Field reversed configuration (FRC) is a prospective high $\beta$ magnetic system for high efficiency D–$^3\text{He}$ fusion reactor. Self-consistent FRC plasma profiles and static electric field for reactor calculations are discussed in framework of the model including flow equilibrium and collisionless transport equations. The extrapolations to reactor regimes of plasma confinement scaling laws are considered.

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1. INTRODUCTION

The field reversed magnetic configuration (FRC) is the cylindrical magnetic trap with high $\beta$ ($\beta$ is the ratio of plasma pressure to magnetic field pressure). In FRC plasma is confined in the region of the closed force lines of the magnetic field. Magnetic field in FRC plasma is generated both exterior magnetic coils and a diamagnetic current. Plasma places around of a neutral line (or a neutral layer) where pressure of plasma has a maximum, magnetic field $B=0$ and $\beta=1$. Closed lines area is bounded by the separatrix. Accordingly terminology of toroidal systems FRC has a high elongation, and it’s aspect ratio equal to unity. Usually magnetic field in the FRC is supposed to be pure poloidal, but FRC equilibria with small toroidal component are possible [1].

One of the important problems of present FRCs is high anomalous transport across magnetic field. In the present paper possible confinement scaling laws are discussed and compared with reported data of experiments [2–8]. One can suppose that L-mode was realized in mentioned experiments. Note that H-mode formation has led to improvement of a plasma lifetime in reversed field pinch (RFP) [9].

High $\beta$ values allow consider FRC as a base for high efficiency D–$^3\text{He}$ fusion reactor. The main goal of this work is physical justification of D–$^3\text{He}$ reactor based on FRC. To estimate confinement time for H-mode reactor operation regimes we modify L-mode confinement scaling laws taking into account anomalous transport suppression by flow shear. To calculate flow velocities, static electric field, plasma density and temperature profiles we use self-consistent model of plasma equilibrium with flows and transport [10]. In this model thermodynamic approach to flow invariants is similar to the model of two-fluid equilibria with flows [1].

FRC reactor parameters are calculated from power balance of high-$\beta$ D–$^3\text{He}$ fusion plasma [11, 12]. We also compare D–$^3\text{He}$ FRC reactor concept with D–$^3\text{He}$ spherical tokamak [13].

2. FLOW EQUILIBRIUM CALCULATIONS

System of equations of flow equilibrium with turbulent transport [10] includes diffusion and energy equations associated with thermodynamic and Maxwell equation. The key equation of this system for “$j$” component ($j = i, e$) of the plasma is

$$\eta_j + \frac{1}{\eta_j} k_B T_j + \frac{m_j u_j^2}{2} + q_j U = h_j(\psi_j),$$  \hspace{1cm} (1)

where $\eta_j = \nabla T_j / \nabla n_j$; $k_B$ is the Boltzmann constant; $T_j$, $n_j$, and $u_j$ are temperature, density and flow velocity; $m_j$ and $q_j$ are the mass and the charge of the particle; $U$ is the potential of the static electric field; $h_j(\psi_j)$ is the surface function of so-called adiabatic surface; $\psi_j$ is the flux function of the adiabatic surface. Using this model we estimate the maximal ion flow shear parameter as

$$\gamma_{\text{shear}} = k_B T_i / (q_i B b^2),$$  \hspace{1cm} (2)

where $b$ is the width of flow shear region.

3. CONFINEMENT TIME SCALING LAWS

3.1. L-MODE

Recently good agreement of low-frequency drift wave scaling laws [14] with experimental data [2–8] was shown. Confinement time also can be estimated using the results of calculations of the electrostatic finite $\beta$ ITG-like instability driven by non-adiabatic particles and magnetic force line curvature [15].

Let’s consider “universal” scaling for L-mode particle confinement time in form

$$\tau_L = C_1 \left( \frac{a}{\rho_T} \right)^{C_2} \frac{a^2 e B_0}{k_B T_i},$$  \hspace{1cm} (3)

where $C_1$ and $C_2$ are some constants, $a$ is the separatrix radius, $\rho_T = \sqrt{m_j k_B T_i / (e B_0)}$, $e$ is the electron charge, $B_0$ is the external coil magnetic field (vacuum value), $T_e = T_i + T_i$ is so-called total temperature.

In limiting case $C_2 = 0$ (or $C_2 = 1$) Eq. 3 corresponds to Bohm (or gyro-Bohm) scaling.
For example, gyro-Bohm scaling (in usual SI units exclude \( T_i \) in eV) is \( \tau_{\text{gyro-Bohm}} = 4 \times 10^3 a^3 B_0^2 T_i^{-3/2} \). The comparisons of particle confinement time values measured in experiments [2–8] \( \tau_{\text{exp}} \) with the gyro-Bohm scaling are presented in Fig. 1. Note for Bohm scaling with \( C_1 = 10 \) [16] agreement with experimental data not worse than for gyro-Bohm one.

### 3.2. H-MODE EXTRAPOLATION

Taking into account turbulence suppression by flow shear [17] one can write confinement time

\[
\tau = \tau_L (1 + \gamma^2 \tau^2_c),
\]

where \( \tau_c \) is the turbulence correlation time having an order of inverse linear instability increment. Correlation time can be estimated from the overage diffusivity for L-mode \( (D_L) \) as follows

\[
\delta^2 / \tau_c = D_{\text{shear}} = a^2 / \tau_L,
\]

where \( \delta = b \) is the width of the turbulent layer near FRC separatrix.

So, extrapolation of the confinement time to reactor H-mode is \( \tau = \tau_L + (\delta / a)^2 \gamma^2 \tau^2_L \). For high efficiency reactor strong flow shear is needed: \( \gamma_{\text{shear}} \gg \gamma_L, \tau \gg \tau_c \), \( \tau = (\delta / a)^2 \gamma^2 \tau^2_L \). Let’s consider the most pessimistic L-mode scenario with Bohm confinement time scaling law \( \tau_L = \tau_{\text{Bohm}} = 10a^2 eB_0 / (k_B T_i) \). In this case for reactor calculation we use extrapolation in form

\[
\tau = 10a^2 eB_0 / (k_B T_i) \left( 1 + 100 a^2 \delta^2 / b^2 \right).
\]

Also for reactor configuration we assume \( \delta = b = 0.1a \).

### 4. FUSION PLASMA POWER BALANCE AND FRC REACTOR CONCEPT

For FRC reactor plasma we consider temperature and density profiles connected as follows \( T \propto n^2 \) with \( \eta = 2 \) and \( T_e = T_i \). Corresponding \( \beta \) profile is plotted in Fig. 2.

D–\( ^3 \)He fusion plasma and FRC reactor parameters we calculate using models of D–\( ^3 \)He fuel cycles [11] and FRC fusion plasma [12]. These models are based on integral power balance

\[
\left( 1 + \frac{1}{Q} \right) P_{\text{fus}} = P_n + P_{\text{br}} + P_s + \int \frac{\sum_{k} k T_j}{\tau} dV,
\]

where \( Q \) is the plasma power amplification factor; \( P_{\text{fus}}, P_n, P_{\text{br}} \) and \( P_s \) are fusion power, neutron power, bremsstrahlung power and synchrotron radiation power integrated over plasma volume \( V \).

In Fig. 3 radial power distributions for D–\( ^3 \)He FRC fusion reactor are plotted. Results of calculations are presented in the Table. For comparison Table contains parameters of D–\( ^3 \)He spherical tokamak reactor [13].
Parameters of D–\(^{3}\)He reactors based on FRC and spherical tokamak for regimes with Q=20

<table>
<thead>
<tr>
<th>Reactor type</th>
<th>FRC</th>
<th>Spherical tokamak [13]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel cycle</td>
<td>D–(^{3})He, (n_{3\text{He}}/n_{D}=1)</td>
<td>D–(^{3})He with (^{3})He self-supply, (n_{3\text{He}}/n_{D}=0.36)</td>
</tr>
<tr>
<td>Plasma radius (a), m</td>
<td>1.6</td>
<td>3</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>Elongation</td>
<td>–</td>
<td>3.8</td>
</tr>
<tr>
<td>Magnetic field (B_{0}), T</td>
<td>5</td>
<td>3.2</td>
</tr>
<tr>
<td>Maximal/averaged (\beta)</td>
<td>1/0.46</td>
<td>0.95/0.54</td>
</tr>
<tr>
<td>Maximal/averaged (T), keV</td>
<td>60/28</td>
<td>50/40</td>
</tr>
<tr>
<td>Synchrotron wall reflectivity (\Gamma)</td>
<td>0.5</td>
<td>0.65</td>
</tr>
<tr>
<td>Confinement time (\tau), s (scaling)</td>
<td>2.5 (Eq. (6))</td>
<td>16 (ITER)</td>
</tr>
<tr>
<td>Fusion power (P_{\text{fus}}), MW</td>
<td>32.3 per meter of plasma cylinder</td>
<td>1500</td>
</tr>
<tr>
<td>Bremsstrahlung power fraction (P_{b}/P_{\text{fus}})</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Synchrotron power fraction (P_{s}/P_{\text{fus}})</td>
<td>0.052</td>
<td>0.023</td>
</tr>
<tr>
<td>Neutron power fraction (P_{n}/P_{\text{fus}})</td>
<td>0.072</td>
<td>0.15</td>
</tr>
<tr>
<td>Neutron wall load (W_{n}), MW/m(^2)</td>
<td>0.18</td>
<td>0.2</td>
</tr>
</tbody>
</table>

REFERENCES


РАВНОВЕСИЕ ТЕЧЕНИЙ ПЛАЗМЫ, ЗАКОНЫ УДЕРЖАНИЯ И ТЕРМОЯДЕРНЫЕ ПЕРСПЕКТИВЫ ОБРАЩЕННОЙ МАГНИТНОЙ КОНФИГУРАЦИИ

А.Ю. Чирков

Обращенная магнитная конфигурация (FRC), – магнитная ловушка с высоким \(\beta\), является перспективной системой для высокоэффективного D–\(^{3}\)He-термоядерного реактора. Самосогласованные распределения параметров плазмы FRC и статического электрического поля для расчетов реактора обсуждаются в рамках модели, включающей уравнения равновесия течений и бестолкновительного переноса. Рассматривается экстраполяция сейзлингов для удержания плазмы в область реакторных режимов.

ПИВНОВАГА ТЕЧЕЙ ПЛАЗМЫ, ЗАКОНЫ УТРЯМНИЯ И ТЕРМОЯДЕРНЫЕ ПЕРСПЕКТИВИ ЗВЕРНЕНОЙ МАГНИТНОЙ КОНФИГУРАЦИ

А.Ю. Чирков

Звернена магнитная конфигурация (FRC), – магнитная пастка z высоким \(\beta\), е перспективною системою для високоэфективного D–\(^{3}\)He-термоядерного реактора. Самоузгоджени розподіли параметрів плазми FRC i статичного електричного поля для розрахунків реактора обговорюються в рамках моделі, що включає рівняння рівноваги течій і безштовхувального переносу. Розглядається екстраполяція сейзлингів для утримання плазми в область реакторних режимів.