14 MeV Neutron Source for Material Testing

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Various methods of obtaining neutron sources for fusion technology studies are discussed. The combination of an ion beam and a target does not appear to give a sufficient neutron flux. A possible method, drift cyclotron heated mirror, is suggested.

I. INTRODUCTION

Radiation damage of structural material is one of the severest problems in fusion technology. Nonavailability of intense 14 MeV neutron source makes it difficult to study the damage experimentally. In this note, a study on possible methods of obtaining the neutron source will be made and a promising method will be proposed.

II. NEUTRON FLUX REQUIREMENT AND POWER REQUIREMENT

The structural material of a fusion reactor will have to take neutron effluence of roughly 10^{22} neut cm⁻² in its lifetime. If the irradiation time of a test sample is of the order of 10^7 sec, the neutron source has to have a neutron flux f of 10^{15} neut cm⁻² sec⁻¹. If the sample is placed at a distance L from the neutron source, the total power in neutrons P_n is given by

$$P_n = 4\pi L^2 f \times 14 \text{ MeV} \quad (1)$$

We define the power efficiency ϵ of the neutron source by

$$\epsilon = P_n \left(\frac{17 \text{ MeV}}{14 \text{ MeV}} \right) / P_i \quad (2)$$

where P_i is the total input power of the neutron source. The ratio (17/14) is to take the power output in the charged particle into account. If the source is a hot plasma, the break-even point as a fusion power source is $\epsilon = 1$. If the source is a beam-target system, ϵ may be as small as 10^{-5} according to R. F. Post.¹

By combining Eqs. (1) and (2), we obtain

$$P_i = \epsilon^{-1} 4\pi L^2 f \times 17 \text{ MeV}$$

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The smallest value for L is probably a few cm. By using $f = 10^{15} \text{ cm}^{-2} \text{ sec}^{-1}$ and $L = 10 \text{ cm}$, we have

$$P_i = 4\epsilon^{-1} 10^6 \text{ Watt} \quad (4)$$

The required power is rather large considering the fact that ϵ is a small number. Because of a large power involved, it is worthwhile to increase the efficiency ϵ . However, if the improvement of ϵ required a complicated system which increases the cost of the input power, the advantage will be lost. There is probably an optimum value of the efficiency ϵ between the lower limit of 10^{-5} for a beam-target system and a value larger than unity for a fusion reactor.

III. LIMITATION ON POWER INPUT

A. Power Limit on Unneutralized Ion Beam

The power density of an ion beam is limited by the space charge effect. If a beam is transported through a lens system with a focal length l , the defocusing due to self electric field sets the limit on the current density. For a beam of circular cross-section, the equation of trajectory of an ion is given by

$$\frac{d^2 r}{dz^2} = -\frac{r}{l^2} + \frac{e}{2W} E_r \quad (5)$$

where r is the radial position of the ion, z is in the direction of the beam, W is the energy of the ion, and E_r is the radial electric field. By assuming a uniform distribution of ions in the beam we have

$$E_r = \frac{en_b}{2\epsilon_0} r \quad (6)$$

The condition for the beam to stay focused is given by

$$\frac{e^2 n_b}{4W\epsilon_0} < \frac{1}{l^2} \quad (7)$$

The beam current I is limited to the value given by

$$I = 4\pi \left(\frac{r^2}{l^2} \right) \frac{W\epsilon_0}{e} v \quad (8)$$

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where v is the velocity of ions. The power in the beam P_b is given by

$$P_b = 4\pi \left(\frac{r^2}{\ell^2} \right) \frac{W^2 \epsilon_0}{e^2} v \quad (9)$$

$$\approx \frac{r^2}{\ell^2} W(\text{eV})^{5/2} \times 10^{-6} \text{ Watt for deuteron beams.}$$

If we equate the beam power given by Eq. (9) with the power requirements given by Eq. (3), we obtain the lower limit on the ion energy

$$W = [4\epsilon^{-1} L(\text{cm})^2 (\ell^2/r^2)]^{2/5} \times 10^4 \text{ eV} \quad (10)$$

With values, $L = 10 \text{ cm}$, $\ell = 2r$, and $\epsilon = 10^{-5}$, we have

$$\begin{cases} W \approx 1 \times 10^7 \text{ eV} \\ P_i = 1 \times 10^{12} \text{ Watt} \end{cases} \quad (11)$$

If we use a more optimistic set of numbers; $\epsilon = 10^{-3}$, $L = 3 \text{ cm}$, and $\ell = 2r$, we obtain

$$\begin{cases} W = 1.2 \times 10^6 \text{ eV} \\ P_i = 4 \times 10^8 \text{ Watt} \end{cases} \quad (12)$$

These estimates suggest that the combination of the ion beam and target is not useful unless the value of ϵ is close to unity. This can not easily be done since this is equivalent of achieving a fusion break-even point with the beam target combination.

The situation is a little better if the ions are first neutralized by charge exchange reactions before being brought into the target area. However,

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the efficiency of converting the ion beam into neutral beams decreases rapidly with increasing ion energy. It will be difficult to convert an ion beam to a neutral atom beam efficiently at high energies.

B. Neutralized Beam

If an ion beam is neutralized with electrons, the space charge limit becomes irrelevant. The beam current is limited by the magnetic effects. It is well known that the magnetic limit is larger than the space charge limit by a factor $(v/c)^2$ where c is the velocity of light. The limiting current is given by

$$I = 4\pi \left(\frac{r^2}{\ell^2} \right) \frac{W \epsilon_0}{e} \times v \times \left(\frac{c}{v} \right)^2 \quad (13)$$

The beam power is then given by

$$\begin{aligned} P_b &= \left(\frac{r^2}{\ell^2} \right) \frac{W^2 \epsilon_0}{e^2} \frac{c^2}{v} \\ &\approx \frac{r^2}{\ell^2} W(\text{eV})^{3/2} \times 10^3 \text{ Watt} \end{aligned} \quad (14)$$

By equating Eq. (14) and Eq. (3), we obtain the lower limit on the ion energy

$$W = (4\epsilon^{-1} L^2 \ell^2 / r^2)^{2/3} 10^{2/3} \text{ eV} \quad (15)$$

For two cases calculated in the previous section, the lower limits are given by

$$\begin{aligned} W &= 2 \times 10^6 \text{ eV} \quad (L = 10 \text{ cm}, \quad 2r = \ell, \quad \text{and} \quad \epsilon = 10^{-5}) \\ \text{and} \\ W &= 1.4 \times 10^4 \text{ eV} \quad (L = 3 \text{ cm}, \quad 2r = \ell, \quad \text{and} \quad \epsilon = 10^{-3}) \end{aligned} \quad (16)$$

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The neutralized beam has much smaller values for the ion energy limit than those for the un-neutralized beam. However, the acceleration of a neutralized beam is much more troublesome. If an electrostatic acceleration is used, the beam must be neutralized after the acceleration and a method has to be developed to prevent neutralizing electrons from backstreaming into the acceleration region.

C. Plasma

There is a continuous transition from a neutralized beam to a plasma, i.e., a peaked distribution function to a near-Maxwellian distribution function. Acceleration should be more appropriately called heating for the plasma. There are several limitations on parameters. If the plasma is confined in a magnetic field, $\beta (\equiv 2\mu_0 nkT/B^2)$ must be less than unity.

$$\beta < 1 \quad . \quad (17)$$

A plasma will shield out an electrostatic field, unless it becomes a wave field in the plasma. A non-wave electric field may penetrate the plasma if the electric field is inductively produced and the field lines close inside the plasma region. The following conditions are necessary for this to occur.

Suppose an electric field $\tilde{E}$ perpendicular to static magnetic field B is produced by the time varying magnetic field $\tilde{B}$ with an angular frequency ω in a plasma with a radius r , then we have

$$\tilde{E} \approx \omega r \tilde{B} \quad . \quad (18)$$

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The electric field will generate a current in the plasma. The one source of the a.c. current is the modulation of the diamagnetic current. The diamagnetic current j is given by

$$j \approx \frac{nkT}{Br} \quad (19)$$

We assume a 100% modulation of the diamagnetic current by the a.c. electric field. Then the limiting condition is that the original a.c. field is much larger than the field produced by the modulated diamagnetic current, i.e.

$$\tilde{B} > \mu_0 \frac{nkT}{B} \quad (20)$$

or

$$\beta < \frac{\tilde{B}}{B}$$

The electric field may drive the dielectric or magnetohydrodynamic current j_ϵ which is given by

$$j_\epsilon \approx \frac{mn}{B^2} \tilde{E}\omega \quad (21)$$

This will lead to the condition given by

$$\beta < v_1^2 / (r^2 \omega^2) \quad (22)$$

If the transit time of ions across the plasma is shorter than the period of the a.c. electric field, the condition (22) is automatically satisfied by condition (17).

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If conditions (17), (18), and (22) are satisfied, the "vacuum" electric field may penetrate the plasma.

The heating rate is given by

$$\begin{aligned} \frac{d}{dt} (nkT) &= E \cdot j \\ &= \frac{\tilde{B}}{B} \omega nkT \delta \end{aligned} \quad (23)$$

where δ is the product of the modulation depth of the current and the cosine of phase difference between the current and the electric field.

The heating rate must be longer than the energy loss rate of plasma. This condition is given by

$$\frac{\tilde{B}}{B} \omega \delta \approx 1 / \tau_E \quad (24)$$

where τ_E is the energy confinement time of plasma and is related with ϵ by (for D-T reaction)

$$\tau_E = \left[\epsilon / n(\text{cm}^{-3}) \right] \cdot 10^{14} \text{ cm}^{-3} \text{ sec} \quad (25)$$

Since $|\tilde{B}/B| < 1$ and $\delta < 1$, there is a lower limit on ω , i.e.

$$\omega > \left(\frac{n(\text{cm}^{-3})}{\epsilon \times 10^{14} \text{ cm}^{-3} \text{ sec}} \right) \quad (26)$$

For $n = 10^{14} \text{ cm}^{-3}$ and $\epsilon \sim 10^{-3}$ we have $\omega > 10^3$.

The required power has two parts; the "useful" power P_i given by Eq. (3) and the wasted power P_c in the coil-system which produce the a.c. magnetic field. The latter is given by

$$P_c \approx \frac{\tilde{B}^2}{2\mu_0} \left(\frac{4}{3} \pi r^3 \right) \cdot \frac{\omega}{Q} \quad (27)$$

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where r is the radius of the device and Q is the Q -value of the coil system. By using Eq. (24), Eq. (27) becomes

$$P_c \approx \frac{nkT}{\beta} \left(\frac{4\pi}{3} r^3 \right) \frac{1}{\omega \delta_Q^2} \left(\frac{n}{\epsilon \times 10^{14} \text{ cm}^{-3} \text{ sec}} \right)^2. \quad (28)$$

The condition that the wasted power is not too large compared to the useful power is given by

$$n^3 (\text{cm}^{-3}) \lesssim \epsilon \omega \delta_Q^2 \beta \left(\frac{17 \text{ MeV}}{RT} \right) \left[\frac{3L^2 (\text{cm})}{r^3 (\text{cm})} f (\text{cm}^{-2} \text{ sec}^{-1}) \right] \cdot 10^{28} \quad (29)$$

For $L = 2r$, $r = 5 \text{ cm}$, $kT = 10 \text{ keV}$, $f = 10^{15} \text{ cm}^{-2} \text{ sec}^{-1}$ and $\delta_Q^2 \beta \approx 1$, we have

$$n \leq (40. \epsilon \omega)^{1/3} \cdot 10^{15} \text{ cm}^{-3}. \quad (30)$$

Even with a small value of ϵ , this limit on the density is not restrictive

As discussed above, the power requirement for plasma cases is easier to satisfy than the beam-target cases. The disadvantages of using plasma are that an efficient heating method with a good coupling between the input power and the plasma must be developed and there are numerous instabilities to be dealt with to obtain a reasonable value for ϵ .

In the above discussion, the heating method using a wave electric field is not included. The more complex analyses are required for cases of wave electric field.

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IV. DRIFT ORBIT CYCLOTRON HEATING (DOCH)

A. Drift Orbit Cyclotron (DOC)

The drift orbit cyclotron is a resonance acceleration method using synchronous drift orbits. Consider an axially symmetric magnetic field with a median plane. The vertical component of the magnetic field B_z is given by, on the median plane,

$$B_z(z = 0) = B_0 \exp(-k^2 r^2) \quad . \quad (31)$$

The magnetic field off the median plane may be calculated from the Eq. (31).

The trajectory of the guiding center of a charged particle is given by

$$\left\{ \begin{array}{l} \frac{d\theta}{dt} = \frac{\mu}{e} \frac{\partial B_z}{\partial r} \end{array} \right. \quad (32)$$

$$\left\{ \begin{array}{l} \frac{d^2 z}{dt^2} \approx - \frac{\mu}{m} \frac{\partial B}{\partial z} \end{array} \right. \quad . \quad (33)$$

Where μ is the magnetic moment, m is the mass, and e is the charge of the particle. The radial motion on the median plane is described by

$$\frac{d\theta}{dt} = - 2k^2(\mu/e) \equiv \Omega \quad . \quad (34)$$

The angular velocity is therefore the constant since μ is a constant of motion.

A cyclotron-like acceleration will occur, if an azimuthal electric field of a proper frequency is applied. A pair of cyclotron D's produce

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an electric field which contains the Fourier component given by

$$E_{\theta} = E_0 \cos \theta \cos(\omega t - \varphi_0) \quad (35)$$

where E_0 is the magnitude and φ_0 is the phase of the electric field.

The guiding center equation of motion is given by

$$\frac{dr}{dt} = \frac{E_{\theta}}{B_z} = \frac{E_0 \cos \theta \cos(\omega t - \varphi_0)}{B_z} . \quad (36)$$

By keeping only the resonance term, we have

$$\frac{dr}{dt} \approx \frac{E_0}{B_0 \exp(-k^2 r)} \cos(\theta - \omega t + \varphi_0) . \quad (37)$$

Since we have $\theta = \Omega t$, Eq. (37) becomes

$$\frac{dr}{dt} \approx \frac{E_0}{B_0 \exp(-k^2 r)} \cos[(\Omega - \omega)t + \varphi_0] . \quad (38)$$

The resonance particles ($\Omega = \omega$) with a proper phase will spiral inwards into a stronger magnetic field region. Since the magnetic moment is a constant of motion, the particle energy increases in proportion to the magnetic field strength. The radial velocity decreases as the particle spirals inwards. The particle density n is proportional to the reciprocal of the radial velocity in a steady state and is given by

$$n \propto B_0 \exp(-k^2 r^2) / E_0 \cos \varphi_0 . \quad (39)$$

Therefore the electric field not only accelerates the particles but compresses them radially.

The particle motion is described by Eq. (33). The particle is mirror-trapped and the motion is oscillatory. The magnetic field strength

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B on a flux line is given by

$$B \approx B_0 \exp(-k^2 r_0^2) (1 + 4k^2 z^2) \quad (40)$$

where r_0 is the radius where the flux line intersects the median plane and $k^2 z^2 \ll 1$ is assumed. Then Eq. (33) becomes

$$\begin{aligned} \frac{d^2 z}{dt^2} &\approx - \frac{8\mu}{m} B_0 \exp(-k^2 r_0^2) k^2 z \\ &= - 4v_L^2 k^2 z \end{aligned} \quad (41)$$

The oscillation frequency is $2v_L k$.

B. Inductive Acceleration

For plasma heating, the electric field is produced inductively and also the electric field lines close on themselves to avoid shielding by the plasma.

We consider a vector potential given by

$$\begin{cases} A_r = [A_{r0}(r, \theta) + z^2 A_{r2}(r, \theta)] \cos \omega t \\ A_\theta = [A_{\theta0}(r, \theta) + z^2 A_{\theta2}(r, \theta)] \cos \omega t \\ A_z = (z^2 A_{z2}) \cos \omega t \end{cases} \quad (42)$$

The higher order terms A_{r2} , $A_{\theta2}$ and A_{z2} may be calculated from the lower order terms. The condition that the electric field is divergence free gives

$$\frac{\partial(rA_{r0})}{\partial r} + \frac{\partial A_{\theta0}}{\partial \theta} = 0 \quad (43)$$

We assume the form

$$A_{\theta0} = a(r) + b(r) \cos \theta \quad (44)$$

There are two cases where the field lines close;

a) Case where the field lines form eccentric circles. This requires that $|a| > |b|$.

b) Case where the field lines form closed curves in each half of the plane. This requires $a = 0$ and $b(r)$ has an extremum.

Case (a) has a disadvantage in that the azimuthally independent part of the electric field does not contribute the heating, while case (b)'s disadvantage is that there is a radius where the azimuthal electric field vanishes.

We calculate the particle orbits on the median plane for case (a). The equations of guiding center orbits are given by

$$\begin{cases} v_r = E_\theta / B_z \\ v_\theta = r\Omega - E_r / B_z \end{cases} \quad (45)$$

By using

$$\begin{cases} E_\theta = \omega[a(r) + b(r)\cos\theta]\cos\omega t \\ E_r = \omega[c(r)\sin\theta]\cos\omega t \\ \frac{d}{dr}[rc(r)] = b(r) \end{cases} \quad (46)$$

Eq. (45) becomes

$$\begin{cases} \frac{dr}{dt} = \frac{\omega(a+b\cos\theta)\cos\omega t}{B_z} \\ \frac{d\theta}{dt} = \Omega - \frac{\omega}{B_z r} c(r)\sin\theta\cos\omega t. \end{cases} \quad (47)$$

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Neglecting the non-resonant terms, we obtain

$$\begin{cases} \frac{dr}{dt} \approx \frac{\omega b}{2B_z} \cos(\theta - \omega t) \\ \frac{d\theta}{dt} \approx \frac{-\omega c}{2B_z r} \sin(\theta - \omega t) \end{cases} \quad (48)$$

We define the phase $\varphi = \theta - \omega t$ which satisfies

$$\frac{d^2\varphi}{dt^2} = \left\{ \left(\frac{\omega c}{2B_z r} \right) - \left(\frac{\omega b}{2B_z} \right) \frac{d}{dr} \left(\frac{\omega c}{2B_z r} \right) \right\} \cos \varphi \quad (49)$$

This equation describes the phase oscillation as in a synchrotron. The acceleration rate is determined by $\cos \varphi$ and the phase stability depends on $\sin \varphi$.

The average radial velocity depends on $b(r)/B_z$. Therefore by choosing an appropriate form for $b(r)$, a desired radial density distribution, for example, peaked near the center, may be obtained.

c) DOCH

When a DOC type electric field is applied to a plasma, particles are accelerated or decelerated depending on their phase relative to the electric field. To find the net heating rate, we calculated the response of the plasma to the electric field. We use the drift approximation and the distribution function f satisfies,

$$\frac{\partial f}{\partial t} + v_\theta \frac{\partial f}{r \partial \theta} = - \frac{E_\theta}{B_z} \frac{\partial f}{\partial r} \quad (50)$$

By putting

$$f = f_0(r, \mu) + f_1 \quad (51)$$

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where f_0 is the undisturbed distribution function. The linearized equation is given by

$$\frac{\partial f_1}{\partial t} + v_\theta \frac{\partial f_1}{r \partial \theta} = - \frac{E_\theta}{B_z} \frac{\partial f_0}{\partial r} \quad (52)$$

The undisturbed orbits are given by

$$\begin{cases} \frac{d\theta}{dt} = - 2k^2(\mu/e) = \Omega \\ r = \text{const} \end{cases} \quad (53)$$

We neglect E_r and write E_θ in the form

$$E_\theta = E_0 \exp[i(\theta - \omega t)] \quad (54)$$

By integrating Eq. (52) over the orbits given by Eq. (53), we obtain

$$f_1 = - \frac{E_0}{B_z} \frac{\partial f_0}{\partial r} \frac{\exp[i(\theta - \omega t)]}{i(\Omega - \omega)} \quad (55)$$

The power input P is given by

$$\begin{aligned} P &= e E_\theta^* \int v_\theta f_1 d\mu \\ &= \frac{-e E_0^2}{B_z} \int \frac{r \Omega \partial f_0}{i(\Omega - \omega) \partial r} d\mu \end{aligned} \quad (56)$$

Since we are interested in the real part of the power, we keep only the contribution from the pole. The net power is given by

$$P = + \frac{\pi e^2 E_0^2}{2k^2} \left| \frac{\omega}{B_z} \right| r \frac{\partial}{\partial r} f_0 \left(\mu = \left| -e\omega/k^2 \right| \right) \quad (57)$$

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There is a net heating if more particles are in resonance in a weaker field region. If we assume a simple form for f_o given by

$$f_o = \frac{nB}{T} \exp(-\mu B/T) \quad , \quad (58)$$

the condition for net heating is

$$\frac{\partial n}{n \partial r} + \frac{T}{B} \frac{\partial}{\partial r} \left(\frac{B}{T} \right) \left(1 - \frac{B}{T} \left| -e\omega/k^2 \right| \right) > 0 \quad . \quad (59)$$

If the initial state is a uniform plasma, there is a strong heating. The heating will stop when the temperature and density gradient become comparable to the magnetic field gradient.

The heating also produces the radial flow. The flow F is given by

$$\begin{aligned} F &= \frac{E_\theta^*}{B_z} \int f_1 d\mu \\ &= - \left(\frac{E}{B_z} \right)^2 \int_{-\infty}^{\infty} \frac{\frac{\partial f_o}{\partial r}}{i(\Omega - \omega)} d\mu \quad . \end{aligned} \quad (60)$$

The net flow is given by

$$F = - \left(\frac{E}{B_z} \right)^2 \pi \left| \frac{-e}{k^2} \right| \frac{\partial}{\partial r} f_o \left(\mu = \left| \frac{-e\omega}{k^2} \right| \right) \quad . \quad (61)$$

When there is a net heating, there is a net flow towards the region of stronger magnetic field.

Both electrons and ions are heated and pumped radially. If their distribution functions are similar, the pumping will not produce an ambipolar potential. However, the axial confinement (minor confinement) is

better for ions because of their smaller collision frequencies. This will lead to a positive plasma potential. The DOC frequencies are then shifted upwards for ions and downwards for electrons. A steady state will be reached, when the loss rate balances the pumping rate with the self-consistent ambipolar potential.

C. Stochastic DOCH

In the above calculations, the drift orbit cyclotron frequency Ω is assumed to be independent of the radius. The ambipolar potential, the imperfection of the magnetic field or deliberate tailoring of magnetic field distribution will make it dependent on the radius. The acceleration or heating of particles are still possible with c.w. A.C. power in a manner similar to stochastic cyclotron⁽²⁾. The detailed analysis will not be discussed here. The essence of the method is to apply a noise voltage, the frequency band of which contains DOC frequencies at all radii. It requires more power to obtain a given heating rate, simply because the frequency band width is larger than the single frequency method. It may become necessary to use this method, if the ambipolar potential turns out to be sizeable.

D. Instabilities

The magnetic configuration is essentially a minor configuration and is susceptible to the same instabilities present in a mirror geometry.

I) Interchange instability

The stability condition is given by

$$\frac{\partial}{\partial r} (pV^\gamma) \frac{\partial V}{\partial r} > 0 \quad (62)$$

where p is plasma pressure, V is the volume of flux tube and γ is the ratio of specific heat.

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By putting $V \propto 1/B$, we obtain

$$\frac{\partial}{\partial r} (p/B^\gamma) \frac{\partial B}{\partial r} < 0 \quad . \quad (63)$$

For the field distribution with $\partial B/\partial r < 0$, Eq. (63) becomes

$$\frac{\partial}{\partial r} (r/B^\gamma) > 0$$

or

$$\frac{\partial n}{n \partial r} - \frac{T}{B^\gamma} \frac{\partial}{\partial r} (B^\gamma/T) > 0 \quad . \quad (64)$$

This condition has a similar form as the condition for heating given by Eq. (59). Except near the outer edge of plasma where the density is very small, stable heating can occur.

II) High frequency instabilities

There are many types of high frequency instabilities in a mirror geometry. However, the plasma loss due to these instabilities is relatively small to the extent that a mirror configuration is still considered to be a candidate for a fusion reactor. These instabilities simply moderately decrease the efficiency ϵ for a neutron source.

D. Design Considerations

The following formulas may be relevant to designing of the DOCH neutron source. The neutron yield $\partial N/\partial t$ is given by

$$\frac{\partial N}{\partial t} = n_D n_T \langle \sigma v \rangle V \quad (65)$$

where $\langle \sigma v \rangle$ is fusion reaction probability and V is the reaction volume.

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The neutron yield required for producing the flux f is

$$\frac{\partial N}{\partial t} = 4\pi L^2 f \quad (66)$$

The efficiency ϵ is given by

$$\epsilon = \frac{\tau (\partial N / \partial t) 17 \text{ MeV}}{2Vn_D T} \quad (67)$$

where τ is the confinement time of plasma. The injection current I_{inj} is

$$I_{inj} = 2eVn_D / \tau \quad (68)$$

where the particle confinement time τ is assumed to be roughly equal to the energy confinement time. By using Eqs. (66) and (67) in (68) we obtain

$$I_{inj} = \frac{2e}{\epsilon} \frac{17 \text{ MeV}}{2T} \quad (69)$$

With $\epsilon = 0.1$, $f = 10^{15} \text{ n/cm}^2\text{-sec}$, $T = 50 \text{ keV}$, and $L = 3 \text{ cm}$ we have

$$I_{inj} = 50 \text{ Amp}$$

The plasma density is found from Eqs. (65) and (66) by assuming $n_D = n_T$.

We have

$$n_D = 4\pi L^2 f / \langle \sigma v \rangle V \quad (70)$$

By putting $V = (4\pi/3)L^3$, $L = 3 \text{ cm}$, $f = 10^{15} \text{ neut/cm}^2\text{-sec}$, and $\langle \sigma v \rangle \sim 10^{-15} \text{ cm}^3\text{-sec}^{-1}$ we obtain

$$n_D \sim 10^{15} \text{ cm}^{-3}$$

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It would require a very high magnetic field ($\sim 100 \text{ kT}$) to keep β small at this density. In addition, the coils are in a large neutron flux and superconductor coils may not be used. However, the volume of the high magnetic field region is small and it requires only a moderate power to produce the field with an ordinary conductor. In order to keep the total power low, it is preferable to have a small reaction volume. The minimum size of the reaction volume is limited by ion gyroradius and also by the gradient length of the magnetic field. The density and temperature gradient length can not be shorter than the magnetic field gradient length for stable heating. The magnetic field gradient length is dictated by the distance h between the magnetic coil and the median plane, namely,

$$kh \leq 1$$

Also the drift approximation requires that $kp_i < 1$.

The static magnetic field may be produced by a pair of pancake coils with an appropriate current distribution. The a.c. field may be produced with a similar pair of coils which are placed off set relative to the axis of symmetry.

The source of particles may be an ion source or a plasma source. When an ion source is used, a higher injection energy is preferred for obtaining a larger current. DOCH is used primarily for pumping and not so much for heating in this case.

For a plasma source case, DOCH is primarily for heating, since a high density low-temperature plasma is easier to obtain. The outer region of the magnetic field may be smoothly connected to a toroidal quadrupole configuration in a similar fashion as a diverter. A plasma may be produced or injected in the quadrupole and may be pumped into the DOCH region by stochastic heating.

E. SUMMARY

Numerology of neutron sources is studied. The combination of an ion-beam and a target, gas or otherwise does not appear to give a sufficient neutron flux. The neutralized beam or the plasma approach seems more promising. However, these methods share many problems associated with plasma confinement. A possible method, DOCH pumped mirror, is discussed. It appears promising. However, further studies are needed before the feasibility of the method becomes convincing.

REFERENCES

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