A New Device Concept of Magnetic Confinement Deuterium–Deuterium Fusion

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A two-stage cascade magnetic compression scheme based on field reversed configuration plasma is proposed. The temperature and density of plasma before and after magnetic compression are analyzed. In addition, the suppression of the two-fluid effect and the finite Larmor radius effect on the tilting mode and the rotating mode of major magnetic hydrodynamic instability is studied, and finally, the key physical and engineering parameters of the deuterium–deuterium fusion pulse device are introduced. Further analysis shows that the fusion neutrons can be produced at an energy flux of more than 2 MW/m^2 per year, which meets the material testing requirements for the fusion demonstration reactor (DEMO). If the recovery of magnetic field energy is taken into account, net energy outputs may be achieved, indicating that the scheme has a potential application prospect as a deuterium–deuterium pulse fusion energy.

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With the advancement of fusion research, people continue to think about fusion configurations. Field reversed configuration (FRC) plasma has characteristics of complete axisymmetric symmetry, relatively simple structure, pressure ratio (β) close to 1, etc., which are ideal for heating plasmas through magnetic compression. Magnetic compression, as a pulse heating method, has been used since the earliest pinch experiments with remarkable results. Magnetic adiabatic compression has been studied in ATC facility of Princeton University [1,2] and FRX-C/LSM facility of Los Alamos National Laboratory. [3] Those studies have verified that both plasma temperature and density have improved greatly. Based on them, in this Letter we investigate two-stage magnetic compression based on C-2 series device plasma. Then the heating effect of magnetic compression and plasma instability are analyzed. Finally, we propose a new design of deuterium–deuterium (DD) pulse fusion device and provide a reference for the research and development of magnetic confinement fusion energy.

As a typical representative of the field reversed configuration plasma device, the C-2W device of the American TAE Technology Company uses a magnetic field of about 0.2 T to confine the high-performance FRC plasma with a density $n = 3\times10^{19}\mathrm{m}^{-3}$, a total temperature of $T = T_\mathrm{e}+T_\mathrm{i}$ of 3 keV (T_e and T_i are electron and ion temperatures, respectively), and its maintenance time reaches 30 ms. [4] This plasma can thus be used as the initial target plasma for magnetic compression. The structure diagram of the DD pulse fusion device is shown in Fig. 1(a), which mainly includes FRC plasma generators, magnet system, power supply system, vacuum chamber system, and neutral beam injection system, etc. The FRC plasma generator generates high-quality FRC plasma and injects the plasma into the collision fusion zone at high speed. In contrast to the usual magnetic compression, the DD pulse fusion device employs a two-stage magnetic compression (TSMC) mode. Figure 1(b) shows the TSMC timing diagram with a large compression ratio. Among them, the first stage is a fast magnetic compression or the adiabatic compression (from 0 to t_1). It is to increase the plasma temperature and density simultaneously to greatly improve the fusion reactivity rate, especially DD fusion reactivity rate. The second stage of slow magnetic compression (from t_1 to t_2) is to avoid magnetic diffusion of plasma, so the FRC is maintained and fusion reaction time is also maintained to elevate the fusion products in a single pulse.

As a plasma heating method, adiabatic compression has a relatively complete theoretical model, which is in good agreement with the experiments. [3,4] The evolution laws of length, temperature, density and boundary magnetic field of FRC plasma during compression can be obtained as follows: [4]

$$
\begin{aligned}
L &\propto \chi_\mathrm{s}^{2(3-\epsilon-\gamma)/\gamma}\langle\beta\rangle^{-(1+\epsilon-\gamma\epsilon)/\gamma},\\
T_m &\propto \chi_\mathrm{s}^{-2(3-\epsilon)(\gamma-1)/\gamma}\langle\beta\rangle^{(1+\epsilon)(\gamma-1)/\gamma},\\
n_m &\propto \chi_\mathrm{s}^{-2(3-\epsilon)/\gamma}\langle\beta\rangle^{-(1+\epsilon)(\gamma-1)/\gamma},\\
B_\mathrm{w} &\propto \chi_\mathrm{s}^{-3+\epsilon},
\end{aligned}
$$

where L is the axial length of plasma; $\chi_\mathrm{s} = R_\mathrm{s}/R_\mathrm{w}$ is the ratio of the plasma interface radius R_s to the vacuum chamber radius R_w; ϵ is balance profile coefficient, its value

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is between -1 and 0; $\gamma = 5/3$ is the adiabatic coefficient; T and n are the total plasma temperature and plasma density respectively; and the subscript m is the maximum value. $B_{\rm w}$ is the magnetic field at the wall of the vacuum chamber; $\langle\beta\rangle$ is the ratio of the average plasma pressure to the magnetic pressure.

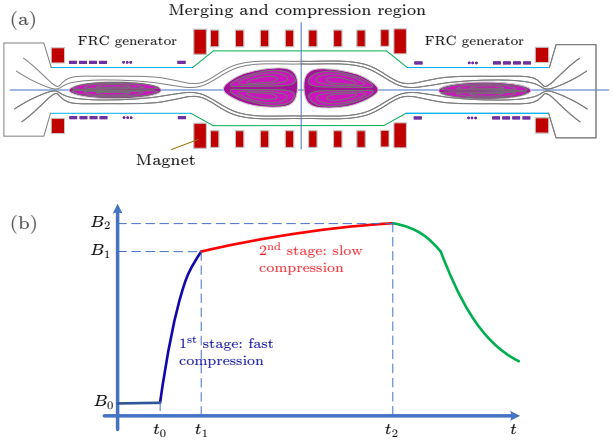

Fig. 1. (a) Schematic diagram of the DD pulse fusion device and (b) diagram of two-stage magnetic compression with large compression ratio.

If it cannot meet the condition of magnetic compression rate much higher than the energy loss rate, the plasma loses energy during the magnetic compression. At this point, the total energy $W_{\rm tot}$ of the FRC plasma can be expressed as

$$\frac{dW_{\rm tot}}{dt} = -\frac{W_{\rm tot}}{\tau_{\rm E}} + P_{\rm in}, \tag{1}$$

where $\tau_{\rm E}$ is the energy loss rate, and $-W_{\rm tot}/\tau_{\rm E}$ represents associated energy loss rate during magnetic compression. $P_{\rm in}$ is the heating power of plasma by magnetic field in the process of magnetic compression. When the energy loss is slow, it can be estimated according to the power of magnetic field compression in the adiabatic compression.[4] Then we consider the energy loss rate. The high temperature plasma has a variety of energy loss channels due to its huge temperature and density gradient. The abnormal transport caused by turbulence makes the classical energy transport analysis results differ greatly from the experimental results. The energy confinement time scaling has become an important method for magnetic confinement fusion research. Compared with tokamak configurations, the FRC plasma is less studied, and its energy confinement time still lack practical verifications. However, the C-2 series devices of novel field reverse plasma have provided meaningful results. The scaling law of electron energy confinement time of C-2 series devices is as follows:[5,6]

$$\tau_{\rm E,e} = \tau_{\rm E,e0}\left(\frac{R_{\rm s}}{R_{\rm s0}}\right)\left(\frac{T_{\rm e}}{T_{\rm e0}}\right)^2\left(\frac{B_{\rm w}}{B_{\rm w0}}\right)^{-1.3}, \tag{2}$$

where $\tau_{\rm E,e}$ is the electron energy confinement time, $R_{\rm s}$ is the plasma interface radius, $T_{\rm e}$ is the electron temperature, $B_{\rm w}$ is the magnetic field at the wall of the vacuum chamber, and the subscript 0 represents the initial value before compression.

In the FRC plasma, the energy confinement times of electrons and ions are often different, and the total energy loss includes the energy losses of electrons and ions. Therefore, the total energy loss rate and the energy loss rate of electrons and ions meet the following relationship:

$$\frac{W_{\rm tot}}{\tau_{\rm E}} \geqslant \frac{W_{\rm e}}{\tau_{\rm E,e}} + \frac{W_{\rm i}}{\tau_{\rm E,i}}, \tag{3}$$

where $W_{\rm tot}$, $W_{\rm e}$, and $W_{\rm i}$ are the total energy, electron energy, and ion energy, respectively; $\tau_{\rm E}$, $\tau_{\rm E,e}$, and $\tau_{\rm E,i}$ are correspondingly the total energy confinement time, electron energy confinement time and ion energy confinement time. The experimental results of the C-2 device show that the total energy confinement time is higher than the electron energy confinement time ($\tau_{\rm E}/\tau_{\rm E,e} = 3.4$,[6] 4.64 and 5.22[7]). In addition, the experimental results of ATC apparatus also show that $\tau_{\rm E,i}$ is greater than $\tau_{\rm E,e}$.[2] In order to estimate the changes of $\tau_{\rm E}$ in the process of magnetic compression, some approximate simplification is made here. Firstly, it is assumed that the electron temperature $T_{\rm e}$ changes synchronously with the plasma temperature T_m, so that the ratio of them remains constant during compression. Furthermore, suppose the total energy confinement time $\tau_{\rm E}$ is always 3.4 times larger than the electron energy confinement time $\tau_{\rm E,e}$ in the whole compression process, so the scaling law of $\tau_{\rm E}$ can be obtained as follows:

$$\tau_{\rm E} = 3.4\tau_{\rm E,e0}\left(\frac{R_{\rm s}}{R_{\rm s0}}\right)\left(\frac{T_m}{T_{m0}}\right)^2\left(\frac{B_{\rm w}}{B_{\rm w0}}\right)^{-1.3}, \tag{4}$$

where energy confinement time $\tau_{\rm E}$ is related to plasma temperature T_m. Suppose that the energy loss is mainly conductive, convection can be ignored (assuming that the particle loss is 0), so the energy loss will cause temperature changes. The thermodynamic relationship between plasma temperature and energy can be expressed as

$$T_m = \frac{W_{\rm tot}(\gamma - 1)}{n_m V}, \tag{5}$$

where $\gamma = 5/3$ is the adiabatic coefficient, V is the plasma volume, which can be approximated from the size evolution in the adiabatic compression. Finally, Eqs. (4) and (5) and energy balance Eq. (1) are solved by differential numerical method to obtain the parameter variations before and after the FRC plasma magnetic compression with energy loss.

The initial design parameters of the C-2W device meet temperature $T_m = 3\,{\rm keV}$ and density $n = 5 \times 10^{19}\,{\rm m}^{-3}$. Based on the designed parameters of the C-2W device, the plasma temperature is to be increased by 1.5 times when considering the further operation optimization. The initial total temperature is set as $T_m = 4.5\,{\rm keV}$, the initial density $n = 5 \times 10^{19}\,{\rm m}^{-3}$, and the initial magnetic field $B_{\rm w0} = 0.3\,{\rm T}$. On the assumption that the compression magnetic field waveform is $B_{\rm w} = B_{\rm max}\sin[2\pi t/(4t_{\rm rise})]$, a quarter of the sinusoidal variation cycle 5000 μs is used as rising characteristic time $t_{\rm rise}$ of the magnetic field, $B_{\rm max}$ for primary magnetic compression field can reach a maximum of 12 T (B_1 in Fig. 1 is set to 12 T) from 0.3 T, and other parameters are listed in Table 1. The evolution of the FRC plasma temperature and density with the compression magnetic field is gained (see Fig. 2), including ideal adiabatic compression and quasi-adiabatic compression processes. At the initial stage of compression, the

results with energy loss are with little difference from the ideal adiabatic model. As the energy confinement time decreases in inverse proportion to the magnetic field, the ion temperature is lower than that of the adiabatic model (57 keV), but its value is still above 51 keV, and DD fusion reaction can still be realized, which preliminarily shows the possibility of magnetic compression application in the DD pulse fusion device.

Table 1. Key plasma parameters of the DD pulse fusion device.

Parameter	Before compression	After compression
$B_{\rm w}$	0.3 T	12 T
n	5.0×10^{19} m^{-3}	4.1×10^{21} m^{-3}
$T_{\rm i}$	3 keV	51.2 keV
$T_{\rm e}$	1.5 keV	25.6 keV
S/κ	0.66	3.5
$R_{\rm s}$	0.55 m	0.16 m
L	21 m	3 m
1st-stage time	5 ms	
2nd-stage time	60–100 ms	

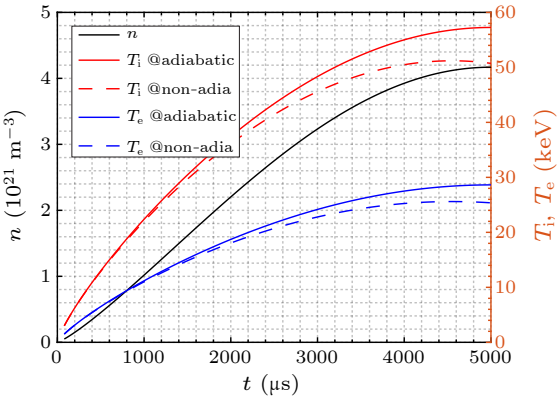

Fig. 2. Evolutions of the FRC plasma temperature and density with the compression magnetic field.

As a DD pulse fusion device, it is very important to maintain high performance plasma for a certain time to achieve longer fusion reaction. Compared with conventional magnetic compression, the proposed device will supplement the corresponding flux loss by the second-stage magnetic compression process after the adiabatic magnetic compression stage is completed. Confining flux is the main way to maintain the configuration of FRC plasma, and the current diffusion is an important cause of flux loss. C-2 series device experiments show that the current carried by high-energy ions plays an important role in stability.[8] The Spitzer resistance of ions can be used to estimate the corresponding current diffusion time:[9] $\tau_\eta = \mu_0\sigma_\perp(R_{\rm s}/2)^2 \sim 1.25$ s, where $\sigma_\perp$ is the resistance of plasma perpendicular to the magnetic field line. The characteristic length is $R_{\rm s}/2$. Considering that the flux attenuates in an exponential form, then the change of the flux Ψ with time can be expressed as $\Psi = \Psi_0 e^{-t/\tau_\eta}$, where Ψ_0 is the flux captured by the plasma at the end of first-stage compression. After 60–100 ms, the flux in the plasma changes to 95.35% and 92.3% of Ψ_0, which means that the flux loss is expected to be less than 10%. If the magnetic field still increases slowly and proportionally during the corresponding time (assuming that the magnetic field increases by 15%, that is, $B_2 = 1.15\times B_1 = 13.8$ T), the current induced by slow magnetic compression can well compensate the flux loss caused by current diffusion and maintain the stability of plasma flux.

Energy loss is another problem for fusion devices. Since compression pushes the plasma away from the wall of vacuum chamber, the increased vacuum gap reduces the radial energy conduction loss. Therefore, plasma bremsstrahlung radiation will be the main channel of plasma energy loss. Bremsstrahlung radiation loss can be expressed as[9] $P_{\rm brem} = 1.54\times10^{-38} n_{\rm e}^2\sqrt{kT_{\rm e}}Z_{\rm eff}^2$ W·m^{-3}, where $n_{\rm e}$ is electron density, k is Boltzmann's constant, $Z_{\rm eff}$ is the effective charge number of the plasma. Considering that the plasma temperature after compression is about 50 keV and $Z_{\rm eff}$ of the C-2W device is 1.2,[10] the $P_{\rm brem}$ can be estimated to be about 11.9 MW. Although the effective charge number $Z_{\rm eff}$ will increase slightly with the generation of fusion products in the second-stage magnetic compression process, it only increases by 1% according to the calculation results. In addition, the high magnetic field will also enhance the electron cyclotron radiation, and its radiation power density is $P_{\rm cyc} = (e^4/3\pi\varepsilon_0 m_{\rm e}^3 c^3)B^2 n_{\rm e}T_{\rm e}$ W·m^{-3}.[9] Multiplied by the plasma volume, $P_{\rm cyc}$ can be estimated to be about 217 MW, but in consideration of the optical thickness of the plasma, the final electron cyclotron radiation power is about 10^{-2}–10^{-3} of the calculation result,[9] meaning that $P_{\rm cyc}$ is about 2.2 MW. At the same time, the self-heating effect of DD fusion reaction will gradually show up. The primary reaction of DD fusion will produce fusion power of 17.5 MW. It is possible to compensate the corresponding power loss and to keep the plasma temperature relatively stable, although the high-energy particles will slow down. Furthermore, compression also reduces the wall backflow, and further reduces the $Z_{\rm eff}$ of the device and the corresponding radiation loss, which is also an advantage of magnetic compression devices.

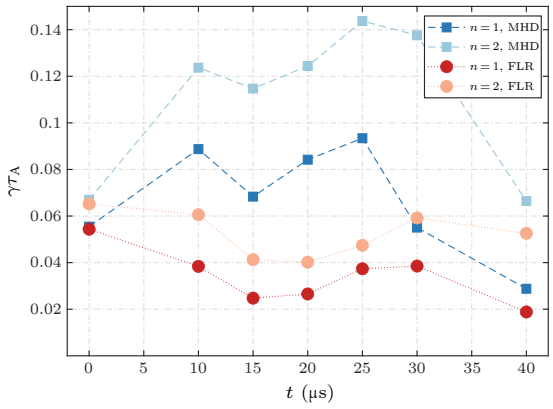

Fig. 3. The FLR effect on the growth rates of the sequence of FRC configurations obtained from magnetic compression at different times.

Like all other magnetic confinement fusion devices, the FRC is subject to the influence of macroscopic instabilities. For an FRC plasma, the tilt ($n = 1$, n is the toroidal mode number) and the rotation ($n = 2$) modes are the most dominant magnetohydrodynamics (MHD) instabili-

ties. Due to the reversal of the magnetic field in the FRC plasma, a wide presence of weak and even null magnetic fields exists. The finite Larmor radius (FLR) effects of the thermal and the energetic ions cannot be ignored. Linear NIMROD calculations show that the FLR effects can significantly reduce the growth rates of the $n = 1$ and $n = 2$ modes of the FRC configurations obtained from the axisymmetric 3D MHD simulations on the magnetic compression of FRC at different times (Fig. 3).[11]

Furthermore, if the kinetic effects of thermal ions and externally injected fast particles are fully considered in the hybrid kinetic MHD model, the FLR effects of thermal ions and fast particles are expected to completely suppress the primary MHD instabilities in the FRC. The C-2 experiments have reported the experimental evidence of suppressing the MHD instability using neutral beam injection, which has also been confirmed in NIMROD simulations.[12] This suggests that instability is not an insurmountable problem in field anti-plasmas.

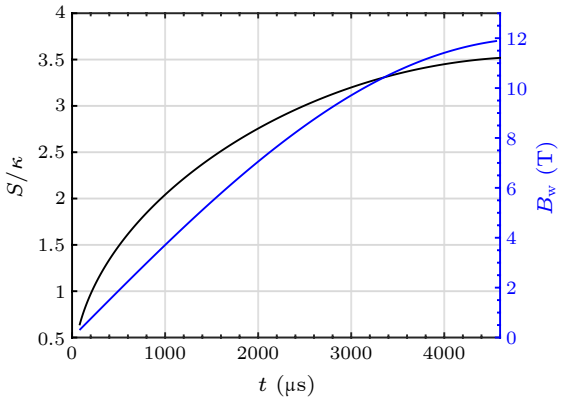

Fig. 4. FRC in the first-stage of magnetic compression S/κ and compression magnetic field B_w versus time.

Based on current experimental studies and taking the kinetic effect correction into account, the empirical criterion for the stability of FRC operation is typically obtained as $S/\kappa < 3.5$, where κ is the ratio of the axial dimension to the radial dimension of the FRC separatrix surface, which is the elongation of the separatrix surface, and S is the ratio of the radius R_s of the separatrix surface to the ion skin depth: $S = R_s/\delta_i$.[13] If the magnetic compression process is slow enough, which means that the compression characteristic time is much longer than the equilibrium relaxation time of the FRC plasma, the process can be considered to be approximately quasistatic. The parameter conditions satisfying the empirical criterion are given. Plasma parameters before compression are listed in Table 1. The initial plasma length $L_i = 21$ m, which is increased in comparison to the C-2W with elongation ratio around 38. Although the elongation is slightly beyond the experimental range[14] of the early simple FRC plasma ratio ($\kappa = 3$–30), it is still within the reasonable range considering the advances in FRC plasma control technology. Calculation result shows that S/κ gradually increases with the compression magnetic field and reaches 3.5 when the first-stage magnetic compression is near the end, as shown in Fig. 4. According to the above analysis, the FRC plasma is in the MHD stability region during the magnetic compression process when the quasistatic approximation is satisfied.

In the following we consider the possibility of this device as a deuterium–deuterium (DD) pulse fusion neutron source. Fusion neutrons, due to their high energy, will cause not only more atomic dislocation damage but also transmutation reaction in the fusion reactor materials, which will seriously affect the key properties of fusion reactor materials. Therefore, the design and construction of fusion neutron source can truly demonstrate the characteristics of fusion materials under fusion neutron irradiation, which can provide an essential prerequisite for the construction of fusion reactor. Currently, the international fusion materials irradiation facility (IFMIF) has been constructed in the European Union and Japan by accelerating deuteron to collide with lithium target with the beam intensity of 250 mA. Due to its wide neutrons power spectrum between 14 MeV and 40 MeV, it will affect the actual fusion neutron irradiation to the material, and at the same time, the device cannot simulate the real plasma environment faced by the fusion reaction.[15]

Regarding to the DD fusion reaction, its secondary reactions and the related nuclear reaction rate,[10] the DD neutron flux is $0.5k_{DD}n_Dn_DV/S$ and the deuterium–tritium (DT) neutron flux is $k_{DT}n_Dn_TV/S$, where k_{DD} and k_{DT} represent the reaction rates of the DD fusion reaction and its secondary DT reaction, respectively; n_D and n_T are the density of deuterium and tritium, V is the plasma volume, and S is the surface area of plasma. In this device, considering the plasma parameters after the plasma compression in Table 1, the average pulse neutron flux at the plasma boundary $1.05 \times R_s$ after 60 ms can be obtained. The density is 4.3 MW/m^2 (including 2.45 MeV DD neutrons and 14.1 MeV DT neutrons), and its average neutron flux density is about 2.15 MW/m^2 under the condition of 50% duty cycle, meeting the fusion demonstration reactor (named as DEMO) test requirements.

In addition to being a pulsed neutron source, this device can also play an important role in the exploration of DD fusion energy, the ultimate energy source for human beings, because it expectantly achieves higher plasma parameters. Compared with neutron source, energy devices have strict requirements on net energy output. The main working mode of the magnetic compression deuterium–deuterium fusion device is pulsed, not steady-state output, so it is not required that the plasma can be burned in a steady state, but the magnetic compression heats the plasma to fusion conditions in each pulse and produce fusion energy. Net energy output can be achieved as long as the energy loss due to the fact that magnetic compression is less than the fusion energy produced in each pulse.

In the magnetic compression, a part of the total energy input W_{ex} will be converted into the reactant thermal energy W_p, and the conversion efficiency is $k_{ex,p}$. For the pulse operation mode, the reactant thermal energy (fusion reaction, particle, radiation, etc.) is absorbed by blankets after each pulse, and can be partially recovered, assuming the recovery coefficient as k^p_{rec}. Another part of W_{ex} is converted to energy that does not efficiently heat the reactants $W_M = W_{ex} - W_p$. This part of energy includes the ohmic heat consumed by the magnetic compression power supply

system and the coils, and also the total magnetic energy filled in the vacuum region outside the plasma. After magnetic compression, the vacuum region will occupy most of the device space and will be filled with strong magnetic fields, making the total magnetic energy very large. From the perspective of heating the plasma, this part of the magnetic energy is useless, resulting in extremely low energy efficiency. Then, from the perspective of energy storage, this part of magnetic energy does not disappear, but is stored in the magnet coil, which can be recovered through inverter technology, and the energy recovery efficiency of this part is $k_{\mathrm{rec}}^{\mathrm{M}}$. Fusion energy is produced when the reactant is heated to fusion conditions. Let the fusion energy produced by a single pulse be W_{f}, and the ratio of this energy to the plasma thermal energy be $R_{\mathrm{p,f}} = W_{\mathrm{f}}/W_{\mathrm{p}}$. The fusion energy recovery efficiency is $k_{\mathrm{rec}}^{\mathrm{f}}$. Finally we can reach

$$W_{\mathrm{net}} = \left[k_{\mathrm{rec}}^{\mathrm{f}} R_{\mathrm{p,f}} k_{\mathrm{ex,p}} - \left(1 - k_{\mathrm{rec}}^{\mathrm{M}}\right)\left(1 - k_{\mathrm{ex,p}}\right) - \left(1 - k_{\mathrm{rec}}^{\mathrm{p}}\right) k_{\mathrm{ex,p}}\right] W_{\mathrm{ex}}.$$

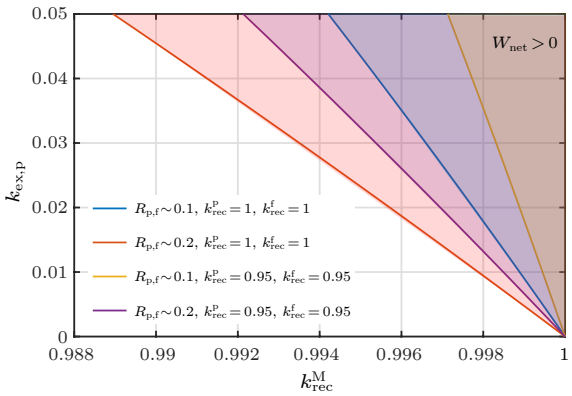

Fig. 5. Parameter space of net energy output under different parameters.

According to the above equation, if $k_{\mathrm{rec}}^{\mathrm{M}}$ and $k_{\mathrm{rec}}^{\mathrm{p}}$ are equal to 1, then there must be a net energy output. Figure 5 shows the relationship between heating efficiency $k_{\mathrm{ex,p}}$ and magnetic field energy recovery efficiency $k_{\mathrm{rec}}^{\mathrm{f}}$ at a certain thermal energy recovery efficiency $k_{\mathrm{rec}}^{\mathrm{p}}$ and fusion energy recovery efficiency $k_{\mathrm{rec}}^{\mathrm{f}}$ when the net output energy is 0, where the typical values of $R_{\mathrm{p,f}}$ are about 0.1 and 0.2, respectively. The upper right of each solid line (shaded area) is the parameter area where the net output energy is greater than zero. The negative slope of each solid line indicates that the requirement of heating efficiency $k_{\mathrm{ex,p}}$ can be reduced by increasing the magnetic field energy recovery efficiency $k_{\mathrm{rec}}^{\mathrm{M}}$. Moreover, with enhanced $R_{\mathrm{p,f}}$, the region with net output energy greater than zero expands (purple line and red line), which indicates the importance of the second-stage magnetic compression. As $k_{\mathrm{rec}}^{\mathrm{p}}$ and $k_{\mathrm{rec}}^{\mathrm{f}}$ increase, the region of net output energy greater than zero (blue and red lines) is also expanded. This design has included a magnetic energy recovery scheme based on medium frequency inverter technology. If high temperature superconducting coil and power topology optimization based on power electronics technology are employed, net fusion energy output is much more promising.

In summary, we have proposed a new fusion device scheme based on FRC plasma for two-stage cascade magnetic compression, which is expected to take advantage of the characteristics of high pressure ratio of FRC plasma and obtain high-temperature and high-density plasma. Preliminary calculations show that this scheme can be used to design DD fusion neutron source. After analyzing the energy balance of the magnetic compression pulse device, it is shown that improving the heating efficiency of the two-stage magnetic compression process will help the device to obtain a net energy output, which reflects the bright prospect of this design in the research of DD fusion energy.

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