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COMPRESSION SYSTEM

BY

J. C. CITROLO

PLASMA PHYSICS
LABORATORY

MASTER

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

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Towards Fusion Reactor Ignition The Adiabatic Toroidal Compression System*

J. C. Citrolo
Plasma Physics Laboratory
Princeton University
Princeton, New Jersey

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Abstract

A major problem area in the study of the feasibility of fusion reactors is the attainment of hot dense plasma for experimental study and the determination of a heating scheme to reach ignition conditions in a reactor. Adiabatic compression in minor and major radius of Tokamak configuration plasmas was proposed as a means of reaching this end. The Adiabatic Toroidal Compressor (ATC) was built at the Princeton Plasma Physics Laboratory to determine experimentally the feasibility of this technique. This paper describes the engineering features of this machine. Preliminary results indicate that compression heating is a possible method of assisting reaching fusion ignition temperatures.

Introduction

The determination of a heating scheme, that will heat experimental toroidal plasmas above one kilovolt and will enable a fusion reactor to reach ignition temperatures, has been a major problem area in the study of fusion reactor feasibility. Ohmic heating, in which a current is caused to flow in the plasma, is the principal method of heating plasmas in experimental devices. However, for a particular plasma density, there is a limiting temperature that occurs because the bremsstrahlung radiation losses increase with temperature, while the resistivity (and thus heating) decreases. Other heating methods, such as ion cyclotron resonance and magnetic pumping, present difficult problems in reactor-size devices and, at present, seem unlikely to be a practical solution.¹

Furth and Yoshikawa² proposed a method of increasing the temperature and density of a previously established plasma by adiabatic compression of the plasma column. This compression would take place on a time scale which is short with respect to the energy confinement time, but long in comparison to the particle collision time; so radiation cooling should not be a limiting factor in reaching ignition.

Figure 1 shows a toroidal plasma as would be formed in a tokamak device. Particle confinement is obtained by the combination of two magnetic fields: the toroidal field B_θ provided by an external current I_t , and the poloidal field B_p due to the plasma current I_p . The toroidal field varies inversely with machine radius. The plasma, a current carrying loop, experiences electrodynamic forces that tend to expand it. The kinetic gas pressure also increases the expansion force. Plasma radial equilibrium is accomplished by the addition of another magnetic field B_z perpendicular to the plane of the plasma. This field is described by the equation:³

$$B_z = \frac{\mu_0 I_p}{R} \left[\eta_n \frac{8R}{a} + \frac{2\mu_0 n k T}{B_p^2} + \frac{l_1 - 3}{2} \right]$$

where:

n = particle density
 k = Boltzmann's constant
 T = plasma temperature
 μ_0 = permeability in vacuum
 l_1 = plasma internal self-inductance per unit length

This field is provided by an external coil system. An increase of B_z will effect a compression in major radius. Assuming perfect plasma conductivity, during the time of compression, the flux within the plasma must be conserved:

$$a^2 B_\theta = \text{const.}$$

This relationship also describes the mechanism of minor radius compression. The effects of compression in terms of minor radius (a) and major radius (R) are:

density $n \rightarrow a^{-2} R^{-1}$
Temperature $T \rightarrow a^{-4/3} R^{-2/3}$
Plasma current $I \rightarrow R^{-1}$

Three types of compression were discussed. The first is a compression of minor radius at constant major radius. This can be achieved by increasing the toroidal field, B_θ , but the vertical field, B_z , must also be increased to maintain equilibrium in R . However, the total magnetic energy of the machine strongly increases with compression, while the energy of plasma increases more slowly ($W_p \rightarrow W_m^{1/3}$). The second and third types of compression were termed Type A and Type B, and both have compression of the major and minor radius. Type A is the stronger compression using an increasing vertical field to compress the plasma in major radius, and move it to a higher toroidal field region. This causes a minor radius compression which is enhanced by also increasing the toroidal field. The increase in machine and plasma energy is more favorable: $W_p \rightarrow W_m$. Type B compression uses a static toroidal field. Compression is achieved by increasing the vertical field to compress the major radius, move the plasma to higher toroidal field region, and cause a minor radius compression which is milder than in Type A. The energy stored in the vertical field is much smaller than the total magnetic energy, and is comparable to the plasma energy. In a toroidal device the toroidal field represents a large stored energy and the time variation of this field can require a considerable amount of power, which while possible can be difficult. Since Type B compression avoids this problem, an experiment to examine this type of compression was proposed. Johnson, Green and Weimer made a thorough analysis of equilibrium during compression and suggested size parameters for the device.⁴ The machine was designated the Adiabatic Toroidal Compressor (ATC).

Description of the ATC

Physical Arrangement

Figure 2 is a cutaway view of the device. The toroidal field B_θ is produced by an array of 24 T.F. coils with a total NI of 9×10^6 ampere turns. The major radius of the machine is 77 cm. The inside diameter of the coils is 115 cm. The maximum field at the

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inner edge of the coil is 90 kG and the field at the torus major radius is 23.3 kG. Each coil is made with ten turns of hard-drawn copper bar with internal water cooling, and is designed to be self-supporting against the centering and hoop forces. The structure (not shown) supports the coils against the slight overturning moment produced on the coils by the vertical fields.

The vertical field, which restricts the expansion of the toroidal plasma due to the electrodynamic forces, is provided by the SF coils. See Fig. 3. Increasing the current in these coils increases the vertical field and provides the mechanism for compression. There are 15 turns of specially fabricated water-cooled copper cable distributed in three separate coil cases. The total NI before compression is 20 kA turns and 150 kA turns during compression.

Most tokamak devices receive partial plasma stabilization from a toroidal copper liner which surrounds the plasma. Image currents in this liner oppose motion of the plasma and enhance stability. However, a copper liner is not compatible with compression, because it would exclude a rapid rise in SF field. Complete stabilization with an SF field only is a new feature of the ATC machine.

The initial plasma current is induced by another vertical field, which is produced by the OH coils. The plasma and these coils essentially form an air-core transformer with the plasma as a one turn secondary. The OH coils are arranged to provide a flux through the center of the plasma toroid, but no field at the plasma itself. These coils are physically distributed in the same coil cases as the SF coils. They consist of 16 turns of water-cooled cable with a total NI of 160 kA turns.

The vacuum chamber was designed to have a high electrical resistivity to permit the penetration of the rapidly changing SF field. This was achieved by the use of a bellows-type construction. The material is stainless steel .030 in. thick with a mean pitch of 3 convolutions per inch. The resulting equivalent electrical thickness is .005 in. and the equivalent structural thickness is 3/4-in. The vacuum chamber supports the full atmospheric pressure. There are also six rigid sections between the bellows sections, which facilitate the introduction of ports on the vacuum chamber. These are used for connection to the vacuum pumps and the mounting of diagnostic probes.

The Operating Cycle

The vacuum chamber is pumped down to a pressure of 2×10^{-8} torr. Hydrogen or deuterium gas is then admitted to the chamber until a pressure of 2×10^{-6} to 2×10^{-5} torr is reached. With full current in the toroidal field coils, the OH coils are energized to produce their maximum field of 3000 gauss through the eye of the plasma torus. The field in the region where the plasma discharge will occur, at $R = 88$ cm, is approximately 20 gauss. Figure 4 shows the field patterns of the OH and SF fields. After preionization by a 100 kHz, 30 kW coupling loop inside the vacuum chamber, the OH current is sharply reduced, and a current in the plasma is established. Simultaneously the SF coil current is increased to provide a vertical field at the plasma of 300 gauss which provides radial stabilization of the plasma. A slight curvature to this field also provides vertical stabilization. The OH coil current continues to decrease, but at a slower rate than the initial phase, to maintain the plasma current. Figure 5 shows the current time histories of the OH, SF and plasma currents. This is the ohmic heating phase, and continues for 15 msec. The SF current is then rapidly increased. The vertical field increases to 1,500 gauss, driving the plasma from a machine radius of 88 cm to 38 cm. The plasma minor radius changes from 17 cm to 10.7 cm. Compression

occurs in 2 msec.

Experimental Results

The ATC has been in operation since May, 1972, and has been operated at approximately 67% of the maximum designed values of toroidal field. Experimental results of this operation were reported by K. Bol, et al.⁵ A pre-compression plasma current of 60 kA is achieved with a plasma loop voltage of 3 - 5 V. This corresponds to a discharge resistance of $\sim 40 \mu\Omega$, which exceeds the classical resistance for a $Z = 1$ plasma by a factor of 3 - 5, suggesting high Z impurity of the present plasma. The central plasma density is 1 to $3 \times 10^{13}/\text{cm}^3$. The density is measured by a combination of Thomson scattering of ruby-laser light and microwave interferometer measurement. After compression the density increases to 1.4×10^{14} .

The ion temperature, as reported, is the charge exchange temperature derived from neutrals emerging tangential to the plasma circumference. This temperature is typically 200 eV after heating and prior to compression. The ion temperature increases to 600 eV after compression. The increase in density, current, and ion temperature is in good agreement with the adiabatic compression scaling law.

The electron temperature prior to compression is 1 keV at the center of the plasma. After compression it is 1.7 keV. The electron energy confinement time of the 60 keV discharge is only 2 msec, so that T_e could not be expected to follow the adiabatic compression laws, whereas the ion thermal equilibrium time is long with respect to compression time, and does show good agreement. When operation with full design values is achieved the energy confinement time for electrons should increase, and the electron compression should be more nearly adiabatic.

Figure 6 is a plot of the profiles of the density and electron and ion temperatures before and after compression. Unfortunately, data are available only for the inner half of the profile of the compressed plasma. This is due to the other portion being obscured by one of the SF-OH coils.

Reactor Application of Compression

The initial results of the ATC experiment are in agreement with the compression scaling laws. Some investigation of these scaling laws, as applied to reaching plasma ignition temperatures, was accomplished by Mills.¹ Using a computer program, which included the effects of bremsstrahlung and synchrotron radiation, alpha particle heating, injection of cold gas, diffusion losses, and energy exchange among the plasma components, he examined the effects of ohmic heating alone and with Types A and B compression. The plasma considered had a 90 cm radius and was initiated with a 20 eV temperature. The particle confinement time used was .05 sec, and the compression was considered to occur between .1 and .2 sec. Using ohmic heating alone the ion temperature was limited to a few hundred volts. The addition of Type B compression brought it to 3 keV and with Type A, 7 keV. The ignition temperature of a deuterium-tritium plasma is considered to lie between 4 and 5 keV. This analysis implies, for the conditions considered, a compression somewhat milder than Type A could be used. Since Type B compression was inadequate, a temporal increase in toroidal field would be required, but this would be less than in a true Type A compression.

Other aspects of compression must be investigated with relation to a full reactor design. These include the possible increase in reactor size, the pulsed power requirements, and the effects of initiating a plasma at what may be a non-optimal aspect ratio. However, compression does seem to be a possible method

of assisting other plasma heating schemes to boost a plasma to ignition temperatures.

The ATC experiment also demonstrated another important feature for tokamak-type reactors: that plasma equilibrium can be maintained using magnetic fields without a copper shell.

Acknowledgement

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Fig. 1. Tokamak geometry.

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Fig. 2. Cutaway view of the ATC showing all major components, except the structure.

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Fig. 3. Schematic cross section of the ATC.

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Fig. 4. Vertical field patterns.

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Fig. 5. Plasma, ohmic heating and vertical field current histories.

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Fig. 6. Plasma ion temperature, electron temperature and density spatial distributions.

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