FUSION WITH FISSION POWER AMPLIFICATION

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A scheme of a sub-critical system driven by fusion neutrons from a stellarator-mirror device is considered. In addition, a power production scheme which uses fusion power amplification by depleted uranium mantle is discussed.

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1. INTRODUCTION

To sustain fission reactions in a sub-critical system, which is attractive owing to its inherent safety, an external neutron source is required. In a fusion driven system (FDS) energetic neutrons are generated in hot plasma by fusion reactions between deuterium and tritium.

The rather small number of theoretical studies carried out so far on FDS have mainly considered tokamak based FDS [1]. An advantage of a tokamak is the achieved plasma confinement quality, but this scheme has also several disadvantages. One is the lower limit for the output power of a tokamak FDS which impedes an experimental study of that scheme. A second drawback is that the fission mantle surrounds almost the whole plasma column, restricting the access to the plasma. Some discharge sustaining tokamak systems such as radio-frequency (RF) antennas should, therefore, operate inside the reactor active zone with high neutron fluxes that causes technical problems.

In a recently proposed mirror-based FDS [2], which uses sloshing ions for neutron generation, the fission mantle surrounds only a part of the plasma column, nearby the mirror reflecting points of the sloshing ions [2]. This gives a possibility to place the neutral beam injection, plasma diagnostics etc. aside of the reactor active zone. However, for reason of the poor plasma energy confinement the energy efficiency of such a scheme is low and it is positioned in [2] rather as a transmutation than an energy producing device.

The compact DRACON-based neutron source was proposed in [3]. It has a localized neutron output at the mirror part. However, the idea of plasma confinement of the DRACON concept needs to be experimentally tested.

In the present report the ideas presented in [2] and [3] are developed further for a combined stellarator-mirror device. The major points of the report are shortly presented in [4].

An argument for feasibility of a combined stellarator-mirror machine is that mirror parts were present in earlier stellarators of the "racetrack" type, namely Model-C [5] and Uragan [6]. These devices had two straight parts without rotational transform, and there was also an option to lower the magnetic field at the straight parts for magnetic beach heating at the ion cyclotron frequency. The Wendelstein branch of stellarators is also often viewed as a linked mirror concept [7].

2. FUSION-FISSION REACTOR AND COMPUTATION MODEL

The FDS version studied theoretically here (see Fig.1) consists of a stellarator with a small mirror part containing two-ion component plasma. The RF heated hot ion component (tritium) has a highly anisotropic velocity distribution, and is trapped in a magnetic well of the mirror part, where it produces fusion neutrons. The stellarator part, which connects to the mirror parts, is aimed to provide confinement of the electrons and cold plasma ions (deuterium). The neutron generating mirror part in the FDS is surrounded by a sub-critical fission reactor core.

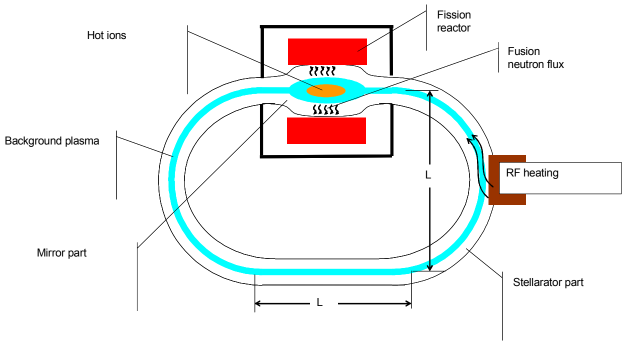

Fig.1. Sketch of fusion driven fission reactor

In the two-component plasma, ion cyclotron resonance heating (ICRH) pumps up the perpendicular minority tritium ion energy. This causes a high anisotropy of the hot ion distribution function. It is assumed that the tritium distribution function is anisotropic Maxwellian with different perpendicular $T_\perp$ and parallel $T_\parallel$ temperatures. In a high temperature regime the distribution function is close to collissionless, which following Jeans theorem must be a function of the motional invariants, i.e. the energy and the magnetic moment. For an anisotropic Maxwellian distribution this means that the perpendicular temperature and particle density decreases with an increasing magnetic field. The reduction rate for both of them equals

$$D = [(R-1)F+1]/R\,, \tag{1}$$

where $R = B_{st}/B_{mir}$ is the mirror ratio, $F = T_\perp/T_\parallel$ is the anisotropy factor. The parallel ion temperature does not vary with the magnetic field. The perpendicular ion pressure, being proportional both to the plasma density and the perpendicular temperature, decreases as D^2. If the anisotropy is high, even for a small mirror ratio hot tritium ions are trapped at the mirror part of the device.

The tritium energy balance is determined by the electron drag. It dominates over the ion-ion collisions since the ratio of perpendicular tritium temperature to the background plasma temperature is high, i.e. $T_\perp / T_{bg} > 100$. The ion-cyclotron heating increases only the perpendicular ion energy. The parallel tritium temperature $T_\parallel$ increases owing to scattering of the hot ions on the background ions, while the electron drag tends to decrease $T_\parallel$. The balance of these two factors determines the value of $T_\parallel$:

$$T_\parallel = 1.5\pi C_{corr} T_e \mathrm{v}_{Te}/\mathrm{v}_{T\perp} , \tag{2}$$

where C_{corr} is a coefficient order of unity and $T_e = T_{bg}$. Equation (2) shows that $T_\parallel$ increases with the electron temperature as $T_e^{3/2}$. Thus, if the background plasma temperature is high enough it is difficult to provide a strongly anisotropic hot ion distribution.

The beta values at the stellarator and open trap parts are limited by the maximum values β_{st} and β_{mir}, where

$$\beta_{st} \approx \frac{8\pi k_B (2n_{bg}T_{bg} + n_{hi}T_\perp / D^2)}{B_0^2} , \tag{3}$$

$$\beta_{mir} \approx \frac{8\pi k_B n_{hi} T_\perp R^2}{B_0^2} . \tag{4}$$

Here $k_B = 1{,}602 \cdot 10^{-12} erg/eV$. The tritium concentration optimized for the neutron production rate is determined by the maximum product of the hot and cold ion concentrations at the mirror part, and corresponds to equal values of the two terms in the brackets in (3). The optimum particle densities at the mirror parts are then

$$n_{bg} = \frac{\beta_{st} B_0^2}{32\pi k_B T_{bg}} , n_{hi} = \frac{\beta_{st} B_0^2 D^2}{16\pi k_B T_\perp} . \tag{5}$$

The corresponding mirror ratio is calculated from formulas (1,3) and (4)

$$R = 1 + (\sqrt{2\beta_{mir} / \beta_{st}} - 1) / F . \tag{6}$$

The RF heating power compensates the power of the electron drag both in the stellarator and mirror parts of the machine

$$P_{RF} \approx P_d = \pi a^2 L < \sigma_{ie}\mathrm{v} > n_e n_i k_B \widetilde{T} , \tag{7}$$

Here a is the minor radius and L is the length of the straight part of the stellarator (see Fig. 1). The electron drag

$$< \sigma_{ie}\mathrm{v} > = C_{\sigma\mathrm{v}} / T_e^{3/2} \tag{8}$$

determines the hot ion energy losses, where

$$C_{\sigma\mathrm{v}} = \frac{4\sqrt{2\pi}}{3} \frac{e^4 \lambda_{Col} \sqrt{m_e}}{m_i k_B^{3/2}} = 1.19 \cdot 10^{-8} cm^3 eV^{3/2} / s ,$$

$$\widetilde{T} = \eta R T_\perp + \frac{\pi + 2 - \eta}{D} (T_\perp / D + T_\parallel / 2) . \tag{9}$$

Here $\eta = L_{mir} / L$ is the ratio of the mirror length to the straight part stellarator length. The power leakage from the stellarator owing to transport losses is

$$P_{tr} = 5 k_B n_{bg} T_{bg} V_{st} / \tau_E , \tag{10}$$

where $V_{st} = \pi(\pi + 2 - \eta + R\eta)(1/2 + 1/\pi)^2 \varepsilon^2 L^3$ is the volume of the device, $\varepsilon = a / R_{tor}$ and R_{tor} is approximated by $R_{tor} = (1/2 + 1/\pi)L$. The energy confinement time is determined by the *ISS04* stellarator scaling [8]

$$\tau_E = C_E a^{2.28} R_{tor}^{0.64} P^{-0.61} n_{bg}^{0.54} B_0^{0.84} \iota^{0.41} . \tag{11}$$

In CGS units $C_E = 3.69 \cdot 10^{-14}$. Equating the electron drag power (7) and the transport power (10), the stellarator size can be found.

The tritium perpendicular temperature $T_\perp$ should be high enough to provide efficient D-T fusion and neutron generation. For its optimization the target function $H = < \sigma_{DT}\mathrm{v} > / T_\perp \propto p_{DT} / p_{RF}$ is introduced, which is proportional to the ratio of fusion to RF heating power densities. It has a maximum at $T_{\perp opt} = 83\, keV$, and its half-value tolerance range

$$30\, keV < T_\perp < 277\, keV \tag{12}$$

is very broad.

3. CALCULATION RESULTS

A constant value $T_\perp / T_{bg} = 150$ has been taken for the ratio of the tritium perpendicular temperature to the background plasma temperature. Following formula (3) the parallel tritium temperature then becomes proportional to the background temperature and the anisotropy factor becomes $F = 5.25$. For higher tritium anisotropy it is difficult to provide equilibrium and stability. We choose $\beta_{st} = 0.02$ and $\beta_{mir} = 0.2$, i.e. $\beta_{mir} \sim 1/F$. For this choice formula (7) gives the mirror ratio $R = 1.66$, and formula (1) provides $D = 2.69$. The hot ion concentration at the mirror part $C_T = n_{hi} / n_{bg}$ does not depend on the perpendicular temperature and we obtain $C_T = 0.097$. The perpendicular ion temperature is varied in the range (12) and the plasma density, heating power, fusion power P_{fus} and device dimensions are calculated. The fission power $P_{fis} = C_m P_{fus}$ is proportional to the fusion power. Since in our scheme the fission reactor part is similar to the one calculated in [2] the power multiplication coefficient is estimated using the result of that paper, i.e. $C_m = 154$. The electric Q-factor (electric efficiency) is estimated as $Q_{el} = C_{RF} C_{ec} P_{fis} / P_{RF}$, where the RF heating efficiency is assumed to be $C_{RF} = 0.7$ and the thermal power conversion efficiency is $C_{ec} = 0.4$. In the calculations the reverse mirror ratio is $\varepsilon = 0.1$.

Calculations results are displayed in the Table bellow. First what should be noticed is the acceptable values of the electric Q-factor indicating that energy production is possible within the chosen reactor scheme. Higher perpendicular ion temperature could be achieved in larger stellarators. The electric efficiency would also be higher in larger machines. The calculation results show that the scenario can also be realized with a small device. The efficiency is lower, but a net electric energy output is achievable. An increase of the magnetic field strength decreases the machine size, but has almost no influence on the power output for the optimum device. By varying the magnetic field it would be possible to fit the size of the stellarator-mirror part to the fission mantle size.

FDS parameters for a proof-of-principle device (scenario 1) and reactor (scenario 2)

Parameter	Scenario 1	Scenario 2
Perpendicular tritium temperature	99 keV	276 keV
Background plasma temperature	0.67 keV	1.8 keV
Stellarator magnetic field	3 T	4 T
Plasma density	1.7×10^{14} cm^{-3}	1.1×10^{14} cm^{-3}
RF power	17 MW	92 MW
Neutron generation at mirror part	3.7×10^{17} neutrons/s	4.8×10^{18} neutrons/s
Fission power	129 MW	1.7 GW
Plasma minor radius	17 cm	50 cm
Torus major radius	170 cm	500 cm
Mirror length	150cm	430 cm
Electric efficiency	2.1	5.1

4. ENERGY AMPLIFICATION IN U^{238} MANTLE

An additional possibility pointed out in [9] arises if the fusion plasma is surrounded by a fission mantle consisting in depleted uranium. The fusion neutrons cause fission of U^{238}, but they do not initiate a chain reaction because the secondary neutrons do not have enough energy to make further fission of U^{238}. The energy gain in a fission reaction exceeds the energy of fusion by more than 10 times. However, this gain cannot be obtained fully because of neutron particle and neutron energy losses in competing nuclear reactions. Depleted uranium is a good neutron reflector. Therefore, to achieve a necessary fusion neutron concentration inside the mantle, it should cover most of the surface of the plasma column.

The comparatively low energy amplification with U^{238} mantle makes this scheme possible only for large devices: the size of the plasma device (tokamak, stellarator or mirror) needs to be close to the size of a fusion reactor.

Fission reaction results in additional neutrons. These extra neutrons could be used for tritium reproduction by fission of the lithium.

CONCLUSIONS

The combination of a stellarator and a mirror is beneficial to localize the fusion neutron outflux to the mirror part of the device surrounded by a fission mantle. This facilitates the design and operation of all plasma systems which can be placed aside the region of the high neutron flux. The calculations predict that the scheme is highly efficient in the reactor version despite that the fusion part has a smaller dimension than a fusion reactor. Besides the commercial potential, a practical usage of such a power plant would contribute to the knowledge of fusion plasma handling. A small proof-of-principle device may even have a net power output.

Energy amplification in a U^{238} mantle is another prospective option for a fusion-fission reactor.

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ТЕРМОЯДЕРНЫЙ СИНТЕЗ С УСИЛЕНИЕМ МОЩНОСТИ ЗА СЧЕТ РЕАКЦИЙ ДЕЛЕНИЯ

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Рассмотрена схема подкритической сборки, управляемая термоядерными нейтронами, рожденными в плазме ловушки на основе комбинации стелларатора и пробкотрона. Кроме того, обсуждается схема усиления термоядерной мощности с помощью бланкета из обедненного урана.

ТЕРМОЯДЕРНИЙ СИНТЕЗ З ПІДСИЛЕННЯМ ПОТУЖНОСТІ ЗА РАХУНОК РЕАКЦІЙ ПОДІЛУ

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Розглянуто схему підкритичної збірки, яка керується термоядерними нейтронами, що народжені в плазмі пастки на основі комбінації стеларатора та пробкотрона. Окрім того, обговорюється схема підсилення термоядерної потужності за допомогою бланкету із збіднілого урану.