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PLASMA HEATING*

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There have been significant developments in supplementary plasma heating systems over the past few years. Neutral beam heating has evolved from a new concept to a proven technique. Various types of rf heating have been tested. The present technological and experimental status of auxiliary heating techniques in tokamaks, mirrors, and pinches is reviewed. The possibility that these techniques can be extrapolated to fusion reactors is examined.

I. INTRODUCTION

The heating of plasmas to fusion temperatures ($\gtrsim$ 10 keV) is not usually an intrinsic part of plasma confinement schemes. Rather, it must be accomplished separately through one or more supplementary heating systems. At the time of the first ANS Topical Meeting on the Technology of Controlled Nuclear Fusion (April 1974), some prospective methods of auxiliary heating (neutral beam, radio-frequency heating, etc.) were beginning to be developed and tested, but none had yet been shown to be capable of substantial plasma heating. Since that time a number of auxiliary heating methods have been tested and found to heat plasmas substantially. Perhaps most noteworthy is the fact that neutral beam heating has roughly doubled (to $\gtrsim$ 1.8 keV) the maximum ion temperatures attained in tokamaks. Along with these recent successes in heating has come a growing realization that plasma heating is not really an "auxiliary" part of fusion reactors; rather, it is becoming an integral part of present fusion devices and reactor designs, whose cost and complexity is a substantial fraction of the overall system.

The basic requirements for supplementary heating systems are:

(1) Availability of adequate energy and/or power at reasonable cost and in convenient size modules.

(2) Ability to be absorbed and yet penetrate deeply enough to provide bulk rather than simply edge heating.

(3) Processes that can efficiently thermalize the absorbed energy with beneficial, or at least with no significant deleterious, effects on plasma confinement, and

(4) Experimental demonstration of significant heating in a manner that can be extrapolated to larger devices.

These requirements can be discussed in detail only in terms of specific supplementary heating systems. However, in order to provide the context for such a discussion, we will next deal with the scale of energy and/or power required.

The required auxiliary energy and/or power per unit volume can be estimated simply if we assume that the fusing plasma is brought up to and/or held at fusion reaction conditions primarily by the

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supplementary heating system. For steady state or near steady state systems where the heating is sustained for many energy confinement times, the required power (P) per unit volume (V) is simply the plasma energy density (3nT) divided by the energy confinement energy time (τ_E):

$$P/V \sim (3nT)/\tau_E$$
$$\simeq 0.5\frac{(n/10^{14}cm^{-3})^2(T/10keV)}{(n\tau_E/10^{14}\ cm^{-3}\text{-sec})}Mw/M^3 \quad (1)$$

If the plasma ignites, then the confined charged particle reaction products can provide a part or all of this power. For pulsed systems where the heating occurs rapidly and the plasma does not react for more than one energy containment time, the required energy (E) per unit volume (V) is

$$E/V \sim 3nT$$
$$\simeq 0.5(n/10^{14}cm^{-3})(T/10keV)MJ/m^3 \quad (2)$$

This is also the minimum energy required to produce the initial plasma state in steady state systems.

Approximate auxiliary heating requirements for fusion breakeven conditions are listed in Table I. Here, the plasma volume required for breakeven is roughly an order of magnitude smaller than those of the fusion reactor systems reviewed by Ribe.[1]

Table I. Parameters and Auxiliary Heating Requirements for Fusion Breakeven Conditions ($n\tau_E \geq 10^{14}$ cm^{-3} -sec, T $\geq$ 10 keV) for the three principal magnetic confinement approaches

Confinement Approach	Operational Type	$n(cm^{-3})$	T(keV)	Volume (m^3)	Auxiliary Heating Requirements	
Tokamaks	near steady state	10^{14}	10	200	$0.5MW/m^3$	100 MW
Mirrors	steady state	10^{14}	200	10	$10MW/m^3$	100 MW
Pinches	pulsed	10^{16}	10	2	$100MW/m^3$	100 MJ

The important point to note from these numbers is that the auxiliary heating requirements are quite large, even for breakeven experiments. They are even larger in fusion reactors. Given typical costs in the range of \$0.80-\$1.60 per watt, at least for present neutral beam systems,[2] it is readily apparent that the cost of the auxiliary heating systems in fusion breakeven systems can easily run in the $\gtrsim$ 100M\$ cost range.

There are two major methods of adding energy to a plasma: (1) by streams of particles bringing in additional kinetic energy, and (2) by electromagnetic means. The former technique is presently dominated by neutral beams. The electromagnetic means include rapid compressional heating and turbulent heating, as well as a wide variety of proposed wave (or rf) heating techniques. The various possible heating techniques in the three major magnetic confinement approaches — tokamaks, mirrors, pinches — are reviewed in the following sections. Since the greatest number of the proposed heating schemes have been tested on tokamaks, we discuss most of the schemes first in terms of tokamak plasma heating before we go on to discuss their application in mirrors and pinches. Throughout the following discussion on plasma heating systems, we have tried to elucidate the status of each system with respect to the four basic requirements listed above.

II. TOKAMAK PLASMA HEATING

In tokamaks[2,3] the current induced by the flux change in the transformer provides both plasma heating and the rotational transform in the magnetic field required for equilibrium and gross stability. However, it is well known[3,4] that since the plasma resistivity decreases as $T_e^{-3/2}$ as the plasma is heated, ohmic heating cannot heat a plasm to more than a few keV. Thus, tokamaks require supplementary heating to reach fusion breakeven and fusion reactor conditions.

Auxiliary heating in tokamaks may also have beneficial effects on the plasma equilibrium and stability. In a general sense any heating process that changes the electron temperature profile changes the plasma current and hence rotational transform profile. Since the rotational transform profile seems to determine the presence or lack of various instabilities[4] and the level of transport they induce, if one controls the electron temperature profile one may be able to control plasma equilibrium, stability, and transport. At present neither relevant theory nor experimental results are well enough developed to ascertain the viability of "profile control" by auxiliary heating. However, one specific example of a beneficial effect of intense auxiliary heating that has been developed in some detail is the flux-conserving tokamak (FCT) concept[5] in which the magnetic fluxes are "frozen in" during the heating process. Much higher β (up to 30%) are found to be accessible through the FCT process than previously thought possible.

IIA. Neutral Beam Heating

This method of heating[6] is the one most relied upon in present, next generation, and future tokamaks. A neutral beam source consists of only a few basic parts. First, there is a plasma source of either the duoPIGatron[7] or filament[8] (Berkeley) type. Ions are extracted from the plasma through a multiple aperture plate and the resultant ion beam is accelerated to high energy in a multiple aperture accel-decl electrode system. Next, the ions go through a charge-exchange cell where a substantial fraction is converted to neutrals (cf. Fig.1) The fraction of the beam that is not neutralized is bent out of the beam path by a magnetic field. Since molecular ions (H_2^+, H_3^+, etc.) are accelerated as well as hydrogen ions (H^+), the neutral beam usually has E_0, $E_0/2$ and $E_0/3$ components, where E_0 is the accelerating voltage. As an example of the present state of the art, the present 10 cm diameter neutral beam sources[9,10] on ORMAK produce about 140 kW of neutrals at 30 keV from an ion beam of about 10 amperes-equivalent of hydrogen atom current. A PLT ion beam operating on a test stand delivers 60 A of ions at 30-35 keV, for 50 msec.[11] Design goals for this system are 60 amp at 40 keV for .3 sec. Finally, 150-keV test stands have been built at ORNL[10,12] and LBL[12] with the objective of producing 1 MW D^0 beams at 120 keV. As shown in Fig. 1, for deuterium energies above about 100-150 keV, reasonably high efficiencies for the neutral beam systems call for negative ion beams - a step that requires the development of a new technology. The present status of neutral beam injector research and development work in the U.S.A. is summarized in Ref. 12.

The energetic neutrals in the beam are absorbed in passage through a plasma by charge-exchange and by electron and ion impact ionization processes. The mean free path for "ionization" is given by

$$\lambda = \frac{1}{n_e\sigma} = \frac{5.5 \times 10^{13}\,\mathrm{cm}^{-3}}{n_e A}\,(E_0/1\ \mathrm{keV}), \qquad (3)$$

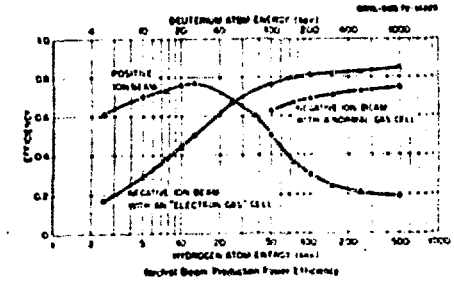

FIGURE 1. Efficiency of conversion of a charged beam to a neutral beam by passage through a charge neutralizing cell. The source efficiency is included in the overall efficiency values shown. (Courtesy of L. D. Stewart, ORNL-WASH-1295.)

where n_e is the plasma density and A is the atomic number of the energetic neutrals. This formula is taken from work by Sweetman[11] and is valid for 20 keV < E_o/A < 100 keV. For tangential injection into a tokamak it has been found[14] that the criterion for sufficient beam penetration to peak the beam power deposition near the plasma center is

$$\lambda > a/4 \ , \qquad (4)$$

where a is the plasma minor radius. For the potentially-more-convenient-near-perpendicular injection, the numerical factor in Eq. (4) apparently changes by less than a factor of 2.[15] The combination of Eqs. (3) and (4) indicates an upper limit on $n_e a$ for adequate beam penetration at a given beam energy. This functional relationship is plotted in Fig. 2. For present experiments $n_e a \lesssim 3 \times 10^{14}$, $E_o/A \sim 30$ keV and the beams have little difficulty penetrating. In TFTR with $n_e a \lesssim 10^{15}$ and $E_o/A \sim 60$ keV, penetration is reasonable as long as the impurity level can be kept low enough so that $Z_{eff} < 2$. For a larger, denser plasma, one can apparently penetrate adequately only by going to higher energy and hence probably to negative ion beams. One possible means of reducing these potential penetration difficulties is through a "ripple-injection" process.[16,17] The proposed process would take advantage of the fact that ripples in the toroidal magnetic field caused by the discrete coils in turn cause high energy ions to drift vertically in a tokamak, either by trying to drift in and collisionally trap beam ions,[16] or by using the process as an assist to perpendicular injection of a neutral beam.[17] This concept is presently being investigated at PPPL and ORNL; given uncertainties in adiabaticity, ergodicity, etc. in the basic fast ion drift orbit physics, it is too early to say if ripple injection will prove to be a viable scheme.

The fast ions that are produced as the neutral beam is absorbed transfer their energy and momentum into the background plasma as they slow down by Coulomb collisions with it. The thermalization time is roughly 0.12 $(T_e/1\ \text{keV})^{3/2}\ A/(n_e/10^{13}\ \text{cm}^{-3})$, which is typically about 0.01 to 0.1 sec and hence short compared to usual or expected energy containment times. The stored fast ion component and the momentum inputs from the neutral beams can in principle produce distortions of the plasma equilibrium, stability, and transport.[18] However, theoretically, the induced perturbations should be small and experimentally no significant deleterious effects have been observed except with counterinjection in some initial experiments.[19] The one significant effect that has been observed is a difference in the characteristics of co- versus counterinjection (relative to the ohmic current), for plasma currents below 150 kA.[19] For coinjection the observed heating was in agreement with theory; for counterinjection there was little or no

heating and the plasma had a tendency to become unstable.[20] This effect is apparently caused by the difference in particle drift orbits for these two cases and is negligible in most future, high current devices where the current is large and the ratio of fast ion gyroradius in the poloidal magnetic field to plasma radius is smaller.[18,21] Finally, we should note that a beam trapping instability has been hypothesized[22] in which if the beam initially deposits most of its energy near the outer edge of the plasma it may harden the energy spectrum of charge-exchange neutrals hitting the wall. The neutrals can then increase the sputtering of impurities from the wall, thereby increasing Z_{eff} at the plasma edge and decreasing beam penetration (cf. Fig. 2). The result may be an "instability" in which the beam penetration is impaired in large, high density devices in which Z_{eff} is important (cf. Fig. 2). So far no evidence of such an instability has been observed in the present small, moderate density experiments where there is little problem with penetration.

The first tests of neutral beam heating in a tokamak were performed on CLEO[19] in 1973. They showed a very slight (~ 10%) heating of the plasma ions with no deleterious effects on plasma confinement. Subsequent tests at higher injection power on ATC[24] and ORMAK[19] succeeded in raising the ion temperature by 30 to 50%. Recent very encouraging high power injection heating in ORMAK[9] (~ 360 kW tangential injection) and TFR[25] (~ 600 kW perpendicular injection) have succeeded in raising the ion temperature from the 0.5-1.0 keV range to the 1.5-2.0 keV range. In so doing they have caused the ion temperature to exceed the electron temperature for the first time in tokamaks. Also, it is important to note that these ion temperatures are the highest ever reached in tokamaks by any means. The electron temperature has not been increased significantly, apparently because (1) the neutral beam power input is still less than the ohmic heating power, and (2) the electron energy containment may be deteriorating a bit. The experiments have been so successful in heating ions because a substantial fraction of the beam power is transferred to the ions, and in the absence of neutral injection the ions are only weakly heated ($\lesssim$ 100 kW) by the collisional electron-ion energy transfer process.[9,18] Tests of neutral beam heating at higher power levels, in particular higher than the ohmic heating power level, are planned for PLT (~ 2-4 MW in 1977) and for ORMAK Upgrade (~ 2-4 MW in 1979).

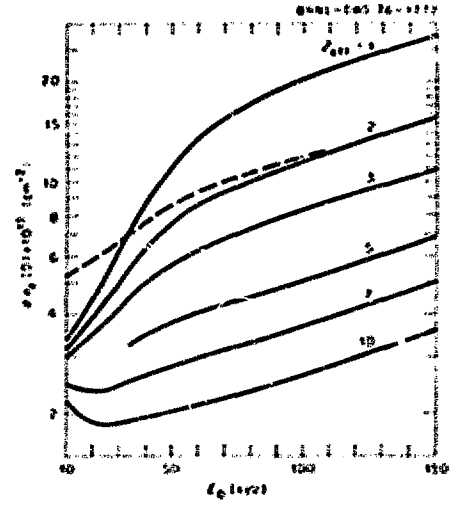

FIGURE 2. Beam penetration boundaries as a function of the impurity concentration parameter Z_{eff}. Below the curves penetration is adequate in the sense of peaking the power deposition profile at the plasma center. The ordinate is the product of the plasma density and the minor radius of the device. The abscissa is the beam energy per nucleon. Note that the energy required for penetration into a given plasma is twice as high for deuterium as for hydrogen.

In summary, neutral beams seem to satisfy the four basic requirements for supplementary heating systems listed in Section I quite well, with the possible exception of potential penetration difficulties in large, high density tokamaks.

IIB. Wave (RF) Heating

Wave heating,[26] which is also referred to as rf (radiofrequency) heating, encompasses heating by electromagnetic waves from very low ($\lesssim$ 1 MHz) to very high ($\lesssim$ 200 GHz) frequencies. The major attraction of wave heating is the fact that large amounts of power can be generated with up to 60-70% efficiency from presently available vacuum tubes ($\lesssim$ 100 MHz, $\lesssim$ 10 MW) and microwave sources ($\lesssim$ 3 GHz, $\lesssim$ 3 MW). Higher frequency ($\lesssim$ 50 GHz) microwave sources are also available at smaller power levels ($\lesssim$ 10 kW). A development program aimed at producing even higher frequency ($\lesssim$ 120 GHz), moderate power ($\lesssim$ 200 kW) microwave sources by the late 1970's is presently under way.[26]

While high power sources are most readily available at the lowest frequencies, unfortunately the problem of coupling rf power to the bulk of the plasma tends to become easiest at the highest frequencies. The basic reason is that the plasma is transparent to electromagnetic radiation at almost all frequencies above the electron plasma frequency ($f_{pe} \sim 100$ GHz) but is opaque, except possibly for some narrow frequency bands, to lower frequency waves. While the plasma opacity is desirable in the sense that it is likely that the waves can be absorbed in the plasma, it generally means that without special precautions the wave energy is deposited near the plasma surface; it is then not very useful for bulk heating. Another complication that occurs as the wave frequency is decreased is that the free space wavelength becomes larger than the plasma being heated. At high frequencies (100-300 MHz) the typical wavelengths are usually short compared to the plasma size and we have either multiple node normal modes or wave packets, which propagate along complicated access paths into the plasma. The wave launching apparatus for the high frequency waves is often simply the open end of a microwave horn. For low frequencies ($\lesssim$ 10-30 MHz) the plasma vacuum chamber becomes a small cavity which has a finite number of combination plasma and torus spatial eigenmodes. Then, in order to couple power effectively into the plasma, one must design and test <u>in situ</u> special antenna structures. These structures, and in particular their insulators, are potentially vulnerable to sputtering, radiation damage, and electrical breakdown. In the intermediate frequency regime (10 MHz < f < 300 MHz), variations in plasma parameter can cause the eigenmode frequencies to vary; in order to efficiently couple to such variable frequency eigenmodes one uses a mode tracking system with a fairly broadband, and hence lower efficiency, rf source.

The present theoretical and experimental status of the various types of wave heating[26] is, in order of increasing frequency, as follows: (1) Low-Frequency Sheaf Alfven Wave Heating (1-2 MHz). Ideal magnetohydrodynamic (MHD) theory predicts resonant absorption of wave energy at the point where the critical density for this mode occurs. The wave energy would be coupled into the plasma through transit-time and Landau damping. While this scheme has the potential advantages that accrue at very low frequency, it appears to require a complex internal antenna and has not yet been tested experimentally.

(2) Low-Frequency Fast Alfven (Magneto-acoustic) Wave Heating (1-10 MHz). The fast, magnetosonic wave is possible only in plasmas at least as large as those projected for TFTR. The energy in such waves could be weakly absorbed by transit-time and Landau damping. While heating by this method cannot be tested until very large fusion devices become operational, some of its physics features may be explored in smaller devices. This heating system would have a fairly simple internal antenna, but would require mode tracking.

(3) Ion Cyclotron Resonance Heating (ICRH-$f \sim f_{ci} \sim$ 30-200 MHz). As the shear Alfven wave frequency increases up to the ion cyclotron frequency it becomes the ion cyclotron wave. A number of small experiments have shown successful ion cyclotron resonance heating — most notably, a 600-eV ion temperature rise was achieved in the racetrack model C stellarator. However, since the wavelength of this mode along the magnetic field is quite small, it becomes progressively more difficult to design antennas that can launch this wave efficiently as plasmas increase above their present size.

(4) Ion Cyclotron Range-of-Frequencies (ICRF); Fast Wave Heating ($f_{ci} < f \lesssim 2f_{ci}$). In this frequency range the energy of the fast Alfven wave [cf. (2) above] is absorbed predominantly by ion cyclotron damping, at either the fundamental or second harmonic of the cyclotron frequency. Soviet, American, and French experiments have documented the occurrence of discrete toroidal fast wave eigenmodes in tokamaks.[26] Ion temperature increases of up to 150 eV have been produced by ICRF in more than one experiment and this mode must be considered a leading candidate for the rf heating of present generation tokamaks. In current devices this scheme uses an internal antenna and requires mode tracking. As the devices become larger it may be possible to use waveguides for antennas, but then the mode spectrum becomes so dense that it approaches a continuum. There are conflicting opinions as to the difficulty of coupling, and as to whether bulk or surface heating will occur in these circumstances. Even if surface heating does result, then the physics base developed for ICRF fast wave heating will aid in implementing low frequency heating [cf. (2) above] in reactor-sized systems. One cautionary note on ICRF fast wave heating is that in experiments on ST it was found to increase the influx of neutrals into the plasma, and for energy inputs greater than a few hundred joules thereby to stimulate a disruptive instability which extinguishes the discharge. This influx has been tentatively explained in part by cyclotron resonant absorption and subsequent wall bombardment by highly ionized impurities (e.g., O^{n+}), and in part by deuteron resonant absorption at the surface of the plasma. The fact that the ion drift orbits bombard the wall seems similar to the fast ion containment problems in neutral beam injection into tokamaks when the plasma current is less than 150 kA;[21] thus, this deleterious effect should go away in higher current devices such as PLT where the gyroradii in the poloidal magnetic field are a much smaller fraction of the plasma radius. Plans are under way to test ICRF heating in PLT in 1978.

(5) Lower Hybrid Heating ($\sim$ 1 GHz). Theoretically, waves launched into the plasma with frequencies near the lower hybrid frequency ($\simeq \omega_{pi}$, the ion plasma frequency) can propagate into the interior of the plasma if their wave number spectrum has a sufficiently large component along the magnetic field. This can be arranged by simple arrays of two to four waveguides. If the waves do get

into the plasma they can be absorbed by electron Landau damping, linear mode conversion, or nonlinear parametric processes. Experiments on Alcator and ATC have observed the efficient coupling of energy into the tokamak plasma, but there appeared to be little bulk heating of the ions.[26] There may have been some edge heating in these preliminary experiments; however, the main channel for energy deposition in the plasma remains unresolved experimentally.

(6) Electron Cyclotron Resonance Heating (ECTR-- $f \sim f_{ce} \sim 30\text{-}200$ GHz). Since this frequency is usually greater than the plasma frequency (ω_{pe}), there is little difficulty with penetration. When $\omega_{pe} < \omega_{ce}$ it is still reasonably easy to assure wave propagation into the center of the plasma.[26,27] The mechanism of wave absorption through the electron cyclotron resonance phenomenon is fairly well understood. Highly effective electron heating at modest power levels ($\lesssim$ 50 kW) has been observed in both open and closed geometry experiments using ECRH.

In summary, in terms of the four basic requirements for supplementary heating, only ICRF and ECRH, of all the possible rf heating methods, have been successful experimentally. ICRF seems most appropriate for present size devices; for larger devices it may go over to low frequency fast Alfven wave heating (2) above . The use of ECRH is apparently limited only by the availability of microwave sources of high enough frequency and power.

IIC. Compressional Heating

The adiabatic compression technique which could be thought of as an extremely low frequency wave heating process, has been used successfully a number of times in the past to heat plasmas to high temperatures and densities.[28,29] The idea is to preheat the plasma in a relatively weak magnetic field, and then carry out a (reversible) adiabatic compression to a higher final field strength.[30] This heats the plasma uniformly throughout its volume without distorting the distribution function if the compression takes place rapidly compared to the energy containment time. In tokamaks it is possible to compress the plasma either by increasing the toroidal magnetic field strength in time[31] or by increasing the vertical field, thus displacing the plasma inward in major radius to a region where the toroidal field strength is higher.[32] Both types have worked successfully in tokamaks: TUMAN-2 has used toroidal field compression from 4 to 12 kG to increase the plasma energy by a factor of 4,[31] in ATC radial compression of a neutral beam heated plasma has increased the ion temperature from 0.25 to 0.7 keV.[32] Compression in major radius has the great practical advantage that the process involves the pulsing of magnetic energies comparable to those in the poloidal field, rather than comparable to the 10^2 times larger energies in the toroidal field. However, even this technique is not generally expected to be used in reactors because of the low volumetric efficiency of toroidal magnetic field utilization in this concept. It might, though, be used as a slight assist to push a plasma to ignition.

IID. Turbulent Heating

This process could also be referred to as stochastic wave heating. However, the major driving force is the application of a very large electric field to the plasma which is desired to produce drift velocities larger than the electron thermal velocity and hence a multitude of strong plasma instabilities. The objective is to heat a plasma very quickly to very high temperatures, where its subsequent decay is hopefully much slower.

Substantial heating has been demonstrated experimentally in low density ($\lesssim 10^{12}$ cm^{-3}), small (< 10 cm radius) toroidal plasmas, with resultant keV temperatures.[33,34] The Texas Turbulent Tokamak (TTT) demonstrated substantial heating at low densities, but was plagued by inadequate penetration of the turbulent heating (skin penetration length $\sim c/\omega_{pi}$) at high densities.

III. MIRRORS

Plasma confinement in magnetic mirror devices[35] is provided by the vacuum magnetic field configuration. Since for the irreducible coulomb scattering level of collisions, the particle confinement time is comparable to the energy confinement time, plasma particles must be supplied at roughly the same rate that plasma heating occurs. Thus, magnetic mirror machines typically use high current, high power neutral beams to simultaneously "fuel" and heat the plasma, rather than using rf heating and then having to fuel separately. Since the ions escape with energies comparable to the injection energy, the plasma ion temperature is roughly given by the injection energy. However, the electron temperature is typically about an order of magnitude lower than the ion temperature because electrons are only weakly heated by the electron-ion collisional energy transfer process during their lifetime in the machine. This, coupled with the fact that effectively there are only two degrees of freedom in a mirror machine, makes the plasma kinetic energy density about nT_i instead of the $3nT$ in tokamaks. Thus, for mirror machines the factor of 3 in Eqs. (1) and (2) should be replaced by unity.

Magnetic compression has long been the basic scheme for heating gun-injected plasmas in the 2x-II mirror machine from a few hundred eV to the 1-10 keV range.[28] The resultant plasmas decayed with an anomalously short lifetime of about 400 μsec. While the compression technique is very useful now, it is not expected that it can be extrapolated to reactor regimes because of the large pulsed energies involved. Recently, high current neutral beam injection (200-300A, 3 MW) has been used to sustain the plasma against the anomalous losses.[36] The neutral sources used are similar to those used in tokamaks; the status of that development program has been reviewed in Section IIA above. High power neutral beam injection has also made possible some very interesting new experiments through its ability to sustain the plasma energetically against extra losses. The first such experiment of this type was the introduction of a low temperature plasma[36] (through added streams of neutral gas), whose presence stabilized the microinstabilities causing the anomalous losses[37] and thereby allowed the losses to become close to the classically predicted minimum. A further experiment along this line was the buildup of a plasma to high density ($\sim 10^{14}$ cm^{-3}) and energy ($\sim$ 10 keV) from a low temperature gun-injected plasma.[38] This last experiment is very important for mirror machines since it shows that high density, high temperature plasmas can be achieved without compression through high power neutral beam injection.

Rf heating has not been extensively used in mirror machines, but may be used for tailoring distribution functions in attempts to raise Q in the future. Turbulent heating from $\vec{E} \times \vec{B}$ drifts has been tried in the Burnout series of experiments.[39] However, since the required radial electric field can apparently only be produced by an internal

electrode and very high electric field strengths are required, it is not generally thought that this heating method can be extrapolated to reactors.

In summary, while the nonextrapolatable compression heating method works well in mirrors, the introduction of high power neutral beams into mirrors has made possible qualitatively new and considerable improvements in mirror-confined plasmas. The improvements have come about more because of the extra power input available to sustain the plasma against additional losses than by plasma heating per se. It appears that neutral beams will continue to be the main "plasma heating" scheme in mirrors, with little difficulty expected in penetration even for reactor sized plasmas. The only caveat is that since the energies required in fusion breakeven experiments and reactor exceed 200 keV, it appears that the beam technology will have to evolve from positive to negative ion sources to maintain the required high electrical efficiency.

IV. PINCHES

Since pinches are devices that are pulsed very rapidly ($\lesssim$ 1 usec rise times), their heating requirements are better discussed in terms of the amount of energy that can be delivered quickly to the plasma. Thus, they tend to use electromagnetic energy delivered to the plasma from capacitor banks or other energy storage devices through low inductance coils. Present theta pinches use a combination of implosion heating and compression heating. The implosion heating is produced by the rapid application of a current around the preionized plasma column. This induces an inward and very rapidly moving magnetic piston that drives a plasma implosion. After ions are propelled through the center of the plasma, the piston field is removed for a short while, and then the field is reapplied. Ideally the resultant plasma almost fills the chamber volume and the plasma kinetic energy is a significant fraction of the energy derived from ions moving at the piston speed. After implosion, a slower adiabatic compression is used to heat the plasma still further. Recent experiments in Scyllac[40] have used large compression ratios, thereby producing plasmas whose radii(a) are much smaller than the chamber radius(b). In the future it is desired to have much less compression in order to: (1) make possible wall stabilization[40] which apparently requires b/a > 2-3; and (2) make better use of the chamber volume. Thus, in the staged theta pinch reactor designs[1] the dominant energy input comes in the implosion or shock heating phase, with the compression phase adding only a little more energy to the plasma. The power level of most of the plasma heating techniques discussed in the preceding sections is too low to assist in the initiation phase of the theta pinch. However, if the plasma can be stabilized against magnetohydrodynamic instabilities and held for a fairly long time (e.g., 0.30 sec in the reactor designs),[1] then it would seem that neutral beams and/or rf heating might be helpful in keeping the plasma hot or in further heating it.

V. CONCLUSION

The most important conclusion concerning auxiliary heating techniques at present is that some of them have been developed and implemented to such an extent that they have produced significantly higher ion temperatures — in both tokamaks and mirrors — than would have been possible without them. Along with their success, auxiliary heating systems are becoming significant cost items.

At present neutral beam heating is enjoying the greatest success, having roughly doubled ion temperatures in tokamaks to 1.8 keV and having powered mirror plasmas up to 10-13 keV. The most successful versions of rf heating are ICRF and ECRH which, in modest experiments, have produced modest temperature increases. As we look toward the larger, higher density plasma devices of the future, neutral injection may begin to encounter penetration difficulties unless high energy sources (> 200 keV), probably of the negative ion type, can be developed. Similarly ICRF may be limited by the overlapping of spatial eigenmodes unless it evolves into the low frequency fast Alfven wave heating [IIB(2)]. ECRH is apparently only limited by the availability of high frequency sources at high enough power levels.

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REFERENCES

1. F. L. Ribe, Rev. Mod. Phys. 47, 7 (1975).

2. J. W. Willis et al., "Neutral Beam Energy and Power Requirements for the Next Generation of Tokamaks," ERDA 76-77, June 1976.

3. L. A. Artsimovich, Nucl. Fusion 12, 215 (1972).

4. H. P. Furth, Nucl. Fusion 15, 487 (1975).

5. J. F. Clarke, "High Beta Flux-Conserving Tokamaks," ORNL/TM-5429, June 1976; J. F. Clarke and D. J. Sigmar, ORNL/TM-5599, August 1976; R. A. Dory and Y-K. M. Peng, ORNL/TM-5555, August 1975; J. D. Callen, FCT paper submitted to Comments on Plasma Physics and Controlled Fusion, September 1976.

6. G. G. Kelley, O. B. Morgan, L. D. Stewart, and W. L. Stirling, Nucl. Fusion 12, 169 (1972).

7. L. D. Stewart, R. C. Davis, J. T. Hogan, T. C. Jernigan, O. B. Morgan, and W. L. Stirling, paper E12 at Third International Symposium on Toroidal Plasma Confinement, Garching, March 26-30, 1973; W. L. Stirling, R. C. Davis, T. C. Jernigan, O. B. Morgan, J. J. Orzechowski, G. Schilling, and L. D. Stewart, paper d-5 at Second International Conference on Ion Sources, Vienna, 1972.

8. K. W. Ehlers and W. B. Kunkel, paper d-3, ibid.

9. ORMAK Group, "Confinement and Neutral Beam Injection Studies in ORMAK," Paper CN-35/A4-1 at 6th International Conference On Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, FRG, October 6-13, 1976 (proceedings to be published).

10. O. R. Morgan et al., "The Development and Application of Neutral Injection Heating for ORMAK," invited talk given at the International School of Plasma Physics Symposium on Plasma Heating and Toroidal Devices, Sept. 6-17, 1976, Varenna, Italy. (Plasma Heating and Fueling Section TM#88, Sept. 8, 1976.)

11. O. B. Morgan et al., "The Development of Neutral Injection Heating for Large Tokamaks and Reactors at ORNL," Ibid. (Plasma Heating and Fueling Section TM #89, September 8, 1976.)

12. L. D. Stewart et al., "Neutral Beam Injector Research and Development Work in the USA," paper CN-35/1-5 at 6th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, FRG, October 6-13, 1976 (proceedings to be published).

13. D. R. Sweetman, Nucl. Fusion 13, 157 (1973).

14. J. A. Rome, J. D. Callen, and J. F. Clarke, Nucl. Fusion 14, 141 (1974).

15. J. A. Rome, private communication.

16. J. D. Callen, "Magnetic Field Ripple Effects in Tokamaks," Seminar at DCTR, ERDA, Wash., D.C., Jan. 9, 1976.

17. D. L. Jassby and R. J. Goldston, "Enhanced Penetration of Neutral-Beam-Injected Ions by Vertically Asymmetric Toroidal Field Ripple, Princeton Report MATT-1206, Feb. 5, 1976; MATT-1244, May 1976.

18. J. D. Callen, R. J. Colchin, R. H. Fowler, D. G. McAlees, and J. A. Rome, Plasma Physics and Controlled Nuclear Fusion Research, 1974 (IAEA Vienna, 1975), Vol. I, p. 645.

19. L. A. Berry et al., ibid., Vol. I, p. 113; L. A. Berry, J. D. Callen, R. J. Colchin, G. G. Kelley, J. F. Lyon and J. A. Rome, Phys. Rev. Letters 34, 1085 (1975).

20. ORMAK Group (presented by J. F. Lyon) In Controlled Fusion and Plasma Physics (Proc. 7th European Conf. Lausanne, 1975) 2, Lausanne (1975) 24.

21. J. A. Rome, D. G. McAlees, J. D. Callen and R. H. Fowler, Nucl. Fusion 16, 55 (1976).

22. J. T. Hogan and H. D. Howe, "An Impurity Seam-Trapping Instability in Tokamaks," ORNL/TM-5361, 1976.

23. J. G. Cordey et al., Nucl. Fusion 14, 441 (1974); Nucl. Fusion 15, 441 (1975).

24. K. Bol et al., Phys. Rev. Letters 32, 661 (1974).

25. TFR Group (presented by R. Dei-Cas), "Neutral Injection Heating in TFR," 3rd International Meeting on Theoretical and Experimental Aspects of Heating of Toroidal Plasmas," Grenoble, France, June 28 to July 2, 1976.

26. For a recent and quite extensive review of wave heating see: L. D. Smullin et al., "Report of the Ad Hoc Panel on Rf Heating in Tokamaks," ERDA-76/115, July 1976 and references cited therein

27. V. V. Alikaev, Yu. N. Dnestrovskii, V. V. Parail and G. V. Pereverzev, "Prospects for Using Electron-Cyclotron Waves to Heat Plasmas in Large-Scale Tokamaks," Kurchatov Report No. IAE-2610 (1976).

28. F. H. Coensgen et al., Plasma Physics and Controlled Nuclear Fusion Research 1971 (IAEA, Vienna, 1972), Vol. II, p. 721.

29. S. C. Burnett et al., ibid., Vol. III, p. 201.

30. H. P. Furth and S. Yoshikawa, Phys. Fluids 13, 2593 (1970); H. P. Furth, paper B9-1 at the Third International Symposium on Toroidal Plasma Confinement, Garching, March 26-30, 1973.

31. E. L. Berezovsky, V. K. Gusev, V. A. Ipatov, M. G. Kagansky, S. G. Kalmykov, A. I. Kislayakov, G. T. Razdobarin, K. G. Shakhovetz, I. D. Shpritz in Controlled Fusion and Plasma Physics (Proc. 7th European Conf. Lausanne, 1975) 1, Lausanne (1975) 5.

32. K. Bol et al., Phys. Rev. Letters 29, 1495 (1972); Ref. 24.

33. S. M. Hamberger et al., Plasma Physics and Controlled Nuclear Fusion Research 1971 (IAEA, Vienna, 1972). Vol. II, p. 37; S. M. Hamberger and J. Jancarik, Phys. Rev. Letters 25, 999 (1970) and references cited therein.

34. E. K. Zavoisky et al., Plasma Physics and Controlled Nuclear Fusion Research 1971 (IAEA, Vienna, 1972), Vol. II, p. 3. (English translation: Nucl. Fusion Supplement 1972, p. 81) and references cited therein.

35. R. F. Post, "Mirrors" paper at this conference.

36. F. H. Coensgen et al., Phys. Rev. Letters 35, 1501 (1975).

37. D. E. Baldwin, H. L. Berk, and L. D. Pearlstein, Phys. Rev. Letters 36, 1051 (1976).

38. F. H. Coensgen et al., Phys. Rev. Letters 37, 143 (1976).

39. I. Alexeff et al., Plasma Physics and Controlled Nuclear Fusion Research 1971 (IAEA, Vienna, 1972), Vol. II, p. 221.

40. E. L. Cantrell et al., Plasma Physics and Controlled Nuclear Fusion Research 1974 (IAEA, Vienna, 1975), Vol. III, p. 13.