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^{3}He FUNCTIONS IN TOKAMAK-PUMPED LASER SYSTEMS

By

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ABSTRACT

^{3}He placed in an annular cell around a tokamak fusion generator can convert moderated fusion neutrons to energetic ions by the ^{3}He(n,p)T reaction, and thereby excite gaseous lasants mixed with the ^{3}He while simultaneously breeding tritium. The total ^{3}He inventory is about 4 kg for large tokamak devices. Special configurations of toroidal-field magnets, neutron moderators and beryllium reflectors are required to permit nearly uniform neutron current into the laser cell with minimal attenuation. The annular laser radiation can be combined into a single output beam at the top of the tokamak.

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I. INTRODUCTION

The most straightforward way to utilize fusion neutrons for laser pumping is to moderate (slow down) the fusion neutrons and generate energetic ions in a laser gas mixture by one of the reactions shown in Table I and indicated schematically in Fig. 1. The fast ions in turn produce energetic electrons which are responsible for most of the atomic excitation. The ^{3}He(n,p)T reaction is especially attractive from the points of view of ease of use, safety, compatibility of ^{3}He with numerous lasants, and uniform volumetric pumping. There has also been considerable experimental work done in pumping lasers with fission reactor neutrons via the ^{3}He(n,p)T reaction [1-3].

^{3}He appears to be unsuitable for practical fission-reactor-pumped lasers for several reasons: (1) At most, one neutron can be made available per fission event (190 MeV) to react with ^{3}He, and the 0.76 MeV reaction energy gives low overall pumping efficiency. (2) The laser cells and optical systems must be installed throughout the reactor core in order to utilize all the free neutrons. (3) The huge absorption cross section of ^{3}He would require that excess reactivity be added to the fission system, which could cause a dangerous power excursion in the event of an escape of ^{3}He gas.

In a fusion reactor, on the other hand, one neutron is available per 17.6 MeV, so that the system can be a factor of 11 energetically more favorable than the fission reactor case. Practically all the neutrons can be made to emerge from the fusion source, either by direct streaming, or indirectly by reflection from beryllium surfaces. Absorption (or reflection) of the neutrons has absolutely no effect on the fusion source.

The $^3He(n,p)T$ reaction cross section decreases roughly inversely with neutron velocity, so that nearly thermalized neutrons are desirable to permit reasonable pressures in the laser cell. Thus the energy spectrum of the source neutrons is of no concern, and all lasers studied to date with fission reactor neutrons can be pumped by fusion neutron sources of sufficiently high intensity. The <u>threshold</u> neutron fluxes necessary to pump laser gas mixtures with a ^3He host gas are generally in the range 10^{14} to 10^{17} $n/cm^2/s$ [1-3]. Tokamak fusion generators are capable of producing fluxes exceeding 10^{15} $n/cm^2/s$, including both uncollided and scattered neutrons.

Of special importance for D-T fusion sources, the $^3He(n,p)T$ reaction regenerates the triton used to produce the fusion neutron, so that the usual breeding requirement can also be satisfied. (That would be an issue only in systems that experience large duty factor averaged over a year.) The tritium can be retrieved continuously from the laser-gas mixture, eliminating the need for a reprocessing plant.

The purpose of this paper is to present configurations for converting virtually the entire neutron output of a tokamak fusion source to energetic ions by the $^3He(n,p)T$ reaction, in order to pump laser-gas mixtures with simultaneous tritium breeding and optional electrical power production.

II. TOKAMAK & LASER CELL CONFIGURATION

Figure 2 shows a TPL (tokamak-pumped laser) system with an annular laser cavity. We will consider configurations where the annular cavity is either broken up into cells that fit between adjacent coils, or where it is located outside the TF (toroidal-field) coils. These arrangements are most amenable to extraction of the laser output and to servicing of the laser cells, as well as implementing a support structure that ensures minimal vibration.

In either case the two key neutronics objectives are 1) achieving adequate reflection of neutrons from the inboard regions of the torus, and 2) moderating the entire fusion neutron production with minimal loss before the neutrons impinge on the laser gas cells. As large a fraction as possible of the uncollided and reflected neutrons must be transmitted between — or through — the outboard TF coil legs.

II.A. DISCRETE TF COILS

The discrete coil arrangement shown in Fig. 3 resembles that used in most present-day tokamaks. Laser cells are placed in the bore of the TF-coil set, but must be supported by a structure independent of the tokamak in order to eliminate vibration. In the case of a single-pass laser, the lasing regions shadowed by the upper arms of the TF coils cannot contribute to the total output; the annular laser is in effect divided into N cells, where N is the number of TF coils. The width of the upper arms is constricted in the region just outside the plasma chamber to permit the laser cells to have greater toroidal breadth.

An annular layer of D_2O in front of the laser cell moderates the incident neutrons and carries away most of the nuclear heat. A beryllium neutron reflector is placed immediately behind the laser cell. A 20-cm layer of beryllium is also located immediately behind the inboard, top and bottom surfaces of the plasma chamber, to multiply fusion neutrons and reflect all neutrons to the outboard side.

The disadvantages of discrete coils are some nonuniformity of the total neutron flux, the need for a substantial anti-torque coil structure, which could interfere with the laser optical systems, and possibly an adverse effect of the magnetic field on the lasing process. The neutron flux incident on the laser cell is uniform over most of its toroidal extent, but may vary significantly toward the upper and lower ends of the cell. The ambient magnetic field at the cell position shown in Fig. 3 is 2 to 3 T, which can be reduced by moving individual cells radially outward, but with some reduction in neutron flux. (Pumping of a single He-Ne laser cell has been proposed for an experiment on the TFTR device [4], which will investigate the magnetic field issue.)

II.B. CONTIGUOUS TF COILS

Uniform neutron flux may be essential for a TPL because of the high power density deposited in the laser medium. If this deposition is markedly nonuniform, then the resultant nonuniformity of gas excitation may degrade the laser action. Density variations will also arise in the laser gas, causing serious diffraction.

One approach to increasing uniformity of the incident flux is to place the laser cavity outside the TF coils, with the latter having contiguous outboard legs thin enough to minimize attenuation of the neutron flux. Figure 4 shows the general arrangement. This method also improves access to the laser cell.

Homogeneous TF Coil Legs. We define T_n as the ratio of the transmitted neutron current at all energies to the incident neutron current at a single energy. The copper shell must have a high T_n not only for fusion neutrons, but also for lower energy neutrons reflected from the inboard, top, and bottom of the torus. Neutronics calculations for a 10-cm thick shell consisting of 90% Cu and 10% H_2O show $T_n \leq 0.5$ for neutrons of any energy up to 14 MeV [5]. For acceptable power dissipation and mechanical strength, the thickness of the outboard TF coil legs probably needs to be at least 15 cm, which results in impractically high neutron attenuation. (For coil thicknesses giving the same electrical resistance, T_n is about the same for Cu and Al.)

Perforated TF Coil Legs. A good balance between discrete coils and homogeneous contiguous coils is offered by "perforated coils," which consist of contiguous coils with a pattern of periodic through-holes in the outboard legs, as indicated in Fig. 5. The TF coils would be constructed of single-turn thick plates cooled by D_2O. With typical dimensions of 9-cm diameter and 20-cm length, the through-holes permit essentially 100% transmission of neutrons that are directly incident on the holes. With the penetrations comprising about 30% of the plate end-on cross section, most neutrons incident on the copper portions will eventually scatter into the holes and are then likely to be transmitted with little loss. This configuration results in neutron attenuation in the range of 15-20%.

Scattering in the D_2O moderator outboard of the TF coils results in a uniform flux of neutrons entering the annular laser cell.

Powering of Single-Turn Coils. The single-turn plate coils in the configuration of Figs. 4 and 5 can be driven by homopolar generators. For the system shown in Fig. 2, there could be 75 plates of 36-cm width and 20-cm radial thickness, each plate carrying 800 kA to provide $B \sim 5$ T on the plasma axis. Adjacent plates would actually be separated by thin ceramic insulation such as magnesium aluminate. A homopolar generator would feed several of the plates in series, with the currents in all generators carefully equalized.

The advantages of contiguous perforated coils are uniform neutron flux at the laser cavity, elimination of the need for an anti-torque structure, and negligible magnetic ripple in the plasma even for close-fitting coils, which in effect form a highly conducting partial shell. This shell is also expected to improve plasma stability. (The upper and lower arms of the coils would not be contiguous, in order to allow penetration of the field from external equilibrium-field coils.)

The contiguous coil set has a significantly larger resistance in the outboard legs compared with the system of discrete coils shown in Fig. 3. The disadvantages of this configuration are increased TF coil power consumption, reflection of some part of the incident neutron flux toward the inboard tokamak regions, and difficulty of access to many tokamak components. Some fraction of the plates would have removable joints to alleviate the access problem. Alternatively, the generators could supply higher current, allowing a reduction in the number of magnet plates and a corresponding increase in their toroidal thickness. Then bolted access doors could be installed in individual plates.

II.C ANNULAR LASER RESONATOR

In the configuration of Fig. 4, the entire annular cavity can serve as a single optical resonator and oscillate in modes distinctive to the annular geometry [6]. The annular output radiation is focused onto a central conical mirror, as indicated in Fig. 2, and fed to a beam compactor. In this way the total neutron emission of the tokamak can be used to pump a single high-power coherent laser beam.

In all configurations, the single annular cell or N individual cells can serve as amplifiers of a very low-power laser beam. The latter would first be spatially expanded by a beam splitter so that it uniformly illuminates the bottom of the annular laser region. The amplified beams could be combined to give a single output beam as in Fig. 2.

III. NEUTRON ECONOMY AND TRITIUM BREEDING

Achieving good neutron economy is important both to maximize pumping power density in the lasant, and to obtain large global tritium breeding ratio, $[TBR]_g$. An invaluable material for enhancing neutron conservation is beryllium, which has a total number albedo of at least 0.8 for neutrons of any energy, at least 0.9 for most energies, and about 1.5 for 14-MeV neutrons when deployed in thicknesses $\gtrsim$ 20 cm [7]. A 20-cm layer of Be is placed immediately behind the 1-cm wall of the plasma vessel at the inboard, top, and bottom sides to maximize neutron reflection. The top and bottom surfaces are sloped as shown in Fig. 4 to take advantage of the $\cos\theta$ emission of the reflected neutrons, a property that is independent of the energy or direction of the incident neutrons [8]. Taking into account the small neutron multiplication in tokamak device components (typically made of stainless steel or copper), estimates show that a neutron current of approximately 80% of the total fusion neutron production rate can be made to enter the laser cells.

Achieving $[TBR]_g = 1.0$ is extraordinarily difficult, because ^3He is not a neutron multiplier. Tritium production can be augmented by placing ^3He in portions of the tokamak that are unlikely to reflect neutrons into the laser cells. In this case, the equivalent of 90% of the fusion neutrons can eventually be thermalized and captured in ^3He in the laser cavity and elsewhere, to replenish the burned tritium. (High-pressure ^3He could even be used as a coolant for in-vessel components, but at the penalty of a substantial increase in ^3He inventory.)

IV. POWER CONVERSION

The laser efficiency is defined as the ratio of the laser output power to the power deposited by the energetic ions from the $^3He(n,p)T$ reaction. The ^3He-pumped lasers identified to date have very low efficiencies, generally only 0.1-1% [1-3], although as much as 5% has been claimed for the ^3He-Co laser oscillating near 5 µm [9]. The laser efficiency defined with reference to the fusion power would be 23 times smaller, assuming that for every fusion neutron there is one neutron that eventually reacts with ^3He. Then even a 1,000-MW fusion source could produce at best a 2-MW beam in the mid-infrared, and only much smaller powers at near-infrared or visible wavelengths. For cost effectiveness the reactor will probably have to be used for some other purpose as well as laser pumping.

In the configurations of Figs. 3 and 4, most of the nuclear heat is deposited in the D_2O moderator and in the inboard beryllium multiplier/reflector. Conversion of some of this heat to electricity would be practical in quasi-steady-state operation. The thermal power flow into the beryllium, which is cooled by helium or D_2O, can be readily transformed. To convert heat from the neutron moderator would require that it be operated at high pressure, and therefore must be contained in a thick-walled vessel, which would attenuate some of the neutrons destined for the laser cell. Only moderate pressures giving relatively low thermal conversion efficiencies would be allowable.

The power generated in the laser gas mixture by the $^3He(n,p)T$ reaction is about 5% of the fusion power, and must be removed by continuously flowing the gas. In general the temperature of the laser gas must be kept low to avoid overpopulation of certain energy levels.

In the external laser cell arrangement of Fig. 4, a significant fraction of the nuclear heat is deposited in the copper TF coils, but conversion of this power might not offset the increased resistive power loss incurred by operating the coils at higher temperature.

V. INVENTORY & SUPPLY OF ^{3}He

V.A. LASER-CELL INVENTORY

To absorb essentially all the incident neutrons in a single pass, the thickness of the ^{3}He in the laser cell must be about 2 mg/cm^2, which corresponds to 2 mean-free-paths for thermal neutrons. All slow neutrons ($E_n \lesssim 1$ eV) are likely to be absorbed, taking into account that the neutrons enter the annular cavity isotropically, and that the beryllium backing plate reflects neutrons back into the cavity. This thickness, which corresponds to 15 atm-cm, gives essentially uniform power density of energetic ions in the cavity [10]. The actual geometric thickness will depend on the optimal gas pressure for the lasant of interest, which is in the range 0.3 to 5 atm.

For a representative annular cavity of 5-m major radius and 6-m height (see Fig. 2), the surface area is about 200 m^2, and the ^{3}He inventory is 4 kg. When necessary to increase $[TBR]_g$, additional ^{3}He to the extent of about 1 kg would be deployed in portions of the tokamak that are unlikely to reflect neutrons into the laser cells. ^{3}He can presently be purchased for about $1,500 per gram, so that the total inventory cost would be nearly $8 million.

A tokamak operated primarily for laser pumping may experience a low annual capacity factor, even though the pulse length can be tens to hundreds of seconds. If the fusion power is 1000 MW, the time-averaged duty factor is 1%, and one neutron per fusion neutron is captured in ^{3}He, then the annual consumption of ^{3}He is 600 g, costing about $1 million. This cost is comparable with that required to operate the tokamak electrical systems, and small compared with the total plant operating cost. If a much higher duty factor is required, electrical power production could compensate for the larger cost of ^3He consumption. (About 10% make-up of the tritium burned is also required from an external source.)

V.B. ^3He RESOURCES

Reference [11] documents present and future supplies of ^3He. From now until the year 2000, a cumulative amount of hundreds of kg of ^3He could be made available from the decay of man-made tritium and from separation of the helium components of natural gas. More than 10 kg per year can be made available after the year 2000. Thus for the next several decades there would be no problem in obtaining adequate amounts of ^3He to stock and maintain the inventories of at least several tokamak-pumped lasers operating at low duty factor, even with other intensive demands for ^3He.

Exceptionally large quantities of ^3He are found in the atmosphere (~4,000 tons) and in the lunar surface soil (~ 30 kg/km^2) [11]. If either of these sources can eventually be tapped, then hundreds of kg of ^3He per year could be supplied almost indefinitely. The cost of retrieving ^3He from the atmosphere or lunar soil can only be speculative at the present time.

VI. ALTERNATIVE MATERIALS FOR EFFICIENCY ENHANCEMENT

Because of the low overall efficiency of ^3He-pumped lasers, it is desirable to consider the neutron-induced reactions in Table 1 that have larger energy releases in energetic ions.

VI.A. ^{6}LI PUMPING

An analogous breeding/lasing situation as for ^3He can be established with $^6Li(n,\alpha)T$, where a vapor of Li or of a Li compound such as LiD might be used in the gas cell. This reaction releases six times more energy than $^3He(n,p)T$, and there is no problem of lithium supply. However, the 5 times smaller cross section for the ^6Li reaction will require much higher pressure in the laser cell to realize substantially greater power density than with ^3He, and it is not clear if there are any lasants that are compatible with high densities of Li or its compounds.

More practically, the Li would be deposited as a coating on the wall of the gas cell. On the average, each neutron-induced reaction would inject one-half or less of the 4.8 MeV reaction energy into the gas cell. The particle range is relatively small and excitation of the gas would not be uniform. Thus there might not be any advantage in power density over ^3He pumping. But this system would be compatible with more lasants, since use of ^3He in the gas mixture would not be required. In general, maximum pumping power density might be achieved by using ^6Li together with ^3He.

VI.B. ^{235}U PUMPING

^{235}U-oxide has often been used in research on fission-reactor-pumped lasers, in the form of thin coatings or foils installed in the laser cells [1-3]. On the average, each fission event will deposit one-half or less of the 165 MeV of fission fragment energy into the lasant. Then the pumping power is increased by the factor $[1-f + f\times(82/0.76)]$, where f is the fraction of moderated neutrons that undergo fission. If $f = 0.1$, pumping power density is increased by a factor of order 10. For lasants having an efficiency of 1% with reference to the energetic-ion energy deposition, the laser power output can be increased to 0.5% of the fusion power. If fission fragments supply the bulk of the pumping power, it would still be advantageous to use ^{3}He in the laser mixture to breed tritium.

The penalties for adding ^{235}U are the need to dispose of fission products, the difficulty of removing large amounts of heat from the ^{235}U substrate, and possibly the inconvenience of a significant ^{235}U inventory (~ 100 g/m^2).

VII. CONCLUSIONS

It is technically feasible to moderate and convert most of the neutron output of a tokamak fusion plasma to energetic ions by the ^{3}He(n,p)T reaction in an annular array of gas cells surrounding the tokamak. The energetic ions pump a gaseous lasant, and the entire output from the annular resonator or array of resonators can be combined into a single laser beam. The fusion neutrons are moderated by D_2O assisted by some of the tokamak components. Special toroidal-field magnet design and judicious application of beryllium neutron reflectors ensure that the tritium generated in ^{3}He can replenish about 90% of the tritium burned in the fusion plasma. A large tokamak-pumped laser system would have a total ^{3}He inventory of 4 to 5 kg, and would consume ~ 1 kg of ^{3}He per year in low duty factor (~1%) operation of the laser. Numerous systems of this type could be operated with presently available ^{3}He resources. For high average duty factor, additional resources would be required.

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Table I

ENERGETIC-ION PRODUCTION BY SLOW NEUTRONS

Reaction	Energy in Charged Reaction Products	Cross Section for Thermal Neutrons (barns)
$^{3}He(n,p)T$	0.76 MeV	5300
$^{6}Li(n,\alpha)T$	4.8 MeV	920
$^{10}B(n,\alpha)^{7}Li$	2.35 MeV	3800
$^{235}U(n,ff)FF$	165 MeV	575

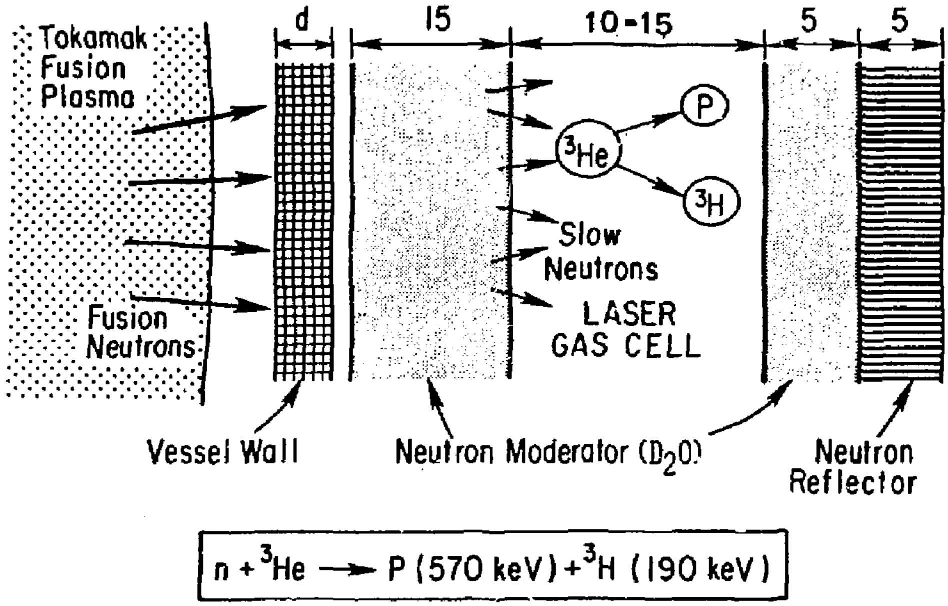

Figure 1. Conversion of fusion neutrons to energetic ions for laser pumping. Dimensions in cm. Equivalent d = 5 to 12 cm, depending on the location of the laser cells.

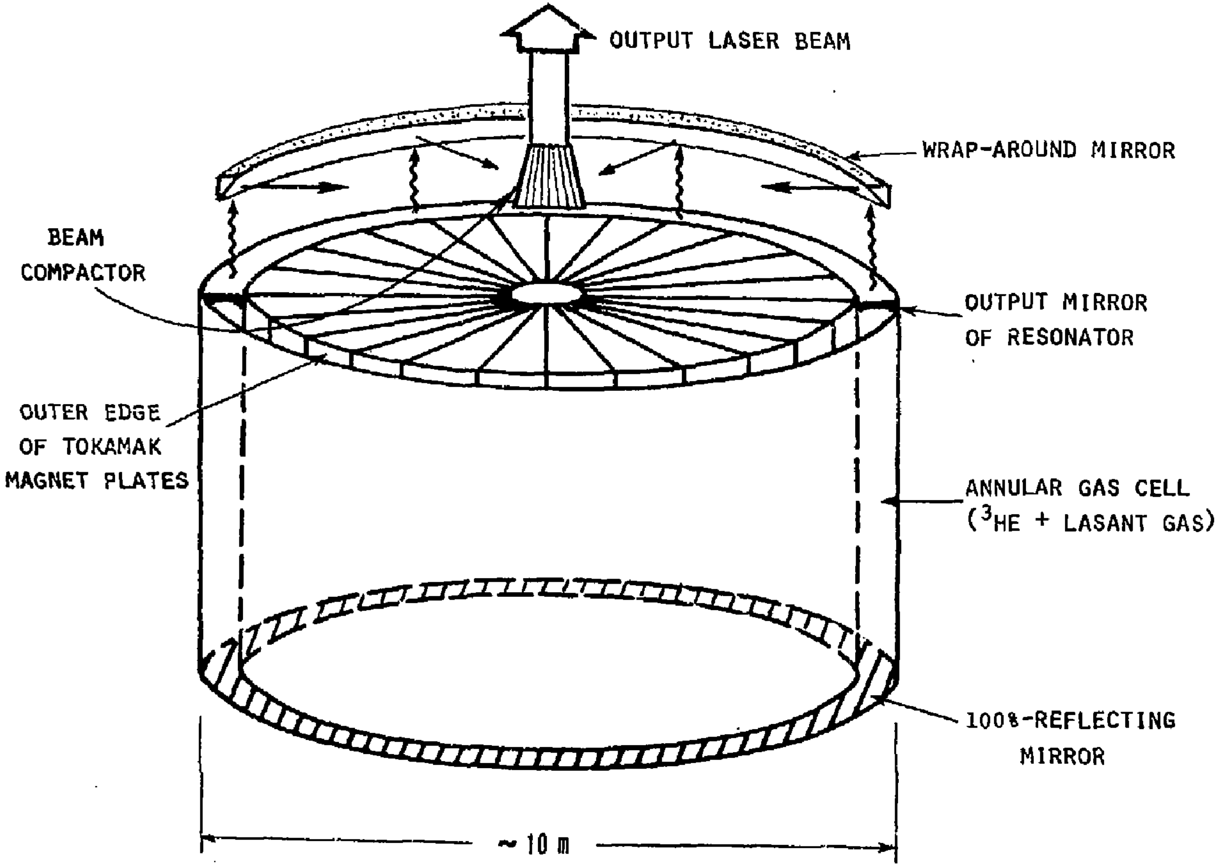

Figure 2. Tokamak-pumped laser configuration with annular laser resonator. The beam compactor is located at the focus of the wrap-around mirror.

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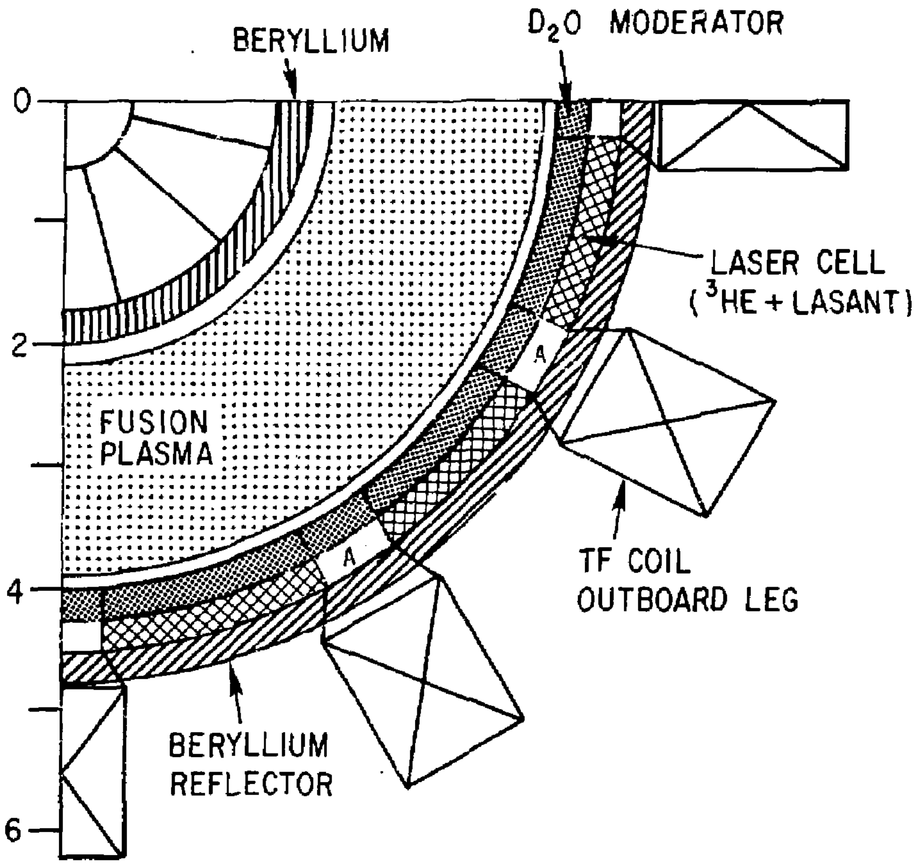

Figure 3. Plan view of one quadrant of tokamak-pumped laser system with 12 discrete TF (toroidal-field) coils. Region A is shadowed by the upper arms of the TF coils, and is used only for multi-pass lasing.

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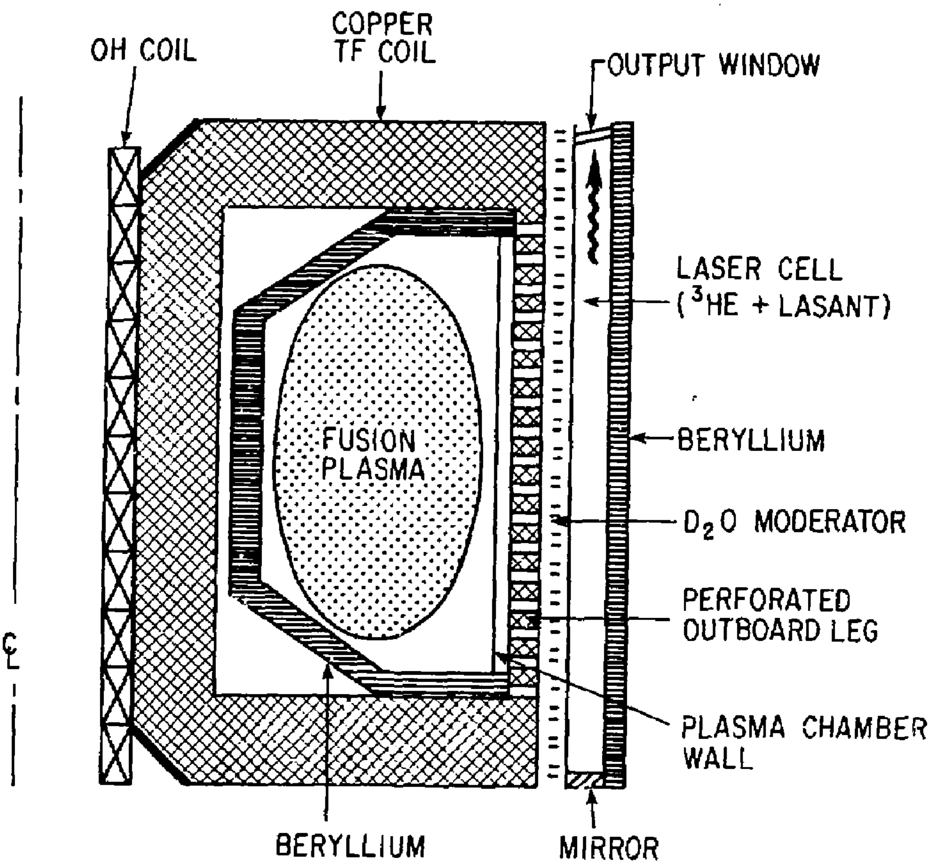

Figure 4. Elevation view of tokamak-pumped laser with contiguous TF (toroidal-field) coils. The outboard legs are perforated to maximize neutron transmission into the annular laser cell. (Not to scale.)

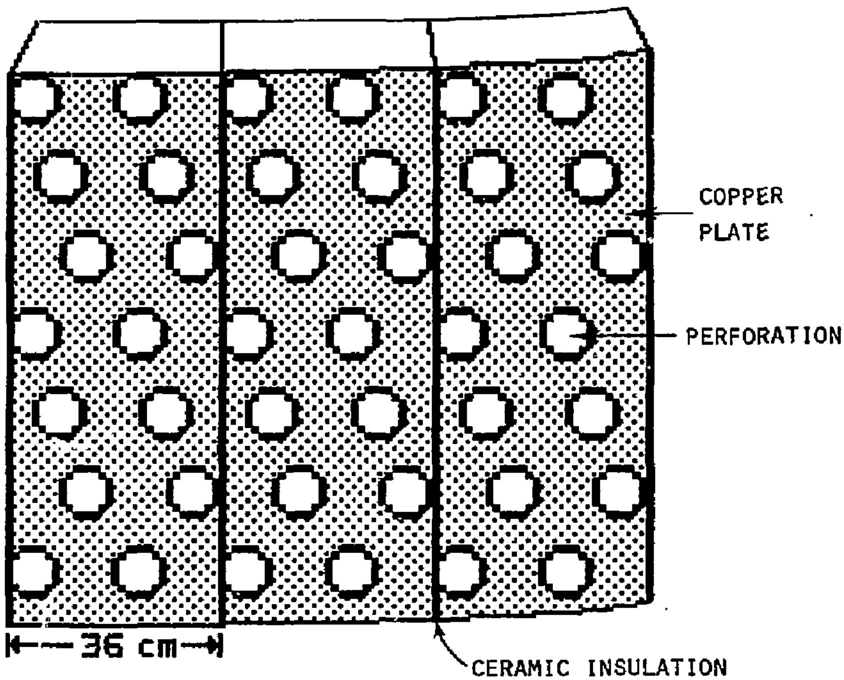

Figure 5. End-on view of outboard TF coil legs of Fig. 4, showing penetrations.

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