Isothermal Confinement

Tihiro OHKAWA

TOYO Technologies Inc, La Jolla, California, USA

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The concept of isothermal confinement is presented. The idea is a revival of the early magnetic fusion concepts with new insight. The plasma core is confined magnetically and is surrounded by a quasi-vacuum region. The temperature of the core is uniform and the turbulence associated with the temperature gradient is absent. The quasi-vacuum region is unstable against the pressure gradient and the turbulent transport rate is much larger than that of the core. Two modes of operation, pulsed and steady state, are considered. Recent experimental results in LHD and CDX-U appear to support the concept.

Keywords: magnetic confinement, classical transport, turbulent transport, pulsed operation, steady state operation, tokamak, stellerator

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1. Introduction

Historically the nuclear fusion effort has been divided into the inertial confinement and the magnetic fusion. At the onset the magnetic confinement meant the hot plasma is surrounded by magnetic field away from the material wall. The plasma pressure is balanced by the magnetic pressure and the plasma was more or less isothermal. The pinch experiments were typical. Tokamaks changed the concept of confinement to the magnetic thermal insulation. The thermal diffusivity of the plasma is reduced by the magnetic field and the temperature gradient between the hot plasma and the cold wall is maintained. Both the experimental and the theoretical works have shown that the plasma is unstable against the temperature gradient driven modes and the turbulent thermal diffusivity is greater than the classical value. Consequently the device size for the fusion power production turns out much larger than the size originally thought.

The theory of the micro-instabilities [1] indicates that the turbulence in the isothermal plasma is more benign and the particle diffusivity may be much less than the thermal diffusivity observed experimentally. The recent experiments at LHD [2] and CDX-U [3] have shown that the plasma parameters improve when the recycling at the wall is reduced. The recycling is the source of cold plasma and cools the plasma edge. The situation where the region between the plasma edge and the wall is almost devoid of plasma was realized in the multipole experiment [4] to measure the classical diffusivity, performed in the late 1960s and early 1970s. In the multipole magnetic configurations, the plasma edge is located at the critical flux surface defined as the boundary between the flute stable and the unstable region. The particle diffusivity in the magnetic well region is classical and is small, whereas the region outside is unstable and the particle diffusivity is large. The continuity of the particle flux ensures the density in the out side region is small.

The inertial confinement approach is an inherently pulsed operation but the thermal insulation approach may be a pulsed or steady state operation. The isothermal approach may also be pulsed or steady state operation. In the pulsed operation, the pulse is over before the plasma reaches the wall and the recycling at the wall is not an issue. It merely affects the time required to clear the region near the wall back to vacuum and affects the repetition rate. In the steady state operation, the key issue is how to keep the plasma density in the outside region very low and the recycling becomes the crucial factor.

Since the key features to be addressed are different, we discuss the two operations separately.

2. Pulsed Operation

We discuss the pulsed operation in this section and begin by estimating the confinement time.

The plasma is created in a magnetic configuration and reaches equilibrium quickly. The equilibrium is MHD stable and the plasma temperature is uniform. The plasma starts to diffuse and eventually reaches the wall. The confinement time is defined as the time between the establishment of the equilibrium and the start of the recycling. To make the analysis tractable we assume the temperature is kept constant by external agents and the configuration is a cylinder of length L with axial uniform magnetic field. The plasma expands radially while the force balance is maintained.

The continuity equation is given by

$$\partial n/\partial t = r^{-1}(\partial/\partial r)rD\partial n/\partial r, \tag{1}$$

where n is the plasma density and D is the diffusion coefficient.

author's e-mail: tohkawa@san.rr.com

The total number of the plasma particle N is conserved,

$$N = 2\pi L \int_0^\infty nr\mathrm{d}r = \text{constant}. \tag{2}$$

We look for the solution where the density profile remains unchanged and only the radial scale length increases. We put

$$n = f(t)g(\xi), \tag{3}$$
$$\xi = r/R(t). \tag{4}$$

The total number becomes

$$N = 2\pi L f R^2 \int_0^\infty g\xi\mathrm{d}\xi. \tag{5}$$

Since N is constant, we have

$$fR^2 = N^* = N \bigg/ \left(2\pi L \int_0^\infty g\xi\mathrm{d}\xi\right) = \text{constant}. \tag{6}$$

Noting the fact that the instabilities in the isothermal plasma are benign, if they persist, we assume that the diffusion is classical, for the transparency of argument, and use

$$D = \eta n k_\mathrm{B} T/B^2, \tag{7}$$

where η is the electrical resistivity and B is the axial magnetic field.

By using Eq. (3) and Eq. (6) in Eq. (1) we obtain

$$R^2 f'/f^2 = (\eta k_\mathrm{B} T/B^2)(g + g'\xi/2)^{-1}\xi^{-1}(\xi g g')' = -\alpha, \tag{8}$$

where the prime denote the derivative with respect to the argument and α is a constant.

The solution for the time dependence is given by

$$f = f_0\{1 + t/\tau\}^{-1/2}, \tag{9}$$
$$R = R_0\{1 + t/\tau\}^{1/4}, \tag{10}$$
$$\tau = N^*/(2\alpha f_0^2). \tag{11}$$

The local density decrease as $t^{-1/2}$ and the radial scale length increases as $t^{1/4}$. The characteristic time τ is determined by the equation for the space dependence and depends on the diffusion coefficient.

The equation for the profile is given by

$$\xi^{-1}(\xi g g')' = -(\alpha B^2/(\eta k_\mathrm{B} T))(g + g'\xi/2). \tag{12}$$

We expand g in power series of ξ and look at the solution at the limit small ξ and set

$$g = g_0 - g_2\xi^2 - g_4\xi^4 \cdots. \tag{13}$$

The coefficients are determined by using Eq. (12),

$$g_2 = \alpha B^2/(4\eta k_\mathrm{B} T), \tag{14}$$
$$g_4 = 0,$$

and

$$g \approx g_0 - g_2\xi^2. \tag{15}$$

It shows that a parabolic profile is pretty good approximation. We define r^* as the radius where the density vanishes in the parabolic profile and obtain

$$g \approx g_0\left\{1 - r^2 \Big/ \left[{r^*}_0{}^2(1 + t/\tau)^{1/2}\right]\right\}. \tag{16}$$

Near $r = r^*$ the approximation breaks down and the profile deviates from the parabola.

We choose the initial condition given by the parabolic profile given by

$$n_0 = n_{00}(1 - r^2/{r^*}_0{}^2). \tag{17}$$

The approximate solution is given by

$$n \approx n_{00}(1+t/\tau)^{-1/2}\left\{1 - r^2 \Big/ \left[{r^*}_0{}^2(1 + t/\tau)^{1/2}\right]\right\}, \tag{18}$$

where

$$\tau = B^2{r^*}_0{}^2/(8\eta k_\mathrm{B} T n_{00}) = (1/4){r^*}_0{}^2(\mu_0/(\eta\beta_{00})). \tag{19}$$

The radius of the plasma r^* expands as

$$r^* = {r_0}^*(1 + t/\tau)^{1/4}. \tag{20}$$

We estimate the fusion Q using the above solution. The instantaneous fusion power $P(r, t)$ is given by

$$P = (1/4)\langle\sigma\, v\rangle F n^2, \tag{21}$$

where $\langle\sigma\, v\rangle$ is the DT fusion rate and F is the energy released per reaction. The 1/4 arises from assuming the plasma is $1/2D$ and $1/2T$, and n is the total density.

The Q value is defined as

$$Q = 2\pi L \int \mathrm{d}t \int r\mathrm{d}rP/(3k_\mathrm{B} T N), \tag{22}$$

where the losses such as the Bremsstrahlung are neglected. The upper bound of the radial integral is r^* and the upper bound of the time integral is t_1 given by

$$r_\mathrm{w} = {r_0}^*(1 + t_1/\tau)^{1/4}, \tag{23}$$

where r_w is the radius of the wall.

We obtain

$$Q = (1/9)\langle\sigma\, v\rangle(F/(k_\mathrm{B} T))n_{00}\tau(r_\mathrm{w}/{r_0}^*)^2, \tag{24}$$

assuming $r_\mathrm{w} \gg {r_0}^*$. If we use Eq. (19) to eliminate the plasma density, the above equation becomes

$$Q = (1/9)\langle\sigma\, v\rangle(F/(k_\mathrm{B} T))(B^2/(8k_\mathrm{B} T\eta)){r_\mathrm{w}}^2. \tag{25}$$

One of the characteristics of collisional transport is that the product of the plasma density and the confinement time is independent of the plasma density and the above equation does not contain the density.

We choose the DT mixture at 10 keV. The parameters are $\langle \sigma v \rangle = 10^{-22}\ \mathrm{m^3/s}$, $F = 17.6\ \mathrm{MeV}$ and $\eta = 10^{-9}$ ohm-m. We obtain

$$Q = 1.5 \times 10^3 B^2 r_{\mathrm{w}}{}^2. \tag{26}$$

For $B = 2\ \mathrm{T}$ and $r_{\mathrm{w}} = 5\ \mathrm{cm}$, we have $Q = 15$.

The configuration must probably be toroidal instead of cylindrical to avoid the loss in the direction parallel to magnetic field. Toroidal effects increase the transport rate. We simply replace B with the effective magnetic field B_{eff} in the above formula to account for the toroidal effects. A realistic value for B_{eff} may be 0.5 T. The wall radius has to be increased to account for the lower magnetic field. For $B_{\mathrm{eff}} = 0.5\ \mathrm{T}$, the wall radius is 20 cm to obtain $Q = 15$.

The choice of the plasma density determines the confinement time therefore the repetition rate. At low densities the time averaged power is low. The upper limit of the density is given by the beta limit of the configuration.

3. Steady State Operation

In the steady state operation, particles and energy are supplied at the plasma center and they are removed at the wall. In order to obtain the isothermal plasma condition, the production of cold plasma at the wall has to be prevented. The injection of particles and energy that matches the plasma density and the temperature may be done by neutral beam injection and pellet injection. The loss is assumed to be convective and not conductive and the neutral beam power and the pellet injection rate are adjusted to match the convective loss.

The isothermal condition at the wall is more difficult to achieve because recycling at the wall produces cold plasma. Thus reduction of recycling is the key to approaching isothermal conditions near the wall. If the diverter magnetic configuration is employed the cold plasma flows towards the plasma edge and creates a temperature gradient. If the limiter is used, the plasma edge is very close to the limiter surface and a large temperature gradient is present in front of the limiter.

We consider the possibility of creating a zone between the plasma edge and the wall where the plasma density is very low. It is like the situation of the octopole experiment [3]. Inside the plasma edge, the magnetic configuration is flute stable whereas it is unstable between the plasma edge and the wall. The plasma is stable against the MHD modes with long wave length. The zone is unstable against the interchange modes with short perpendicular wave length. A possible way to achieve this may be to eliminate magnetic shear by keeping the safety factor constant in the zone.

In steady state, the particle flux per unit length $2\pi\Gamma$ is constant

$$\Gamma = -rD\partial n/\partial r = \text{constant}, \tag{27}$$

where D is the diffusion coefficient. Inside the magnetic well the diffusion coefficient is classical and the outside the well the diffusion coefficient is large because of the interchange mode turbulence. Consequently the density gradient outside of the plasma edge is much smaller than the gradient inside the well. Most of the density drop occurs inside the well.

In the isothermal steady state, thermal conduction is absent and the heat flux H is given by the convective transport

$$H = 3k_{\mathrm{B}}T\Gamma. \tag{28}$$

Since Γ is constant, so is H. In the case of classical transport, the diffusivity of the particle is smaller than the thermal diffusivity by the square root of the electron-ion mass ratio. As a result, the heat flux of the convective transport is much smaller than that of the conductive transport.

We divide the plasma into three regions; a) the source region, $0 < r < r_1$, b) the confinement region, $r_1 < r < r_2$ and c) the quasi-vacuum region, $r_2 < r < r_{\mathrm{w}}$. The source region is where the particles and the power are injected. The intensity of the particle injector and the power injector are adjusted to obtain desired density and temperature. These injectors could be a combination of pellet injector and neutral beam.

In the confinement region, the transport is assumed classical and the diffusion coefficient is given by

$$D = n\eta k_{\mathrm{B}}T/B^2. \tag{29}$$

In the quasi-vacuum region the transport is turbulent. We assume that the diffusion coefficient is the Bohm diffusion coefficient given by

$$D = k_{\mathrm{B}}T/(16eB). \tag{30}$$

It is not essential to assume a certain formula for the diffusion coefficient as long as it is much larger than the classical diffusion coefficient.

The particle flux and the heat flux are constant throughout the three regions. In an isothermal steady state, the constancy of the particle flux assures the constancy of the heat flux. The density profile is calculated by matching the density and particle flux at the boundaries. The boundary condition at the wall depends on the assumption of the degree of the recycling at the wall. We calculate the case without recycling first, namely the wall completely absorbs particle and heat.

The density profile in the confinement region is calculated from Eq. (27) using the diffusion coefficient given by Eq. (29).

$$n^2 = n_2{}^2 - \Gamma(2B^2/(\eta k_{\mathrm{B}}T))\ln(r/r_2). \tag{31}$$

The density n_1 at $r = r_1$ becomes

$$n_1{}^2 = n_2{}^2 + \Gamma(2B^2/(\eta k_{\mathrm{B}}T))\ln(r_2/r_1). \tag{32}$$

For $n_1 \gg n_2$, we have

$$n_1 \approx [\Gamma(2B^2/(\eta k_{\mathrm{B}}T))\ln(r_2/r_1)]^{1/2}. \tag{33}$$

In the quasi-vacuum region, we use the diffusion coefficient given by Eq. (30) and obtain

$$n = n_2 - \Gamma(16eB/(k_B T)) \ln(r/r_2). \quad (34)$$

The density at the wall becomes

$$n_w = n_2 - \Gamma(16eB/(k_B T)) \ln(r_w/r_2). \quad (35)$$

The flux to the wall is given by

$$\Gamma = r_w n_w v_s, \quad (36)$$

where v_s is the velocity determined by the sheath condition.

As it will become clear in the following, the precise estimate of v_s is not needed as long as it is not too small. Nevertheless we estimate v_s by assuming that the upper limit of $k_\perp$ of the turbulence is limited by the ion gyroradius ρ_i, namely $k_\perp \rho_i \leq 1$ and the sheath thickness is given by $k_\perp{}^{-1}$ and therefore by ρ_i. With this assumption, the velocity v_s is given by

$$v_s \sim (k_B T/(16eB))/\rho_i = v_i/32, \quad (37)$$

where v_i is the thermal velocity of the ions.

By eliminating n_w with the combination of Eq. (35) and Eq. (36), we obtain

$$n_2 = \Gamma[(1/(r_w v_s)) + (16eB/(k_B T)) \ln(r_w/r_2)]. \quad (38)$$

The use of Eq. (37) yields

$$n_2 \approx \Gamma(16eB/(k_B T))[\rho_i/r_w + \ln(r_w/r_2)]. \quad (39)$$

If we assume $\rho_i/r_w \ll 1$, the above equation becomes

$$n_2 \approx \Gamma(16eB/(k_B T)) \ln(r_w/r_2). \quad (40)$$

The above estimate does not contain v_s and the precise estimate of v_s is not needed.

The use of the above estimate in Eq. (32) yields

$$n_1{}^2 = n_2{}^2 + n_2(B/(8e\eta))[\ln(r_2/r_1)/\ln(r_w/r_2)]. \quad (41)$$

The first term is small and we obtain

$$n_2 \approx n_1{}^2(8e\eta/B)[\ln(r_w/r_2)/\ln(r_2/r_1)]. \quad (42)$$

For $n_1 = 10^{20}\,\mathrm{m}^{-3}$, $\eta = 10^{-9}$ ohm-m and $B = 1\,\mathrm{T}$, the density n_2 is about $10^{13}\,\mathrm{m}^{-3}$ and the assumption $n_2 \ll n_1$ is justified. Also the designation of the quasi-vacuum is appropriate.

There will be some recycling at the wall and next we consider the effect of the recycling on the confinement. The particle flux and the heat flux from the plasma on the wall produce neutral particle flux back into the plasma. The neutrals are ionized and are heated to the plasma temperature. As a result the plasma density near the wall is increased and the plasma temperature is reduced.

We introduce the recycling coefficient G defined by

$$\Gamma = r_w n_w v_s(1 - G). \quad (43)$$

In the absence of recycling, $G = 0$, the above equation is reduced to Eq. (36). If $G = 1$, the wall is unable to absorb particles and steady state is not possible. With $0 < G < 1$, the recycling increases the plasma density at the wall for a given flux Γ. The heat flux balance is given by

$$H = 3k_B T_w \Gamma/(1 - G), \quad (44)$$

where it is assumed that the energy required to ionize the neutrals is small compared to the energy to heat the recycled ions to the plasma temperature. If the recycling involves the sputtering of the high Z wall material, this assumption is no longer valid. The complete ionization involves the excitation radiation of high energy levels and the ionization energy might exceed the thermal energy. Since n_w is larger with recycling, the plasma temperature at the wall decreases for a given heat flux.

The magnetic configuration of the quasi-vacuum region is designed in such a way that the plasma is unstable to the pressure driven flute modes. The transport is driven by the resultant turbulence only if the radial pressure gradient is negative. If the recycling eliminates or even reverses the pressure gradient, the modes become stable and the transport rate becomes classical and much smaller. The particle and the heat flux to the wall are reduced and the particle flux from the wall diminishes. This prevents n_w from becoming large enough to influence n_2.

With recycling, the plasma temperature is no longer uniform and the density profile for the isothermal case given by Eq. (34) is not accurate. However we assume that the recycling coefficient is not very close to unity and the relationship between n_2 and n_w is given approximately by Eq. (35). The combination of Eq. (35) and Eq. (43) yields

$$n_2 \sim \Gamma(16eB/(k_B T))[(\rho_i/r_w)/(1-G)+\ln(r_w/r_2)]. \quad (45)$$

The first term is not important if

$$1 - G > (\rho_i/r_w)/\ln(r_w/r_2). \quad (46)$$

Since $\rho_i/r_w \ll 1$, the above condition is satisfied unless G is very close to unity. For moderate values of G the density n_2 remains unchanged from that in the absence of recycling because the density at the sheath is much smaller than n_2 and the particle transport in the quasi-vacuum region is not affected by the increase of n_w. The density at the wall is given by

$$n_w \approx n_2(\rho_i/r_w)/[\ln(r_w/r_2)(1 - G)]. \quad (47)$$

In the quasi-vacuum region, the transport is assumed to be due to the turbulence and is convective. With a temperature gradient, the heat flux is given by

$$H = 3k_B T\Gamma\{1 + [(\mathrm{d}T/\mathrm{d}r)/T]/[(\mathrm{d}n/\mathrm{d}r)/n]\}. \quad (48)$$

The assumption here is that nT is convectively mixing because the turbulence is driven by the pressure gradient. The heat flux is increased for a given particle flux by the temperature gradient.

A rough estimate of the effect is given by

$$H \sim 3k_B T_2 \Gamma[1 + (T_2 - T_w)/T_2]. \quad (49)$$

By equating the heat fluxes given by Eq. (44) and Eq. (49) we obtain

$$T_w \sim [(1 - G)/(1 - G/2)]T_2. \quad (50)$$

Unless the recycling coefficient is close to unity, the temperature drop is modest. The heat flux at the wall becomes

$$H \sim 3k_B T_2 \Gamma/(1 - G/2). \quad (51)$$

The particle flux and the heat flux at the wall have to match the input fluxes into the confinement region. The density n_2 hardly changes with modest recycling and the condition $n_2 \ll n_1$ still holds. The density profile in the confinement region is therefore little affected by the recycling. The thermal diffusivity of the classical transport is much larger than the particle diffusion coefficient. An increased heat flux can be accommodated by a modest increase of T_1 without affecting the particle transport. The main effect of the increased heat flux is to reduce the fusion Q.

The fusion Q value is defined as

$$Q = \int_{r1}^{r2} r\mathrm{d}rP/H. \quad (52)$$

By using the profile given by Eq. (31), Q for the isothermal case is given approximately by

$$Q \approx (1/24)(F/(k_B T))(B^2/(\eta k_B T))\langle\sigma v\rangle \{r_2{}^2 - r_1{}^2(1 + 2\ln(r_2/r_1))\}. \quad (53)$$

At $T = 10$ keV, we have

$$Q \approx 4.6 \times 10^3 r_2{}^2 B^2. \quad (54)$$

Note that Q is proportional to square of Br_2. With $B = 1$ T, and $r_2 = 5$ cm we have $Q = 11.5$ and the same Q value with $B = 0.5$ T and $r_2 = 10$ cm.

With recycling the heat throughput must be increased to counter the increased heat loss to the wall. The Q value is reduced roughly by $(1 - G/2)$.

The above estimate of the Q value ignores the heat loss not associated with the transport, such as Bremsstrahlung and the heat gain by fusion burn. The real Q value must be calculated by including those effects.

4. Discussion

In this section, 4.1 recent relevant experiments, and 4.2 comparison of pulsed and steady state approaches are discussed.

4.1 Recent relevant experiments

Two recent experiments are relevant to the concept of the isothermal confinement. We discuss them separately.

(i) LHD experiment [2]

Plasma with a very high density core, called Super Dense Core (SDC), has been obtained. The core is surrounded by a region of low density. The boundary, called Internal Diffusion Barrier (IDB), between the regions is located close to the minimum of the rotational transform. The key ingredients are: 1) Pellet injection for fueling, 2) Magnetic configuration where the core region is a magnetic well and the outer region is a magnetic hill and 3) Diverter with small recycling coefficients.

The pellet fueling and the low recycling diverter are very important to achieve low density in the surrounding region. The particle transport is outward from the source to the diverter. That is not the case for the gas puff fueling.

The magnetic configuration with a magnetic well and hill is like the one discussed in the steady state operation of the isothermal confinement in Sec. 3 above. The difference is that ballooning modes rather than flute modes may be stable in the well and unstable in the hill region.

The particle diffusion coefficient at IDB, calculated from the experimental measurements, is $0.02\,\mathrm{m^2/s}$. If we ignore the effects of the helical field and use the following parameters; $B = 2.64$ T, $R = 3.75$ m, $r = 0.3$ m, $q = 2.2$, $T = 850$ eV and $n = 2.7 \times 10^{20}\,\mathrm{m^{-3}}$, the effective collision frequency is a little larger than the bounce frequency. The plasma is in the plateau regime. If we extrapolate the diffusion coefficient in the collisionless regime given by

$$D_{NC} \approx (R/r)^{3/2} q^2 D_C, \quad (55)$$

where D_C is the classical diffusion coefficient, we obtain $D_{NC} \approx 4.5 \times 10^{-2}\,\mathrm{m^2/s}$. The diffusion coefficient in the plateau regime is expected to be smaller than that given by Eq. (55). The measured diffusion coefficient is in reasonable agreement with the neoclassical diffusion coefficient.

The diffusion coefficient in the plateau regime depends weakly on the collision frequency. For a given beta value, the combination of higher density and lower temperature is more likely to put the plasma in the plateau regime. It may be that the knob twisting during experiments to reach higher $n\tau$ value finds the plasma in the plateau regime.

If steady state with higher temperature and lower density, keeping β value unchanged, can be attained by adjusting the heating power and the pellet fueling, the isothermal steady state at thermonuclear temperature becomes possible.

(ii) CDX-U experiment [3]

This experiment uses a liquid lithium limiter to reduce recycling in an ohmically heated tokamak. The diffusion coefficient of deuterium in molten lithium is very large and the recycling of deuterium is greatly reduced. The energy confinement time is significantly improved. Unfortunately the particle fueling is done by gas puffing and the direct relevance to the isothermal confinement is unclear. Future experiments with diagnostics on the temperature and the density profiles would clarify the cause of the improvement.

For the steady state isothermal confinement the reduction of the recycling improve the fusion Q value by reducing the heat throughput. For the pulsed operation the technique of this experiment shortens the period between the pulses and improves the duty cycle.

4.2 Comparison between the pulsed and the steady state operation

The advantages of the pulsed operation are: 1) absence of the recycling during the pulse, 2) device size can be smaller and 3) proof of principle experiment may be cheaper. The disadvantage is that the energy and the particles have to be injected in a period much shorter than the pulse duration and it necessitates high peak performance injectors. These features are somewhat similar to the inertial confinement schemes.

The greatest near term advantage may be that the proof of principle experiment can be done with a small power throughput, on the order of 100 kW. We consider a tokamak configuration and assume that the particle diffusion coefficient is the neoclassical rate. The Q-value given by Eq. (26) of the second section is modified to

$$Q \approx 1.5 \times 10^3 (r_w/R)^{3/2} q^{-2} B^2 r_w{}^2. \tag{56}$$

The diffusion time coefficient given by Eq. (19) becomes

$$\tau = r_0{}^{*2} (r_w/R)^{3/2} q^{-2} (\mu_0/(\eta\beta_{00}))/4. \tag{57}$$

We choose the parameters, $R = 0.3$ m, $r_w = 0.1$ m, $r_0{}^* = 0.05$ m, $B = 4$ T, $k_B T = 10$ keV and $\beta_{00} = 0.1$ corresponding to the average β of 5%. The peak density at $t = 0$, n_{00} is 4×10^{20} m^{-3} and the diffusion time coefficient τ is 0.35 sec. The pulse duration t_1 is 5.3 sec. The Q-value is 11.5.

The total number of the particles is 3×10^{18} and the total energy is 14 kJ. If the particles and the energy are to be injected in one tenth of the pulse period, namely 0.5 sec, the injection rates are 6×10^{18}/s or 0.96 amp and 28 kW. If the neutral beam of 30 kV voltage and 1 ampere current is injected, it satisfies the both requirements. However the target volume is small and the power density and the current density are rather large. It might be necessary to use higher voltage neutral beams for energy and pellet injection for the particles.

The near term advantage of the steady state operation is that the existing devices may be used for the proof of principle experiment, as the recent LHD result indicates. The stellarators have large aspect ratio and the neoclassical transport rate is larger for given size and magnetic field. However based on the recent excellent experiment, the regime of the isothermal confinement may be approached. The tokamak experiment has to proceed in a somewhat different direction to approach the isothermal regime. The gas puff fueling should be switched to pellet injection. In order to take advantage of isothermal confinement, the H-mode that keeps the edge density high should be avoided. The separatrix diverter may not be the best choice because it connects the plasma edge to the diverter plate along the path parallel to the magnetic field. The creation of a quasi-vacuum region by incorporating the turbulent transport between the plasma edge and the wall may be the missing key ingredient.

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