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Discussion on Some Additional Heating Schemes of an FRC Plasma

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Abstract

Effect of some additional heating schemes so far done on plasmas with field-reversed configuration (FRC), 1. adiabatic magnetic compression, 2. magnetic axial compression and, 3. application of fast rise magnetic pulse are studied. A theoretical model for heating which takes into account of empirical scaling law is proposed and is successfully used for the study. Experimental results that, item 1. has remarkable heating capability but degrades plasma confinement and the heating capability of item 2. is modest but it improves confinement, were explained theoretically.

Keywords:

FRC plasma, additional heating, adiabatic compression, confinement improvement, confinement scaling law

1. Introduction

As no material structures are linking the plasma with field-reversed configuration (FRC) [1] produced in a theta-pinch machine, it can be translocated or translated from a production region made of a fragile quartz discharge tube which is surrounded by massive, high voltage pinch coils, to a confinement region which consists of metal vacuum chamber. By this technique of "translation", accessibility of heating and diagnostic facilities to the FRC apparatus improved to a large extent and additional heating experiment became to be done. Actually, on the FRX-C/LSM apparatus in Los Alamos, high power magnetic compression heating experiment was done and remarkable heating was observed [2]. However, confinement was degraded. On the FIX apparatus in Osaka, fast rise magnetic pulse was applied. Though the result was modest, simultaneous heating and improvement of confinement was observed [3]. Also on the FIX apparatus, the FRC was compressed axially by decreasing the distance of a pair of mirror coils keeping the magnetic flux between the separatrix and the chamber wall at a constant value. By this experiment, considerable improvement of confinement was seen [4,5]. Here, a simple model is introduced and comparison with experiments is shown.

2. Theoretical Model

In all of the heating schemes stated above, energy is assumed to be fed into plasma in a time sufficiently shorter than confinement times. By this assumption, we have only to compare change of plasma parameters just before and after heating. In the case of compression heating, in which heating time becomes comparable with confinement times, interpretation of experiments by this model must be done carefully. It is also assumed

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that the plasma is cylindrical in shape with radius r_s and length ℓ_s. Therefore, the plasma volume is given by

$$V = \pi r_s^2 \ell_s . \tag{1}$$

Separatrix radius r_s is related to the magnetic axis radius R by $r_s = \sqrt{2}R$ [6] and is written as $r_s = x_s r_w$, where r_w is the chamber (magnetic flux conserver) wall radius. Total particle inventory is written as

$$N = n_{\max} \langle \beta \rangle V, \tag{2}$$

where, $n_{\max}$ is the plasma density at the magnetic axis and $\langle\beta\rangle$ is the volume averaged beta value. As the magnetic flux is conserved inside the vacuum chamber, solenoidal magnetic field strength with the plasma B_w and without the plasma B_{vac} are related by

$$B_w = B_{vac} / (1 - x_s^2). \tag{3}$$

The most important ingredient of the present model is to associate empirical scaling law [7,8]

$$\tau_N \propto R^2 / \rho_i , \tag{4}$$

to the heating process, where, ρ_i is ion gyro radius in the solenoidal field. So far, there are only few data base on the dependence of τ_N on ℓ_s, in which weak dependence like $\tau_N \propto \ell_s^{0.2}$ is reported [1]. There are also experiments in which stronger dependence of τ_N on x_s are reported [1]. The preciseness of above scaling law must be examined in future by accumulating data base for confinement.

In the case of heating by the application of a magnetic pulse, plasma pressure increases with heating and therefore, R or r_s increase until the increase of the external magnetic pressure balances to it. Resultant x_s value is related to the pressure balance temperature T_{tot} by

$$\frac{x_s^2 \langle \beta \rangle}{(1 - x_s^2)^2} = \left[\frac{N}{\pi r_w^2 \ell_s} \right] \left[\frac{2\mu_0}{B_{vac}^2} \right] \kappa T_{tot} . \tag{5}$$

A dependence of $\langle\beta\rangle$ on x_s is required to solve above equation and to find the dependence of x_s on T_{tot}. But as $\langle\beta\rangle$ is close to 1 (about 0.9), serious error will not result even if we approximate $\langle\beta\rangle$ by 1 or $1 - x_s^2/2$. Latter relation is expected if the FRC is not suffering from the effect of mirror fields [6,9,10]. When the increment of temperature $\delta T_{tot}/T_{tot}$ and of the normalized radius $\delta x_s/x_s$ is small, above equation is linearized and following result is obtained.

$$\delta T_{tot} / T_{tot} = \left(2 \frac{1 + x_s^2}{1 - x_s^2} \right) \left(\frac{\delta x_s}{x_s} \right) + \frac{d\langle \beta \rangle}{\langle \beta \rangle} . \tag{6}$$

If $\langle\beta\rangle$ is assumed to be $1 - x_s^2/2$, then

$$\mathrm{d}r_i / r_i = \frac{1}{1 - x_s^2} \left(\frac{r_h / r}{1 - x_s^2 / 2} - 2x_s^2 \right) \left(\frac{\delta x_s}{x_s} \right), \tag{7}$$

and

$$\mathrm{d}t / t = \frac{1}{1 - x_s^2} \left(2 - \frac{r_h / r}{1 - x_s^2 / 2} \right) \left(\frac{\delta x_s}{x_s} \right), \tag{8}$$

are obtained, where, $r = T_i/(T_e + T_i)$ and $r_h = \delta T_i / \delta T_{tot}$.

In the case of heating by magnetic compression, compression is assumed to be done adiabatically. In general, the adiabatic invariant μ is a function of the magnetic flux function and should be conserved in each magnetic flux tube. Here, we are not dealing with the change with compression of detailed profiles [11] of n, B and T but we wish to find approximate behaviour of global quantities such as $n_{\max}$, B_w and T_{tot}. We adopt $n_{\max}^{1-\gamma} T_{tot}$, which is correct on the magnetic axis locally, as the adiabatic invariant, where γ is the adiabatic constant.

Different treatment is required depending on how the compression is done; three dimensional compression or one dimensional axial compression. When the strength of the confining magnetic field is increased, and when the FRC is not leaning to the mirror field, it is compressed not only radially but also axially due to increase of tension of magnetic field which is confining the FRC axially, and therefore, compression is done three dimensionally. In this case, the trapped reversed magnetic flux may be written as follows [11].

$$\phi = \frac{\pi}{2} r_w^2 B_w \left(\frac{x_s}{\sqrt{2}} \right)^{3+\varepsilon}, \tag{9}$$

where, ε changes with radial magnetic field profile and it takes a value between 0 and 1. By using conservation of trapped flux, together with the conservation of the particle inventory, constancy of μ and the radial pressure balance equation, the change of normalized plasma radius before (x_i) and after (x_f) the compression is written by the compression ratio c_B (= B_f/B_i) as

$$x_f / x_i = c^{-\frac{1}{3+\varepsilon}} \tag{10}$$

The change of the temperature and the density are given below.

$$T_{tot\,f} / T_{tot\,i} = c^{2\left(1 - \frac{1}{\gamma}\right)} \tag{11}$$

$$n_f / n_i = c^{\frac{2}{\gamma}} \tag{12}$$

As stated before, the plasma length changes with compression and is given by

$$\frac{\ell_{\mathrm{f}}}{\ell_{\mathrm{i}}} = c^{\frac{2}{3+\varepsilon}-\frac{2}{\gamma}}\left(\frac{\langle\beta\rangle_j}{\langle\beta\rangle_i}\right)^{-1}. \tag{13}$$

As the change of parameters with compression is written by T_{tot}, while the confinement times are written by T_{i}, a relation between T_{tot} and T_{i} is required to see the effect of the compression on the confinement. Here we introduce a parameter r (= $T_{\mathrm{i}}/T_{\mathrm{tot}}$). Then,

$$\tau_{\mathrm{f}}/\tau_{\mathrm{i}} = c^{\frac{1}{\gamma}-\frac{2}{(3+\varepsilon)}}(r_{\mathrm{f}}/r_{\mathrm{i}})^{-\frac{1}{2}}, \tag{14}$$

When $\gamma = 5/3$, $\varepsilon = 0$ and $r_{\mathrm{f}}/r_{\mathrm{i}} = 1$, then $\tau_{\mathrm{f}}/\tau_{\mathrm{i}} = c^{-\frac{1}{15}}$.

In the case of one dimensional compression, the compression is done in such a way as to decrease the distance between a pair of mirror fields from ℓ_{i} to ℓ_{f}. In this case, explicit expression to calculate trapped flux is not obtained, because the radial magnetic field profile changes. Therefore, conservation of solenoidal magnetic flux (magnetic flux between the separatrix and the chamber wall) is used. The change of the plasma radius when the plasma length is compressed from l_{i} to l_{f} is obtained from the following equation.

$$\frac{1-x_{\mathrm{f}}^2}{1-x_{\mathrm{i}}^2} = \left(\frac{\langle\beta\rangle_{\mathrm{f}} x_{\mathrm{f}}^2 \ell_{\mathrm{f}}}{\langle\beta\rangle_{\mathrm{i}} x_{\mathrm{i}}^2 \ell_{\mathrm{i}}}\right)^{\frac{\gamma}{2}}. \tag{15}$$

As stated previously, serious error may not result even if we put $\langle\beta\rangle$ to $1 - x_{\mathrm{s}}^2/2$. Anyway, the term in the parenthesis of above equation is written as $n_{\mathrm{f}}/n_{\mathrm{i}}$, and the result of compression is more easily be written by $c_n = n_{\mathrm{f}}/n_{\mathrm{i}}$, or the compression ratio $c_{\mathrm{B}} = c_n^{\gamma/2}$.

$$B_{\mathrm{f}}/B_{\mathrm{i}} = c_n^{\gamma/2} = c_{\mathrm{B}}, \tag{16}$$

$$T_{\mathrm{tot\,f}}/T_{\mathrm{tot\,i}} = c_n^{\gamma-1} = c_B^{2\left(1-\frac{1}{\gamma}\right)}, \tag{17}$$

$$n_{\mathrm{f}}/n_{\mathrm{i}} = c_n = c_B^{2/\gamma}. \tag{18}$$

The ion gyro radius and the confinement time change as follows.

$$\rho_{\mathrm{f}}/\rho_{\mathrm{i}} = c_n^{-\frac{1}{2}}(r_{\mathrm{f}}/r_{\mathrm{i}})^{\frac{1}{2}} = c_{\mathrm{B}}^{-\frac{1}{\gamma}}(r_{\mathrm{f}}/r_{\mathrm{i}})^{\frac{1}{2}}, \tag{19}$$

$$\begin{aligned}\tau_{\mathrm{f}}/\tau_{\mathrm{i}} &= (x_{\mathrm{f}}/x_{\mathrm{i}})^2 c_n^{\frac{1}{2}}(r_{\mathrm{f}}/r_{\mathrm{i}})^{-\frac{1}{2}} \\ &= (x_{\mathrm{f}}/x_{\mathrm{i}})^2 c_{\mathrm{B}}^{\frac{1}{\gamma}}(r_{\mathrm{f}}/r_{\mathrm{i}})^{-\frac{1}{2}}.\end{aligned} \tag{20}$$

Above expression shows that the confinement time becomes longer by the compression if r does not change seriously, as x_{s} increases with the compression.

3. Experiments

A fast rising (rise time ≈ 3 μs; comparable to or faster than Alfven transit time across the radius of the FRC) magnetic pulse is applied to the translated FIX-FRC plasma. The translation chamber (confinement region) of the FIX has the length of 3 m and the diameter of 0.8 m and x_{s} is about 0.4. The magnetic pulse is produced by a pair of half turn coils with the radius of 0.33 m which is installed in the vacuum chamber coaxially to the axis of the chamber. When the pulse was applied, plasma volume became larger by about 10% than in the case without the pulse. The energy confinement time also increased by about 10%. As the interferometer data were not reliable enough to calculate τ_N in this experiment, direct comparison with the previous analysis for the heating by the application of a magnetic pulse is not possible. But considering that $\tau_N \approx 2\tau_{\mathrm{E}}$ in many experiments, it may be possible to conclude that simultaneous heating and confinement improvement is consistent with the previous analysis if ion heating rate is not too large, or favorable effect on confinement caused by the increase of R prevails the unfavorable effect caused by the increase of ρ_i. Axial compression experiment was also done in the FIX apparatus with 3.4 m long, 0.8 m diameter confinement chamber. The length between a pair of mirror field of 3.4 m was decreased to 2.4 m in 35 μs. Due to natural decay of the trapped magnetic flux by transport, the separatrix radius became smaller with the time constant of about 150 μs. If r_{s} did not change with time, we could have easily compared the experimental result with the model. Previous analysis for the one dimentional compression predicts that r_{s} increases by 15% from $r_{\mathrm{s}} \approx$ 16 cm to 18.4 cm and τ_N increases by 16% when the FRC is compressed axially by 30%. While in the experiment, at the time when the axial compression field starts to increase, the value of r_{s} is ~16 cm and it decays in 18 μs to 15 cm before it begins to increase. Further 18 μs is required before r_{s} increases to ~16.4 cm. Then, r_{s} starts to decay again. The consequence of this process is that r_{s} increased by ≈ 13% compared with the case of no compression at corresponding time and the configuration life time of ≈ 500 μs increased by about 50 μs. Adiabatic compression or three dimensional compression experiment was done on the FRX-C/LSM apparatus in Los Alamos. The FRC produced by a 2 m long, 0.75 m diameter theta pinch was translated into a 3.6 m long, 0.4 m diameter quartz vacuum chamber. The confining magnetic field was increased from 0.4 T to 1.5 T in 55 μs and the plasma was heated from T_{tot} of 0.6 keV to 2.2 keV. The result was consistent with the adiabatic compression theory. Though the heating was remarkable, the confinement properties became poor. The particle confinement time τ_N decreased by a factor of ≈ 2 to 35 μs. By the theoretical model, the decrease of τ_N should be only 8%. The reason of the discrepancy will be explained by the fact that the compression time is almost the same as confinement times and further, they have strong dependence on R, which decreases with compression.

4. Conclusions

So far, adiabatic magnetic compression experiment, magnetic axial compression experiment and application of fast rise magnetic pulse were done as additional heating experiments on the FRC plasmas. A theoretical model which took into account of the empirical scaling law of confinement to the heating was shown to explain the experimental result at least qualitatively: In three dimensional magnetic compression, remarkable heating was obtained but confinement was degraded. In one dimensional compression, heating was modest but confinement was improved. In the application of a magnetic pulse, modest but simultaneous heating and confinement improvement was seen. To test the validity of this model further and to do quantitative comparison with experiments, transport loss and process of heating must be taken into account.

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