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Importance of a Mirror-Based Neutron Source for the Controlled Fusion Program

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Abstract

This comment discusses the importance of a neutron source for the controlled fusion program and the compatibility of mirror machines operating in a beam-target mode, with neutron source requirements. It is pointed out that the 2XIIB experiment has already established most of the feasibility characteristics of the neutron source. However, before a decision can be made to build a mirror machine source, additional experiments are needed to guarantee that the necessary improvement of plasma parameters can be indeed achieved.

I. Introduction

Controlled fusion research has progressed to where plasmas are now produced with containment properties close to that needed for achieving controlled fusion from a D-T reaction. Commercial fusion power based on this reaction offers a tangible solution to very serious global energy problems that are now arising from the use of established energy sources, e.g., the accumulation of CO_2 from the burning of fossil fuels, the safety and sociological problems associated with fission reactors, etc. Hence there is some urgency to achieving controlled fusion power in a reasonable time period and a forward-looking fusion program needs to not only solve the issue of plasma containment, but needs to address essential long-term material problems associated with the neutron flux inherent in the D-T cycle.

There has been an effort by material scientists to develop a neutron source for material studies. In recent months there have been several meetings (e.g., U.S.-Japan, Osaka, June 1988; IEA Workshop, San Diego, February 1989; U.S.-U.S.S.R. Workshop, Livermore, February 1989) among material, accelerator and plasma scientists discussing feasible plasma and accelerator sources. One of the most promising neutron sources is based on the use of mirror containment of a beam target system. Most of the containment physics and neutral beam technology has already been demonstrated. Such a system also has the advantage that it would operate in many ways as a fusion reactor and it could then supply invaluable systems information for an environment where high availability is a requirement. Thus there exists a strong rationale for supporting mirror research that can be applied to the development of a neutron source. The purpose of this comment is to present a perspective to the general plasma physics community on the need of a neutron source and to point out that, with support, the successful development of a mirror-based neutron source is extremely likely.

In the following sections we shall discuss why a neutron source is important for a controlled fusion program based on the D-T reaction. We then discuss the reasons why a mirror contained beam-target neutron source[2,3] is particularly compatible with the needs of a fusion reactor. Further, we present a status report of two mirror neutron source proposals, for which many of the physics containment issues have already been experimentally established.

II. Rationale for a Neutron Source

The D-T reaction is most likely to be the initial basis of commercial thermonuclear power. Alternative fuel cycles, such as D-D and D-He^3, are in many ways more desirable since they produce a much lower neutron fluence and therefore induce less severe material problems. However, there is not as yet sufficient evidence that the required plasma containment properties can be achieved for these fuel cycles. Further, the D-He^3 cycle further requires an independent source of He^3 and the practicality of attaining such a source, from say lunar mining, still has to be established. Thus today the D-T fuel cycle is the only one for which there is general confidence that the required criteria for plasma confinement and fuel availability can be met. This cycle indeed meets long-term energy needs as the availability of fuel from lithium (from which T is bred) and deuterium is essentially unlimited, and radioactivity problems are perceived to be relatively minor compared to those of fission reactors (it is likely that these problems can be further reduced if low activation materials can be developed). In addition many of the relevant technologies needed to support a fusion reactor are developing rapidly.

The most difficult technological problem associated with D-T operation, other than plasma containment, is the understanding of material properties when they are subjected to large fluences of 14 MeV neutrons, which supply 80% of the energy produced in the DT reaction. When these neutrons interact with matter which surrounds the plasma (first wall, blanket, etc.), secondary neutrons appear whose flux typically exceeds that of "primary" DT neutrons by an order of magnitude, and energy spectrum extends from 14 MeV down to zero. The combined action of primary and secondary neutrons creates conditions which are difficult to achieve in any device, except a real fusion reactor.

The neutron irradiation affects material properties in many ways[1]: e.g., they produce energetic recoil nuclei which in turn produce various types of defects in the crystal lattice; they generate hydrogen and helium via (n,p) and (n,α) reactions; they change the material chemical composition via different nuclear reactions, some of which lead to formation of radioactive elements. All these effects are strongly dependent on the neutron spectrum. In particular, the rate of hydrogen and helium production will be quite different in a fusion reactor than in a fast breeder. The same is true for the spectrum of the recoil nuclei (which produce material defects) and for the rate of nuclear transmutations. All these phenomena occur in the material bulk as the penetration distance of 14 MeV neutrons in typical materials is many centimeters.

In a prototype tokamak fusion reactor the flux of primary fusion neutrons will be at least $1-2\,\mathrm{MW/m^2}$ i.e., $5\cdot10^{13}-10^{14}\,\mathrm{n/cm^2s}$ (economics requires that a commercial reactor have an even higher wall loading, $\sim 3-5\,\mathrm{MW/m^2}$, but this level is not likely to be achieved until considerable reactor operation experience is attained). The operating time of a prototype reactor is estimated as 10-20 years, which corresponds to the fluence of $\sim 30\,\mathrm{MW\cdot yr/m^2}$. It is quite certain that the mechanical, electrical and thermal properties of the materials will be significantly changed for such a fluence.

For these as well as other reasons, the decision on the construction of a prototype commercial fusion reactor after ITER can only be made on the basis of extensive materials and component testing program. Important results will be available from simulation experiments; e.g., the irradiation of materials by fast protons and α-particles give information on structural changes in surface layers, and fast breeders and accelerators can be used as neutron sources (a general overview of these options can be found in the issue where Ref. 1 appears). However, the basis of a really reliable decision in choosing materials for long-lived reactor components still needs testing under the action of the neutrons that is nearly identical to that of a fusion reactor.

III. Mirror-Based Neutron Source

The ultimate purpose of a neutron source is to achieve a large neutron fluence through relatively small samples. To acquire this fluence in a short enough time, a high intensity flux of neutrons is essential, but the irradiated surface area can be very small compared to reactor dimensions. This compactness allows for the operation of a system that is considerably cheaper in capital and operational cost than a fusion reactor, even if the neutron source operates at a relatively low energy efficiency.

It has already been experimentally demonstrated that high energy compact steady-state plasmas can be produced from beam target plasmas in mirror machines.[4] These plasmas have achieved β-values (β is the ratio of particle pressure to magnetic pressure with an average β-value of unity being the upper theoretical limit) of about unity without any indication of MHD instability or loss of equilibrium.[4,5] Thus, these results indicate that with a mirror machine one can make a plasma neutron source as intense and compact as is theoretically possible. The experimentally demonstrated steady-state operation also shows that the beam target system can be the basis of a neutron source with a continuous flux, a property that is probably essential for neutron source operation. Further, the neutron energy spectrum of this neutron source should be nearly identical to a fusion reactor. This follows because the primary neutron energy spectrum is identical as both systems produce neutrons from the D-T reaction. The secondary neutron spectrum should be quite similar as neutrons will slow down from collisions with the material walls and both in the tokamak reactor and the mirror neutron source the walls can be viewed as a long cylindrical shell surrounding a long cylindrical plasma.

The above listed properties indicate that mirror machine operation of a beam-plasma system is extremely compatible with the following basic requirements of a "good" neutron source[5]:

1. Be relatively simple and inexpensive (both as capital and operational cost);
2. Provide a continual flux of 14 MeV neutrons;
3. Provide a similar secondary neutron spectrum as that of a fusion reactor.

To understand the importance of the maximum β in regards to the intensity that can be achieved in a compact plasma system, let us consider the following general arguments. In a mirror-type target approach, one of the components (say tritium) is cold and dense. It forms a "target" for the fast ions of the other components (say, deuterium). Then as long as the partial pressure of the cold component is low compared to the hot component, the density of the cold component (n_T) can be made quite high. This enhances the specific power, η, from fusion reactions, which for fixed beam energy and background temperature, scales as

$$\eta \propto n_D \, n_T \, . \tag{1}$$

Thus, by increasing the value of n_T, the rate of neutron production is increased. A given plasma system has a maximum β established by stability and equilibrium considerations. If the plasma pressure is primarily due to the pressure of the beam, the value of n_T can be raised until the partial pressure of the background plasma approaches the beam pressure. Thus, $n_T \, T \lesssim n_D \, \overline{E}_D$ where T is the temperature of the plasma (the electron temperature is assumed comparable to the tritium temperature in this argument). Thus maximum intensity is achieved when both n_T and n_D have comparable partial pressures and then both n_T and n_D are proportional to the total pressure $p \propto \beta B^2$. Then, from Eq. (1), the maximum specific power scales as

$$\eta \propto \beta^2 \, B^4 \, . \tag{2}$$

This strong dependence of specific power on β indicates an extremely favorable aspect for the mirror system where β can approach the theoretical limit of unity.

Another important characteristic of the beam target neutron source is the scaling of the input power with the local plasma temperature. As input injected beam power equals the power loss rate, and the injected beam energy, E_{D0}, is comparable to the mean beam energy E_D, the specific input power, η, scales as

$$\eta = \frac{n_T \overline{E}_D}{\tau_E} \propto E_{D0}\, n_D\, n_T / T^{3/2} \ .$$

A beam energy $\sim 150\,\mathrm{keV}$ maximizes neutron production. The remaining parameter T is primarily determined by the quality of plasma heat containment.

Major improvements of efficiency (and thus operational cost) is possible if T can be improved. The situation in mirror research is that high beta, but relatively low electron temperature experiments have been achieved in the 2X-II-B experiment. As will be discussed in the next section, the principles used in 2X-II-B operation can be used to build a suitable neutron source. However, improved operational efficiency can be achieved if higher background plasma temperature can be achieved. The Gas Dynamic Trap is an experiment that has been designed to make use of the favorable properties of a beam-plasma system. Some of its details will be discussed in the next section. For now we only note that it has been designed to operate at high mirror ratio which ought to allow a significant increase in electron temperature.

Neutron source proposals based on the 2X-II-B experiment and the Gas Dynamic Trap will make use of other intrinsic advantages of mirror beam plasma systems: (a) the stability problem is essentially resolved as it is well established that the beam-plasma is more stable to microfluctuations than an axially contained mirror system as the loss cone which drives micro-instability, is filled, (b) by flaring the magnetic fields the exhaust heat can be spread over a relatively large and surface area so that solid walls through which the heat convects away, can tolerate the heat flux.

IV. Possible Parameters of the Neutron Source

One of the principal proposals for a neutron source made by the Livermore group[2,7] is based on a direct extrapolation of the 2XIIB experiment.[4] In this experiment high energy (20 keV) neutral beam ions were trapped in a plasma with a relatively low electron temperature in a min-B mirror field with the central field B_0 varying from 4 to 8 KG. The following plasma parameters were attained:

1. A steady state (limited only by the beam pulse length) hot ion plasma was achieved where the mean ion thermal energy, $\overline{E}_i$, was $\sim 13\,\text{keV}$.
2. High density and high beta plasmas were attained with the central density, $\widehat{n}$, in the range $3 - 10 \times 10^{13}\,\text{cm}^{-3}$, and the central beta, $\widehat{\beta} \equiv 8\pi\,\widehat{n}\overline{E}_i/B_0^2$, value ~ 1.
3. The ion energy containment time was usually the classical Spitzer energy drag time to electrons whose temperature, T_e, was typically 100 eV.
4. Ion cyclotron noise was maintained at a sufficiently low level to allow plasma sustainment with the neutral beam. Thus, this noise usually did not alter the energy containment time from the Spitzer loss rate. In fact, with a sufficiently intense target source, ion cyclotron noise could be almost entirely eliminated.

Because these high grade plasma parameters were achieved during quasi-steady state operation, the 2XIIB mode of operation is very close to what is needed for a neutron source. For such operation the D° injection energy $\sim 150\,\text{keV}$ is close to optimum for neutron production and compatible with neutral beam technology which is already well advanced. Today neutral beams are available at JET with $E_b \approx 150\,\text{keV}$ with pulse times of 10-20 seconds. The extension to steady-state operation is considered straightforward. The major future technological developments in this area need to be in improving the beam's efficiency. Either negative ion beam or direct conversion techniques need to be developed.

The major shortcoming of the 2XIIB parameters was that the achieved electron temperature was rather low. The low temperature is associated with the unconfined source plasma that needs to be present to prevent a high level excitation of ion cyclotron instability. The outflow of the plasma source forces a short electron lifetime that constrains the electron temperature to be $\simeq 100\,\mathrm{eV}$. This electron temperature is a key parameter in determining the input power, P_{in}, needed to drive the source.

The relation between input power and output power, P_N, is given by

$$P_{in} \simeq 7 P_N / T_e^{3/2}(\mathrm{keV})\ G(E_b)$$

where $G(E_b)$ is a slowly varying function which for deuterium injection has a peak value $G(E_b) = 1$ at $E_b = 160\,\mathrm{keV}$. The neutron source should be designed to attain a given fluence through a material surface in a shortest possible time. Thus, a neutron source should have the highest neutron flux, $F = P_N/S$ (with S the surface area of wall material surrounding the plasma), compatible with material thermal stress loads which is generally taken as $\sim 5\,\mathrm{MW/m^2}$. Then, to reduce the input power, we need to increase the electron temperature in the injection region.

In the Livermore neutron source proposal improvement of the electron temperature is to be attempted by using a plasma stream in a long column of total length ℓ_c with the electron mean free path λ less than the column half length. Electron thermal loss is then due to a random walk process that leads to the Spitzer thermal conduction formula.[8] For a central temperature, T_e, column length ℓ_c, column radius $a/\sqrt{R}$ (a is the radius of the hot region and R the mirror ratio of the column with respect to the central field of the neutron source) the Spitzer formula leads to the following relation[7] between input power P_{in} and T_e:

$$P_{in}(\mathrm{MW}) = 2.4 \times 10^6 \, \frac{T_e^{7/2}(\mathrm{keV})\, a^2(\mathrm{cm})}{\ell_c(\mathrm{cm}) R} \ . \qquad (3)$$

Now equating the input power to the electron drag power transfer rate between the neutral beams and electrons yields

$$T_e(\text{keV}) = 0.22 \left(\frac{R}{3} \cdot \frac{n_h(\text{cm}^{-3})}{8 \times 10^{14}} \cdot \frac{n_e(\text{cm}^{-3})}{3 \times 10^{15}} \cdot \frac{\ell_h(\text{cm})}{15} \frac{\ell_c(\text{cm})}{10^3} \frac{E_h(\text{keV})}{50} \right)^{1/5} \tag{4}$$

where n_h and n_e is the injected particle central density and central electron density, ℓ_h is the length of hot injection region, ℓ_c is the length of the column, E_h the mean energy of the injected ions (typically $3E_h \approx E_0$) and R is the mirror ratio. A consistent set of parameters is given in Table I. Schematic of Livermore source is shown in Fig. 1.

This proposed neutron source is designed so that the dimensionless parameters of the 2XIIB experiment are reproduced as much as possible. However, the long column is a major new physics element in this proposal. According to classical diffusion theory the plasma stream can remain collimated. However, as anomalous diffusion is a characteristic of nearly every plasma experiment, it is essential to establish that the plasma stream collimation can be maintained in a narrow radial column. It is interesting to note that by impressing a unidirectional flow, V_{flow}, to the stream, a considerable amount of anomalous diffusion can be present without deteriorating the plasma confinement properties as the flow would allow particles to leave axially before they radially diffuse, with a negligible penalty on heat loss. The anomalous radial diffusion time is given by

$$\tau_{\text{anom}} \simeq \frac{a^2}{6R\,D_{\text{anom}}} \tag{5}$$

where D_{anom} is the anomalous diffusion coefficient. The electron thermal conduction time, τ_{thm}, (defined as $\frac{3nT}{\tau_{\text{thm}}} \frac{\pi a^2 \ell_c}{R} = P_{in}$) is given by

$$\tau_{\text{thm}}(\text{sec}) = 3.5 \times 10^{-5} \left(\frac{\ell_c}{10^3} \right)^2 \left(\frac{n_e}{10^{15}} \right) \left(\frac{0.2}{T_e(\text{keV})} \right)^{5/2} . \tag{6}$$

If

$$\tau_{\text{thm}} < \frac{\ell_c}{V_{\text{flow}}} < \tau_{\text{anom}} \ ,$$

the thermal conduction properties described here do not change. Thus, if the anomalous coefficient

$$D_{\text{anom}}\left(\frac{\text{cm}^2}{\text{sec}}\right) < \frac{5\times10^5}{R}\left(\frac{a}{10}\right)^2\left(\frac{10^{15}}{n_e}\right)\left(\frac{T_e}{0.2}\right)^{5/2}\left(\frac{10^3}{\ell_c}\right) \qquad (7)$$

neither deterioration of the column structure or of the electron temperature will arise when proper flow conditions are established. Bohm diffusion, $D_B = \dfrac{cT_e}{16eB}$, gives a standard estimate for anomalous diffusion. For $B \simeq 10^5$ Gauss, $T_e = 200\,\text{eV}$, we find $D_B \simeq 10^4\,\text{cm}^2/\,\text{sec}$. This value for D_B is considerably less than anomalous diffusion permitted by Eq. (7). Hence, with plasma flow, it is very likely that the integrity and thermal insulation of the plasma column can be maintained.

The second project[3] mentioned above is an axisymmetric simple mirror machine with a high mirror ratio $R \simeq 20$, the so-called "Gas-Dynamic Trap."[9] A schematic of the device is shown in Fig. 2. The mean free path of target plasma ions (deuterium) is small enough so that the target plasma's longitudinal loss is determined by the gas-dynamic equations (from which derives the name of the device). MHD stability is provided by the favorable curvature of the field lines in the expander where the plasma's momentum flux (the dynamic pressure $\rho\, v^2$) is considerable (in contrast to the conventional mirror machines with a nearly collisionless plasma). This stabilization technique was successfully tested experimentally at Novosibirsk[10] at the device GDT whose configuration is close to the needs of a neutron source.

The electron thermal insulation from the ends of the device is supposed to be achieved by the large expansion of a magnetic flux tube beyond the mirror point, which would enable the plasma density near the absorbing wall to become 3-4 orders of magnitude smaller than that in the center of the device. Under this condition, the electron thermal flux to the walls is strongly inhibited by a natural electrostatic potential barrier formed in the expander. It has been shown that because of the large magnetic field expansion, the electron temperature near the wall will be much lower than in the plasma trap, even in the long mean free path limit. The situation here is similar to that in the TMX experiment where the insulation from the end wall was sufficiently high for the electron temperature to approach 200 eV.

For the neutron source application "sloshing" ions in the form of fast tritons with the energy $E_0 \simeq 200\,\text{keV}$ are injected into the system at a small angle ($20-30°$) to the magnetic axis with a small angular spread. As the target plasma temperature is low ($T \sim 0.5 \sim 1.0\,\text{keV}$) the injected tritons are slowed down by the electrons much more quickly than they are scattered by the plasma ions. Hence, their angular distribution will not differ greatly from the angular distribution of the primary neutrals. Due to the small angular spread the turning points of the sloshing ions are in a limited spatial region (where the local mirror ratio is $\simeq 8$) where their density will have large maxima. Hence, according to Eq. (1), the local neutron flux is peaked in the vicinity of the turning points.

The critical problem for this concept for the neutron source is that of microstability of the sloshing ion population. It is generally thought that sloshing ions are more stable than the ones injected perpendicularly to the magnetic field (see e.g., Ref. 11). In the above mentioned experiment on the GDT device[10] no indications of the microinstabilities were revealed for the sloshing ions with the angular spread as small as 5°. However, as the achieved plasma parameters cannot be directly scaled to those of the neutron source, further experiments are required.

The main parameters of the neutron source of GDT-type are as follows: $B_{\text{min}} = 1.25\,\text{T}$, $B_{\text{max}} = 25\,\text{T}$, mirror-to-mirror length 5 m, plasma radius in the midplane 6.5 cm, target plasma density $2.7 \times 10^{14}\,\text{cm}^{-3}$, neutron flux at the plasma surface near the turning points $3.9\,\text{MW/m}^2$, the total length of two test zones 1 m, injection power trapped by plasma 20 MW, overall electric power consumption of the device $50-60\,\text{MW}$.

There are also other proposals for mirror-type neutron sources (a survey can be found e.g., in Ref. 12) but they are based on more optimistic assumption of plasma parameters that need to be achieved (especially in regards to T_e) and thus require much more extrapolation from the present experimental database. It may be better to view these proposals as intermediary steps to mirror fusion than the shortest way to a dedicated neutron source.

V. Technical Feasibility

In both projects the technical requirements for the subsystems are weaker than the ones needed for the ITER project and are very close to presently achieved technological levels. For instance, the neutral beam power trapped in the ITER is expected to be 100 MW and the beam energy $0.45 - 1.6$ MeV,[13] while in the two projects described here the corresponding figures will be $20 - 50$ MW and $0.15 - 0.25$ MeV.

The only new specification (with respect to present technology) which is required from the neutral beam injectors is a continuous mode of operation. This technology seems well on its way toward development.

Another important characteristic of a neutron source is the tritium inventory. The tritium is contained mostly in the reprocessing system. An estimate of 200 gm has been made for the Novosibirsk project. It is likely that a similar amount of tritium would be contained in the Livermore source. This should be compared with $3 - 5$ kG of the INTOR project.[14]

The physical size of a neutron source will be much smaller than that of ITER or INTOR (e.g., the volume of the vacuum chamber will be several hundred times smaller). Thus, the capital cost of a neutron source will only be a fraction ($\sim 5 - 10\%$) of ITER's cost.

VI. Conclusion

It is very difficult to imagine the serious development of the fusion program in the post-ITER phase without having a dedicated neutron source operating from about the same time that experiments on ITER are being performed. The basis for this conclusion is the relatively low neutron loading planned in ITER ($\sim 1\,\mathrm{MW/m^2}$) and, even more important, a low operational duty cycle (which probably will reach the value of 0.1 around 2005 or 2010). Thus it is hard to expect the fluence to surpass $1-2\,\mathrm{MW\ yr/m^2}$ by the year 2020. It is quite evident that the transition to fusion devices after ITER will certainly require reliable data on material and subcomponent behavior at the fluences exceeding $20\,\mathrm{MW/m^2}$. An insuperable delay would appear in the transition between ITER and post-ITER device, if there would be no complementary device (a dedicated neutron source) built at the proper time.

This device may come from accelerator technology or plasma technology. We hope that we have shown that the mirror-based neutron source is at least one prime candidate that can come from plasma technology. It has several obvious advantages:

1. Experimental geometry and neutron spectrum identical to that of a fusion reactor.
2. Physics and technology suitable for continuous operation, a mode that is essential for the adequate simulation of the mainline fusion reactor conditions.
3. Relatively low capital and operational cost at a rather high neutron flux ($4-8\,\mathrm{MW/m^2}$) in a test volume of $10-200$ liters. (Note that with nearly continuous operation of a neutron source, even a somewhat smaller flux of $1.5-2\,\mathrm{MW/m^2}$ would allow the accumulation of the necessary fluence in ~ 10 years.)
4. The use of technologies that are either already developed (e.g., neutral beams) or need to be developed for the fusion reactor program (e.g., remote handling systems).

An aspect that might be considered a disadvantage is the necessity for having a tritium system which is not required in accelerator based neutron sources. On the other hand, the use of tritium is unavoidable for fusion applications, so that the option of having intensive experience in running the tritium system might well be considered an advantage. In more general terms, the mirror-based neutron source can be the first fusion producing "instrument" that operates as a user service rather than as an experiment whose main purpose is to determine operational characteristics. Such a service will give invaluable experience to the operational procedures of a future fusion producing system. The very design philosophy of such an instrument where high reliability and high availability are the dominant requirements, is quite different from that of experimental fusion devices including ITER where flexibility is considered at least as important as reliability and availability.

Another option worth considering is the construction of the neutron source on the ITER site (or on the site of an analogous national project as for example OTR in the USSR). This would allow the common use of some subsystems (like power supplies, tritium purification, hot cells, etc.) and make a neutron source less expensive (note that the cost of neutron source is relatively small compared with ITER).

It might seem that the lifetime for the use of a dedicated neutron source is limited as irradiation test could be made in commercial fusion reactors after they are placed into operation. However, the experience obtained in the development of fission reactors indicates that a relatively inexpensive dedicated neutron source for material studies should still be highly desirable. In fact, the process of creating a fully operational fusion power industry would likely demand that inexpensive neutron source be available. Such a source would also allow the interesting option of providing an additional means of funding by the selling of part of the testing volume to researchers in neutron physics, solid state physics, etc.

An important feature of the two proposals considered in our paper in that they are based on relatively modest assumptions on the achievable plasma parameters. The physics of the beam-target interaction region of the Livermore proposal is nearly identical to the proven operation of 2XIIB, with the major unknown being the physics and reliability of the required plasma column. In the gas dynamic trap the stability of sloshing ions is well established while the principal uncertainty is the ultimate beta and maximum electron temperature that can be achieved. From our present knowledge of plasmas a high confidence factor exists for the ultimate successful development of both proposals. However, a decision on the type of neutron source to build will certainly require an overwhelming confidence level on its reliability, and therefore to guarantee success it is necessary to have intermediate experiments. These experiments should check the most critical physics issues at conditions close to the ones expected for the neutron source. In a few years (perhaps less than five) the fusion program will probably need to have a neutron source built. Hence, mirror experiments we described should be started immediately if they are to be considered as a viable candidate. These experiments can be rapidly assembled as considerable equipment from past facilities is still available.

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Figure Captions

1. Schematic of Livermore neutron source. Central section of vacuum chamber and neutron shielding of superconducting magnets are not shown.
2. Schematic of GDT based on neutron source: (1) expander vacuum chamber; (2) plasma absorber; (3) superconducting part of the mirror coil; (4) water-cooled part of the mirror coil; (5) one of the coils of superconducting solenoid; (6) shield; (7) vacuum chamber of a mirror cell; (8) zone of a moderate neutron flux; (9) zone of a high neutron flux; (10) neutron reflector. The plots below show the relative magnetic field B and the relative dependence of neutron flux F_N on the position.

	$\beta = 1$	$\beta = 0.25$
D° beam energy (keV)	150	150
D° beam power (MW)	60	50
Neutron wall loading (MW/m^2)	7.2	11.6
Total fusion power (MW)	1.0	1.1
Peak Plasma β	1.0	0.25
Hot ion density, $\widehat{n}_h(r = 0)(m^{-3})$	8×10^{20}	8×10^{20}
$\widehat{n}_e(r = 0)(m^{-3})$	3.2×10^{21}	6.3×10^{21}
Electron temperature, $T_e(r = 0)$ (keV)	0.22	0.21
Average hot ion energy, E_h (keV)	50	51
$\ell_h(m)$	0.15	0.30
$a(m)$	0.04	0.02
Edge radius, $r_p = 2a(m)$	0.08	0.04
$\rho_i(m)$	0.02	0.01
Column length, $\ell_c(m)$	10	10
Central magnetic field $B_0(T)$	4	8
Column magnetic field $B_c(T)$	12	12
Quadrupole magnetic power (MW)	6.8	0

Table I: Neutron Source Parameters of the Livermore Proposal

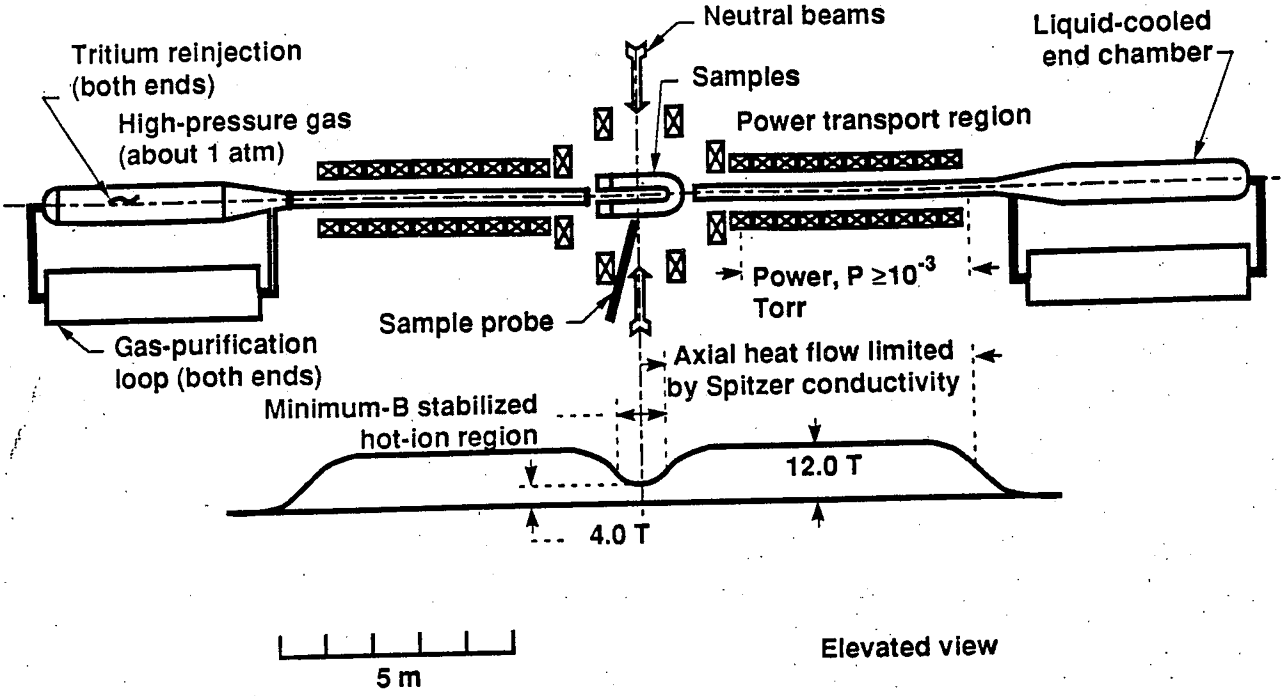
Neutral beams
Liquid-cooled end chamber
Tritium reinjection (both ends)
Samples
High-pressure gas (about 1 atm)
Power transport region
Power, P ≥10^{-3} Torr
Sample probe
Gas-purification loop (both ends)
Axial heat flow limited by Spitzer conductivity
Minimum-B stabilized hot-ion region
12.0 T
4.0 T
5 m
Elevated view

Fig. 1

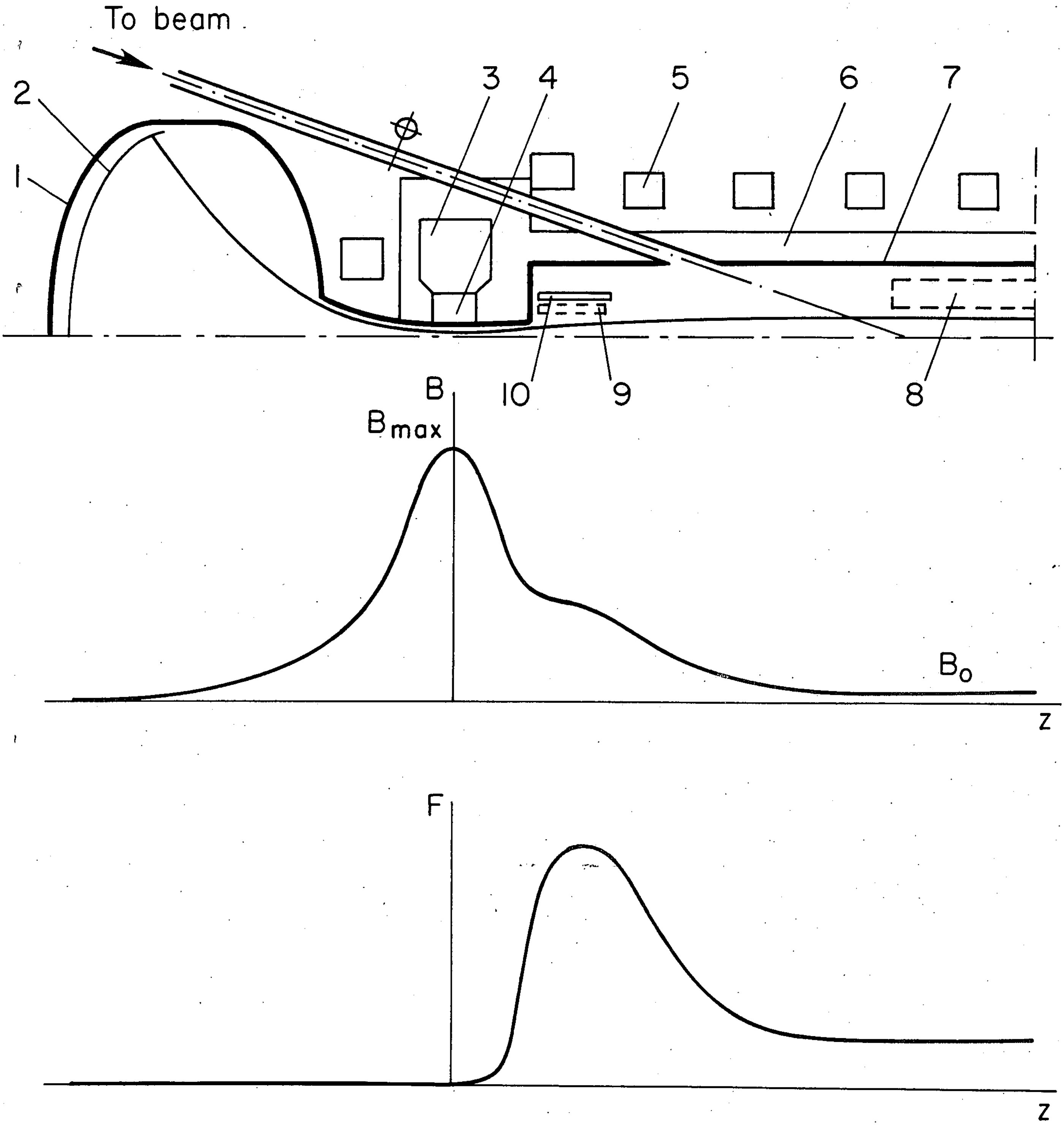

Fig. 2

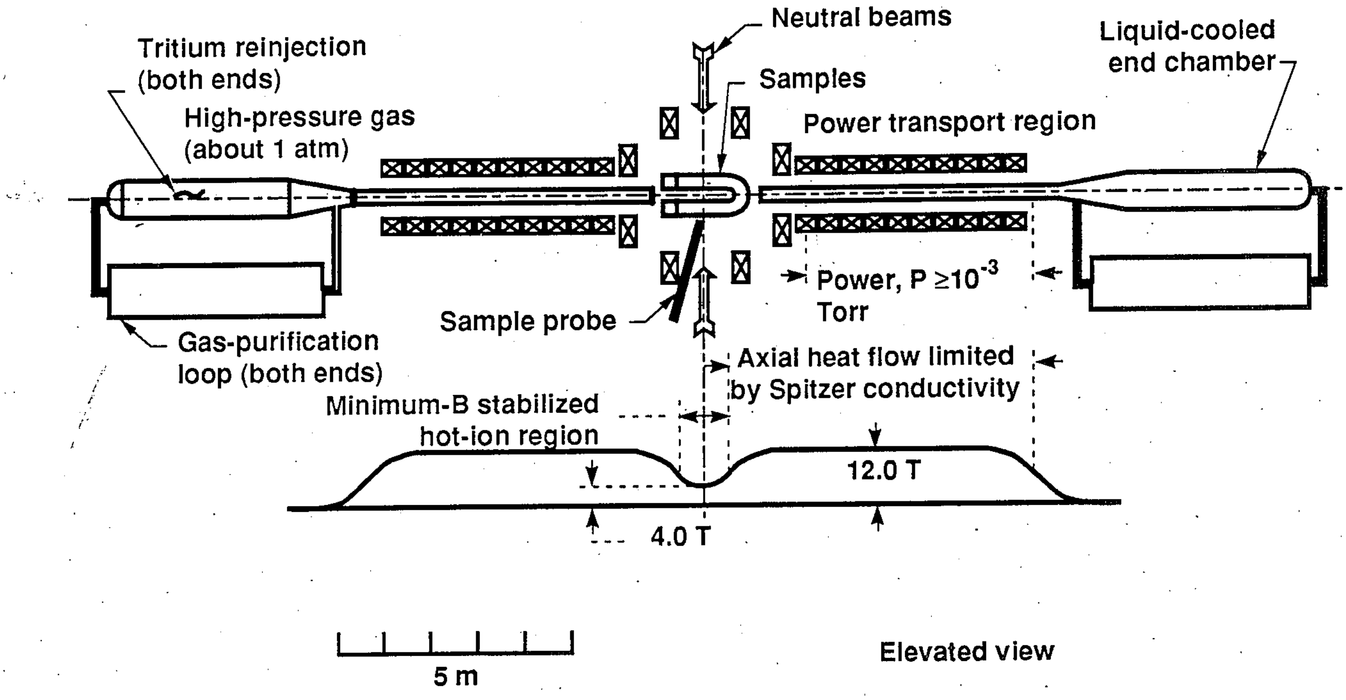
Neutral beams
Tritium reinjection (both ends)
High-pressure gas (about 1 atm)
Samples
Liquid-cooled end chamber
Power transport region
Power, P ≥10⁻³ Torr
Sample probe
Gas-purification loop (both ends)
Axial heat flow limited by Spitzer conductivity
Minimum-B stabilized hot-ion region
12.0 T
4.0 T
5 m
Elevated view

Fig. 1