COMBINED STRAIGHT FIELD LINE MIRROR-MULTI-MIRROR FUSION DRIVEN SYSTEM

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An advantage of a mirror system as a fusion neutron source for a sub-critical fast fission assembly is its simplicity. In contrast to tokamak, plasma sustaining systems and diagnostics could be located apart from the neutron rich region [1]. However, the major drawback of a mirror device is poor energy confinement which results in a low efficiency in energy production. The calculations in [1] show that the efficiency of electricity production, the ratio of produced and consumed electric power, $Q_{el} = P_{gen,el} / P_{cons,el} \sim 1$, is marginal for a single cell GDT type mirror hybrid reactor. For commercial energy production this quantity should be increased at least three times. The purpose here is to investigate if this could be solved by a proper choice of neutron generation scenario and by improvement of the plasma confinement.

The mostly theoretically studied neutron generation scenario consists in formation of a dense mirror confined hot deuterium-tritium sloshing ion population in warm background plasma. Neutrons are generated in D-T fusion collisions. Warm background plasma serves as a stabilizer for kinetic loss-cone instabilities. Its density should be as small as possible. Another scenario is to have only one hot sloshing fusing isotope [2-4] (T or D) in the background plasma formed by the other isotope (D or T). A specific feature of this approach is the very high density of the background plasma in which the background ion mean free path is short. This situation can be used to improve the plasma energy confinement by attaching multi-mirror chains to the main mirror ends.

The hot ion energy is much higher than the background plasma thermal energy. In such situations, the electron drag is responsible for the hot ion energy balance and for the anisotropic velocity distribution formation. The hot ion temperature anisotropy is [4]

$$F = T_{\perp} / T_{\parallel} = \frac{4}{3\pi} \sqrt{m_e / m_i} (T_{\perp} / T_{bg})^{3/2} \qquad (1)$$

where m_e and m_i are the electron and hot ion masses, $T_{\perp}$, $T_{\parallel}$ and T_{bg} are perpendicular, parallel hot ion and background plasma temperatures. For the reason of smallness of electron-ion mass ratio, the anisotropy of hot ion distribution is not high, but still enough for hot ions to be confined in the straight field line mirror [5] central cell even with a relatively small mirror ratio [4] $R \approx 1.5$.

The energy balance is the following: Radio-frequency (RF) heating transfers power to the hot ions sustaining them in a hot anisotropic state. The hot ions transmit energy to the cold electrons via Coulomb collisions. Finally the energy leaks out though the mirror ends with cold plasma outflow.

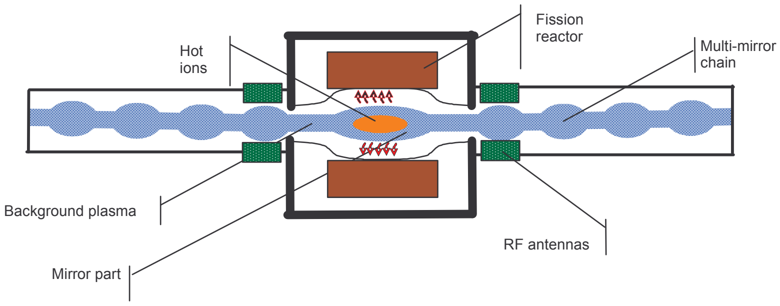

Fig.1 Sketch of the sub-critical reactor.

The sub-critical nuclear reactor core responds linearly on the fusion neutron flux: The fission power $P_{fis} = C_m P_{fus}$ is proportional to the fusion power. The energy multiplication coefficient is of the order of one hundred [4] for a reactor with neutron multiplication factor $k_{eff} \approx 0.95$. For these calculations it is chosen as $C_m = 120$.

The electric Q-factor is estimated as

$$Q_{el} = C_{RF} C_{ec} P_{fis} / P_{RF}, \qquad (2)$$

where the RF heating efficiency is assumed to be $C_{RF} = 0.625$ and the thermal power conversion efficiency is $C_{ec} = 0.4$. The RF heating power compensates the power of the electron drag in the central mirror cell

$$P_{RF} \approx P_d = <\sigma v>_{ie} n_{bg} k_B n_i T_\perp (1 + 1/F) V, \qquad (3)$$

where k_B is the Boltzman constant, n_i and n_{bg} are hot ion and background plasma densities, $<\sigma v>_{ie}$ is the ion-electron collision rate, V is the volume occupied by the hot ions. The fusion power is

$$P_{fus} = <\sigma v>_{fus} n_{bg} k_B n_i E_{fus} V, \qquad (4)$$

where $<\sigma v>_{fus}$ is the fusion collision rate, $E_{fus} = 14.1\, MeV$ is the fusion neutron energy. With usage of the formulas (3) and (4) the electric Q-factor becomes

$$Q_{el} = C_{RF} C_{ec} C_m \frac{<\sigma v>_{fus} E_{fus}}{<\sigma v>_{ie} T_\perp} \frac{F}{F+1}. \qquad (5)$$

The expression for electron-ion collision rate is

$$<\sigma v>_{ie} = \frac{16\sqrt{\pi}}{3} \frac{e^4 \lambda_{Col}}{m_i m_e \mathrm{v}_{Te}^3} = C_{ie0} A_{hi}^{-1} T_e^{-3/2} \qquad (6)$$

with $C_{ie0} = \frac{4\sqrt{2\pi}}{3} \frac{e^4 \lambda_{Col} \sqrt{m_e}}{m_p k_B^{3/2}} = 2.38 \cdot 10^{-8} cm^3 eV^{3/2} / s$ and $A_{hi} = m_i / m_p$ is the hot ion and proton mass ratio. The ratio $C_{fus} = <\sigma v>_{fus} / T_\perp$ is approximately $C_{fus} / A_{hi} \approx 5 \cdot 10^{-21}$ cm^{3}c^{-1}eV^{-1} for a wide range of $T_\perp$. Formula (5) then reads

$$Q_{el} = \frac{C_{RF} C_{ec} C_m C_{fus} E_{fus}}{C_{ie0}} \frac{F}{F+1} T_e^{3/2} \tag{7}$$

Assuming F=4 for the hot ion anisotropy and with the above specified values of power efficiencies formula (7) becomes

$$Q_{el} = 2.2 \cdot 10^{-4} T_e^{3/2} . \tag{8}$$

The electric Q-factor depends strongly on the electron temperature and turns out to be higher than unity starting from $T_e = 270$ eV .

To find the electron temperature, we equate electron drag power and the energy end losses. For end losses Mirnov and Ryutov [6] have evaluated the expression

$$q_i = C_q \, n_{bg} \mathrm{v}_{Ti} \tag{9}$$

with $C_q = 0.66$ and $\mathrm{v}_{Ti} = \sqrt{2T_{bg} / m_{bgi}}$. The corresponding energy flux is

$$Q_{fl} = C_{fl} q_i T_{bg} , \tag{10}$$

where $C_{fl} = [4 + 1/2 \ln(m_i / m_e)] \approx 8.1$. Thus the heat outflow rate is

$$P_{tr} = 2C_q C_{fl} k_B n_{bg} T_{bg}^{3/2} \sqrt{2k_B / m_{bgi}} S / R , \tag{11}$$

where $S = V / L$ is the plasma average cross-section, L is the central cell length. The electron drag power (3) can be written as

$$P_d = \frac{C_{ie}}{T_e^{3/2}} n_{bg} (1 + 1/F) \frac{\beta_{hi} B_0^2}{4\pi} SL , \tag{12}$$

where β_{hi} is the hot ion beta, B_0 is the magnetic field at the midplane. From the power balance the electron temperature is calculated

$$T_{bg}^3 = \frac{C_{ie0} \sqrt{m_p}}{8\pi \sqrt{2} C_q C_{fl} k_B^{3/2}} \frac{\sqrt{A_{bg}}}{A_{hi}} \beta_{hi} R B_0^2 L (1 + 1/F) \tag{13}$$

with account of $m_{bgi} = A_{bg} m_p$. With the above specified temperature the electric efficiency is

$$Q_{el} = \frac{C_{RF} C_{ec} C_m C_{fus} E_{fus}}{2^{7/4} \pi^{1/2} C_{ie0}^{1/2} C_q^{1/2} C_{fl}^{1/2}} \frac{m_p^{1/4}}{k_B^{3/4}} \sqrt{\frac{F}{F+1}} \frac{A_{bg}^{1/4}}{A_{hi}^{1/2}} \beta_{hi}^{1/2} R^{1/2} B_0 L^{1/2} . \tag{14}$$

There are very few handles in the scheme chosen to improve the efficiency: magnetic field strength and the central cell length could not be chosen huge. If the confinement would be improved and the energy outflow would be decreased in α times, then, following (13), the electric Q-factor will increase in $\alpha^{1/2}$ times. The confinement could be improved with two multi-mirror sleeves attached to the central straight field line central cell [5] from both ends. The average force balance along the mirror axis reads

$$2 \frac{d}{dz} n_{bg} T_{bg} = -m_{bgi} < \sigma v >_{ii} n_{bgtr} q_i . \tag{15}$$

In the left-hand side is the gradient of the total pressure and the right side represents the passing-trapped ion friction. Since trapped particle density is proportional to the background plasma density $n_{bgtr} = C_{tr} n_{bg}$ and the temperature is almost constant, the solution of equation (15) is

$$n(z) = n_{bg} \exp\left[-\frac{C_q C_{tr} n_{bg} < \sigma v >_{ii}}{\alpha v_{Ti}} (L/2 + z) \right]. \quad (16)$$

Formula (16) allows one to calculate a multi-mirror sleeve length for given confinement improvement α

$$L_{mm} = \frac{v_{Ti}}{C_q C_{tr} n_{bg} < \sigma v >_{ii}} \alpha \ln \alpha . \quad (17)$$

Table 1. Parameters of sub-critical reactor with multi-mirror enhancement of confinement (α=6). Numbers in brackets correspond to the case of absence of enhancement.

Parameter	Value
Hot ion beta β_{hi}	0.15
Background plasma beta β_{bg}	0.2
Perpendicular deuterium temperature $T_{\perp}$	45 keV
Background plasma temperature T_{bg}	570 (310) eV
Magnetic field in central plane B_0	4 T
Mirror ratio R	1.5
Plasma density n_{bg}	1.4×10^{16}cm^{-3}
Minority concentration (in mirror part)	0.01
Electric power	1 GW
Plasma average radius a	2.3 cm
Mirror length L	10 m
Multi-mirror sleeve length L_{mm}	30 m
Electric efficiency Q_{el}	3 (1.2)

Results with the above formulas of parameters of a sub-critical reactor with multi-mirror enhancement of confinement is given in Table 1. Q_{el} is increased from a marginal value 1.2 to 3. New Q_{el} value is acceptable for a power plant. A cost is the attachment of two 30 m multi-mirror sleeves that increase the device dimensions. The extrapolation of GOL-3 experiments [7] would give a shorter device. RF heating is hardened with a very high plasma density and small plasma radius together with a small minority concentration. To avoid a too high neutron flux, the first wall radius has to be much larger than the plasma radius. The small plasma radius (2.3 cm) is comparable with GOL-3 experiments.

References

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