power in the very low frequency (VLF) region. Such systems as the "B-Oscillator" and the "Test MOPA," for use in magnetic pumping, operated in a frequency range of 100-200 kHz. In 1957, T. Stix of Princeton University proposed and demonstrated that a high frequency (HF) rf system would couple energy efficiently to the plasma at the ion cyclotron resonance frequency. Experimental results conducted with rf source capabilities of 1 MW on the B-65 at 12 MHz and the B-66 at 16 MHz indicated that rf energy was a strong candidate for reactor heating. Problems of confinement and impurity influx plagued plasma studies for the next decade. These anomalies limited rf heating studies to power levels of a few hundred kilowatts, even though significant developments were made in megawatt rf power sources up to and including the very high frequency (VHF) range.

At fusion laboratories the world over, starting about 1975, major commitments were made to heat plasmas by means of ion cyclotron resonance heating (ICRH), electron cyclotron resonance heating (ECRH), and hybrid schemes with high power rf sources. Success in varying degrees has been achieved. As experiments and theoretical calculation continued, other roles for rf heating were devised. Each method of heating and/or plasma control requires a particular part of the spectrum for proper operation.

[a]Operated by Union Carbide Corporation under contract W-7405-eng-26 with the U.S. Department of Energy.

The ion cyclotron range of frequencies (ICRF) lies in that portion of the rf spectrum that includes such services as the AM broadcast band [medium frequency (MF), 300-3000 kHz], the international communications and broadcast band (HF, 3-30 MHz) and the VHF television/FM broadcasting band (VHF, 30-300 MHz). Many years of development and operation in these frequency ranges by commercial and government interests enabled the fusion program to move to relatively high power levels without a major equipment development program. However, this fortuitous circumstance is no longer applicable, and much research and development in component parts, such as vacuum tubes, will be required to construct rf systems to meet the needs of present and future machines.

The primary role that ICRF heating will play in the tokamak reactor will be in heating the plasma at the fundamental and second harmonic regimes. For the first fusion reactor, this mode of heating will require rf power levels in the 100-MW range. At this time, existing rf systems for plasma machines are capable of only 5 MW. In addition to resonance heating, the ICRF power sources will be used for plasma current drive. This scheme is particularly practical in large reactor vessels, where physical spacings will allow for arrays of waveguide launchers in a fast wave configuration.

The lower hybrid range of frequencies (LHRF) covers that portion of the rf spectrum which is used for ultrahigh frequency (UHF) television and microwave heating (UHF, 300-3000 MHz). The primary role envisioned for LHRF is "current drive." The rf energy is used to provide excitation to electrons in a unidirectional mode so that a net current flow in the plasma will allow continuous operation of the tokamak reactor. LHRF may also be used for plasma heating. However, further investigation is required to prove that this method of heating is practical. Power levels of 10-50 MW are envisioned for current drive of a full-size reactor. Post-World War II development of high power gridded tubes and ~0.5-MW klystron amplifiers has provided the means to satisfy power requirements of existing experimental machines up to the size of the Tokamak Fusion Test Reactor (TFTR).

Experimentation in the heating of plasmas by excitation of electrons at their resonant frequency has been under way since 1960 at Oak Ridge National Laboratory (ORNL). With the development of the gyrotron oscillator in Russia, the heating mode (ECRH) of the electron cyclotron range of frequencies (ECRF) has become an additional factor in the role that rf energy will play in fusion power generation.

The low frequency end of the ECRF extends from 10 to 30 GHz; the high frequency end, from 30 to 300 GHz. This band of frequencies has been used mainly for radar, communications, and radio astronomy with systems in which average power levels are quite low. Much development work is still under way for high power sources that operate in the range from 60 to 300 GHz. To date, levels of several hundred kilowatts represent the state of the art. Tokamaks, as presently conceived, will have field strengths that produce electron resonances between 30 and 200 GHz. The major roles now envisioned for ECRF are plasma start-up and profile control of the plasma by means of selective heating.

To accomplish cost-effective rf operation of a reactor, tube and component development beyond the present state of the art will be required. Development of new techniques to raise the operating efficiency of whatever sources are ultimately used will also be required to minimize reactor operating costs.

HISTORICAL BACKGROUND

According to a history of Project Matterhorn,[1] Lyman Spitzer, Jr., chairman of the Princeton University astronomy department; John Wheeler, a Princeton physicist; and J. Tuck of Los Alamos Scientific Laboratory met at the headquarters of the Atomic Energy Commission on May 11, 1951, to discuss a possible method to confine a thermonuclear plasma. In the same history, it is noted that in March 1953 a paper by Spitzer and Witten first addressed the problem of plasma heating, and a method called "induction heating" was chosen to heat the first fusion devices. Another method of ionization and heating, which is still used, was devised by J. M. Berger and E. A. Frieman, also in 1953, and described in a paper entitled "On the Pulse Method of Ionization and Heating of a Plasma."[2] A high voltage electric field, magnetically coupled into the confinement vessel, results in the ionization of a controlled amount of hydrogen or deuterium and causes ionization of the gas. This is followed by a unidirectional pulse of current coupled into the ionized gas. The plasma is then heated ohmically to a temperature between 1.0 and 30 million kelvin, where the resistance of the plasma is so low that no further heating occurs. Since this temperature (1 keV = 10 million kelvin) was well below the 100 million kelvin required for reactor operation, a number of auxiliary heating methods described by Spitzer and Witten's survey were considered. Various experiments to heat by magnetic pumping[3] on the B-2 stellarator were made but proved disappointing in that they did not reach their goal.

The real beginning in the use of rf energy for fusion machines came from results of the successful ICRH on the B-65 and B-66 machines, a direct result of basic ideas put forth by T. Stix in a paper published in the *Physical Review*, "Oscillations of a Cylindrical Plasma."[4] This highly successful idea has been used at Princeton on the Model C Stellarator, the ST tokamak, the Adiabatic Toroidal Compressor (ATC), and the Princeton Large Torus (PLT). Proposals are being developed to install ICRH on the largest U.S. fusion machine, TFTR. During the period from 1960 to 1970, much of the physics of ICRH heating was developed by use of a 25-MHz, 4-MW, short pulse generator. This unit is still in use, having been most recently modified to a 30-MHz, 2-MW, long pulse generator. The period from 1970 to 1980 saw great strides in heating, first on ST and then on PLT. Joel Hosea proposed a half-turn rf coil as the coupler of energy to the plasma. Despite the fact that the operating frequency of the high power generator was too low for good high field machine operation, a doubling of ion temperature was achieved on the ST machine. After another successful ICRH run on ATC, in which the rf power in joules was increased 10-fold over that of the ST machine, a decision was made by Princeton to continue ICRH experiments on PLT, and two high power (55-MHz), 2.5-MW, long pulse generators were built and later modified to 42 MHz. These generators and the 25-MHz generator have over the past four years raised the ion temperature to 2.3 keV above the 0.5-keV ohmic temperature.[5] It is at this point that the technological problems are beginning to loom as large as the physics problems.

In the early 1960s, experiments in lower hybrid heating were tried on the B-3 machine. A 25-kW television transmitter was coupled to the plasma through single-turn coils at 500 MHz. Plasmas were produced in which the energy penetrated to the center of the plasma. However, the lower hybrid heating phenomenon was not observed, and as Dr. Tanner points out most succinctly in his history,[1] the "subject of lower hybrid heating was put to one side, for a while." In 1972, W. Hooke and S. Bernabei restarted investigation of the lower hybrid phenomenon. Shortly thereafter, they were joined by R. Motley, who began experiments on coupling by phased arrays based on studies by Lallia and Brambilla in Grenoble. In 1976, four high power klystrons (55 kW at 800 MHz) and a 4-waveguide phase array were installed to couple lower hybrid energy into the ATC machine. The results, again, were disappointing, not from the coupling standpoint, which was excellent, but from the apparent contradiction in data. Unfortunately, the tests were concluded before the conflict in data could be resolved because the ATC area had been allocated for the new Poloidal Divertor Experiment (PDX) machine. The lower hybrid physicists and engineers were undaunted, however, and upgraded the rf system to six generators, each with a 200-kW output and long pulse capability, for use on the PLT machine to resolve once and for all the physics of lower hybrid heating. In addition, this rf system was used to determine if this frequency range could be used to drive an unidirectional current in the plasma. At this time, the jury is still out on lower hybrid heating. However, great strides have been made in driving a current in PLT.[6] The caveat on the current drive is that at 800-MHz excitation there is a density limit at about 7×10^{12} cm^{-3}, which is too low for a working reactor.

High power, lower hybrid experiments have been performed at other laboratories, including those at the Massachusetts Institute of Technology (MIT) and General Atomic Company (GA) in the United States; at the Japan Atomic Energy Research Institute (JAERI), Nagoya University, and Kyoto University in Japan; and in France, Italy, and the Federal Republic of Germany. Each of these groups has contributed to the physics and technological store of knowledge.[7]

In the years since 1960, there has been a consistent effort by Dandl, England, and others to study and define the role that ECRH would have in a reactor. Work was done first in simple mirror machines[8] and later in the ELMO Bumpy Torus (EBT), a closed mirror machine.[3] In this same time period, the Russians developed a high power millimeter wave oscillator or "gyrotron" and were heating tokamaks with ECRH. Varian Associates, under subcontract to ORNL, started a study of gyroklystron (gyrotron) devices and was confident that tubes with 200-kW output power up to 120 GHz in frequency could be built. This program, under the guidance of Oak Ridge, has produced reliable 28- and 60-GHz tubes at the 200-kW output level.

POTENTIAL USES FOR RF ENERGY

The history of rf energy in fusion experiments indicates that the majority of work done, to this point, has been directed toward bulk heating of the plasma components. As we move closer to a functioning reactor, rf energy will be a strong contender for many ancillary tasks as well. The roster of these tasks shown in Table 1 is by no means complete, since we do not know all the problems that will be encountered in a reactor. This last statement may seem presumptuous, but if one considers the following facts, there is surely a good basis for believing that rf energy application can solve many reactor problems.

Table 1. RF energy tasks

A. Heating
   1. Ions (resonant coupling)
   2. Electrons (resonant coupling)
   3. Electrons (wave coupling)

B. Current drive

C. Start-up

D. Profile control

E. Particle control
   1. Heavy impurities
   2. Light impurities

First, the ionized fuel particles in a plasma, both ions and electrons, when confined in a magnetic field, have gyrofrequencies identical to the frequencies of rf generators that can be built and used to drive these resonances. Second, rf energy can be imparted to the ionized particles in different directions simply by phasing the coupling devices. Third, the conduit by which energy is fed into the fusion machine can be bent and shielded so that high energy neutral particles produced by the machine do not enter the heating source but can be captured by the heat exchange blankets that surround the machine. Fourth, rf generators can be operated at frequencies that are the gyrofrequencies of impurities in the plasma. By ingenious coupler design, one might be able to remove or divert the impurities. Fifth, rf energy is in the form of electromagnetic waves when it leaves the antenna or coupling device; this energy can be made to travel around a closed device to deposit energy in the center of the plasma.

The most serious problem we face at this time is to decide which tasks to concentrate on and which frequency will give the optimum results.

BASIC RF PARAMETERS

There are only a few plasma equations with which the average rf engineer must be conversant. However, some of the relationships of frequency to machine conditions will clarify the magnitude of the scope of probable uses of rf in fusion machines. The equations for ion (f_{ci}), electron (f_{ce}), and hybrid (f_{lh}) gyrofrequency and ion (f_{pi}) and electron (f_{pe}) plasma frequency are as follows:

$$f_{ci} = \omega_{ci}/2\pi = 1.52 \times 10^3 Z\mu^{-1}B \ , \quad (1)$$

$$f_{ce} = \omega_{ce}/2\pi = 2.80 \times 10^6 B \ , \quad (2)$$

$$f_{LH}^2 = \frac{f_{pi}^2}{1 + (f_{pe}^2/f_{ce}^2)} \quad , \quad \frac{f_{pe}^2}{f_{ce}^2} = \frac{f_{pi}^2}{f_{ci} f_{ce}} \quad , \quad (3)$$

$$f_{pi} = \omega_{pi}/2\pi = 2.10 \times 10^2 Z \mu^{-1/2} \eta_i^{-1/2} \quad , \quad (4)$$

$$f_{pe} = \omega_{pe}/2\pi = 8.98 \times 10^3 \eta_e^{1/2} \quad , \quad (5)$$

where Z is the charge state, μ is the ratio of the ion mass to the proton mass, B is field strength (in gauss), and η is density.

If we take a reasonable range of magnetic field strengths that might occur in a fusion reactor, we find that curves may be drawn to show the approximate operating frequencies that must be provided for the test and final reactors. Figure 1 shows a plot of such calculations for

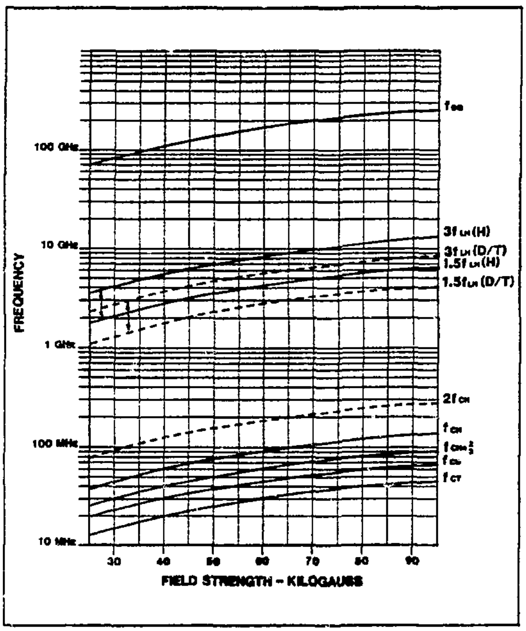

Fig. 1. Frequency variation with field strength.

hydrogen, helium, deuterium, and tritium. There are some unique occurrences on this graph that should be noted. At a given field strength, the second harmonic of deuterium ions is the same as the fundamental frequency of hydrogen ions, and the second harmonic of tritium ions is the same as the fundamental frequency of helium ions. It should also be noted that f_{ce} in any HF or even MF machine is extremely high [in the superhigh frequency (SHF) range], and much work needs to be done in this area. The curves for lower hybrid heating and current drive are based on plasmas with an equal electron plasma frequency and gyrofrequency, $\omega_{pe} = \omega_{ce}$. The curves of $1.5f_{lh}$ for lower hybrid heating and $3f_{lh}$ for lower hybrid current drive are good approximations.[10] The largest U.S. tokamak, TFTR, would normally operate at 50 kG and would require an ion cyclotron generator that operates from 25 to 150 MHz, a lower hybrid generator that operates from 2.45 to 7.0 GHz, and an ECRH generator that operates at about 140 GHz.

That is the most straightforward portion of the basic rf parameters. The more difficult portion in the case of heating (or plasma current value of some magnitude in the case of current drive) is the determination of power requirements. Some approximations of the various conditions are given below. These should be used with great caution since there are no adequate experimental data or schemes to optimize either coupling mechanisms or modes.

EQUIPMENT TO ACCOMPLISH RF TASKS

In thinking about rf energy in a "global" sense, whether it be a radio transmitter, a radar unit, a microwave heater, or a fusion generator, there are some basic components and some special components. Fortunately for the fusion community, there are engineers who can move from one discipline to another, and if we can interest one or two universities in teaching the fine art of electron tube design and high power circuit computation and design, there will be a supply of engineers to build the high power rf systems shown in Fig. 2.

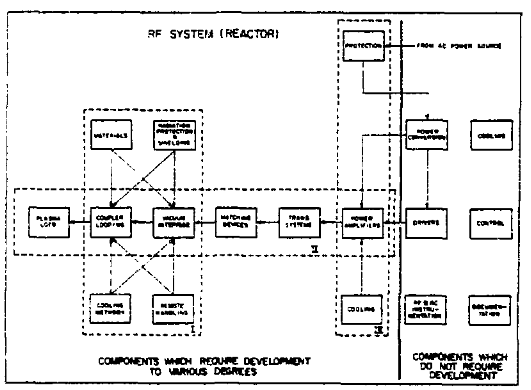

Fig. 2. High-power rf system for reactor.

With the exception of the special reactor facets in block I, the present-day rf generators fit the diagram in Fig. 1. In the ICRF range, we are able to approach 2.5 MW out of a single tube; in the lower hybrid range, 500 kW out of a single tube; and in the ECRH range, 200 kW out of a single tube. These power levels are very impressive. However, for a reactor this would mean 100 unit amplifier systems for ICRF, 20 to 40 unit amplifier systems for lower hybrid, and 100 unit amplifier systems for ECRH. Such a large number of unit systems would not be cost-effective in terms of space, manufacturing, or reliability because of the sheer number of components. One must compromise between what can be done with present-day components and the production of a cost-effective, reliable system. In order to make this compromise and to develop components to achieve the compromise, we should examine each block of Fig. 2 in some detail for the three basic systems: ICRF, LHRF, and ECRF.

Two of the items in block I, the vacuum vessel interface and the coupler, are part of the rf power flow to the plasma load. These items must therefore be capable of handling the power, in terms of the voltage and current and of the frequency in the ICRF range. A typical example for a near-reactor-size machine[11] shows that a ridged waveguide could support up to 48 MW into a matched load and that it is realistic to think of 10 MW per waveguide with two guides stacked one above the other so that >100 MW could be transferred into a machine in the manner shown in Fig. 3. The next block in the path toward the power amplifiers is the vacuum interface, which, because it is made of ceramic and metal, is more susceptible to radiation damage than the all-metal coupler. Therefore, the vacuum seals must be placed in the coaxial feed lines behind radiation shields. The development of the vacuum interface will depend to a large extent on the uniformity of the plasma load in a reactor or on the variation in the standing wave ratio caused by the plasma load changes during the heating cycle.

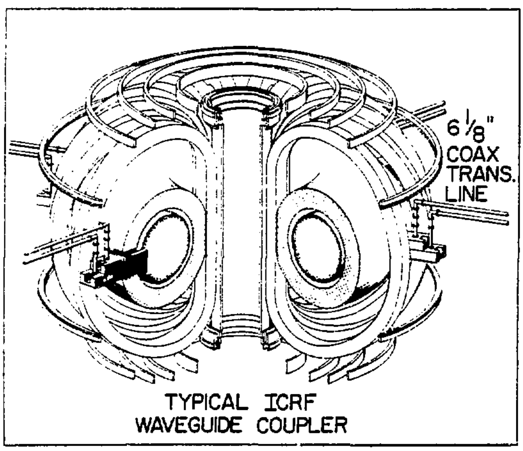

Fig. 3

The other parts of block I have to do mainly with reactor performance and design. Close cooperation between machine designers, rf physicists, and engineers will be required. Materials for the couplers and vacuum interfaces will be of the same material as the first wall of the machine, with some type of high conductivity plating in high current areas to minimize rf source power losses. Cooling and remote handling will also follow the design of the machine, with special consideration given to areas that have rf current interfaces with the sources.

As we continue toward the source of rf energy, matching devices will be required to minimize VSWR losses and maximize the amount of power that can be carried over a transmission line. These units should not be too difficult to build and should not require tuning in a reactor. The transmission system for ICRF will most likely be coaxial lines, the power handling capability of which is well documented. The design in Fig. 3 shows 10 MW in 6.125-in. copper lines.[11] This is accomplished by pressurizing the line at 20 psig with SF_6 and cooling the inner conductor with water. This scheme is not the optimum design, but it does demonstrate the power handling capability of realistic components.

Generating the 10 MW of power that the transmission system can handle requires diplexing or multiplexing at least four state-of-the-art amplifiers. There are problems of phasing and load sharing with this scheme, but they are not insurmountable, and systems such as this have been used when product need was insufficient to produce new designs. However, we may well have reached the point at which there is a need for such high levels of continuous wave (cw) rf power and new tubes should be developed.

With the exception of cooling and protection of high power systems (tubes in particular), other components are well developed and present no problems for rf design engineers. Cooling and protection, however, are serious problems when one considers that from the motor-generator (MG) set to the plasma load the system efficiency will be about 40%. This means that for a 100-MW system, the power dissipated as heat in the system will be 150 MW, or 3000 MJ of energy, for a 20-s pulse. Somehow we must improve system efficiencies. In the area of generator protection, abnormally fast shutdown of equipment, such as tube faults, will have to be kept to a minimum since there will be almost zero impedance between the power source (fusion reactor) and the load (fusion heater).

Consider the LHRF case for a near-reactor-size machine. Current drive, in a high efficiency mode, may require 20 MW of power at

2.5 GHz. The state of the art in klystrons is power output of 500 kW (development of a 1-MW tube at 2 GHz is under way in Japan). A typical current drive coupler will consist of stacked 8-waveguide phased arrays; each guide is roughly 11 by 1.5 cm with a total area of 16.5 cm^2. A reasonable amount of power through a guide is 6 kW/cm^2, so 100 kW per guide or 800 kW per phased array is a reasonable amount of power. Thus, 25 phased arrays would be needed in this hypothetical machine. This arrangement would allow stacking five arrays at five places on the machine and, with klystron amplifiers capable of 500 kW, would allow electronic phasing of the arrays and make tube and waveguide manufacturers very happy. To keep the vacuum interface window from looking directly at the plasma radiation, the windows will have to be placed well beyond the point where the toroidal field might not be strong enough to preclude electron cyclotron resonance breakdown. In addition, special consideration will have to be given to the volume of the transmission system between the plasma and the vacuum window.

If generators are limited to 500 kW, the transmission systems to the rf generators will probably be standard waveguide with water cooling. It will be advantageous to make the waveguide as large as possible to reduce losses and minimize cooling requirements. Experiments on PLT will soon be made with the 2.45-GHz generators for current drive. This system will use round waveguides to determine what operating problems might occur from this type of feed. To be a good start-up and current drive generator, the lower hybrid system requires electronic phase shifting. Therefore, a multiplicity of klystrons is not that great a detriment, and a tube capable of 1 to 5 MW should be adequate.

The major uses for ECRH include plasma generation, electron ring formation, and electron bulk heating. As noted above, a need for high powers will, with present gyrotron capabilities, require far too many units. Therefore, a push is needed for higher power gyrotrons as in the present 60-GHz development program. For the larger, higher field machines of the future, gyrotrons in the 100-GHz region at >100 MW are needed. A near-term issue is the feasibility of windowless systems, thereby eliminating this difficult-to-build element. Quasi-optical transmission systems may be a way to avoid some problems with preserving mode purity in waveguide transmission systems. Considerable interest has been focused on important elements such as mode convertors, filters, and polarizers, with emphasis on power handling capability and bandwidth. All of these systems (ICRH, LHRH, ECRH) will be taxed especially hard by the cw needs of future machines. Efficiency becomes a major issue, as does the cooling system design.

RESEARCH AND DEVELOPMENT NEEDS

In Fig. 2, three areas are blocked out for the elements of high power rf generators for fusion reactors. The most difficult problems concern the interface of the coupler and vacuum window with the radioactive plasma. This problem will require close cooperation between the plasma physicists, rf engineers, materials physicists, and mechanical engineers. The second most difficult block (II) is the one that will ultimately have the largest effect on the cost of reactor operation. This channel of energy includes the high power amplifier and transmission system. All efforts should be made to develop high efficiency tubes, low loss transmission lines, and matching devices that will minimize reactive power in the transmission system. It is imperative that tube and circuit engineers work in close concert to achieve the highest efficiency possible. Taking the theoretical case of 100 MW of ICRF power and plotting various input powers required at some range of efficiencies, we obtain the graph in Fig. 4, which points out that any funds spent for improvement here are money well spent. In the

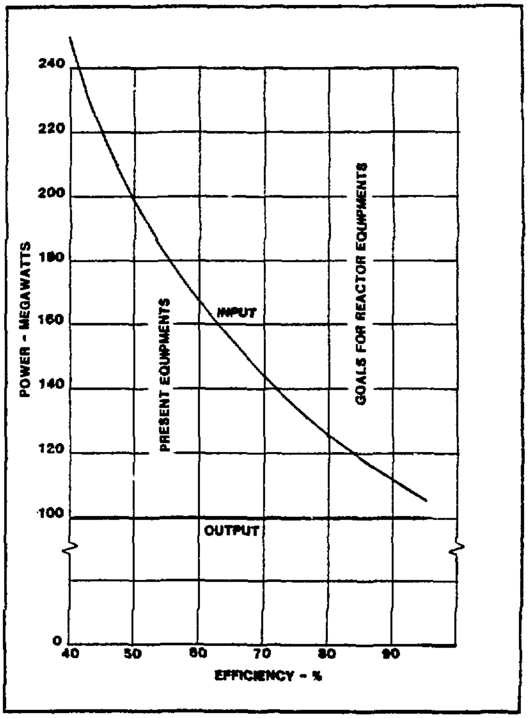

Fig. 4. Line power required vs system efficiency for a 100-MW output.

high frequency ICRF case, this means development of tubes with circuit elements inside the vacuum envelope, which might allow quasi-class D, high efficiency operation. It also means developing computer modeling techniques to optimize all of the components between the plasma load and the final and penultimate rf power amplifiers. Klystron manufacturers should also be encouraged to improve the efficiencies of klystrons and gyrotrons.

Block III is concerned with the development of protective devices. These devices must be developed to control fault conditions that will arise as a result of higher tube input capability and lower effective power line impedances to the 60-cycle source. Additional development is also required to improve the efficiency of the klystrons and gridded tubes.

Tables 2 and 3 give a broad view of the major and minor research and development efforts that will be required before there will be realistic and cost-effective use of rf energy for fusion reactors.

Table 2

MAJOR RESEARCH AND DEVELOPMENT EFFORTS
1. Transmission line RF vacuum windows
2. Transmission line dc safety breaks
3. ECR and multipactor suppression in the evacuated portions of transmission line
4. Materials test facility for both high power and radiation testing of system components
5. RF test on TFTR-1 to determine the limit on RF power density at the plasma surface

Table 3

MINOR RESEARCH AND DEVELOPMENT EFFORTS
1. Development of the 1.25 MW klystron
2. Possible development of a new super power VHF tube for the ICRF system
3. Power supply components
4. RF monitoring and control systems
5. High power coaxial shorted stubs for water cooling of center conductors
6. High power spacer support for coax
7. Theoretical analysis of ridged waveguide
8. A comparison among coax, circular, and elliptical waveguide for the lower hybrid feed system
9. High power testing of coax and waveguide components

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