PLASMA FLOW EQUILIBRIUM, CONFINEMENT SCALING LAWS AND FUSION PROSPECTS OF A FIELD REVERSED CONFIGURATION

A.Yu. Chirkov

Bauman Moscow State Technical University,
2^{nd} Baumanskaya Str. 5, 105005, Moscow, Russia, e-mail: chirkov@power.bmstu.ru

Field reversed configuration (FRC) is a prospective high β magnetic system for high efficiency D–^{3}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 β (β 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 layer (or a neutral line) where pressure of plasma has a maximum, magnetic field B=0 and β=1. Closed lines area is bounded by the separatrix. According 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 equilibriua 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 β values allow consider FRC as a base for high efficiency D–^{3}He fusion reactor. The main goal of this work is physical justification of D–^{3}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-β D–^{3}He fusion plasma [11, 12]. We also compare D–^{3}He FRC reactor concept with D–^{3}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

$$\frac{\eta_j+1}{\eta_j}k_B T_j+\frac{m_j\mathbf{u}_j^2}{2}+q_j U=h_j(\psi_j)\,, \qquad (1)$$

where $\eta_j=\nabla T_j/\nabla n_j$; k_B is the Boltzmann constant; T_j, n_j, and $\mathbf{u}_j$ 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; ψ_j is the flux function of the adiabatic surface. Using this model we estimate the maximal ion flow shear parameter as

$$\gamma_{\text{shear}}\approx k_B T_i/(q_i B b^2)\,, \qquad (2)$$

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 β 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

$$\tau_L=C_1\left(\frac{a}{\rho_T}\right)^{C_2}\frac{a^2 eB_0}{k_B T_{\text{t}}}\,, \qquad (3)$$

where C_1 and C_2 are some constants, a is the separatrix radius, $\rho_T=\sqrt{m_i k_B T_{\text{t}}}/(eB_0)$, e is the electron charge, B_0 is the external coil magnetic field (vacuum value), $T_{\text{t}}=T_i+T_e$ is so-called total temperature.

In limiting case C_2 = 0 (or C_2 = 1) Eq. 3 corresponds to Bohm (or gyro-Bohm) scaling.

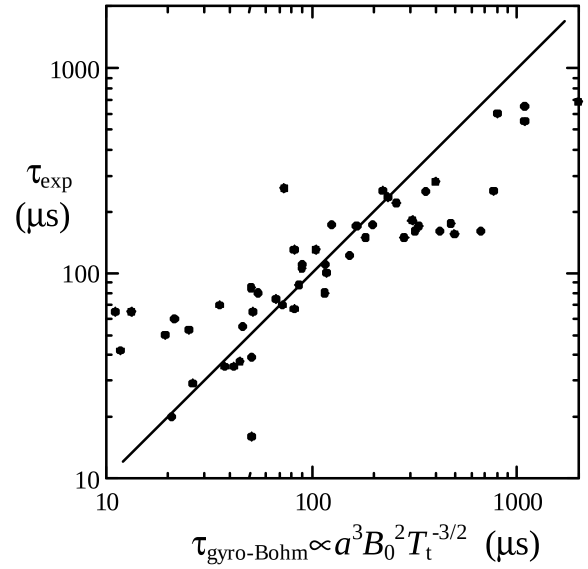

Fig. 1. Comparison of gyro-Bohm scaling with experimental data

For example, gyro-Bohm scaling (in usual SI units exclude T_t in eV) is $\tau_{\text{gyro-Bohm}} = 4\times10^3 a^3 B_0^2 T_t^{-3/2}$. The comparisons of particle confinement time values measured in experiments [2–8] τ_{exp} with the gyro-Bohm scaling are presented in Fig. 1. Note for Bohm scaling with $C_1\approx10$ [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

$$\tau = \tau_L (1+\gamma_{\text{shear}}^2 \tau_c^2), \qquad (4)$$

where τ_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 ($D_{\perp L}$) as follows

$$\delta^2/\tau_c \approx D_{\perp L} \approx a^2/\tau_L, \qquad (5)$$

where $\delta \approx b$ is the width of the turbulent layer near FRC separatrix.

So, extrapolation of the confinement time to reactor H-mode is $\tau = \tau_L + (\delta/a)^2 \gamma_{\text{shear}}^2 \tau_L^3$. For high efficiency reactor strong flow shear is needed: $\gamma_{\text{shear}} >> \tau_L^{-1}$, $\tau >> \tau_L$, $\tau \approx (\delta/a)^2 \gamma_{\text{shear}}^2 \tau_L^3$. Let's consider the most pessimistic L-mode scenario with Bohm confinement time scaling law $\tau_L = \tau_{\text{Bohm}} = 10a^2 e B_0/(k_B T_t)$. In this case for reactor calculation we use extrapolation in form

$$\tau = 10\frac{a^2 e B_0}{k_B T_t}\left(1+100\frac{a^2\delta^2}{b^4}\right). \qquad (6)$$

Also for reactor configuration we assume $\delta \approx b \approx 0.1a$.

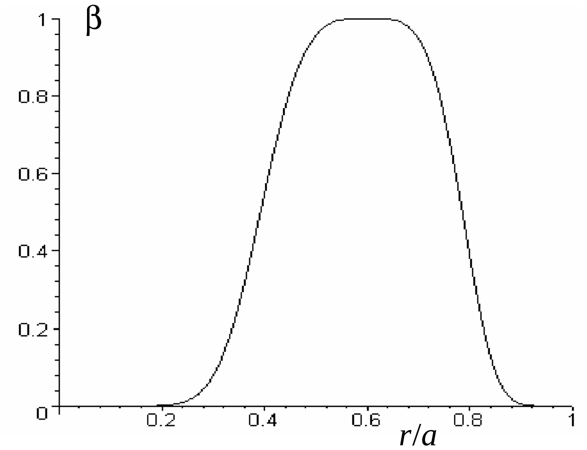

Fig. 2. Plasma β profile for reactor calculations

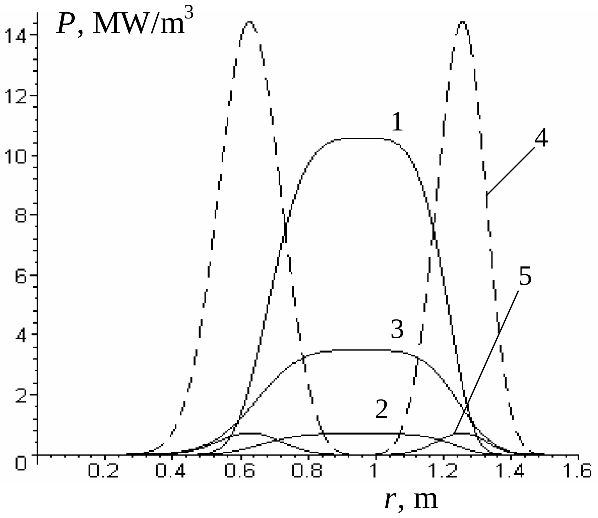

Fig. 3. Power distributions. 1 – fusion power, 2 – neutron power, 3 – bremsstrahlung, 4 – emitted synchrotron radiation power, 5 – synchrotron radiation taking into account absorption

4. FUSION PLASMA POWER BALANCE AND FRC REACTOR CONCEPT

For FRC reactor plasma we consider temperature and density profiles connected as follows $T \propto n^\eta$ with $\eta = 2$ and $T_e = T_i$. Corresponding β 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

$$\left(1+\frac{1}{Q}\right)P_{\text{fus}} = P_{\text{n}} + P_{\text{br}} + P_{\text{s}} + \int_V \frac{\Sigma n_j k_B T_j}{\tau} dV, \qquad (7)$$

where Q is the plasma power amplification factor; P_{fus}, P_{n}, P_{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

Reactor type	FRC	Spherical tokamak [13]
Fuel cycle	D–^{3}He, $n_{3\mathrm{He}}/n_\mathrm{D}$=1	D–^{3}He with ^{3}He self-supply, $n_{3\mathrm{He}}/n_\mathrm{D}$=0.36
Plasma radius a, m	1.6	3
Aspect ratio	1	1.5
Elongation	–	3.8
Magnetic field B_0, T	5	3.2
Maximal/averaged β	1/0.46	0.95/0.54
Maximal/averaged T, keV	60/28	50/40
Synchrotron wall reflectivity Γ_s	0.5	0.65
Confinement time τ, s (scaling)	2.5 (Eq. (6))	16 (ITER)
Fusion power P_fus, MW	32.3 per meter of plasma cylinder	1500
Bremsstrahlung power fraction $P_\mathrm{br}/P_\mathrm{fus}$	0.4	0.6
Synchrotron power fraction $P_\mathrm{s}/P_\mathrm{fus}$	0.052	0.023
Neutron power fraction $P_\mathrm{n}/P_\mathrm{fus}$	0.072	0.15
Neutron wall load W_n, MW/m^2	0.18	0.2

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

А.Ю. Чирков

Обращенная магнитная конфигурация (FRC), – магнитная ловушка с высоким β, 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 бесстолкновительного переноса. Рассматривается экстраполяция скейлингов для удержания плазмы в область реакторных режимов.

РІВНОВАГА ТЕЧІЙ ПЛАЗМИ, ЗАКОНИ УТРИМАННЯ І ТЕРМОЯДЕРНІ ПЕРСПЕКТИВИ ЗВЕРНЕНОЇ МАГНІТНОЇ КОНФІГУРАЦІЇ

А.Ю. Чирков

Звернена магнітна конфігурація (FRC), – магнітна пастка з високим β, є перспективною системою для високоефективного D–^{3}He-термоядерного реактора. Самоузгоджені розподіли параметрів плазми FRC і статичного електричного поля для розрахунків реактора обговорюються в рамках моделі, що включає рівняння рівноваги течій і беззіштовхувального переносу. Розглядається екстраполяція скейлінгів для утримання плазми в область реакторних режимів.