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FEASIBILITY OF LASER PUMPING WITH NEUTRON FLUXES FROM PRESENT-DAY LARGE TOKAMAKS

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ABSTRACT

The minimum fusion-neutron flux needed to observe nuclear-pumped lasing with tokamaks can be reduced substantially by optimizing neutron scattering into the laser cell, located between adjacent toroidal-field coils. The laser lines most readily pumped are probably the ^{3}He-Ne lines at 0.633 μ and in the infrared, where the ^{3}He-Ne gas is excited by energetic ions produced in the ^{3}He(n,p)T reaction. These lines are expected to lase at the levels of D-T neutron flux foreseen for the TFTR in 1989 ($>>10^{12}$ n/cm^2/s), while amplification should be observable at the existing levels of D-D neutron flux ($\geq 5 \times 10^9$ n/cm^2/s). Lasing on the 1.73 μ and 2.63 μ transitions of Xe may be observable at the maximum expected levels of D-T neutron flux in TFTR enhanced by scattering.

I. INTRODUCTION

For present-day tokamaks with relatively modest neutron fluxes, the most straightforward way to establish a laser pumping mechanism is to moderate (slow down) the fusion neutrons and generate energetic ions in the lasant gas by the $^3He(n,p)^3H$ or $^{235}U(n,FF)$ reaction, as indicated schematically in Fig. 1. Inelastic scattering by the tokamak vacuum vessel, protective plates, and other paraphernalia has no adverse effects on this conversion method other than the absorption of a small fraction of the neutron flux. ^3He is especially attractive from the points of view of ease of use, safety, compatibility with numerous lasants, and uniform volumetric pumping. There has also been considerable work done in pumping lasers with fission-reactor neutrons via the $^3He(n,p)$ reaction.[1,2]

The purpose of this report is to point out that by taking optimal advantage of neutron scattering into a laser gas cell, fusion-neutron pumping of ^3He-Ne laser lines may be observable even in deuterium operation of existing large tokamaks, lasing should easily occur with a small percentage of tritium in the fusion plasma, and full D-T operation should permit study of the potentially powerful nuclear-pumped Xe infrared transitions.

The considerations herein apply specifically to the TFTR tokamak[3] at Princeton, but would also hold for comparable-sized tokamak facilities in operation elsewhere.

II. HE-NE LASER

Only a handful of materials are likely to lase at the relatively low TFTR neutron fluxes. One of the feasible candidates appears to be He-Ne, where the usual ^{4}He is replaced by ^{3}He to interact with incident neutrons. Textbooks show[4] that the required pumping power density for He-Ne is ideally 0.5 mW/cc. That power density can be obtained from a thermal neutron flux $\sim 10^{11}$ n/cm^2/s for 3He pressures near 300 torr.

Experiments in thermal fission reactors have demonstrated continuous lasing on the He-Ne transitions[5] at 0.633 μ and 3.39 μ, with a threshold neutron flux of $\Gamma = 2\text{x}10^{11}$ n/cm^2/s. Gain has been measured at Γ down to less than 10^9 n/cm^2/s. To date, TFTR uncollided neutron fluxes (Γ_o) at the vacuum vessel outboard wall have been as large as $8\text{x}10^9$ n/cm^2/s in D-D operation,[6] for pulse lengths of 0.1-0.5 s. It is expected that in 1987 Γ_o will reach $5\text{x}10^{10}$ n/cm^2/s. In 1989, D-T operation should produce fusion power in the range 10 to 25 MW, corresponding to uncollided $\Gamma_o \approx$ 3 to $8\text{x}10^{12}$ n/cm^2/s. Thus D-T neutron fluxes from TFTR should comfortably drive a He-Ne oscillator, while D-D neutron fluxes even at the present levels should be adequate to study small-signal amplification of a He-Ne laser probe.[7]

III. ENHANCEMENT OF LOCAL NEUTRON FLUX

Figure 2 shows a cylndrical laser cell with neutron moderator in one of the TFTR experimental bays. The above considerations indicte that in optimal D-D operation the uncollided flux Γ_o will be a factor of 4 smaller than required to pump a He-Ne laser.

However, the actual total flux of neutrons incident on the moderator will be significantly larger than Γ_o because of scattering from massive tokamak components, principally the various magnetic coils and their support structures. Analysis of TFTR radiation fields[8] show that Γ is enhanced by a factor of 4 for a D-D fusion neutron source and a factor of 5 for D-T, at positions just outside the plasma vessel, and by factors of 2 and 3, respectively, at 30 cm radially outward from the vessel port cover. In practice, the flux enhancement will be significantly smaller because the laser assembly itself will cause a flux depression, and there may be some neutron absorption in large plasma diagnostic components not included in the analysis of Ref. 8.

To further increase the scattered neutron flux incident on the moderator, beryllium neutron reflectors would be deployed behind the experimental region, as indicated in Fig. 2. The reflectors should make it marginally possible with deuterium operation alone to achieve the deposition of 1 mW/cc ($\Gamma = 2\text{x}10^{11}$ n/cm^2/s) required for He-Ne lasing. The addition of just 1% of tritium to the deuterium tokamak plasma (1:100 T-D mixture) would approximately double the uncollided flux, and thereby ensure lasing.

The flux levels at the plasma vessel achievable in full D-T operation of TFTR will be well above the level of $2\text{x}10^{12}$ n/cm^2/s that was found in Ref. 5 to saturate the He-Ne laser output. The large collided flux ensures that lasing would occur even if the laser cavity were placed 1 to 2 meters from the plasma vessel.

IV. FISSION-FRAGMENT-PUMPED LASERS

The $^3He(n,p)T$ cross section is 5300 barns for thermal neutrons, but decreases as 1/v, where v is the neutron velocity. Hence to provide maximum pumping power density in the lasant, the neutrons must be moderated with minimum attenuation. In the event that complete moderation proves difficult, an alternative to using ^3He is the excitation of a ^4He-Ne mixture by fission fragments (FF) from $^{235}U(n,FF)$, where the ^{235}U is deposited as a thin (1-5 μ) coating on the laser cell wall. While only a small fraction of the incident neutrons would cause fission in the U coating, the 165-Mev FF energy would secure adequate pumping power density for lasing at 0.633 μ under the conditions discussed above. The U wall coating and a ^3He-Ne gas mixture could also be used together.

Regardless of the pumping mechanism, the efficiency of the He-Ne laser is not more than 0.03%, and saturation occurs at a very low power level, such as 10 mW/liter.[4,5]

More interesting lasing media are He-Xe and Ar-Xe mixtures. The threshold of thermal neutron flux for quasi-cw lasing on the 1.73 μ and 2.63 μ transitions of atomic Xe has been reported to be in the range 1 to 6×10^{13} n/cm^2/s when mixtures of ^4He-Xe or Ar-Xe were excited by fission fragments from thin ^{235}U-oxide coatings deposited on parallel plates in the laser gas cell.[9,10] (A fission reactor was used to supply the neutrons.) It may be possible to cross the lasing threshold in full D-T operation of the TFTR, with substantial enhancement of the uncollided flux (up to 8×10^{12} n/cm^2/s). In any event, small-signal gain would be observable in the TFTR neutron field, and would permit investigations to optimize the lasing process.

The ^{4}He-Xe and Ar-Xe laser media are attractive for pumping by future tokamaks generating high neutron flux because they were reported to have an efficiency of about 1% with reference to the fission-fragment energy, and a laser output exceeding 1 kW per liter.[9,10]

V. LASER CELL DESIGN CONSIDERATIONS

In order to take maximum advantage of the scattered neutron flux, the laser cell should be small with respect to the distances between major scatterers (~1 m) At the same time, the length should be sufficiently long to permit adequate gain. A suitable geometry is a cylindrical gas cell 75 cm in length and 10 cm in diameter, with either horizontal or vertical orientation (see Fig. 2). This diameter is large enough to capture most of the incident slow neutrons in ^{3}He at a typical gas pressure of about 300 torr (5:1 He-Ne mixture).[5]

The most straightforward approach to a moderator is to surround the laser cell with a polyethylene (CH_2) jacket with thickness of about 5 cm for a D-D (2.5-MeV) neutron source. In the case of a D-T (14-MeV) neutron source, the moderator would have a thickness of about 15 cm in the portion facing the uncollided flux, and 5 cm everywhere else. More attractive moderating materials that will absorb fewer neutrons are CD_2 and D_2O.

In the fission-fragment-excited case, the inner surface of the cylindrical gas cell would be coated with 3 mg/cm^2 of uranium oxide.[9,10] The cell diameter need be only 6 cm because of the generally higher pressures for the He-Xe and Ar-Xe mixtures of interest. Then the total amount of ^{235}U required in the wall coating is about 4 g, which is comparable with that used in neutron detectors on the TFTR and elsewhere.[11]

When the maximum amplifier or oscillator output power is sought, the gas cell should be rectangular in cross section, and designed to bridge the entire space between adjacent toroidal-field coils, as shown in Fig. 3. The laser cell dimensions in the He-Ne case would be approximately 75 cm x 75 cm x 10 cm, containing about 4 g of ^3He (cost ≈ $6,000). For fission-fragment pumping, the wall coating would contain a total ^{235}U mass of about 35 g, which is still only twice as large as used in sensitive neutron detectors on the TFTR.[11] Unless it is subdivided, the rectangular cell might be operated as an unstable resonator.

In the orientation shown in Fig. 2 or Fig. 3, a probe laser beam can be directed through an existing 16-cm-diameter through-hole in the lower intercoil structural component, while the output radiation can be directed through the corresponding hole in the upper structural component. The output radiation strength would be determined with an array of photodetectors, and the signals integrated to give the total power. By monitoring the output power for the ranges of neutron flux incident on the gas cell, the scaling of gain with flux, threshold neutron flux for lasing, and saturation power would be determined.

The rectangular gas cell of Fig. 3 is especially amenable to the use of a multiple-path configuration, for studies of small-signal gain.[12] Here the probe beam would enter one corner of the cell, and the top and bottom mirrors would be adjusted so that the amplified beam exited from the opposite corner. This procedure would eliminate the need to expand greatly the incident probe beam or to consolidate the output radiation.

Under conditions where the neutron flux is sufficient to drive an oscillator, the large rectangular cell could be compartmentalized across its width, with mirrors arranged so that most of the compartments serve as single-pass amplifiers for an oscillator in just one of the compartments.

An experimental program would strive to maximize the scattered neutron flux into the laser cavity, as well as investigate the consequences of inhomogeneous neutron flux and the effect of the ambient magnetic field. In the vicinity of the laser cell, this field may range from 0.1 to 1 tesla. Although magnetic-field effects are expected to be insignificant, they can be investigated by stationing the apparatus at different distances from the TFTR vacuum vessel.

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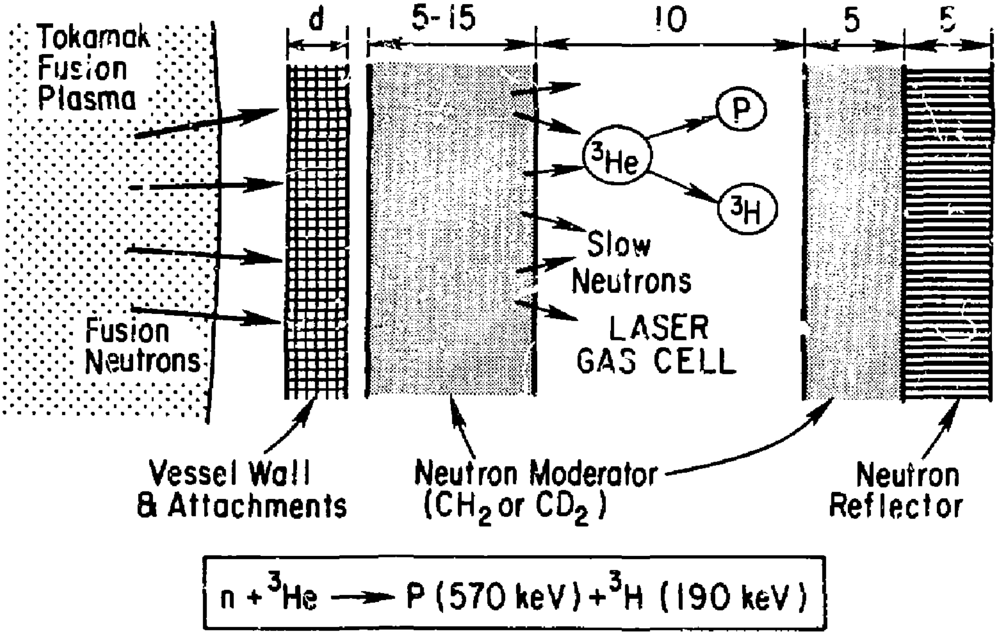

Fig. 1. Conversion of fusion neutrons to energetic ions for laser pumping. Dimensions in cm. For TFTR, equivalent d ≈ 5 cm, including port cover and in-vessel plates.

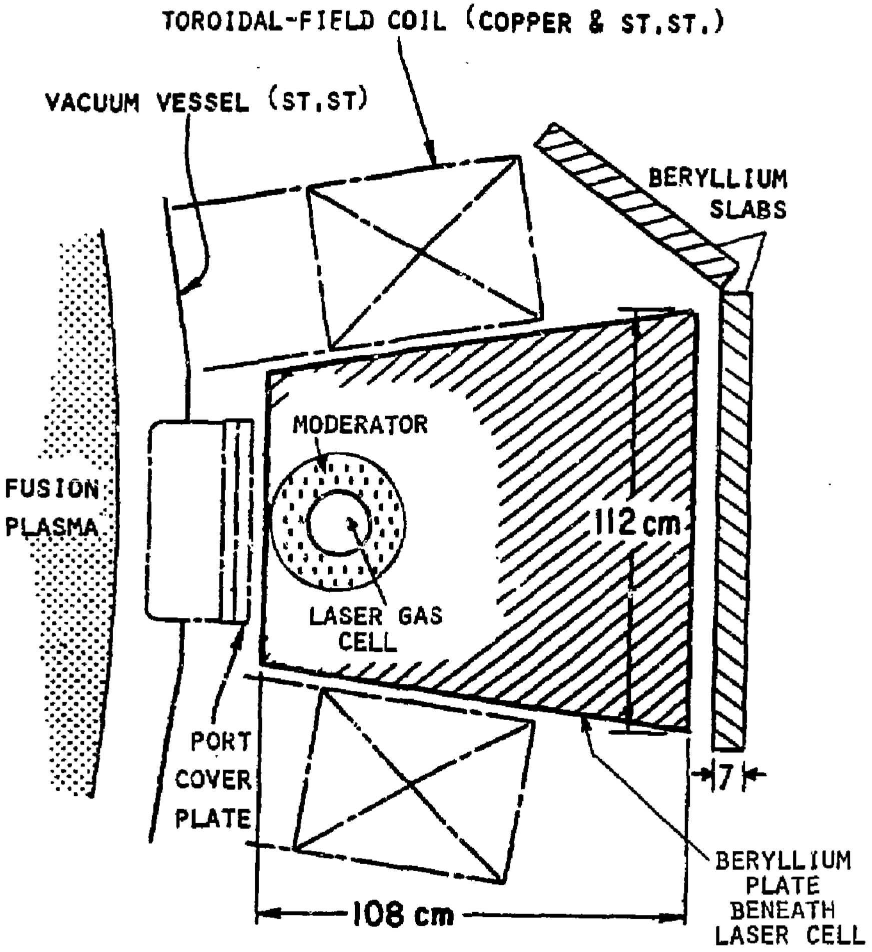

Fig. 2. Plan view showing possible location of cylindrical laser cell in TFTR experimental bay. Moderator is CH_2 or CD_2. The beryllium slabs increase the ambient neutron flux.

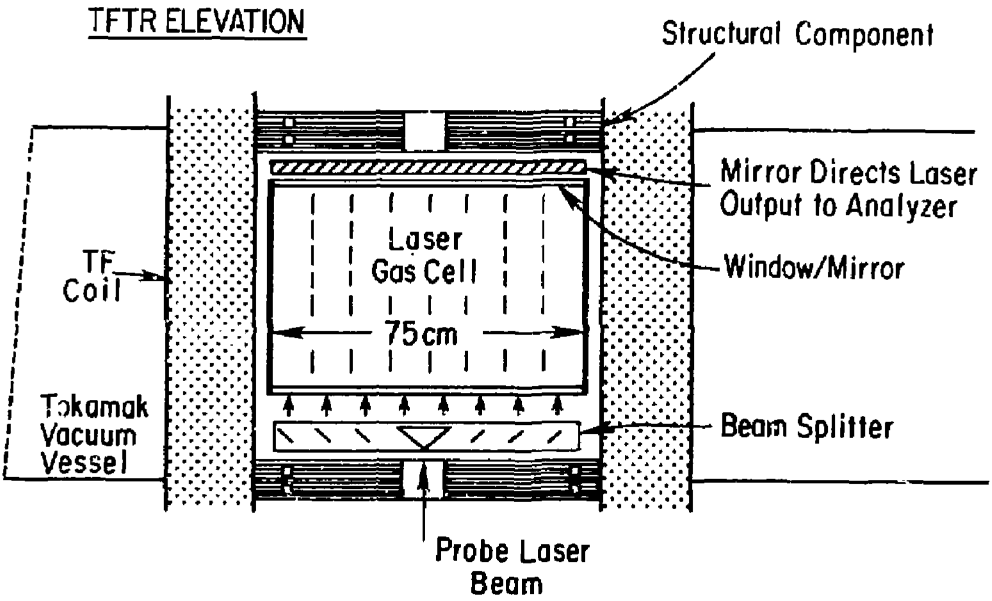

Fig. 3. Elevation view showing rectangular laser cell in TFTR experimental bay. The probe laser beam is used to study gain or for system alignment.

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