Axial compression of an FRC plasma

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Abstract

A new concept for plasma heating using axial magnetic compression of a field-reversed configuration (FRC) plasma is proposed. In this concept, the FRC plasma is compressed only axially, keeping the magnetic flux between the separatrix and the confining chamber (flux conserver) wall unchanged, while allowing the plasma to expand radially. A simple model based on an empirical scaling law of FRC confinement and on the assumption that the compression is done adiabatically, predicts that in addition to heating the plasma, confinement improvement will also be accomplished with this concept. This compression will be done by energizing segmented mirror coils successively in such a way to decrease the length of the confinement region between mirror coils. The apparatus for this axial compression was developed and an experiment was carried out. In this experiment the plasma was compressed by about 30% and the plasma life time of about 500μs was increased by about 50μs.

1. Introduction

A field-reversed configuration (FRC) plasma has only poloidal field and an elongated shape[1]; the ratio of its length to diameter is about 10. Outside the separatrix, plasma pressure drops to zero within a few ion gyro radii[2]. From these facts, the beta value in the axial mid-plane, averaged inside the separatrix of an FRC in a solenoid or a cylindrical flux conserver is given by $<\beta>=1-\left(r_s/r_w\right)^2\big/2$, where r_s and r_w are the separatrix radius and the conductive wall radius, respectively. The separatrix radius $r_s(z)$ at an arbitrary axial position is obtained with good precision from an axial array of diamagnetic probes except for the region near either end of the FRC.

The FRC plasma is produced in our case by a negatively-biased theta-pinch machine, which consists of quartz discharge tube and massive, high voltage pinch coils; therefore access to the plasma for additional heating is extremely poor. As no material structures link the FRC, it can be translated axially from the theta pinch to a confinement chamber. By translating the FRC, additional heating experiments could be performed. On the FRX-C/LSM facility in Los Alamos, high power (1GW) magnetic compression heating was successfully done[3]. On the FRC Injection Experiment (FIX) machine in Osaka, a fast rising (rise time was about an ion gyro period) magnetic pulse from a one turn coil placed coaxially to the machine axis was applied to the translated FRC plasma and heating was observed[4]. In the former experiment, the plasma heating from $T(=T_e+T_i)$ of 0.6keV to 2.2keV was accomplished by increasing the confining magnetic field from 0.4T to 1.5T in 55μs. The result was consistent with the adiabatic compression theory. Though the heating was excellent, the confinement properties became poor. The energy confinement time τ_E shortened by a factor of 2~3 to 35μs. In the latter case, the strength of the magnetic pulse at its maximum was about equal to the strength of the confining field of 0.04T and the rise in the plasma temperature was only about 10% of its initial value. But most importantly, the confinement properties were improved by this heating. The result was explained based on the empirical scaling law $\tau_N \propto R^2/\rho_i$, where, τ_N, R, and ρ_i are particle confinement time, magnetic axis radius and the ion gyro radius in the external field, respectively. The explanation for this is that an unfavorable tendency for the confinement due to the increase of ρ_i was more than cancelled by the favorable effect brought about by the increase of R by the heating.

We propose in this work an axial compression of an FRC plasma as a method to heat as well as improve confinement.

2. Theoretical model

The FRC is compressed axially in a flux conserver without changing the external flux or the magnetic flux between the separatrix and the chamber wall. The plasma is heated by the compression and r_s increases until the magnetic pressure of the external field balances the plasma pressure. The change of the plasma parameters from before to after the axial compression is estimated with a simple model: We assume that the compression is done adiabatically in a time scale faster than the transport time scale. The plasma is assumed to be cylindrical in shape with the radius r_s and the length ls. Therefore, the total particle number N is written by

$$N = n_{\max}\langle\beta\rangle V$$

where, $n_{\max}$ is the density at the magnetic axis and

$$V = \pi r_w^2 x_s^2 l_s$$

where x_s is r_s/r_w and l_s is the plasma length. Plasma temperature is assumed to be uniform. As the adiabatic relation, we use

$$n_{\max}^{1-\gamma} T = const.$$

Conservation of the external flux reads as follows.

$$B_w = B_{vac}\Big/\left(1 - x_s^2\right)$$

where, B_w and B_{vac} are the magnetic fields just inside the flux conserver wall with and without the plasma, respectively. The plasma length before and after compression is written by l_i and l_f. The change of x_s from x_i to x_f is obtained from the above equations to be

$$\left(1 - x_f^2\right)\Big/\left(1 - x_i^2\right) = \left(\langle\beta\rangle_f x_f^2 l_f \Big/ \langle\beta\rangle_i x_i^2 l_i\right)^{\gamma/2}$$

We can obtain an approximate solution to this equation if we set $\langle\beta\rangle_i = \langle\beta\rangle_f = 1$. As $\langle\beta\rangle_i$ is about 0.9 and $\langle\beta\rangle_f$ is closer to 1, serious error will not result from this approximation. The term in the parenthesis of the above equation is written as n_f/n_i. If we define a compression ratio c as $c = B_f/B_i$, c can then be written as

$$c = \left(1 - x_f^2\right)\Big/\left(1 - x_i^2\right)$$

In terms of c, the final temperature and density are

$$T_f/T_i = c^{2(1-1/\gamma)},\ n_f/n_i = c^{2/\gamma}$$

The most important ingredient in this model is to associate an empirical scaling law[5][6]

$$\tau_N \propto R^2/\rho_i\,,$$

with the axial compression. The change of ρ_i and τ_N with the compression is written as follows.

$$\rho_f/\rho_i = c^{-1/\gamma},\ \tau_{N_f}\big/\tau_{N_i} = \left(x_f/x_i\right)^2 c^{1/\gamma}\left(r_{T_f}/r_{T_i}\right)^{-1/2}$$

where, $r_T = T_i/T$ (T: pressure balance temperature, T_i: ion temperature). The results of this analysis are shown below. In Fig.1(a) and (b), $\left(T_f/T_i\right)$ and τ_f/τ_i are plotted against l_f/l_i for some initial x_s values. As is seen in the figure, the heating done by the axial compression is modest because of the one dimensional nature of the compression and also possibly the existence of an upper limit to compression, perhaps due to the tilt instability[7]. The important point is that simultaneous heating and improvement of confinement is predicted for this method of compression.

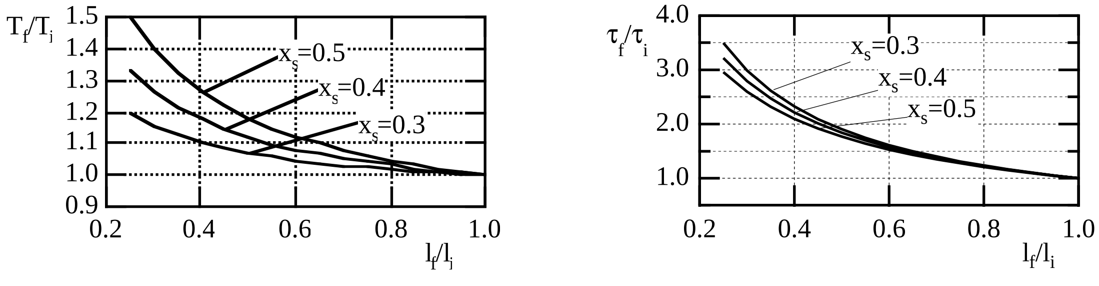

Fig.1 (a) Effect of heating by axial compression for different initial x_s values.
(b) Effect of confinement improvement by axial compression.

3. Apparatus

The FRC is produced in the formation region of the FRC Injection Experiment (FIX) machine. The theta pinch coil of the formation region is 1.26 m long, with an inner radius of 0.155 m. The FRC is then translated into a 3.4 m long, 0.8 m diameter confinement region made of stainless steel, equipped with mirror fields at both ends. The FRC translated into the metal chamber bounces back and forth a few times and settles down in the confinement region[8]. Axial compression of the FRC is done by energizing additional segmented mirror coils successively with time in such a way as to shorten the length of the confinement region. The rise time of the additional mirror field should be slow enough to accomplish a soft compression but faster than plasma decay times. In our case, the rise time was chosen to be 30-50 μs. As this rise time is shorter than the skin time of the metal confinement chamber, the additional mirror coils must be installed in the vacuum chamber. The additional mirror coils are arranged in two segments, each segment consisting of a 0.66m diameter 3-turn winding, each of which is contained in a stainless-steel jacket separated by 0.2m axially. Each jacket consists of two halves, separated by an insulator to prevent azimuthal return currents from flowing. The individual coil segments are spaced at 0.2m intervals along the machine axis. These coils are arranged next to the upstream mirror region. The length of the confinement region can be shortened from 3.4 m to 2.4 m[9]. A schematic drawing of the apparatus is shown in Fig.2.

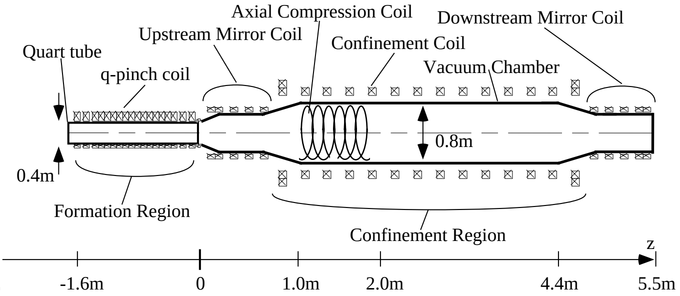

Fig.2 Schematic drawing of the FIX machine.

4. Experiment

An axial compression experiment was done on the FRC injection experiment (FIX) machine. The additional mirror coils were energized when the movement of the FRC plasma associated with the translation ceased. The separatrix shape and its change with time during the compression is inferred from an axial array of diamagnetic probes arranged in the confinement region. The separatrix shape near the additional mirror coils is not obtainable when the coils are energized, because the magnetic field is assumed to be almost straight in calculating r_s. In Fig.3, the change of the separatrix radius with time at 0.6m downstream from the axial midplane is shown for the case with and without compression is shown. By this operation, the length of the confinement region was decreased from 3.4m to 2.4m, or the plasma length was compressed by about 30%. The wavy structure before 200μs is due to the movement of the FRC plasma associated with translation. Without the compression, r_s is seen to decrease monotonically after 200μs. While, with the compression applied at 230μs, r_s begins to increase from 248 to 266μs and then after 310μs it starts to decay with almost the same decay rate as the case without the compression. After all, the configuration life time of about 500μs increased by about 50μs. In the theoretical analysis, the decay process was neglected and therefore r_s takes a different but constant value before and after the compression. In this case the improvement of τ_N can be concluded by simply comparing τ_N before and after the compression. However the following two facts complicate the comparison between analysis and experiment: i) r_s decreases with time as a result of unneglectable loss of plasma particles, energy and trapped magnetic flux: ii) Transport times change with time. To overcome these difficulties and to see the change in confinement due to compression, experimental τ_N was plotted against the confinement time predicted from the empirical scaling law (Fig.4). The empirical τ_N is obtained at each instant of time by

$$\tau_N = \left(\left(dN/dt\right)\ /N\right),\ N = \bar{n}V$$

V is calculated from the measured $r_s(z)$ and as $\bar{n}$ we used a quantity obtained by dividing a side-on interferometer signal by r_s measured at the interferometer location. The fact seen in Fig.4 that τ_N is almost the same for the case with and without the compression, signifies that the result predicted by the analysis is experimentally verified, i.e. that the confinement can be improved by increasing r_s through axial compression. It must be mentioned that τ_N is longer than the predicted τ_N by a factor of about 5 as already noticed in Ref.[4]. However the functional dependence of τ_N on R^2/ρ_i still holds approximately.

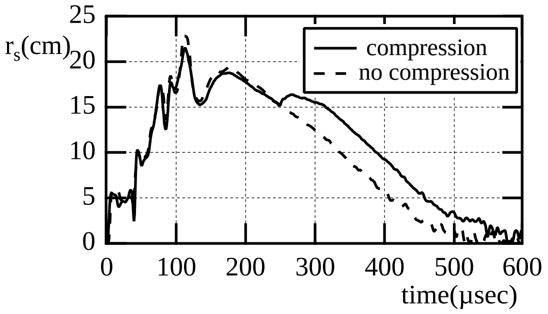

Fig.3 Change in separatrix radius with time at 0.6m downstream from the axial midplane of the confinement region. Dashed line: no compression. Solid line: axial compression field applied at 230μs.

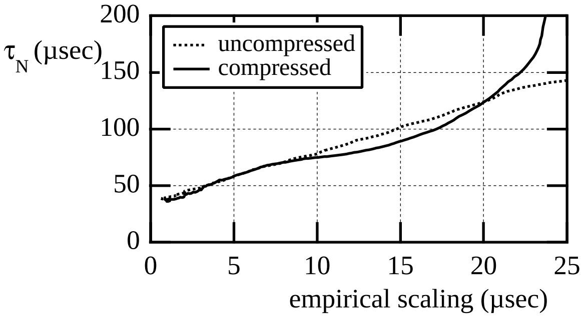

Fig.4 Particle confinement time at each instant of time plotted against the value calculated for the empirical scaling law with (solid line) and without (dotted line) axial compression.

5. Conclusion

A new method for the axial magnetic compression of an FRC plasma in a flux conserver is proposed. The ability of this scheme to heat as well as improve FRC plasma confinement was predicted by taking into account both the empirical scaling law and the adiabatic compression relations. An experimental apparatus to test this concept was built and was installed on the FIX machine. Reflecting the smallness of the compression ratio, heating was not recognized but improvement of confinement was observed by the experiment.

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