TOKAMAK HEATING BY NEUTRAL BEAMS AND ADIABATIC COMPRESSION

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AUGUST 1973

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Presented at

TOKAMAK HEATING BY NEUTRAL BEAMS AND ADIABATIC COMPRESSION

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"Realistic" models of tokamak energy confinement strongly favor reactor operation at the maximum MHD-stable \( \beta \)-value, in order to maximize plasma density. Ohmic heating is unsuitable for this purpose. Neutral-beam heating plus compression is well suited; however, very large requirements on device size and injection power seem likely for a DT ignition experiment using a Maxwellian plasma. Results of the ATC experiment are reviewed, including Ohmic heating, neutral-beam heating, and production of two-energy-component plasmas (energetic deuteron population in deuterium "target plasma"). A modest extrapolation of present ATC parameters could give zero-power conditions in a DT experiment of the two-energy-component type.

I. Introduction

Classical or pseudoclassical energy confinement in tokamaks would imply that \( n_T E \) is independent of plasma density. The heating power required to meet an \( n_T E \)-criterion at given temperature can then be minimized conveniently by going to low density — and correspondingly long energy confinement time.\(^2,3\) On the other hand, scaling laws based on trapped-particle instabilities\(^1\) imply \( n_T E \propto n^2 \), and therefore strongly favor operation at the maximum density consistent with MHD limitations\(^4\) on \( \beta \).

Some familiar theoretical (or semi-theoretical) models\(^1\) have been used in Fig. 1 to indicate a possible scaling of confinement with rising temperature.\(^5\) The solid line represents the expected value of central \( n_T E \) as a function of space-averaged \( T_e \), for a tokamak current \( I = 1 \text{ MA} \), toroidal field parameter \( b_t \equiv B_t/50 \text{ kG} \) = 1, aspect ratio parameter \( A \equiv R/3a = 1 \), poloidal electron beta \( \beta_{pe} \equiv 8\pi n_T e/B_p^2 = 1 \), and effective ionic charge \( Z_{eff} = 1 \). For different values of \( I \), \( b_t \), \( A \), \( \beta_{pe} \) and \( Z_{eff} \), each line segment should be displaced as shown by the respective arrows; the length of each arrow represents a factor-of-10 increase in \( I \) or its coefficient. (Lowest practical aspect ratios \( R/a \sim 3 \) are favored, since they maximize \( I \); for safety factor \( q \sim 2.5 \), and \( T_i \sim T_e \) one then has \( \beta \sim 0.036\beta_{pe} \).) The diagram of Fig. 1 should not be taken
too seriously as a source of quantitative predictions about confinement, but it will serve to orient the present discussion of the tokamak heating problem. For simplicity, the discussion is specialized to tokamaks of circular minor cross-section, though important potential advantages of classical energy transport in the presence of Bremsstrahlung cooling and toroidal confinement, though vertical elongation has not been considered.

Fig. 1. Illustration of hypothetical scaling laws in relation to Lawson diagram.

\[ B_{pe} \approx \left[ K + \left( \frac{1}{1.6} \right) \right]^{-1/2} \]

where \( I \) is in MA. (The result is independent of \( Z_{eff} \).) For large tokamaks, the \( B_{pe} \)-values given by Eq. (1) would thus fall well below the permissible MHD limit \( B_{pe} \lesssim R_2a^{-1} \), even if \( K \) were not large and if there were no line or synchrotron radiation losses. In the context of Fig. 1, we see that for pseudoclassical \( nT \)-scaling, a low \( B_{pe} \)-value does not matter; however, for the probably more relevant trapped-ion-mode scaling, the \( B_{pe} \)-value matters greatly.

To offset the reduction of \( B_{pe} \) by a factor of 3.2 — corresponding to a probable increase of 30-50 in device cost — the following discussion is therefore oriented towards the realization of \( B_{pe} \)-values of order unity (values of \( 1 \)) by non-Ohmic heating methods: specifically, high-powered neutral-beam injection and adiabatic compression.

II. Adiabatic Compression

Adiabatic compression occupies a unique place in tokamak heating technology. Being reversible, it is not among the primary methods for energizing the plasma: Ohmic, high-frequency, and beam heating. Rather, it is a method for transforming the parameters of
tokamak plasmas from an initial irreversible heating phase at low magnetic field, density and temperature, to a final phase at high field, density and temperature. This transformation is not always advantageous compared with the alternative of heating irreversibly in the high-field phase. However, in particular applications, for example as an adjunct to Ohmic heating against radiation cooling, it can have significant advantages. Some scaling laws for adiabatic compression of well-conducting tokamak plasmas at, respectively, constant $R$ or constant $B_t$ are given in Table I.

Experimentally, the compression of the tokamak discharge in either minor or major radius appears to function well. Present-day compression experiments are somewhat too small to give good adiabaticity (i.e., they do not obey $\tau_{\text{comp}} \ll \tau_E$); even so, the plasma parameters obtained have been quite satisfactory. In the ATC (Fig. 2), compression of an Ohmically-heated plasma gives peak values $n \sim 10^{14} \text{cm}^{-3}$, $T_e \sim 2.5 \text{ keV}$, $T_i \sim 600 \text{ eV}$. Comparable temperatures have been obtained in the somewhat larger T-4 and ST tokamaks, but the 5-fold volume-compression in the ATC permits exceptionally high particle and energy densities to be reached.

The most useful type of adiabatic compression for practical thermonuclear purposes appears to be the compression in $R$ at fixed $B_t$, rather than

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>$B_t$-compression, $R$-compression, $C^{-1/2}$</th>
<th>Constant $R$, Constant $B_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor radius $a$</td>
<td>$C^{-1}$</td>
<td>Constant $C^{-1/2}$</td>
</tr>
<tr>
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<td>Constant $C^{-1}$</td>
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<td>Density $n$</td>
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<td>$C^2$</td>
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<tr>
<td>Temperature $T$</td>
<td>$C^{1/3}$</td>
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<tr>
<td>Plasma Current $I$</td>
<td>$C^{-2/3}$</td>
<td>Constant $C^{1/3}$</td>
</tr>
<tr>
<td>Plasma $\beta_p$</td>
<td>Constant $C^{-2/3}$</td>
<td>$C^{4/3}$</td>
</tr>
<tr>
<td>Plasma $\beta_t$</td>
<td>Constant $C^{1/3}$</td>
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<tr>
<td>Safety factor $q$</td>
<td>Constant $C^{-2/3}$</td>
<td>$C^{4/3}$</td>
</tr>
<tr>
<td>Aspect ratio $R/a$</td>
<td>Constant $C^{1/2}$</td>
<td>$C^{4/3}$</td>
</tr>
</tbody>
</table>

Fig. 2. Schematic of ATC. Neutral beams are tangential to torus magnetic axis.
the converse: both because it gives the most appropriate final plasma parameters (high current, high $\beta$, low aspect ratio), and because it avoids the necessity of pulsing the very large energy contained in the toroidal field. Considerably less optimism about energy confinement is required to envisage ignition in a larger device of the ATC type than with simple Ohmic heating.$^{10}$ Nonetheless, the technique of Ohmic heating plus compression over practical ranges of $R$ does not exploit the maximum $\beta$-values permitted by MHD considerations.

The use of irreversible compression$^{11}$ in $R$ by a rapidly modulated vertical field ($\tau_{\text{comp}} \ll \tau_{ii}$) would in principle permit continuous heating to high $\beta$-values. An extension of this technique to strongly $R$-dependent vertical fields$^{12}$ appears to enhance its engineering feasibility. Other high-frequency techniques — ion sound or cyclotron heating,$^{13}$ and heating at the lower hybrid frequency$^{14}$ — also appear promising, especially when used in conjunction with adiabatic compression, which lowers $\omega_p$ and $\omega_c$ in the precompression plasma, and multiplies the effective input power. The present discussion, however, will focus on the possibilities of neutral-beam injection, alone or in conjunction with adiabatic compression.

III. Neutral-Beam Heating

The injection of toroidal plasma with energetic neutral beams has long been a theoretically attractive possibility: in a closed system, the beam need not build up the plasma density, but need merely serve as a source of heat: a single injected particle can provide the thermal energy of 10–100 "hot" plasma particles. The advent of multi-ampere neutral-beam sources$^{15,16}$ with energies in the range 10–30 keV has now made neutral injection a practical experimental approach for tokamaks.$^{2,17,18}$

Initial beam-injection experiments on the ATC device$^{19}$ (Fig. 3) have made use of a 30–45 kW, ~15 keV beam, from one of two sources of ~70 kW maximum capability each, which were developed and built at the Lawrence Berkeley Laboratory.$^{16}$ Several times larger powers can be injected with a peak energy component of 30 keV from the four guns of the ORMAK device.$^{17}$ Even allowing for imperfect energy transfer to the plasma ions, these injected powers are competitive with the 50–100 kW input from electrons to ions in present-day
Ohmic-heated tokamaks. Sources with individual ratings approaching 1 MW are now being developed; their capabilities should be well suited to the heating requirements of next-generation tokamaks.

To obtain sufficient trapping of the injected beam in a tokamak discharge is not difficult, owing to the high ionizing power of the plasma target. (For tangential injection into ATC, for example, essentially all the beam is trapped — though not all into contained ion orbits.) The real problem for tokamaks is excessively good trapping, which will force the use of inconveniently high beam energies (>200 keV) to reach the central plasma regions of large future devices. The penetration problem can be solved, of course, by envisaging operation at low densities, but this approach requires almost the same degree of optimism about plasma energy confinement that is required for Ohmic heating to ignition (see above).

The confinement of injected ion orbits in present-day tokamaks with currents of ~100 kA (60-70 kA for precompression ATC) is rather poor even for ≤15-keV particles. Tangential injection is, in fact, a necessity, since most of the trapped-particle orbits would leave the plasma. (The associated anisotropy of the energetic ion population may possibly become a cause of velocity-space instabilities at higher heating powers.) The orbit-confinement problem will be eased greatly in future tokamaks at the 1-MA level and beyond. Another hypothetical source of trouble is the induction of local or global plasma rotations by the injected beam momentum. At present power levels of the ATC and CLEO experiments, there has been no overt evidence of either velocity-space or rotational effects.

Following the trapping of a neutral-beam particle into a confined orbit, the resultant energetic ion slows down by collision...
with the plasma particles, or is lost by charge-exchange (and possibly retrapped before leaving the plasma). For injected ion energy $W \sim 15T_e$, the rate of energy transfer to electrons and ions is equal; at higher energies, the heating of electrons predominates. In large tokamaks, this consideration is unimportant, since the $nT$-value for electron-ion equilibration is shorter than that for ignition; however, in present-day experiments, ion heating is favored significantly by low-energy injection. The slowing-down time of the injected ions, for example in ATC,\textsuperscript{19} is of order 10 msec; since charge-exchange times in a typical neutral atom background of $\sim 10^9$ cm$^{-3}$ are of order 5 msec, the charge-exchange loss of injected ions is a dominant consideration in the energetics.\textsuperscript{22} (H. P. Eubank points out that, in the present parameter range, raising the injection voltage could actually lower the power input into the plasma ions!) Since the slowing-down of injected ions in large tokamaks of the future will be in the 100-msec range, it is fortunate that neutral atom densities well below $10^8$ cm$^{-3}$ are expected on the interior of these plasmas.

The total plasma ion energy rise in the ATC experiment\textsuperscript{19} is of order 30 J, and takes place in 5-10 msec, i.e., following injection of $\sim 200$ J of beam energy. This result is roughly as expected\textsuperscript{2,22}: two-thirds of the beam energy is lost before thermalization, and about half of the remainder goes into the plasma ions.

In next-generation tokamak experiments, such as the PLT device ($a = 45$ cm, $R = 135$ cm, $B = 50$ kG), fairly large heating powers would be required to reach the $\beta_{pe} \sim 1$ regime. About half a megajoule of energy would then be stored in the plasma; the required power input into the plasma particles would be of order 5 MW. At an appropriate injection energy for beam penetration ($\sim 50$ keV), the efficiency of neutralization for positive source ions would still be moderately good (50-60%). A total input power of 10 MW at the ion gun might thus suffice to give the desired plasma $\beta$-value, and this appears feasible from the point of view of neutral-beam technology. In order to carry out such a plan in practice, a solution must first be found to the problem of wall-atom-sputtering by charge-exchange neutrals, which threatens to become a source of intolerable plasma impurity levels for tokamaks with keV-range ion temperatures.\textsuperscript{23}
In proceeding to still larger tokamaks, intended to approach ignition conditions, one technical problem will be the need to operate at much higher injection energies, where the neutralization efficiency for positive ions becomes small. A second problem has to do with the uncertainty regarding the minimum plasma size required to meet the n\textsubscript{E} criterion. If confinement scales with temperature in the manner illustrated in Fig. 1, a tokamak current of ~10 MA would be sufficient, corresponding to a plasma energy content of ~300 MJ, and a heating power of ~100 MW deposited into the plasma particles.

IV. Compression of Injection-Heated Plasmas

In the ATC experiment,\textsuperscript{19} the moderate ion temperature increments of 30-50 eV produced by neutral-beam injection at 30-45 kW can be amplified ~3-fold by compression. ATC data taken in the preheating phase are still insufficient to establish the functional dependence of \( T\textsubscript{i} \) on injection power. If the dependence is roughly linear, then the total ATC ion-heating capability is equivalent to ~3 times the maximum preheat injection power, i.e., about 400 kW. If the dependence is weaker than linear, the equivalent power of injection plus compression would be increased substantially.

There are several other potential advantages of compression in the context of injection-heating larger tokamak plasmas. The problem of beam penetration is solved by injecting into the pre-compression plasma, where the product \( n\textsubscript{a} \) is reduced by the factor \( \left( \frac{R\textsubscript{1}}{R\textsubscript{O}} \right)^{3/2} \). Furthermore, since the compression amplifies the initial energy input by the factor \( \left( \frac{R\textsubscript{O}}{R\textsubscript{1}} \right)^{4/3} \), the energetic efficiency of the source becomes a far less critical consideration in the over-all energetics. The impurity-evolution problem is not so severe in the precompression state, and one can hope to maintain good purity at least transiently in the compressed plasma by keeping it from making wall or limiter contact.\textsuperscript{24} Finally, plasma decompression at the end of the cycle has the attraction of recovering the energy of the plasma (and charged reaction products) with an efficiency \( 1 - \left( \frac{R\textsubscript{1}}{R\textsubscript{O}} \right)^{4/3} \). This is of appreciable interest in regard to reactor economics, and also in regard to the nontrivial problem of terminating a larger tokamak discharge in a harmless fashion.
The principal draw-back of compression (of the ATC-type) is the added magnetic field volume required by the plasma motion: the total toroidal field energy, however, would be enhanced only by factors of 2-3 in an optimized coil system. If magnetic divertors must be incorporated into tokamaks to solve the impurity problem, as now seems likely, magnetic energy enhancement factors of order 2-3 may no longer appear excessive.

V. Two-Energy-Component Reactors

A conventional toroidal reactor can achieve arbitrarily large amplification factors for fusion power output relative to plasma heating power input, by operating sufficiently close to the "ignition condition" of Fig. 1. Alternatively, it is possible to envisage useful reactors with quite small power-amplification factors, as in the case of mirror machines. For this type of operation, a promising toroidal system is the so-called two-energy-component reactor, or "wet-wood burner." As shown in Ref. 25, an energetic deuteron beam (100-200 keV) decelerating in a toroidally confined tritium plasma with moderate electron temperature \( T_e = 5-10 \text{ keV} \) and arbitrary ion temperature, can achieve somewhat better power amplification than a conventional-mirror machine, and about the same amplification as a two-component mirror reactor.26

A conventional toroidal reactor operated near ignition is obviously preferable to the wet-wood burner as a long-range goal for large-scale economic power production. The main drawback from the point of view of present-day reactor experiments is that the minimum size of a reactor plasma is not yet known. The linear size of the plasma must scale as \( a = D^{1/2} \), where \( D \) is a measure of the energy transport coefficient; the cost scales roughly as \( \$ \propto D^{5/4} \); unfortunately, authoritative present-day opinions concerning the magnitude of \( D \) in a reactor plasma range over considerably more than a factor of 10. An encouraging element in the situation is that an effective increase in confinement could apparently be obtained at reduced cost by improving the design of the torus minor cross-section,27 instead of increasing its overall scale. In relation to the plasma heating problem, it is useful to note that the required power scales as \( P \propto D^{3/2} \). On the other hand, once \( D \) is known for conventional reactors, the dependence of heating power on size is rather weak, scaling as \( P \propto a \).
Experimental operation of next-generation tokamaks should serve to reduce the uncertainty in \( D \) substantially.

The wet-wood-burner approach has the significant short-range advantage that the required plasma target has parameters similar to those obtained in present-day experiments on small tokamaks. The required injection power and the output power are extremely steep functions of size \( (P \propto a^3) \) so that the plasma of a wet-wood burner both can be, and indeed has to be, rather small, even for injection powers as high as 100 MW. Accordingly, the size of the required tokamak plasma target can be estimated fairly accurately (something like the plasmas in PLT or T-10). Whether the approach of marginal power amplification in a tokamak is of genuine economic interest, of course, remains an open question. Addition of a fissionable blanket would eliminate all doubts about the power economics, but would reintroduce some other drawbacks that fusion power is intended to surmount. Attainment of a zero-power tokamak wet-wood burner thus seems more likely to stimulate interest in progressing to a conventional tokamak reactor, than to supplant it as a practical goal.

Initial experiments on the ATC are testing some of the mechanisms of the wet-wood burner approach. A deuterium beam of \(-15\; \text{keV}, -3\; \text{A}, \) was injected into a precompression deuterium plasma of \( T_e \approx 600\; \text{eV} \) (Fig. 4). The slowing-down of the injected ions can be determined both from direct observation of tangentially emitted charge-exchange neutrals and from the decay of the neutron emission after beam shut-off. The observed decay rate of \(-1\; \text{keV/msec} \) is roughly consistent with expectation. The neutron production rate of \( -5 \times 10^8\; \text{sec}^{-1} \) appears slightly too low (by a factor of \(-2\)), but this remains to be verified. When the plasma is compressed immediately following injection, the neutron production rate increases to \( -5 \times 10^{10}\; \text{sec}^{-1} \).

Fig. 4. Deuterium beam injection into ATC deuterium plasma. Ratio of neutron yield to electron density is roughly constant throughout discharge time.
again somewhat below expectation, perhaps because of noncontainment of the most energetic ion orbits.

As an introductory example of the two-energy-component idea, it is of interest to consider an uneconomical "mini-reactor" with about the same plasma parameters and dimensions as the compressed plasma in ATC: \( n \sim 10^{14} \text{ cm}^{-3} \), \( T_e \sim 2 \text{ keV} \), a volume of \( 10^5 \text{ cm}^3 \), and a current of \( \sim 200 \text{ kA} \). If this plasma is tritium, injected with 500 kW of 60 keV deuterons, the result is \( \sim 50 \text{ kW} \) of fusion products. The required reaction time of the energetic deuterons is \( \sim 10 \text{ msec} \). Evidently, the charge-exchange and orbit-confinement problems in ATC would need to be improved somewhat — and, of course, velocity-space instabilities are assumed to be absent. The present measured neutron-production density of \( 10^6 \text{ cm}^{-3} \text{ sec}^{-1} \) in ATC, would rise to \( 10^9 \text{ cm}^{-3} \text{ sec}^{-1} \), if one were to use a tritium target plasma and deuterons of 60 keV initial energy. The energetic deuterons density would rise from the present level of \( 10^{11} \text{ cm}^{-3} \) to the \( B_p \)-limited density of \( 10^{13} \text{ cm}^{-3} \), and the neutron production would reach the desired operating level of \( 10^{11} \text{ cm}^{-3} \text{ sec}^{-1} \). This is about the same reaction rate as that in a conventional DT plasma.

A plasma somewhat smaller than PLT could be used to cross the zero-power reactor condition. If the tritium target plasma has parameters \( n \sim 10^{14} \text{ cm}^{-3} \), \( T_e \sim 4 \text{ keV} \), volume \( 10^6 \text{ cm}^3 \), and is injected with a 10 MW deuteron beam at 150 keV, the fusion power output could also be \( 10 \text{ MW} \) (Fig. 5). If one imagines the plasma thermal energy to be recovered with good efficiency (e.g., by decompression), this power amplification factor (\( F = 1 \)) would be sufficient to "cross the zero-power condition." This example assumes an energetic-deuteron density of \( 10^{13} \text{ cm}^{-3} \). The required reaction time is \( 35 \text{ msec} \) (Fig. 5); during this time, the energetic deuterons must not be lost, or degraded appreciably by means other than collision. Thus we have for the energetic particles, the criterion \( n_{T_e} \gg 3 \cdot 10^{11} \text{ cm}^{-3} \text{ sec} \). "Zero-power operation" also implies that we do not require heating of the target electrons other than by the deuterons. This condition is met, provided that \( \tau_{Te} > 20 \text{ msec} \), or \( n_{T_e} > 2 \cdot 10^{12} \text{ cm}^{-3} \text{ sec} \) for the target plasma.
To proceed from this point to the generation of useful power, the injection power should be raised and the amplification factor $F$ should be doubled; this implies a plasma electron temperature of 10 keV. The plasma ion temperature, however, can remain low. In view of the rather weak $n_T$-conditions, this regime should still prove relatively straightforward to attain in a device with a PLT-size plasma.

![Diagram](image)

**Fig. 5.** Calculated slowing down of energetic deuterons in tritium plasma. Mean fusion energy release becomes equal to initial deuterons energy, at point $F = 1$.

**Acknowledgments**

I should like to thank Drs. J. D. Callen, R. A. Ellis, Jr., H. P. Eubank, P. H. Rutherford, and T. H. Stix, for helpful discussions.

This work supported by U. S. Atomic Energy Commission Contract No. AT(ll)-3073.

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