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Steady-State Current Drive In Tokamaks Workshop Summary

February 1979

U.S. Department of Energy

Assistant Secretary for Energy

Office of Fusion Energy

Division of Magnetic Confinement Systems

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Foreword

In July 1978 a workshop on improving the tokamak fusion reactor concept was held. (The summary report is available as DOE Report CONF-780758.) A major topic considered was steady state vs. pulsed operation and one of the workshop conclusions was that "Increased emphasis should be placed on identifying mechanisms for achieving steady state, or near steady state, operation and on determining if steady state operation is, in fact, more desirable, considering what it will take to achieve it".

Subsequently, this workshop was held at the DOE Germantown Office on September 26-27, 1978 with representatives of national laboratories, industries, and universities participating. The objective was to identify the most promising techniques for non-inductive current drive in tokamaks and to recommend a program for demonstrating such techniques. The viability of using rf, neutral beams and electron beams was discussed.

Specific actions since the workshop include the funding of an experiment on Versator at MIT to study the use of lower hybrid frequency waves to drive current. Plans to follow this study with a 1 MW experiment on PLT are being formulated.

Neutral beam driven current experiments will be conducted within the existing ISX-B, PDX, PLT, and D-III programs. Preliminary experiments using runaway electrons to provide the tokamak current channel have been conducted on Macrotron at UCLA. Discussion of relativistic electron beam driven current experiments continues.

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I. Introduction

Since the inception of the tokamak program, considerable attention has been devoted to investigating possible means of minimizing the dependence of the tokamak reactor on inductive processes for the establishment or maintenance of the toroidal plasma current. Recently there was renewed interest in the area of driving currents in the tokamak configuration. At the same time, studies have been continuing to understand the possible engineering or technological simplifications that could result if the tokamak reactor could be operated in a steady-state mode. A meeting* held on the subject of improving the tokamak reactor concept pointed out several of the undesirable features characterized by the pulsed nature of the tokamak. Some of these features could be eliminated if current drive could be demonstrated in a tokamak. The areas which were specifically discussed on the pulsed nature of the tokamak included:

- Need for thermal "flywheel" to provide continuous output power
- Cyclic thermal and mechanical excursion effects on reactor (e.g., first wall) life
- More complex control system

*Workshop on Improving the Tokamak Fusion Reactor Concept held in Germantown on July 13-14, 1978

- Substantial recirculating power required for startup
- Sensitivity of superconductors to large pulsed fields
- More costly power storage and transfer system

A number of approaches have been considered for generating a continuous current in a tokamak configuration. One scheme is to inject rf power into a tokamak plasma such that the wave momentum is directed parallel to the toroidal field. An electric current is then generated by the plasma electrons as the electrons absorb momentum from the waves. Key features of using rf to generate this toroidal current are that high power rf sources are readily available in the frequency ranges required by tokamak devices and that rf can also serve the role of auxiliary heating.

Another approach for current generation is to use an energetic neutral beam injected tangentially into a tokamak to transfer momentum to set up a net positive ion circulation in the plasma. A third approach is to use a relativistic electron beam (REB) where the beam can both heat the plasma and produce the confining field for the plasma.

A workshop on the subject of current drive by rf or beams was held Germantown on September 26-27, 1978. Representatives from national laboratories, industry and universities participated in an open discussion on the viability of driving currents by rf, neutral beams and electron

beams. The purpose of the workshop was to identify the most promising techniques and to outline the expectations for tokamak reactor concepts. The group which included beam and rf specialists were asked to assist in the preparation of specific recommendations for the establishment of a program directed at demonstrating current drive. This report includes the recommendations and conclusions as prepared by A. Bers, D. Jassby, and T. Hsu and the summary papers submitted by the participants describing the various experiments and studies presented at the workshop.

II. CONCLUSIONS AND RECOMMENDATIONS ON RF CURRENT DRIVE IN TOKAMAKS

On the basis of the two-day discussions and presentations it is recommended that an aggressive program should be undertaken to establish the feasibility of RF current generation for eventually achieving a steady-state (or quasi-steady-state) tokamak reactor plasma. Such a program must be a balanced one: on the one hand pursuing basic, detailed, yet unanswered questions through experiments, theory and computations, and on the other hand initiating experiments on the generation of appreciable currents (50% or more of ohmic current) by RF in state-of-the-art tokamak plasmas. An obvious by-product of such a program would also be the possible control by RF of the current profile in a tokamak for the purpose of maximizing its β .

A critical sequence of experiments can be identified which would yield results in time to affect the design of the ETF, which is now beginning. By following this critical path of phased studies, the RF current drive option could be developed to the point where it could radically simplify the ETF design, by alleviating or eliminating the OH current drive requirement from the poloidal coil complex.

In the following three sections we outline briefly: 1. Recommendations for the critical rf current drive experiments. 2. The basis for rf current generation and the status of various experiments and theories relevant to this. 3. A basic research program consisting of experiments, theory, and computations. 4. Existing and proposed toroidal experimental facilities useful for producing rf driven currents comparable to the ohmic heating current. Details on the various topics can be found in the appended summaries of talks submitted by the speakers.

1. Recommendations for the Critical RF Current Drive

On the basis of the information presented at the workshop and the discussion that followed a general consensus was reached that a critical sequence of experiments is required to establish the feasibility of rf current drive in tokamaks. Given the benefits (e.g., steady state) of this technique it is imperative that the fusion program support the following experiments starting this year.

(a) The Versator-II experiment at MIT which has as its primary mission to study lower hybrid using phased arrays of waveguides, requires a second slow-wave launcher with a 6 waveguide-grill and a new phase shifting network to initiate current drive experiments. Currents in the range of 6-60 kA ($I_{OH} \sim 30-50$ kA) should be generated with absorbed rf power of 100 kW.

(b) A full scale demonstration on PLT which is the best diagnosed tokamak in operation is needed to provide the confidence level to effect a radical change in the ETF design. As with Versator-II a lower hybrid heating program is planned on PLT which is to begin in early 1980. An early demonstration that current/power ratio ≥ 100 A/kW can be achieved under realistic conditions will maximize the impact of rf current drive schemes on reactor plasmas.

2. Basis for, and Status of, Current Generation by RF.

- (a) The fundamental principle supporting this type of current generation is that in wave-particle (electron) interactions wave momentum can be transferred to particle (electron) momentum.
- (b) In the period of 1952-1978 a variety of experiments have shown that the excitation of travelling waves in a plasma leads to current generation, and such currents have been measured. Many of these experiments have been rather complex in that the RF wave was simultaneously used to generate the plasma. None of these experiments have been performed in a state-of-the-art tokamak plasma. All of these experiments have been accompanied by only qualitative explanations of the results.
- (c) Theoretical work on current generation by travelling waves has been active since 1971. Various waves and schemes have been analyzed. The most relevant calculations to date include two-dimensional (velocity-space) Fokker-Planck computer calculations for a homogeneous plasma. On the basis of analyses and computations to date, scaling to a steady-state reactor looks promising in that the estimated power needed to drive the steady-state current is a small fraction of the fusion power output. However, these calculations need to be extended to apply to a realistic experiment. None of the detailed theories so far have been tied in with a specific experiment.
- (d) Recent experiments related to RF heating of plasma electrons by lower-hybrid waves have shown that good coupling to electrons is possible. These experiments have been done in both a linear and a tokamak plasma. Other, very recent experiments on lower-hybrid heating in some tokamaks have shown that at high power densities the coupling from an array of waveguides becomes relatively independent of the external phasing of the waveguide. This could be a serious problem since the efficient generation of a travelling

wave requires a progressive phasing of the waveguides.

(e) The generation of appreciable currents by RF will require high power sources. Such sources, in the megawatt range per source are available now up to and including the microwave frequency regime (a few gigahertz), and at high efficiencies (50%-70% at UHF and 40%-50% at MW).

3. Basic Research Programs in Current Generation by RF.

(a) The T-1 experiment at PPPL. This is a small-scale steady-state (the plasmas is produced by long pulses of RF power and there is no ohmic current, i.e., this is not a tokamak) torus in which detailed measurements on various aspects of RF current drive can be made. The modest plasma parameters will allow measurements with probes inside the plasma. Thus, unresolved questions of nonlinear effects on coupling and propagation can be properly studied. Estimates also show that appreciable current can be generated with modest RF powers. The coupling will however be done by rings rather than waveguides. The proposed experimental program will be supported by ongoing theoretical work, and by a power electronics engineering group. The milestones for this experiment call for completion of construction by February 1979, and start of RF power operation by August 1979. The immediate need for this experiment is additional funds (\$100 K - \$200 K) for 25 kW - 50 kW of RF power at 200 MHz.

(b) The APEX tokamak at ANL. This medium-sized tokamak experiment is currently in the design-construction phase. Large amounts of pulsed RF power will be available to study the effects of current generation. Appreciable currents will not be generated because only short pulses of RF power are available. Loop voltage measurements with parallel and anti-parallel launching of waves would be the major diagnostic on current generation. Nonlinear effects in waveguide coupling could be studied. Machine construction has started. Experiments on current generation could start in August 1979. The construction and some of the initial operating expenses are supported by Argonne internal funds. The immediate need is for additional \$50 K to extend the RF pulse, and for the construction of the launching structures.

(c) Theoretical and computational programs. Three main schemes of current generation by RF were discussed: (i) The use of suprathreshold lower-hybrid waves or high-frequency Alfvén waves. (ii) The use of subthreshold, low-frequency Alfvén waves. (iii) The use of electron cyclotron waves. The first is by far the most advanced in that it now includes, for electrostatic waves, two-dimensional Fokker-Planck computations on the evolution of the electron velocity distribution function. Further work is however urgently needed to include: spatial profiles and transport effects; the effects of the applied ohmic electric field and possible distortions in the initial electron distribution function; and toroidal effects. Both the second and third schemes require similar detailed computational work carried out and proposed for lower-hybrid waves. In addition the electron-cyclotron wave "bootstrap" current scheme needs further analysis of the basic proposed mechanism. For all mechanisms, further analysis of nonlinear effects in coupling and propagation is also required. Strong theoretical groups with expertise in RF heating of tokamak plasmas, and current generation by RF, exist at GA, PPPL, and MIT. These groups should be strongly encouraged to pursue such studies in general and provide support for ongoing and planned experiments.

4. RF Current Generation Experiments in Tokamaks.

In the following we outline an experimental program aimed at generating appreciable RF driven currents ($I_{RF}/I_{OH} \gtrsim 0.5$) in state-of-the-art tokamaks. The primary scheme, with the currently most advanced theoretical and computational basis, is to use lower-hybrid waves by phased-array waveguide excitation. The experiments are listed in the order in which they may be expected to produce results.

(a) Versator II at MIT. The tokamak and diagnostics are expected to be completed and operational by November 1978. The RF current drive experiment is currently being designed and its construction could be finished by February 1979. Experiments on current generation could start in April 1979. The immediate need of this experiment is for one post-doctoral associate engaged full-time on RF current drive, and additional funds (\$110 K).

(b) PLT at PPPL. This machine and its diagnostics equipment are currently fully operational. Detailed plasma properties are known over a range of operating conditions. Design and construction of the RF current drive experiment would take from January to September 1979. The machine would presumably be available for these experiments late in 1979 or say January 1980. Immediate needs include additional funds (\$250K in FY 1979 and \$100K in FY 1980) and a firm commitment by the PLT team.

(c) RST at GA. This machine is currently in the design stage. Its aim is to demonstrate full steady-state tokamak operation. It will be designed to accomodate, in addition to lower-hybrid drive, easy conversion to experimenting with magneto-sonic cavity drive or electron-cyclotron drive. Its construction would utilize the Doublet II-A facilities and take about two years -- from April 1979 to April 1981. Current generation experiments could start in May 1981. Machine approval is needed immediately

for proceeding with this schedule (MDF \$4.3M + research and operations cost). Support for the final design of a steady-state machine should be initiated as soon as possible.

All of these experiments need to supply further details, especially in relation to the interplay between energy confinement time, L/R time constants, RF power pulses, and other relevant operating characteristics to achieve $I_{RF}/I_{OH} \gtrsim 0.5$. Such information should be requested from each of the above proposed experiments and evaluated.

Finally, it is recommended that a closer interaction be established between this group, concerned with RF current drive, and people in the Division of Development and Technology concerned with studies of tokamak reactor operation. What is really meant, and desired, by steady-state, or quasi-steady-state, operation, given constraints imposed by ash-removal and refueling in a reactor, needs to be clarified.

III. CONCLUSIONS AND RECOMMENDATIONS CONCERNING BEAM-DRIVEN CURRENTS

Details of the theoretical basis and experimental status of neutral-beam-driven currents in tokamak plasmas can be found in the presentations of this Workshop. The first section below presents the conclusions reached at the Workshop regarding the existence and potential application of such currents. The second section outlines a program for identifying and utilizing beam-driven currents that are comparable in magnitude to the ohmic current. This experimental program is intended to make use of existing tokamaks and beam injectors. A program for studying REB-driven currents in a tokamak is also recommended.

A. CONCLUSIONS

High-power neutral beam injection experiments in tokamaks have shown that the fast-ion slowing down and pitch-angle scattering rates are close to classical, even in regimes where the injected beam power is several times the ohmic power. These results justify essential assumptions in the theory of beam-driven currents. In the near term, such currents are expected to be an inherent feature of beam-heating experiments with tangential or quasi-tangential injection. Hence their effects on plasma confinement and stability must be understood.

No neutral-beam-driven current has yet been definitively observed in a tokamak plasma, although a very small beam-driven current was identified in a toroidal multipole device at Culham. Nevertheless, because neutral-beam injection has been shown to be effective in plasma heating and is a well understood process, it seems likely that a strong beam-driven current will soon be identified. This current would offer the best opportunity for facilitating a near-term demonstration of steady-state tokamak operation—if such a demonstration were needed.

Reactor Applications

In order that current drive by injected energy be viable in a "pure fusion" reactor that is to be a producer of electrical power with an acceptable plant efficiency, it is necessary that $P_{in} \ll P_{el}$, where P_{in} is the electrical power input to the current-sustaining system, and P_{el} is the gross electrical power of the reactor. At best P_{el} will be 0.40 times the fusion power output, P_f . We specify that $P_{in} \approx 0.25 P_{el} \approx 0.10 P_f$, and assume that the efficiency of converting P_{in} into power that is injected and is used directly for current sustaining is 0.50. Then we must have $P_{injec.} \approx 0.05 P_f$, or $Q \geq 20$, where $Q =$ (fusion power)/(injection power). These remarks apply independent of the method of current drive.

For high-Q or near-ignited tokamak reactors intended to produce net electrical power, neutral-beam injection appears to be an undesirable method of maintaining a steady-state current. The principal reason is that minimizing the injected power while injecting large numbers of fast ions to carry the current demands relatively small beam energy, so that a low density plasma must be used to permit neutral-beam penetration. Low density is generally associated with low $n\tau_E$, which implies a small Q . At any rate, methods of steady-state fueling, ash removal, and long-time burn control must be demonstrated before steady-state plasma currents in ignited or near-ignited reactors can be deemed essential.

Intensely driven tokamak fusion plasmas with steady-state beam-driven currents can probably be made to work at $Q \approx 3$. Such plasmas could find use as neutron sources for fissile breeding, radiation testing, or other special applications. The neutral beams would also fuel and heat these plasmas as well as maintain the toroidal current.

Start-Up. The neutral-beam-driven current, together with the equilibrium-field system, could possibly be used to *start up* the plasma current in *ignited* tokamak plasmas, without the assistance of a central ohmic-heating transformer. This current would decay on either the "skin time" scale,

or the L/R time, both of which can be several hundred seconds for a plasma of ignition size and temperature. By this technique, an extremely compact ignited tokamak reactor might be made feasible, although operation would be pulsed.

For the above two potential applications of the beam-driven current, the density-radius product of the plasma is such that 80 to 120 keV neutral beams (D^0) are adequate for penetration. The principal advancement needed in neutral-beam technology beyond the TFTR injectors is the development of steady-state beams.

RELATIVISTIC-ELECTRON-BEAM INJECTION

In experiments on the SPAC-5 torus at Nagoya, a 2.6-kJ externally injected REB produced 30 kA of beam-driven net toroidal current, and a plasma ion temperature of 300 eV with $n_e \sim 10^{14} \text{ cm}^{-3}$. The beam-plasma system was stable at a significant β_t for one millisecond. These experimental data are in reasonable agreement with theoretical prediction.

Thus injection of pulses of relativistic electron beams with voltage of the order of 10 MV offers *in principle* an attractive means of periodic "refreshment" of the plasma current in ignition-sized tokamaks. Some urgent questions concerning the penetration and confinement of the relativistic electrons need to be investigated experimentally.

B. RECOMMENDATIONS FOR FURTHER WORK ON NEUTRAL-BEAM-DRIVEN CURRENTS

1. EXISTING TOKAMAKS

a. PLT

Preliminary searches for a beam-driven current have already been made on PLT, with no definitive identification, but with results that are at least interesting. Careful comparisons of the time variations of the plasma current, loop voltage, electron temperature profile, and Z_{eff} during high-power co-injection alone, and during counter-injection alone, at low plasma density and high beam power, *should be continued* in an attempt to make a definitive identification.

b. ISX-B

ISX-B is now equipped with high-power unidirectional neutral beam injection and offers the best opportunity in the near term for a definitive demonstration of a large beam-driven current. *Such a demonstration should be pursued in FY 1979.* If successful, consideration should be given to providing the ISX-B injectors with long-pulse ion sources in FY 1980, and to modifying the equilibrium-field circuitry, if required, so that a plasma current drive only by the beams (i.e., with zero loop voltage) and maintained for up to 1.0 s could be demonstrated.

c. PDX

A steady-state beam-driven current due to trapped-electron effects in a $Z_{\text{eff}} \sim 1$ plasma, if feasible, offers a potential near-term application in the form of facilitating long-pulse high-beta tokamak operation, in which the beams heat and fuel the plasma as well as drive the toroidal current. If this current is shown to be feasible in the ISX-B experiments, then consideration should be given to equipping the PDX injectors with 10-s ion sources in FY 1981, and to reorientating these injectors for tangential injection. Then 10-s high-beta plasma operation, with the plasma current of 300 kA driven by the injected beams, would become possible. (The plasma current is limited to 300 kA, because resistive

heating of the toroidal-field coils limits the magnetic field to 10 kG during 10-s pulses.) A principal motivation of this experiment would be the testing of the means of disposal of high fluxes of particles and heat (≈ 5 MW) in the divertor burial chamber in quasi-steady operation -- a demonstration that is necessary before reactor application of poloidal divertors can be made.

2. THEORY

Theoretical analyses of the neutral-beam-driven current should be extended to include further realistic effects such as rotation of the bulk ions, stability of the current profiles, and a valid treatment of the effect of neoclassical electron trapping on the beam-driven current.

3. REACTOR APPLICATIONS

The practicality of utilizing the beam-driven current in the potential reactor applications that have been identified should be examined in more detail, with particular reference to one or more conceptual tokamak reactor designs that have already been formulated.

4. TECHNOLOGY DEVELOPMENT REQUIREMENTS

The high-power 120-keV D⁰ beams currently under test have adequate penetration for practical applications of the beam-driven current. But work must be accelerated on the development of *steady-state* positive-ion-based neutral-beam injectors.

This area is the only one where additional funds might be needed in FY 79. In later fiscal years, funds will be required to procure long-pulse ion sources for existing injectors.

C. RECOMMENDATIONS FOR FURTHER WORK ON RELATIVISTIC-ELECTRON-BEAM-DRIVEN CURRENTS

1. RELATIVISTIC ELECTRON PHYSICS IN TOKAMAKS

While many important aspects of the behavior of intense relativistic electron beams in tokamak plasmas can be studied only by REB injection itself, some aspects may be simulated by generating large populations of "runaway electrons" in existing tokamaks. These latter topics include the following:

- (i) Confinement of the fast electrons during minor disruptions (although it is recognized that runaway electrons constitute a "weak beam" that may have different confinement properties than those of a strong injected beam.)
- (ii) The possibility of operating at very low q-values with the plasma current carried almost entirely by runaway electrons.
- (iii) The effectiveness of the poloidal divertor in PDX in removing runaway electrons that escape the discharge.

2. REB INJECTION EXPERIMENTS

A moderate-sized existing tokamak device should be identified in FY 79 to serve as a testbed for REB injection. Following a programmatic review, funds for REB injection experiments into this existing tokamak should be provided in FY 80 or FY 81. The following critical issues must be investigated in this experimental program:

- (i) whether the relativistic electrons can penetrate into the center of a tokamak plasma of interesting size (e.g., plasma radius $\gtrsim 25$ cm);
- (ii) the increase in the net toroidal current as a function of the REB parameters;
- (iii) the fraction of the injected REB energy which appears as poloidal-field magnetic energy, and the fraction which appears as plasma thermal energy;
- (iv) whether the fast electrons give up all their energy before they escape the plasma (and bombard various components);
- (v) whether the fast electrons remain confined during minor disruptions (which occur frequently in most tokamaks);

(vi) whether very low q -values can be sustained for extended times.

3. THEORY

Theoretical analyses of the penetration of REB-injected electrons and of their interaction with the bulk plasma should proceed in conjunction with the experiments proposed above. The experimental data should be compared with scaling laws such as those developed at Physics International. A related conceptual design study could define the characteristics of an REB-driven tokamak reactor operating at very low q .

IV. BASIS FOR CURRENT DRIVE BY RF

The purpose of this brief introduction to the workshop is to review the basic principles, and describe various experiments and theories, relevant to current generation in a plasma by externally RF-driven travelling waves. This is (hopefully) done in a critical way so as to bring out the solved as well as the unsolved problems in this area.

1. Fundamental Principles

It is well known that waves in a plasma carry both energy and momentum. These can be described by the respective conservation equations:¹

For energy,

$$\nabla \cdot \bar{s}_k + \frac{\partial w_k}{\partial t} + p_k = p_{\text{ext}} \quad (1)$$

and momentum

$$\nabla \cdot \bar{t}_k + \frac{\partial \bar{g}_k}{\partial t} + \bar{f}_k = \bar{f}_{\text{ext}} \quad (2)$$

Here, w_k is the time-(or space-) averaged energy density

$$w_k = \frac{\epsilon_0}{4} \omega \left[\bar{E} \cdot \frac{\partial \bar{D}_h}{\partial \omega} \cdot \bar{E}^* \right]_{\det \bar{D}_h = 0} \quad (3)$$

where, for the weakly-damped wave, $\bar{D}_h$ is the hermitian part of the dispersion

tensor ($\det \bar{D} = 0$ is the dispersion relation), and the wave electric and magnetic fields are allowed to have slowly varying amplitudes in space and time. All the other wave quantities are related to it through the group velocity $\bar{v}_g$, inverse phase velocity $\bar{k}/\omega$, and damping rate γ_k :

$$\begin{aligned} \text{Energy flow,} & \quad \bar{s}_k = w_k \bar{v}_g \\ \text{Power dissipated,} & \quad p_k = 2\gamma_k w_k \\ \text{Momentum,} & \quad \bar{g}_k = (\bar{k}/\omega) w_k \\ \text{Momentum flow (stress),} & \quad \bar{t}_k = \bar{g}_k \bar{v}_g \\ \text{Force dissipated,} & \quad \bar{f}_k = 2\gamma_k \bar{g}_k \end{aligned}$$

Both p_{ext} and $\bar{f}_{\text{ext}}$ are, respectively, the power density and force density supplied by external sources that excite or interact with the wave.

For the generation of a current in a plasma the wave momentum is to be transferred to particle momentum. For generating an electron current in a tokamak, consider the unidirectional particle momentum parallel to the magnetic field g_p and the component of unidirectional wave momentum in that same direction g_w . In the steady-state, the wave momentum transferred to the particles is dissipated at a rate 2γ , where γ is the wave damping rate due to wave-particle interactions, and the current carrying particle momentum is transferred to other particles by collisional dissipation at a rate 2ν . Thus the global picture of momentum flow and dissipation is as follows:

where V_w is the volume of plasma occupied by the wave, and V_p is the plasma volume.

This, of course, ignores detailed profile effects.) Hence in steady-state $g_p = g_w (\gamma/\nu) (V_w/V_p)$, the current density generated is $J_p = (e/m)g_p$, and the

associated power density dissipated is $p_w = (\omega/k)2\gamma g_w$. The efficiency of various schemes (waves, etc.) for RF current generation will thus depend upon the detailed evaluation of the appropriate g_w , p_w , γ and v .

2. Experiments on Current Generation by RF.

Since 1952 there have been (at least) nine experimental undertakings to study current generation in a plasma by travelling waves of various types.²⁻¹⁰ In all of these experiments appreciable current generation is observed. Unfortunately, in most of these experiments the toroidal plasma was produced with the same RF that was to drive the current. This makes it very difficult to interpret and evaluate the results, especially in regard to efficiencies for current generation. None of these experiments have been done in a state-of-the-art tokamak plasma. All of the experiments are interpreted only qualitatively and none have been tied to a firm theoretical model from which scalings could emerge.

3. Theoretical Work To-Date.

Since 1971 various theoretical models describing current generation in a plasma by a travelling wave have been published and presented.¹¹⁻¹⁶ The most recent ones^{15,16} include detailed Fokker-Planck analyses and computations. On the basis of these two, current generation by RF extrapolates favorably to achieving a steady-state tokamak reactor: the power dissipated in generating sufficient current for confinement is a small fraction of the fusion power out. These calculations are, however, rather incomplete: two and three-dimensional Fokker-Planck computations are just underway; transport properties in finite geometries have not been analyzed; the effects of distortions in the electron distribution function (possible runaways) have so far been ignored; toroidal effects have been ignored; and the details of wave excitation (nonlinear effects) at the plasma wall have not been addressed. Finally, none of the theoretical

work to-date has given a quantitative explanation of the experiments performed so far. As explained in Section 2 above, this is in large part due to the complexity of these experiments.

4. Experiments Related to RF Heating.

As shown in Section 1, the generation of an electron current by RF has associated with it power dissipation in, and hence heating of, the electrons. Recent rf heating experiments using lower-hybrid waves have shown that good coupling to electrons is possible.^{17,18} On the other hand, other experiments have recently shown that at high power densities the coupling (reflection coefficient) from an array of waveguides becomes relatively independent of external phasing of the waveguides.^{19,20} At this stage it is not known what effect this has on the excited waves in the plasma, but this must be carefully studied since the efficient generation of a travelling wave for current generation is thought to require a progressive phasing of the waveguides.

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A. PROMISING APPROACHES TO RF CURRENT DRIVE

In principle, it should be possible to drive steady plasma currents with any plasma wave that can be absorbed preferentially by the plasma electrons, and can transfer parallel momentum or induce a bootstrap current. In practice, as we illustrate below, RF current drive does indeed appear feasible using a wide variety of waves. Here we emphasize magnetosonic waves, lower hybrid waves, and electron cyclotron harmonic waves. Other wave mechanisms which are not included here may also appear promising in some situations. We are mainly concerned with approaches amenable to experimental investigation in relatively small tokamak devices. Other approaches such as low-frequency magnetosonic waves ($\omega \ll \Omega_i$) may require large, dense plasma columns to sustain the desired eigenmode.

General Atomic has proposed to construct a superconducting tokamak, RST, ("RF Heated, Steady-State Torus") capable of steady-state operation and designed to permit a wide range of experiments in RF heating and current drive. Here we illustrate the types of RF current drive experiments which can be carried out on RST and review the conditions necessary to drive steady currents with magnetosonic, lower hybrid, and electron cyclotron harmonic waves. The conclusion we draw is that RST would provide a sufficiently flexible facility to test the critical issues in each of these approaches.

We first consider magnetosonic wave current drive using pump waves at frequencies well above the first two harmonics of the ion gyrofrequency. This frequency range is chosen to avoid strong ion cyclotron damping of the

applied wave. The basic conditions for magnetosonic current drive are summarized on two vugraphs. In fact, magnetosonic wave current drive has been demonstrated experimentally in a Japanese experiment called "Synchromak." Some results of experiments are indicated in the third vugraph. These results have been analyzed theoretically at General Atomic by Cheng Chu using a code, *MOTHR*A, which solves for toroidal eigenmodes of the magnetosonic waves. The simulation parameters are listed in the fourth vugraph; and the main results of the theoretical study are listed in the fifth vugraph. There is substantial agreement between this analysis and the experiment as regards geometrical features of the current profiles and the efficiency of the current drive, measured through the ratio of current to power, I/P_{RF} . But the small-signal wave absorption model is clearly inadequate and predicts far too large a value of $\tilde{B}$, the wave magnetic field, for the applied power of 75 kW. Contours of constant current density are shown in the sixth vugraph.

This same simulation technique has been used to extrapolate the Synchromak approach to the RST device. The basic parameters are listed in the seventh vugraph. Note that power levels of around 250 kW should drive plasma currents of 10 kA.

We next consider lower hybrid wave current drive, the theory of which has recently been elaborated by Fisch and Bers. Again, the basic conditions are summarized in the eighth and ninth vugraphs. In particular, we emphasize the condition for linear mode conversion which sets an upper limit on the density, above which some fraction of the wave power is likely to be absorbed by ions. The value of this critical density in Doublet IIA is shown for three different antennas as a function of electron temperature in the tenth vugraph. Note that the critical density increases as the square of the toroidal magnetic field and can exceed $5 \times 10^{13} \text{ cm}^{-3}$ for $B \sim 15 \text{ kG}$ as in RST. Contours of constant power deposition (in the plane of electron density and temperature) are shown in the eleventh vugraph for the case of $n_{||}$ which has been used for electron heating in Doublet IIA. This power deposition model has been used successfully in one-dimensional, time-dependent transport models of RF heating experiments in Doublet IIA. But of greater interest

from the point of view of current drive is the evolution of the tail of the distribution function under illumination with unidirectional traveling waves. Fokker-Planck studies of this process have been carried out by R. W. Harvey and K. Marx using a two-dimensional Fokker-Planck code developed by Marx. Typical results for a Doublet IIA configuration are shown in the twelfth vugraph, and compared with corresponding one-dimensional results in the thirteenth vugraph (using the critical efficiency parameter, I/P_{RF}).

Finally, we consider an interesting but more speculative approach to RF current drive using electron cyclotron harmonic waves. Doppler-shifted resonance is proposed to achieve preferential wave absorption by electrons of one sign of $v_{||}$. These electrons would then be preferentially trapped by the resulting increase in perpendicular energy, thus depleting the number of passing electrons able to carry current with the corresponding sign and enhancing the current in that direction.

The conditions for electron cyclotron heating have been summarized in the fourteenth vugraph; and the conditions for wave propagation in the ECH frequency range are illustrated for Doublet IIA in the last three vugraphs.

These three vugraphs show the relative positions of fundamental (for 33 GHz) and second harmonic (for 60 GHz) resonances and the upper hybrid resonance surface. It remains to evolve a model for the quasilinear response of the electron distribution function to unidirectional traveling waves such as these, which have been launched with an initial value of $n_{||}^2 \approx 0.55$, 0.35, and 0.38, respectively. But because these millimeter waves can propagate in a quasi-geometrical way, and are relatively free of many of the (possibly parasitic) parametric processes to which the lower frequency waves may be susceptible, it seems an option well worth investigating.

BASIC CONDITIONS FOR MAGNETOSONIC CURRENT DRIVE

$$1. \quad \omega \geq 3\Omega_i$$

$$\text{whence } f \geq 46 \text{ MHz } \left(\frac{B}{10 \text{ kG}} \right) \left(\frac{M_p}{M_i} \right)$$

$$2. \quad \sqrt{\frac{3(1-\epsilon)}{2\epsilon}} \leq \frac{\omega}{k_{||} v_e} \leq \sqrt{\frac{7(1-\epsilon)}{2\epsilon}}$$

$$\text{whence } 2 \leq \frac{\omega}{k_{||} v_e} \leq 3$$

3. Suitable cavity modes must exist:

$$n_{\text{toroidal}} \sim 8 \left(\frac{f}{50 \text{ MHz}} \right) \left(\frac{R}{m} \right) \sqrt{\frac{1 \text{ keV}}{T_e}}$$

$$n_i a^2 \geq \frac{\pi^2 \epsilon_0}{e^2} M_i c^2 \left(\frac{\Omega_i}{\omega} \right)^2 \approx \frac{5 \times 10^{15}}{\text{cm}} \left(\frac{\Omega_i}{\omega} \right)^2$$

BASIC CONDITIONS FOR MAGNETOSONIC CURRENT DRIVE (CONTINUED)

4. $P_{abs} \sim n_e T_e / \tau_E$

But

$$P_{abs} \approx \frac{\omega}{Q} \cdot \frac{\tilde{B}^2}{2\mu_0}$$

and

$$Q \geq \frac{1}{\sqrt{\pi}} \frac{B_o^2}{\mu_0 n_e T_e} \frac{e x^2}{x}, \quad x = \frac{\omega}{k_{||} v_e}$$

whence

$$\frac{\tilde{B}}{B_o} \sim \sqrt{\frac{1}{\omega \tau_E} \frac{e x^2}{x}}$$

SYNCHROMAK OBSERVATIONS

- $I/P_{RF} = 3.33 \text{ amp/kW}$
- $\tilde{B}$ IS PEAKED ON AXIS
- $j(r)$ IS SOMEWHAT HOLLOW
- NOTE THAT THE COUPLER EXCITES $m = 0$ MODES

SYNCHROMAK SIMULATION

- $n_e = n_o \sin\left(\frac{\pi x}{2a}\right) \sin\left(\frac{\pi y}{2b}\right)$

$$n_o = 5 \times 10^{12} \text{ cm}^{-3}$$

$$a = b = 5 \text{ cm}$$

- $T = T_o \left[\sin\left(\frac{\pi x}{2a}\right) \sin\left(\frac{\pi y}{2b}\right) + 0.001 \right]$

$$T_o = 6 \text{ eV}$$

- $\vec{B} = \hat{z} B_o [1 + (x - a)/R]^{-1}$

$$B_o = 128 \text{ Gauss}$$

$$R = 25 \text{ cm}$$

- $\nu = 3 \text{ MHz}$

$$\frac{\omega}{k_{||}} \doteq 4.3 \times 10^7, \quad 1.0 \times 10^8, \quad 1.9 \times 10^8 \text{ cm/sec}$$

SIMULATION RESULTS FROM MOTHRA

- ONLY ONE MODE HAS A DOMINANT $m = 0$ COMPONENT:
 $\tilde{B}$ IS PEAKED ON AXIS FOR THIS MODE
- $\omega/k_{||} = 1.08 \times 10^8$ cm/sec FOR THIS MODE.
- $j(r)$ IS HOLLOW FOR THIS MODE
- $I/P_{RF} = 3.296$ amp/kW FOR THIS MODE

SPECIAL POINTS TO NOTE:

- AN $m = 1$ MODE GIVES $j(r)$ PEAKED ON AXIS
- SMALL-SIGNAL THEORY PREDICTS $\tilde{B} = 600$ G AT 75 kW

CONTOUR OF INDUCED CURRENT 4.40
MAX= 1.83865E-02

A 09/08/78

EXTRAPOLATION TO RST USING MOTHRA

$$T_0 = 500 \text{ eV} , \quad B_0 = 10 \text{ kG} , \quad n_0 \geq 2 \times 10^{13} \text{ cm}^{-3}$$

$$R = 80 \text{ cm} , \quad a = b = 20 \text{ cm} , \quad \nu = 45.6 \text{ MHz}$$

- $I/P_{RF} = 42 \text{ amp/kW}$ WITH $Z_{eff} = 3$
- $j(r)$ CAN HAVE VARIOUS PROFILES, DEPENDING ON MODE SPECTRUM DRIVEN BY COUPLERS
- $P_{RF} \geq 250 \text{ kW}$ SHOULD DRIVE 1 - 10 kA

BASIC CONDITIONS FOR LOWER HYBRID WAVE CURRENT DRIVE

1. $\omega \gg \omega_{LH}$

$$\frac{\omega^2}{\omega_{LH}^2} = \frac{\omega^2}{\Omega_e \Omega_i} \left(\frac{n_e}{n_i} + \frac{\Omega_e \Omega_i}{\omega_{pi}^2} \right) \approx \hat{\omega}^2 \left(\frac{n_e}{n_i} + \frac{\Omega_e^2}{\omega_{pe}^2} \right)$$

choose $\hat{\omega}^2 = 2 - 4$ (> 1)

whence $f = (0.9 - 1.3) \text{ GHz} \left(\frac{B}{10 \text{ kG}} \right) \sqrt{\frac{M_p}{M_i}}$

2. $\omega/k_{||} \lesssim 3 v_e$ or $n_{||} \gtrsim c/(3 v_e)$

whence $n_{||} \gtrsim 5.3 \sqrt{\frac{1 \text{ keV}}{T_e}}$

For accessibility,

$$n_{||}^2 > 1 + 2 \frac{\omega_{pe}^2}{\Omega_e^2} - \frac{\omega_{pi}^2}{\omega^2} + 2 \frac{\omega_{pe}}{\Omega_e} \left(1 + \frac{\omega_{pe}^2}{\Omega_e^2} - \frac{\omega_{pi}^2}{\omega^2} \right)^{1/2}$$

BASIC CONDITIONS FOR LOWER HYBRID WAVE CURRENT DRIVE

3. $n_e < n_{e,crit}$ (mode conversion)

$$n_{e,crit} \cong \frac{\epsilon_0 B^2}{m_e} \left[\frac{n_i}{n_e} \frac{1}{\hat{\omega}^2} + 2\sqrt{3} \frac{k_{||} v_e}{\omega} \left(1 + \frac{1}{4} \frac{n_i}{n_e} \frac{T_i}{T_e} \frac{1}{\hat{\omega}^4} \right)^{1/2} - 1 \right]^{-1}$$

where

$$\hat{\omega}^2 \equiv \omega^2 / \Omega_i \Omega_e$$

4. $P_{abs} \sim n_e T_e / \tau_E$

and

$$P_{abs} \cong \frac{16 \pi e^4 n_e n_{||} \ln \Lambda}{m_e c} \times \frac{1}{\sqrt{\pi}} \left(\frac{k_{||} v_e}{\omega} \right)^2 \left[\int_0^{\frac{\omega}{k_{||} v_e}} dt e^{-t^2} - \frac{\omega}{k_{||} v_e} \exp \left(- \frac{\omega^2}{k_{||}^2 v_e^2} \right) \right] \\ \times \frac{8}{3} \frac{n_e}{\sqrt{\pi}} \left(\frac{\Delta v}{v_e} \right)^3 \exp \left(- \frac{\omega^2}{k_{||}^2 v_e^2} \right)$$

FORMATION OF RAISED PLATEAU

CONDITIONS FOR ELECTRON CYCLOTRON CURRENT DRIVE

1. RESONANT SURFACES MUST EXIST DEEP IN THE PLASMA

$$B_{\text{res}} \cong \frac{3.57 \text{ kG}}{m} \left(\frac{\nu_{\mu}}{10 \text{ GHz}} \right)$$

$$m = \begin{cases} 1 & , \text{ cold plasma} \\ 2 & , \text{ warm plasma} \end{cases}$$

2. RESONANT SURFACES MUST BE ACCESSIBLE TO WAVES

$$n_{\text{max}} \Big|_{\text{res}} \cong 1.24 \times 10^{12} \text{ cm}^{-3} \left(\frac{\nu_{\mu}}{10 \text{ GHz}} \right)^2 \begin{cases} 1 + \frac{1}{m} & , \text{ extraordinary mode} \\ 1 & , \text{ ordinary mode} \end{cases}$$

3. POWER DENSITIES AROUND 1 WATT/cm³ MUST BE AVAILABLE IN THE FREQUENCY RANGE ~100 GHz.

F
 3.30×10^{10}

NO
 1.48×10^{13}

BO
 1.20×10^4

NIISO
0.55

F
 6.00×10^{10}

NO
 4.84×10^{13}

BO
 1.10×10^4

NIISO
0.35

F
 6.00×10^{10}

NO
 4.84×10^{13}

BO
 1.15×10^4

NIISO
0.38

B. EXPERIMENTAL REALIZATION OF A STEADY-STATE TOKAMAK

In view of the present encouraging physics outlook for the Tokamak as a fusion reactor concept, we must look for means to simplify the Tokamak and reduce its technical complexity. The demonstration of steady-state Tokamak operation would have major impact on this effort to produce a simpler more saleable reactor concept.

Theoretical analysis of rf current drive proposals shows a variety of possible approaches are suitable. Evidence of modest rf current drive exists from several experiments utilizing different waves. (1-5). This favorable outlook and the importance of a steady-state Tokamak for reactor development requires a vigorous United States program to evaluate the possible approaches and to demonstrate a steady-state Tokamak.

The proposed RST device (Rf driven Steady-State Torus) is a machine designed to demonstrate true steady-state Tokamak operation at the earliest possible time and at modest cost. RST parameters are shown on the attached table and the machine views. The innovative engineering design of RST allows the access required to evaluate the possible options for rf current drive, and the superconducting toroidal field system allows the chosen option to be carried to full steady-state operation.

Analysis of ECH (6), Lower Hybrid wave (7), and magnetosonic cavity modes (8) show that full current drive can be achieved with power levels on the order of 1 MW. Engineering studies indicate it is feasible to have a universal power supply suitable for all three approaches.

Proposed joint electron cyclotron heating experiments between General Atomic Company and JAERI on JFT-2 will provide the physics base required for evaluating this alternative. Present lower hybrid wave electron heating experiments on Doublet IIA are providing the physics base for this approach. Demonstrations of partial current drive in operating devices would insure the earliest possible realization of steady-state Tokamak operation in RST.

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RST

R(F DRIVEN) S(TEADY STATE) T(ORUS).

- RF DRIVEN PLASMA CURRENT
- CONTINUOUS OPERATION
- INNOVATIVE ENGINEERING

MAJOR RADIUS	80 cm
MINOR RADIUS	20 cm
TOROIDAL FIELD	15 kG
PLASMA CURRENT	90 kA
PLASMA DENSITY	$2 \times 10^{13} \text{ cm}^{-3}$
ELECTRON TEMPERATURE	600 eV
ENERGY CONFINEMENT	10 msec

63-13
SCALE: 1/2

C-C
SCALE: 1/2

C. RF DRIVEN CURRENT IN VERSATOR II

Versator II is a research tokamak which was built recently at M.I.T. Its mission during the coming year is to study lower-hybrid heating of plasmas (using phased-arrays of waveguides as a wave launcher). The construction of the device is complete, and initial plasmas have been formed at densities $n \approx 10^{13} \text{ cm}^{-3}$, and pulse lengths of the order of 12 msec. The finely tuned machine parameters are expected to be as follows: $B_0 \approx 15 \text{ kG}$, $I \approx 30\text{--}50 \text{ kA}$, $R = 40 \text{ cm}$, $a = 14 \text{ cm}$, $t_{\text{pulse}} \approx 30 \text{ msec}$, $T_e \approx 4T_i \approx 200\text{--}600 \text{ eV}$, $n_0 \approx 4 \times 10^{13} \text{ cm}^{-3}$. The magnets have been tested to 15 kG. The device is characterized by excellent accessibility (due to the large number of ports) and a multitude of diagnostic techniques will be provided. An 800 MHz, 200 kW klystron unit has been installed, with a pulse length of 20 msec. The rf power will be transmitted through a grill of 4 waveguides, phased $0, \pi, 0, \pi$. This wave launcher has been built at Princeton (the experiment is a joint MIT-PPPL experiment) and will be used to launch a standing wave-type slow wave which is aimed at studying ion heating mechanisms. These experiments are expected to commence in another month.

In the present proposal we ask for additional funds to (1) build a second slow-wave launcher, with a six waveguide grill, phased by $\pi/2$ or $3\pi/2$ (relatively); (2) build an adapter to the present 4-waveguide grill so that the grill dimensions could be re-

duced so as to heat electrons (rather than ions); (3) build a new phase shifting network to allow feeding the 6 waveguide grill. Both of these systems should launch slow-waves in one direction. By adjusting the phase velocities appropriately, according to the recent theories of Fisch, significant dc currents should be generated due to the quasi-linear plateau formation. Depending upon parameters, currents in the range of 6-60kA should be generated (the higher current would be associated with the higher electron temperatures quoted). These currents are associated with net absorbed power of 100kW (which should be comprised with the 200kW available at the source). Thus, under favorable conditions these currents correspond to 100% of the ohmic heating current. In our device some special diagnostics would be available, such as Thomson scattering measuring $T_{e||}$. Thus, changes in the ohmic heating current could be monitored directly, and it could be distinguished from current generation by the rf power. A detailed list of diagnostics is available in the previous Versator II RF heating proposal.

These experiments could be started in 5-6 months time after approval if an additional research scientist would be added to our staff. We believe that testing of current generation has to be done using waveguides so that extrapolation to reactor regime could be creditable. In particular, the technical and physics problems associated with such wave launching techniques must be understood.

The initial phases of the current driven experiments could be completed by the end of FY 1979.

D. RF CURRENTS IN TOKAMAKS

Reactor Requirements

We have made some preliminary estimates of the effects of rf driven currents on startup and steady state reactor operation. We have assumed that the frequency would be about $1.5-2.5 f_{LH}$. Preliminary results from startup studies (Fig. 1) show that currents can only be created slowly (~ 10 MA in 30 sec) because the L/R current rise time limits the power that can be applied to a small fraction of the ~ 100 MW required to maintain the current in an ignited tokamak. Optimizing the j/P_{rf} and P_{fusion}/P_{rf} ratios imply: high T-low n operation, large reactors, and current production near the plasma edge (Fig. 2). Edge currents are consistent with and possibly required for high β equilibria. In general, LHRH rf currents would require high power levels for reactors $\approx 50-100$ MW/($Eff(DC \rightarrow rf) \cdot Eff(rf \rightarrow currents)$)).

Experimental Proposal

Argonne is presently building a small tokamak suitable for surface and rf studies. Optimizing $T_e(OH)/cost$ has meant maximizing B_T and minimizing R, and the final design parameters are: $B_T = 2.5$ T (can be increased to ~ 4.5 T), $R = 51$ cm, $r = 15$ cm. In order to avoid parametric instabilities, we believe that f/f_{LH} should be as high as possible (i.e., $\sim 1.7-2.0$) requiring high B_T . Values of $T_e \sim 1$ keV require n_{11} spectra centered around 6, this means that the grill elements (width of waveguide plus wall) must be in the range of 1 cm for 1.3 GHz or 0.5 cm at 2.8 GHz. Power supplies at these frequencies are presently available at Argonne, but these supplies require some work (\$20 K) to extend the pulse length to 500 μ sec. These supplies produce ~ 500 kW (1.3 GHz) and 1 MW (2.8 GHz).

We feel that a measurement of the loop voltage offers the most unambiguous simple measurement of driven currents. Because competing effects (plasma motion, absorption of input wave, T_e and $1/R_p$ increases, impurity influx, etc.) may be significant, we propose to use two launchers capable of injecting current either parallel or antiparallel to each other, thus $\Delta V_L = \Delta V_1 \pm \Delta V_2$. The advantages of the high power, short pulse system would be that large currents could be produced without changes in Z_{eff} , T_e , and R_p and the total cost should be less than for comparable system using a CW source. If loop voltage changes are clearly seen, these could become a very useful diagnostic tool for the study of turn-on times, nonlinear effects, edge effects, and launcher parameters, which are difficult to unfold from measurements of plasma temperature and current changes.

Fig. 1

PENETRATION VERSUS MINIMUM n_i

Fig. 2

E. POSSIBLE LOWER HYBRID HEATING EXPERIMENTS ON PLT AND PDX

A lower hybrid heating experiment is scheduled for the PLT device in early 1980. The power level will be ~ 1 MW and the frequency 800 MHz. While the fundamental objective of this experiment will be to study the physics of the wave heating, we plan to study the generation of DC currents by the lower hybrid waves.

We plan to use six klystrons, each operating at ~ 180 kW for pulses up to 70 ms. Two of the RF sources were constructed at PPL and have been loaned to GA for their Landau heating experiment on Doublet IIA. All parties concerned have agreed these units will be returned to PPL during June of 1979. A third unit has been sent to MIT from PPL, and by mutual agreement between MIT and PPL, this source will be returned in November of 1979. The remaining units will be constructed from components on hand at PPL.

Two waveguide arrays will be used in this experiment. The first will be designed so that with $\Delta\phi = 180^\circ$ conditions for linear Landau damping in the plasma center will be satisfied. (Here $\Delta\phi$ is the phase difference between adjacent waveguides.) With a different pattern of applied phases this coupler should generate waves which will avoid Landau damping altogether such that the linear mode conversion layers become accessible for ion heating. Of

more concern here is the second coupler which will be designed so that with $\Delta\phi = 90^\circ$ we should achieve current generation in the center of the PLT plasma. Figure 1 shows schematically the dimension of the phased array being used for the current generation experiments. Figure 2 shows the self consistent Fourier spectrum for this coupler. The asymmetric spectrum labeled $\Delta\phi = 90^\circ$ will be used for the current generation experiment. In using this spectrum for estimates of the current generation we take the half-power points for W_1 and W_2 , where W is the phase velocity relative to the electron thermal speed. For the spectrum in Figure 2 the ratio $W_2/W_1 = 2.17$. Using the relations for current generated and power dissipated developed by Bers and Fisch^{1,2}, we plot in Fig. 3, the current and power vs. W_1 for conditions expected in PLT. We assume that the PLT peak temperature is 1.5 keV and that this temperature peak has an effective radius of $a = 10$ cm. It is very important in comparing estimates of current generation for different devices that we make corresponding and consistent assumptions concerning the temperature profiles. From Fig. 3 we conclude that on PLT for $W_1 = 3$, for a power of $\sim 1/2$ MW we can generate a current of ~ 130 kA.

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Lower hybrid wave generation of currents of the order of 100 kA is planned as part of the PLT experiment scheduled for 1980. We believe that this experiment on PLT with its excellent diagnostics will constitute a proof of principle level of effort.

Fig. 1

Waveguide dimensions
20 cm x 1.4 cm

Fig. 2

Fig. 3

F. THEORETICAL INVESTIGATIONS OF RF-DRIVEN CURRENTS AND PROPOSED EXPERIMENTS

Although the idea of current generation with RF waves has a long history, it was only recently discovered that fast phase velocity waves are especially useful and satisfy basic scaling requirements to tokamak reactors.¹ With only minor assumptions, it was possible to identify the crucial cost factor, $\epsilon = P_D/P_f$, in terms of fundamental reactor parameters (density, temperature and dimensions), i.e.,

$$\epsilon = \frac{4}{w_1^2 (n_{14} T_{10} a_1 R_1)^{1/2}}$$

where P_D/P_f is RF power dissipated over fusion power output. For typical reactors, it was shown that $\epsilon \sim 5\%$ and that lower hybrid waves represent an attractive current-drive.

Preliminary computer calculations² using a 2-D (in velocity space) Fokker-Planck code substantially verify the important results of the 1-D analytic calculation used in deriving the cost factor. Of most importance to reactor scaling is that the resistance to the RF current is nearly as predicted, deviating only at very high phase velocities where it is somewhat less (0.6 the predicted value at $w = 5.25$). Qualitative confirmation of analytic theories is also apparent in other aspects such as the turn-on time¹ and the flattening in perpendicular velocity space.³ The perpendicular flattening is thought to have important implications (e.g. runaway production) when a DC electric field is present.

The power dissipated in driving a plasma current is minimal either when the momentum is absorbed by high-velocity electrons as above, or when the momentum is equally absorbed by all electrons, for example, in DC electric field operation. Some minimization is crucial in order to obtain a low cost factor. One might conjecture that low phase velocity RF waves could be candidates for driving currents by making use of the latter type of minimization. We show, however, that the feasibility depends crucially on the acceleration mechanism. Current drive utilizing acceleration by means of a parallel electric field, e.g. in Landau damping of Alfvén or magneto-sonic waves, is not practical because of large power dissipation. However, transit-time magnetic pumping at the same phase velocity could be practical, since momentum is preferentially deposited in high- $v_{\perp}$ electrons. Computer verification of these results is in progress.

Other remaining theoretical problems include the determination of tolerable cost factors from overall reactor considerations. Spatial effects such as current spreading and MHD equilibrium require investigation. Finally, observables in present experiments must be identified, where a DC electric field complicates the isolation of RF effects. Also interesting is to determine whether useful phase information can be extracted by using modulated RF, similar to the method of modulating the neutral beam in neutral beam induced currents.⁴

Helpful experimental measurements include those of J , J/P_D , the enhanced $f(v_{\perp})$ for $v_{\perp}$ large, and $f(v_{\parallel})$. Since $v_0 L/R$ is usually large, running the tokamak at constant loop voltage and then shutting off the RF may be the best handle on J/P_D . Cyclotron emission should yield information on $f(v_{\perp})$. We suggest that the

measure of excellence of experiments at this stage should be the flexibility to produce and diagnose a wide range of sharply defined spectra rather than the capability to extract a particularly large current.

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G. TOKAMAK CURRENTS DRIVEN BY ALFVEN WAVES

There are two approaches to maintaining steady-state currents in tokamaks. Both methods strive to reduce the power/volume $\dot{U}$ required to maintain a steady-state current. To understand the difference between the approaches, let us start with the relation between $\dot{U}$ and the momentum/volume-time $\dot{P}$ which must be transferred to the electrons to maintain the current. This relation is¹

$$\dot{U} = v_g \dot{P} \quad (1)$$

where v_g is a characteristic velocity. For the cases studied most intensively, the expression for v_g is

$$v_g = \begin{cases} \frac{1}{2} v_{\text{beam}} & \text{parallel neutral injection} \\ \omega/k_{\parallel} & \text{wave driven currents} \end{cases} \quad (2)$$

The two approaches to maintaining currents differ as follows: the first approach, due to Ohkawa,¹ strives to reduce $\dot{U}$ by reducing v_g , and accepting that the collisional drag on the electrons will be determined by the electron-ion collision frequency.² The second approach, put forward by Bers and Fisch,³ has the current carried by superthermal electrons so that $\dot{P}$ is well-below the value for Ohmic heating, but v_g becomes somewhat

larger than $(2T_e/m)^{1/2}$. Both methods succeed in reducing $\dot{U}$ to acceptable levels.

This work shows that wave driven currents can be maintained via momentum transfer from Alfvén waves where v_g must be $v_g \approx 2v_A$ and v_A denotes the Alfvén speed. Since the momentum will be transferred from the wave to electrons whose parallel velocity is $v_{||} = \omega/k_{||} \approx 2v_A$ and hence small compared to the electron thermal velocity, the current will decay via the usual electron-ion collisions. As such, this work is a variant at the Ohkawa approach with $1/2 v_{beam}$ replaced by $2v_A$. Ohkawa's paper did not recognize that perfectly satisfactory absorption of waves occurs when $\omega/k_{||} \ll (2T_e/m)^{1/2}$. Alfvén waves are polarized so this absorption is weak but not negligible, and high-Q modes of the toroidal cavity become possible.^{4, 5}

Since generally $2v_A > 1/2 v_{beam}$, the Alfvén wave method will require more power than the beam method. The relative advantages of the Alfvén wave method are: (1) No momentum is transferred to the ions; (2) No penetration problem; and (3) Generating Alfvén waves may well be an easier technology than high-voltage injection sources. Clearly, it is premature to choose in favor of one method over another.

At this point, let us remark that the value of v_g associated with Ohmic heating is $v_g = v_D$, where v_D is the electron-ion drift velocity and is much less than either v_{beam} or v_A . While Ohmic heating can drive the currents required for tokamak confinement, it is not sufficient to heat plasmas to thermonuclear temperatures because of its low value of v_g . All the processes considered at this workshop are superior to Ohmic heating in that the process used to

induce the current is also sufficient to heat the plasma to thermonuclear temperatures. But Ohmic heating will still be required in the start-up phase when the resistivity is high.

Let us now turn to estimating how much power will be required to drive currents via Alfvén waves, and how it scales plasma parameters such as density, toroidal field, etc. The amount of momentum density which must be transferred to the electrons to maintain a drift velocity v_D with respect to the ions is

$$\dot{p} = m v_D \nu n \quad (3)$$

with

$$\nu = C_1 \frac{n e^4 \ln \Lambda}{m^{1/2} T^{3/2}} \quad (4)$$

where the numerical constant $C_1 \approx 2$ must be determined by Fokker-Planck calculations. Utilizing the well-known relations

$$q = \frac{r B_z}{R B_\theta}, \quad B_\theta = \frac{2\pi j_o r}{c}, \quad j_o = n e v_D \quad (5)$$

We can express $\dot{p}$ as

$$\dot{p} = \frac{B_z c m \nu}{2\pi R q e} \quad (6)$$

Then, employing the relations

$$\frac{3nT}{\tau_E} \equiv \dot{u} = 2v_A \dot{p} = \frac{v_A B_z c m \nu}{\pi R q e}$$

we can write $n\tau_E$ as

$$n\tau_E = \left(\frac{6\pi^{3/2}}{C_1 \ln \Lambda} \right) \frac{q n^{3/2} T^{5/2} R}{B_z^2 e^3 C} \left(\frac{M}{m} \right)^{1/2} \quad (8)$$

or in practical units,

$$n\tau_E = \left(6 \cdot 10^{14} \frac{\text{sec}}{\text{cm}^3} \right) q \left(\frac{n}{10^{14} \text{ cm}^{-3}} \right)^{3/2} \left(\frac{T}{10 \text{ keV}} \right)^{5/2} \left(\frac{R}{2m} \right) \left(\frac{50 \text{ kG}}{B_z} \right)^2 \quad (9)$$

The interpretation of this result is that τ_E is a heating time scale associated with the current drive processes. Clearly, it is longer than the time scale for thermonuclear energy generation (characterized by $n\tau_E \sim 2 \cdot 10^{14} \text{ sec cm}^{-3}$).

This means that the energy required to drive currents via Alfvén waves will be less than thermonuclear energy produced. But there are not many orders of magnitude difference, so the Alfvén wave heating power will be large. Clearly, the scaling indicates that a higher temperature ($T = 20 \text{ keV}$), lower density plasma is preferable, given a constraint on β .

Implementation. The transfer of momentum between Alfvén waves and electrons is best accomplished utilizing compressional (magnetosonic) Alfvén waves which are weakly damped eigenmodes of the toroidal cavity.⁴ In order that the low density evanescent region be relatively modest, it is appropriate to choose the frequency so that the mode is close to the fundamental radial mode.⁶ Further, in order to avoid large absorption via the shear Alfvén resonance,⁵ it is preferable to utilize the $m=0$ mode, and rely on electron transit time magnetic pumping to absorb that wave energy,^{6,7} a process that will be efficient at the high β 's — about 3% — expected of reactor grade tokamaks. In this regime, transit-time magnetic pumping of electrons will produce a cavity $Q \sim 1/\beta$, which is adequately high to utilize the toroidal eigenmodes with the consequent improvement in antenna loading, but will dominate absorption by the shear Alfvén resonance. Since the absorption via transit time damping is proportional to the electron temperature, most of the momentum impacted to the electrons from the wave will be deposited in the central region of the plasma, as desired.

The frequency associated with the $m=0$ fundamental mode is

$$\nu = 3 \text{ MHz} \left(\frac{2m}{a} \right) \left(\frac{B}{50 \text{ kG}} \right) \left(\frac{10^{14} \text{ cm}^{-3}}{n} \right)^{1/2}$$

which is substantially below the deuterium-cyclotron frequency $\Omega_D = 36 \text{ MHz}$ at 50 kG. The parallel wavelength, $\lambda_{||} \approx 2a$, can be generated by a series of $m=0$ loop antennas, phased so as to launch a wave travelling in the opposite direction to the desired plasma current.

Conclusion. Many details remain to be worked out, but general estimates suggest that Alfvén waves can successfully drive currents in tokamak plasmas. We have not discussed overall toroidal momentum which would similarly increase in a truly axisymmetric device, but may well be dissipated by toroidal field ripple. Large tokamaks, such as PLT or PDX, are required to perform meaningful experiments⁵ at frequencies below the ion-cyclotron frequency.

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H. SUMMARY OF THE PROPOSED EXPERIMENT ON T-1

Purpose

To generate steady-state current in a toroidal plasma with unidirectional lower hybrid waves and to investigate the effects of nonlinear processes on the current generation efficiency.

Approach

T-1 is a steady-state torus with major radius = 58 cm, minor radius = 10.8 cm, toroidal field = 5.8 kG without rotational transform. Estimates based on a zero-dimension model indicate that several kiloamperes of current can be generated by 50 kW lower hybrid waves at 200 MHz in a plasma with $n \approx 10^{12} \text{ cm}^{-3}$, $T_e \approx 30 \text{ eV}$. Since T-1 has no initial plasma current, the RF driven current can be easily measured by Hall probes in steady-state operation and magnetic probes or Rogowski loops in pulsed operation. Unidirectional waves will be launched by arrays of electrostatic rings that have been tested at low power levels on our linear test devices (L-3 and H-1) in which the wave-generated current has been observed. For a 50 kW experiment on T-1, nonlinear effects like parametric decay and ponderomotive force effects may become important. Due to the modest plasma parameters, wave penetration and nonlinear phenomena can be investigated by local measurements with probes inside the plasma.

Cost Estimates

Option 1: 50 kW, 200 MHz CW oscillator - \$198 K
Option 2: 50 kW, 200 MHz CW surplus oscillator - \$134 K
Option 3: 30 kW, 200 MHz CW surplus oscillator - \$107 K
Option 4: 5 kW CW, 25 kW pulsed (10 ms), wideband (100 MHz - 200 MHz)
amplifier - \$100 K

Personnel

Experimentalists: S. Bernabei, W. Hooke, R. Motley,

M. Ono, K. L. Wong

Theorist: N. Fisch

Engineers: PPL power electronics group headed by J. Lawson

Milestones

Feb. 1979 Complete T-1 construction
May 1979 Obtain optimum plasma
June 1979 RF oscillator installed
low power operation begins
Aug. 1979 High power operation
Aug. 1980 Experiment completed

I. ON CURRENTS PRODUCED BY MICROWAVES AT ELECTRON CYCLOTRON RESONANCE

There are several characteristics of the linear theory of electron cyclotron heating that are pertinent to current drive proposals. One concludes that currents are produced indirectly with an efficiency that depends on the untested details of plasma transport.

First: The quasilinear velocity diffusion,^{1,2} driven by the external microwave fields, is very anisotropic, producing perpendicular heating. Conclusion: A plasma current must be driven indirectly.

Second: For heating at the fundamental resonance, this perpendicular diffusion is practically independent of the perpendicular velocity. For cyclotron heating this is very good. For a current drive scheme this is not so desirable, since the incident energy is spread over the entire velocity space. In contrast, for Landau damping near the lower hybrid frequency, the wave energy is absorbed in a narrow region of velocity space, increasing the efficiency of the current drive. Numerically one finds that ECH diffusion is of the same order as collisional diffusion, for any reasonable microwave flux.

The perpendicular heating at the second harmonic is proportional to $V_{\perp}^2$, depending on finite cyclotron radius. This heating is also not concentrated in velocity space.

Third: The diffusion coefficient is anisotropic in parallel velocity.² The resonance condition is

$$\omega - N\omega_c - k_z V_z = 0$$

For a tokamak with resonance surface at $x = 0$ one has

$$N\omega_c = \omega (1-x/R)$$

so that the Doppler shifted resonance occurs at

$$n_z V_z = x/R.$$

For a given ray direction, the axial velocity of a resonant electron depends upon x , and a ray which crosses the resonant surface interacts with electrons with positive V_z on one side and negative V_z on the other.

To selectively heat electrons with one sign of V_z , the ray must be absorbed on one side of the $x = 0$ surface. Absorption coefficients are indeed large enough for the $\bar{X}$ mode to interact with one sign of V_z .^{2,3}

Fourth: As is well known the density limit for either mode to propagate to resonance is given by $\omega < \omega_{ce}$ for the O mode and $\omega_{pe} < \sqrt{2} \omega_{ce}$ for the $\bar{X}$ mode. This density limit applies to plasma heating also.

In the scheme proposed by Ohkawa,⁴ electrons are driven into the trapped particle region of phase space, inducing a bootstrap current. The viability and efficiency of this mechanism depend on the details of particle transport and are difficult to predict. An experimental test is rather easy with apparatus designed for a heating experiment. One must launch the $\bar{X}$ mode in a tight beam at a small angle to the magnetic field. The $\bar{X}$ mode should be absorbed on one side of resonance, producing an anisotropy in V_z . The bootstrap current should appear within a collisional relaxation time. The experiment currently planned for the ISX device at ORNL should have sufficient flexibility for this experiment.

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V. THE POTENTIAL OF BEAM-DRIVEN CURRENTS IN TOKAMAK PLASMAS

Introduction

Neutral-beam injection can play 4 different roles in tokamak plasmas: (1) Heating of electrons and bulk ions. (2) Fueling. (3) Direct fusion production by beam-target (and beam-beam) reactions. (4) Driving a net toroidal current [1]. In principle, these 4 roles can be performed simultaneously.

In beam injection experiments to date, the first 3 applications have been demonstrated with great success. However, there has been little evidence thus far of the ability of the neutral beams to drive plasma currents. The paucity of hard evidence is not surprising, inasmuch as theoretical analyses predict relatively small values of I_{bd} (net beam-driven current) for the experimental conditions and beam powers which have prevailed so far. Still, an I_{bd} of the order of 1 A has been observed in the toroidal levitron at Culham [2], and the magnitude of I_{bd} agrees fairly well with a sophisticated theoretical model. However, the levitron experiment is characterized by plasma parameters which are far removed from those of tokamaks: The electron temperature (1 to 5 eV) is so small that the electron velocity is comparable to or even less than the beam injection velocity; the plasma resistance is so high that electromagnetic skin-current effects are negligible; the fast ions are essentially monoenergetic, because the charge-exchange loss time is a small fraction of the slowing-down time. *Nevertheless, the Culham experiment has brought the beam-driven current from the stage of rank speculation to the level of a scientific curiosity.*

Motivation

Interest in the neutral-beam-driven current is motivated by a number of potential applications:

- (1) Steady-state beam-driven plasmas. In the case where the beams drive

all the plasma current as well as heat and fuel the plasma, values of Q (fusion power/injection power) are limited to about 3 for practical conditions. The essential reason is that high beam energies are required to penetrate the high-opacity ($n\alpha_p$) plasmas that are needed to obtain high Q (i.e., high $n\tau_E$), while large beam currents are required to fuel and drive the plasma current. Thus very high beam powers must be injected, thereby limiting the attainable Q -value. Nevertheless, $Q = 1$ to 3 is adequate for specialized tokamak applications such as fissile breeding or radiation testing.

2) In a tokamak plasma of ignition size and temperature, the "classical skin time", which determines the decay time of the toroidal current, is in the range of 100 to 1000 s. This period considerably exceeds the fuel burn-up time. Hence unless methods can be found for refueling and for removal of the fusion ash (i.e., the ^4He reaction product), there is no need to drive a steady-state current. Nevertheless, the beam-driven current could be used to assist the equilibrium field coils in current start-up, and effectively eliminate the need for the flux swing from a central ohmic-heating solenoid [3]. This application would make possible a compact ignited tokamak reactor, with a pulse length of up to several hundred seconds.

(That the skin time is essentially "classical" after the formation of a relatively quiescent tokamak plasma with a well-defined profile of rotational transform was demonstrated with the compressed ATC plasma, where an unsustained toroidal current was found to decay on the expected time scale [4].)

3) Reserving the flux of the central solenoid to sustain the plasma current, once established by the beam-driven current together with the EF coils.

4) The possibility of resetting of the central solenoid without nulling the plasma current, by utilizing a beam-driven current during the resetting period.

Elimination of the central current-inducing solenoid (i.e., the OH transformer) would be possible in the first 2 applications above, and would have a number of advantages:

- Simplicity of construction of the core of the tokamak.
- Reduction in stored energy and peak power requirements of the tokamak electrical systems.
- Reduced eddy-current heating of superconducting TF coils.
- Elimination of the liquid-helium refrigeration load incurred by a superconducting central solenoid.

- The possibility of reduced major radius and aspect ratio, giving a more compact reactor [3].

Injector Characteristics

Very advanced, high-voltage beam technology is not required for driving the beam-driven current, as the applications of practical interest (see above) call for plasmas of small to medium opacity. The beam energies required are in the range of 80 to 120 keV deuterium, and less for present experiments. These energies are essentially within the state-of-the-art. (For example, a prototype TFTR beam injector delivering 5 MW of 120-keV D^0 with a pulse length of 0.5 s will be operating at LBL in a matter of months.) *The principal improvement required in injector performance is extension of the pulse length to essentially steady-state operation.*

An exception to the above remarks will occur if the bootstrap current [5] exists; for then a beam of relatively low power but at very high voltage could produce the seed current in the center of an ignition-sized plasma to drive a large bootstrap current.

Detection of the Beam-Driven Current

The circulating fast-ion current set up by injected neutral beams ($Z_b = 1$) is opposed by an electron "shielding current", which is due to the momentum given up to electrons by the fast ions, and also by an electromagnetic "return current", which decays on the classical skin time. The net beam-driven current is zero unless $Z_{eff} > 1$, or unless some fraction of the electron population is trapped, a condition that will always hold in tokamaks. The most profitable method of searching for I_{bd} is to examine reductions in the loop voltage during injection, especially when the plasma current is regulated by a constant-current system. (In a steady-state plasma, the loop voltage would be zero.)

Experiments on which I_{bd} should be observable have recently commenced operation: PLT at PPPL, ISX-B at ORNL, and DITE at Culham. An analysis has been carried out during the last several months of various PLT data obtained with co-injected beams alone, and with counter-injected beams alone, under similar plasma conditions. A small number of pulses have been identified where the evolution of $T_e(r)$ is such that the change in loop voltage and in plasma current during injection could provide a reasonably accurate determination of the presence and magnitude of I_{bd} , but no definitive statement can yet be made.

It now behooves us to insure that thorough experiments will be performed on PLT and especially on ISX-B, where the unidirectional beam power will be much greater, to sharpen our theoretical analyses, and to pore over the data in order to obtain definitive evidence concerning the existence or absence of I_{bd} . If in 12 months there is still not clear evidence of a significant beam-driven current in tokamaks, then its absence must be regarded as mysterious as the lack of observed toroidal plasma rotation during the first years of beam-injection experiments—until beam-induced rotation of the expected magnitude was observed on PLT in 1977!

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A. THE INTERACTION OF BEAM DEPOSITION PROFILES, CONDUCTIVITY PROFILES, AND POWER-SUPPLY REGULATION WITH BEAM INDUCED CURRENT

Before neutral beam injection, the plasma current profile is determined by the conductivity profile and after all injection induced transients have died away, the current is determined by the beam deposition profile and the profile of the beam momentum which is transferred to plasma electrons. The question then arises as to whether a transition can be made between these two states without having current profiles of an unstable nature.

To gain a feeling for the processes involved in this transition, we consider the case of a conducting cylinder with prescribed beam current and conductivity profiles. We then consider two cases of power supply regulation—current regulation for which $\partial E_z / \partial r = 0$ at $r = a$, and voltage regulation for which $E_z = \text{const.}$ at $r = a$. For conductivity profiles which are independent of r , this problem can be solved analytically for beam current profiles of the form $J_f(r) = C [1 - (\frac{r}{a})^2]^p$, where p is an integer.

The results of this model calculation for the current regulated case show the following features:

- The beam induces a current in the plasma which initially exactly cancels the fast ion current.
- This induced current rapidly decays to the lowest eigenmode which has zero net current.
- If the beam current lies primarily outside of the first zero of the eigenfunction, the voltage at $r = a$ can reverse quickly.
- The current profile during the transition period is the sum of the beam current plus the first eigenmode, J_{total} will have changed shape rapidly if the beam current profile didn't have the shape of the first eigenfunction.

If we allow the conductivity profile to vary, σ being small but non-zero at the edge, the problem must be solved numerically. In this case, the key factor is whether the J_f profile is more or less peaked than the σ profile.

- For J_f more peaked than σ , the current profile becomes more peaked and the E-field goes to zero at the edge after a skin time.
- For J_f peaked at the edge and σ peaked at the center, the E-field at the edge goes quickly to zero and then negative. The current profile becomes increasingly hollow.
- For J_f and σ profiles which are nearly the same, the J profile is almost constant and E at the edge will gradually go to zero.

More work is needed to see what happens if E is clamped to zero at the plasma edge before a skin time, i.e., if we change from current regulation to voltage regulation when v goes through zero.

B. PLANNED EXPERIMENTS ON NEUTRAL BEAM INDUCED CURRENTS ON ISX-B

The main problem in the area of neutral beam induced currents is not the generation of these currents, but rather their measurement. Experiments on ORMAK in 1976 using 360 kW of coinjected 30 kV H^0 beams into an H^+ plasma with $\bar{n}_e = 1.7 \times 10^{13} \text{ cm}^{-3}$ and $B_T = 17.5 \text{ kG}$ should have produced a (calculated current I in the plasma). However, even at this level it was not possible to measure this effect conclusively because of associated changes in T_e , Z_{eff} and plasma profiles. For example, if an uncertainty of $\pm 30\%$ in I_{bd} is desired, then the total uncertainty needed in $\Delta V/V$, $3/2 \Delta T_e/T_e$ and $\Delta Z_{\text{eff}}/Z_{\text{eff}}$ is $\leq 8\%$ if $I_{\text{bd}} = 20\%$ of I , $\leq 30\%$ if $I_{\text{bd}} = 0.5 I$, and $\leq 120\%$ if $I_{\text{bd}} = .8 I$. Similar arguments hold for changing the current direction or measuring radial profiles of $J(r)$, $q(r)$.

However, the measurement problem is simplified if $I_{\text{bd}} \sim I$. Predicted values for I_{bd} in ISX-B are 100-150 kA out of a total current of 150-200 kA. These large values are expected in ISX-B because the uni-directional power per unit volume is very large. However, optimization of I_{bd} requires high Z_{eff} and low n_e whereas optimization of plasma beta requires low Z_{eff} and high n_e . Although beam driven currents may not be dominant for the most relevant set of ISX-B conditions, they are never the less important because of their role in understanding tokamak beta limits and possibly large associated toroidal flow velocities. Extension of $I_{\text{bd}} \approx I_{\text{total}}$ (to permit long pulse operation) at high n_e and low Z_{eff} would require higher beam power (3 MW upgrade) and long pulse beam lines (modification of source grids, target cooling, and beam entrance geometry on 3 MW upgrade).

C. RATIONALE FOR STUDYING BEAM-INDUCED CURRENT EFFECT

The possible reasons for studying neutral beam induced currents are:

- such currents may significantly extend the pulse length of tokamak reactors, thus improving their economic competitiveness.

- the beam induced current is an important prediction of neutral injection theory and its existence should be proven, given the heavy reliance of the US program on neutral beam injection.

- beam induced currents will contribute significantly to the shear profile, and should be known accurately to interpret the results of high- β_T experiments.

The neutral beam induced current has drawbacks from a reactor point of view, in that I_{bd} is largest for high Z_{eff} (~ 5) and low density ($\bar{n}_e \lesssim 3 \cdot 10^{13} \text{ cm}^{-3}$). Reactors require $Z_{eff} \sim 1$ and $\bar{n}_e \gtrsim 5 \cdot 10^{13} \text{ cm}^{-3}$.

The theory of neutral injection seems to be in relatively good shape, and programmatic pressure for results in other areas is strong. Nonetheless, the dependence of the mainline US program on neutral injection is so strong that an active search for possible anomalies seems warranted.

At present, the various linear ideal MHD stability codes are contending the role of shear in setting high β_T limits. A comparison with the present status of nonlinear resistive tearing instabilities theory suggests that the shear changes introduced with $I_{bd}/I \sim \beta_T$ will be significant, even though the currents are not large. This warrants experiments in the regime where I_{bd} is large in order to have confidence that the effects being seen are being interpreted correctly.

D. DETECTION OF BEAM-DRIVEN CURRENT IN PLT AND OTHER TOKAMAKS

The net steady-state beam-driven current I_{bd} consists of a circulating ion current and a shielding current due to electrons dragged along with the circulating ions. The classical behavior of the circulating ions has been demonstrated by charge-exchange measurements, but no measurement of the net beam-driven current in a tokamak has yet been made.

A straightforward method for detecting I_{bd} is to measure the 'back emf' which is produced as the beam-driven current builds up in the plasma. With high power coinjection, the loop voltage V_{loop} should be driven negative shortly after the onset of injection if the total plasma current is maintained approximately constant. This result would provide an unambiguous demonstration of the beam-driven current. Theory predicts that negative loop voltages should be obtainable in the future with low density plasmas in ISX-B (2.4 MW full energy at 40 keV coinjection with volume average density $\langle n_e \rangle = 3.5 \times 10^{13} \text{ cm}^{-3}$), in PDX (if equipped with 4.8 MW coinjection, or 4.8 MW perpendicular and 3.2 MW coinjection, at 50 keV), and in TFTR (15 MW coinjection at 120 keV) [1].

About 3 MW of coinjected beam power (full energy at 40 keV) would be required to produce a negative loop voltage in PLT. With the lower power actually available in PLT (1 MW coinjection and 1 MW counterinjection at 38 keV full energy), it is most profitable to compare V_{loop} for nearly identical shots with co- vs. counterinjection. Successive co- and counterinjection shots allow optimal use of the good shot-to-shot reproducibility which can be obtained on PLT. Care must be taken, however, to use the observed plasma current I_{tot} as a condition on the current diffusion equation [2] when computing the expected loop voltage.

The results obtained from calculating the loop voltage, using a piecewise linear fit of the observed I_{tot} traces from two PLT shots as boundary conditions on the current diffusion equations, are shown in Fig. 1. These results assume parabolic-squared T_e profiles, and are presented only to show the magnitude of the loop voltage difference expected from the changing sign of I_{bd} with co- and counterinjection in present PLT experiments.

Existing data from a very small number of 1 MW shots is compatible with the expectation of a lower V_{loop} in the coinjected plasma resulting from the

build-up of the beam-driven current, but a complete analysis of the data has not yet been made, and alternate explanations (such as differential impurity influx) have not been ruled out.

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Figure 1. Evolution of density-averaged temperature $\langle T_e \rangle$ and calculated loop voltage V_{loop} in PLT with 1 MW coinjection or counterinjection, from $t = 0.45$ s to $t = 0.60$ s. Beam energy = 37 keV (D^0). $n_e = 3.4 \times 10^{13} (1 - r^2/a^2)$ cm $^{-3}$. The calculation of V_{loop} uses the observed change in plasma current.

E. THE RELEVANCE OF FAST ION CHARGE-EXCHANGE MEASUREMENTS TO BEAM-DRIVEN CURRENTS

There are three basic elements to the physics of beam-driven currents:

I. The beam ion behavior; II. The electron response, and III. The response of the bulk ions. It is my thesis in this talk that the crucial elements of all three have already been observed with charge-exchange measurements on ATC and PLT. All that remains is the final confirmation by observing a substantial loop voltage deficit, or a substantially increased plasma current.

The basic physics of beam-driven currents (ignoring neoclassical effects) is shown in the first slide. Electron dynamics view the ions as a single group, so long as $V_b \ll V_e$, and the velocity of that group is given by

$$V_{Z^2} = \sum_i n_i Z_i^2 V_i / \sum_i n_i Z_i^2$$

However, the electrodynamics view the ions as a current

$$J_i = \sum_i V_i n_i Z_i e$$

or one could say, see the ions moving with

$$V_Z = \sum_i n_i Z_i V_i / \sum_i n_i Z_i$$

Thus a low Z , high V ion component can contribute to V_Z without contributing substantially to V_Z^2 (or equivalently: without giving a proportional amount of momentum to the electrons), and thus can give rise to a beam-driven current.

Slide 2 shows the process by which we measure the fast ion distribution function in a Tokamak. The nuclei we eventually measure change charge state 5 times in the process. Neutral hydrogen gas enters the ion source, and is ionized in the arc discharge. The resulting ions are accelerated into the neutralizer cell, where they charge-exchange and pick-up an electron. The neutral beam then crosses the toroidal and poloidal magnetic fields and enters the tokamak plasma where it is ionized by ion or electron impact, or by charge-exchange with plasma ions. The fast ions which are so generated circulate the torus many times, with a circulation time of $\sim 5\text{-}10\ \mu\text{sec}$, as they slow down in $5\text{-}50\ \text{msec}$. During this process they may encounter neutral hydrogen atoms in the plasma and charge exchange once more, becoming neutrals that can escape the plasma. We sample these escaping neutrals with a multi-angle charge exchange detector. In the apparatus we have a small helium-filled gas cell where the fast neutrals are stripped by collisions with the helium atoms, so that they can then be electrostatically energy analyzed, and collected on particle detectors.

Slide 3 shows some early (1973) slowing-down measurements made with such an apparatus. Here we measured pulses of fast ions slowing down, and confirmed that the energy loss was in agreement with the theory, both in terms of the collisional drag, and in terms of the effect of the toroidal electric field on the fast ions.

Slide 4 shows a quasi steady-state fast neutral spectrum on ATC as a function of energy and angle, showing the strongly anisotropic nature of f_b , which constitutes the beam current, J_b . Slide 5 shows a similar distribution in

the lower- Z_{eff} PLT plasma. Slide 6 shows the $1/e$ fall time of the fast neutral signal after beam shutoff in PLT. In this case the analyzer faces the plasma at the same angle as the beam, so the variation of fall time with energy reflects the slowing-down rate, and it shows good agreement with theory.

Slide 7 discusses the fact that these measurements clearly show the presence of J_b , and its reasonable agreement with theory, which constitutes the important physics of point I mentioned above. We can also show that the critical elements of point II have been seen on the ATC and PLT experiments. The electrons could shield out the beam driven currents if the counter-streaming of the fast-ions and the Spitzer-Harm electron distribution gives rise to an anomalous friction. In this case, however, E_ϕ would also be shielded from the fast ions, but we have clearly observed its effects on ATC, as shown in the steady state fast ion distribution of slides 8 and 9, as well as the good agreement between theory and experiment on PLT shown in slide 10. (Theoretical $T_{\text{tail}} = 2.6 \text{ keV}$) It remains only to demonstrate the $1 - 1/Z_{\text{eff}}$ scaling, and to observe the neoclassical effects. These may be do-able in low Z_{eff} PLT discharges. However, the theoretical neoclassical calculation needs to be extended, since it is only valid in the banana regime, and the very core of the plasma can never be in the banana regime, due to the R/r scaling of v_{eff} . Furthermore, the calculation gives unphysical results for $Z_{\text{eff}} < 2$, $r/R > 0.2$. (Slide 11) Presumably, carrying the calculation to next order in r/R is required. Note that if the present calculation is correct, the beam-driven current is quite large even for a $Z = 1$ plasma at $r/R = 0.05$, near the center of the plasma (7.5 cm in PLT).

We have also observed toroidal rotation in PLT with unbalanced tangential injection. Slide 12 shows that the absolute magnitude of the fast neutral spectrum is higher and $d/dE(\ln f)$ is smaller when the plasma is rotated towards

the analyzer, than when the plasma is rotated away from the analyzer. Making use of the ratio of fast neutral fluxes as a function of energy, $R(E)$, we have:

$$\frac{V_{\phi}}{T_i} = 1.09 \times 10^7 \frac{\ln(R(E))}{[E(\text{keV}) \times A_p]^{1/2}}$$

V_{ϕ}/T_i vs. time is shown in Slide 13. Since T_i is expected to be ≤ 2 keV in this case, we have $V_{\phi} \sim 10^7$ cm/sec. This has been confirmed by observation of the doppler shift of the $m=1/n=1$ precursor oscillations of $m=0/n=0$ sawteeth. The ~ 60 msec fall time of V_{ϕ}/T_i is about twice the ion energy containment time, τ_{Ei} , so it indicates that the toroidal momentum containment time τ_{ϕ} is comparable to τ_{Ei} .

Slide 14 discusses the implications of this result. In short, the beam input power compared to the bulk ion energy scales as $(V_b/V_i)^2$, but the input momentum compared to bulk ion thermal velocity times mass, scales as (V_b/V_i) . Thus if $\tau_{\phi} \approx \tau_{Ei}$, $V_{\phi} \ll V_i$, a relatively safe condition from the point of view of rotational instabilities.

In conclusion, we have discussed fast ion charge exchange measurements relating to

- I. Fast-Ion Behavior
- II. Electron Response
- III. Bulk-Ion Response

which show in each case that the important physics relevant to beam-driven currents has at least been preliminarily confirmed. It remains now to find unambiguous evidence of beam-driven currents on the loop voltage or plasma current traces. On the basis of the fast-ion measurements, we feel confident that when and if conditions are created where the beam-driven current should be unambiguously observable, it will certainly be seen.

Slide 1

Cause of Beam-Driven Current:

Electrons are pulled by the electric field, with respect not to the center-of-mass of the system, or with respect to the lab frame, but with respect to the "center-of- Z^2 ".

$$V_{Z^2} = \sum_i n_i Z_i^2 V_i / \sum_i n_i Z_i^2$$

but the current is given by:

$$J = \sum_i V_i n_i Z_i e - n_e e V_e$$

thus a low Z , high V ion component contributes to J without proportionally contributing to V_{Z^2} , and so it doesn't pull the electrons along with it proportionally, and J increases

$$\Delta J = J_b (1 - 1/Z_{eff})$$

or the loop voltage drops

$$\Delta V_L = V_L \Delta J/J$$

SLOWING-DOWN MEASUREMENTS

Slide 3

Fig. 1 (a.) Tangential charge-exchange energy spectrum at time t after turn off of 1 msec. injection pulse at $E_{inj} = 14.2 \text{ keV}$.

Fig. 3 Experimental fast neutral spectra at three angles for injection near the magnetic axis, theoretical

Slide 7.

- We have certainly observed J_b - in the sense that we can measure the anisotropy of f_b , and it agrees well with theory (I).
- But can we say something about the electron response on the basis of the c-x and neutron measurements? (II)

- The calculation of the electron momentum balance gave:

$$\Delta J = J_b (1 - 1/Z_{eff})$$

and this is reminiscent of the calculation of E^* , the effective toroidal electric field that acts on the fast ions:

$$E^* = E_\phi (1 - 1/Z_{eff})$$

The reason that they are so similar, is that they are, in fact, calculations of the same thing -- electron momentum balance in a multi-species plasma, with a parallel electric field!

- Thus the experimental observation of the effect of E^* on fast ions indicates that the electrons are not coupling momentum equally well to the beam ions as to the (higher Z_{eff}) bulk ions (or the electrons would shield out E_ϕ altogether). Thus the essential physics of beam-driven currents were demonstrated on ATC in 1973!
- It remains to look for the $1 - 1/Z_{eff}$ scaling, and to look for the trapped-electron effect.

Fig. 1 (b.) Tangential charge-exchange energy spectrum
for quasi steady-state parallel injection

Fig. 1 (c.) Tangential charge-exchange energy spectrum
for quasi steady-state anti-parallel injection
($E_{inj} = 13.6$ keV)

Figure 29. High energy beam-ion tail above the injection energy, analyzer aimed tangentially, tracing counter-going ions. (PPPL-783910)

Slide 11

Small Aspect Ratio, Banana Regime Calculation

$$\frac{\Delta J}{J_b} = 1 - \frac{1}{Z} + \frac{1.46 (1 + 0.7/Z)}{Z} \left(\frac{r}{R} \right)^2$$

$r/R \backslash Z$	1	2	3	4	5
0	0	0.5	0.67	0.75	0.80
0.05	0.55	0.72	0.80	0.85	0.87
0.1	0.78	0.81	0.86	0.89	0.91
0.2	1.11	0.94	0.94	0.94	0.95
0.3	1.36	1.04	1.00	0.98	0.98

Slide 13

Figure 31. V_ϕ/T_i vs. time deduced from tangential thermal fast neutral flux.
 (PPPL-783906)

Slide 14

Is Toroidal Rotation a Limiting Factor for Driving Plasma

Current with N. B. I.? (III)

Power Balance:

$$G_i n_b (\frac{1}{2} m_b v_b^2) = \text{energy input to ions / sec. cm}^3$$

$$n_i (\frac{1}{2} m_i v_i^2) = \text{energy content of ions/cm}^3$$

$$\frac{n_i (\frac{1}{2} m_i v_i^2)}{\tau_{E_i}} = G_i n_b (\frac{1}{2} m_b v_b^2)$$

$$G_i = 1/4 \rightarrow 3/4$$

Momentum Balance:

$$\dot{n}_b m_b v_b = \text{momentum input to plasma/sec. cm}^3$$

$$n_i m_i v_\phi = \text{momentum content of plasma/cm}^3$$

$$\frac{n_i m_i v_\phi}{\tau_\phi} = \dot{n}_b m_b v_b$$

$$\frac{v_\phi}{v_i} = \frac{1}{G_i} \frac{\tau_\phi}{\tau_{E_i}} \frac{v_i}{v_b}$$

PLT results imply: $\tau_\phi \sim \tau_{E_i}$, $v_\phi \sim \frac{1}{6} v_i$

If this $\tau_\phi \sim \tau_{E_i}$ holds for other large (r) devices, then with completely unbalanced injection, $v_\phi < v_i$; a relatively safe condition.

F. APPLICATION OF INTENSE RELATIVISTIC ELECTRON BEAMS TO STEADY-STATE TOKAMAKS

The attractiveness of the tokamak power reactor as an energy producer would be enhanced if it could be operated as a steady state device. Present day tokamaks are limited to a pulsed mode of operation because in a resistive plasma the toroidal plasma current cannot be maintained indefinitely by transformer action. We propose the periodic injection of an intense relativistic electron beam (REB) to maintain the toroidal current in a tokamak reactor and thus permit a steady state mode of operation. The periodic injection of a 6.6 MeV REB with an average power of 1.5 MW can maintain 15 MA of toroidal current in a typical tokamak fusion reactor.

The experimental evidence for the REB current drive concept is found in the experiments of Mohri (Reference 1), where drift injection, energy loss trapping (References 2, 3, and 4) is used to inject and trap a REB in a torus. A 2.6 kJ REB is injected into the toroidal device SPAC-V, (Reference 5) which is filled with a gun injected preionized plasma of density $n_e \approx 10^{13} - 10^{14}/\text{cm}^3$. The REB is injected for approximately 60 ns. Prior to REB injection there is no net toroidal current. At the end of injection the net current remains small even though there are several hundred kiloamperes of counterstreaming beam and plasma current. The net toroidal current then increases over a timescale on the order of ~ 1 μs until it reaches a peak of 28 kA to 150 kA depending on the experimental conditions. Plasma ion temperatures of up to 300 eV are observed in the experiments. The beam-plasma system, which has a rather large toroidal beta of $\beta_t \approx .2$, is stable for up to a millisecond. These experiments, in which up to 60% of the injected REB energy appears as an increase in poloidal magnetic field energy, provide convincing experimental evidence for the REB current drive.

Prior to REB injection the toroidal plasma currents are decaying due to resistive dissipation. The REB is injected parallel to the toroidal magnetic field and trapped in the toroidal plasma column by the mechanism of drift injection, energy loss trapping (References 2, 3, and 4). When the REB is injected in the same direction as the original plasma electron drift, the REB induces a back emf which reduces the plasma electron drift velocity in such a manner as to maintain the net current, plasma current plus REB current, approximately constant. Since the injection time of the REB is much longer than the transit time of a relativistic electron around the torus, the REB wraps up on itself and the circulating REB current can be much larger than the injected REB current. At the end of beam injection, the counterstreaming plasma electron current cancels a portion of the beam current and the net current is approximately equal to the initial net current. As the counterstreaming plasma current is dissipated by the frictional force between the plasma electrons and ions, the absolute magnitude of the plasma electron current decreases, and the counterstreaming plasma current cancels less and less of the beam current. This causes an increase in the magnitude of the net toroidal current. The rising net toroidal current induces a toroidal electric field, which takes kinetic energy out of the REB and drives the plasma current. Thus, a portion of the beam kinetic energy is dissipated in increasing the poloidal magnetic fields, and a portion is dissipated in plasma heating by maintaining the decaying currents. After the REB energy has been significantly degraded the relativistic electrons give up their momentum to the background plasma electrons by coulomb collisions. Because of the strong inductive coupling of the beam-plasma system the net current will remain constant during this momentum transfer.

Simple formulas for calculating the increase in the net toroidal current per injected REB pulse, the time scale for this increase, and the fraction of the injected beam energy which appears as increased poloidal magnetic field energy are presented. The increase in the net toroidal current is a linearly increasing function of the kinetic energy of the injected REB and is inversely

proportional to the inductance per unit length of the beam-plasma system. For example, in a reactor geometry, injection and trapping of a single pulse of a 15 MeV intense REB will increase the net toroidal current by 1 MA while four pulses of the same beam will produce an increase of ~ 4 MA. The time scale for this increase in net toroidal current is shown to be significantly shorter than the normal L/R decay time of the plasma. The fraction of the injected REB energy which is initially converted to poloidal magnetic field energy or plasma heating can be adjusted by changing the parameters of the injected REB.

For the application of REB current drive to a tokamak reactor, the UWMAK III reactor was considered. The average power of the injected REB required to maintain the 15.6 MA toroidal current in the reactor was found to scale inversely with the kinetic energy of the injected REB. The periodic injection of a 6.6 MV REB with an average power of 1.5 MW could maintain the 15.6 MA of toroidal current in UWMAK III. In this example approximately 80% of the injected beam energy is converted to increased poloidal magnetic field energy.

Intrinsically, the REB is one of the highest efficiency ($\sim 80\%$), highest power ($\leq 10^{13}$ W), and highest energy (currently > 2 MJ) beam sources available. A long pulse (100 kJ, 1.5 μ s) generator has been operated at Physics International and the technology exists to produce a long-pulse generator of significantly higher total energy (≥ 3 MJ). In addition a three pulse, 10^{11} W peak power generator with variable time spacing between the pulses has been developed at PI. The proven technology of magnetically insulated transmission lines, which are capable of transporting power at $> 10^{10}$ W/cm², is available to bring the power from the generator to the beam injector in the torus. The technology of REB generators is such that significant experiments for the REB current drive concept can be carried out immediately.

In summary, the concept of periodic injection of a REB to maintain the toroidal current in a tokamak reactor and thus permit a steady state reactor has been discussed. Experimental evidence for the concept has been presented in which an externally injected

REB produced 30 kA of net toroidal current in a torus and the beam-plasma system was stable at a large β_t for a millisecond. The results of the theoretical investigation of this concept are in qualitative agreement with the experimental data. The average REB power level required to maintain the toroidal current in a reactor was found to be significantly less ($\sim .1 - .01$) than that required by RF heating. The REB generator technology was reviewed and suggestions were made for experiments directed toward a steady state reactor. Finally the major technical areas requiring further research were outlined.

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