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STELLARATOR-MIRROR BASED DRIVEN FUSION-FISSION REACTOR

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A sub-critical fast fission reactor which is attractive owing to its inherent safety needs an external neutron source. In a fusion driven system (FDS) the driving neutrons are generated in hot plasma by fusion reaction between deuterium and tritium. A rather limited number of theoretical studies carried out so far on FDS have mainly considered tokamak based FDS [1]. This scheme has several disadvantages among which two should be remarked. The first one is the high lower bound on power of a tokamak FDS, and the scheme could not be made in small scale for scientific and technical research. Another one comes from the fact that the fission mantle surrounds the whole plasma column. Therefore, certain discharge sustaining tokamak systems such as radio-frequency (RF) antennas should operate inside the reactor active zone, which creates serious 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 the reason of the poor plasma energy confinement the energy efficiency of such a scheme is low and it is positioned in [2] more a transmutation than an energy producing device. The compact DRACON-based neutron source was proposed in [3]. It has localized neutron output at the mirror part. However, the idea of plasma confinement in DRACON was not sufficiently studied experimentally. In the present report the ideas presented in [2] and [3] are developed further for a combined stellarator-mirror device.

The version of FDS theoretically investigated in the present report consists of a stellarator with a small mirror part containing two-ion component plasma. The RF heated hot ion component (tritium) having highly anisotropic velocity distribution with high perpendicular energy is trapped in a magnetic well of the mirror part, where fusion neutrons are generated. The stellarator part, which connects to the mirror parts, is aimed to provide confinement of the cold plasma ion component (regularly deuterium). The neutron producing mirror part in the FDS is surrounded by a mantle of fission materials in which the fusion neutrons initiate fission of the nuclear fuel with a successive neutron multiplication.

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

$$D = [(R-1)F + 1]/R \qquad (1)$$

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, while the ion pressure decreases as D^2. Thus, even for small mirror ratios highly anisotropic ions are trapped in the mirror part of the device and their pressure is low at the stellarator part.

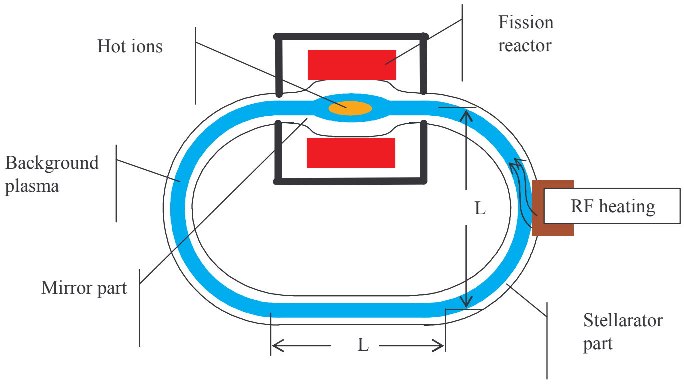

Fig.1 Sketch of FDS scheme

The energy balance of hot ions is determined by the electron drag. It dominates over the ion-ion collisions since the ratio of perpendicular hot ion temperature to the background plasma temperature is high, i.e. $T_\perp / T_{bg} > 100$. The ion-cyclotron heating increases the perpendicular hot ion energy. The parallel temperature appears for the reason of scattering of hot ions by the background ions. Electron drag tends to decrease $T_\parallel$ and the balance of this two factors allows one to find the value of $T_\parallel$. The parallel energy balance can be written as

$$n_{hi} m \mathrm{v}_{T\parallel}^2 / 2(\nu_{ii}^{\perp\parallel} - \nu_{ie}^{\parallel\parallel}) = 0 \,, \qquad (2)$$

where n_{hi} is the hot ion density in the mirror part, ν denotes collision frequencies and v_T is the thermal velocity. From (2) we obtain the expression for parallel temperature

$$T_\parallel = 1.5\pi C_{corr} T_e \mathrm{v}_{Te}/\mathrm{v}_{T\perp} \qquad (3)$$

where C_{corr} is the coefficient which value is close to unity and $T_e = T_{bg}$. $T_\parallel$ increases with the electron temperature as $T_e^{3/2}$. When the background plasma temperature is high it is difficult to provide a strongly anisotropic hot ion distribution.

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

$$\beta_{st} \approx \frac{8\pi k_B (2n_{bg}T_{bg} + n_{hi}T_\perp / D^2)}{B_0^2},\ \beta_{mir} \approx \frac{8\pi k_B n_{hi} T_\perp R^2}{B_0^2}\ . \qquad (4)$$

Here $k_B = 1{,}602 \cdot 10^{-12} erg / eV$. The optimum of the hot ion concentration, which is determined by the maximum of the product of hot and cold ion concentrations at the mirror part, corresponds to the equal values of two operands in the brackets in (4). Thus the maximum particle densities at the mirror parts are

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

The optimum mirror ratio is calculated from formulas (4)

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

The RF heating power is mainly the power required to balance the electron drag both in the stellarator and mirror parts, i.e. $P_{RF} \approx P_d = \pi a^2 L < \sigma_{ie} \mathrm{v} > n_e n_i k_B \widetilde{T}$, (7)

Here a is the minor radius and L is the length of straight part of the stellarator. The confinement of ions trapped in the mirror part is assumed to be sufficient. The electron drag rate is $< \sigma_{ie} \mathrm{v} >= C_{\sigma\mathrm{v}} / T_e^{3/2}$ (8)

where $C_{\sigma\mathrm{v}} = \frac{4\sqrt{2\pi}}{3} \frac{e^4 \lambda_{Col} \sqrt{m_e}}{m_i k_B^{3/2}} = 1.19 \cdot 10^{-8} cm^3 eV^{3/2} / s$, $\widetilde{T} = \eta R T_\perp + \frac{\pi + 2 - \eta}{D}(T_\perp / D + T_\parallel / 2)$.

Here $\eta = L_{mir} / L$ is the ratio of the mirror part length to the straight stellarator part length. The power leakage from the stellarator is $P_{tr} = 5 k_B n_{bg} T_{bg} V_{st} / \tau_E$ (9)

where $V_{st} = \pi(\pi + 2 - \eta + R\eta)(1/2 + 1/\pi)^2 \varepsilon^2 L^3$ is the volume of the stellarator part $\varepsilon = a / R_{tor}$ and R_{tor} is suggested to be $R_{tor} = (1/2 + 1/\pi) L$. The energy confinement time is determined by the *ISS04* scaling $\tau_E = C_E a^{2.28} R_{tor}^{0.64} P^{-0.61} n_{bg}^{0.54} B_0^{0.84} ι^{0.41}$ (10)

In CGS units $C_E = 3.69 \cdot 10^{-14}$. Equating electron drag power (7) and the transport power (9), for given reverse aspect ratio ε one can find the dimensions of the stellarator

$$L^{1.09} = \frac{(5\pi)^{0.61} [(\pi + 2 - \eta + R\eta)]}{C_E (1/2 + 1/\pi)^{1.7} \varepsilon^{1.06}} \frac{(k_{BSI} T_e)^{0.61}}{< \sigma\mathrm{v} >^{0.39} n_e^{0,32} B_0^{0.84} ι^{0.41}} \left(T_\perp / \widetilde{T}\right)^{0.39} \frac{1}{D^{0.78}} \qquad (11)$$

The calculations show that with increase of device scale the optimum perpendicular hot ion temperature increases, but the anisotropy factor F decreases for the reason of increase of background plasma temperature. Because of strong isotropization of the hot ion distribution, it is hard to provide hot ion trapping in the mirror part when $T_{bg} > 2\text{keV}$. Increase of the perpendicular temperature increases trapping, but this also increase neutron generation in the stellarator part of the device. The minority concentration at the mirror part of the device is about 10% in different regimes. The optimum mirror ratio does not exceed 1.8 in the variety of scenarios studied. In table 1 the calculation results for two selected scenarios are given. The first scenario is for a proof-of-principle experiment while the second one is related to a power producing station.

Table 1.

Parameter	Scenario 1	Scenario 2
Stellarator beta β_{st}	0.02	0.02
Mirror beta β_{mir}	0.2	0.2
Perpendicular tritium temperature $T_{\perp}$	100 keV	250 keV
Background plasma temperature T_{bg}	0.5 keV	1.5 keV
Stellarator part magnetic field B_0	2.5 T	4 T
Mirror ratio R	1.43	1.6
Aspect ratio ε^{-1}	10	10
Plasma density n_{bg}	1.6×10^{14}cm^{-3}	1.4×10^{14}cm^{-3}
Minority concentration (in mirror part)	0.098	0.1
RF power P_{RF}	10 MW	63 MW
Neutron generation at mirror part	1.5×10^{17} neutron/s	2.7×10^{18} neutron/s
Fission power*	94 MW	1.7 GW
Tritium anisotropy factor F	8.8	6.2
Plasma minor radius a	15 cm	36 cm
Torus major radius R_{tor}	150 cm	360 cm
Mirror length ηL	125 cm	310 cm
Electric efficiency $Q = P_{el}^{out} / P_{el}^{RF}$	2.4	6.7

*Calculation assumes that fission output is 3.8 GeV for each fusion neutron [2].

The calculation results are promising for the chosen scheme of FDS. It is highly efficient in the reactor version. Even in a small scale of proof-of-principle device the calculation predicts a positive power output.

References

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