

## Plasma Conditions of Mirror Based Volumetric Neutron Source (FEF-II)

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### 1 Introduction

The importance and necessity of the intense 14MeV neutron sources for development of the fusion reactor materials and also for fusion nuclear engineering has been recognized by the fusion community. The mirror machine is a strong candidate for the plasma based neutron source. The conceptual design studies of mirror based plasma neutron source with the name of FEF have been carried out since 1981 [1][2], and recently, FEF-II (up-grated version of FEF) design studies have been started. FEF-II is two-component plasma system (the target plasma and fast ion of the sloshing ions), and has multi-pole field (Version 1) or RF plugged cusp (Version 2) for MHD stability. Configuration of magnetic field is formed basically by long solenoid with mirror field at both end. In the earlier papers[3], we reported the condition of the parameters of the neutron source for the preliminary irradiation test ( $\sim 0.1\text{MW}/\text{m}^2$ ) by use of the Fokker-Planck simulation. The data on irradiation tests by the full scale volumetric neutron source (VNS) is required to design the DEMO fusion reactor. In the present paper, we study the optimal condition for the VNS which is required the neutron flux  $2\text{MW}/\text{m}^2$ . The simulation code has been formed by combination of the Fokker-Planck equation for the sloshing ions and the rate equations for the plasma parameters of the target plasma[4].

### 2 Plasma Model

We consider the two component plasma system (target plasma and sloshing ions). We assume that the target plasma which consist of electrons and the nuclei of deuterium and tritium and the sloshing ion is deuterium. We also assume that the target plasma is isotropic and Maxwellian. The distribution function of the sloshing ions is calculated by the Fokker-Planck equation[5],

$$\frac{\partial f}{\partial t} = \frac{1}{v^2} \frac{\partial}{\partial v} \left[ v^2 \left( Af + D_{\parallel} \frac{\partial f}{\partial v} \right) \right] + \frac{1}{v^2} D_{\perp} \frac{\partial}{\partial \zeta} \left[ (1 - \zeta^2) \frac{\partial f}{\partial \zeta} \right] - \frac{f}{\tau_{\text{cx}}} + S \quad (1)$$

where  $f$  is the distribution function of the sloshing ions,  $\tau_{\text{cx}}$  is the charge-exchange loss time,  $\zeta$  is the cosine of the pitch angle. The Fokker-Planck coefficient  $A$ ,  $D_{\parallel}$  and

$D_{\perp}$  represent the slowing down, the energy diffusion and the pitch angle scattering, respectively. The production term  $S$  is represented as

$$S = \frac{I}{4\pi^2 e \Delta v v_0^2 \Delta \zeta V} \exp \left[ - \left( \frac{v - v_0}{\Delta v} \right)^2 - \left( \frac{\zeta - \zeta_0}{\Delta \zeta} \right)^2 \right] \quad (2)$$

where  $I$  is NBI trapped current,  $V$  is the plasma volume,  $v_0$  is the velocity of injected particle and  $\zeta_0$  is the cosine of injection angle. The particle and energy balance equations for target plasma are expressed as follows[6]:

particle balance

$$\left( \frac{dn_a}{dt} \right)_{loss} = - \frac{4}{\sqrt{\pi}} Z_a \frac{n_a T_a}{\tau_a e \phi} \frac{\exp \left( -\frac{e\phi}{T_a} \right)}{G(RZ_a)} I \left( \frac{T_a}{e\phi} \right) \quad (3)$$

energy balance of ions

$$\frac{3}{2} \left( \frac{d(n_i T_i)}{dt} \right)_{loss} = e\phi \left[ \frac{1}{I(T_i/e\phi)} + \frac{3}{2} \frac{T_i}{e\phi} \right] \left( \frac{dn_i}{dt} \right)_{loss} + Q_{ie} + Q_{if} + Q_{sup} - Q_{cx} + Q_{ih} \quad (4)$$

energy balance of electrons

$$\frac{3}{2} \left( \frac{d(n_e T_e)}{dt} \right)_{loss} = e\phi \left[ \frac{1}{I(T_e/e\phi)} + \frac{3}{2} \frac{T_e}{e\phi} \right] \left( \frac{dn_e}{dt} \right)_{loss} + Q_{ei} + Q_{ef} + Q_{sup} - Q_{ea} \quad (5)$$

where  $a$  is plasma species (ion, electron),  $\phi$  is ambipolar potential,  $Z_a$  is 0.5 for ion and 1 for electron,  $R$  is mirror ratio and  $Q_{ab}$  is energy flow from  $b$ -species to  $a$ -species.  $Q_{sup}$  and  $Q_{cx}$  represent energy flow by particle supply and charge exchange, respectively.  $Q_{ih}$  is the external ion heating.  $Q_{ea}$  is the anomalous loss of the electron energy.  $I(x)$  and  $G(x)$  expressed as follows:

$$I(x) = 1 + \frac{1}{2} (\pi x)^{1/2} \exp \left( \frac{1}{x} \right) \left[ 1 - \operatorname{erf} \left( x^{-1/2} \right) \right] \quad (6)$$

$$G(x) = (1 + x^{-1})^{1/2} \ln \left[ \frac{(1 + x^{-1})^{1/2} + 1}{(1 + x^{-1})^{1/2} - 1} \right] \quad (7)$$

In the simulation, we set that the density of target ions keeps constant by the particle supply. The parameters of FEF-II for the simulation are listed in Table 1.

### 3 Results and Conclusions

To meet the requirement as a VNS of 2MW/m<sup>2</sup>, we made following consideration. In the previous paper[3], we obtained plasma parameters for the neutron source with 0.1MW/m<sup>2</sup> for the preliminary irradiation test. The mechanism of neutron production in this case was mainly fusion reaction between the sloshing ions and the target ions. As is demonstrated in the mirror experiments, the electron temperature of the plasma confined in mirror magnetic field is much lower than the temperature of the ions. This may be attribute to anomalous energy loss of the electrons in the plasma. According

to the result of our simulation, the ion temperature goes down due to the electron cooling. To have neutron flux of  $2\text{MW}/\text{m}^2$ , the ion temperature should be higher than  $20\text{KeV}$ . To keep the ion temperature high, we have to input energy to heat. In the present simulation, we found that this heating power should be higher than  $50\text{MW}$ . Fig.1 shows the temporal evolution of the temperature for the target plasma and the energy density for the sloshing ions. Fig.2 shows the temporal evolution of the density for the sloshing ions. The axial distribution of the neutron flux is shown in Fig.3. The result the neutron flux is  $1.9\text{MW}/\text{m}^2$  at midplane. The final parameters of FEF-II are listed in Table 2. It is shown that the external ion heating is necessary to sustain ion temperature. These conditions for the plasma parameters from simulation are quite realistic experimentally.

## References

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Initial plasma density ( $\text{cm}^{-3}$ )	$4 \times 10^{14}$
Initial ion temperature (keV)	15
Initial electron temperature (keV)	0.4
Neutral particle density ( $\text{cm}^{-3}$ )	$1 \times 10^8$
Plasma volume ( $\text{cm}^3$ )	$9.4 \times 10^4$
Plasma radius (cm)	10
Mirror ratio	3.4
Mirror to mirror distance (m)	3.3
Magnetic field at midplane (T)	4.7
Injection energy of NBI (keV)	100
Injection angle of NBI	$45^\circ$
Injection current of NBI (A)	100

Table 1: Simulation parameters of FEF-II

Electron temperature (keV)	1.0
Ion temperature (keV)	23
Sloshing ion density ( $\text{cm}^{-3}$ )	$1.4 \times 10^{13}$
Sloshing ion energy	96
Neutron flux ( $\text{MW}/\text{m}^2$ )	1.9

Table 2: Final parameters of FEF-II

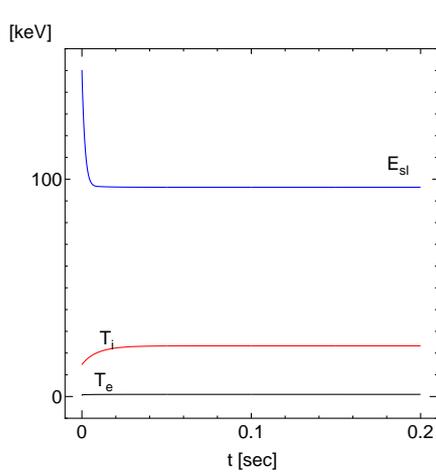


Figure 1: Temporal evolution of target plasma temperature and sloshing ion energy

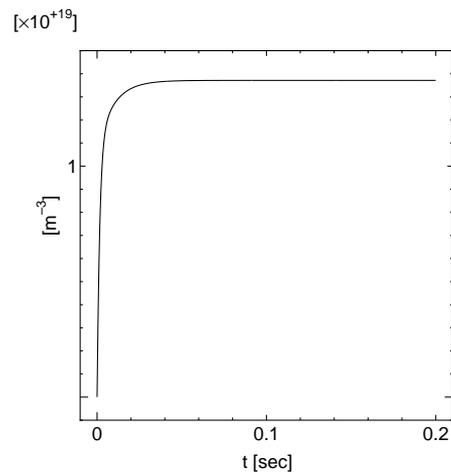


Figure 2: Temporal evolution of sloshing ion density

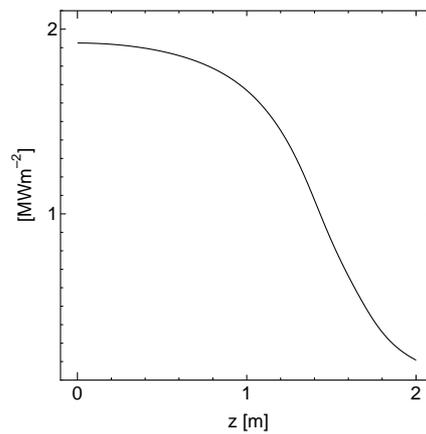


Figure 3: Axial distribution of neutron flux